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Ultra-lightweight concrete: Conceptual design and performance evaluation

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ABSTRACT

The present study presents a methodology to design ultra-lightweight concrete that could be potentially applied in monolithic concrete structures, performing as both load bearing element and thermal insulator. A particle grading model is employed to secure a densely packed matrix, composed of a binder and lightweight aggregates produced from recycled glass.

The developed ultra-lightweight concrete, with a dry density of about 650–700 kg/m^3, shows excellent thermal properties, with a thermal conductivity of about 0.12 W/(m K); and moderate mechanical properties, with a 28-day compressive strength of about 10–12 N/mm^2. Furthermore, the developed concrete exhibits excellent resistance against water penetration.

1. Introduction

The history of lightweight concrete (LWC) dates back to over 3000 years ago [1]. There are several LWC structures in the Mediterranean region, of which the most notable structures like the Port of Cosa and the Pantheon Dome were built during the early Roman Empire [2]. Because of its many advantages such as low density, good thermal insulation and fire resistance, LWC has been widely studied as both structural and nonstructural material. Among various types of lightweight aggregates (LWA) used nowadays, synthetic LWAs such as Leca (Denmark), Liapor (Germany) Liaver (Germany) and Poraver (Germany), produced in special industrial processes, are widely used in LWC because of their properties (e.g. low density, low water absorption, high strength) [3].

Lightweight aggregates concrete (LWAC) has been extensively investigated. Many applications of LWAC can be found in structures such as long span bridges, high rise buildings, buildings where foundation conditions are poor, or highly specialized applications such as floating and offshore structures. Loudon [4] summarized the thermal properties of lightweight concrete, and reported that density and moisture content are the main factors affecting the thermal conductivity, while the mineralogical properties of aggregate material can affect the thermal conductivity of LWC up to 25% under a similar density condition. Zhang and Gjørv [5] reported that the cement paste penetrates into lightweight aggregates during the mixing, but the amount highly depends on the microstructure of the surface layer of the aggregate, particle size distribution of cement and viscosity of the cement paste. Wasserman and Bentur [6] found that both physical and chemical characteristics of LWA affect the strength of LWAC due to the processes taking place at the interfacial transition zone. Alduaij et al. [7] researched lightweight concrete in hot coastal areas applying expanded clay as LWA. They reported a compressive strength increase from 15.5 N/mm^2 to 29.0 N/mm^2 when increasing the cement content from 250 to 350 kg/m^3, while keeping similar densities of about 1500 kg/m^3. Demirboğa and Gül [8] investigated the thermal conductivity and compressive strength of expanded perlite aggregate concrete with mineral admixtures. They reported that silica fume and fly ash used as cement replacement can decrease the thermal conductivity up to 15%, while the density and compressive strength of the concrete is also reduced, up to 30%. Ünal et al. [9] developed a lightweight concrete block applying diatomite as LWA with a 28-day compressive strength of 3.5–6.0 N/mm^2 and densities of 950–1200 kg/m^3. A linear relation between the cement content and thermal conductivity of the LWAC was derived as the thermal conductivity increased from 0.22 to 0.30 W/(m K) with the increase of cement content from 250 to 400 kg/m^3. Liu et al. [10] developed a lightweight aggregates concrete with high resistance against water and chloride-ion

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penetration. With the cement content of 500 kg/m^3 and unit density of 1400 kg/m^3, applying expanded clay and expanded glass as lightweight aggregates, the 28-day compressive strength of the LWAC reached 24 N/mm^2. Wang and Tsai [11] investigated lightweight aggregate concrete using dredged silt as LWA with different particle densities between 800 and 1500 kg/m^3 and applying different binder contents of 364, 452 and 516 kg/m^3. A 28-day compressive strength of 18–42 N/mm^2 with a thermal conductivity of 0.5–0.7 W/(m K) was obtained. Results show that the LWA density significantly affects the compressive strength of concrete with the same water and cement dosages, while the thermal conductivity is more complexly influenced by factors such as water content, cement content and LWA (type and content). Ling and Teo [12] researched lightweight concrete bricks applying expanded polystyrene (EPS) and rice husk ash (RHA) as lightweight aggregates. An optimal cement replacement by RHA of 10 wt.% was found and water curing was suggested to be the most effective curing method. Karakurt et al. [13] studied the effect of zeolite addition on the properties of autoclaved concrete using aluminum as a pore-forming agent. Zeolite was used as the quartz aggregates replacement with a total content of 535 kg/m^3. A maximum compressive strength of 3.2 N/mm^2 was achieved with a 50% replacement, with a thermal conductivity of 0.19 W/(m K). Wongkeo et al. [14] studied the properties of autoclaved concrete using bottom ash as partial cement replacement and with aluminum powder as a pore-forming agent. With a bulk density of about 1400 kg/m^3, an increase in compressive strength from about 9 N/mm^2 to 11.6 N/mm^2 is seen when the bottom ash content is increased from 0 to 30%, but the thermal conductivity also slightly increases, from 0.5 to 0.61 W/(m K). Akçaözoglu et al. [15] studied lightweight concrete applying waste PET as LWA. A thermal conductivity between 0.4 and 0.6 W/(m K) was achieved with the unit dry density between 1530 and 1930 kg/m^3, with the corresponding compressive strength at 28 days of 9.5 to 25.3 N/mm^2.

It can be summarized that the literature reviewed above shows a significant variation regarding both mechanical and thermal properties, indicating both the effect of the used materials and applied mix design methods. Although some mix design methods have been investigated [1,16,17], no systematic mix design methodology of ULWC has been addressed to the best knowledge of the authors, especially considering a balance between mechanical properties and thermal properties. Most research focused either only on obtaining a LWC suitable for structural purposes (e.g. with high strength) or as nonstructural material with low thermal conductivity, and therefore additional insulation materials or load bearing elements are often needed when applying LWC in buildings. Moreover, currently great attention is paid to sustainability in concrete research, for instance by applying low cement content and partially replacing cement by secondary cementitious materials (SCM). This is economically and ecologically attractive since cement is a highly energy-intensive material and great amounts of CO_2 are emitted during its production process, while about 90% cumulative energy needed for concrete production is spent in the production of cement [18].

The present research aims at the development of an ultra-lightweight concrete (ULWC) with a good balance between the mechanical and thermal properties, i.e. concrete with excellent thermal properties (e.g. a very low thermal conductivity) while retaining a reasonable strength. The developed ULWC could be a suitable material for novel monolithic building concept with the following advantages: (1) cost saving, due to the exemption of extra insulation installations; (2) more flexibility for architects and structural engineers for the building design; (3) sustainability, since monolithic structure will ensure a relatively easy maintenance requirement and it is easier to recycle. The effect of different types of cements produced by incorporating different SCMs such as fly ash or granulated blast furnace slag is investigated. A lightweight material produced from recycled glass is used as LWA in the present study. This type of LWA has a particle density ranging from 300 to 800 kg/m^3 (depending on the size fraction), with a crushing resistance of up to 6 N/mm^2 [2], which indicates that concrete produced using this aggregates can be potentially used for structural purposes [19,20].

2. Mix design

2.1. Materials

The four types of cement used in this study are CEM I 52.5 N, CEM II/B-V 42.5 N, CEM III/A 52.5 N and CEM V/A (S-V) 42.5 N [21] provided by ENCI HeidelbergCement (The Netherlands), and the detailed information is listed in Table 1. The lightweight aggregates used here are commercially available product manufactured from recycled glass in Germany. These LWA contain a number of air pores (cellular structure) encapsulated in rather closed and impermeable outer shells, as can be seen in Fig. 1. The LWA have very low particle densities, which provide a great freedom for the design of lightweight concrete with desired low density, as can be seen in Table 2. Limestone powder, with the density of 2710 kg/m^3, is used as filler to adjust the powder amount. A nano-silica (AkzoNobel), with a solid content of 50%, density of 1.4 kg/l and a BET surface area of the silica particles of 50 m^2/g, is used here to investigate its effect. A polycarboxylic ether-based superplasticizer (BASF) is used to adjust the workability. An air-entraining agent (Cugla), with a density of 1.05 kg/l and resin acid soaps as active agent, is applied here to adjust the density of the lightweight concrete.

2.2. Design methodology

For the design of the LWAC, a mix design methodology previously used for normal density mortars and concretes was considered [20]. This mix design tool is based on the insight that superior properties of a granular mix are achieved when a so-called geometric grading curve is designed and obtained, i.e. the ratios of particle sizes and the ratios of pertaining quantities are constants. In the case of continuous distributions, the cumulative finer fraction of the entire mix is determined from the modified Andreasen and Andersen model [22], reads:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \tag{1}$$

where $P(D)$ is a fraction of the particles being smaller than size D, D is the particle size (μm), $D_{\max}$ and $D_{\min}$ are the largest and smallest particle size (μm), respectively, in the mix, and q is the distribution modulus.

This particle packing principle insight has been transformed into a numerical mix design, in which all the solid mixture ingredients, which all have their own particle size distributions

Table 1
Properties of the used cement.

Cement	Density (kg/m^3)	Clinker content (%)	Fly ash content (%)	Slag content (%)
CEM I 52.5 N	3180	95–100	0	0
CEM II/B-V 42.5 N	2980	73	25	0
CEM III/A 52.5 N	3000	48	0	52
CEM V/A (S-V) 42.5 N	2870	55	23	22

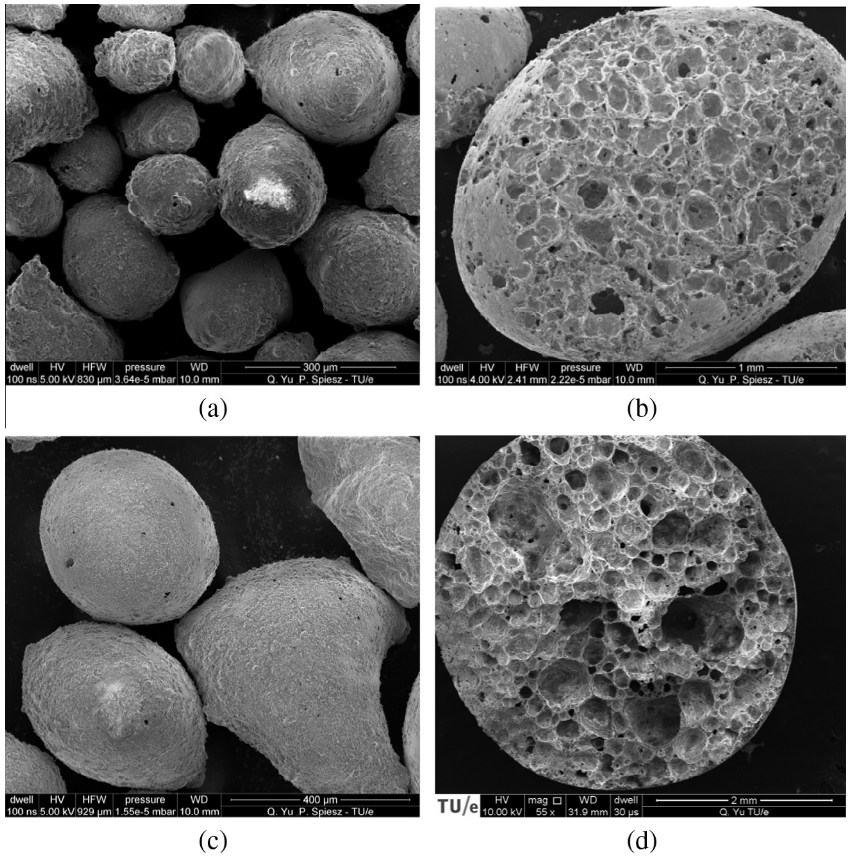

Fig. 1. SEM pictures of (a) external surface of LWA 0.1–0.3 mm, (b) internal surface LWA 1–2 mm, (c) external fracture surface of LWA 1–2 mm, and (d) internal structure of LWA 2–4 mm.

Table 2
Physical properties of the used LWAs.

Materials	Bulk density (kg/m^3)	Specific density (kg/m^3)	Crushing resistance (N/mm^2)
LWA A	300	540	>2.9
LWA B	250	450	>2.6
LWA C	220	350	>2.4
LWA D	190	310	>2.2
LWA E	170	300	>2.0

(PSDs), are combined via a mathematical optimization routine, i.e. the "target curve" is approached best. The optimization of the particle size grading of the ingredients helps to increase the packing of the solids in the concrete mixture. This results in improved hardened state properties, a reduced water demand as well as an improved workability, since more water is available to act as lubricant between the particles [23]. The concept is to include all the solid particles in the mixture grading, i.e. the cement and other solids. Funk and Dinger [24] reported a value of 0.37 for q in Eq. (1) for an optimal packing of continuous particle distribution, which was confirmed by Villar et al. [25]. Brouwers [26] further demonstrated that theoretically a q value of about 0.28 would result in an optimal packing. This design methodology has been successfully applied to design earth-moist concrete [18,27], self-compacting concrete [28], gypsum based composite [20,29], lightweight concrete [19,20,30,31] and high performance concrete [32,32–35]. Fig. 2 shows an example of the mix optimized by the above mentioned methodology.

In addition to the targeted strength, a low thermal conductivity is also aimed in this study, while it is strongly related to the density and porosity of the composite [29,36]. Hence, a densified concrete developed applying this design concept will show an opposite effect, i.e. the resulting thermal conductivity will increase as the void content is minimized. Nevertheless, the low density will be achieved by applying a lightweight material as aggregate (LWA) instead of normal density aggregates in the mixture, and furthermore by applying an air-entraining agent.

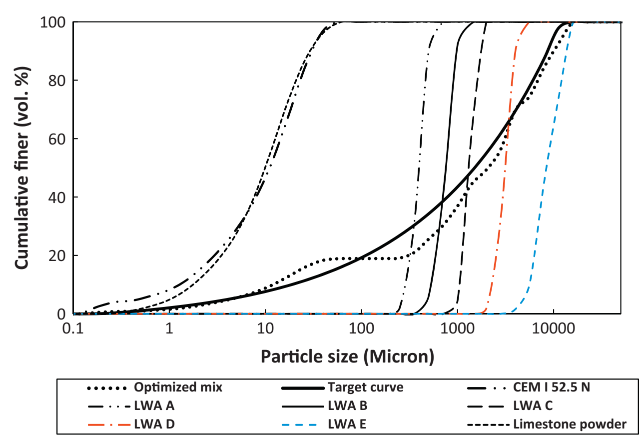

Fig. 2. PSDs of the involved ingredients, the target curve and the resulting integral grading curve of the mix.

The water absorption of LWA is an influential factor in the lightweight aggregates concrete design and production, as the LWAs normally absorb a certain amount of free water from the fresh mixture. It has been shown that the water absorption of lightweight

Table 3
Mix design of the ULWC (per m^3).

Mixture	Mix A	Mix B	Mix C	Mix D	Mix E	Mix F	Mix G
Cement type	CEM II/B-V 42.5 N	CEM III/A 52.5 N	CEM I 52.5 N	CEM II/B-V 42.5 N	CEM V/A (S-V) 42.5 N	CEM III/A 52.5 N	CEM I 52.5 N
Cement content (kg)	450.0	450.0	355.0	405.0	405.0	405.0	315.0
Nano-silica (kg)	0.0	0.0	40.0	45.0	45.0	45.0	35.0
Limestone powder (kg)	0.0	0.0	52.6	0.0	0.0	0.0	106.0
LWA (kg)	212.2	212.2	207.8	212.2	212.2	212.2	205.4
Water (kg)	225.0	225.0	223.5	225.0	225.0	225.0	228.0
SP[a]	0.0	0.0	1.0	1.0	1.0	1.0	1.0
Air entraining agent (kg)	2.25	2.25	2.25	2.25	2.25	2.25	2.25

[a] Here SP is the mass percentage based on the binder, i.e. the total amount of cement and nano-silica.

Fig. 3. Test pictures of (a) thermal property; (b) water penetration under pressure.

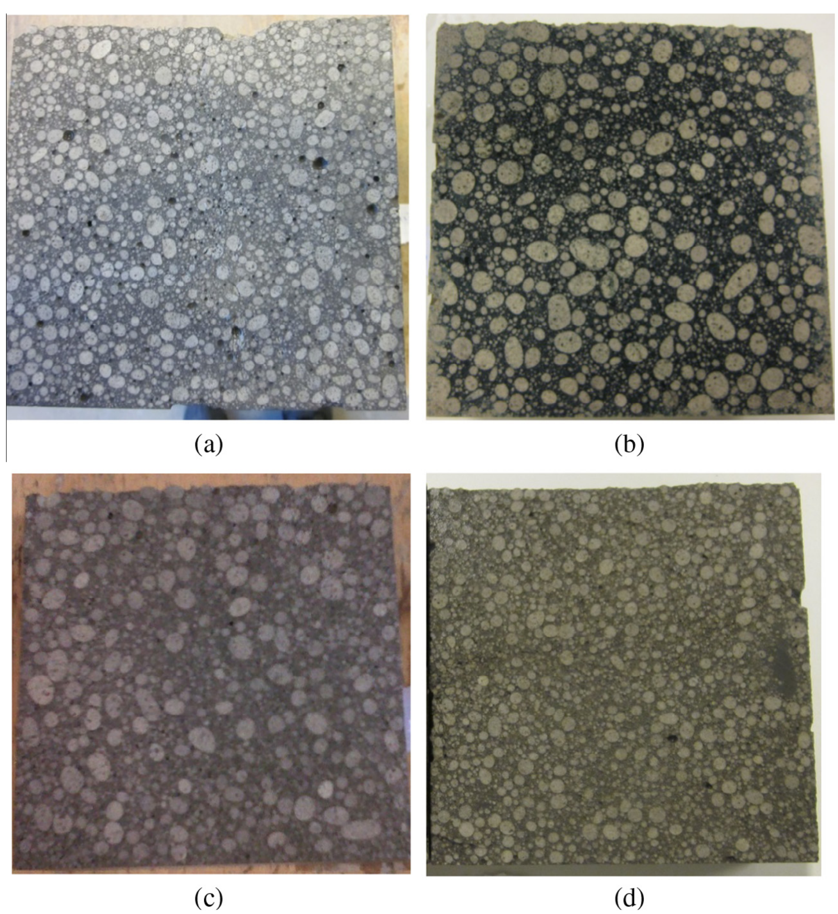

Fig. 4. LWA distribution in (a) Mix A, (b) Mix B, (c) Mix D and (d) Mix G.

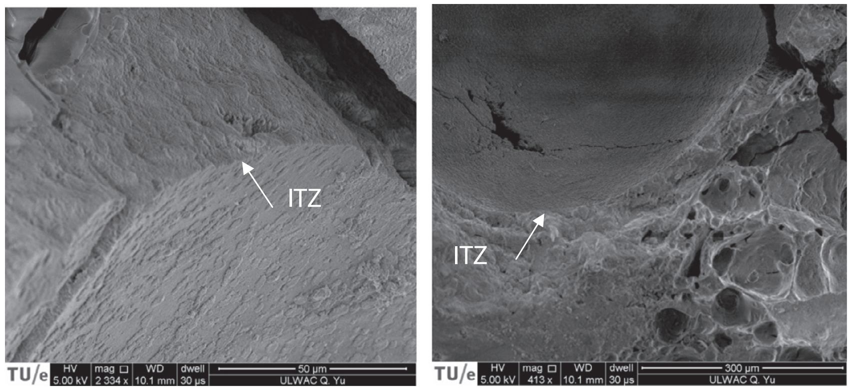

Fig. 5. SEM pictures of the interfacial transition zone (ITZ) of the ULWC (Mix D).

Table 4
Penetration of water under pressure.

Property	Mix A	Mix B
Maximum water penetration (mm)	35.0	11.7
Standard deviation (mm)	7.8	0.9

aggregates has a negative influence on the workability, when mixing them with other materials under dry conditions prior to adding water [1,3,10,37]. However, this negative effect depends not only on the amount of the lightweight aggregates used, but also significantly on their type and production process. There are two mixing methods that are widely used to address this issue, i.e. either to presoak the LWA in water for a certain period (e.g. 24 h presoaking is often considered while practically 30 min to 1 h presoaking prior to concrete mixing is often applied [1,5]), or to add a certain amount of extra water which is calculated normally based on 1-h LWA water absorption [10]. Both methods have disadvantages considering the LWA used in the present study. The presoaked LWA should be surface-dried before mixing with other materials, otherwise large amount of extra water would be incorporated into the mixture. However, for the lightweight aggregates used here, this could cause considerable technical problems and errors due to their very small particle size. On the other hand, the additional water could easily cause segregation or bleeding in the mixture, especially in the case of self-compacting lightweight mortar or concrete. However, as already investigated in [20], the water absorption of the LWA used in this study is relatively low, especially in the first hour (approximately 1.0 wt.%), due to their rather closed external shells. Hence, the LWA applied here shall not affect the workability significantly. Therefore, in the present study, the LWA are applied in air dry conditions directly to the mixture and no extra water is added.

The LWA applied here have a very low particle density, ranging from 300 to 540 kg/m^3, as shown in Table 2. This indicates a possibility of segregation of cement paste from the LWA in fresh concrete, if the proportions of the solids and the amount of water and superplasticizer (SP) are not suitably designed. Therefore the amount of powders in the developed mixture is crucial. The powders consist of cement, but from the economic and ecological point of view, an alternative is to use also other powders as cement replacement. Limestone powder in this regard is a suitable option due to its similar particle size distribution to that of cement. Here cements of different types are also used in order to study their effect on the final properties of the LWC. Considering the amount of powders needed to bound the applied aggregates and a desired workability, a distribution modulus (q) of 0.32 is chosen in the present study for designing the LWAC.

Micro-silica/nano-silica, as an amorphous polymorph of silicon dioxide, has been investigated intensively and successfully applied to improve the properties of concrete due to its very fine particle size and high pozzolanic activity. It is also applied in the present research to improve the properties of the LWAC and to modify the viscosity of the fresh mixture in order to prevent segregation and bleeding problems.

Therefore, following the presented mix design concept, the obtained lightweight concrete (LWC) should have a compact structure/matrix and a large fraction of non-interconnected pores contributed by the LWA. This should secure a concrete with sufficient mechanical properties as well as good thermal insulation properties.

Based on the above mentioned criteria, 17 mixes were designed, with varied cement amounts and types, different amounts of filler (here limestone powder), different amounts of nano-silica, and some selected mixtures' compositions are listed in Table 3.

3. Experiments

The experiments were performed on both fresh and hardened concrete. The slump tests of the fresh concrete were carried out following EN 12350-2:2009 [38]. The flow table tests were performed following EN 12350-5:2009 [39]. The density of the fresh concrete was determined following EN 12350-6:2009 [40], using a container with a volume of 8.0 dm^3. Samples with the size of $100 \times 100 \times 100$ mm^3 and/or $150 \times 150 \times 150$ mm^3 were then cast for further testing. The LWAC was produced using a planetary concrete mixer following a normal concrete production procedure and the concrete was vibrated for about 30 s using a vibration table. Then the samples were covered with a plastic foil to prevent moisture loss. Subsequently, the samples were stripped from molds after 24 h from casting, and stored in a climate chamber with a relative humidity of over 95%, at room temperature (~20 °C), following EN 12390-2:2000 [41], until the test age was reached.

The apparent density of the samples was determined in both ambient conditions and oven dry conditions, by calculating from the measured size and mass of the samples. The air content in fresh state was determined experimentally by the following procedure. Firstly the fresh mixes were poured into a cylindrical container of a known volume, followed by compaction on a vibration table. Then, the mass of the concrete was measured and, assuming that the fresh concrete is homogeneous, the air content was derived from the density difference between the designed and prepared concrete.

The compressive strength tests were performed on cubes with the size of $100 \times 100 \times 100$ mm^3 by applying a load rate of 4.0 kN/s until fracture.

Prior to the thermal conductivity measurement, the samples were dried in a ventilated oven at 105 °C until a constant mass, following EN 12390-7:2009 [42]. Then, the samples were cooled down to the room temperature. Subsequently, the thermal conductivity tests were performed on these samples employing a heat analyzer. The analyzer applies a dynamic measurement method to determine simultaneously the volumetric heat capacity ($J/(m^3 K)$) and the thermal conductivity (W/(m K)) of materials with a measurement time of about 8–16 min. The measurement is based on the analysis of the temperature response of the tested sample to heat flow impulses, while the heat flow is excited by electrical heating of a resistor heater inserted into the probe which is in direct contact with the test sample. Three probes with different thermal conductivity measurement ranges of 0.04–0.3, 0.3–2.0 and 2.0–6.0 W/(m K) with an accuracy of 5% of reading plus 0.001 W/(m K) are equipped. A picture including the heat analyzer and testing sample is shown in Fig. 3a.

Durability is an influential factor determining the quality of concrete, especially LWC. One of the most important parameters influencing the durability of concrete is its permeability to fluids. In concrete of a high permeability, the transport of deleterious substances (e.g. $Cl^-, CO_2, SO_4^{2-}, Mg^{2+}$) is facilitated. This may lead to the deterioration of concrete. Permeability of concrete is governed by its porosity and the connectivity of the pores. In the case of LWA concretes, the porosity is very high and often coupled with an increased interconnectivity of the pores. Hence, the durability of the developed ultra-lightweight concrete is investigated, by means of water penetration under a continuous pressure, following EN 12390-8:2009 [43]. The penetration was tested at the age of 28 days. The samples (three 150 mm cubes for each investigated mix), prepared and conditioned in the same way as described for the compressive strength test, were exposed to water under a constant pressure of 5 bars for 72 h (a test picture is shown in Fig. 3b). Subsequently the samples were split in order to measure the maximum depth of the obtained water penetration front.

4. Results analysis

4.1. Fresh state behavior of ULWC

In overall, all the developed mixes show very good workability, no traces of segregation or bleeding were observed while performing the workability tests. For instance, the slump results show that Mix A (195 mm) can be classified in the slump class of S4 and Mix B (83 mm) in S2, according to EN 206-1:2000. The flow table test results show that Mix A (460 mm) falls under the flow class of F3 and Mix B (390 mm) under F2. The better workability in the case of Mix A can be explained by the fly ash incorporated in CEM II/B-V as it is known that fly ash blended cements show improved workability than other cements under the same water dosage [28].

The fresh state densities of the concrete mixtures are calculated from the measured mass and the fixed volume, yielding between 760 kg/m^3 and 830 kg/m^3. The determined air content in the ULWAC ranges from about 7% to about 15%. This indicates the cement type, nano-silica and superplasticizer may have an effect on the efficiency of the air entraining agent. The differences in the air content in fresh concrete are caused by the different air entraining agent efficiency for different binder systems, and a deviation of the measured ULWAC density from the designed values (Table 3) is caused by the air entraining agent effect.

4.2. The microstructure of ULWC

As already explained, in the development of lightweight concrete, a proper spatial distribution of lightweight aggregates is crucial especially when LWAs of a very low density are used. In the present study the used LWAs have a very low density, as listed in Table 2, holding in the range of 300–540 kg/m^3, indicating a very high segregation potential of the cement paste from the LWA if the mixture is not properly designed. Therefore, the distribution of the LWAs in the concrete matrix was investigated.

Fig. 4 shows the cut surface of the selected samples after performing the compressive strength test. As can be seen in this figure, in all the developed mixtures the LWAs are very homogeneously and evenly distributed in the concrete matrix. This confirms that there was no segregation in the mixtures developed in the present study, indicating the suitability of the applied concrete design method as well as the sufficiently high viscosity of the cement paste.

The relatively closed surface structure of the applied LWAs, as shown in Fig. 1, causes the penetration of only a small amount of water and binder into their pores in fresh state. Nevertheless, this phenomenon might optimize the interfacial transition zone of the LWAC, as reflected by the good quality of the ITZ shown in Fig. 5. This would contribute to increased mechanical properties.

4.3. The effect of cement type

The effect of the used cement type is studied by changing the cement type at a fixed cement dosage of 450 kg/m^3, while keeping the apparent concrete density the same, as shown in Table 3 for Mixes A and B. Figs. 6 and 7 show the compressive strength and thermal conductivity of the LWAC produced with different cement type but with the same cement amount (450 kg/m^3), respectively. All the measured compressive strength values have a standard deviation within 10%, for example Mix A shows a 28-day compressive strength standard deviation 8.5% while Mix B shows 2.0%.

As can be seen in Fig. 6, the compressive strength of all the samples at the age of 7 days has already reached over 85% of their strengths at 28 days. This is in line with the authors' previous study [19] and also with [1]. With the used four types of cement, all the samples have an average 7-day compressive strength higher than 10 N/mm^2. The mixture with CEM I as binder has the lowest 7-day and 28-day strength among the four mixtures, which is unexpected. This might be attributed to the standard deviation of the experiments. Furthermore, this might be explained by the densities of the applied cements. As the used CEM I cement has a specific density of 3150 kg/m^3 while the other three cements have similar densities of between 2900 and 3000 kg/m^3, hence volumetrically in the mixture with CEM I as binder cement has a slightly lower proportion and this contributes a lower concrete strength. The mixtures with CEM V/A (S-V) and CEM III/A have a higher strength increase between the 7-day and 28-day curing period, due to the presence of a slower reacting ground granulated blast-furnace slag (GGBS) and fly ash in the cement. Furthermore, the mixture with GGBS incorporated shows a higher 28-day compressive strength compared to the mixture using CEM I 52.5 N, as shown in Fig. 6. This is in line with Neville [37] who reported a 28-day compressive strength increase of about 38% with a 40 wt.% cement replacement by GGBS. Fly ash has a complex effect on the concrete strength when applied directly as cement replacement [1,37,44,45], as the effect is related very much to the type of the used cement and the particle size of the fly ash. In the present study, the concrete produced using CEM II/B-V 42.5 N shows a higher strength, probably resulting from its finer PSDs which contributes to a denser microstructure development. As introduced in Section 3, the thermal conductivities were determined on the oven-dried samples, which have the oven-dry densities of 650–700 kg/m^3 for all the developed mixtures. The thermal conductivities of the concrete samples prepared with the four different cement types, as shown in Fig. 7, are rather similar, about 0.12–0.13 W/(m K). In addition, the thermal conductivities have reached already stable values at the age of 7 days.

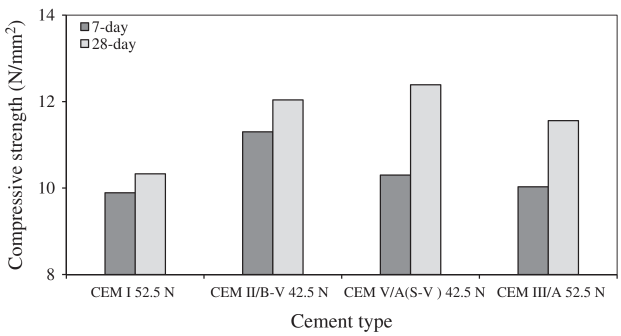

Fig. 6. Compressive strength versus cement type.

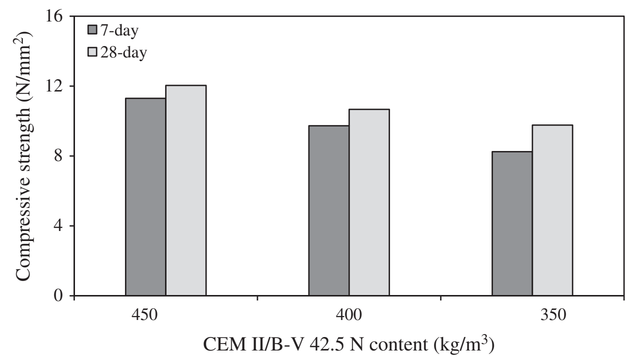

Fig. 8. Compressive strength versus cement content.

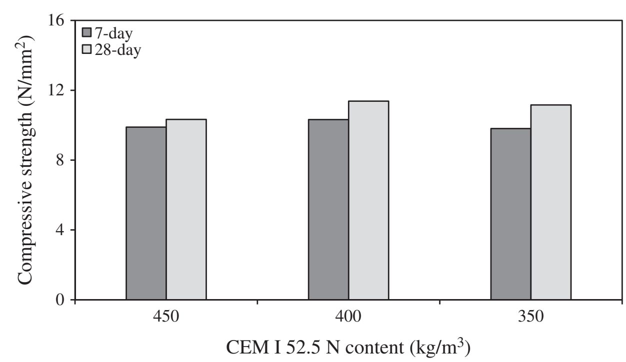

Fig. 9. Compressive strength versus cement content.

4.4. The effect of binder content

The effect of binder dosage was studied on two different cement types: CEM II/B-V 42.5 N and CEM I 52.5 N by applying three different contents, 450 kg/m^3, 400 kg/m^3 and 350 kg/m^3 and following the mixing proportions of Mixes A, C and G in Table 3 (using the both above mentioned cement types). Here the binder is composed of the cement and nano-silica, while the content of nano-silica is kept constant, i.e. 10 wt.% of cement. As shown in Table 3, the amount of the solids, especially the proportions of LWA were kept at the same level in order to compare the influence of the binder content. The cement is replaced volumetrically with limestone powder. As explained previously, these two materials have rather similar particle size distributions so the replacement would not change significantly the cumulative PSDs of the composed mixtures.

Figs. 8 and 9 show the compressive strength of the ULWAC produced with different dosages of CEM II/B-V 42.5 N and CEM I 52.5 N, respectively. Fig. 10 shows the optical microscopy picture of the cracks pattern in the sample caused by the compressive strength test. Figs. 11 and 12 show the thermal conductivity of the ULWAC produced with different dosages of CEM II/B-V 42.5 N and CEM I 52.5 N, respectively.

As shown in Fig. 8, the compressive strength at 28-day slightly decreases from 12.0 to about 10 N/mm^2 when the CEM II/B-V 42.5 N content is reduced from 450 kg/m^3 to 350 kg/m^3. The compressive strength at both 7 and 28 days remains relatively similar when varying the cement content in the case of CEM I 52.5 N. This can be attributed to the LWAs. The compressive strength of the applied LWAs is relatively low compared to the hardened cement paste matrix. Hence, especially in the case of CEM I 52.5 N, the cracks induced in the sample during the compressive strength test run mainly through the lightweight aggregates particles, as shown in Fig. 10. In other words, the used cement amount is actually excessive, and a certain additional part does not contribute the compressive strength of the concrete due to the mechanical weakness of the applied LWAs.

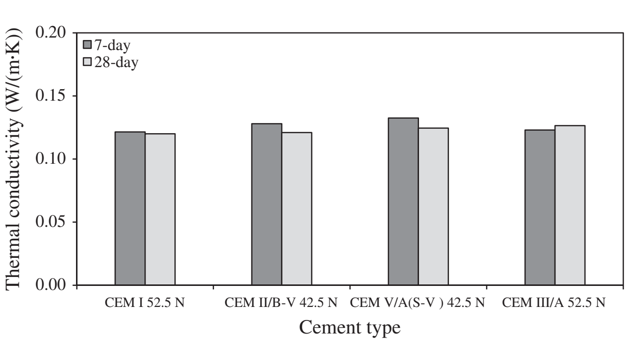

Fig. 7. Thermal conductivity versus cement type.

Neville [37] and Chandra and Berntsson [1] reported that when using materials such as vermiculite, perlite, expanded clay, expanded slag and expanded slate as LWA, the compressive strength of the LWAC increases as the cement content is increased. However, in addition to the difference between the crushing resistances of the applied LWAs, another clear difference between the cited literature and the present study is that here the apparent densities of all the investigated ULWACs are kept constant while only the cement content is varied. This is in order to eliminate the influence of the density on the compressive strength, as Chandra and Bernstsson [1] reported that under fixed water to cement ratios, the density of LWAC has a linear relation with its compressive strength using different types of LWAs. Chandra and Bernstsson [1] reported that the LWAC using expanded glass as LWA has a compressive strength of about 15 N/mm^2 with a demolding density of about 1100 kg/m^3, and a LWAC using expanded clay as LWA has a compressive strength of about 7 N/mm^2 with a demolding density of about 1000 kg/m^3. Zareef [2] reported a LWAC with compressive strength of 7.4 N/mm^2 and an oven dry density of 760 kg/m^3 using expanded clay as LWA. Neville [37] reported that a cellular concrete has a compressive strength of 2.0 N/mm^2 with an oven dry density of about 760 kg/m^3, which is also confirmed by Kearsley and Wainwright [45]. Schauerte and Trettin [46] reported a 28-day compressive strength of 2–4 N/mm^2 for foamed concrete with a density of about 1000 kg/m^3. Neville [37] also reported a compressive strength of 4.5–6.3 N/mm^2 with a dry density range of 600–675 kg/m^3 in the case of autoclaved concrete. Therefore it can be clearly noted that the currently developed ULWAC possesses a considerable improvement in terms of compressive strength at the similar density range (i.e. an oven dry density of about 650 kg/m^3).

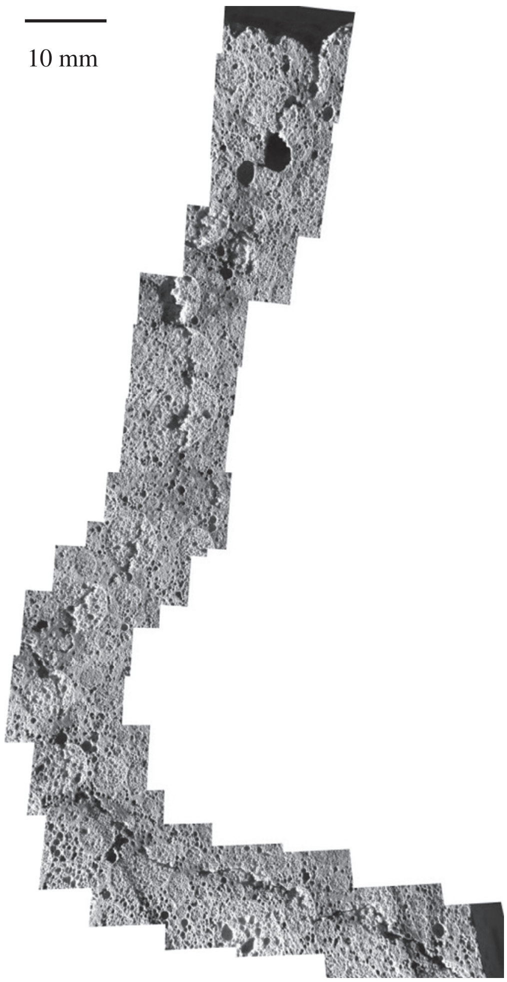

Fig. 10. The internal cracks resulted from the compressive strength test.

The thermal conductivities of the samples, produced with different cement contents, as shown in Figs. 11 and 12, are very similar, between 0.12 and 0.13 W/(m K). This indicates that the thermal conductivity is not directly related to the cement content in the investigated cement content ranges (assuming a rather constant density of LWAC). Again the results shown in Figs. 11 and 12 confirm that the thermal conductivities are already quite stable at the age of 7 days. Chandra and Berntsson [1] reported a linear relation between the oven dry density and thermal conductivity of LWAC using different types of lightweight materials as aggregates and a thermal conductivity of 0.20 W/(m K) is derived at a density of 630 kg/m^3 from this relation (i.e. the same density range obtained in the present study). Zareef [2] reported that using expanded clay as LWA, a LWAC with a thermal conductivity of 0.18 W/(m K) and an oven dry density of 760 kg/m^3 was produced. Thus, it can be seen that the ULWAC developed in this study possesses a much lower thermal conductivity within a similar density range.

4.5. The effect of nano-silica

As introduced in the previous sections, micro- and nano-silica have been proven to have positive effect on the mechanical properties of concrete, anti-bleeding and segregation of fresh concrete mixture and durability. Owing to their extreme fineness and high amorphous SiO_2 content, micro- and nano-silica are highly reactive pozzolanic additives. Their reaction with $Ca(OH)_2$, generated upon the hydration of cement, leads to a significant densification of the paste matrix and the paste-aggregates ITZ, thus results in a concrete with an improved durability and mechanical properties.

The nano-silica used here is in slurry form, i.e. colloidal silica, with a particle size range of 19–156 nm by SEM/STEM and of 79–186 nm by laser light diffraction (nanosizer) measurement [47]. By far the effect of the nano-silica addition to concrete has not been agreed as many contradictory results on its influence on concrete strength development were reported [48]. The effect of the nano-silica addition is therefore investigated in the present study, by varying its dosage in concrete, with different cement contents. Here, for each fixed cement content case, the cement is replaced with the same mass of nano-silica, as listed in Table 3.

Figs. 13–15 show the compressive strength and thermal conductivity of ULWC with different dosages of nano-silica, using CEM II/B-V 42.5 N but with different contents of 450 kg/m^3, 400 kg/m^3 and 350 kg/m^3, respectively. As shown in Figs. 13–15, in all these three investigated cases, nano-silica has a clearly positive effect on the compressive strength. For example, a compressive strength increase of 21% and 22% was reached with the binder content of 450 kg/m^3 and 400 kg/m^3, respectively. Nevertheless, the thermal conductivity values are quite stable at different nano-silica dosages, indicating a negligible effect of the nano-silica application on the thermal conductivity. This finding is in line with Demirboğa and Gül [8] who reported very similar thermal conductivities of LWC when replacing 10% of cement by silica fume.

4.6. The effect of air-entraining agent

Fig. 16 shows the compressive strength and thermal conductivity of the LWAC produced with the cement CEM I 52.5 N with the content of 450 kg/m^3 (Mix A in Table 3 but with different cement type), applying different air-entraining agent dosages. A clear

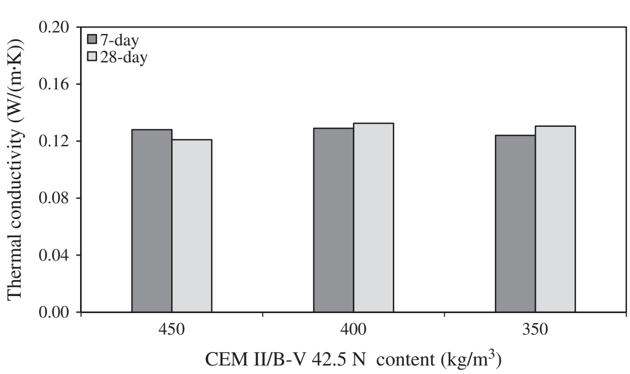

Fig. 11. Thermal conductivity versus cement content.

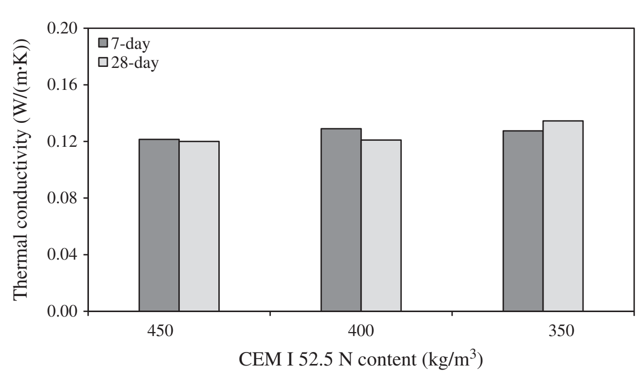

Fig. 12. Thermal conductivity versus cement content.

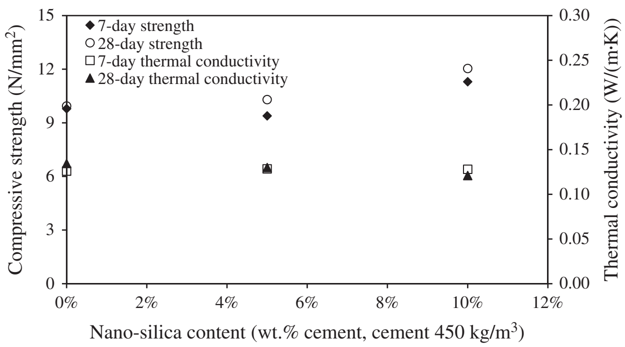

Fig. 13. Properties of the ULWC with the cement content of 450 kg/m^3, at different dosages of nano-silica.

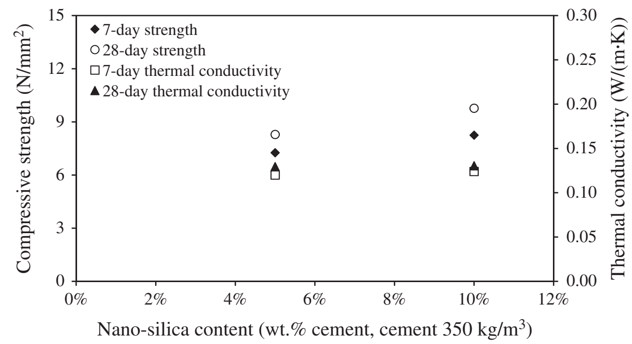

Fig. 15. Properties of the ULWC with the cement content of 350 kg/m^3, at different dosages of nano-silica.

effect of the air-entraining agent was observed on both compressive strength and thermal conductivity of the developed lightweight concrete. The compressive strength decreased from 15.5 N/mm^2 to 10.3 N/mm^2 when dosing 2.25 kg/m^3 air entraining agent into the concrete. Meanwhile, the thermal conductivity increased from 0.12 W/(m K) to 0.15 W/(m K) when the air-entraining agent was not used. The results also show that concrete can be designed with or without the application of air entraining agent, depending on the design requirements.

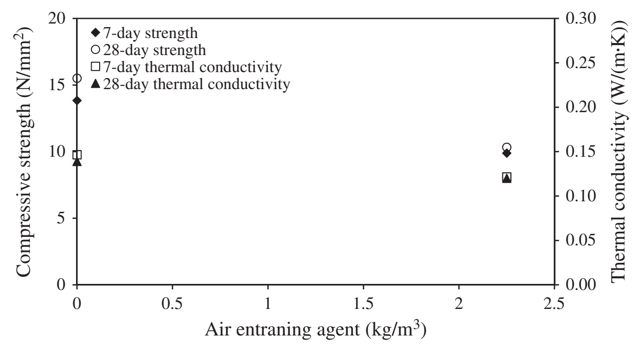

Fig. 16. Properties of the ULWC with the cement content of 450 kg/m^3, but with different air entraining agent dosage.

4.7. Water penetration under pressure

The values of the obtained water penetration depths performed to two mixes (Mix A and B in Table 3) are shown in Table 4, and the split samples after the tests are shown in Fig. 17. The results show that although the designed ultra-lightweight concrete has a very high total porosity, the permeability to water under the pressure of 5 bars during 72 h is very low (e.g. 11.7 mm in the case of Mix B). Hence, the developed ultra-lightweight concrete has an excellent resistance against water penetration. The water penetration difference between Mix A and Mix B can be explained by the applied cement, as the GGBS in CEM III is reacting faster than fly ash in CEM II. Furthermore, in the present study, CEM III/A 52.5 N is used in Mix B while CEM II/B-V 42.5 N is used in Mix A so the finer particles in the used CEM III contribute a further faster reaction, which leads to a denser concrete matrix. As a comparison, a self-compacting concrete, designed with a cement content of 340 kg/m^3 and water to binder ratio of 0.45, reaches a 28-day compressive strength of 78.5 N/mm^2 and a water penetration depth of 26 mm with the standard deviation of 7 mm [34]. As can be seen, even for a slightly higher water to binder ratio (0.5 in the present study compared to 0.45 in [34]), the water penetration resistance of Mix B developed in the present study is excellent.

Fig. 17. Split surfaces of cubes after the water pressure permeability test; water ingress from the side of the bottom surface (1: Mix A; 2: Mix B).

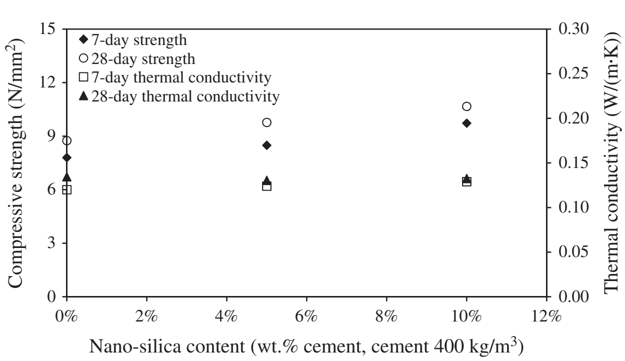

Fig. 14. Properties of the ULWC with the cement content of 400 kg/m^3, at different dosages of nano-silica.

5. Discussions

Lightweight concrete is normally categorized to 3 grades: low density concrete with a density lower than 800 kg/m^3, moderate strength concrete with a density between 800 kg/m^3 and 1400 kg/m^3 and structural concrete with a density between 1400 kg/m^3 and 2000 kg/m^3 [49]. Ultra-lightweight concrete is also sometimes referred to as the super lightweight concrete [2], infra-lightweight concrete or low density concrete with a dry density lower than 800 kg/m^3, which is the lower limit of the definition of lightweight concrete according to the standard EN 206-1 [50]. This type of lightweight concrete is normally used for insulation

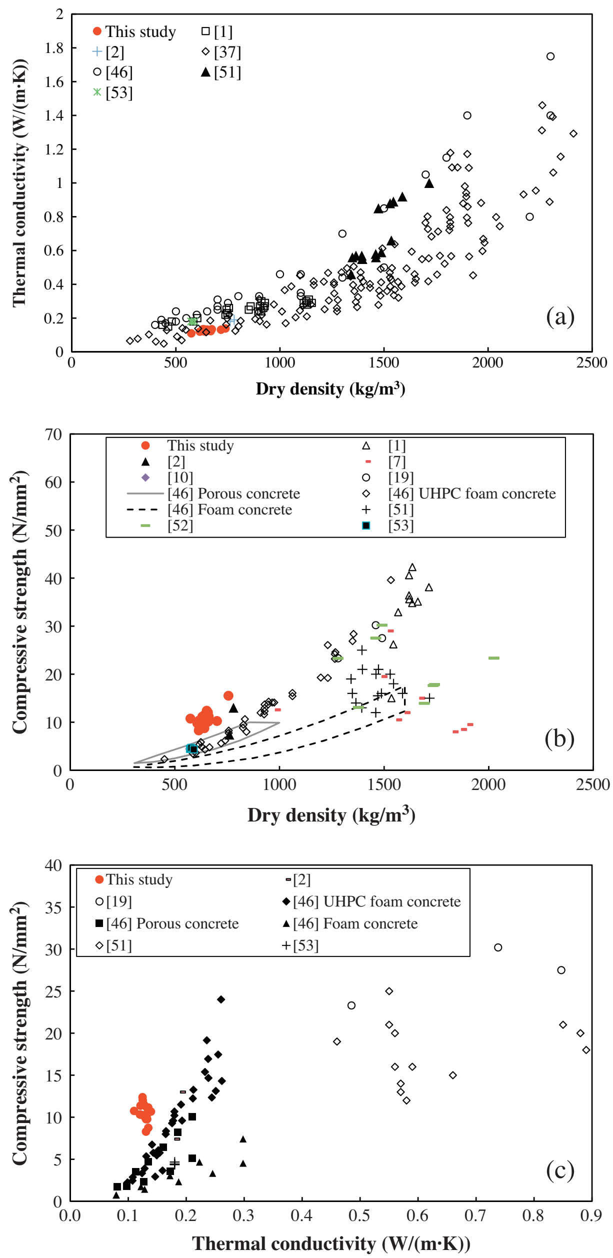

Fig. 18. The relationship between (a) density and thermal conductivity, (b) density and compressive strength, and (c) thermal conductivity and compressive strength of concrete.

purposes due to its very low thermal conductivity and it is usually characterized by a very low compressive strength (ranging from about 0.69 to 6.89 N/mm^2 [49]).

The present research aims at the development of ultra-lightweight aggregates concrete, with the density lower than 800 kg/m^3 but with a moderate strength, capable of bearing load. As can be seen in the previous sections, applying the introduced mix design methodology, a durable LWAC mix with a dry density of about 650–700 kg/m^3 was successfully developed with a thermal conductivity of about 0.12 W/(m K) and a 28-day compressive strength higher than 10 N/mm^2. Fig. 18 summarizes the relation between the density, thermal conductivity and compressive strength of lightweight concrete. As can be clearly seen, the results obtained here are much better than all the data retrieved from the literature [1,2,4,7,10,37,46,51–53]. Furthermore, this concrete mix design is relatively cost effective as no expensive ingredients such as nano-silica are necessary to be applied in order to reach comparable properties, as discussed in the previous sections.

The LWA used in this study is produced from recycled glass. On the one hand, this further contributes to the sustainability of concrete, but on the other hand, the possibility of alkali–silica reactivity (ASR) shall be taken into consideration because of SiO_2 present in LWA (about 70% by mass). Ducman et al. [54] reported that although the expanded glass aggregates are reactive, they do not cause expansion or cracking in concrete. This is attributed to the very porous structure of the aggregates, which provides sufficient space for ASR products, which is also confirmed by [1]. Zhang and Gjørv [55] also reported that, although there is a certain degree of pozzolanic reaction between the cement paste and the LWAs, which contain SiO_2, Al_2O_3, and Fe_2O_3 up to 85% in total, the effect is very small and can be neglected. In our previous research, the possible ASR in lightweight concrete has been addressed by observing the possible alkali silica reaction products in the ITZ by SEM analysis and the obtained results indicate that there is no chemical reaction between the LWA and cement matrix [19,30]. In the present study, this is further investigated, by carrying out experiments following the RILEM TC 106-AAR guideline [56], and two mixtures using different cement types were tested (Mix A and Mix C). The results, as shown in Fig. 19, clearly demonstrate that there is no alkali–silica reaction in the tested concrete matrix as the measured deformation is constantly about 0% after over 300 h test. This indicates that the used lightweight aggregates can be applied in lightweight concrete without the risk of the alkali–silica reaction.

6. Conclusions

The present study aims at the development of an ultra-lightweight aggregates concrete (ULWC), with good mechanical properties and a very low thermal conductivity, in order to develop a material suitable for monolithic concrete structures, thus performing as both load bearing element and thermal insulator. Based on the presented study, the following conclusions can be reached:

- An ultra-lightweight concrete with a dry density of about 650–700 kg/m^3 was developed.
- The developed ULWC has a good workability and all the lightweight aggregates are homogeneously distributed in the concrete matrix.

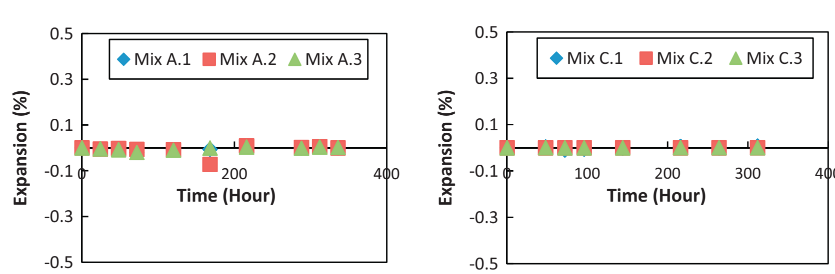

Fig. 19. Expansion of concrete due to the ASR: left: CEM I 52.5 N as binder; right: CEM III/A 52.5 N as binder.

- The developed ULWC shows a 28-day compressive strength above 10 N/mm^2, and a thermal conductivity of about 0.12 W/(m K).
- The developed ULWC shows an excellent resistance against water penetration and the LWA do not create the alkali–silica reaction risk.

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