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Development of Lightweight Mortars Targeted on the High Strength, Low Density and Low Permeability

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Abstract
This article presents a mix design methodology for the development of cement-based lightweight mortars. Expanded-glass lightweight aggregates were used in this study as the lightweight material. The mix design was developed applying the packing theory using the modified Andreasen and Andersen model to obtain the optimal grading curve of all the solids in the mixture. Two self-compacting and one conventionally vibrated mortar were designed. The developed mortars had a low thermal conductivity while retaining good mechanical properties. The permeability of the developed mortars was quantified based on the measurements of the capillary water absorption, water penetration under pressure and chloride transport properties. The results of the tests indicate that the produced self-compacting mortars are very permeable, while the permeability of the vibrated mortar is very low. When fine fractions of the lightweight aggregates were used, the produced composites were very permeable. On the other hand, a low-permeable lightweight mortar was developed by combining cement paste of a good quality (low water/cement ratio) with normal-density sand and only coarse fractions (1 – 4 mm) of lightweight aggregates.

Keywords: Lightweight mortars, Lightweight aggregates, Strength, Permeability

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Introduction

Concrete and mortar, by far, are the most used manmade building materials. Although lightweight aggregates concrete (LWAC) is a well known material and it has its roots already in the ancient period (about 3000 years ago) when volcanic materials were used as lightweight aggregates [1], its importance is still very high. Because of its many advantages such as low density, good thermal insulation and good fire resistance, LWAC has been widely developed and used in both structural and non-structural applications recently. Nevertheless, often there is still a strong unwillingness to use LWAC, as it is expected to be more permeable (less durable) and mechanically weaker compared to conventional, normal density concrete. There is still no systematic study on the mix design methodology of the LWAC targeted on the performance of such concrete. Usually, the LWAC design is mainly focused only on one material characteristic: either low density (low thermal conductivity) or high strength. In such design, the durability properties are generally not included. Due to their large porosity, the lightweight aggregates can potentially be very permeable, significantly increasing the overall permeability of the concrete, in which these LWA were applied.

The aim of this study is to present a mix design methodology for lightweight cement-based mortars, which in hardened state are characterized by a good balance between their mechanical properties (compressive and flexural strengths) and density (thermal conductivity). Additionally, the durability-related properties of the produced mortars are investigated water transport properties (capillary water absorption, penetration of water under pressure) and chloride transport properties (accelerated and natural chloride intrusion).

Used materials

The cement used in this study was on Ordinary Portland Cement (OPC) CEM I 52.5 N, provided by ENCI (the Netherlands). A polycarboxylic ether-based superplasticizer is used to adjust the workability. Commercially available expanded-glass lightweight aggregates were used as well as normal-density aggregates (broken sands with fractions of 0-1 mm and 0-4 mm and micro-sand with the maximum particle size of 1 mm). The used materials are summarized in Table 1 and Figure 1.

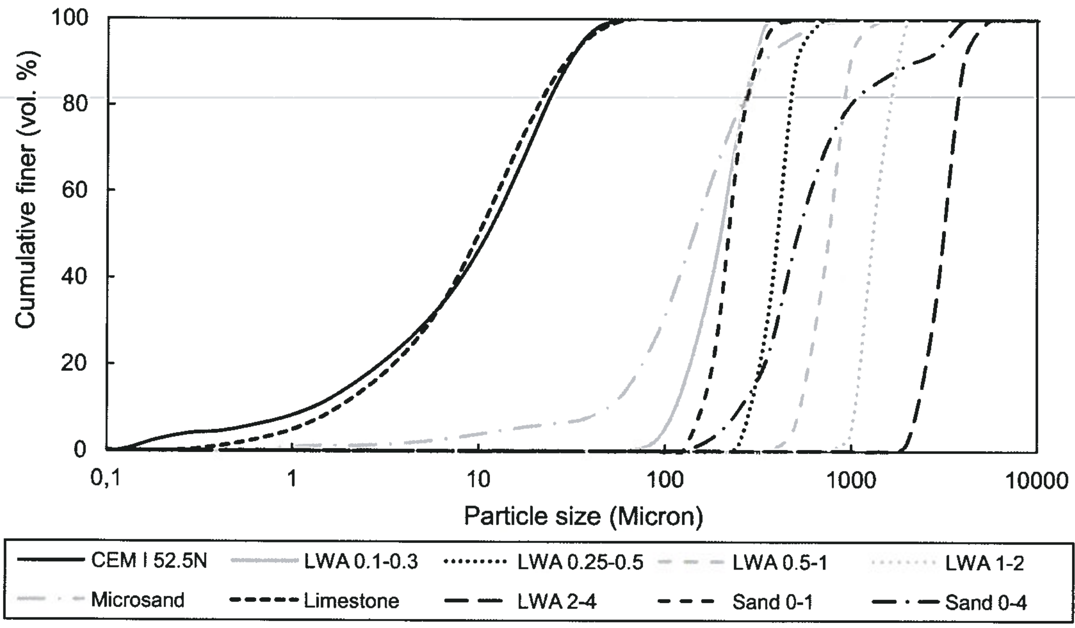

Figure 1: Particle size distribution (PSD) of the used materials

Table 1: Properties of materials used

Material	Type	Specific density (kg/m^3)
Cement	CEM I 52.5 N	3180
Filler	Limestone powder	2710
Fine sand	Micro-sand	2720
Fine sand	Sand 0-1 mm	2650
Coarse sand	Sand 0-4 mm	2650
LWA	Expanded glass	310-810*
Superplasticizer	Polycarboxylate ether	1100

* - depends on the size fraction

As can be seen in Table 1, five different size fractions of the LWA were used in this study: 0.1 – 0.3 mm, 0.25 – 0.5 mm, 0.5 – 1 mm, 1 – 2 mm and 2 – 4 mm. The water absorption of LWA is often an influential factor in the design and production process lightweight aggregates concrete, since LWA can absorb a certain amount of free water from the mixture before the setting. Nevertheless, the LWA used in this study have a low water absorption ability – depending on their size fraction, the measured 1-hour water absorption was between 0.5 – 1 % by weight of the aggregates. Such low water absorption can be attributed to the unique cellular structure of the LWA used in this study. As can be seen in Figure 2, the aggregates are composed of a closed external shell and a number of internal air pores, encapsulated within that shell.

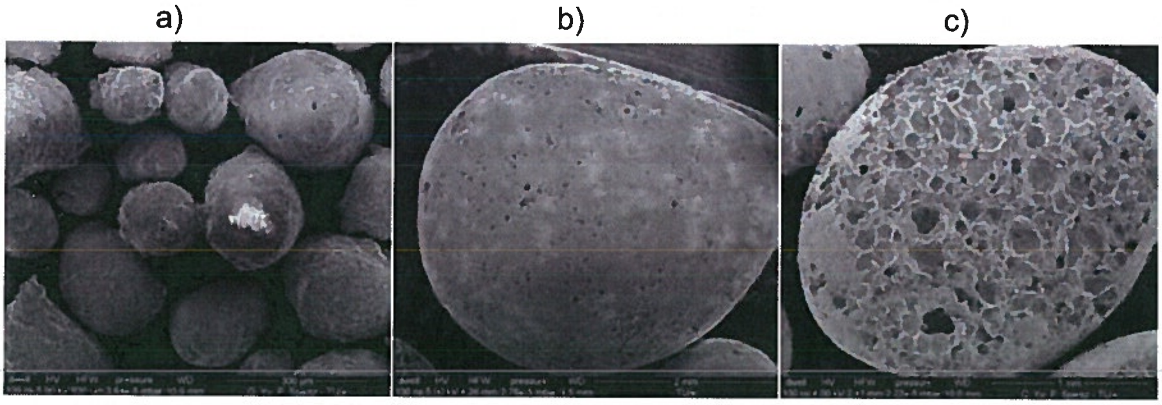

Figure 2: SEM pictures of the external surface of LWA 0.1 - 0.3 mm (a), LWA 1 - 2 mm (b) and the internal structure of LWA 1 - 2 mm (c)

Therefore, an increased porosity introduced in the material by the LWA, does not necessarily have to cause an increased permeability of the produced lightweight mortars, as the pores in the LWA remain close.

Mix design

Three mortar mixes were developed in this study, using the particle packing optimization algorithm [2], based on the modified Andreasen and Andersen (A&A) equation for the packing of continuously graded solid particles. Two of these mixes were self-compacting mortars, while the third one was a conventionally vibrated mortar. To produce the self compacting mortars, an increased amount of fine materials had to be applied, and therefore, besides the cement and limestone powder, also fine fractions of LWA were used. For the vibrated mortar such high amount of the fines was not needed and therefore only the coarsest fraction of the LWA and no limestone powder were used (1 – 2 and 2 – 4 mm). The optimization of the mixture grading curve following the A&A equation helps to increase the packing density of all the solid particles present in the mixture. This optimization is especially important from the point of view of the mechanical properties of the hardened material, as the void fraction is minimized, which in turn improves the strength. In general, the increased void fraction is usually required in lightweight concrete or mortar to reduce the density of the material. However, in the approach followed in this study, the low density of the material will be supplied by the application of the LWA described earlier, in different size fractions, to improve their packing density. Thus, the volume of the air voids can be minimized by the dense packing of the solids, which will positively contribute to the strength of the mortar [2, 3]. The material designed in such way is expected to have both: low density and sufficient mechanical properties. The application of the LWA which have a high closed porosity and a low open porosity, as shown in Figure 2, should also result in a reduced permeability of the hardened mortars, as the fluids penetrating the material could not permeate through the LWA.

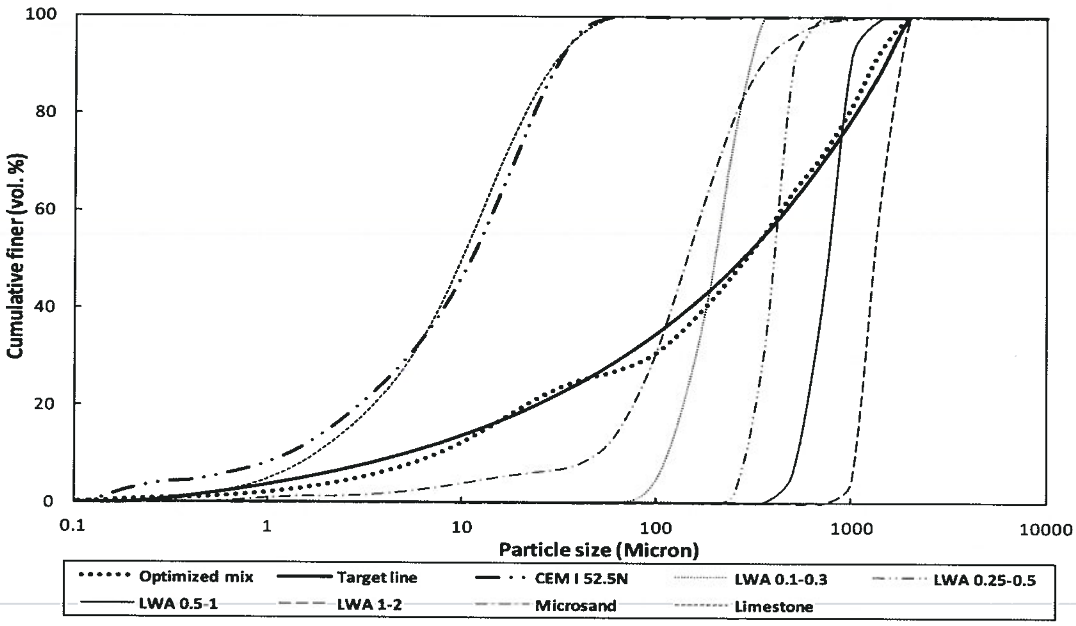

Figure 3: Grading curve of the developed SCM1 together with the target curve

In the mix design stage, the target grading curve of the mixture was determined using the modified A&A equation. Subsequently, the proportions of the individual materials used in the mix design are adjusted until an optimum fit between the composed mix and the target curve is reached. This is done using an optimization algorithm based on the Least Squares Method (LSM), following which the deviation between the target curve and the composed mix is minimized [10-12]. It was demonstrated that the optimization of the mixture grading curve to follow the target curve will minimize the void fraction in the mixture and improve its fresh-state behaviour characteristics. As an example, Figure 3 shows the optimized grading curve of the first prepared self-compacting lightweight mortar (SCLM). The mix proportions of two optimized self-compacting lightweight mortars (SCLM) and one conventionally vibrated lightweight mortar (VLM) are given in Table 2. Similar amount of cement was used in all the prepared mixtures. The two designed SCLM were differing with their densities (amount of the used LWA). The VLM designed density was chosen to be similar to the density of the

SCLM2, in order to compare the properties of self-compacting and vibrated mortars of similar densities.

Table 2: Composition of designed mortars

Material	SCLM1 kg/m³	SCLM2 kg/m³	VLM kg/m³
CEM I 52.5 N	425.3	423.5	419.7
Limestone powder	111.9	259.6	-
Sand 0-4	-	-	407.0
Sand 0-1	-	95.6	-
Microsand	381.5	424.6	306.0
LWA 0.1-0.3	56.0	68.3	-
LWA 0.25-0.5	44.8	-	-
LWA 0.5-1.0	56.0	54.9	-
LWA 1.0-2.0	44.8	39.4	63.6
LWA 2.0-4.0	-	-	71.6
Superplasticizer (% bwoc)	1.0%	1.0%	0.8%
Water	250.9	230.3	159.4
Water/cement ratio	0.59	0.54	0.38
Water/powder ratio	0.35	0.26	0.29
Vol. of LWA [dm³/m³]	404.2	318.7	412.6
Total porosity [%]	47.5	38.4	42.0

Strength tests, density and thermal conductivity measurements

The compressive and flexural strength tests were performed on 40 x 40 x 160 mm mortar prisms, at the age of 1, 3, 7 and 28 days, following EN 196-1 [4]. Each test was performed on three prisms. The obtained strengths are given in Figure 4. The density and the thermal conductivity of the mortars were measured on 100 x 100 x 100 mm cubes at the age of 28 days. The results of these measurements are given in Table 3.

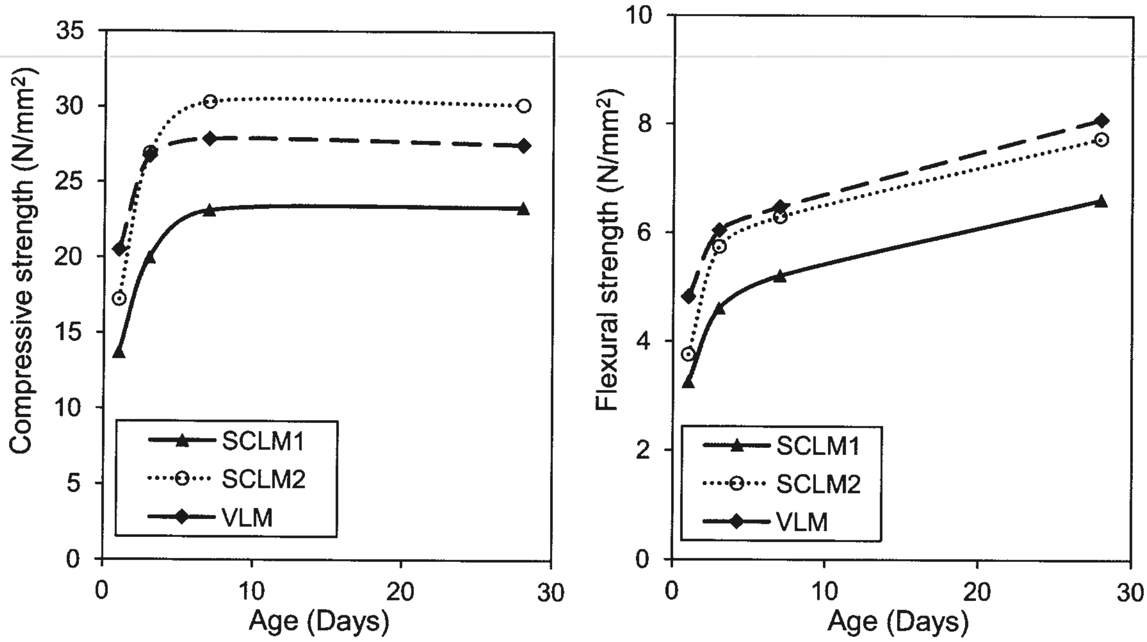

Figure 4: Strength test results

Table 3: Thermal conductivity and density measurement results

Mix	Density kg/m³	Thermal conductivity W/(m×K)
SCLM1	1280	0.485
SCLM2	1460	0.738
VLM	1490	0.847
Reference	2300	1.700

It can be noticed in Figure 4 that the measured strength of the developed mortars is a function of the water/powder ratio adapted in the design stage. Additionally, it can be observed that the highest compressive strength was obtained on the mortar with the lowest volumetric content of the LWA. All the developed mortars have good compressive and flexural strengths, which allows using them even as load-bearing elements in structural applications instead of conventional concrete or mortars.

It can be seen in Table 3 that with an increasing density, the thermal conductivity of the three developed mortars also increases. The obtained thermal conductivities are in the range of the conductivities for lightweight mortars, however at the same the mortars obtained in this study have better mechanical properties. This can be attributed to the employed mix designed method, which helps to improve the packing density of the solid ingredients. The thermal conductivity coefficient of the mortar SCLM1 is about four times lower than that of a reference mortar of a normal density. At the same time, the strength of the reference mortar (about 55 N/mm^2) is about two times higher than that of the SCLM1.

Water permeability, capillary suction and chloride ingress tests

The water permeability test was performed on 150 x 150 x 150 mm cubes at the age of 28-days, following BS-EN 12390-8 [5]. Three cubes for each prepared mortar mix were tested, applying water under pressure of 5 bar for 72 hours. The tests performed on the cubes of SCLM1 and SCLM2 had to be terminated after only a few hours from the start, as significant amount of water flowing out of the sides of the cubes was observed, as indicated in Figures 5a. Therefore, it can be concluded that both self-compacting mortars had very high permeability to water under pressure. On the contrary, the VLM mix was almost impermeable to water, as shown in Figure 5b.

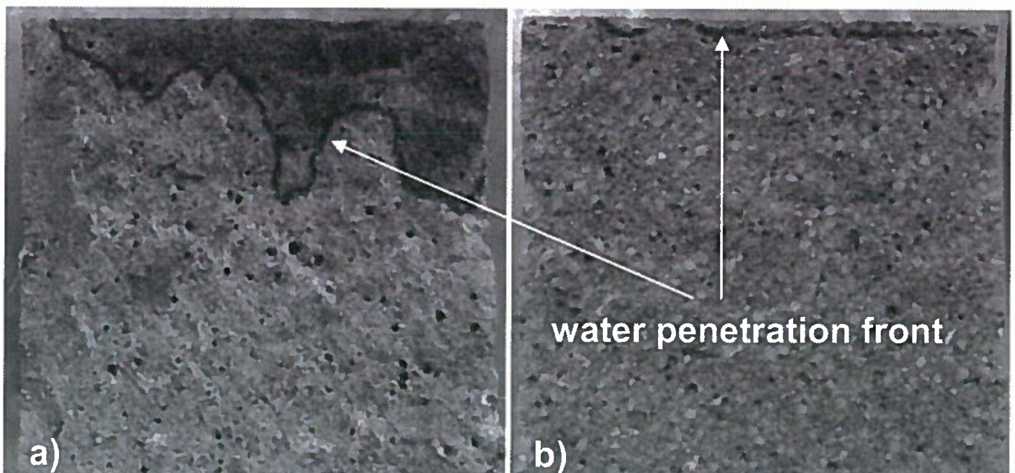

Figure 5: Split surfaces of cubes after performing the water pressure permeability test; water ingress from the side of the top surface. (a) SCLM2 and (b) VLM

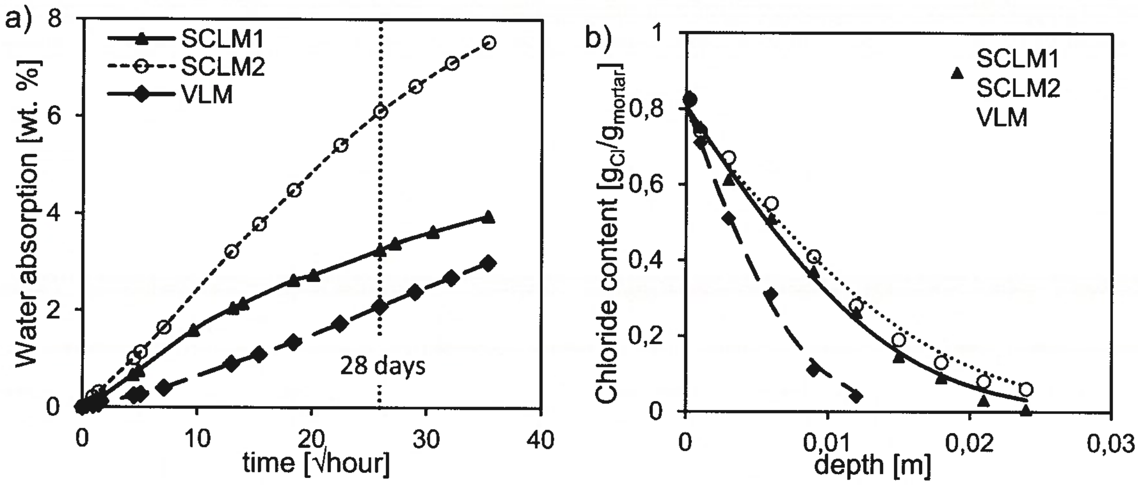

Figure 6: (a) Capillary water absorption and (b) chloride diffusion test results

The capillary water absorption test was performed on six prisms (40 x 40 x 160 mm) for each prepared mix, following the procedure described in BS-EN 480-5 [6]. During the period of 56 days, the mortar samples were weighted periodically. The results of the tests, shown in Figure 6a show that he self-compacting mortars (SCLM1 and SLCM2) have much higher capillary water absorption compared to the vibrated mortar (VLM). The capillary water absorption ability reflects on the pore system in the material, i.e. higher water absorption reflects on a higher interconnectivity of the pores. Therefore, the results shown in Figure 6a confirm the finding of the water penetration test, that the connectivity of the pores in the produced self-compacting mortars is much higher than in the vibrated mortar.

Chloride ingress speed in the designed mortars was also investigated in this study. Both long-term and accelerated tests were performed at the age of 28 days. For the long-term, the diffusion test according to NT Build 493 [7] was performed, during which the mortar samples were exposed to a chloride solution for 91 days. After that period, the chloride concentration profiles were measured in the samples, as explained in [8]. Figure 6b shows the obtained profiles. Based on these measured profiles, the chloride diffusion coefficients (D_{app}) were obtained, and are given in Table 4. For the accelerated chloride tests, the Rapid Chloride Migration test was performed, following the NT Build 492 guideline [9]. In such migration test, the chlorides penetrate the samples at a high rate, as they were accelerated by the application of the electrical field. From these tests, the chloride migration coefficients (D_{RCM}) were obtained, as given in Table 4.

Table 4: Chloride diffusion and migration coefficients

mix	D_{RCM} ($\times 10^{-12}$ m^2/s)	D_{app} ($\times 10^{-12}$ m^2/s)
SCLM1	20.63	12.30
SCLM2	> 29*	18.00
VLM	4.04	3.76

* - samples failed the test (chloride breakthrough observed)

The values of the chloride migration and diffusion coefficients shown in Table 4 show again that the developed self-compacting mortars (SCLM1 and SCLM2) had much higher permeability (connectivity of the pores) compared to the vibrated mortar (VLM). Additionally, it is important to notice that the permeability to chlorides of the samples of mortar SCLC2 was so high, that during 24 h of the test, the chlorides were able to penetrate the entire volume of the sample. Both chloride diffusion and migration coefficients of the designed vibrated mortar (VLM) were about 3-4 times lower compared to both self-compacting mortars.

Discussion and conclusions

Various permeability tests performed in this study showed exactly the same trend: the permeability of both developed self-compacting mortars was much larger compared to the vibrated lightweight mortar. This large difference in the permeability can be attributed to the presence of the fine size fractions of the lightweight aggregates in the self-compacting mortars. Apparently, the small LWA particles contributed to the capillary porosity of the hardened concrete paste, facilitating the transport of liquids. In the case of the developed vibrated mortar, only the coarse size fraction of the LWA were applied, and the obtained results indicate that the permeability of this mortar is very low, and in fact comparable to the permeability of a good quality concrete (especially in terms of the obtained water under pressure penetration and chloride diffusion and migration coefficients). Therefore, based on the results obtained in this study, it is recommended using only the coarse fraction of the LWA in order to reduce the permeability of the mortars.
The obtained strength of the produced mortars was a function of the used water/powder ratio and of the volume of the used LWA. All the produced mortars are characterized with good mechanical properties: the 28-days compressive strength in the range of 22 – 31 N/mm^2 and the flexural strength in the range of 6 – 8 N/mm^2. These strengths were obtained using about 420 kg of cement per one m^3 of mortar.
The obtained thermal conductivity coefficients of the mortars are found to be a function of the density, and as expected, for the mortar of the lowest density the thermal conductivity coefficient was the lowest.

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