Summary report: Highly insulating, monolithic concrete panels made of architectural lightweight concrete

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1. Aim of the research project

The combination of the physical properties of a highly insulating lightweight concrete with the optical properties of a so-called architectural concrete enables construction components to be designed so that the deliberately emphasised form of the concrete building material can be combined with current and future foreseeable energy requirements regarding the characteristics of external construction components. Compared to a conventional multi-layered exterior wall, a homogeneous, a solid architectural concrete wall made of lightweight concrete presents advantages in terms of design options, the avoidance of joints, construction time, heat retention and recycling of building materials. By optimising the material properties of architectural lightweight concrete, a monolithic wall (wall thickness approx. 50 cm) can be made according to ENEV 2009 criteria, which also meets high standards in terms of optical and physical construction requirements.

The aim of the research project was the development of highly insulating monolithic lightweight concrete construction components made of exposed concrete, which were to be made from recyclable materials (expanded glass, etc.) and a cement with an optimized Life Cycle Assessment, within the context of "sustainable construction" as a research focus at the University of Kaiserslautern.

Monolithic exterior construction components made of heat-insulating lightweight concrete are sensitive to water/moisture and other penetrative, corrosive media as a result of their low density and porous structure. Furthermore, the demands made regarding the properties of fresh concrete and regarding mechanical requirements had to be unerringly met. Achieving sufficient material properties is therefore dependent on having a surface which is as closed and homogeneous as possible, but simultaneously allowing a high quality of exposed concrete. The monolithic construction component without additional insulation should meet the requirements of ENEV 2009 (U value of 0.28 $W/(K \cdot m^2)$) and achieve a U value of 0.2 $W/(K \cdot m^2)$ with core insulation. Core insulation materials suitable for this purpose should be used which take particular account of the aspects of sustainable building and make the recyclability of the entire construction possible. In the project in question, the development of an architectural lightweight concrete with the following requirements was to occur:

- High quality of exposed concrete with a surface which is as structurally dense as possible
- Wall construction meets the requirements of ENEV 2009
- Raw materials meet sustainability requirements
- Fresh concrete: slight compressibility, mixture stability
- Set concrete: compressive strength LC 8/9, density < 750 kg/m^3
- Sufficient resistance to the ingress of gases (air permeability, wind) and water
- Optimisation of shrinkage properties

The computational design procedure for the monolithic structure made of the newly developed architectural lightweight concrete was performed at the "Concrete Structures and Structural Design" department of the University of Kaiserslautern (Prof. Dr.-Ing. J. Schnell).

2. Implementation of the research project

2.1 Optimisation of the concrete composition

2.1.1 General

Due to the particular desired properties, such as good thermal insulation of the architectural lightweight concrete along with a high imperviousness against moisture and gases despite low bulk density and foamed cement matrix, special requirements had to be placed on the selected raw materials.

2.1.2 Cement

Because of the very low thermal conductivity required, the resulting hydration heat in the fresh concrete was removed very slowly. The cements used at the start of concrete development (CEM II/A-S 42,5 N, white cement CEM I 42,5 R) led to fresh concrete temperatures above 100 °C in larger samples (approx. 400 dm^3). The use of a special CEM III/B 32,5 N, which has an extremely slow hydration heat process according to the manufacturer, led to a significant reduction in the maximum temperature reached, which, however, still resulted in a warming of the specimen to about 70 °C after 40 hours (Figure 1).

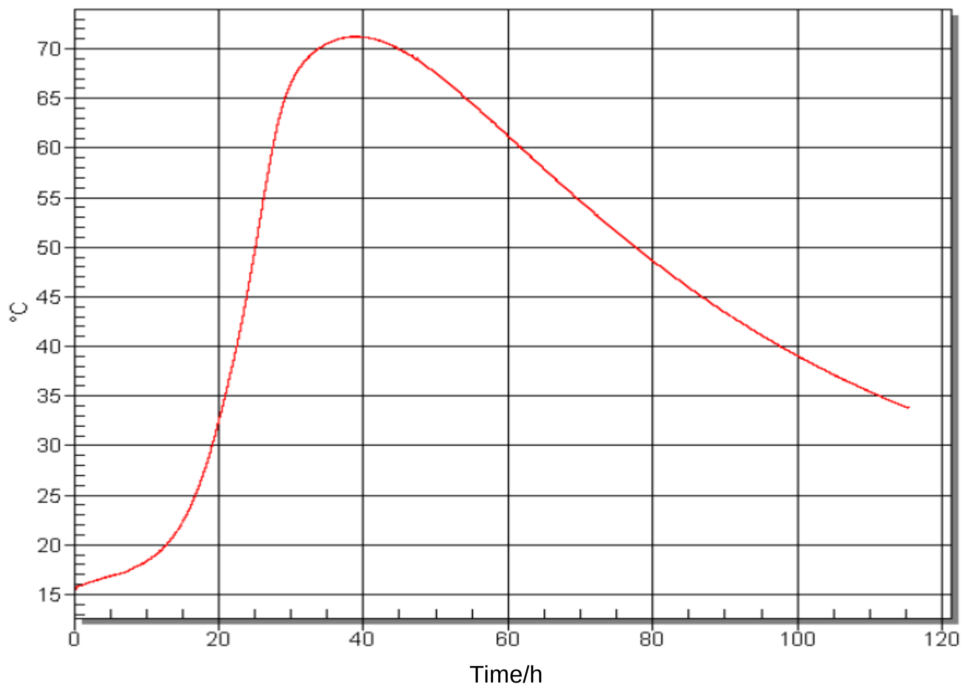

Figure 1: Hydration heat for architectural lightweight concrete with CEM III/B 32.5 N

2.1.3 Aggregate

Based on the results of the extensive preliminary tests, various lightweight aggregates, such as expanded clay and pumice, were excluded from consideration as a suitable aggregate for the architectural lightweight concrete. The desired properties in terms of water absorption and thermal conductivity could only be realised using a light aggregate made of industrially produced recycled expanded glass, which stood out due to its low particle density and low water absorption, along with sufficient compressive strength. To obtain a continuous particle size distribution, the particle size fractions as shown in Figure 2 were deployed.

Lightweight aggregate made from recycled expanded glass

Particle size		
0.25 mm to 0.5 mm	1 mm to 2 mm	4 mm to 8 mm
Particle density		
590 kg/m³	390 kg/m³	300 kg/m³

Figure 2: Lightweight aggregates for architectural lightweight concrete

2.1.4 Concrete additives

The desired product properties of architectural lightweight concrete were only achievable by using a sophisticated "admixture cocktail". To achieve the self-compacting flow properties, a highly effective PCE superplasticiser was required. In order to counteract signs of separation, stabilizer was added. The desired low dry density could not be achieved simply with the use of expanded glass, but required the use of a foaming agent to expand the cement matrix. This high proportion of pores held a risk of increased water absorption, which was reduced through the use of a water-repellent additive. The risk of increased crack formation due to the drying shrinkage was reduced by the use of a so-called "shrinkage reducer". To successfully optimise the concrete properties, the addition of five admixtures was therefore necessary.

2.1.5 Result of concrete optimisation

The concrete optimisation had to fulfill conflicting requirements, e.g. sufficient compressive strength alongside minimum bulk density, and low water absorption despite an expanded cement matrix. The investigations led to the architectural lightweight concrete composition shown in Table 1. This architectural lightweight concrete used for the construction of the research building had a fresh concrete density of about 720 - 740 kg/m³. The fresh concrete density given as an objective (at least 750 kg/m³) was therefore below the limit (dry bulk density of approx. 650-700 kg/m³).

Table 1: Composition of architectural lightweight concrete

Material	kg/m³	Material	kg/m³
Expanded glass 0.25/0.5	74.1	Superplasticiser	5.8
Expanded glass 1/2	74.1	Stabilizer	0.5
Expanded glass 4/8	61.6	Hydrophobic treatment	1.3
Cement CEM III/B 32.5 N	370.3	Shrinkage reducer	9.2
Water	135.8	Foaming agent	7.4

2.2 Properties of the architectural lightweight concrete

2.2.1 Consistency

Due to the extremely lightweight aggregate fractions from industrially produced expanded glass, a self-compacting consistency of the architecture lightweight concrete was required, as an intensive feed of compaction energy led to signs of separation and allowed the light particles to float. The optimisation of the concrete composition led to an architectural lightweight concrete which had a slump flow of about 680 - 700 mm (Figure 3). As Figure 3 shows, the lightweight concrete developed did not tend to cause water separation.

Figure 3: Slump flow of the optimised architectural lightweight concrete formulation

2.2.2 Mechanical properties of architectural lightweight concrete

The lightweight concrete LC 8/9 is designed according to the lowest standard strength class of DIN EN 206-1 [1]. However, these standardised lightweight concretes have a bulk density (oven-dry) of at least 800 kg/m³. Due to the lower bulk density, the compressive strength of the architectural lightweight concrete was, as expected, below the compressive strength class LC 8/9 (after 28 days at between 6.0 MPa and 6.5 MPa).

Table 2: Mean values for compressive strength of cubes (150 mm) made of architectural lightweight concrete

Age of sample [d]	3	7	14	28	56	90	180
Compressive strength [MPa]	2.6	3.7	5.4	6.3	8.7	9.2	9.2

In accordance with the low compressive strength of the architectural lightweight concrete, the bending tensile strength, as determined for prisms after 28 days, stood at approx. 1.3 MPa. In order to assess the development of tensile strength over time, the splitting tensile strength according to DIN EN 12390-6 [2] was determined at different time points (28 d: 0.9 MPa; 56 d: 1.1 MPa).

The modulus of elasticity of the architectural lightweight concrete, as determined after 28 days for cylinders with a height of 300 mm and a diameter of 150 mm, averaged around 3.5 GPa, and reached an average of around 4.0 GPa after 180 days. Despite the relatively low elasticity modulus compared to ordinary concretes, the 3.5 GPa value achieved by the architectural lightweight concrete can be described as relatively high compared to materials with similar bulk density (e.g. aerated concrete).

2.2.3 Resistance to water penetration and gases

The water absorption coefficient determined according to DIN EN ISO 15148 [3] lay at values below 0.1 kg/m² $h^{0.5}$ (classification: Type II, water-repellent), corresponding to the newly developed architectural lightweight concrete's very limited capacity to absorb capillary water. This value was clearly below the water absorption of normal concrete (C 25/30), which generally has a water absorption coefficient of about 0.7 kg/m² $h^{0.5}$. For the desired thermal insulation properties of the monolithic exterior construction components made of architectural lightweight concrete, the classification as a water-resistant concrete was of crucial importance, as soaked construction components with high water contents have significantly poorer properties in terms of heat flow. The low water absorption was due to the use of the water-repellent admixture.

The testing of water penetration depth under pressure was carried out in accordance with DIN EN 12390-8 [4], though under a reduced water pressure of 100 kPa (1 bar, corresponding to a hydrostatic head of 10 m). After 72 h at a water pressure of 100 kPa, the maximum water penetration depths ranged between approx. 10 mm and 15 mm.

By means of gas permeability measurements made pursuant to the German Committee for Structural Concrete's Issue no. 422 [5], the structural density of the concrete which is crucial for the transport of liquids and gases was determined. Conventional concretes exhibit a permeability coefficient of between 10^{-14} m^2 and 10^{-19} m^2.

The determined permeability coefficient of between 0.7 x 10^{-16} m² and 3.1 x 10^{-16} m² showed that the architectural lightweight concrete had a gas permeability comparable to normal concrete with a high water/cement ratio (about 0.7).

2.2.4 Shrinkage

The examined specimens of architectural lightweight concrete with shrinkage reducers displayed a mean shrinkage of about 0.7 mm/m after half a year, with a further slight increase in shrinkage to be expected thereafter. Comparative measurements (over the same period of time) without shrinkage-reducing additives, though which were otherwise of the same composition of architectural lightweight concrete, displayed shrinkage of around 1.4 mm/m to 1.6 mm/m due to the high proportion of foamed cement matrix and the porous expanded glass additive with a very low modulus of elasticity. The shrinkage achieved with shrinkage-reducing admixtures was within a range that slightly exceeded the shrinkage of normal concrete.

2.2.5 Thermal conductivity

For a monolithic architectural lightweight concrete wall with a thickness of 50 cm, the thermal conductivity value (λ value) of the architectural lightweight concrete of about 0.15 W/(K·m) gives a heat transfer coefficient (U value) of 0.28 W/(K·m²) and thus meets the requirements of ENEV 2009 regarding the heat transfer coefficient of an external construction component. By incorporating mineral foam insulation panels with a thickness of 8 cm as the core insulation, a heat transfer coefficient (U value) of 0.20 W/(K·m²) is reached for a total wall thickness of 50 cm (Passivhaus standard).

2.3 Construction of a research building made of architectural lightweight concrete

The results obtained in the laboratory were checked for reproducibility and for the possibilities of transfer to a practical construction context through the construction of a research building made of architectural lightweight concrete on the campus of the University of Kaiserslautern. This single storey research building made of architectural lightweight concrete was built with a floor area of approximately 7 m x 5 m and a wall height of nearly 4 m. The sides of the roof structure were designed to be translucent: therefore side windows in the walls could be dispensed with (Figure 4).

Figure 4: Experimental building made of architectural lightweight concrete, after concrete work

The production of the architectural lightweight concrete for the research building occurred in the ready-mix concrete plant, whereby the correct proportions of the various expanded glass fractions were added directly into the truck mixers by means of "bigbags". After the addition of the cement paste, intensive mixing occurred in the truck mixer and the self-compacting architectural lightweight concrete was incorporated using buckets, without further compression. The walls and roof were produced monolithically, with a thickness of 50 cm.

The reinforcement used was galvanized prior to installation. So as to be able to track the moisture and temperature profiles in of the architectural lightweight concrete under natural weathering, ten multi-ring sensor electrodes (MRSE) were placed into the walls and ceiling, which permitted the permanent monitoring of the external construction components.

Using the built-in multi-ring sensor electrodes, the relationships between weather events and moisture absorption of the external construction components could be continuously recorded and analysed. The findings in this respect are crucial for the assessment of the thermal insulating properties and of durability considerations, as soaked construction components display significantly poorer properties on both counts. Investigations into the moisture profiles showed that, despite the porous cement matrix and the light expanded glass fractions in the architectural lightweight concrete material, there was a pronounced moisture gain only in the section down to 20 mm from the concrete surface. The remaining areas of the 50 cm-thick outer wall remained virtually unaffected by spontaneous precipitation events and thus remained fully functional in terms of their thermal insulation properties.

3. Summary of findings

The composition of the architectural lightweight concrete, (i.e. recycled expanded glass and blast furnace cement (CEM III/B 32,5 N) reduced in Portland cement clinker) developed with regard to sustainability aspects, had to meet high requirements in terms of bulk density, durability and thermal conductivity. The desired properties of the fresh concrete so as to achieve the self-compacting flow properties without separation were achieved by the use of a PCE-flow agent in combination with a stabiliser. The desired low bulk density (< 750 kg/m³) required the use of a foaming admixture to expand the cement matrix. To improve durability, further shrinkage-reducing and water repellent admixtures were used.

For dry bulk densities of well under 700 kg/m³, a 28-day compressive strength of 6.3 MPa (56 d: 8.7 MPa; 90 d: 9.2 MPa) and an elasticity modulus of about 3.5 GPa were determined after 28 days. The gas permeability was, despite the foamed cement matrix, about the same as that of a normal concrete, whereas the capillary water absorption was below that of an average normal concrete, due to the hydrophobic admixture.

The most important requirement of the lightweight concrete to be developed were its properties with respect to thermal insulation, for which a thermal conductivity value of λ = 0.15 W/(m·K) was ultimately achieved for the architectural lightweight concrete. This resulted in an overall heat transfer coefficient (U value) of 0.28 W/(K·m²) for the wall thickness of 50 cm used here. The calculated U value thus meets the requirements of ENEV 2009 regarding the heat transfer coefficient of an external construction component. Using a mineral foam-core insulation as incorporated in one wall of the experimental building, a U value of 0.20 W/(K·m²) was achieved.

The transfer possibilities presented by the findings from the laboratory were verified by the construction of an approximately 7 m x 5 m x 4 m research building made of architectural lightweight concrete. Continuous measurements via the multi sensor ring electrodes (MRSE) built in to the walls and ceiling provided information on temperature and moisture changes in order to enable a concluding statement to be made as to the actual thermal insulation properties and the durability of the architectural lightweight concrete in the presence of natural ventilation.

References

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[4] DIN EN 12390-8:2009-07; Testing hardened concrete - Part 8: Depth of penetration of water under pressure;

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