# Development of cold-bonded lightweight concrete aggregates using biowaste

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## Abstract

The use of lightweight concrete could overcome some of the disadvantages of normal-weight concrete. However, the fabrication of lightweight aggregates is energy intensive and considerably draws on non-renewable resources. The positive consequences from lighter weight on supporting structural components' dimensions are frequently outrun by the increase in carbon footprint of up to 65% stemming from the lightweight aggregates. On this background, fabrication of lightweight aggregates in a low-energy cold-bonding pelletizing process, using bio-based waste and by-products, and alternative binders in combination with or instead of cement was explored. Presented results cover reflections for recipe mix design, observations made in the pelletizing and hardening process, results obtained for density, strength, thermal properties, and carbon footprint of this alternative way to produce lightweight aggregates for concrete.

**Keywords:** lightweight aggregates; pelletizing; biowaste; alternative binders; structural properties; thermal properties; carbon footprint.

## 1 Introduction

Concrete is the second most used material by mankind (after water), due to its many advantages: it has a simple recipe (basically aggregates, cement, and water), is cheaply and widely available, and is easily handled as it is pourable, possibly self-compacting, and self-hardening. Furthermore, concrete provides good acoustic insulation, fire protection and thermal storage capacity.

However, its intensive and widespread use heavily draws on non-renewable natural resources. More importantly, cement production is responsible for vast amounts of greenhouse gas emissions. In building construction, minimum dimensions of components are often dictated by execution while the concrete strength is hardly governing. And its high density may require additional material volume in supporting structures.

The use of lightweight concrete (LWC) could overcome some of these disadvantages. But the fabrication of lightweight aggregates (LWA), such as expanded glass or clay, is very energy intensive and draws on non-renewable resources, too (sand, in particular). The possible reduction of material quantity and of the associated carbon footprint, due to reduced density of LWC, is outrun by the added carbon footprint from LWA (up to 65%).

On this background, fabrication of LWA in a low-energy, cold-bonding pelletizing process from sawdust (an ample waste from timber production), calcium-rich wood ashes (an abundant waste from district heating in Switzerland), and alternative binders such as hydraulic lime and metakaolin in combination with or instead of cement is explored. This paper reports on challenges encountered and observed performances in this initial step towards an alternative way to produce LWA for concrete.

## 2 Materials and processes

Considering that aggregates occupy about 80% of the volume of concrete, it has a direct impact on concrete density to make them as light as possible.

The starting point to fabricate alternative LWA was to use mineral materials and industrial waste or by-products vastly available, to provide them with new valorization tracks.

### 2.1 Mineral materials

Mineral components shall work as binder, such as CEM I 42.5N (Holcim Normo 4®), hydraulic lime (Jura Hydradur® NHL5) and metakaolin (Poraver Metapor®). The latter is obtained from calcinating kaolin or naturally altered soft white clay, respectively (an essential ingredient for porcelain). Calcining kaolin also does require elevated temperatures (700-800°C) but considerably lower than in cement production (1450°C). Moreover, transforming kaolin does not emit chemically formed $CO_2$. Furthermore, limestone filler (KFN Nekafor® 15, $CaCO_3$) is used in combination with metakaolin as an efficient substitute to cement [1].

Less known materials considered in the mix design are ashes from wood combustion and sawdust from timber transformation. The former are suspected to have a reactive component while the latter serve as lightweight filler.

### 2.2 Wood combustion ashes

Wood ashes (WA) are a large waste source from district heating in Switzerland, being differentiated into fly ashes and grate ashes. They were obtained from a nearby district heating plant and sieved to a maximum size of 0.5 mm, eliminating larger pieces to obtain a homogeneous material.

To characterize these non-standardized materials, chemical analysis was performed in fluorescent X-ray spectrometry, see Table 1. The grate WA contain large proportions of calcium and potassium and moderate quantities of phosphor and sulfur. X-ray diffraction analysis showed that the calcium phase is composed of quicklime CaO, portlandite $Ca(OH)_2$, and calcite $CaCO_3$. In addition, periclase MgO and potassium minerals were identified.

The fly WA are rich in potassium and sulfur but hardly contain calcium. Sulfur should not be combined with cement, as it may strongly reduce hardening speed or lead to expansion. Therefore, only a few mix designs considered fly WA. Also, CaO and the water in the mix can be transformed into $Ca(OH)_2$ which, in turn, can react with the $CO_2$ in the air to form calcium carbonate. These processes may result in undesirable expansion and require careful proportioning of ashes added to the mix.

### 2.3 Particle size distributions

Figure 1 shows the average and cumulated particle size distributions (PSD) of some components. WA have a similar PSD as the other components, not requiring further grinding.

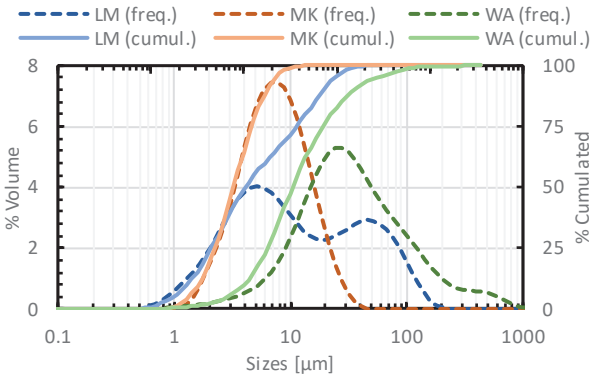


*Figure 1. PSD of MK, LM, and grate WA*

### 2.4 Sawdust

Sawdust (SD) is an abundant waste source from wood transformation. It was obtained from a nearby sawmill and sieved to max. 2 mm in size. It has a bulk density of 425 kg/m$^3$.

Its water absorption capacity WAC is essential for the mix design, determined to be 150%. Furthermore, its natural humidity content needs to be considered in the mix design, too.

*Table 1. Wood ashes composition from XRF, expressed in oxide equivalent weight fraction.*

| Element | $SiO_2$ | $Al2O_3$ | $Fe_2O_3$ | $Mn_3O_4$ | MgO | CaO | $Na_2O$ | $K_2O$ | $P_2O_5$ | $SO_3$ | Cl | Other | LOI |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Grate WA | 2.10 | 0.34 | 0.53 | 0.69 | 3.98 | 55.03 | 0.17 | 9.43 | 2.03 | 2.27 | 0.10 | 0.47 | 10.12 |
| Fly WA | 0.14 | 0.04 | 0.09 | 0.15 | 0.56 | 4.56 | 0.69 | 46.95 | 0.41 | 17.02 | 0.96 | 0.56 | 14.11 |


*Figure 2. Fabrication process of lightweight aggregates and lightweight concrete*

### 2.5 Pelletizing process for LWA

Figure 2 shows the fabrication process for creating LWA and LWC with the considered materials.

LWA or pellets, respectively, are produced in a low-energy, cold-bonding process from SD, WA, and alternative binders in combination with or without cement, using an EIRICH® TR10 pelletizer.

In pelletizing, fine powders turn into variable size pellets thanks to the adhesive forces from added fluids (water in the present case). The size of particles can be steered to a certain extent through rotation speed and inclination of the pelletizer. In addition, binders react with water (or other components in the mix) and start hydrating. Fresh pellets are very soft but stable. Once the desired sizes are obtained, they are left to harden.

### 2.6 Fabrication of LWC

The fabrication of LWC follows the same process as regular concrete mixing, using a standard concrete mixer and the chosen mix design (i.e., material proportions). Alternative LWA, binder, and possibly lime filler (LM) and superplasticizer (SP) are mixed until homogeneous. Water is progressively added until desired workability is reached.

## 3 Mix design evaluation

The development undertaken here was performed in several steps, considering earlier knowledge [2] and exploring new mix designs for LWA and LWC. Figure 3 shows the main ingredients (with regular cement missing) and 1st generation BioLA (from Bio-based Lightweight Aggregate).


*Figure 3. Components of G1 BioLA © R. Serpell*

Evaluation of LWC properties concerned cylinder compressive strength $f_c$ and density ρ. Thermal properties – specific heat capacity $c_p$ and thermal conductivity $\lambda_t$ – were also determined (but are not reported to the full extent here), as they play a key role in non-structural uses, i.e., if used in the secondary structure.

### 3.1 First trials

First LWC mix designs used G1 BioLA [2], selected from particle compressive strength $f_{cp}$, where $F$ is the crushing force for a particle of diameter $D$:

$$f_{cp} = \frac{2{,}8 \cdot F}{\pi D^2} \quad (1)$$

*Table 2. Mix design and properties of G1 ECon-BioLA*

| Mix ID | BioLA (G1) [kg/m³] | SD [kg/m³] | CEM I [kg/m³] | LM [kg/m³] | SP [kg/m³] | Water [kg/m³] | $\rho_{fresh}$ [kg/m³] | $f_c$ [MPa] |
|---|---|---|---|---|---|---|---|---|
| T1 | 1050 | 0 | 195 | 195 | 3.9 | 426 | 1635 | 0,62 |
| T2 | 1116 | 0 | 144 | 144 | 2.9 | 353 | 1603 | -- |
| T3 | 1110 | 0 | 162 | 162 | 1.9 | 338 | 1467 | -- |
| T4 | 1006 | 0 | 173 | 173 | 2.1 | 317 | 1599 | 0,59 |
| T5 | 1139 | 37 | 101 | 128 | 1.4 | 312 | 1460 | 0,47 |
| T6 | 1141 | 39 | 107 | 136 | 1.5 | 282 | 1612 | -- |

### 3.1.1 G1 ECon-BioLA

For the 1st generation of ECon-BioLA mixes (from Ecological Concrete with BioLA), the strongest G1 BioLA were selected. Table 2 shows their mix designs and main results of mechanical properties.

The mixes hardened very slowly, and the expected compressive strength was not reached (partially not even be measured). This was attributed to an insufficient consideration of the water absorbed by the BioLA, leading to a substantial decrease in water available for hydration, combined with an inadequate volume of binder paste to compensate for the suboptimal granulometry of the BioLA.

G1 BioLA have a rather high carbon footprint of 135 $kgCO_{2eq}/m^3$, compared to LWA made of expanded glass (27 $kgCO_{2eq}/m^3$) or clay (89 $kgCO_{2eq}/m^3$), due to the relatively high cement content and being the reason for turning towards alternative binders.

### 3.1.2 G2 and G3 BioLA

New mix designs (G2) were conceived with MK, HL or CEM as binders, and characterized on mortar specimens. These mortars can serve for BioLA fabrication or as matrices in ECon-BioLA.

MK mixes showed highest strength, followed by CEM mixes, while HL mixes had much lower performance. MK hydration is activated by alkalis in the WA. MK mixes did less or not expand, and they gained more strength than mixes with similar CEM dosages, Figure 4. CEM mix designs needed adaptation (G3), as large expansion was observed. It diminished with increased MK dosage (quicklime is consumed in its reaction with MK).

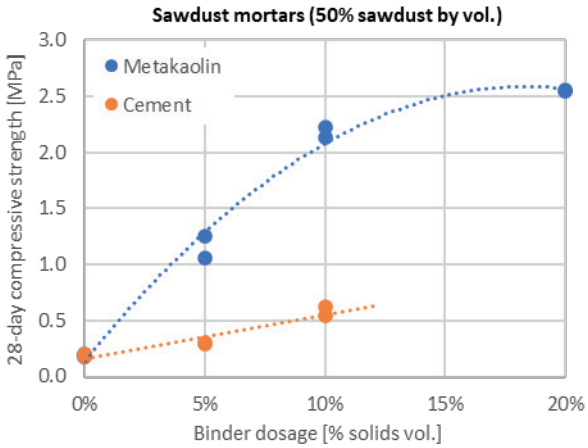


*Figure 4. G3 BioLA strength vs. binder dosage*

### 3.1.3 G2 ECon-BioLA

BioLA were produced using the most performing G3 recipes and applied in a 2nd generation of ECon-BioLA mix designs, containing CEM, LM as filler but no SD in the binder matrix.

Mix design adaptation yielded better fresh state performance. But slow hardening for specimens containing BioLA with WA persisted (while it did not without WA), and they also exhibited a dark green color and a vanilla-like scent. Concluding that the alkalis in the WA decompose the cellulose or lignin in the SD (part of BioLA) into glucose – the perfect retarder or preventer of CEM hydration. Maximum strength $f_c$ amounted to 3.5 MPa with a density of 1290 kg/m³ for a mix without WA.

Therefore, further BioLA mix designs (G4) were evaluated, to identify optimal proportioning of WA, MK, CEM and LM and taking qualitatively into consideration the associated carbon footprint.

### 3.2 G4 BioLA and G3 ECon-BioLA

More than 20 BioLA mix designs, with a constant SD volume of 50%, were produced and evaluated for particle compressive strength according to Eq. (1).

Even though BioLA mix designs with CEM showed considerably higher strength $f_{cp}$ (up to 3.4 MPa) than mixes with MK (up to 0.4 MPa), only the latter were considered in a G3 ECon-BioLA evaluation, as the CEM-based BioLA would heavily add to the carbon footprint, see section 3.1.1.

Half of the specimens were cured in a climate chamber while the other half was left to dry in the air. They all exhibited slower hardening but less pronounced than preceding generations and without expansion effects. Cured specimens had a higher average strength $f_c$ at 28 days (2.4 MPa) than dry specimens (2.0 MPa) but also a slightly higher coefficient of variation COV (6.9% for cured and 4.7% for dry specimens). Density was 1200 kg/m$^3$ for cured and 1220 kg/m$^3$ for dry specimens, both with a COV of around 2%.

As the strength of G3 ECon-BioLA was inferior to comparable G2 mixes containing BioLA without WA (i.e., using CEM-based BioLA), it was decided to refine G4 BioLA recipes by adding small amounts of cement to the pellet mixes while compensating it in the binder mix using MK and WA exclusively.

### 3.3 G5 BioLA and G4 ECon

In contrast to the G4 BioLA mix design (where no CEM was incorporated), a new G5 BioLA recipe considered a binder mix of CEM and MK with WA.

Table 3 compares the mix designs of G4 and G5 BioLA and shows results for saturated surface-dry density $\rho_{SSD}$ (i.e., pellets dry at the surface but not in the volume) and water absorption capacity WAC. Both properties affect the mix design formulation of ECon-BioLA to be produced with these pellets. Particle compressive strength was not determined for the G5 BioLA pellets as focus lied on G4 ECon-BioLA properties. Figure 5 shows lab fabricated G5 BioLA. Using the two PP05 BioLA (G4 and G5), two distinguished mix designs for new G4 ECon-BioLA were formulated and tested, using binder mixes with MK and WA exclusively and evaluating the impacts of adding BioLA of different composition on mechanical and thermal performances.

*Figure 5. G5 BioLA*

In addition, mortar recipes AMK (from ashes + MK) without adding BioLA were evaluated, using MK and WA binder mixes only and adding SD or not. This intentional variation targeted a possibly better aptness for non-structural applications and how ingredients affect the final properties.

Table 4 shows the ECon and AMK mix designs and their mechanical and thermal properties at 28 days. As ECon recipes are also targeting structural applications, Young's modulus was measured at 2.7 GPa (ECon 1) and 2.4 GPa (ECon 2), respectively – which is equivalent to a quite soft material. Basically, the tested ECon and AMK mixes are comparable to rubber materials while a structural LWC made with expanded glass or clay aggregates would be linked to porous ceramics, with approximately $\rho$ = 1750 kg/m$^3$, $f_c$ = 25 MPa, $c_p$ = 2,3 MJ/m$^3$·K and $\lambda_t$ = 0,23 W/m·K. Thus, should our mixes better target non-structural applications?

*Table 3. Mix design recipes for G4 and G5 BioLA*

| BioLA mix | CEM I [kg/m$^3$] | MK [kg/m$^3$] | WA [kg/m$^3$] | LM [kg/m$^3$] | Water [kg/m$^3$] | $\rho_{SSD}$ [kg/m$^3$] | SD [kg/m$^3$] | WAC [--] |
|---|---|---|---|---|---|---|---|---|
| PP05 (G4) | 0 | 138 | 291 | 452 | 435 | 1530 | 137 | 54,3% |
| PP05 (G5) | 73 | 73 | 254 | 394 | 517 | 1507 | 120 | 50,5% |

*Table 4. Mix designs and performances of G4 ECon-BioLA and AMK mortars*

| ID | BioLA [kg/m³] | MK [kg/m³] | WA [kg/m³] | SD [kg/m³] | Water [kg/m³] | SP [kg/m³] | ρ [kg/m³] | $f_c$ [MPa] | $c_p$ [MJ/m³·K] | $\lambda_t$ [W/m·K] |
|---|---|---|---|---|---|---|---|---|---|---|
| ECon 1 | 669 (G4) | 213 | 265 | 0 | 367 | 0.9 | 1450 | 6,4 | 11,7 | 0,69 |
| ECon 2 | 684 (G5) | 221 | 274 | 0 | 345 | 0.9 | 1419 | 5,1 | 11,3 | 0,68 |
| AMK 1 | 0 | 445 | 553 | 0 | 603 | 1.5 | 1522 | 4,3 | 11,3 | 0,66 |
| AMK 2 | 0 | 361 | 449 | 67 | 517 | 1.2 | 1392 | 3,6 | 11,6 | 0,59 |

## 3.4 Materials for finishings

With the last results, it became clear that non-structural applications could be more promising for the materials explored so far, where density, thermal properties and carbon footprint are more important than mechanical strength.

Screeds on floor slabs can serve as an example in this context: they provide the support for flooring but also a damping mass for acoustic insulation and passive heat storage mass. The screed is heated up by solar radiation during the day. After sunset, the stored heat is radiated back to the room and allows to delay heating (thermal inertia). From a structural point of view, they require a minimum strength but should have a low density as they are dead loads.

An internal study [3] of a residential building showed that floor slabs are a main contributor to the total carbon footprint. In these, the finishing (flooring, screed, acoustic insulation) contributes 45% (for a concrete slab) to 85% (for a timber slab) to the carbon footprint while about half of it comes from using a cement screed. Thus, the screed is a substantial source of carbon footprint.

Currently, screeds are usually made with cement or anhydrite mortars, showing ρ = 1850-2000 kg/m³, $c_p$ = 1,6-2,8 MJ/m³·K and 180-220 $kgCO_{2,eq}/m^3$ in carbon footprint. In comparison, the carbon footprint of G4 ECon amounts to 128 $kgCO_{2,eq}/m^3$ (ECon 1, minimum) to 190 $kgCO_{2,eq}/m^3$ (AMK 1, maximum) [3] while their densities are about 20-30% lower – and their specific heat capacity is about 4 to 7 times higher (Table 4).

### 3.4.1 Non-structural G5 mortars

Based on these findings, new recipes for alternative mortars were explored. In total, 27 recipes were conceived with various levels of SD content (10/30/50%), partially replacing CEM with LM (5/20/35%), variable cement content (33/50/70% of binder) and replacing CEM with variable WA-MK blends (90-10/70-30/50-50%). 9 mix designs were selected and tested for cube strength $f_{cc}$ at 7d and 28d on 40 mm mortar specimens and for thermal properties with variable relative humidity content (0/50/80%) between 28d and 35d. Figure 6 shows mix designs, expected fresh densities and carbon footprint of the evaluated G5 mortar recipes.

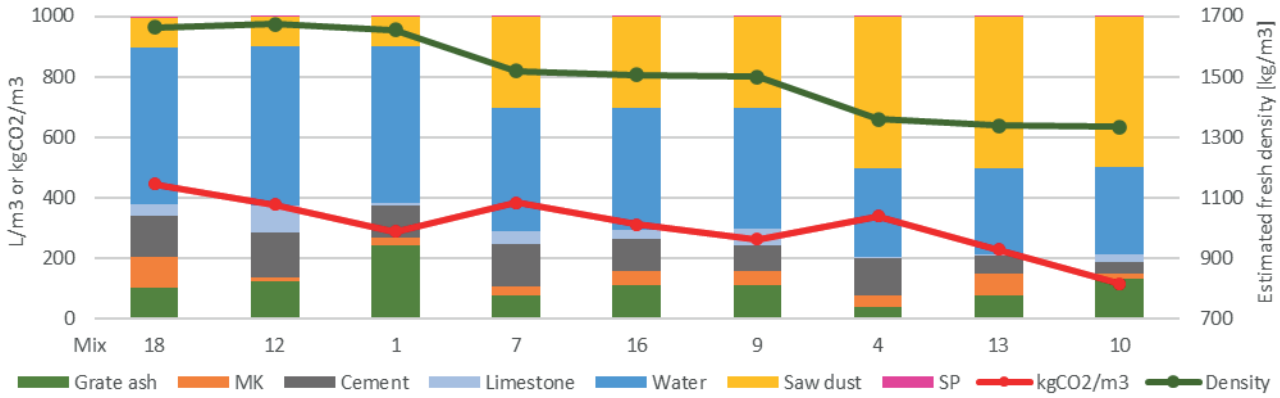


*Figure 6. G5 mortar mix designs, expected fresh densities and carbon footprint*

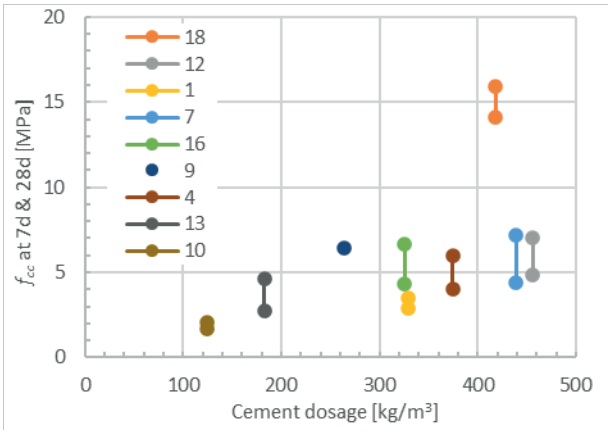


*Figure 7. G5 mortar cement dosage vs. strength*

Figure 7 presents cube compressive strength at 7d (lower points) and 28d (upper points) as a function of cement dosage. The strength increases up to a cement dosage of approx. 270 kg/m$^3$ and levels off beyond – except for recipe 18 with an exceptionally high strength, confirmed in validation tests. It was further concluded that adding WA is favorable for strength while increasing SD volume decreases it.

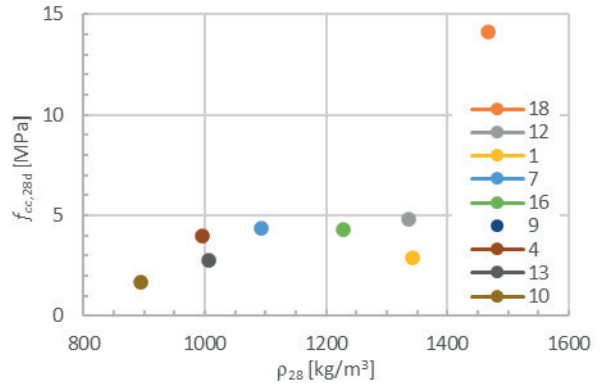


*Figure 8. G5 mortar density vs. strength*

Figure 8 displays cube compressive strength at 28d versus density. The high compressive strength of recipe no. 18 is not due to a denser material, and the strength seems to level off at a density of approx. 1100 kg/m$^3$ for the others. An anticipated effect is that hardened densities are much lower than fresh densities, due to water evaporation from the pre-saturated saw dust with high WAC (section 2.4). Mixes with low SD dosage (nos. 18, 12, 1) lost about 10-15% in density over 28 days while mixes with high SD content (nos. 4, 13, 10) showed density losses of about 30%.

In terms of carbon footprint, G5 mortar recipes are generally less performing than a traditional screed (with 180-220 kg$CO_{2,eq}$/m$^3$), apart from recipe no. 10 with a carbon footprint of 115 kg$CO_{2,eq}$/m$^3$. This recipe is characterized by a 50% SD volume (i.e., a by-product with negligible carbon footprint) and very low CEM content, Figure 6, while for all other recipes the relatively large dosages in CEM and MK, both with considerable carbon footprint, lead to total carbon footprints exceeding that of screeds (up to 444 kg$CO_{2,eq}$/m$^3$). However, the carbon footprint evaluation should also consider the specific heat capacity or the heating energy, that such a material can save over the life cycle of a building, respectively [4].

## 4 Overall evaluation

Considering the large variety of results obtained, an overall evaluation was performed. In view of potential application fields, material properties are differentiated between structural functions, where density and strength play key roles, and non-structural functions, where density and specific heat capacity are more relevant. For both application domains, carbon footprint is integrated in the evaluation and in the comparison to commercial competitor materials. No specific difference of materials containing aggregates (i.e., with LWA) or mortars (i.e., without LWA) is made.

### 4.1 Structural application

Figure 9 compares performances of all alternative materials in terms of density, strength, and carbon footprint. It becomes obvious – again – that the materials developed here cannot compete with the strength of regular LWC made with expanded glass or clay aggregates (also see section 3.3).

However, almost 80% of the alternative mixes could compete with structural masonry, which has average compressive strength ranging from 2,2 MPa (for thermally insulating lightweight masonry) to 15,9 MPa (for regular heavy-duty masonry) and densities of 1300-2000 kg/m$^3$, see hashed green lines in Figure 9 – while the alternative mixes with competitive strength have 950-1520 kg/m$^3$ density.

Regular masonry usually has a carbon footprint of 260-310 kg$CO_{2,eq}$/m$^3$ (as low as 220 kg$CO_{2,eq}$/m$^3$ in exceptional cases), see dotted red lines in Figure 9. The carbon footprint of alternative materials with

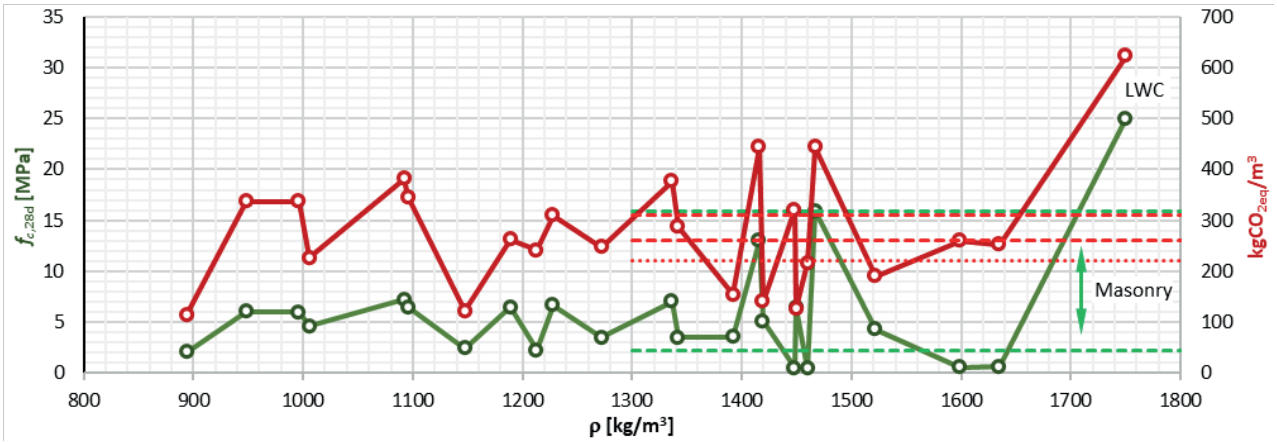


*Figure 9. Overall evaluation of study results for structural applications*

adequate strength varies between 122 $kgCO_{2,eq}/m^3$ ($f_c$ = 2,4 MPa) and 444 $kgCO_{2,eq}/m^3$ ($f_c$ = 15,9 MPa).

The most promising materials are the four given in Table 4, with 128 $kgCO_{2,eq}/m^3$ (ECon 1) to 190 $kgCO_{2,eq}/m^3$ (AMK 1). The mix tested for G3 ECon-BioLA (see section 3.2) with the lowest carbon footprint of 122 $kgCO_{2,eq}/m^3$ has a strength of 2,4 MPa only but also a density as low as 1150 $kg/m^3$ only. Among the other mixes, recipe 13 (see Figure 6) could be a further candidate with a strength of 4,6 MPa, 1000 $kg/m^3$ density, and a carbon footprint of 227 $kgCO_{2,eq}/m^3$.

## 4.2 Building-physical application

Figure 10 shows results for thermal storage capacities $c_p$ [$MJ/m^3K$] of the alternative materials, in comparison to regular screed materials (cement or anhydrite), see section 3.4.

The latter have a density of 1850-2000 $kg/m^3$ (i.e., principally heavier), 1,6-2,8 $MJ/m^3{\cdot}K$ specific heat capacity and 180-220 $kgCO_{2,eq}/m^3$ carbon footprint, see dashed lines in Figure 10. Note that for materials showing zero specific heat capacity, this property was not measured.

The most performing alternative materials for heat storage are the four in Table 4, again. Recipe AMK 1 is the least interesting as it has a carbon footprint in the range of regular screeds and the highest density of the shortlist. The highest thermal storage can be reached with ECon 1 which has the lowest carbon footprint at the same time but also the second highest density.

Mix AMK 2 would be the best choice, showing the lowest density, nearly the same heat storage capacity as ECon 1, and an only 21% higher carbon footprint.

Among the mixes with a specific heat capacity in the same range as regular screeds, none would provide a lower carbon footprint than the latter.

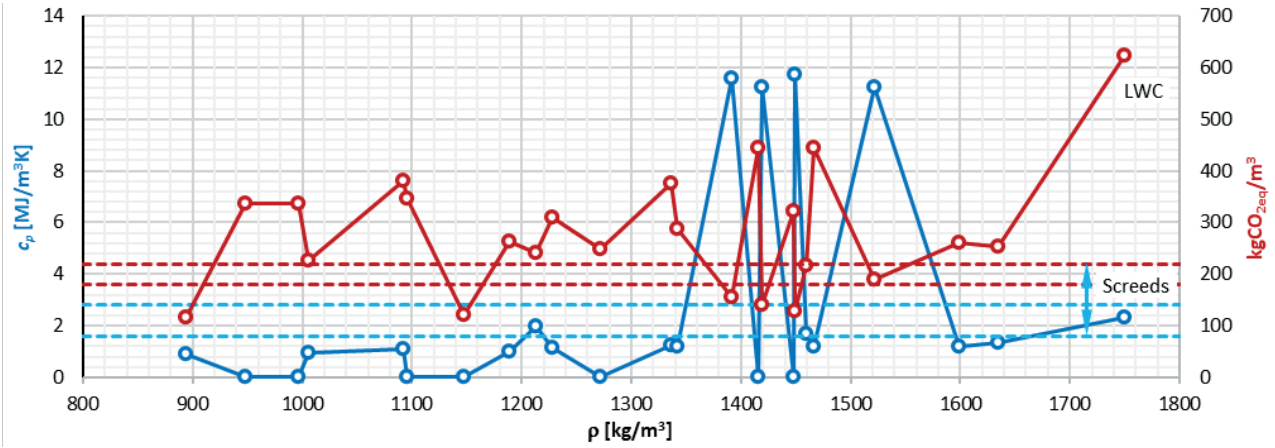


*Figure 10. Overall evaluation of study results for thermal storage applications*

## 5 Conclusions and outlook

This exploratory work aimed to assess the viability of using wood ashes and saw dust – two largely available waste by-products from industry – for the fabrication of lightweight aggregates by pelletizing or of other alternative construction materials.

The inclusion of saw dust allows to obtain lightweight materials (900 to 1700 kg/m$^3$), while substituting cement with wood ashes, metakaolin and limestone decreases the carbon footprint of the binder. Although the mechanical properties of the developed mixes cannot compete with commercial lightweight concrete, non-structural applications such as screeds with a passive thermal function could be the ideal setting for these low-carbon, waste-incorporating materials.

More research is required to better understand the synergies and interactions between the numerous mix components, to optimize proportioning in the mix designs and to estimate long-term and durability performances, such as freeze-thaw behavior (if outside applications are intended), water absorption/release cycles (e.g., for internal comfort), or carbonation behavior (if these alternative materials shall be used in combination with potentially corrosive reinforcement).

## 6 Acknowledgements

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