Recycling Potential of Cellular Lightweight Concrete Insulation as Supplementary Cementitious Material

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Abstract. Buildings are responsible for 40% of the total energy consumption annually in Europe, along with the respective greenhouse gas emissions. To mitigate these impacts, intensive research is ongoing in the sector of Nearly Zero-Energy Buildings (NZEBs). Within EU-funded project iClimaBuilt, RISE is developing and improving the formulation of cellular lightweight concrete insulation (CLC) as a sustainable and recyclable alternative for organic insulation materials (ex. Expanded polystyrene (EPS)). Compared to EPS, this material is non-combustible and achieves similar performance as existing insulation materials (thermal conductivity of 40 mW/(mK)) while economically more attractive (EPS 60 EUR/m^3, CLC 50 EUR/m^3). In addition, the material is easily recyclable since it is 100% mineral based. It is also similar or lighter in weight than traditional EPS (around 80 kg/m^3). At these ultra-low densities as for concrete, the material integrity was ensured by adding polypropylene micro-fibres. To further improve the thermal conductivity of CLC, granulated silica aerogels were implemented in the mix. The CLC was implemented in a lightweight sandwich-panel in form of a prefabricated block similar to currently used EPS-sheets. The recyclability of the material as an SCM for new cement production is being evaluated by a reactivity study of grinded and reheated (recalcined) material. The panel prototypes will be tested in a laboratory and validated in the living labs – real-life test and experimentation buildings in different climate zones in Europe.

Keywords: Concrete · Cellular-Lightweight Concrete · Insulation · Reactivity · SCM

1 Introduction

1.1 Background

Considering growing energy prices and environmental crisis major transition is necessary in our technologies. The construction sector has a crucial impact on energy consumption and carbon emissions in the European Union: Buildings account for 40% of the total energy consumption and are responsible for 36% of greenhouse gas emissions in

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Europe. The major reduction of those factors can be achieved by improving energy efficiency of our buildings to achieve Near-Zero-Energy standards, thus reducing heat losses by for instance applying better insulation. Secondary, the transition requires changing the paradigm of linear economy to circular approach reusing and recycling building components and materials.

One of potential materials supporting the green transition can be cellular lightweight concrete (CLC) due to its mineral composition thus full recyclability and very good insulation properties at low densities. CLC is a very versatile material that allows for fairly easy adjustment to different applications by changing the density with cement slurry and foam ratio with eventual modification of the binder composition and adding fine aggregate in case of higher densities. For densities lower than 600 kg/m^3 the CLC is used in non-structural applications as compartment walls, acoustic or thermal insulation [1], while for higher densities it can be applied as load-bearing material for single-layer external walls, road embankments etc. [2].

1.2 Aim and Goals

Within the EU-funded project iClimaBuilt CLC is applied as an insulation layer in façade concrete sandwich panels fulfilling the requirements for NZEBs. Within this study the CLC with different densities and with additions of silica aerogels was tested for thermal and mechanical properties. The aim was to achieve the thermal conductivity $\lambda < 40$ mW/mK. The produced CLC blocks are to be prefabricated and shipped to other project partners for casting in sandwich panels in combination with carbon-textile reinforced high-performance concrete.

The second goal of this study was to investigate the end-of-life scenarios for the CLC insulation as a supplementary cementitious material for cement production. In the first step the reactivity of the CLC waste powder was evaluated and strategies for increasing the reactivity were studied, including mechanical grinding and heat treatment.

2 CLC Material

2.1 Constituents

To obtain ultra-lightweight CLC with a density below 300 kg/m^3 a very fast setting time is needed. To achieve that a blend of different binders was used in this study. The presented results were obtained with water to binder ration $w/b = 0.45$. To secure the integrity of the hardened material, which is brittle in nature, the polypropylene microfibres were introduced in the cement slurry mix in proportion of 0.5% of cement weight. The consistency of the slurry was improved with polycarboxylate superplasticizer. The density of the final product was achieved by proportioning the cement slurry and the synthetic foam obtained with foam generator FG-6 from Aercrete using a synthetic foaming agent Aercell-7, which is a surfactant based, stable foam with air cells in the magnitude of 60–90 microns.

2.2 Production Process of CLC

The CLC in this study was produced in standard pan concrete mixer. In the first step the binders are dry mixed for 30 s and then water containing additives is added for another 30 s. After 2 min of mixing, polypropylene microfibres are added to the slurry. After the slurry obtains the desired consistency and the mix becomes homogeneous the foam is injected to the mixer during its operation with a rate of 100 L/minute. The mixing time is usually 10–15 min. The density of the CLC is checked, if the target density is obtained in two subsequent measurements the mix is ready for casting, otherwise the mixing process is continued. The samples are casted in dismantlable moulds with anti-adhesive grease and covered with polyethylene foil for curing. The samples are demoulded 24 h from casting and cured in 65% RH and 20 °C for 7 days. After that the samples are moved to 50% and 20 °C for another 21 days. The samples for mechanical testing are then tested, while samples for thermal conductivity are further cured in 50% RH and 20 °C until mass stabilization.

2.3 CLC Properties

The compression test for is performed according to modified standard method EN12390-3. The samples are measured for determination of density prior to testing. The testing protocol consists of sample positioning, placing the steel plate on the top of the sample and applying pre-load of 100 N. From that point the samples are loaded with continuous deformation of 0.1 mm/min until force drop of 80% from the maximum force or deformation of more than 2%. In that way both the initial stiffness, compressive strength and post-critical behaviour can be captured. Exemplary results from many trials performed by RISE during this project and Lightcoce EU project the material development are depicted in Fig. 1.

The thermal conductivity is tested according to the EN12664:2001 in 20 °C using hot plate flow meter at samples with size of 400 × 400 × 60 mm. The samples surface was always prepared with sandpaper grinding to ensure good connection between the hot plate and the material. Some results of the CLC with different formulations in relation to the as-received density were presented in Fig. 2.

To improve the thermal conductivity granulated silica aerogels are introduced in the CLC mix during addition of the foam to the mix. In the presented study, the 40% and 60% of cement slurry volume was investigated for the CLC with a wet density of 200 kg/m^3. The commercial hydrophobic aerogels were used in this study. The results from this study were compared with other formulations used before at Fig. 3. The as-received densities varied between 180 and 140 kg/m^3. The Sample with 60% AG at the density of 140 kg/m^3 achieved the desired thermal conductivity of 40 W/m^{2}K. The addition of the AG improved the thermal conductivity in all cases by 5–7% comparing with the trend line for CLC without aerogels.

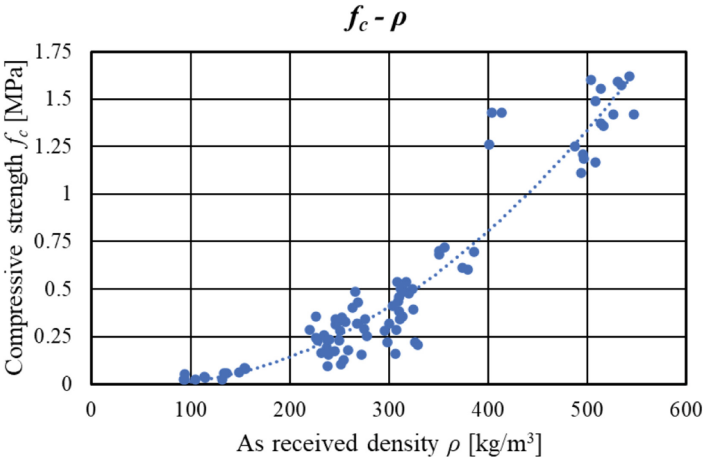


Fig. 1. The relationship between the compressive strength and the density as received of CLC with different densities and formulation.

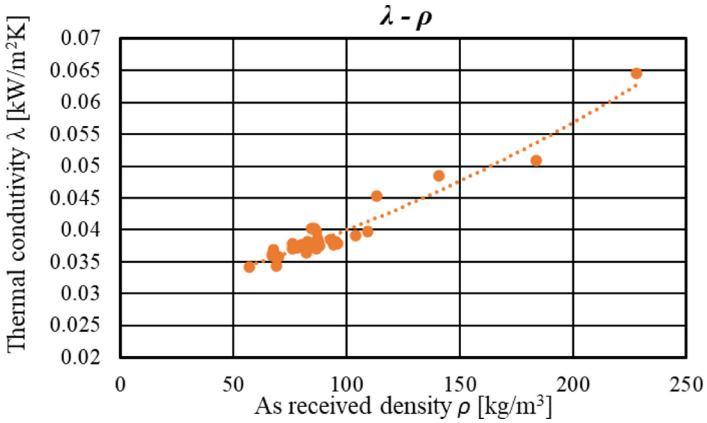


Fig. 2. The relationship between the thermal conductivity and the density as received of CLC with different densities and formulation.

The CLC used in this study has a GWP 54 kg CO2 eq per m^3 and embodied energy of 99.3 MJ/m^3 [8] in cradle to gate LCA calculation which is lower than EPS with similar properties with GWP 78 kg CO2 eq per m^3 and embodied energy of 2227 MJ/m^3 [9].

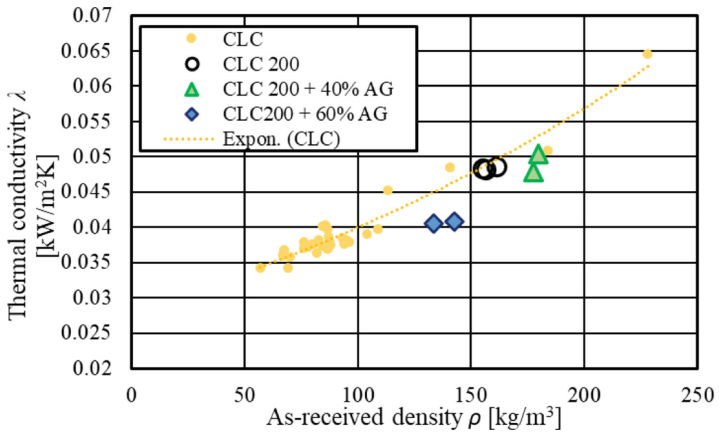


Fig. 3. The results of thermal conductivity for different CLC densities without aerogel (empty circles) and with 40% (triangles) and 60% (diamonds) aerogel content by volume of cement slurry

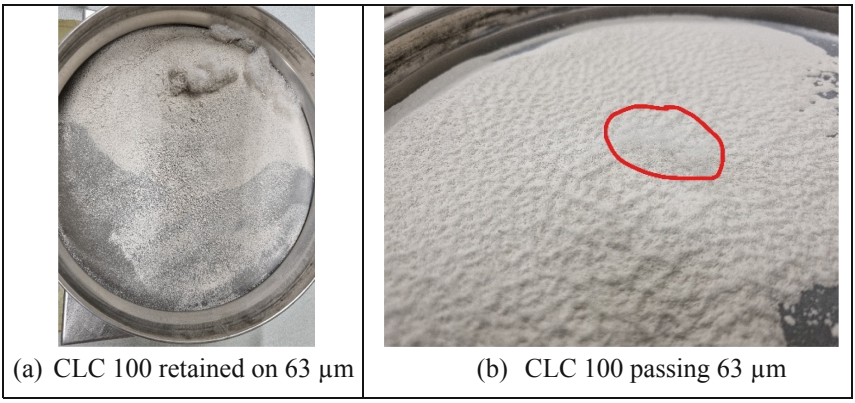
3 Recycling of CLC

3.1 Samples Preparation

One of the biggest limitations in recycling of the hydrated cement pastes (HCP) in concrete and mortar demolition wastes is the difficulty in segregating the HCP pastes from the aggregates. Another limitation is the amount of energy required to mill the HCPs to finer fractions. The absence of aggregates and the low strength of CLC eliminate both these limitations, making it highly suitable for recycling of the HCP. The objective was to explore the possibility to recycle HCP to be used as supplementary cementitious materials (SCM). The samples were the CLC presented previously without aerogels (CLC150) and two other CLC densities (CLC100 and CLC300), with different densities realized by modification of slurry to foam ratio. For the recycling studies, old (>1 y) CLC panels left after thermal conductivity testing, exposed to the uncontrolled indoor laboratory environment were used. This was done by testing the SCM reactivity of the finer fractions using standard R^3 tests [4].

3.1.1 Sieving

For the R^3 test, the low strength of the panels allowed them to be hand crushed into fine powder. Thereafter, to separate the fibers from the HCP, they were sieved using a 63 μm sieve for 15 min using a sieve shaker. Figure 4(a) and Fig. 4(b) respectively exhibit the fractions that were retained and passed through when the crushed CLC100 was sieved. Figure 4(a) shows that most of the fibers retained at 63 μm sieve formed agglomerates resulting from the sieving action. Figure 4(b) shows the finer fractions that pass through the sieve. Moreover, in passed fractions, agglomeration of the small amounts of finer fibers that have passed through the sieves can also be observed (identified by a red marker in the figure).



(a) CLC 100 retained on 63 μm (b) CLC 100 passing 63 μm

Fig. 4. CLC 100 that has been hand crushed and sieved using 63 μm, where (a) shows fraction retained on sieve, and (b) shows the passing fraction

3.1.2 Thermal Treatment

For each sample, the fractions passing 63 μm were further divided into two halves. One half was subjected to R^3 test without treatment and the other half was subjected to thermal treatment. For this, an alumina crucible containing the samples was placed inside a furnace (GLM 11/7, Carbolite) and the temperature was increased from room temperature to 650 °C, and then maintained at 650 °C for 2 h. The samples were immediately removed thereafter. The temperature of 650 °C was chosen since the ignition point of the fibers was reported to be 593 °C in the product data sheet of SikaFiber® 6FF [3] used to produce the CLC.

3.2 R^3 Test for SCM Reactivity

The R^3 reactivity tests were performed by adapting the standard process as mentioned in [4]. Isothermal calorimetry (Tam Air, TA instrument) was used in this study. The signal was stabilized at 40 °C for ~24 h and the isothermal calorimetry was calibrated before the experiments. Thereafter, before beginning the calorimetry tests, the baseline was collected for 90 min. The mix design is shown in Table 1. Dry powder, composed of CLC, portlandite, and calcite, was mixed by hand for 1 min. The KOH - K_2SO_4 solution was mixed with the dry powder for 2 min at 1600 rpm with an overhead stirrer (RZR 2020, Heidolph). After mixing, about 5–6 g of fresh paste was transferred to the ampule immediately. The ampules were sealed and carefully placed into the calorimeter. The cumulative heat release was calculated starting from 1.2 h to avoid the non-thermal equilibration of the sample. The cumulative heat release at 3 and 7 days was taken as an indication of heat release.

3.3 Results and Discussion

Figure 5 exhibits the cumulative heat of CLC compared before and after heat treatment at 650 °C. Before the heat treatment, the cumulative heat release is increased with higher

Table 1. Mix design for R^3 test

Component	Calcite	SCM	Portlandite	KOH + K_2SO_4 solution
Mass (g)	1.00	2.00	6.00	10.80

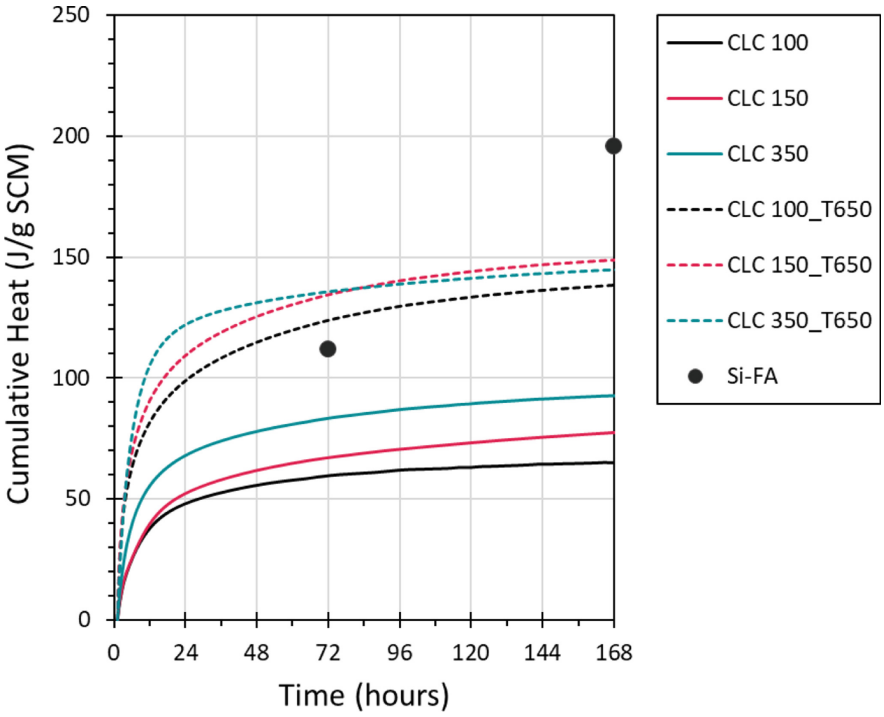


Fig. 5. Cumulative heat release from R^3 test of CLC100, CLC150 and CLC 350 compared between before (solid line), after (dash line) heat treatment at 650 °C (T650) and average values of siliceous fly ash (Si-FA) at 72 and 168 h from [4].

density of CLC. From Fig. 4, it clearly shows an increase of heat release after the heat treatment. Before 3 days, the effect of density of CLC can be observed. The higher density of CLC contains more cement content in the mix design and releases higher cumulative heat. However, the heat release values are comparable for all the samples after the heat treatment at 7 days. The increase of heat release after the heat treatment for all samples indicates that the heat treatment can enhance the reactivity of recycled CLC. This may, to some extent, be attributed to the increased surface area, porous morphology, and increased CaO content of the thermally treated material. Such influence of physical properties is known to be more dominant during the early hydration, thereby giving relatively higher early heat but comparable cumulative heat of hydration [5, 6]. This difference in physical properties could also explain the slight increase in viscosity while mixing the pastes with thermally activated CLC. The increased overall reactivity of

the thermally treated CLC agrees with the earlier studies [7] in which the increased reactivity of the thermally treated cement paste was attributed to the presence of partially dehydrated forms phases like Tobermorite and Jennite in the thermally treated pastes.

When comparing treated CLC to other SCM (calcined clay, slag and siliceous fly ash), the treated CLC has comparable reactivity to siliceous fly ash, as shown in Fig. 5. The heat release of treated CLC at 7 days has much lower reactivity than calcined clay (537 J/g SCM) and slag (511 J/g SCM) [4]. However, the reactivity of treated CLC could be improved with finer particles which will be investigated in the next step.

4 Conclusions and Future Work

- The CLC is a versatile material capable of matching the requirements for thermal insulation for NZEB facades, providing inexpensive, inflammable and fully mineral alternative to currently used EPS.
- The addition of silica aerogels improves the thermal conductivity of CLC at low densities 5–7%. This is most probably due to already very good thermal conductivity of the CLC without aerogels.
- CLC has the potential to become a circular material by reusing it as an SCM in new cement production. Its reactivity can be improved by thermal treatment.
- Among the non-heat treated CLC samples, the samples with higher density exhibited relatively higher reactivity.
- The heat treatment enhances the reactivity of recycled CLC, with all the heat treated samples exhibiting comparable cumulative heat in 7 days.
- Several aspects still need to be studied in more detail from SCM reactivity perspective. Most importantly, since the CLC was produced using limestone, the accelerating role of $CaCO_3$ in hydration through nucleation and filler effect need to be explored in terms of the limestone contents of the respective CLCs. Another important aspect to be studied is if the dehydrated HCPs hydrate through the dissolution-precipitation mechanism or rehydration and re-combination of dehydrated phases in the presence of water.
- The water demand increases in thermally treated materials. This needs to be quantified, and it may be needed to either increase the amount of water or use admixtures.

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