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DESIGN OF ULTRA-LIGHTWEIGHT CONCRETE: TOWARDS MONOLITHIC CONCRETE STRUCTURES

This study addresses the development of ultra-lightweight concrete. A moderate strength and an excellent thermal conductivity of the lightweight concrete are set as the design targets. The designed lightweight aggregates concrete is targeted to be used in monolithic concrete façade structure, performing as both load bearing element and thermal insulator. The developed lightweight concrete shows excellent thermal properties, with a low thermal conductivity of about 0.12 W/(m·K); and moderate mechanical properties, with 28-day compressive strengths of about 10—12 N/mm^2. This combination of values exceeds, to the researchers' knowledge, the performance of all other lightweight building materials. Furthermore, the developed lightweight concrete possesses excellent durability properties

Key words: ultra-lightweight concrete, lightweight aggregates, mechanical properties, thermal conductivity, durability.

The history of lightweight aggregates concrete (LWAC) dates back over 3000 years ago [1]. Because of its many advantages such as low density, good thermal insulation and fire resistance, LWAC has been widely applied as both structural and nonstructural material. However, the available literature shows a great variation regarding both mechanical and thermal properties, indicating the effect of the used materials and mix design method. Nevertheless, no systematic study on an optimized LWAC mix design has been addressed. In addition, the majority of the research focused on either to obtain a LWC as structural material with only good strength or as nonstructural material with only low thermal conductivity. Hence, extra insulation materials or load bearing elements are needed.

The present research aims at the development of a sustainable and durable ultra-lightweight concrete with a good balance between the mechanical properties and the thermal properties. This design concept indicates that a monolithic concrete structure will be in reach. The monolithic concrete structure concept leads to the following advantages: 1) cost saving, due to the exemption of extra insulation installations; 2) provides architects and structural engineers with more flexibility for the building design; 3) sustainability, as waste materials are used as raw materials and the monolithic structure will ensure a relatively easy maintenance requirement and it is much easier to recycle.

Mix design and experiments

The LWAC is designed applying an innovative mix design method presented in [2]. This mix design tool is based on the insight that superior properties of a granular mix are achieved when a so-called geometric grading line is designed and obtained, applying a model known as the modified Andreasen and Andersen model. This particle packing principle insight has been transformed into a numerical mix design, in which all mix ingredients, having their own specific densities and particle size distributions (PSDs), are volumetrically combined via a mathematical optimization routine, i.e. the "target curve" is approached best. This results in improved hardened state properties as well as an improved workability, since more water is available to act as lubricant between the particles [3]. This mix design methodology has been already successfully applied for the design of self-compacting concrete [3, 4], zero-slump concrete [5, 6] and gypsum-based composites [2].

A very low thermal conductivity is one desired objective here, which is achieved by applying a lightweight material as aggregate (LWA). The LWAs used here, made from recycled glass, have a very low particle density ranging from 300 to 540 kg/m^3. This indicates the possibility of segregation of cement paste and the LWA in fresh concrete state, if the proportions of the solids and the amount of water and superplasticizer (SP) are not suitably designed. Here cements of different types are also used in order to study their effect on the final properties of the LWAC.

Therefore, by using cement as binder, lightweight material as aggregates and applying the mix design concept, the obtained LWAC will have a compact matrix with a large amount of non interconnected pores. Theoretically this will lead to obtaining sufficient mechanical properties as well as good thermal insulation. The PSDs of one designed mix (in total 17 mixtures were designed in this research) are shown in Figure 1. Multiple experiments are performed on the mixtures, including: the slump and density in fresh state; the apparent density, compressive strength, thermal conductivity and durability in terms of water penetration under pressure in hardened state.

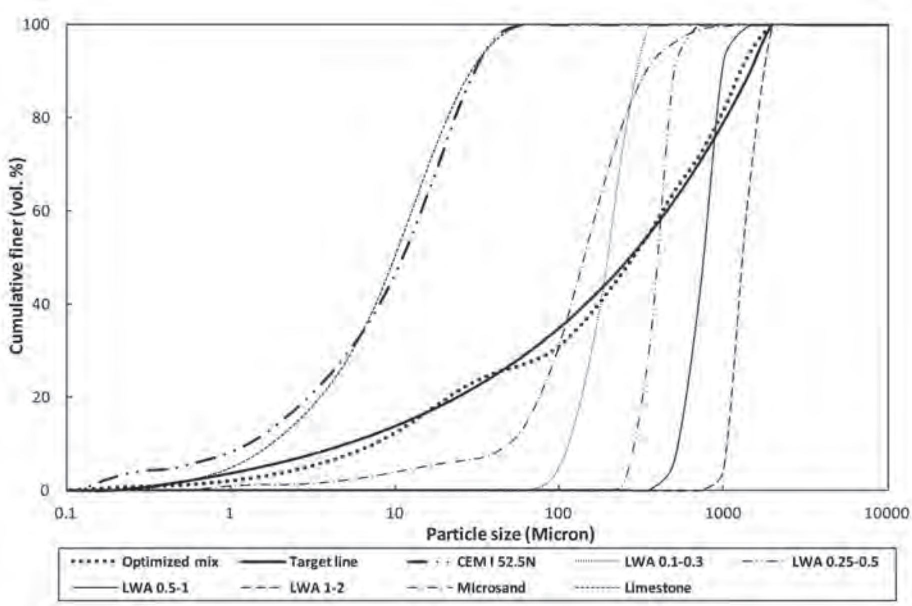


Fig. 1. PSDs of the involved ingredients, the target line and the resulting integral grading line of the mix

Analysis results

It is clear from Table that both mixes show good workability, with that Mix A in the slump class of S4 and Mix B in S2, and Mix A in the flow class of F3 and Mix B in F2. It should be realized that in order to achieve this flowability, no superplasticizers were dosed nor needed, which is an additional feature of the used mix design method, also observed when SCCs were designed [3]. The fresh density test shows that these two mixes have 837 kg/m^3 and 778 kg/m^3, respectively. As it can be seen, the air introduced by the air entraining agent are different, despite the fact that the same amount of air entraining agent was used in these two mixes. This indicates the cement type has an effect on the efficiency of the air entraining agent.

The results of flow and slump of the mixes

Tests	Flow (mm)			Slump (mm)
	Measure 1	Measure 2	Mean	
Mix A	460	460	460	195
Mix B	390	390	390	83

As explained, in the LWAC design, the distribution of LWA is crucial especially when LWAs of a very low density are used. As can be seen in Figure 2, the cut surface of the samples from some mixes after performing the compressive strength test, 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, as well as the validity of the applied concrete mix design methodology here.

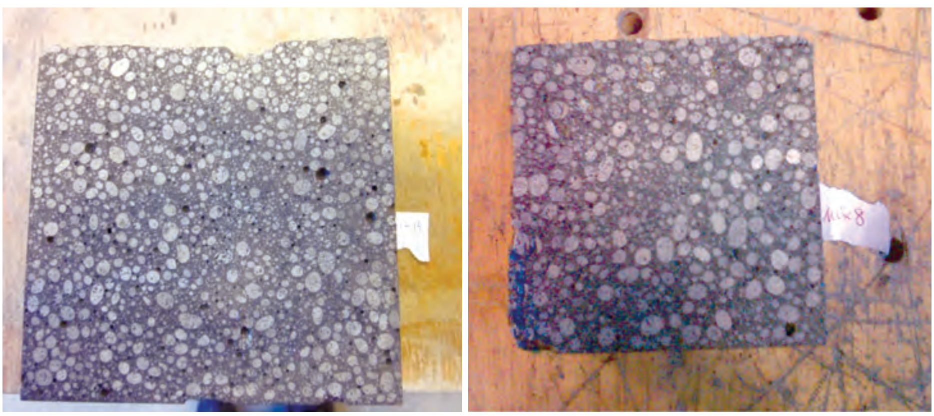
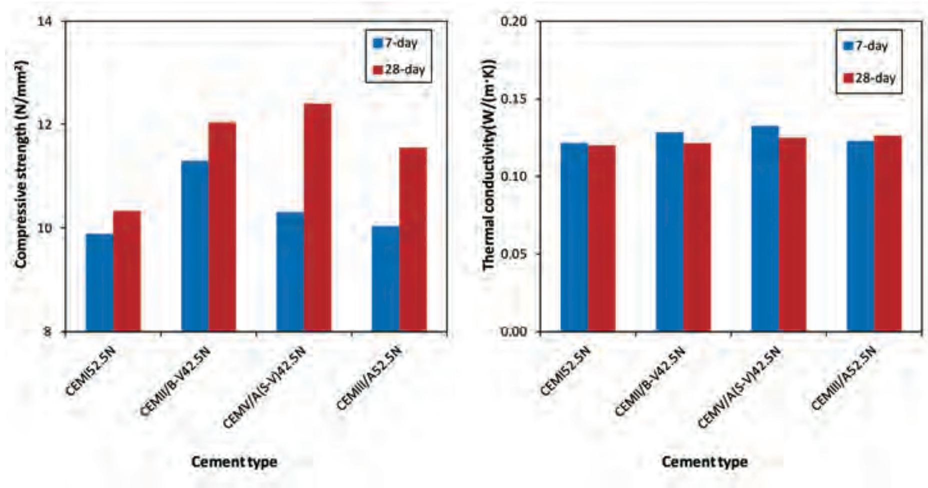


Fig. 2. The pictures of a cut surface of LWAC from two mixes

Figure 3 shows the properties of the LWAC produced with different cement type but with the same cement amount (450 kg/m^3). As it can be seen, all the samples have an average 7-day compressive strength higher than 10 N/mm^2. The mixtures with CEM V/A (S-V) and CEM III/A as binder have a larger strength increase between the 7-day and 28-day curing period, due to the presence of a slower reactive slag in the cement.



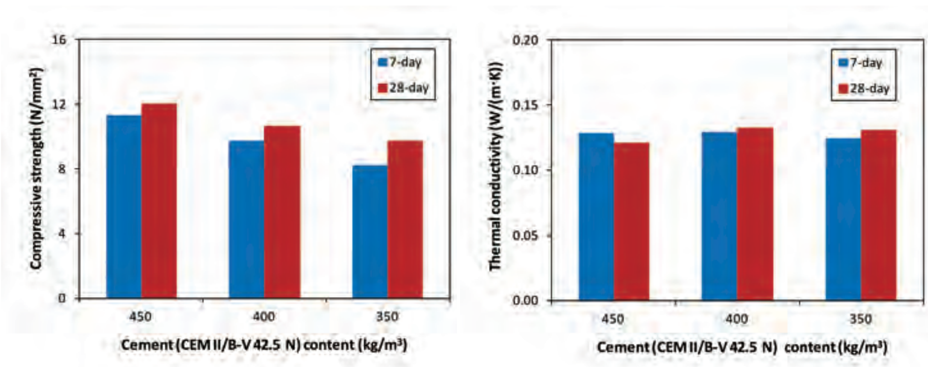
a *b*

Fig. 3. The properties of the LWAC with different cement type (*a*: compressive strength; *b*: thermal conductivity)

Furthermore, the mixture with slag incorporated shows a higher 28-day compressive strength compared to the mixture using CEM I 52.5 N as a binder. The thermal conductivities of all the samples prepared with these four cements are rather similar, about 0.12—0.13 W/(m·K). In addition, the thermal conductivities of these samples are already quite stable at the age of 7 days. Although there are slight differences as the age increases, the variation is negligible.

Figure 4 shows the properties of the LWAC produced with CEM II/B-V 42.5 N as binder but with different amounts. The compressive strength at 28-day decreases from 12 to 10 N/mm^2 when the cement content is reduced from 450 kg/m^3 to 350 kg/m^3. The thermal conductivities of the samples 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 (assuming a rather constant density of LWAC). Chandra and Berntsson [1] reported a linear relation between the oven dry density and thermal conductivity of LWAC using different types of LWA and a thermal conductivity of 0.20 W/(m·K) is resulted at a density of 630 kg/m^3 (i.e. the same density value obtained in the present study). Zareef [7] reported a LWAC possesses a thermal conductivity of 0.18 W/(m·K) with an oven dry density of 760 kg/m^3 using expanded clay as LWA. Thus, it can be seen that the present LWAC possesses a much lower thermal conductivity with a similar density range.

The used nanosilica is in the form of slurry, i.e. colloidal silica, with a particle size range of 19—156 nm by SEM/STEM and of 79—186 nm, measured by laser light diffraction (nanosizer) [8]. By far the effect of the nanosilica addition to concrete has not been agreed as many contradictory data regarding its influence on concrete strength development were reported [9]. Here, at each fixed cement content, the cement is replaced with the same amount of nanosilica. Figure 5 shows the properties of the LWAC produced applying different dosages of nanosilica, using CEM II/B-V 42.5 N, with different contents of 450 kg/m^3 and 400 kg/m^3.



a *b*

Fig. 4. The properties of the LWAC with different cement content (*a*: compressive strength; *b*: thermal conductivity)

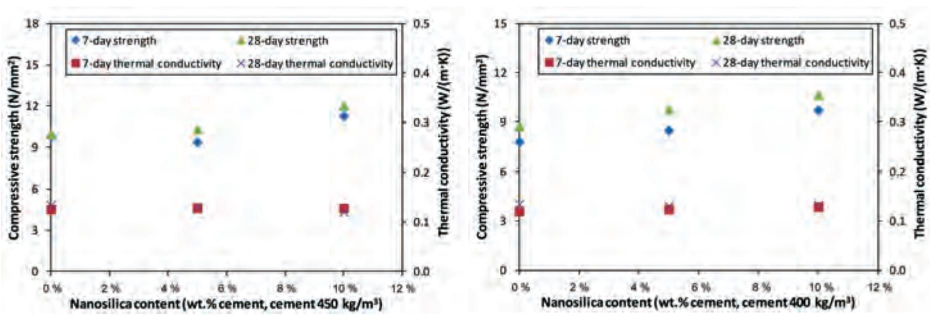


Fig. 5. The properties of the LWAC with different dosages of nanosilica

As shown in Figure 5, in both investigated cases, the nanosilica has a clearly positive effect on the compressive strength. For example, a compressive strength increase of 21 % and 22 % was reached with a 10 % nanosilica replacement with the binder content of 450 kg/m^3 and 400 kg/m^3, respectively. Nevertheless, regarding the thermal conductivity, as shown in Figure 5, the measured values are relatively constant at different nanosilica dosages, indicating a negligible effect of the nanosilica replacement on the thermal conductivity.

The split samples after performing the water penetration tests are shown in Figure 6, together with the marked water penetration depths. The results show that although the designed ultra-lightweight concrete has a very high porosity, the permeability to water under the pressure of 5 bars during 72 h is very low, especially in the case of the samples from Mix B (marked with 2-a/b/c in Figure 6). Hence, the developed ultra-lightweight concrete has an excellent durability, in terms of water penetration under pressure. The low water penetration under pressure further confirms that the applied mix design methodology is a useful tool to design a LWAC: low thermal conductivity, sufficient mechanical properties and good durability are achieved.

Discussions

Ultra-lightweight concrete, with an oven dry density lower than 800 kg/m^3, is also sometimes referred to as *super lightweight concrete* or *infra-lightweight concrete*. This type of LWA is normally used for insulation purposes due to its very low thermal conductivity but it is also characterized by a very low compressive

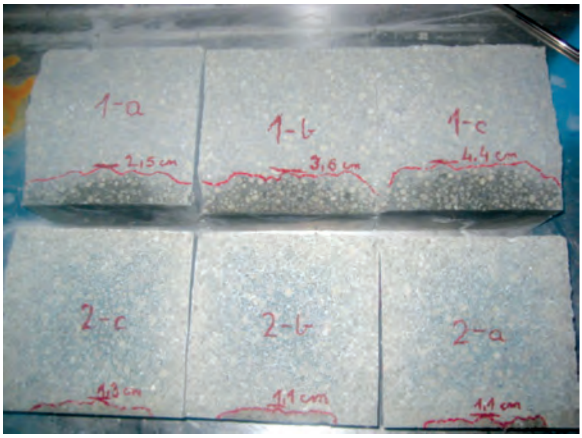
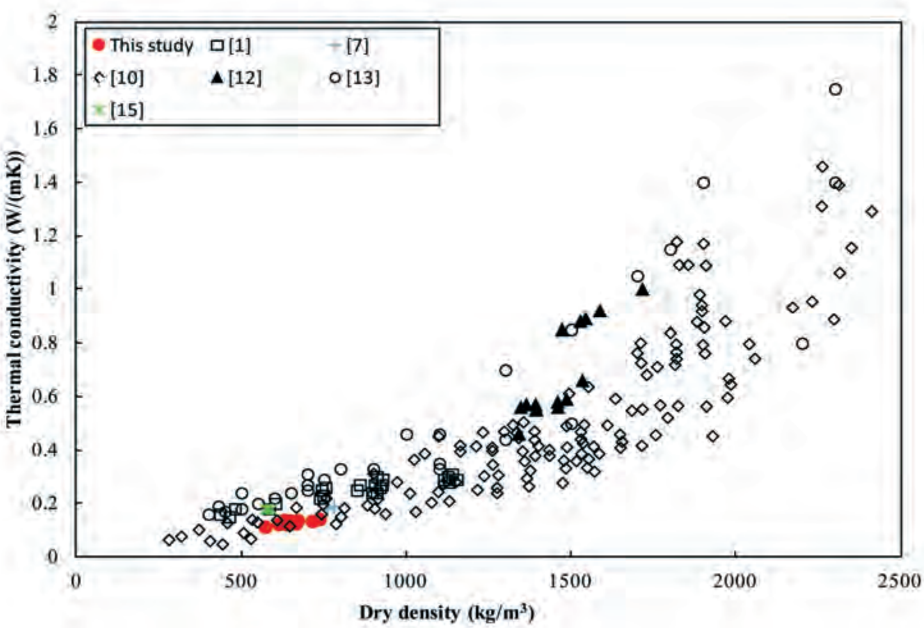


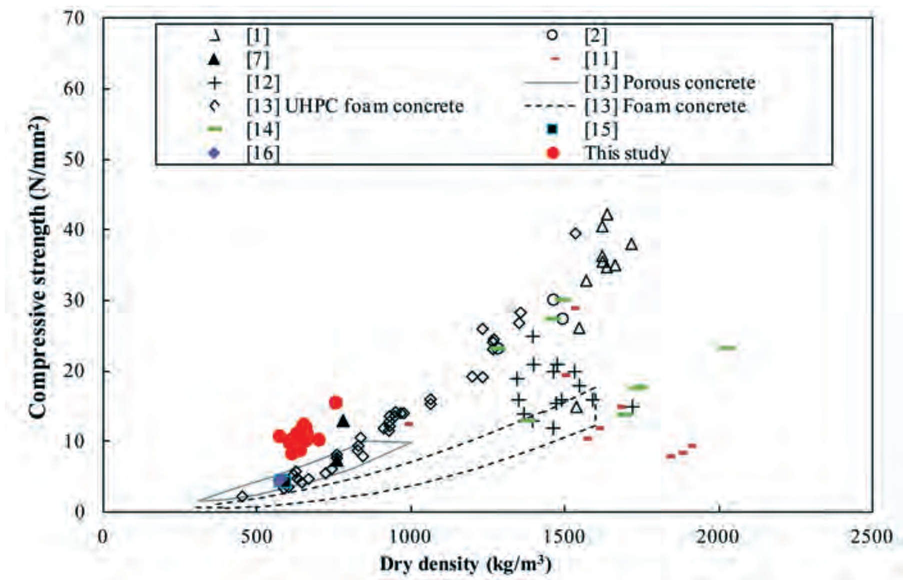
Fig. 6. The split surfaces of cubes after the water pressure permeability test; water ingress from the side of the bottom surface

strength (ranging from about 0.69 to 6.89 N/mm² [8]). This study aims at the development of ultra-lightweight aggregates concrete, with the density lower than 800 kg/m³, but with a moderate strength, capable of bearing load. As it 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/m³ was successfully developed with a thermal conductivity of about 0.12 W/(m·K) and a 28-day compressive strength higher than 10 N/mm². In addition, this concrete mixture is relatively cost effective as no expensive ingredients such as nanosilica were finally needed to reach the above mentioned values. Furthermore, Figure 7 summarizes the relation between the density and thermal conductivity and compressive strength of (lightweight) concrete. As it can be clearly seen, the results obtained here are much better than all available data that could be retrieved from the literature [1, 2, 7, 9—16, 17].



a

Fig. 7. *a*: The relationship between the density and thermal conductivity of concrete



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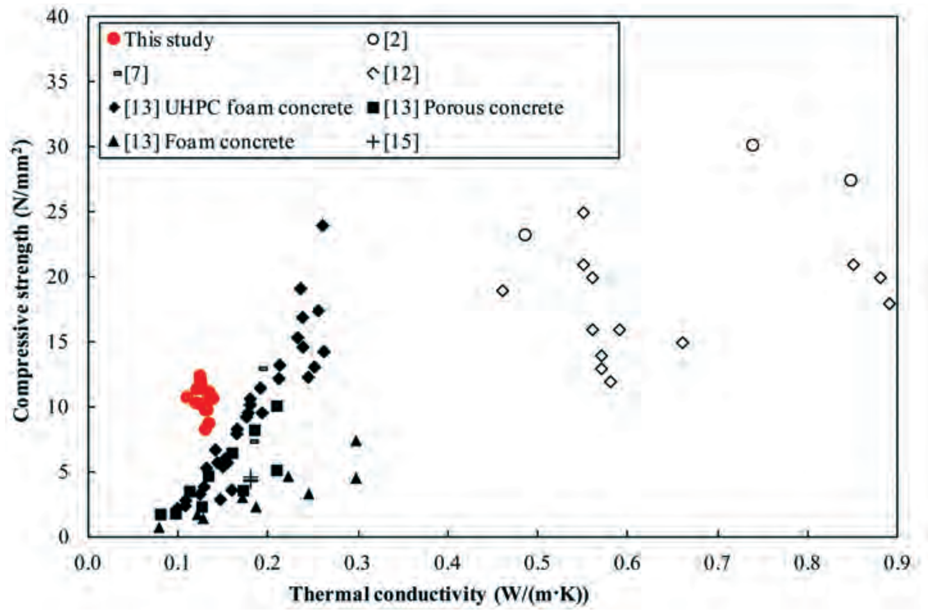

c

Fig. 7. *b*: The relationship between the density and compressive strength of concrete; *c*: The relationship between the thermal conductivity and compressive strength of concrete

Summary

The present study aims at the development of ultra-lightweight aggregates concrete, with good mechanical properties and a very low thermal conductivity, in order to apply this material for monolithic façade concrete structures, performing as both load bearing element and thermal insulator. Based on the performed study, the following findings can be summarized:

an ultra-lightweight aggregates concrete with a dry density of about 650—700 kg/m^3 was developed;

the developed LWAC shows a good workability; and after hardening all the used lightweight aggregates are homogeneously distributed in the concrete matrix;

the effects of the design parameters such as the used cement (type and content), nanosilica on the concrete properties are investigated;

the developed LWAC shows a 28-day compressive strength higher than 10 N/mm^2, and a thermal conductivity of about 0.12 W/(m·K);

the developed LWAC shows an excellent durability in terms of water permeability under pressure.

In future research the concrete will be further optimized with respect to thermal conductivity and strength. Furthermore, the current mix design technology will be used to develop lightweight constructive concrete. This material will combine optimal constructive and density properties, and will be less optimal concerning its thermal performance.

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РАЗРАБОТКА УЛЬТРАЛЕГКОГО БЕТОНА ДЛЯ МОНОЛИТНЫХ БЕТОННЫХ КОНСТРУКЦИЙ

Исследование посвящено разработке ультралегкого бетона. Целью разработки является прочность и высокая теплопроводность легкого бетона. Разработанный бетон на легких заполнителях предназначен для строительства монолитных бетонных конструкций фасада, который является одновременно несущим элементом и теплоизолятором. Разработанный легкий бетон демонстрирует прекрасные тепловые характеристики: низкую теплопроводность — примерно 0,12 Вт/(м·К); умеренные механические характеристики с 28-дневной прочностью на сжатие — около 10...12 Н/мм^2. По оценкам исследователей, эти значения превышают характеристики других легких строительных материалов. Более того, разработанный легкий бетон обладает высокими показателями долговечности.

Ключевые слова: ультралегкий бетон, легкие заполнители, механические характеристики, теплопроводность, долговечность.

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