WOOL2LOOP
Final Report

Mineral wool waste back to loop with advanced sorting, pre-treatment, and alkali activation

wool2loop.eu

Grant Agreement no:	821000
Call / Topic:	H2020 CE-SC5-07-2018-2019-2020 Raw materials innovation for the circular economy: sustainable processing, reuse, recycling, and recovery schemes
Type of action:	Innovation action
Start date of project:	01.06.2019
Duration:	42 months
Coordinator:	Saint-Gobain Finland Oy

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 821000. The opinions expressed in this document reflect only the author's view and in no way reflect the European Commission's opinions. The European Commission is not responsible for any use that may be made of the information it contains.

Table of Contents

WHERE DID ALL OF THIS START? Overview of the project

Mineral wool, meaning glass wool and stone wool, is common, efficient insulation material for buildings, vehicles, and industry. Still significant amount of mineral wool waste is formed during construction and demolition of buildings adding annually up to 2,5 Mt of waste in the EU alone. Now, much of this material ends up landfilled without further utilization even though mineral materials represent remarkable potential for recovery and circular economy. Landfilling mineral wool has economic, environmental, and societal impacts even though it is not hazardous as material itself.

The WOOL2LOOP project was created to close the material loops of mineral wool at the end of its lifecycle by introducing novel geopolymer technology and value chain to construction and demolition waste sorting, analysis, pre-treatment, processing, novel products development, market introduction and commercialization. As geopolymer raw material mineral wools have been found to work as excellent raw materials as ashes, slags, and clays - and as being standardized construction products - being uniform by the composition. Geopolymers have existed for few thousand years, just thinking about volcanic ashes that were used as raw material in ancient concrete that was used in building for example Colosseum, Pantheon, and the pyramids in Egypt.

WOOL2LOOP project has aimed to introduce novel raw material, mineral wool based geopolymer aiming to replace Portland cement (OPC) in various proportions in cementitious construction materials and products. The accusing finger points to cement and concrete industry due to their heavy carbon footprint - 5-8 % share of global CO2 emissions. Blaming cement and concrete industry may be misleading, concrete - having cement as a binder - is the most used construction material in the world in absolute. Still, we need to repair and build in a massive amount in coming decades, so all existing building materials are needed, but all the opportunities to develop novel construction materials and their components are the utmost importance. Geopolymers are viable option for the whole cement and concrete industry to swift to next level in reducing carbon footprint of built environment by alternative low carbon binder systems. Different studies illustrate even 80 % lower carbon emissions for geopolymers in comparison with OPC.

WOOL2LOOP has also aimed to progress approval and standardization of novel construction materials and their main components. Also progressing circularity of material streams traditionally claimed as "waste only", there is a need and future market for "wasterials".

Built environment is built for the people. No sub-optimizing can take place in progressing low carbon, carbon neutral, circular and resource efficient built environment. People health and well-being comes first. Multiple criteria need to be considered e.g., economic viability, safety, health, longevity, aesthetics and so on.

HOW WAS THE PROJECT MANAGED?

WOOL2LOOP consortium consisted of 14 partners from nine European countries:

Saint-Gobain Finland Oy (SG), Finland – Coordinator & Industry partner
University of Oulu (UOULU), Finland – Scientific coordinator
Saint-Gobain Ecophon AB (SGE), Sweden – Industry partner
Timegate Instruments Oy (TG), Finland
Slovenian National Building and Civil Engineering Institute (ZAG), Slovenia
Termit (TER), Slovenia – Industry partner
Clover Strategy Ltd (CLO), Portugal
CWare ApS (CWARE), Denmark
Recycling Assistance BVBA (REAS), Belgium
Technical University of Delft (TUDelft), Netherlands
XTREEE, France – Industry partner
Zavod 404 (ZAV), Slovenia – Industry partner
CRH, Netherlands – Industry partner
Tree Capital (TREE), Poland – Industry partner

Figure 1 WOOL2LOOP Kick-Off Meeting 13.-14.6. 2019

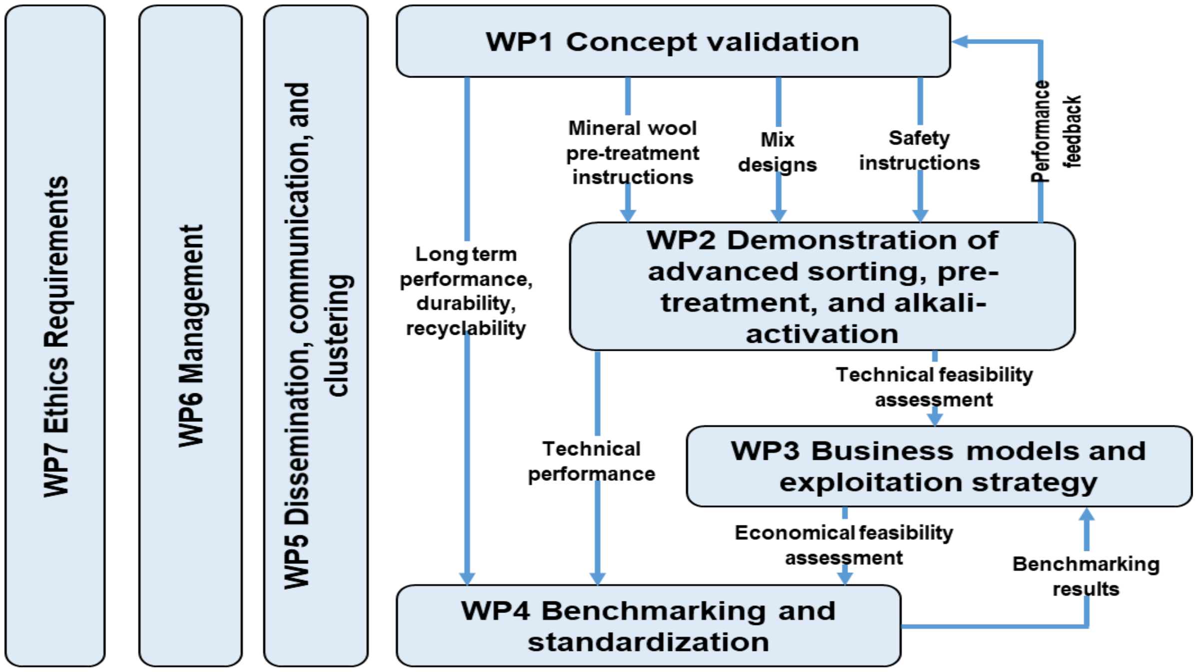


Figure 2 WOOL2LOOP Work Packages

Seven project meetings were organised throughout the WOOL2LOOP project with all partners participating:

- **13.–14.06.2019:** Kick-off; Helsinki, Finland (Host: SG)
- **05.–06.11.2019:** Project meeting 2; Lier, Belgium (Host: CRH)
- **15.06.2020:** Project meeting 3; Virtual (BlueJeans) (Host: SG)
- **23.11.2020:** Project meeting 4; Virtual (MS Teams) (Host: SG)
- **21.06.2021:** Project meeting 5; Virtual (MS Teams) (Host: SG)
- **29.–30.11.2021:** Project meeting 6; Hybrid (MS Teams) & Hyvinkää, Finland (Host: SG)
- **1.–2.6.2022:** Project meeting 7; Hybrid (MS Teams), Ljubljana, Slovenia (Hosts: ZAG, TER, SG)
- **25.10.2022:** Project meeting 8; Lisbon, Portugal (Host: SG)
- **26.10.2022:** WOOL2LOOP Final conference, Lisbon, Portugal (Hosts: UOULU, SG)

As standard elements, the meetings included the following:
- Situation updates by the Coordinator
- Greetings from the EC or External Expert Advisory Board
- Presentation of progress in each WP
- Each partners' presentation of their work since the previous project meeting
- Executive Board meeting
- General Assembly meeting
- Exploitation Committee meeting

WHAT DID WE DO IN THE LAB?

Concept validation and project aims

Based on results obtained in WOOL2LOOP, ball mill is a feasible milling method for mineral wool waste to achieve sufficiently small particle size. However, it is possible to feed only blowing wool type material (lump size <5 cm in diameter) into ball mill as received.

Based on the results there is no significant difference in the ball milling result between different mineral wool types. Additionally, dry vs. wet ball milling was studied. There was no significant difference in the material fineness in dry vs. wet milling process. In addition to ball mill, a hydraulic press was used to mill mineral wool samples. It was concluded that there was no significant difference in the final material fineness between mineral wool samples after pressing.

Figure 3 Mineral wool before and after shredding and milling.

Other critical aspect of mineral wool wastes is their organic resin content and resin type. Based on the literature, possible resin types in mineral wools include, but are not limited to, phenol-formaldehyde-urea resins, phenol-formaldehyde resols, phenol resins, melamine-urea-formaldehyde, polyesters, polyamides, furan-based resins, and polysiloxane-polyol hybrid organo-inorganic binder. Other often used organic binder components are de-dusting oils, emulsifiers, dyes, silanes, ammonium sulphate, ammonium hydroxide, extenders, water, and so-called scavengers (such as ammonia, melamine, dicyanide amide and urea) which are used to minimize free formaldehyde during mineral wool production. The exhaustive listing gives indication of the challenge to analyse, pre-treat and control these components.

Mixtures and properties for applications

APPLICATION	PARTNER CONDUCTING THE PILOT	RESEARCH INSTITUTE DEVELOPING THE MIX DESIGN
Acoustic panels (foaming)	SGE	UOULU
Pavement slabs	TREE	UOULU
Substrate	Cultilene	UOULU
Dry mix mortar	SG	UOULU
Façade elements	TER	ZAG
Concrete slabs	CRH	TUDelft
3D printing	XTREEE, ZAV	ZAG

Figure 4 The table shows different applications for mineral wool waste in the project.

Technical University of Delft's (TUDelft) part in the project was to assist the concrete mixture design with mineral wools, and to evaluate the properties of the mixtures developed by different partners. With blast furnace slag and mineral wool as the main precursors, with the addition of alkali-solution and aggregates, concrete can be made.

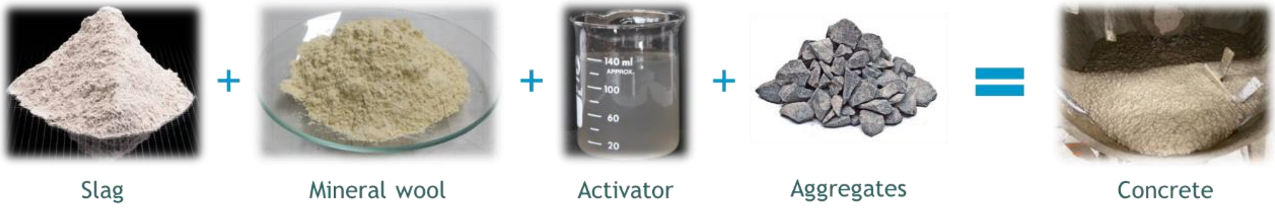


Figure 5 The process of turning mineral wool waste into concrete

To serve as a satisfactory building material, concrete needs to meet several requirements, regarding mechanical properties, durability, volume stability, and so on. The labs in TUDelft are equipped with various facilities and the macro-scale properties are interpreted with the micro-scale characterizations. Partners of WOOL2LOOP sent samples to TUDelft and their performances were comprehensively investigated in TUDelft.

Figure 6 Strength and shrinkage tests

The concrete, especially alkali-activated concrete, will show shrinkage, especially at the early age, either because of external drying, or because of internal consumption of water due to hydration reactions. This kind of shrinkage is normally hard to reduce. Adding mineral wool, however, gives a solution to this issue. During mixing, most of the wool is evenly distributed in the concrete, but due to the fibre-like shape of the wool, some cannot be dispersed and can agglomerate. The good side of the imperfect dispersion is that the wool agglomeration can form liquid reservoirs, which can gradually release liquid, to compensate the consumption due to reaction or drying. In this way, the early-age shrinkage can be mitigated. This is a big advantage for the utilization of mineral wool in concrete since otherwise the shrinkage may lead to cracking of the concrete.

Figure 7 Freeze and thaw damage of concrete without (left) and with mineral (right)

Since the incorporation of mineral wool increases the porosity of the concrete, the carbonation resistance and chloride resistance will become slightly lower. However, the freeze and thaw resistance become better due to the presence of insulated voids, which are helpful to release the expanding pressure when water freezes becoming ice. As can be seen from the figure above, the concrete show less damage when mineral wool is added. The durability results suggest a promising potential of mineral wool to be used in alkali-activated concrete.

Experiments were also conducted on alkali-activated concrete with recycled aggregate containing mineral wool, and the comparable durability of the concrete with and without recycled aggregates shows us the feasibility to reuse the wool-containing concrete at the end of their service life, to further improve the sustainability of alkali-activated concrete.

3D printing

One of the main goals of the WOOL2LOOP project was to find novel applications for mineral waste. Aside from the conventional construction products, TUDelft also developed a mixture design that could be used in 3D printing applications.

Using different industrial by-products, such as fly ash and slag, and glass wool waste obtained from demolition sites it was possible to produce a material that can be used for extrusion 3D printing construction processes.

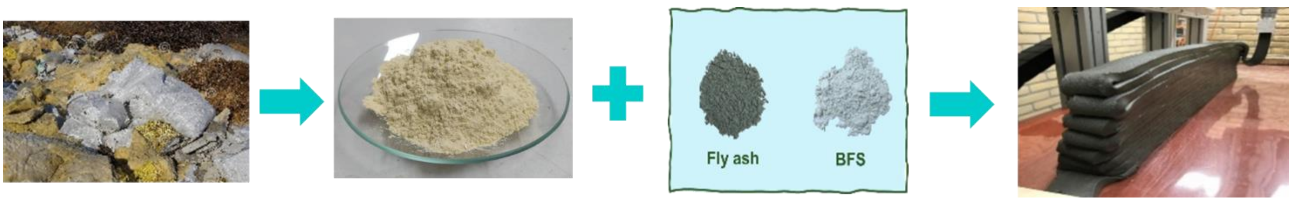


Figure 8 The process of turning mineral wool waste into 3D printable construction material

The main characteristics of these types of materials are three: flowable, good shape retention, and strong enough to sustain layers on top during the printing process. These properties were firstly tested with conventional methods in the construction field, e.g., slump, flow, and compression tests.

Figure 9 3D printable mixture being tested

But to standardize 3D printing requirements, more sophisticated methods are needed, thus during the WOOL2LOOP project several experiments were performed using rheology as a basis to define such methods.

In the end, it has been suggested that four tests are needed for standardizing 3D printable alkali-activated materials using fly ash, slag, and glass wool waste: strain sweep, step strain, frequency sweep, and viscosity tests.

All the properties needed for 3D printable alkali-activated mixtures in this project can be quantitatively measured, and later compared and reproduced with the mentioned tests.

Figure 10 A structure printed with 3D printable alkali-activated mixture

The 3D printable alkali-activated mixture was successfully tested in a medium lab-scale printer. And to finalize the WOOL2LOOP project, the effect of different temperatures on the properties of printable mixtures was studied, showing that temperatures above 30 °C considerably increased the strength of the mixtures.

The large-scale pilot was managed by XTREEE, helping to the industrialization of alkali-activated materials which are known for having a lower CO_2 emission footprint than common Portland cement.

Obtaining and modifying mix designs

Slovenian National Building And Civil Engineering Institute (ZAG) was responsible for developing and optimising the mix design for façade panels. At the beginning of the project, mineral wool waste was obtained from Termit as they are allowed to collect construction and demolition waste, including mineral wool. Since the mineral wool waste contained residues, other construction and demolition waste, it was first cleaned from other contaminants such as wood, pebbles, and other construction debris. The mineral wool waste was also separated into glass and stone wool, and all mineral wool waste was dried prior to further pre-treatment.

In the next step, the mineral wool waste was ground. On a laboratory scale, material could be processed relatively quickly, but on a large scale, processing is more challenging. Several grinding methods suitable for the larger scale were tested, such as the press machine and jaw crusher, but none of them was good: the ground material was not fine enough after the grinding process. The best option was to use a concrete mixer, where steel balls were added along with the material. This way, a finely ground material was obtained in the end.

Figure 11 Concrete mixer for pre-treatment (milling) of mineral wool waste

After the milling, the material was sieved below 63 microns and precursors were ready for characterization. Mineral wool larger than 63 microns was ground again. This milled waste mineral wool was used for preliminary testing in the laboratory and not for larger-scale pilot production.

In 2019 and 2020, many different mixtures were made using only waste glass or stone wool to test the material itself: setting time, curing, and demoulding time. Different alkali activators were tested, sodium silicate, sodium hydroxide, and a mixture of both. The preliminary mixtures were cured at 40 °C for three days and then selected ones were cured at room temperature for further testing. Room temperature was chosen because it consumes less energy. Unfortunately, when only glass or stone wool waste was used, it took about a week to demould the samples. Therefore, different co-binders such as fly ash, slag, metakaolin, or lime were added to speed up the process. In all prepared mixtures to which co-binders were added, as much mineral wool as possible was used.

Figure 12 An example of alkali activated mineral wool before and after curing at 40 °C for three days.

After many trials, first façade panels were produced. They consisted of local slag, local fly ash, and waste stone wool. The mixture had a compressive strength of about 40 MPa and bending strengths of around 15 MPa after 28 days. Panels showed little shrinkage and almost no efflorescence after 28 days. Unfortunately, the top layer sagged when subjected to the freeze-thaw test, so this mix need to be optimized.

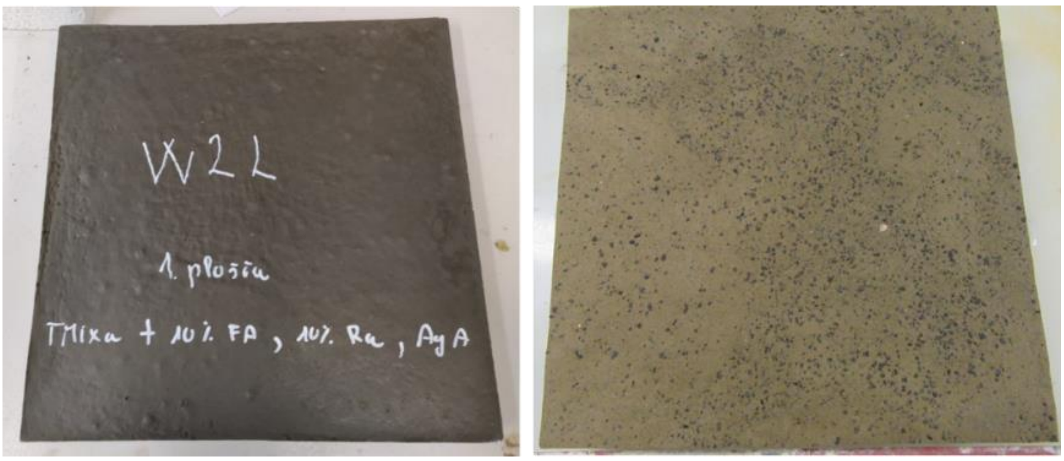


Figure 13 First façade panels prepared at ZAG. Unfortunately, they were not frost resistant.

A few more mixtures were prepared and subjected to the freeze-thaw test before using the mix design to prepare a larger façade panel to see if it was frost resistant or not.

Three mixes were selected: Mix A, consisting of stone wool, sodium silicate, NaOH, local slag, fly ash, and aggregate; Mix B, stone wool, sodium silicate, NaOH, lime, metakaolin, and aggregate; and Mix C, stone wool, sodium silicate, NaOH, lime, metakaolin, local slag, and aggregate.

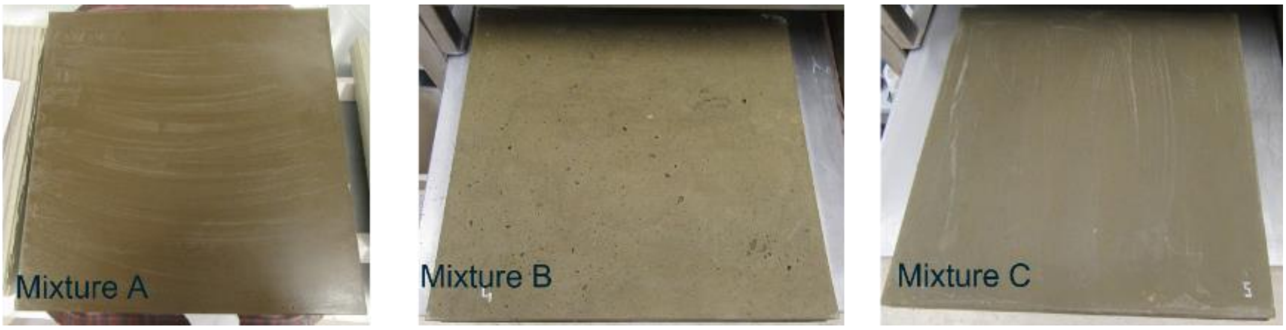


Figure 14 Façade panels prepared after many trials that could be suitable for pilot production. All were cured at room temperature.

Based on the mechanical properties, chemical composition, demoulding time, freeze-thaw tests (mixture A was not resistant) and the workability of the mixtures (slump tests), mix design C was selected for further pilot production. The selected mix design contains 70 wt% stone wool waste, 10 wt% local slags, 18 wt% metakaolin, and 2 wt% lime based on dry mass of precursors.

In October 2020, the pilot production in Termit was started. In the beginning, the mixture design was too liquid, so it had to be changed a little bit by adding more waste wool and less sodium silicate. Different mix designs were tested in Termit until the mix had good workability and a reasonable slump. However, after about 6 months, more problems emerged. The ground mineral wool was not the same quality. Larger particles were found, and the mixture required more liquid for the same workability. In addition, panels could not be demoulded after one day, they showed efflorescence, the workability was poor and some of them were very porous. The main reason for the changed properties of the façade panels is the ground mineral wool that was not homogeneous enough. Ground mineral wool contains a smaller amount of the finest fraction (<63 microns), and this has a great influence on the mechanical and other properties of the panels. Also, the workability is much worse with larger particles. However, due to poor workability, it is very difficult to produce facade panels. Therefore, the mixture should be modified again.

During pilot production, two changes were made to the mix design developed in the lab. First, more/less mineral wool or sodium silicate were added, which was done in Termit and due to the curvature of panels, observed efflorescence, bad workability and porous structure, some more mixtures in the lab were systematically designed and different curing conditions tested to reduce the curvature of the panels, speed up the demoulding process and improve the properties of the finished panels. After many different trials, it was decided to cure the panels at room temperature for three days and then at 60 °C and 60 % humidity for three days. The panels showed good mechanical properties, no curvature, and low efflorescence when cured for three days at 60 °C and 60 % humidity. All panels produced after the second modifications were frost resistant. In addition, three different surfaces of the facade panels were produced: smooth, rough, and imitation of wood.

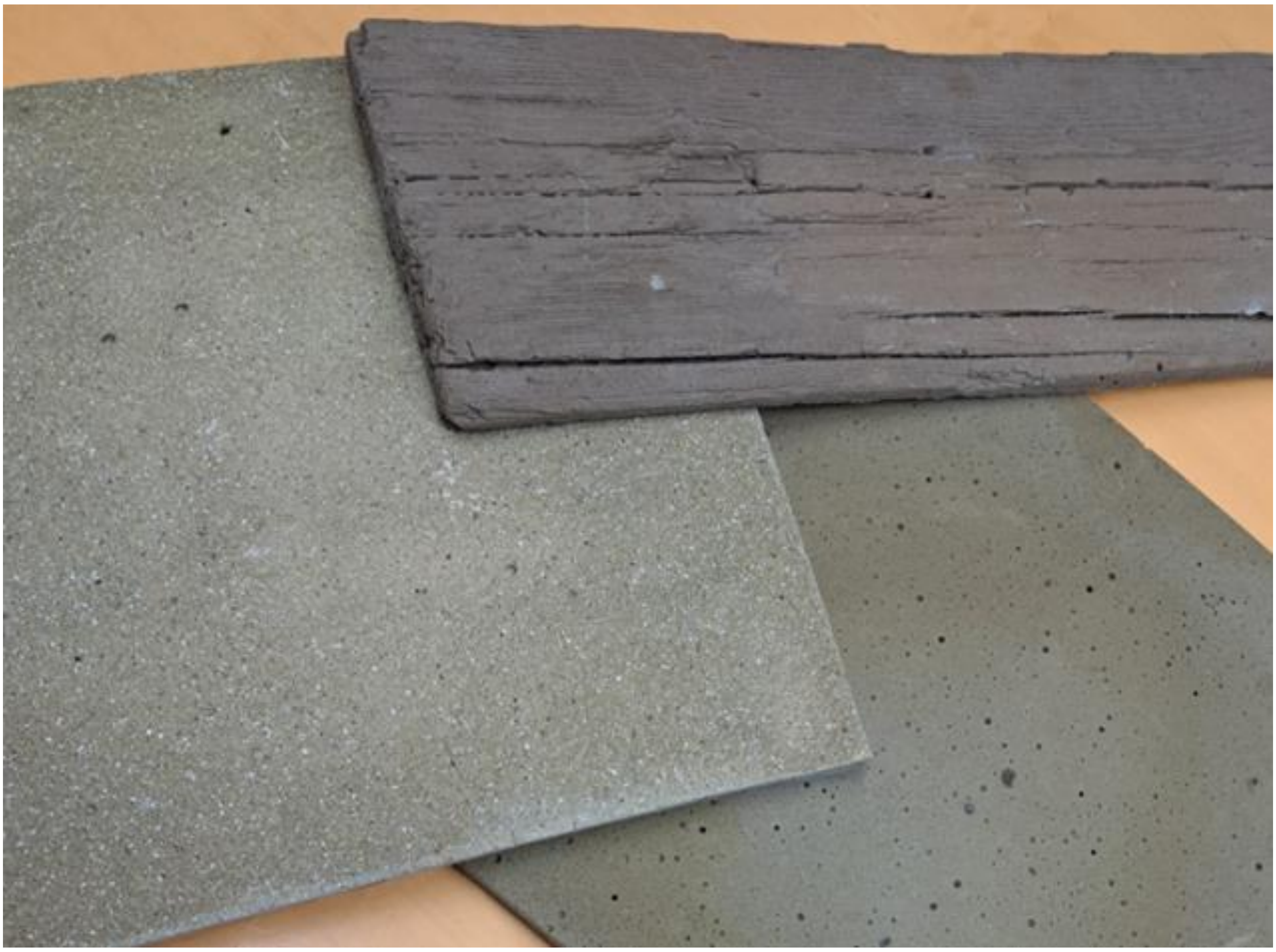


Figure 15 Different surfaces of façade panels prepared in Termit

WHAT DID WE DO ON THE JOBSITES, INDUSTRIAL PLANTS AND BEYOND?

Sourcing and analysing – Grupa TREE

Thanks to many years of experience, TREE GROUP has specialized in complex demolition and earthmoving works. As TREE pays special attention to the environment and how it affects it, one of the most dynamically developing branches of the company is the recycling department. The company is a member of EDA (European Demolition Association) and has taken part in an international project co-financed by the European Union, WOOL2LOOP. As an industry partner TREE was responsible for development of the best demolition practices such as minimizing the contact between mineral wool and operator or to reduce transportation costs. Another task was to develop methods of pavement slabs production and implementation of pilot production line.

Figure 16 TREE Group headquarters

Mineral wool is a popular material used in construction due to its insulating and acoustic properties as well as non-flammability. It is present in the dry walls, suspended ceilings, ventilation ducts, under elevation, and so on. While dismantling, usually manually, it emits dust and irritating particles. To prevent direct human contact with wool and its dust, and to have a possibility to collect mineral wool waste from danger zone or to increase efficiency of collecting wool on site, TREE has developed smart demolition practices. The idea was to use a demolition robot with grapples to collect the wool and to remotely observe robot's work field through VR goggles that stream the image from a system of cameras mounted on the robot.

Although VR technology is present in everyday life it was not easy to develop a system that would survive conditions on site and enables to work efficiently. The system must be resistant to dust and vibrations, easy to move and install on machines, with available and cheap components in case it must be replaced and should assure live-streaming on-site with minimum delays. Also, no need for additional infrastructure like Wi-Fi transmitters or additional network is desired, so it can be easily used on different sites.

Figure 17 Smart demolition with VR technology

Despite of strange COVID times, lack of electronic parts and limited possibilities of interpersonal contact the task was completed, and its efficiency has been checked in the field. In comparison with traditional manual collection of mineral wool the job was done faster with using smart demolition. But it needs to be remembered, that using VR technology requires additional training for robot's operator and additional EHS procedures.

Mineral wool is a material with a very low density. After being dismantled, it takes a lot of space and while being transported in traditional way in containers or trucks, it is mostly air that is transported. So, compression of the wool is required. That allows to lower the costs of transport and reduce the carbon footprint during the demolition works. There are few applicable solutions to do that. First is to reduce the size of mineral wool by shredding it in an industrial shredder. This solution is also a necessary step of pre-treatment of wool for further recycling processes. Second solution is to press the mineral wool in a press-container and third – to press it in a movable baling machine. Each has its pros and cons, so every case (site) needs to be considered individually. There are many factors that can influence the economy of the process such as transportation distance, possibility of return with load, quantity of mineral wool to transport or humidity or type of mineral wool.

Figure 18 Shredding of the wool waste

To find an alternative solution for landfilling the waste wool was to use it as a substrate in production. For that TREE was about to implement pilot production of pavement slabs made from that wool. The idea was to develop a recipe that could be used in a classic production line of pavement slabs – that means the mortar should be appropriate for vibropressing process without moulding. After dozens of tested formulas TREE managed to develop the one that works with vibropress and gives the product with similar or even better mechanical properties than a conventional concrete pavement slabs.

Figure 19 From left milled wool, pavement slabs made with wool and W2L pavement

Wool from demolition site is hard material to handle, as it differs in age, chemical composition, humidity, additives etc. It is hard to foresee its properties and it is almost impossible to create a universal formula for all kinds of wool. In the WOOL2LOOP pilot mix of glass and stone wool was used. Firstly shredded, then milled it for a very fine powder and used in production with other substrates like slag, sand, and chemical activator. Production of pavement slabs with mineral wool is challenging because many factors impact the results. It is crucial to maintain constant temperature and humidity both during production and curing. Other factors that influence the production are type of wool, impurities, type of chemical activator, concentration of chemical activator, type of substrates, type of mixer, pressing force in vibropress and quality of wool milling. But it is not impossible: Click here to see the video from the production site.

Sourcing and analysing – Recycling Assistance

During the WOOL2LOOP project Recycling Assistance BV visited various jobsites. Specially to perform or to check Pre-demolition audit, selective demolition & on-site separation, use of handheld XRF devices, health & safety measurements, and sampling for W2L-partners.

The jobsites that were visited jobsites:

- WTC office building, **Brussels (BE)**
- Proximus office building, **Antwerp (BE)**
- Residential building, **Aartselaar (BE)**
- Residential building, **Turnhout (BE)**
- Office building, **Oudergem-Brussels (BE)**
- Hospital building, **Helsinki (FI)**
- + additional sites for sampling

Figure 20 Photos from different jobsites

Based on the information gathered during the visiting of the jobsites, Recycling Assistance BV formulated guidelines for pre-demolition audits with mineral wool involved. Those guidelines include identifying all types and quantities of mineral wool; (destructively) checking ceilings, internal partition walls, roofs, and external walls; differentiating between glass and stone wool (visually / XRF / TG Raman, etc.); checking quality (visual appearance, contaminants, dryness, etc.); and estimate quantities based on field work and the floor plan of the building.

Why should we use a handheld XRF? The use of a handheld XRF is useful to differentiate between GLASS & STONE wool when visual identification is difficult due to darkness because demolition sites are often disconnected from the grid. It has also been proven useful for to differentiate between GLASS & STONE wool for tiles and panels and milled wool. During the project Recycling Assistance BV also studied the use of a handheld XRF for detailed information on chemical composition (heavy elements) to evaluate the recycling possibilities and the human health risks. The evaluation of the human health risks seems possible because there was a change in composition after the introduction of the bio soluble fibres in the mineral wool. But this last aspect needs more research.

So, as the conclusion of the work of Recycling Assistance BV in the WOOL2LOOP project, it can be said that the pre-demolition audit is the starting point of a good and efficient demolition waste management and recycling scheme and guarantees proper waste identification. Handheld XRF identification of mineral wool waste could add useful information at various stages within the WOOL2LOOP recycling scheme. And Specific guidelines and recommendations regarding pre-demolition audits and selective demolition for mineral wool products were reported in deliverable D2.1: “Guidelines for best practices in mineral wool waste sourcing and pre-treatment”.

In a future which will be focusing on circular construction, the opportunities offered by the WOOL2LOOP project are very promising and the build environment is waiting to be mined for mineral wool!

DEMO CRH

Geopolymer concrete production for precast wall elements

Geopolymer concrete is produced by the alkaline activation of precursors. These precursors used to make the concrete can be from diverse sources including industrial by-products. Currently, ground granulated blast furnace slag and fly ashes are commonly used as precursors in the geopolymers. In the WOOL2LOOP project, mineral wool was experimented as a precursor for making geopolymer concrete. Ground granulated blast furnace slag in combination with the mineral wool was used in the mixtures produced by CRH during the industrial-scale demonstrations of geopolymer concrete.

Industrial-scale production of geopolymer concrete is challenging due to the nature of the raw materials used and the properties of the final product. The alkaline activators used in the production are corrosive in nature and can cause health and safety issues. Any minor changes in the production protocol could significantly impact the performance of the final product. There are also no standards or guidelines for industrial-scale production and quality control of geopolymer concrete elements. Lack of awareness among the workers about the production of geopolymer concrete is another challenge. CRH tried to address these issues during the industrial-scale demonstration within the WOOL2LOOP project.

Figure 21 Mould for the wall elements (left). The elements are kept covered for the first 7 days. Later the sections were transported to the yard and kept exposed.

The development of mineral wool geopolymer concrete to produce precast elements followed a systematic step-by-step approach. In the first stage, a laboratory experimental program was conducted to create the mix designs with sufficient mechanical and durability properties. The upgradation of the Heembeton factory (CRH precast factory in the Netherlands) was the next stage. The factory was equipped with special tanks and piping systems for handling the alkaline activators. A complete safety audit of the production facility was conducted, and necessary changes were made as per the findings of the safety audit to safely produce geopolymer concrete. Once the mix design is finalized and the factory is upgraded, several production trials were conducted at the plant to optimize the production process and to gain experience in industrial-scale production.

A detailed checklist covering all the aspects of the production was created before the final demonstration. Several precast walling sections were created, and the properties of the produced concrete were monitored during the demonstration. The mechanical properties of the concrete were in line with the expectations however the appearance of non-structural cracks on the surface of final products remained an issue with these elements. The researchers are working on a solution to this problem.

The WOOL2LOOP project created a lot of knowledge related to the mix designing, factory production mineral wool geopolymer concrete. The commercialization of precast geopolymer products will depend on approvals from the concerned authorities. Also, the long-term performance of structural elements constructed with geopolymer concrete needs to be better understood through continuous research. As there is a continuous search for the development of sustainable products within CRH, the created knowledge and the production facility would be valuable for the future ahead.

DEMO Saint-Gobain Finland

Milling glass wool with the Mil-Tek IC 60 screw mill

Figure 22 Mil-Tek IC60 screw mill

A special screw mill was ordered to tackle the processing of mineral wool for the project. The mill was installed at the Forssa ISOVER glass wool plant in August 2020. The objective was to mill glass wool waste from the factory process to suitable pre-cursor material for alkali activation.

In January 2021 the mill was transported to the Nokia plant, a Saint-Gobain partner. The new location would be ideal for milling demolition waste, as this material was already handled on site. Demolition waste often contains other mixed waste materials, and so the need for sorting the material before milling is essential.

Figure 23 Construction and demolition mineral wool waste with contaminants

The overall performance of the mill was not totally consistent. When the mill was operating efficiently, the end material particle distribution was totally satisfactory and was deemed suitable for geopolymer raw material with very little additional processing. Larger particles where still mixed in with the fines, which caused quality concerns. Therefore, additional ball milling by an outside partner was needed to obtain the suitable particle size distribution for alkali activation.

In total, approximately 20 tons of process waste as well as construction waste was milled for the project. Useful information from the milled wool has also been obtained, such as particle size distribution, composition data using XRF-spectroscopy, as well as microbiological data.

Laakso hospital wool demolition and wool recovery

Figure 24 Collected mineral wool panels

A demonstration was done for recovering mineral wool from the Laakso health clinic in Helsinki. Mineral wool from the drywalls was collected, milled, and utilized in co-operation with the city of Helsinki circular economy cluster.

The objective was to gather data on demolition resources needed for recovering the wool and to utilize it as raw material for a competition organized by the city, aimed at various concrete manufacturing companies and start-ups in Finland.

A pre-demolition audit was done with a Recycling assistance (REAS Bvba). Locations and amounts of mineral wool were determined and sampling was conducted using a portable XRF-analysis machine.

A total of 11 tons of mineral wool was finally collected and milled by an external partner. An additional 7 tons of mixed mineral wool material was separated during demolition. This included acoustic panels, technical insulation, and insulation from the sandwich elements.

Figure 25 Manual stripping was ten times slower than traditional methods.

Conclusion of the mineral wool recovery pilot showed that it is possible to collect clean insulation material separately, but with a significant cost. The average amount of wool gathered was 15 m^2/hour, with two operators working in the same location, adding to the overall man-hours spent.

Dry mix concrete and masonry mortar

Figure 26 Manually adding the binder to a mixer at Weber dry mix plant in Oulu.

Promising strength results were initially achieved in both dry mix concrete and masonry formulations with a geopolymer, including fine milled glass wool and slag material. laboratory work was conducted to determine further strength development.

Mineral wool pre-cursor material was first produced with a screw mill at the Isover glass wool plant in Forssa and was further ball milled externally. Using this milled wool, a batch of dry mix binder was mixed, and a final industrial-scale pilot production was done at Weber dry mix plant at Oulu, where the binder was manually inserted to the mixer and filler and aggregates were added, to produce both masonry mortar, as well as dry mix concrete. A total of 6 tons of finished masonry mortar and dry mix concrete was manufactured.

A clear practical challenge in production was the mineral wool material itself, which gets stuck in silos and other equipment and cleaning the production line after mixing is very time consuming. The laboratory testing has shown that there is still need for further development for raw material processing, mineral wool behaviour during activation and the long-term performance of the geopolymer binder.

Figure 27 Dry mix flowerpot made for a weathering test

DEMO Saint-Gobain Ecophon

Saint-Gobain Ecophon's first approach to make acoustic panels out of geopolymer was making foam geopolymers, bubble panels, in which foam was incorporated into the geopolymer mix in a wet state followed by curing and drying. Despite the promising results in small-scale prototypes e.g., density (200-300 kg/m^3), reaction to fire properties (A2/B) and appearance, scaling up the panels caused some problems. Due to limited control in the geometry of the pores and limitation in mixing capacity, the larger panel had high dust release, an uneven surface caused by high shrinkage, and a lower porosity which resulted in lower sound absorbing properties. Due to obstacles in scaling up the foam panels, SGE decided to work on a new type of panel by means of surface geopolymerization of shredded glass wool fibres as described below.

In this case, there was no need to mill and sieve the glass wool after shredding, which save time and energy in the process. The shredded fibres were mixed with an alkaline solution and placed in a spin dryer to remove excess liquid. The semi-dry fibres were opened using a fluffing air chamber. The fluffed-up fibres were then moulded in full-size woody moulds (60*60cm), followed by pressing, curing, and drying in the oven. To avoid cracks in the prototypes, during the moulding a few wood sticks were placed in between fibres as reinforcement. The dried panels were then laminated using SGE regular surface veils.

Figure 28 The flowchart of the production process

The density of panels varied between 200-300 kg, depending on the drying time and the moisture remaining in the panels. The flexural 3-point bending strength for the produced panels in comparison with an Ecophon regular product with the same thickness is shown in the table below. As can be seen, even after the climate chamber, the mechanical strength was good enough.

CONDITION	AVERAGE ULTIMATE STRESS (KPA)
ROOM TEMPERATURE	173
CLIMATE CHAMBER (30 °C, 95 %, 28 DAYS)	138
ÈCOPHON REGULAR PRODUCT - REF	120

Cone calorimeter predicted a reaction to fire class of A2/B with no ignition, which is the same as Ecophon regular products. Two panels made of green binder and phenolic binder glass wool waste were sent to an external partner, for VOC emission test M1 (28 days). All the parameters such as TVOC, Formaldehyde and Ammonia were below the limit values and hence, both passed the test.

Reverberation room method was performed to study the sound absorption properties of the produced panels. The averaged reverberation time was compared to the empty room and the values for a standard product of which the absorption properties were known as Class A from a certified lab test.

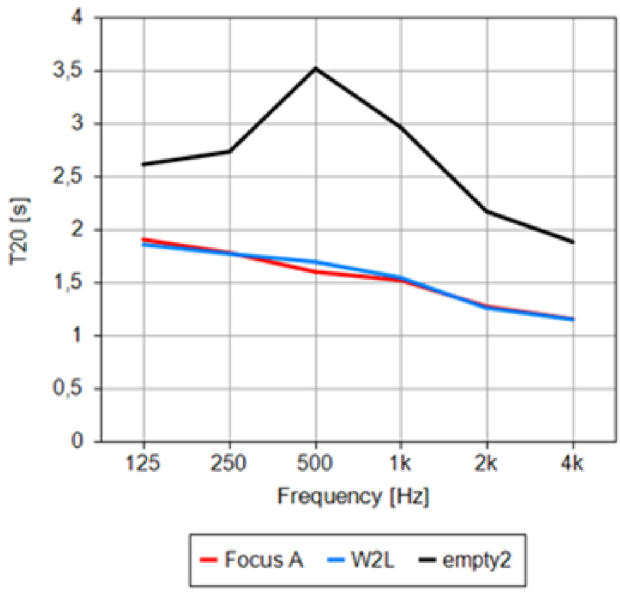


Figure 29 A graph showing the sound absorption test results

Conclusion and future work

Produced panels contain 70-80 wt% recycled content. Although the density of the panels is 2-4 times higher than Ecophon's regular products, it is still in the possible range defined in the project description. Most of the specifications assigned at the beginning of the project have been achieved; however, some more characterization like durability test and sound insulation properties must be investigated. To make the products on an industrial scale, still some modification and optimization in the process are needed.

DEMO TREE

Sourcing and transportation of demolition mineral wool

TREE has adapted its demolition robot to the VR technology. The idea was to remotely observe robot’s work field through VR goggles that stream the image from a system of cameras mounted on the robot.

Figure 30 Dismantling mineral wool with remotely controlled robot

TREE was responsible to find a solution that would optimize the cost of wool transportation. Due to its low-density mineral wool is taking a lot of space so transporting it is very costly. To reduce the volume of the wool TREE tested three solutions. Firstly, TREE tried to reduce the size of mineral wool by shredding it in an industrial shredder. This solution helped to reduce the volume by 25 % and it is a method of pre-treatment of wool for further recycling processes.

Second solution was to press the mineral wool in a press-container. This caused up to 80 % volume reduction in case of dry glass wool. If the wool was wet there was no big difference in the volume reduction. Next equipment was a baling machine. As a result, 15 m3 was compressed to two 1m3 cubes (86 % volume reduction). What is more important this solution enables not only to transport lower volume but also storage in the same shape. However, this method is suitable only for mineral wool in large sheets.

Figure 31 Four containers approx. 30 m3 each transferred to one 20 m3 press-container. On the right, wool before and after pressing.

Production of mineral wool geopolymer pavement slabs

TREE has collected mineral wool differing in type and age from demolition site. Next, of primary shredded mineral wool was milled in a ball mill. Milled wool was used as a raw material in a production of pavement slabs. Other raw materials were: GGBFS, sand and chemical activator. Weighted number of raw materials was mixed in a planetary mixer.

WOOL2LOOP

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 821000. The opinions expressed in this document reflect only the author’s view and in no way reflect the European Commission’s opinions. The European Commission is not responsible for any use that may be made of the information it contains.

After mixing the ingredients a mortar of soil consistency was received. This mortar was put into vibropress where it was pressed and vibrate. Ready slab had to be cured for 28 days in a room temperature and 50 % humidity.

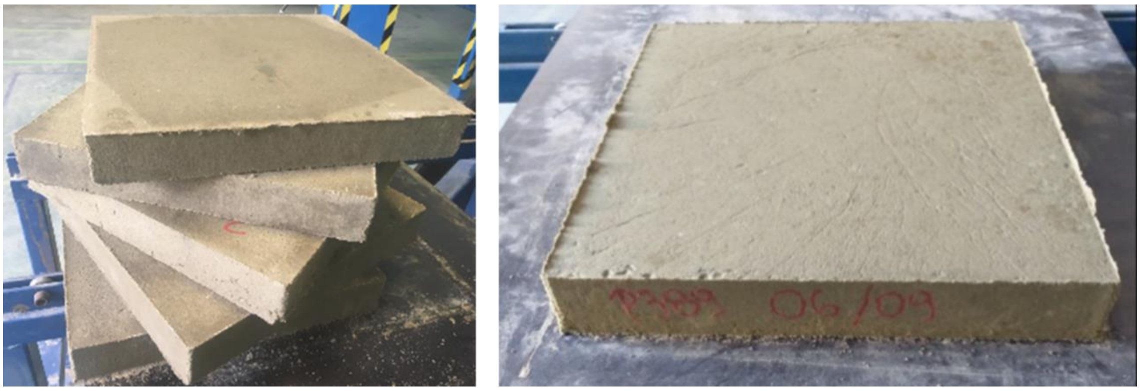


Figure 32 On the left, the ready slabs and on the right the slab made with Geosil

TREE, so far, made 435 pavement slabs with 134 formulas' trials using 2 517 kg of milled wool. Formulas differ in raw materials' ratio and type of chemical activator. Four chemical activators were used: 95 % Betol, water glass, mix of NaOH and water glass, Geosil. The problem was to find a mortar that won't harden before making three slabs and keeping the best mechanical properties simultaneously. After using NaOH solution there were white sediment on the slabs. The best results were received with Geosil. The mortar wouldn't harden too fast, and it was workable. Unfortunately, this solution was found too late (after consulting and visiting Saint-Gobain Ecophon) and there was no time for testing the properties of slabs. Moreover, cost of Geosil was 30 % bigger than Betol while the used amount stayed the same.

Also, to reduce the costs of raw materials TREE tried to produce slabs with local raw materials. Several trials were made based on local slag and water glass. Unfortunately, all slabs made from local slag were fragile. Twenty-four pavement slabs were sent to ZAG for durability tests. TREE managed to determine the most promising formula which has the biggest bending force and that lasts through 150 cycles of freeze-thaw test. TREE made a pavement from ready slabs to observe how the slabs last through time.

Figure 33 Pavement made from WOOL2LOOP slabs

Cloverstrategy took several samples of air, water, and soil to check the influence of pavement slabs on environment and safety during production. Results will be summarised in a public science article.

Conclusion and next step

Observing robot's work field remotely ensures a safety distance between hazardous materials and an operator which eliminates exposition to a dangerous environment and enables to work in hard-to-reach places. In case of mineral wool, it helps to prevent from itching, skin irritation and dust inhalation. Also, doing work with the robot was even three times faster than doing the same work manually (depending on the type of work).

Shredding is a very important method of pre-treatment of wool for further recycling processes. It also shortens time of next processes such as milling.
Pavement slabs made from mineral wool are durable (they can last through 150 cycles of freeze-thaw test) but it was observed that after immersing the slab into water, the water changed colour into red. It is obligatory to made test on chemical content of the water.
It is hard to obtain similar properties of mineral wool from demolition site. Every time it differs in chemical composition, humidity, type, and age. This causes that slab will be different every time that type of wool changes (for e.g., colour of slabs will be different, type of leached substances will differ).

Production of pavement slabs with mineral wool is difficult because many factors impact the results. It is crucial to maintain constant temperature (20°C) and humidity at 50 % level. Any deviations from those numbers can influence the production. Other factors that influence the production are type of chemical activator, concentration of chemical activator, type of substrates, type of mixer, pressing force in vibropress, quality of wool milling and temperature of curing.

TREE found a solution for shorting time of milling. It is possible to mill wool in a disc mill with high efficiency (400 kg/h).

Figure 34 Disc mill and ultrasonic sieving machine

One of the main assumptions of the project was to made slabs from sieved wool. TREE found a solution for high efficiency sieving (ultrasonic – 40 kg/h) but eventually TREE eliminated this step from production (the milling was so efficient that it was possible to skip this step).

DEMO XTREEE

XtreeE has developed two different technologies and approaches to 3D print geopolymers at a large scale and high speed. We demonstrate the ability to use a mix with a sleeping phase between 20 and 45 min and still be able to activate it to be able to 3D print structure with a high building rate. These technologies allow to print complex shape with a good productivity being relevant is the construction market. XtreeE has also developed adapted 3D printing geometries for acoustic panels with optimize shape, allowing best performances regarding different types of spaces.

Figure 35 3D printing in progress

Conclusion and next step

The first technology is based on chemical activation with a liquid activator to acceleration and awake the product from the sleeping face. This technology was paused due to a lake of development and results in an activator with relevant property to activate the Geopolymer. A second technology was developed to achieve and produce a working technology. This is based on heat activation. We manage to print a 3D acoustic panel at a large scale, showing the potential of this technology. Next step, on the one hand, will be to improve the technologies to increase the productivity. On the other hand, to secure the supply chain of raw material to reassure future clients equipped with this technology.

Figure 36 Industrial large scale 3D printing with three different batches and printing parameters

DEMO Zavod 404

Zavod 404 is a private NGO from Slovenija who focuses on machine and software development in different fields of technology. One of these fields is 3D printing. Our role in WOOL2LOOP project was in the segment of technology demonstration.

We were tasked with the development of a geopolymer mixture and a printing system with which we will be able to print it. In addition, we were focusing on smaller scales - on objects that can be printed in a lab with nozzle diabetes up to 2 mm. In contrast to large scale 3D printing smaller scales offer several possibilities of temperature-controlled polymerization - which was the advantage we used in our favour.

Figure 37 Temperature controlled nozzle during extrusion (left) and an example of 3D printed object

Our developed mixture uses up to 40 % of recycled mineral wool, with equal parts of glass wool (20 %) and stone wool (20 %). The mixture is prepared right before printing in small batches and is then pressure fed into the printhead and then extruded into the desired shape. The printed material was then tested for mechanical properties. Additionally, tests were conducted to determine if the material has any dampening effect on the electromagnetic field. The test revealed that there is no significant dampening, there is however a lending effect which could be studied further.

3D printing platform

Figure 38 Screenshots of the online 3D printing platform

The second goal of Zavod 404 was to develop and deploy a 3D printing platform with an active 3D printing simulation. The visitors can choose either from 3 distinct preloaded models and 3 different mixtures, or they can upload their own 3D design files. From all the files they can then check the printing time, weight, and printed volume for each of the selected printing mixtures.

The visitors can also fill out the online contact form to get in touch with one of the partners who is involved in 3D printing of geopolymers. The goal of the platform is to broaden awareness regarding the use of 3D printing in the construction industry as a new emerging technology.

DEMO Termit

Figure 39 Test field in Termit

The task of industrial partner Termit was to find out the method and to produce the non-reinforced structures facade panels out of waste mineral wool. The recipe was given by the research institute ZAG. The panels were made as precast elements and they represent low-risk products. The main requirements for them are compressive and flexural strengths, abrasion resistance, and durability in the representative environment

Termit is a mining company from Slovenia. Termit produces quartz sand and auxiliary materials for foundries and steelworks. Quartz sand is being mined in open pits. Quartz sand is used in the foundry industry, building industry, sports programs (football fields, golf fields, volleyball fields), and agriculture.

Termit has a permit for waste processing. Yearly collect and process around 50,000 tons of waste. The collected waste also includes waste containing waste mineral wool. Termit took mineral wool waste from their dump site and removed all impurities.

For further production, the wool had to be dry (max 0.5 % of humidity). We had put the wool into open boxes, then put it in a warm and dry place and at the end also through the drying machine. The mineral wool was milled to a particle size below 100 μm. We found that the material was the best ground in the concrete mixer with balls.

Termit collected and milled 2 tons of mineral wool. Termit installed all the necessary equipment to produce facade panels (for milling drying sieving, weighing, dosing, mixing, vibrating, curing, and storing) and prepared all the necessary documents (requirements for raw materials, instructions for analyses, technological procedure, work instructions, and safety instructions). The mix design (recipe) was made by ZAG.

TERMIT had produced panels with dimensions 400 mm x 400 mm x 20 mm and profiled panels in the shape of wood in dimensions 500 mm x 190 mm x 20 mm.
The panels had three different surface finishing (smooth, rough, profiled). A rough surface was made with sandblasting.

From the panels that failed, we made a decorative fence (this is also a demonstration of the use of panels after their end of life). Since some of the material for producing façade panels was still available, we also made cobble stones by using the same recipe and the same technological procedure.

Façade panels were used as the cover of facades in our production plant. The most important characteristics are bending strength and durability (resistance to climatic conditions) which are quite harsh in Slovenia. Panels and cobblestones were tested at the laboratory premises of ZAG they are monitored by non-destructive testing throughout the project duration as well as beyond this period. Analysis of the manufactured panels showed that Façade panels are frost resistant (they passed 150 cycles of freezing and thawing) and have compressive and bending strengths above the required limits.

ARE THESE PRODUCTS FIT FOR INTENDED USE?

Alternative recycling methods

Research was done on the existing recycling practices of mineral wool in Europe. Focus was to determine the main operators and methods for recycling, as well as compiling the results using specified sustainability indicators. The methodology used in this evaluation was developed by the Institution of Chemical Engineers (IChemE)

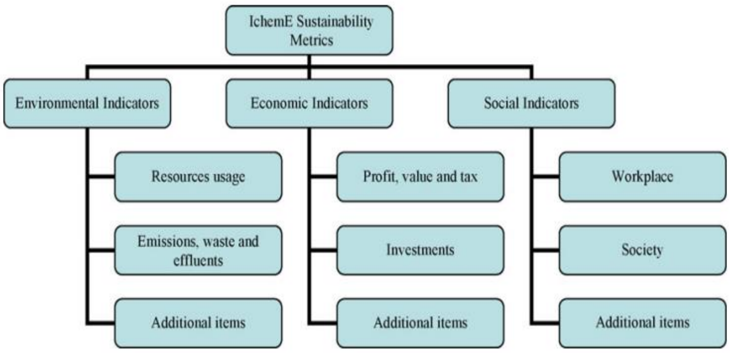


Figure 40 Institution of Chemical engineers' methodology

Majority of the data concerning the processes was collected from public sources. Many key values, such as energy consumption of any given process, were based on estimating the process parameters.

The recycling schemes were graded with a score of 1-5 based on environmental, economic, and social criteria and compared against both landfilling as well as WOOL2LOOP. The basis for grading were environmental, economic, and social aspects of the respective schemes.

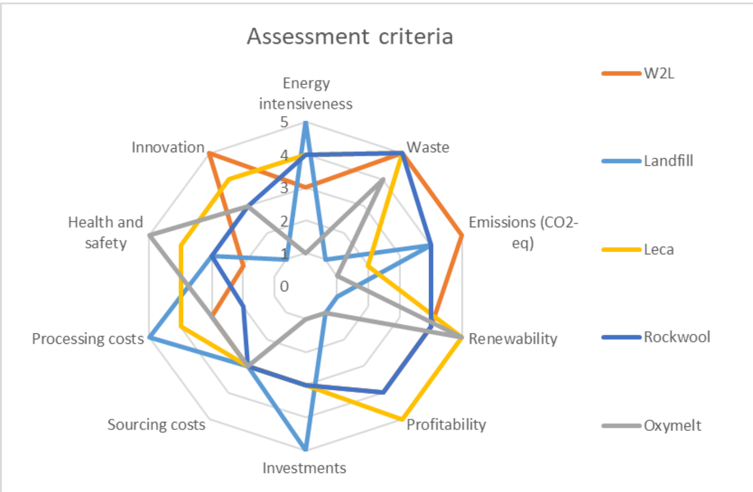


Figure 41 Radar graph presentation of the compared recycling methods

As seen in figure Low scoring was defined as having an undesirable effect (high cost and emissions etc.) and a high score as desirable (low cost, environmentally friendly, etc.).

Oxymelt

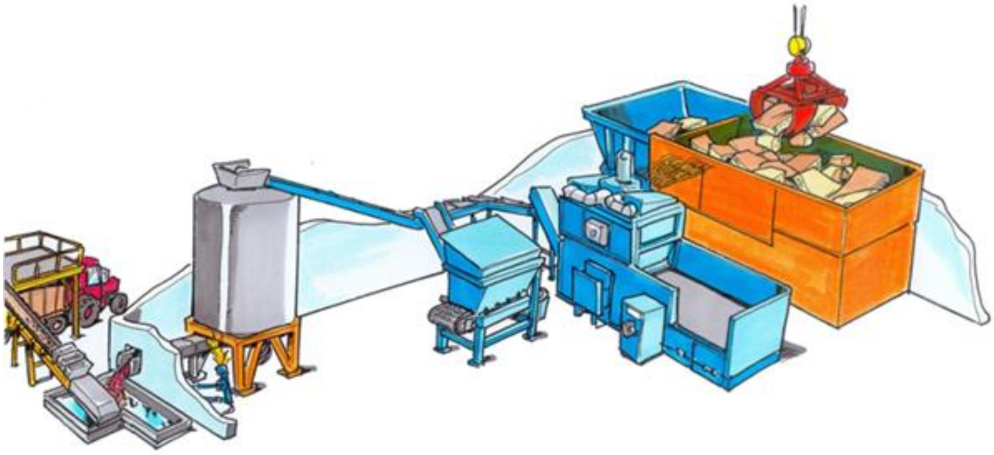


Figure 42 Oxymelt plant schematic

Oxymelt technology was developed in the 1990s, specifically for remelting glass wool waste and is based on burning the glass wool with natural gas with the aid of oxygen input. It can also be used to recycle construction site waste.

The drawbacks of Oxymelt are its high energy consumption and limited capacity, only a small amount of melted material per batch can be re-used in glass wool production. Possible option in the future could be SBM (Submerged Burner Melter) which is more efficient and environmentally friendly and would increase the recyclable amount of cullet and double the recycling capacity with a reduced CO2-emissions by 50 %.

Leca

Figure 43 Mixing mineral wool into natural clay

Mineral wool can partially substitute clay as raw material in the light weight expanded clay manufacturing process. Advantage of using mineral wool is that it is dry, when in contrast, clay contains 35 % water. By adding mineral wool to the clay, the use of heating energy can be reduced. Also, less virgin raw material is needed.

The process does not require large investments and the process is relatively easy to maintain. Either process waste or demolition waste can be used as raw material. Mineral wool material needs to be preprocessed or milled before mixed in the clay material. Thousands of tons of mineral wool can be processed annually in the Leca process.

Rockwool

Figure 44 Construction and demolition waste containing mineral wool.

The “Rockcycle”-recycling system includes containers brought to the construction site. Stone wool residues are collected and separated from other construction waste. Rockwool also collects construction and demolition waste in co-operation with waste management companies.

159,000 tons of stone wool was processed and used Globally for new stone wool products in the year 2019. Insulation from municipal recycling stations and major renovation projects is also collected, granulated, and sent to a Rockwool factory to be utilized as raw material for new products.

Testing, standardization, and product approvals

Current practices of reuse of waste mineral wool

There is 2,5 Mt/year of waste mineral wool landfilled annually what on one side due to its voluminosity present burden for the environment but on the other side it could be reused or serve as a raw material for recycling.

When it comes to the reuse existing practices of recycling were identified as part of the project. As main reuse routes the following were identified: 1) Oxymelt technology (Saint-Gobain, France), ii) to complement virgin materials in stone wool products (Rockwool, BENELUX), and iii) as an additive in lightweight expanded clay aggregate (Leca, Denmark). Oxymelt technology was developed in the 90s, for remelting specifically glass wool waste. It makes it possible to recycle production waste from a glass wool factory as well as to recycle construction site waste. The most mass intensive recycling of waste wool was established in 2019 (Rockwool) which processed around 159 000 tons of wool residues into new stone wool products. Mineral wool can partially substitute clay (natural raw material is preserved) in the production of lightweight clay aggregate. No large investments are needed, and the process is relatively easy to maintain. Beside those identified above some other reuses were found, like plant growing substrate, compressed panels, etc. But still, most of the waste mineral wool is not yet put back into the material loop.

When all these options were compared (by score from one to five based on environmental, economic, and social criteria) to the landfilling and to the potential of WOOL2LOOP solutions, it has been recognized the benefit of WOOL2LOOP solutions in terms of waste disposal, CO_2 emissions, and – innovation.

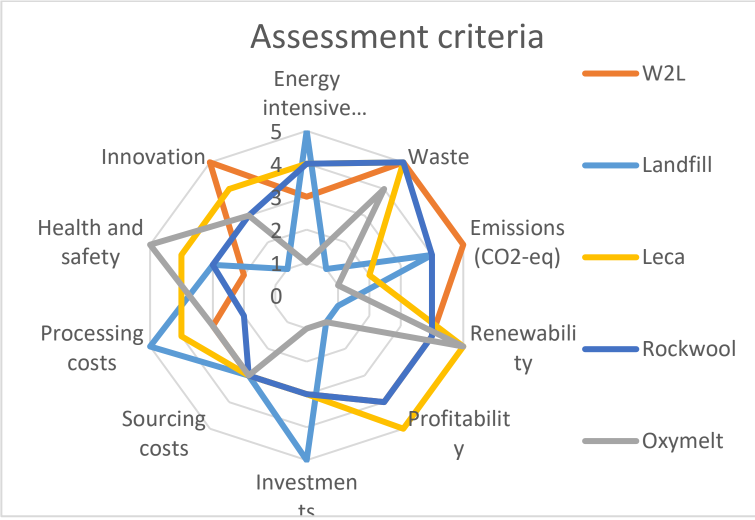


Figure 45 Environmental, economic, and social comparison of identified reuse practices to landfilling or WOOL2LOOP solution

Recycling of waste mineral wool into building products

WOOL2LOOP products belong to the construction sector where it is essential to follow Construction Product Regulation (CPR) to put building products on the market. CPR lays down harmonized rules for the marketing of construction products in the EU. There are harmonized standards for most building products but not yet for the alkali activated building products (except for the acoustic panels from the WOOL2LOOP assortment of products). Therefore, application for European Technical Assessment (ETA), or National technical assessment, alternative procedures for construction products not covered by harmonized standards will need to be applied for that type of products when regular production will take place.

Within the project for all developed product (façade panels, paver units, alkali activated concrete, general purpose mortar/ready dry mix, and acoustic panels), we have defined intended use of products, and conditions of exposure. Based on this we were able to identify which parameters are important to be tested. And since there is no standards for alkali activated material (AAM), provisions from standard for cement based or clay-based products have been used, also considering some recent findings from AAM related Rilem technical committees.

Figure 46 Figure 2: Sieving analysis (left), water glass modulus determination (middle), consistency/spread determination (right)

Beside type testing of the products which addressed all the essential characteristics relevant for intended use, the methodology in all cases also defines factory production control, i.e., permanent and internal control of production in a factory to guarantee the constant quality of the products.

Figure 47 Abrasion resistance of pavers (left), hydrothermal behaviour of façade panels (middle), sound absorption measurement (right)

Most of the parameters qualify products fit for their intended use; among others it has been confirmed that alkali activated products from waste mineral wool can reach high mechanical strength and provide excellent freeze -thaw resistance, but some specific parameters still need to be optimized before industrial upscaling. Additionally demo sites will provide feedback of the products behaviour in real conditions.

Results and findings from this work package will serve as the basis for the assessment of products through national or European Technical Approval systems. In the case of later products will be also able to affix CE mark and to be put on the EU market.

Figure 48 CE marking of building products according to CPR

LCA and CO_2 reduction impacts

One of the aims of the WOOL2LOOP project is to assess the products from the sustainable construction point of view. LCA (Life Cycle Assessment) and LCCA (Life Cycle Cost Assessment) are two methodologies used by the international community to address the environmental and economic impacts of a product.

The main objective of the LCA study conducted is to investigate the environmental impacts associated with different life cycle stages of the products made from large fractions of recycled mineral or glass wool (namely, Architectural façade panels, Pavement slabs, Alkali Activated concrete, Shredded glass wool panels, Dry Concrete S100, Masonry Mortar ML5 and 3D printing mixture). The LCA study has been conducted in accordance with the principles and framework for LCA, which are defined in the international standard for LCA ISO 14040 and ISO 14044. We have also considered European standard for Environmental Product Declarations (EPD) EN 15804: 12 + A2: 2019, which provides core product category rules (PCR) for Type III environmental declarations for any construction product and construction service. The study consists of four phases: the goal and scope definition, inventory analysis, impact assessment and interpretation phase. We have used Thinkstep Gabi software combined with Ecoinvent and Gabi databases to perform calculations.

All life cycle stages of the products have been studied, namely the production phase, installation phase, the product use phase, end of life phase as well as benefits and loads beyond the system boundary.

According to the standard EN 15804:2012+A2:2019, the life cycle impact assessment results are presented with four sets of parameters with different units and models for additional impact categories: 1) Parameters describing core environmental impacts, such as global warming potential, acidification potential etc. 2) Parameters describing additional/optional environmental impacts, such as particulate matter emissions, ionizing radiation, etc., 3) Parameters describing resource use, such as total use of renewable primary energy resources, use of secondary material, etc., 4) Other environmental information describing waste categories (e.g. disposal of hazardous waste) and information describing output flows (e.g. energy emitted).

The overall assessment has shown that most of the environmental burdens arise from the production process for all seven developed products.

Deeper analysis of the WOOL2LOOP products has revealed the environmental hot spots in the whole life cycle of the products that can be used as a guideline during the large-scale production set-up to optimize the environmental performance of the products in question. Due to the nature of the production, which is currently established at the pilot line or laboratory level with sub-optimal transport path lengths, LCA has revealed opportunities to lower the environmental footprint of the production primarily. Generally, alkali activators used in the production stage are in this project the material that is most likely to cause higher environmental burdens even if the mass is smaller. If the process of production is energy demanding, this is one of the first issues to resolve and optimise, too. On the other side, waste mineral wool as a secondary input enters the system with lower environmental burdens due to the calculation principals.

From the environmental performance point of view confirmed through calculating life cycle assessment all innovative products developed during project are very promising and further research in this direction will be productive and desired. The main point of developing such products is lowering the use of virgin materials and seeking new ways to reuse and recycle demolished building materials that are otherwise used in landfills. There is a finite quantity of virgin materials that Earth can offer and finite space that landfilled products can occupy. Attempts to help with these challenges are more that welcome.
The overall assessment of the products from the environmental point of view is favourable. The impacts are generally comparable or better compared to the similar products on the market.

On the other hand, the primary aim of the LCCA of WOOL2LOOP products was to determine the economic performance of the products, expressed in cost terms over the life cycle, also considering the future cash flows related to maintenance and recycling of the product. Such information can form input data when evaluating the life cycle cost of a building.

The methodology used is based on EN 16627:2015 as well as on ISO 15686-5:2017. The concept of modular approach (the same approach also well established in the LCA) and division of life cycle of products into life cycle stages was used.

The analysis included different influential parameters, such as 1) production costs, 2) installation costs, which mainly depend on labour cost, mostly related to the country of installation, 3) maintenance costs which depend mainly on the workload and connected cost as well, 4) end of life costs, 5) the influence of discounting of the costs over the reference service life of products and 6) the externalities costs connected to the environmental burdens calculated in LCA.

Based on the scenarios in each life cycle stage a range of results was calculated using the Discounted Cash Flow Formula, as a part of a valuation method DCF (Discounted cash flow), with various possible discount rates, varying from -0,02 to 0,1.

Results of the calculations of production stage show, that the scale of production and optimisation affect the costs greatly. When a production is not yet optimised, but it is on an industrial scale (or at least pilot scale), the costs are likely to not change as greatly, as in the cases, where the scale of production is laboratory. It must be considered that the assessed productions and production costs are likely to change once they reach an optimised industrial scale.

Relatively high influence is seen in labour cost (i.e., economic region of installation). This influence is particularly important in the countries with very high labour cost. It can be seen from the Eurostat data that hourly cost in construction varies across the EU between 5 EUR/h up to 40 EUR/h.

Maintenance also has important potential influence. The more maintenance is required, the higher the costs, especially if the products need to be repaired. Depending on the discount rate, the price of maintenance is diminished or increased the later in time it happens. Namely discounting diminishes the influence of future cost events if the inflation rate is not considered. The further the event the lesser the importance and vice versa if the discount rate is negative.

The discount rate influences the final LCCA, especially if rates are relatively high or low (e.g., +10 % or -2 % respectively). It is important to note, though, that in the last decade and turbulent times on the financial markets it has become very difficult to predict the discount rate.

We have also calculated the externalities costs of the environmental burdens created in the life cycle of all products. By summarising all environmental burdens from production, installation, use phase and end-of-life phase, we got the amounts of greenhouse gasses, CFCs, VOCs etc. that affect each environmental category. By multiplying the amounts per category by the costs of each pollutant, we got the total external costs that need to be paid. The external costs do not represent a noticeable share of total costs in any of the assessed products.

IS THERE A BUSINESS CASE BEHIND?

Commercialization: Barriers and opportunities

The circular economy concept has become mainstream and a driving policy agenda's both within the corporate domain as well as for cities, regions, and countries. There are two main reasons for this urgency. The first is the rush to cut GHG emissions to a sustainable level. The other reason, equally important but less recognised, is the need to reduce depletion of our natural resources. While the Paris agreement have made countries to agree on a 70 % reduction in CO_2 emission by 2050, there are not similar agreements in place to ensure a sustainable consumption of natural resources. Global use of material resources has triples since 1970 and accounts for 90 % of biodiversity loss and 50 % and GHG emissions (UNEP, 2020).

The WOOL2LOOP project has proven that there is a business case in using waste streams such as mineral wool waste in producing building materials based on alkali activated materials technology. Five different companies have produced five different products: pavement slabs, facade elements, reinforced wall panels, dry mix concrete and acoustic panels. Although, the products are not quite ready for market launch, all the manufacturers (TREE, Termit, CRH, Saint-Gobain Finland and Ecophon) are convinced about the potential of the technology and the potential of applying the circular economy concept. CRH is already in the process of investing in up-scaling the production line, likewise Termit has leased up-scaling production equipment and started production of pavement slabs. Both TREE and Ecophon still needs further testing and refinement of final recipes before final upscaling investment decisions are to be made. Saint-Gobain Finland have got an internal plan approved to further invest in the upscaling possibilities.

During out assessment of understanding the circular economy potential in utilising waste streams or secondary raw materials to produce geopolymer cement, we have identified several barriers as well as opportunities through data collection and interviews with relevant stakeholders.

The five largest challenges identified were:

- Shortage of GGBFS/slags
- Lack of infrastructure to collect and treat SRM
- Lack of building codes
- Investments in upscaling
- Conservative market

On this background we have proposed two sets of recommendations: recommendations that the industry will be able to solve among themselves, and recommendations that needs a societal and regulative lift.

Industry recommendations

- Exploring alternative SRM
- Develop a recipe optimised for local availability of SRM
- Communication along value chain to all stakeholders
- More research into hybrid systems
- Open-source recipes (knowledge sharing and cooperation)
- Ensure easier access to waste streams

Policy recommendations

- Change of mindset (communication and knowledge sharing)
- Legislation to encourage stakeholders to collaborate on SRMs (landfill taxes, CO_2 taxes)
- Faster application processes
- Improve infrastructure for collection of valuable SRMs (such as MWW

CHALLENGES

Human and environmental health

The processes that were discussed have led to identified risks that must be controlled by:

- organisational measures, such as production planning, rotation of operators, facilities' design, and training of personnel;
- quality control of key steps of the process (e.g., milling can be determinant in the homogeneity of the secondary raw materials);
- engineering solutions to key-steps of the process such as encapsulation of reaction vessels and storage areas, ventilation, dedicated exhaust lines, mechanical approaches to all phases of the process, collectively and individually reducing the exposure of workers to hazards;
- engineering solutions to the waste flows of the process to attenuate or prevent impacts on the environmental receptors;
- use of adequate PPE;
- adequate monitoring of the secondary raw materials — starting at the Pre-demolition Audit, and, for new sources, lab-scale testing;
- health and safety monitoring — it's effectiveness can be significatively improved by the adoption of real-time permanent monitors (for ammonia, VOC, CO, CO_2, hydrocarbons, particles), combined with regular inspections;
- adequate health surveillance of the workers.

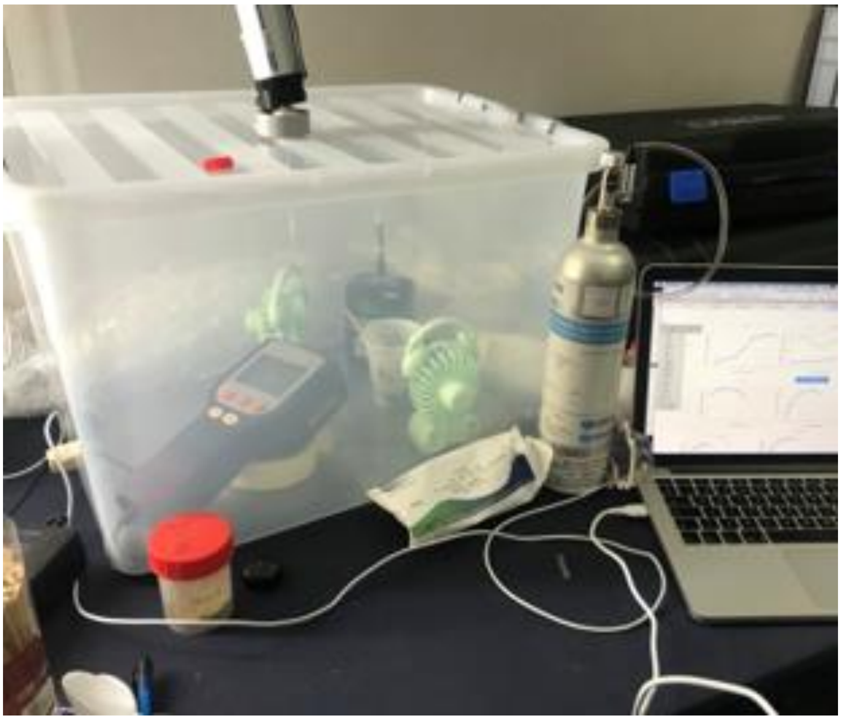


Figure 49 Set-up for sampling Volatile Organic Compounds emitted during alkaline activation.

All means and techniques to control such risks processes are identified and available. As with all industrial products, the economics will define the scale of the production — a fundamental input for the design of the industrial process and of the processes that will prevent or mitigate the identified risks to Environmental and Human receptors.

Milling processes, heterogeneity of raw material and removal of binder

The main challenges identified were the milling process and heterogeneity of raw material and the removal of binder, which was the main source of emissions during the activation and curing process.

Milling and the particle heterogeneity

For the milled material to work properly in the alkali activation process, it was decided that 90 % of all particles should fall under 40 microns. When the Mil-Tek IC60 screw mill was operating efficiently, the end material particle distribution analysis showed that the material was generally suitable for geopolymer raw material with very little additional processing.

However, the overall performance of the mill was not consistent, and the result was end material with a very large particle size distribution. Mixed in with the fines were oversized pieces that had not been milled down at all. Subsequent ball milling also produced material that still contained oversized particles.

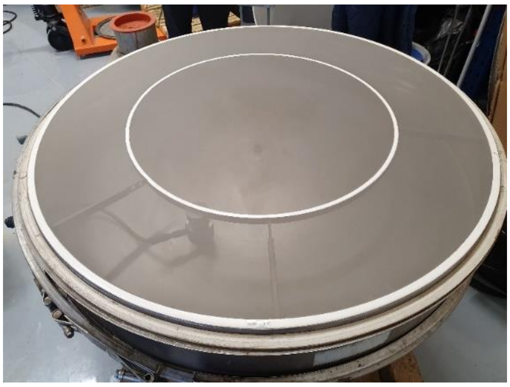


Figure 50 1.2 meters Sweco vibrating circular sieve

It was clear that some type of classifying or sieving of the material was necessary, so a Sweco vibrating circular sieve with a diameter of 1,2 m was used. The bottom most screen housed a component that produced ultrasonic sound waves to help the sieving process. Two ultrasonic sieving tests were conducted in March and April 2022, where material milled with MilTek IC60, as well as ball milled material was used for a total of two test runs.

The first test showed that heavy particle agglomeration is a key force in milled mineral wool, even very fine material clumps together and does not enter the sieve. Effective separation of the oversized particles is very important to for any industrial scale process to achieve the needed particle size range.

Figure 51 Milled material from the first test shows heavy agglomeration (left). On the right, ball milled material is poured on the 415 microns sieve.

The second test was conducted with a regular screen size of 415 µm and ultrasonic screen size of 42 µm. Heavy agglomeration of the particles was clearly visible also for the second test, material agglomerated heavily even when milled down to very fine size and the material having already passed the sieve once. The total amount of below 42µm particles in the ball milled material was approximately 40 %.

	g	%
Total	7 659	99,6
> **415 µm**	400	5,2
42 - 415 µm	4 000	52,2
< 42 µm	3 100	40,5
Left in sieve	128	1,7

Figure 52 Fractions sieved during the second test

Heavy agglomeration with particles of all sizes slows the sieving speed down to 120 l/h, which is not suitable for an industrial process where the volumes need to be closer to tons/hour.

The need for quality control for the particle size distribution is critical for the process and the only practical way to screen the material is a high-capacity dynamic separator as a part of the milling line.

Removal of binder

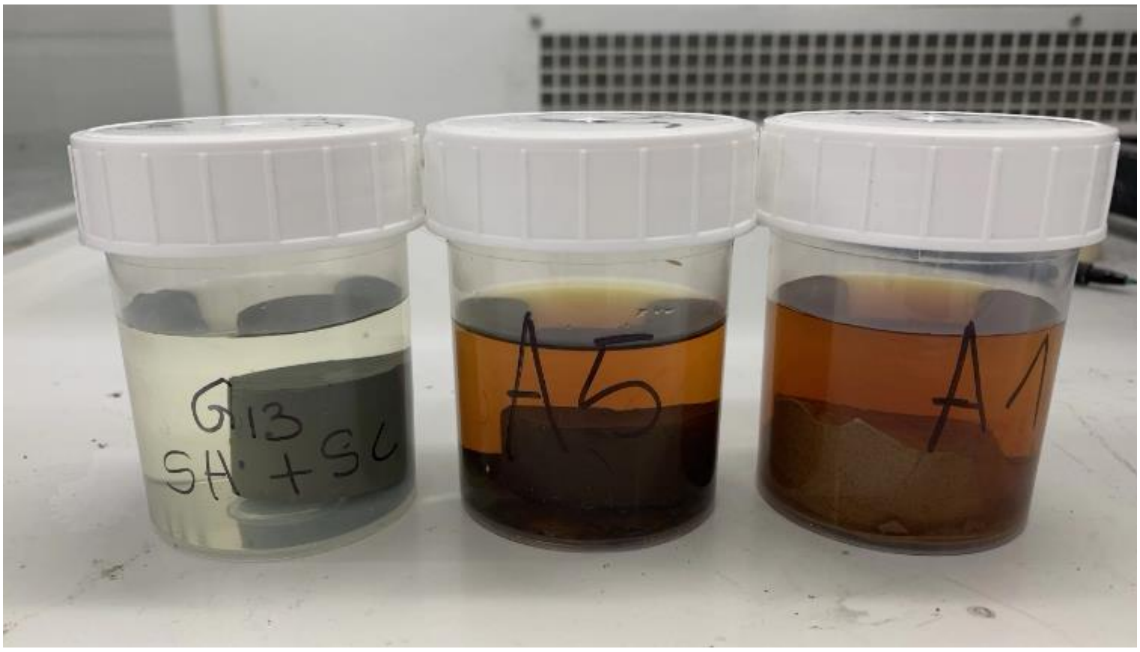


Figure 53 Leaching samples with an activation treated sample on the left

Organic binder in mineral wool is the main source of emissions during activation and curing. Ammonia emissions are higher within glass wool and alkali activation causes leaching, which could be a problem for outdoor applications, where the products are in contact with water.

For indoor uses, air quality measurements and emission limits are critical, as is discoloration. The main ways identified to reduce emissions were lowering PH of activator, heat treatment of mineral wool and activation treatment during milling. Activation treatment could be done during milling, which would not require any additional physical steps in the manufacturing process. Drawbacks are the added costs, as well as health- and environmental effects of the chemicals used in the treatment.

Heat treatment of mineral wool has drawbacks, high energy requirement of the process increases both costs and emissions. Heat treatment would however remove all other negative effects, such as problems with agglomeration and emissions and would make the milling of the mineral wool more manageable.

OVERVIEW OF THE RESULTS OF THE PROJECT

WOOL2LOOP companies will launch 6 new products to the market after the project. Three of those have been introduced by SMEs.

Aim of the IPR and innovation management task

The aim of the Task "IPR and Innovation management" was to detect the intellectual property rights of the partners, which was gained prior the project (background IP) or created during the project (foreground IP) as well as to help and encourage the partners to protect and exploit the IPR efficiently.

What is a role of the IPR in the field of Industry at W2L partners?

A value of the IPR e.g., patent for the industry is moderate and they use the IPR asset passively. The industry protects their own inventions, results for secure their own business operation in a case of potential infringement. They do not actively license or cross-license their IP assets among their competitors. Therefore, the industry is not seeking quantity of the IPR.

IPR and Innovation management in practise during the project

A daily work for harvesting potential new IPR was organized in two operational levels. **Project level** means activities and procedures were provided by the W2L IPR advisor,

- Identify the IPRs which have been gained before the W2L project started and to be used in the project (Background)
- An aim was to identify all potential IPR, which was created during the project (Foreground)
- Of each novel result was communicated to the W2L Exploitation committee via W2L Result assessment form for an evaluation and to the EC's opinion for further actions e.g., protect the invention or a permission for a publication.
- Consultation of the partners in IPR issues

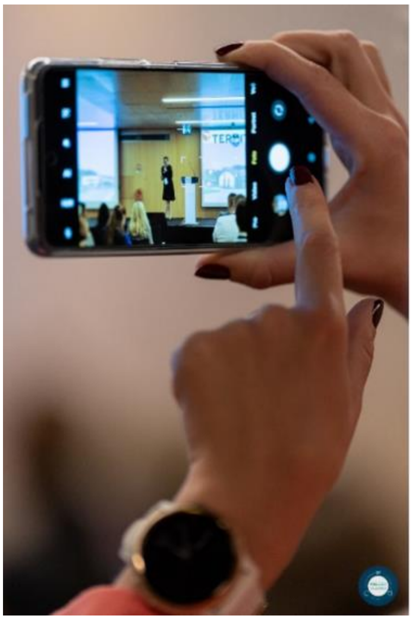
Organizational level means activities and procedures were provided by the W2L partner for its employees according to the law regulates the IPR in the country, where the partner operates

- A partner's innovation policy
- Activate new IP harvesting
- Rewarding according to their innovation reward scheme
- Decision for filing a new IPR protection e.g., patent application

W2L IPRs

In this report is communicated achieved W2L results and registered IPR, which were created by the partners. Companies registered their new IPR-assets according to their own IPR (e.g., patent) strategy. The IPR strategy varies between the W2L partners. In a technology-oriented company e.g., Timegate Instruments Oy aims to have strong patent protection for their product. Instead, in building material industry a patent protection plays a moderate role in the companies' business.

HOW DID WE COMMUNICATE ABOUT PROJECT PROGRESS?



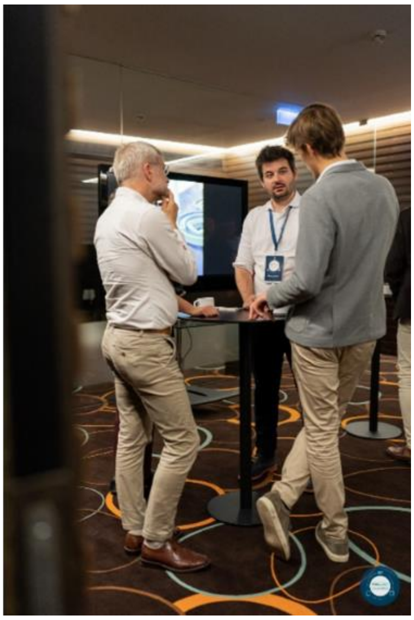


Figure 54 Figure 60 WOOL2LOOP Final Conference was organised in October 2022

Through publications

- 7 academic, peer-reviewed articles
- 84 articles, news items, interviews, blog posts
- 7 press releases

Through events

- 7 events and internal workshops organised
- WOOL2LOOP Final Conference in Lisbon 26th of October 2022 with 159 participants onsite and online
- 36 events attended with conference papers, posters, oral presentations, and exhibition booths

Through collaboration

- Throughout the project, WOOL2LOOP partners have collaborated with multiple projects and organisations such as
- InStreams Hub – An inorganic circular economy research community at the University of Oulu
- a working group between different parties, including H2020 CIRCUIT, WOOL2LOOP and EAKR HYPPY projects.
- Veep project collaboration
- EDA (European Demolition Association) collaboration
- MIMA (Mineral Wool Insulation Manufacturers Association).
- EURIMA (European Insulation Manufacturers Association).

- Helsinki circular economy cluster program, Green Building Council Finland, Ytekki and Verona Growth in organizing an innovation challenge for the concrete companies to test the utilisation of demolition wool in concrete production

Through online presence

- the WOOL2LOOP project website containing all the materials related to the project, public deliverables, and an online 3D-printing platform
- with social media channels in Twitter and LinkedIn with 282 followers in total

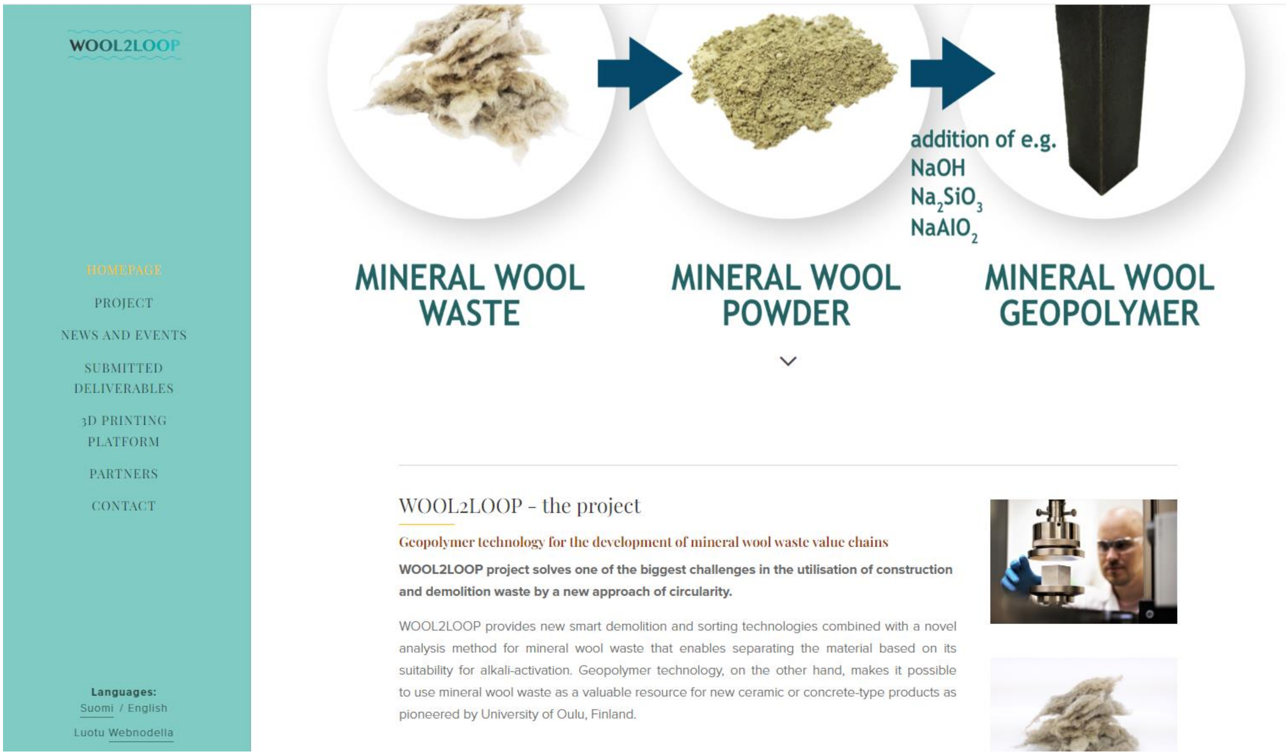


Figure 55 A screenshot of the project's website at wool2loop.eu

FUTURE – IF WE HAD MORE TIME

A group of Ph.D. researchers from Tampere University Doctoral Programmes in Built Environment and Business and technology management joined WOOL2LOOP Final conference with aim to get acknowledged with the topic, reflect, and bring possible questions, out-of-the-box remarks, challenges, solutions, and insights on WOOL2LOOP work and results.

“When listening to the results of the project, the main question that arose was how to scale up the solutions developed in the project to a practical level and how to tackle the identified challenges, such as the impact of variations in the quality of the collected mineral wool waste on the final products. It will be interesting to see how companies will proceed from here after the end of the project, as the transition to the circular economy is complex and requires extensive cooperation between stakeholders. I wish to hear more about these solutions and implementations in the future, hoping that useful and valuable development projects of this kind don’t only remain at the project level but can also be put into practice.”

Lauri Alkki, Doctoral Researcher, Tampere University, Faculty of Management and Business

“It is obvious that like-minded and circular economy -oriented people can do great things together. Likewise, it seems obvious that WOOL2LOOP project had created feasible business cases around geopolymers and alkali-activation. But now the tricky part begins: after the project all the actors need to think how to get those stakeholders engaged that are not that eager to participate? Addressing those who are happy with how things are and want to keep business-as-usual can be a tough nut to crack but after the project there is even more evidence on the table that there are alternative pathways to the construction sector.”

Mikael Nurminen, Doctoral Researcher, Tampere University, Faculty of Management and Business

“My main insights from the panel discussion were that regulation is an important way of enabling circular economy solutions as through regulation the solutions and innovations can also make more business-sense. In conclusion, circular economy will improve fastest when it becomes good business!”

Linnea Harala, Doctoral Researcher, Tampere University, Faculty of Industrial Engineering and Management

Figure 56 The Ph.D. researchers from Tampere University at the WOOL2LOOP Final Conference.

"To conclude, the WOOL2LOOP project was an interesting case of what it entails to turn construction industry waste into new products and therefore close the loop. We also must understand that this is an industry where people do not want to own the first product but maybe the 100th or even 1000th after everything has been verified to be a safe and good solution. But are we entering an era where the market demand for sustainable solutions is so great that even the first product becomes a must-have? This is probably a question that we need to wait for the answer to. In the meanwhile, we must produce quality research to solve the problems that our societies are facing."

Juha Franssila, Doctoral Researcher, Tampere University, Civil Engineering

"This project tackles two problems with one solution which is geopolymer technology. Even though the WOOL2LOOP project as we know it reaches its end, further research and development are needed to mainstream geopolymer-based materials. We need projects and materials like these. Projects where people from both academia and industry cooperate across disciplines and country borders to develop materials that can lower the negative environmental impact of construction. The environmental crises we are amidst are caused by our actions and thus our responsibility is to get back on track and within the planetary boundaries. Re-inventing concrete-like materials is a big step in the right direction."

Ninni Westerholm, Doctoral Researcher, Tampere University, Architecture

THANKS

The WOOL2LOOP project wishes to thank all the partners, all our collaborators around Europe and European Union for their contributions to the project and helping us to get closer to bringing mineral wool waste back to loop!

Figure 57 WOOL2LOOP project partners, keynote speakers and panellists attending the WOOL2LOOP Final Conference

Figure 58 Jonas Hedberg, Program Manager of Raw materials R&I at European Health and Digital Executive Agency (HaDEA), presenting at WOOL2LOOP Final Conference

USEFUL LINKS

WOOL2LOOP website
WOOL2LOOP 3D Printing Platform
WOOL2LOOP Final Conference materials