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ReBuilt

Activity 2.2 – Upscaling and testing of green and bio-concrete products

D.2.2.1 Report on Tested Bio-Concrete Solutions

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1. Introduction

As part of Activity 2.2 – Upscaling and testing of green and bio-concrete products, this deliverable **D.2.2.1 'Report on tested bio-concrete solutions'**, focused on laboratory and pilot tests are planned for the following bio-concrete products:

- Hempcrete panels for sound insulation (PP3, Hempstatic)
- Concrete with natural fibres (PP6)

2. Hempcrete Panels (PP3, Hempstatic)

The hempcrete panels are being developed in collaboration with the start-up Hempstatic. The properties of the panels were tested in the laboratory and in a pilot project at Partner PP3 Nigrad in Dogoše near Maribor, Slovenia. The pilot testing was conducted by ZAG (PP1). The focus of the investigations was on acoustic performance, fire behaviour, and indoor air quality. In addition, a comparison with conventional insulation materials and a life cycle assessment (LCA) were carried out to evaluate the overall environmental impact of the material.

2.1. Materials

2.1.1. Composition and Material Concept

The biocomposites developed and produced by Hempstatic are made from hemp shives, a byproduct of industrial hemp (Cannabis Sativa L.) processing, combined with a lime-based binder and water. Hemp shives are the inner woody core of the hemp stem and represent a renewable agricultural resource.

The resulting material formulation follows four key circular design principles:

1. Reuse
2. Repair
3. Remanufacture
4. Regenerate at the end of its life cycle

No toxic additives or synthetic compounds are used in the mixture, allowing the biocomposites to decompose safely and organically after their service life. This contributes to a non-hazardous end-of-life scenario and supports the development of safer, low-impact construction materials.

2.1.2. Environmental Performance

Hemp is one of the fastest-growing crops cultivated in Europe and it contributes significantly to climate mitigation through its ability to sequester carbon dioxide. Depending on conditions, hemp can bind up to 46 % of its dry biomass weight in CO_2. By using hemp shives as the primary aggregate, the material supports agricultural valorisation and reduces waste.

The lime-based binder used in combination with hemp shives ensures that the biocomposites are naturally resistant to fire, mould, and pests, without requiring additional chemical treatments. The materials are designed for use in building applications where durability, environmental performance, and circularity are key criteria.

2.1.3. Material Properties

Acoustic Performance:

The biocomposites exhibit high acoustic absorption performance, particularly in the mid and low frequency ranges critical for speech intelligibility and tonal balance.

Laboratory measurements confirm that effective sound absorption can be achieved from as little as 15 % surface coverage, making the material suitable for both full and partial wall or ceiling applications. The panels provide consistent surface aesthetics and demonstrate strong colour stability, with a measured UV resistance value of $\Delta E = 1.9$ under standardized conditions.

Fire Resistance:

In terms of fire performance, the materials are classified as B-s1, d0 according to EN 13501-1, indicating limited combustibility, low smoke production, and no flaming droplets. This classification is achieved without the use of chemical flame retardants.

Indoor Air Quality:

The biocomposites support healthy indoor air quality, with measured emissions of:

- Total Volatile Organic Compounds (TVOC): 90 µg/m^3 (EU LCI reference value: 300 µg/m^3)
- Formaldehyde: 0.23 µg/m^3 (WHO guideline: 100 µg/m^3)

These results indicate minimal to no release of pollutants, confirming the material's suitability for interior environments.

Hygrothermal Behaviour:

The vapour diffusion resistance factor (µ) of the material is 5.7, indicating a breathable structure that supports moisture regulation in interior environments.

2.1.4. Circular Design and Environmental Impact

The product system is designed for disassembly, allowing for reuse and repair through modular components and demountable installation techniques. Lifecycle assessments show up to 84 % lower CO_2 emissions compared to conventional alternatives.

At end-of-life, the materials can biodegrade under industrial composting conditions, as the formulation is free from hazardous substances and synthetic polymers. Overall, the material system meets advanced technical, safety and environmental requirements relevant for modern building applications.

2.2. Laboratory Tests

2.2.1. Water Vapour Permeability

The determination of water vapour permeability was performed in accordance with ÖNORM EN ISO 12086. Circular samples with a diameter of 100 mm and a thickness of 40 mm were cut from Hempstatic's biocomposite panels. The samples were mounted as diffusion lids on 0.25 l glass vessels partially filled with dry silica gel to establish a defined low relative humidity. The vessels were sealed with diffusion-tight Parafilm and stored under controlled conditions (20 °C, 65 % relative humidity). The mass increase of the assemblies was recorded over time together with the ambient temperature, relative humidity, and barometric pressure. Under steady-state conditions (constant mass gain over at least five consecutive readings), the tests were concluded.

The water vapour diffusion coefficient of air was calculated using the Schirmer formula, and the water vapour diffusion resistance factor (μ), the equivalent air layer thickness (s_d), and the diffusion coefficient (D) of the material were derived following the equations given in EN ISO 12086. The results for the biocomposite samples are presented in Table 1.

Table 1: Results of the water vapour permeability tests

Parameter	Results
Water Vapour Diffusion Resistance Factor [μ]	5.7 ± 0.2
Equivalent Air Layer Thickness (s_d)	0.21 ± 0.01 m (for 40 mm panel thickness)
Diffusion Coefficient (D)	$(1.23 \pm 0.07) \times 10^{-9}$ m²/s

These values confirm a vapour-permeable structure comparable to open-pored mineral composites and show stable diffusion behaviour independent of sample thickness.

The measured μ-value confirms that the hemp-lime composite allows sufficient vapour diffusion while maintaining moisture regulation comparable to mineral plasters. The low s_d-value supports this by demonstrating that the material permits moisture exchange without risk of condensation buildup in wall assemblies. Together, these parameters confirm that the composite contributes to a balanced indoor humidity environment.

2.2.2. Colour Stability

The accelerated ageing test for colour stability was conducted according to ISO 4892-2, Method B, using a Q-SUN Xe-1 xenon arc chamber (Q-LAB) to simulate solar radiation transmitted through window glass. The irradiance was set to 1.1 $W/m^2·nm$. Hempstatic biocomposite specimens and reference samples (Bachl XPS 300) were measured for colour before exposure and after 100, 200, and 300 hours using a Chroma-Meter CR-410 (Konica-Minolta) under standard illuminant D65 and 2° observer geometry. Colour values were evaluated in the CIE LCh colour space, and the total colour difference (ΔE) was calculated as the Euclidean distance between initial and final values.

After 300 hours of xenon irradiation, the average colour difference was $\Delta E = 1.9 \pm 0.2$, corresponding to a slight increase in lightness (L*) and minor decrease in chroma (C*). Differences within $1 < \Delta E < 2$ are considered minimal and generally imperceptible to an untrained observer. The reference XPS 300 material exhibited a significantly higher colour shift ($\Delta E \approx 19.5$ after 100 h).

The UV-aging performance shows that the material retains its visual and aesthetic properties even under prolonged exposure to simulated sunlight. The minimal colour change ($\Delta E < 2$) indicates a high level of colour fastness, meaning the surface appearance remains stable over time. Compared to conventional synthetic materials, the hemp-lime composite exhibits superior resistance to photodegradation.

2.2.3. Emissions

The emission testing followed EN 16516:2020-10, DIN EN ISO 16000-0, -3, and -6. Tests were performed in a 225 l emission chamber at 23 ± 1 °C, 50 ± 1 % relative humidity, with an air exchange rate of 0.5 h^{-1} and a loading ratio of 1 m^2/m^3. Samples were sealed at the edges and placed directly in the chamber after cutting. Air sampling was conducted after 3 and 28 days.

VOCs were collected on Tenax TA®, thermally desorbed, and analysed by GC-MS/FID, while aldehydes were trapped on DNPH cartridges, eluted with acetonitrile and quantified by UHPLC with diode-array detection. The results are shown in Table 2.

Table 2: Results of the emission testing

Parameter	3 days	28 days	Limit (EN 16516)
TVOC [$\mu g/m^3$]	186	90	≤ 1000
Formaldehyde [$\mu g/m^3$]	0.34	0.23	≤ 100

All measured concentrations are far below the threshold limits defined in EN 16516 and the WHO indoor air quality guidelines.

The very low emission values indicate that the material contributes negligibly to indoor air pollution. VOC and aldehyde levels are significantly below European and WHO reference thresholds, verifying that the composite does not release harmful or odorous substances during its service life and is therefore suitable for interior applications with strict health requirements.

2.2.4. Reaction-to-Fire Classification

The reaction-to-fire classification was determined according to EN 13501-1, based on results from the EN 13823 “Single Burning Item” (SBI) test. The SBI test evaluates the reaction to fire of building products, excluding floorings, by exposing a vertically mounted test specimen (1.5 m × 1.0 m) to a controlled heat source equivalent to a single burning waste-paper basket (30 kW). The setup measures heat release, smoke production, flame spread, and occurrence of flaming droplets under forced ventilation. During the test, the Fire Growth Rate Index (FIGRA) and Total Heat Release within 600 s (THR_{600s}) are derived from oxygen consumption calorimetry, while the Smoke Growth Rate Index (SMOGRA) and Total Smoke Production (TSP_{600s}) are determined by optical density measurements. The absence or presence of flaming droplets or particles is also recorded. These parameters together determine the classification of the product under EN 13501-1, ranging from Class A1 (non-combustible) to F (no performance determined). The results of the tests for reaction of fire are shown in Table 3.

Table 3: Results of the reaction-to-fire classification

Parameter	**Results**
FIGRA 0.2 [W/s]	37.6
FIGRA 0.4 [W/s]	23.1
THR_{600s} [MJ]	2.7
SMOGRA [m^2/s^2]	0.0
TSP_{600s} [m^2]	17.0
Flaming Droplets	None observed

These results correspond to classification B-s1, d0, indicating limited combustibility, very low smoke production, and absence of flaming droplets.

The reaction-to-fire performance confirms that the material achieves class B-s1, d0, one of the highest classifications attainable for organic-based construction materials. This demonstrates limited heat release, minimal smoke formation, and the absence of flaming droplets, all achieved without the use of chemical flame retardants. The results show that the Hempstatic biocomposite meets stringent European fire safety standards and can safely be used in public and residential buildings where fire performance is a key requirement.

The results of the acoustic absorption performance of the material is addressed in detail in the following chapter.

2.3. Life Cycle Assessment (LCA)

2.3.1. Methodology

The life cycle assessment compares Hempstatic's biocomposite insulation panels with a conventional baseline product made of flexible polyurethane (PUR) foam with flame retardant additives.

The analysis covers all major life cycle phases:

- Raw materials extraction
- Production
- Transport
- Use phase

The functional unit (FU) represents one square metre of installed insulation panel. All emissions were quantified in kilograms of CO_2 equivalent (kg CO_2eq/FU).

2.3.2. Results

The detailed results of the LCA for each phase are presented in Table 4.

Table 4: Results of the LCA

Life Cycle Phase	Biocomposite Insulation Panels [kg CO_2eq/FU]	PUR [kg CO_2eq/FU]	Reduction [%]
Raw Material Extraction	-0.079	1.424	106
Production	0.3566	1.424	75
Transport	0.0659	0.0356 *	98
Use Phase (incl. carbonation)	≈ 0	0.10	-
Total	-38.27 kg CO_2eq/m^2	≈ 680 kg CO_2eq/m^2	**≈ -94**

*Indicative values depending on transport inclusion and lifespan assumptions.

The LCA results clearly demonstrate the significant environmental advantage of Hempstatic's biocomposite insulation panels over conventional polyurethane foam.

Across all life cycle stages, the biobased material achieves a reduction in total CO_2 emissions of approximately 94 %.

- This outstanding performance is primarily attributed to:
- Biogenic carbon sequestration during hemp cultivation,
- Low-emission lime-based binders that replace petrochemical inputs,
- Short regional supply chains and reduced transport impacts,
- And potential reuse or biodegradation at end-of-life.

The carbonation effect of the lime binder further enhances the long-term carbon balance during the use phase.

The LCA results indicate that the substitution of emission-intensive synthetic insulation materials with renewable, biobased alternatives provides a significant reduction in greenhouse gas emissions and resource depletion. The forecast is validated as positive and significant, with sensitivity analyses confirming robustness even under conservative assumptions for carbon sequestration and end-of-life decomposition.

2.4. Testing of Hempstatic Panels in Pilot

Sound absorption and reverberation time measurements were performed on the Hempstatic panels in the pilot building at Partner PP3 Nigrad in Dogoše near Maribor, Slovenia, before and after installation to measure their effect. Two larger spaces in the pilot building were used for the assessment and were treated as meeting rooms for this purpose.

2.5. Used Materials and Conditions

2.5.1. Test Location and Conditions

Test specimens were used in two large open rooms in a pilot two-floor building, built at a gravel pit and construction waste processing site in Maribor, Slovenia. One larger room on a ground floor is usually used as a makeshift cafeteria and meeting room and upstairs room is occasionally used as a conference room. Smaller rooms on the ground floor were not used in these measurements and were closed during testing. Testing site is in Figure 1, during measurements without the samples installed.

Figure 1: Photos during initial measurements without panels installed. outside of pilot building (a); ground floor meeting room (b); upstairs conference room (c) and open staircase between floors (d)

When using these rooms in the pilot building as a reverberation room used for assessing the sound absorption properties of the test specimen, some deviations from the standard ISO 354 [1] are readily apparent. The main one is an open staircase between floors that acoustically links both rooms – so any results measured in one room will be affected by the echo from another room. This is of course not ideal for assessing parameters, but it is quite common in practical applications, where different spaces might be linked. Otherwise, the rooms are quite large with volumes of 184 m^3 on the ground floor and 154 m^3 on the 1st floor; so it is just a bit under typical reverberation room size of 200 m^3 prescribed in ISO 354. The rooms are also quite sparsely furnished with most of the surfaces sound reflexing. Furniture, an additional inner wall on the ground floor, and a slanted ceiling on the 1st floor are also beneficial for diffusing sound. Substantial wooden areas and a curtain on the ground floor are the only surfaces that provide any sound absorption. The rooms were also not changed between measurements with and without specimens, with the only change that might affect the results being the inclusion of a wide screen TV on the ground floor – since this has minimal sound absorption the effects of this addition to the overall results are expected to be minimal. Based on this, the spaces are quite suitable for the purpose of studying the sound absorption effects.

2.5.2. Hempcrete Panels

Test specimens were sound absorbing panels made of hemp with gypsum-based bonder and arranged in 500 x 500 mm panels 40 mm thick. The elements have no outside frames and as such provide sound absorption on the side of each panel as well on the larger top surface facing the rooms. While this is a practical way of installing the panels and quite likely to be used in-situ, it is nonetheless much different to how the samples would be installed in an actual reverberation room according to standard ISO 354 – in this case all the side surfaces would typically be covered by sound reflective material. Due to this, we expect the side surfaces of each element to significantly contribute to sound absorption in the room.

The panels were delivered by the producer and glued to the walls of our testing rooms, taking care to try to distribute them around the wall surface. On the ground floor 38 such elements were installed, mostly spaced at least 10 cm from each other, for the total surface area of 9.5 m^2 (face area, without sides). On the 1st floor, only 4.5 m^2 panels by face area were installed with 2 or 4 panels stuck together. Due to this less side of the elements was exposed, with expectation being that this would slightly decrease sound absorption. The arrangement can be seen on the following Figure 2.

Figure 2: Installed test specimens; top: ground floor with panels mounted individually; bottom-left: 1st floor panels mounted in batches; bottom-right: panel detail with side exposed

The producer also supplied as with expected sound absorption coefficients, measured in an actual reverberation room, conforming to standard ISO 354. These laboratory tests of the Hempstatic panels were our initial expected values and are presented in Figure 3 and were used as reference for the pilot testing.

Octave band value																					
f [Hz]	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150	4000	5000	6300	8000	10000
α_s	**0.11**	**0.13**	**0.16**	**0.28**	**0.40**	**0.59**	**0.70**	**0.88**	**0.92**	**0.80**	**0.70**	**0.57**	**0.53**	**0.54**	**0.55**	**0.54**	**0.54**	**0.55**	**0.56**	**0.56**	**0.61**

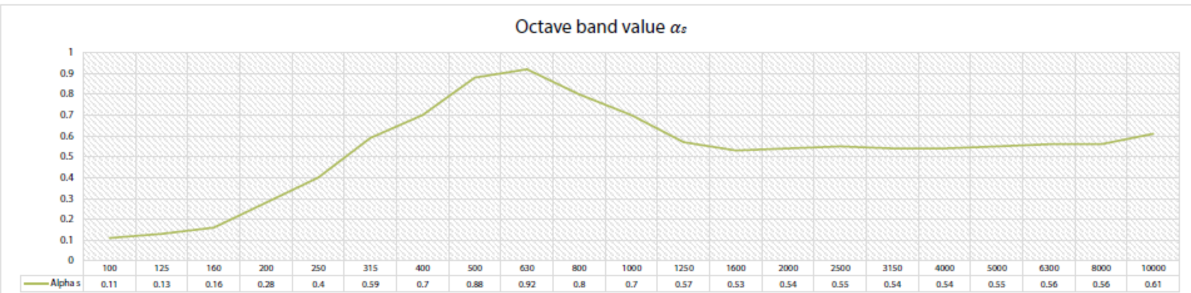


Figure 3: Sound absorption coefficients of Hempstatic panels, measured in reverberation room acc. to standard ISO 354. Note the figure states octave bands, but results are in fact presented in 1/3rd octave bands.

2.6. Pilot Testing

To assess the effect of panels on room acoustics, reverberation time was measured before and after panel installation and results compared. Reverberation time was measured using a standard ISO 3382-2 method intended for ordinary rooms [2]. Additionally, the results of these measurements were assessed in the general method described in standard ISO 354, dealing with measurement of sound absorption in a reverberation room [1]. For assessment, we treated each room in the pilot building as a very basic reverberation room with some obvious shortcomings.

The measuring equipment is shown in Table 5.

Table 5: Measuring equipment

Equipment	**Type**	**ID**
Acoustic Analyser	Type 2270 B&K	ID 3.34.01-019
Calibrator	Type 4231 B&K	ID 1.29.03-007
Omni-Directional Sound Source	Type 4292-L B&K	ID 5.29.01-006
Amplifier	Norsonic Nor280	ID 5.29.01-008
Thermo-Hygrometer	Type EXTECH RHT35	ID 3.06.02-105

2.6.1. Measuring Conditions

Initial measurements were performed on 30.05.2025 and measurements with the panels installed were measured on 08.07.2025. All results were corrected for the change in conditions (humidity) according to ISO 354 [1], see Table 6.

Table 6: Measuring conditions

Condition	**Empty Room** Ground floor / 1st floor	**With Panels** Ground floor / 1st floor
Temperature [°C]	23.4 / 24.6	26.6 / 28.1
Humidity [%]	43 / 44	49 / 45
Barometric Pressure [hPa]	995	978

2.6.2. Reverberation Results

Reverberation time difference with and without Hempstatic panels installed in presented on the following figure, measured according to standard ISO 3382-2 method (average of T_{20} and T_{30} used). Results below 100 Hz proved unreliable due to problems of background noise present at the test site.

As can be seen on Figure 4 for the 1st floor and Figure 5 for the ground floor, the panels were quite effective in reducing the reverberation time, even more so then one would expect from absorption data provided by the producer (Figure 3). To take the data from 500 Hz band, the band typically used for fast assessment in room acoustics, RT is reduced by exactly 0.5 s in both cases. This is a substantial reduction.

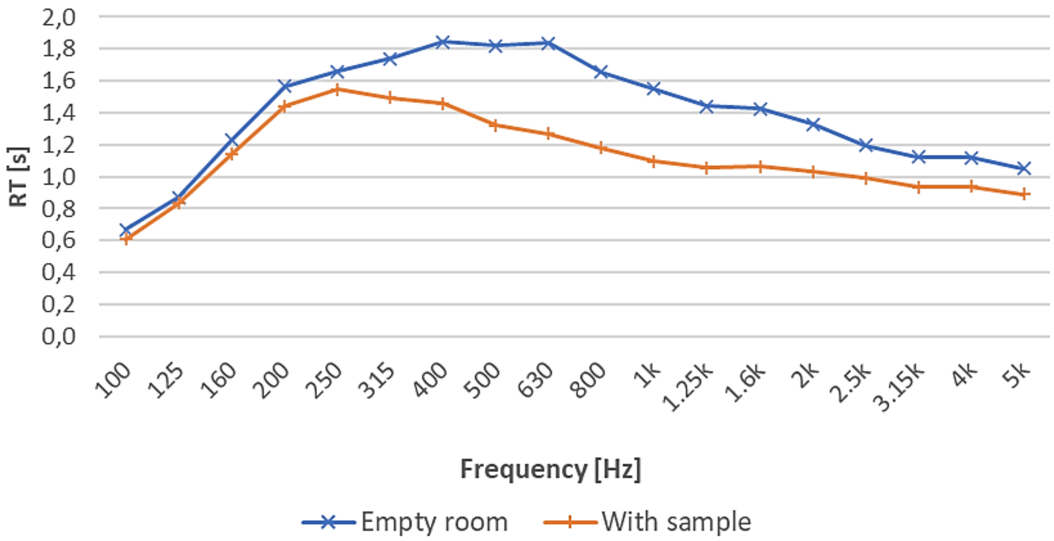


Figure 4: Change of reverberation times in 1/3rd octave bands, with and without panels (1st floor).

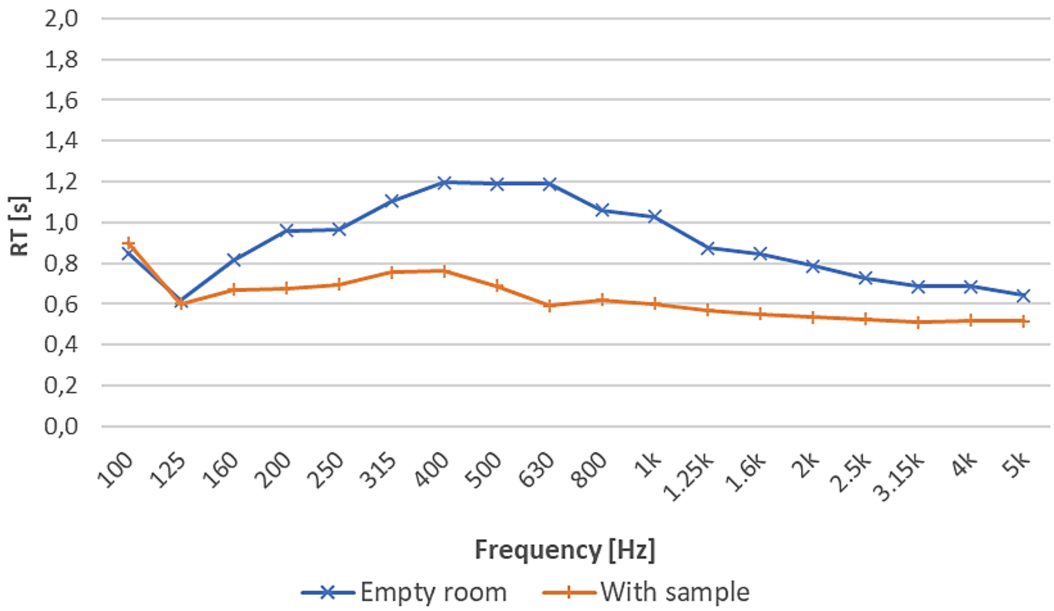


Figure 5: Change of reverberation times in 1/3rd octave bands, with and without panels (ground floor).

2.6.3. Optimum Reverberation Comparison

To put it in perspective, the optimum time for rooms at these volumes (154 or 184 m^3) that require good speech intelligibility is around ~0.9 s [3]. This value with interval ± 20 % can be used as a general requirement for conference halls and applies to the whole spectral range with slightly longer RTs allowed at very low frequencies (below 200 Hz) [3].

By this requirement, adding 9.5 m^2 Hempstatic panels to the ground floor room, and 4.5 m^2 panels to the 1st floor, the reverberation time has been reduced. After installation it is somewhat above optimum for the 1st floor, but it is just slightly below optimum for ground floor. This can be seen on Figure 6, where optimum RT time interval is also presented with upper and lower bound.

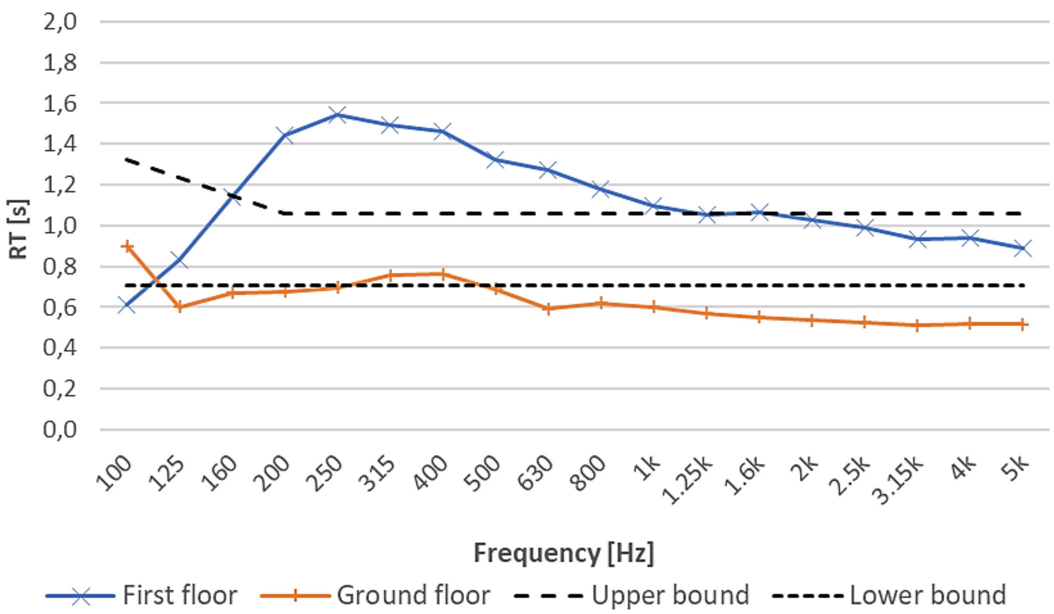


Figure 6: Reverberation times in 1/3rd octave bands, with optimum reverberation time shown (between upper and lower bound) – measured with Hempstatic panels.

By this metric the ground floor room is now slightly below the optimum RT for conference halls, while the first-floor room is still above the optimum. This finding is not unexpected given the context. There is double the number of panels on the 1st floor as opposed to the ground floor, while the volumes of the rooms are only ~20 % apart. In addition, the panels on the ground floor were installed with more spacing, making them more affective in sound absorption.

If prioritizing speech intelligibility is our goal, then the conclusion would be that the first-floor room needs some more sound panels, while the ground floor room needs to have some panels removed to achieve room acoustics with optimum reverberation time.

2.6.4. Apparent Sound Absorption Coefficient

Sound absorption properties are described by sound absorption coefficients in relation to frequency – usually in frequency bands. These coefficients are measured in specialised reverberation rooms under specific conditions following standardized procedures. The sound absorption coefficient (α_s) of a plane absorber is calculated using the formula (see ISO 354 [1]):

$$\alpha_s = \frac{A_T}{S}$$

Where:

- A_T equivalent sound absorption area of the test specimen, calculated from the change in RT and corrected for environmental parameters (mainly air humidity, see ISO 354 [1] or details)
- S area of the specimen in m²

However, as already explained in section 2.1.4.2, the surface area of the specimen is usually meant as the face area without the sides of the panel absorber. In case of this report, the sides of the specimen were typically exposed and contributed significantly to sound absorption. In addition, various other effects can also change the results, as the measurements are done in two impromptu reverberation rooms that are also acoustically connected by open stairway. This acoustic system is hard to predict and the beyond the scope of this report.

Nevertheless, it is possible to calculate the apparent sound absorption coefficients for each room based on this method and compare them to the reference coefficients measured in accordance to standard ISO 354 (see section 2.1.4.2 and Figure 3). "Apparent" in this case means calculated to the surface area of the largest face of each panel only – more of the panel absorbs sound. This is done for informative purposes only and only in relation to this specific case, meaning that any such apparent coefficients are not to be used for panel/material properties qualification in any other setting. The results of such calculations are on Figure 7.

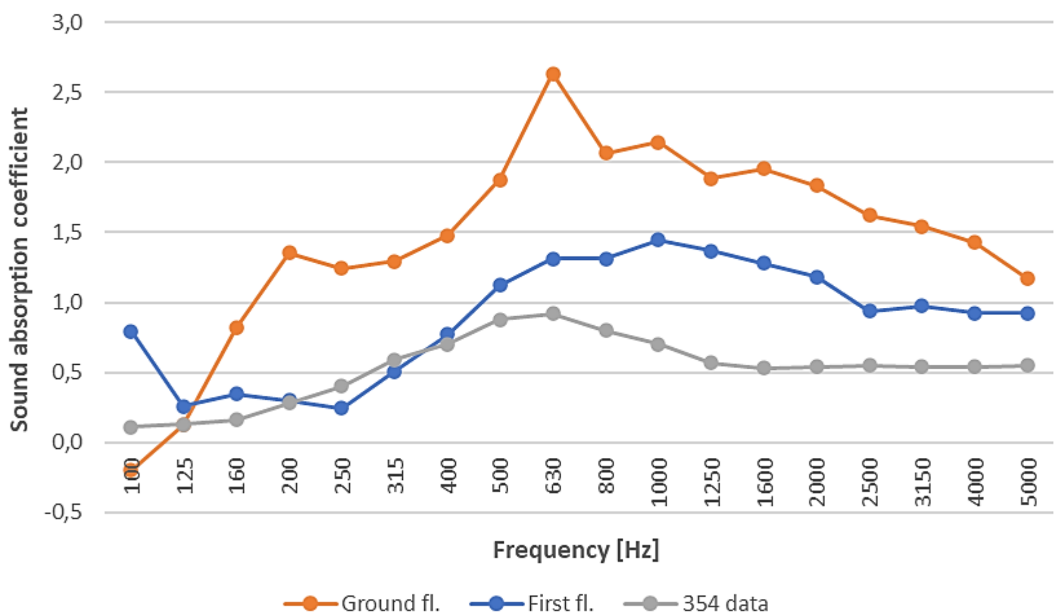


Figure 7: Apparent sound absorption coefficients in 1/3rd octave bands compared to reference coefficients of Hempstatic panels.

Note that the coefficients calculation already corrects for the number of panels (by surface area). So, the comparison on Figure 7 shows the apparent effectiveness of sound absorption in specific settings: on the ground floor with well-spaced panels, on the 1st floor with panels mounted in batches and in an actual reverberation room where presumably all sides were covered by reflective material. With higher values corresponding to higher ability to absorb airborne sound, it is apparent that ground floor panels were much more effective than 1st floor panels, that were in turn much more effective than the expected absorption effect from standard reverberation room. This is broadly in line with expectations as the mounting conditions on the ground floor exposed much more of the panel material. However, any additional effects due to the two rooms sharing and open stairway were not studied, so these results must be assumed to have a large degree of uncertainty.

This is presented to show that the specific use of sound absorption elements can have significant influence on the result – reduction of RT in a room. And if the panels were to be used differently (e.g. hung under a ceiling so all sides are exposed) the difference in effectiveness could be even greater.

2.7. Conclusion and Discussion

In summary, the laboratory testing of the hempcrete panels confirms that the material offers a unique combination of acoustic and environmental functionality, visual durability, very low emissions and strong fire safety characteristics, validating its technical suitability for sustainable interior construction applications. Further the tests in accordance with ISO 354 showed that the Hempstatic panels exhibit high and broadband sound absorption, with absorption coefficients increasing from approximately 0.6 at 500 Hz to over 0.9 at 1 kHz. The results verify that the panels effectively reduce mid- and high-frequency reverberation and perform comparably to conventional porous absorbers of similar thickness.

The acoustic performance of the biocomposites was verified through in-situ (pilot) measurements, in which reverberation times were recorded before and after panel installation. These measurements yielded slightly higher apparent absorption values than those obtained under controlled laboratory conditions. This difference can be attributed to installation geometry, surface exposure, and room boundary effects, which enhance the apparent performance. Despite these variations, both datasets show consistent trends, confirming the reliability of laboratory data for predicting field performance. Overall, the panels demonstrate stable acoustic efficiency, environmental sustainability, and ease of integration into building applications. However, results depend on mounting configuration and edge conditions, which may influence low-frequency performance.

Future studies should focus on optimising panel placement, evaluating long-term durability, and expanding the frequency analysis to refine predictive models for different room types. Measurements of the thermal insulation performance of the panels would also provide valuable additional insights.

In conclusion, the laboratory and pilot studies together confirm that the Hempstatic hemp–lime panels represent an effective, low-emission, and recyclable alternative to conventional acoustic materials, thereby supporting the objectives of sustainable and circular building design.

3. Concrete with Natural Fibres (PP6)

In this part of the project, the aim was to develop a **concrete with natural fibres** comprising of a low carbon binder and 100 % recycled aggregates in order to improve its mechanical properties. The development took place at TU Wien (PP6).

3.1. Used Materials

3.1.1. Hemp Fibres

The natural hemp fibres used in this project are 5 and 10 mm long with diameters ranging from 16 to 50 µm and an estimated density of 1.5 g/cm^3. The fibres were locally available in Hungary. The fibres were not treated and stored under lab conditions (20°). A microscopic and photographic representation is shown in Figure 8 (a) and (b). The hemp has a tensile strength in the range of 270 – 900 N/mm2 [4].

Hemp fibres have the potential for carbon negative impact on building materials due to their natural uptake of CO_2 while forming its cellular structure. The manufacturer did not provide a life cycle analysis. Yet, the negative global warming potential including the CO_2 uptake can be estimate of around -0.2 to -2.5 kg eq-CO_2 per kg hemp fibres [5][6].

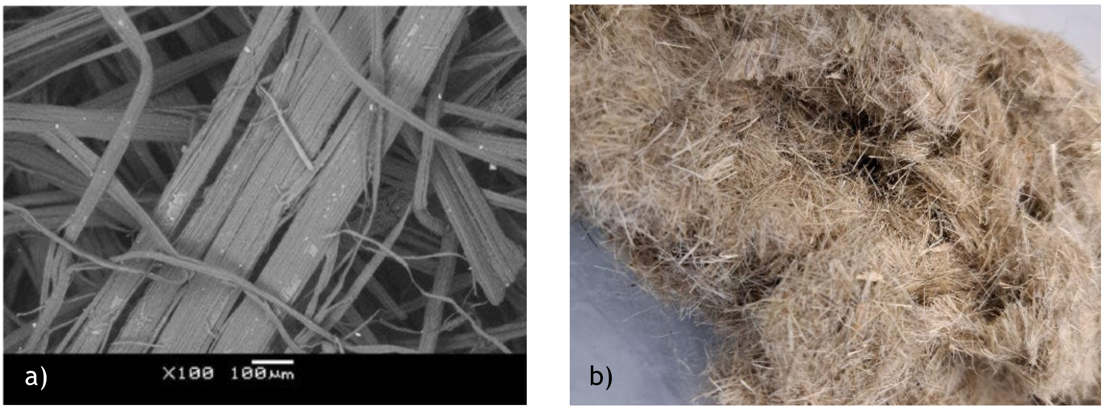


Figure 8: SEM image of used hemp fibres(a) Photographic representation of hemp fibres (b)

3.1.2. Recycled Aggregates

The recycled aggregates (RA) have been delivered by an Austrian manufacturer and are classified as an RB-A1 0/16 RA material. The classification was provided by the technical data sheet. The sieve line was provided by the manufactured and is shown in Figure 9. The density was measured under lab conditions as 2.70 kg/m² and has a water absorption of 5.87 %.

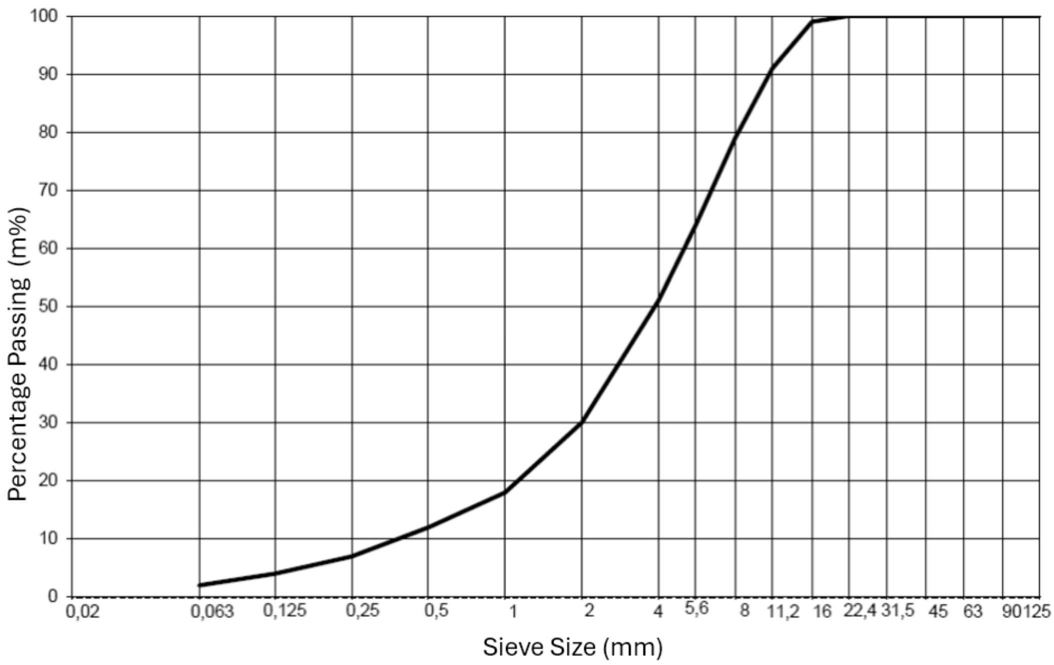


Figure 9: Sieve line RB-A1 material

3.1.3. Cement

The target of the project was to use minimized the CO_2 consumption of a concrete and its used materials. Therefore, a low global warming potential (GWP) blast furnace slag cement, qualified as CEM III/B 32.5 N LH-SR, was introduced to the mortar mixture. The GWP was provided by an LCA analysis through the manufacturer to 0.265 kg eq-CO_2/kg.

The cement was investigated via a particle size distribution (PSD) and is shown in Figure 10.

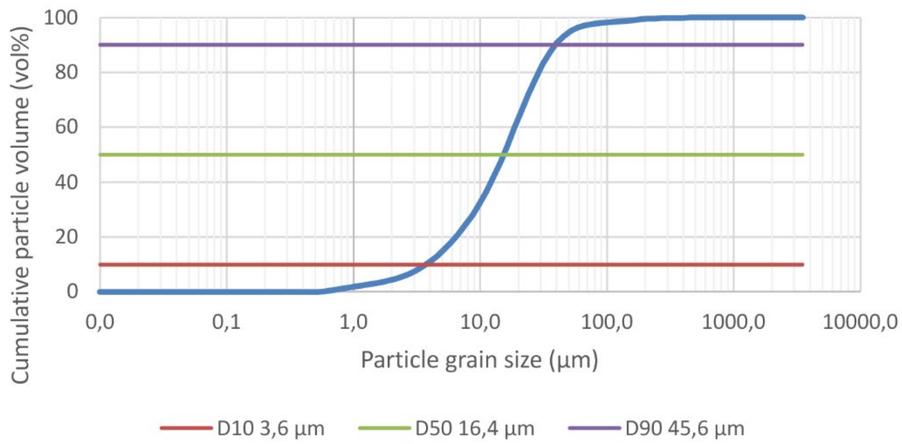


Figure 10:Particle size distribution (PSD) of CEM III/B

3.1.4. Plasticiser

Fibers tend to diminish the workability of mortar mixture. To compensate for the assumed worsened workability of the mortar mixtures, a super plasticising agent has been introduced to the mixture in order to compensate for this behaviour. The product used was especially designed for the use of recycled aggregates.

3.1.5. Concrete Mix Design

The mix design is based on a mortar composition according to the technical standard EN 196-1 which mandates 450 g of binder, 1350 g of a technical norm standard sand and 225 g of water. The recipes used in this project deviates from these parameters as the following:

- The standardized sand was 100 % substituted with recycled aggregate defined as RB-A1 0/16.
- Suction water is added to the recycled aggregate depending on water absorption.
- The water amount of 225 g for each based was adjusted to compensate for the approximated water consumption of the fibres by 2.5 times per gram fibres.
- Hemp fibres of 5 and 10 mm length have been introduced to the recipes by volumetric addition of 0.5 and 1.0 Vol.-%.
- For each recipe 5 g of plasticiser (SP) was added to the mixture.

An overview of all mixtures and their respective composition are shown in Table 7.

Table 7: Overview of mix designs, data [g]

Mix Name	Mix Code	Water (suction water included)	CEM III/B	RB-A1	Hemp Fibres 5mm	Hemp Fibres 10mm	SP
REF	0	225.0	450	1350	-	-	5
Hemp_5mm_0.5vol%	5_0.5	240.6	450	1350	6.23	-	5
Hemp_5mm_1.0vol%	5_1.0	256.2	450	1350	12.46	-	5
Hemp_10mm_0.5vol%	10_0.5	240.6	450	1350	-	6.23	5
Hemp_10mm_1.0vol%	10_1.0	256.2	450	1350	-	12.46	5

The mixing procedure was adapted to address the usage of recycled aggregates and Hemp fibres and is shown in Table 8.

Mixing procedure is based on a two-stage mixing approach. In this way the recycled aggregates tend to show a better mechanical performance as it is going to be prewetted [7]. The mixing was done by a standard mortar mixer as seen in Figure 11.

Table 8: Mixing schedule

2 min	Dry mixing of recycled aggregates
Break	Add ½ of Water
1 min	Wet mixing of aggregates
Break	Add CEM III/B, hemp fibers, rest of water
5 min	While mixing add additives
Finish	Measure Slump Hägermann-Trichter spread with 15 shocks for each batch
24 - 48 h	Demolding
	Stored in a 20°C underwater until testing

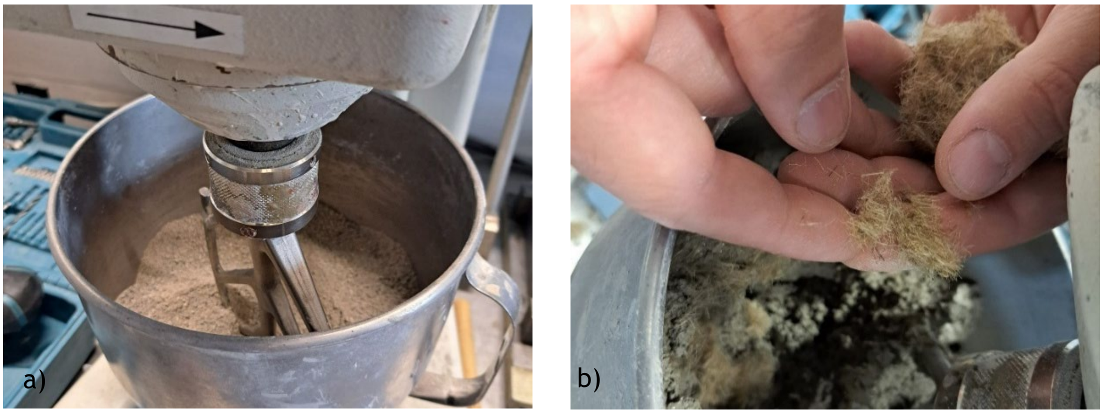


Figure 11:Photographic representation of dry mixing (a) and addition of fibers (b)

3.2. Laboratory Tests

3.2.1. Workability

To investigate the change in workability, the fresh properties have been conducted according to the technical standard EN 196-1. For this a slump spread after 15 shocks was measured via a Haegermann cone. The spread measurements from the test series are shown in Table 9.

Table 9: Workability results

Mix Name	Mix Code	Slump Spread [cm]
REF	0	14
Hemp_5mm_0.5vol%	5_0.5	10
Hemp_5mm_1.0vol%	5_1.0	11
Hemp_10mm_0.5vol%	10_0.5	10
Hemp_10mm_1.0vol%	10_1.0	10

3.2.2. Solid density

The results of the densities measured after 28 days of the sample are shown in Figure 12.

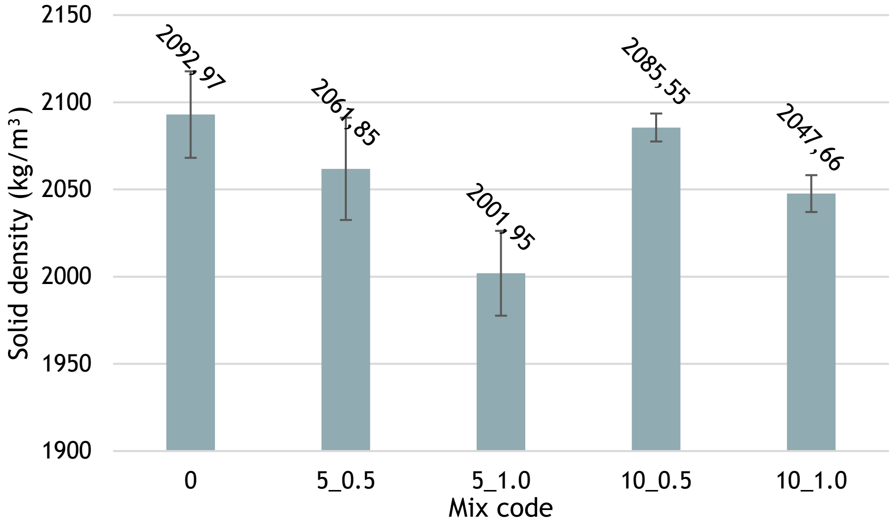
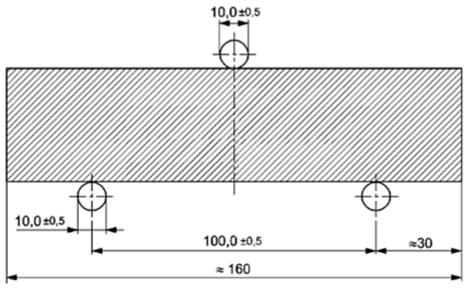


Figure 12:Overview of solid densities measurements

3.2.3. Flexural Strength

The flexural strength of the mortar samples produced was tested after 28 days according to the technical standard ÖNORM EN 196-1 on 40 x 40 x 160 mm samples through a 3-point-bending test with a load velocity of 50 N/s (conducted by the ZWICK / Roell testControl II machine). For this purpose, the samples are placed out of the water storage, surface dried, measured and scaled.

A photography and schematic representation of the test setup and specification are shown in Figure 13.



(b) Illustrated image of the 3-point bending test.

Figure 13:Photographic representation of the 3-point-bending test (a) and schematic of the test setup (b)

The results of the measured flexural strength of the specimen are shown in Figure 14.

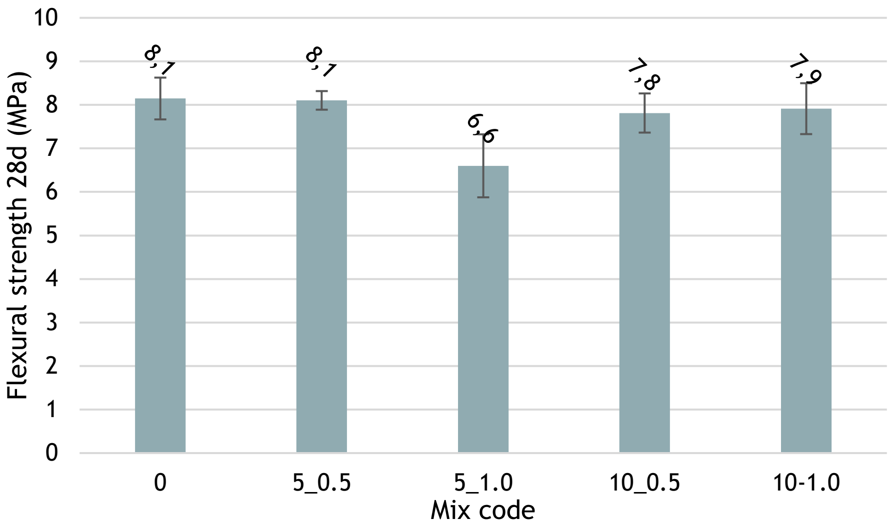


Figure 14:Overview of flexural strength measurements

3.2.4. Post Cracking Behaviour

Due to the presence of fibres in the mixture, the behaviour after cracking is from importance. For this purpose, a setup identical to the flexural strength was used with the following adaptation.

- The midspan deflection of the specimen was controlled by 400 µm per minute.
- A preload and the end of test criteria was set at 20 Newton.
- The age of the specimen of the test was 42 days.

In this way the post crack fracture crack energy $G_{F,post}$ (J/m²) can be derived according to:

$$G_{F,post} = (W_{0,post} + m\,g\,\delta_{20N}) / A$$

Where:

- δ_{20N} deformation at 20 Newton after the maximum force was reached
- $W_{0,post} = \int_{\delta_{max}}^{\delta_{20N}} F(\delta)d\delta$ Area under the deflection curve between the deformation at the maximum force and δ_{20N}, illustrated in Figure 16.

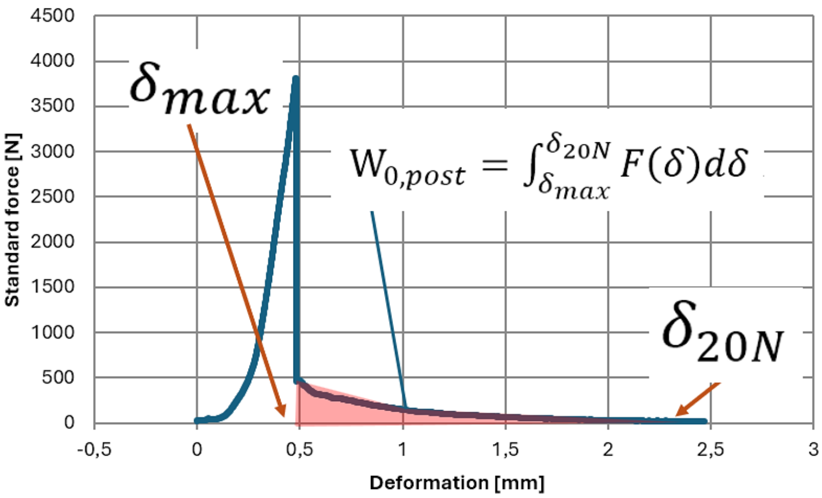


Figure 15:Determining the post-fracture workload by calculating the red area in the force-deformation diagram

The results of the computed post fracture energy are shown in Figure 17. A graphical representation of the load and deformation diagram of all specimens is shown in Figure 18.

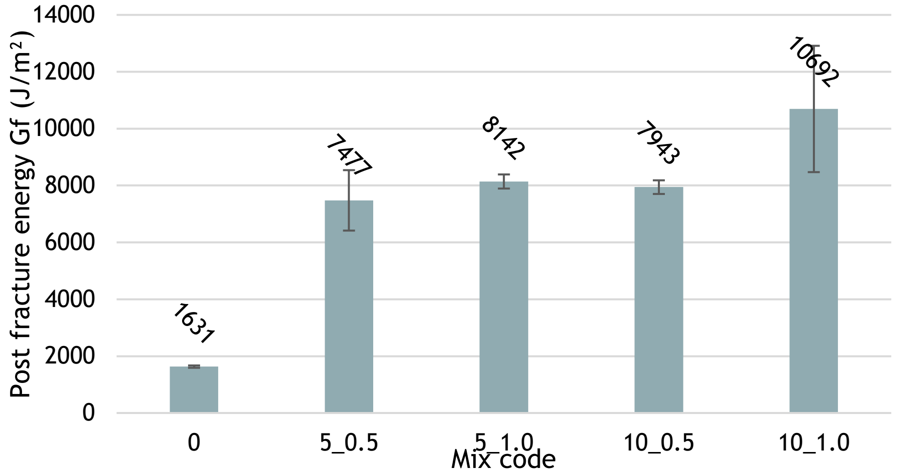


Figure 16:Overview of the computation of post fracture energy measurements

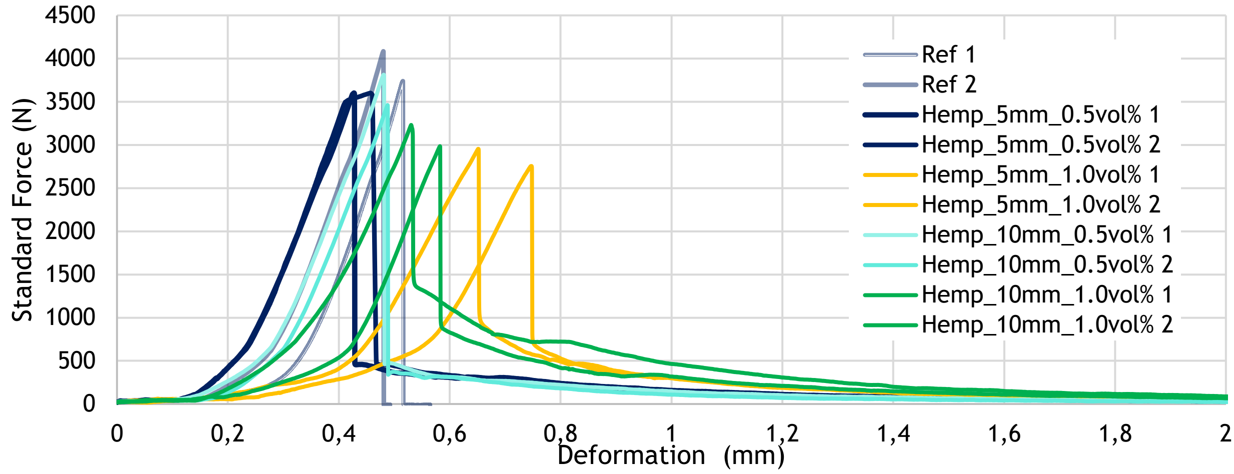


Figure 17:Overview of force deformation diagram for all specimens

3.3. Conclusion and Discussion

One of the main results show that the use of 100 % recycled concrete as aggregates show immensely potential. In this testing it was shown that a substitution of the standardized sand according to the EN 196-1 with a high grad RB-A1 recycled aggregate and the use of a plasticiser showed comparable compressive strengths. The 28 days compressive strength values surpassed the cement classifications provided by the technical datasheet, see Figure 19. The w/b value was set constant to 0.5 in the recipe. Although, suction water for the compensation of the hemp fibres was added by 2.5 g water per 1 g hemp fibres, which was not considered to be affecting the w/b value.

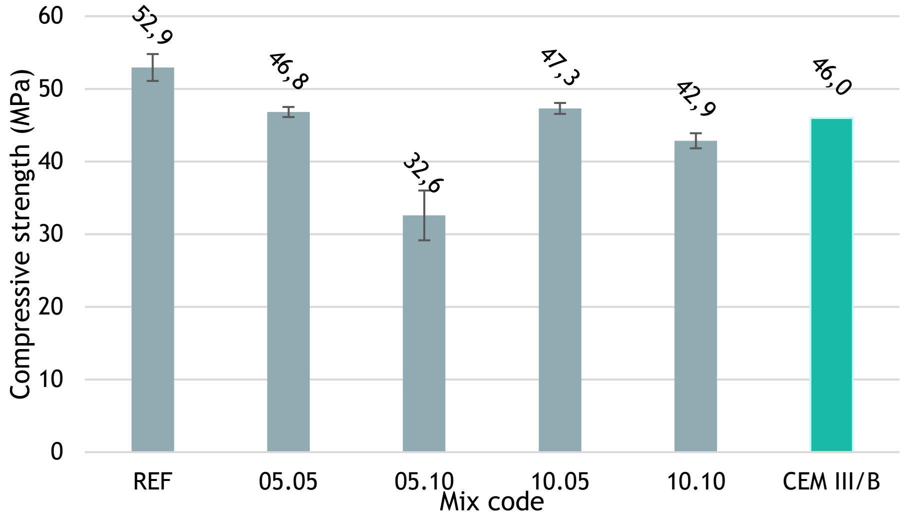


Figure 18:Compressive strength results after 28 days

Another insight of the project was the introduction of short hemp fibres of 5 and 10 mm up to 1 Vol.-% of dosage. The addition led to slightly worsen compressive strengths, most likely to the reduced density of the mortar samples, but with equivalent flexural strength values. Due to the introduction of the carbon negative short hemp fibres, a post cracking behaviour was introduced and showed increasing values for longer fibres. This was obtained by calculating the post fractural energy after the maximum appearing force during a 3-point bending test with deformation-controlled mode of 400 µm/min.

The workability remained and issue through the campaign due to the fibres. Therefore, an additional amount of plasticiser was needed. For future research a focus area on this topic to get constant spread results with changing compositions is needed.

In future project work packages, the aspect of the life cycle assessment of hemp fibres may support an increase in application. A recommended negative global warming potential was only obtained via literature but with a huge range from -0.2 to -2.5 kg eq-CO_2 per kg hemp fibres. A provided data of the manufacturer was not available.

4. Peer-to-Peer Review (PP14)

As part of the laboratory tests and the development of bio-concrete and green concrete, the task is to conduct peer-to-peer reviews. The goal of these reviews was to discuss and evaluate the different results in order to identify optimization potentials.

The following peer-to-peer reviews took place during this activity:

During this activity following peer-to-peer reviews took place:

- ReBuilt A2.2 + A2.1 (July 2024, via Teams)
  - Participants: PP3, PP6, PP10, PP14
- Concrete Party Vol. 1 (October 2024, Munich)
  - Participants: PP3, PP6, PP10, PP14
- ReBuilt A2.2 demos with Hempstatic (June 2025, via Teams)
  - Participants: PP3, PP6
- Concrete Party Vol. 2.1 (August 2025, via Zoom)
  - Participants: PP6, PP14, Hempstatic
- Concrete Party Vol. 2.2 (August 2025, via Zoom)
  - Participants: PP3, PP10, PP14

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