Structural ultra-lightweight concrete – from laboratory research to field trials

Citation for published version (APA):
Spiesz, P. R., & Hunger, M. (2017). Structural ultra-lightweight concrete – from laboratory research to field trials. In H. Justnes, & H. Braarud (Eds.), *Proceedings of the 11th High Performance Concrete conference, HPC Tromso 2017* (pp. 1-10). Article 47.

Document status and date:
Published: 01/01/2017

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 17. Nov. 2023

STRUCTURAL ULTRA-LIGHTWEIGHT CONCRETE – FROM LABORATORY RESEARCH TO FIELD TRIALS

Przemek Spiesz, HeidelbergCement Benelux, The Netherlands
Martin Hunger, HeidelbergCement Benelux, The Netherlands[1] and
BASF Construction Solutions, Germany[2]

ABSTRACT

This article presents the laboratory development and subsequent field trials of a novel structural ultra-lightweight concrete. The concrete is developed aiming at the application in monolithic buildings (i.e. no insulation layer required), which would facilitate the construction and recycling processes, as well as provide new opportunities to architects and structural engineers. The development of the ultra-lightweight concrete presented in this study includes the optimization of its composition (ultra-lightweight aggregates, binders, admixtures) and is targeted on the concrete properties such as the compressive strength, density and thermal conductivity. In order to reduce the risk of an excessive overheating of concrete during its early hydration process caused by its self-insulating properties, the binder composition and amount was further investigated and optimized. Finally, a material of an ultra-low density (< 800 kg/m^3), ultra-low thermal conductivity (as low as 0.14 W/(m·K)) and a compressive strength of 10 MPa was developed. Subsequently, several batches of 2 m^3 of concrete were produced in a ready-mix concrete plant and a L-shaped test-wall was cast. The temperature development as well as hardened concrete properties were monitored. The field tests show that, although there still are some issues to overcome (e.g. workability), the developed material has a very good potential to enter the concrete market and find new applications.

Key-words: ultra-lightweight concrete, monolithic building, density, compressive strength, thermal conductivity

INTRODUCTION

The conventional building concept comprises of constructing “sandwich-type” elements that consist of structural bearing and insulating sections, in order to fulfil the building’s energy efficiency requirements. Such an insulation layer, most often consisting of polystyrene, mineral wool fiber or air, is required by the building codes as the regular building materials such as concrete or masonry bricks have too high thermal conductivity, i.e. provide insufficient thermal insulation. With a novel monolithic building concept, concrete elements/structures could be realized without the need of any additional insulation besides the concrete itself. The need for an insulation layer could be overcome by developing a building material that could fulfil the requirements of sufficient mechanical properties (load-bearing function) and act as a thermal insulator (low thermal conductivity) at the same time. The monolithic building concept would give the architects and structural engineers more possibilities in designing and constructing various buildings and infrastructure, simplify the construction process, could potentially reduce building costs and facilitate the recycling process. As the thermal conductivity of concrete is mainly governed by its density (air voids content), only lightweight concrete of sufficient mechanical strength can be considered in the monolithic building concept. Other types of concrete with very low thermal conductivity, such as foam or autoclaved concrete, are not possessing sufficient mechanical properties to act as a load-carrying member. The EN 206-1 [1] defines lightweight concrete as a concrete with an oven-dry density in the range of 800-2000 kg/m^3. Nevertheless, it does not specify and thus is not applicable to concretes having the dry-densities lower than 800 kg/m^3. One novel type of concrete that falls under this density class has been developed recently in the Netherlands, and is known as “Warmbeton” [2,3] or ultra-lightweight aggregates concrete (ULWAC) [4,5]. The prefix *ultra* used here is justified, as the developed concrete has

---

[1] At the time when this study was executed

[2] Current affiliation

superior properties compared to conventional lightweight concrete. It can be described as a very low density concrete (an oven-dry density of < 800 kg/m^3), mediocre compressive strength (about 10 MPa) and very low thermal conductivity (about 0.12 W/(m·K)). In contrast to foamed or cellular lightweight concrete, no entrained air in the form of synthetically aerated foam is used in ULWAC, but instead, coarse lightweight aggregate fractions of 0.25 – 8 mm (or even larger) are embedded in a conventional cement paste. An air entraining admixture can be also used to fine-tune the density. Therefore, in terms of the mix design, ULWAC is very similar to conventional concrete with the only significant difference that the aggregate fractions are very light. Particle size engineering is hence of importance in order to pack as many possible lightweight aggregates into a unit volume and minimize the void fraction that later needs to be filled with a normal-density paste. Commonly used lightweight aggregates such as expanded clays are not sufficiently lightweight as their apparent densities range between 0.8 – 1.8 kg/m^3. However, the introduction of expanded glass aggregates with apparent densities of 0.3 – 0.8 kg/m^3 gives new opportunities to notably further decrease concrete density. It has to be emphasized that the density reduction of is always accompanied with a decrease of concrete's mechanical properties such as the compressive strength. Thus, the key factor in the development of ULWAC is to maximize the mechanical properties and, at the same time, to minimize its density, i.e. improve the thermal insulation properties. In order to achieve such superior properties not only intensive lab work is required but also the translation from "lab-crete" to "real-crete" need special attention. This means a real challenge for ready-mixed concrete plants that would like to switch from a conventional concrete to ULWAC production, as a number of practical aspects vary notably from working with conventional aggregates. These include the handling of the aggregates (weighing, transporting, storage, etc.). Additionally, the ULWAC production process and its control vary from a conventional concrete – the operators can experience problems with workability, segregation, compaction, homogeneity, etc. One additional factor that requires attention is related to the very low thermal conductivity of lightweight aggregates, which results in the storage of heat released upon cement hydration. This can easily lead to very high temperatures reached in the hardening concrete and thus induce severe micro cracking and concrete spalling.

The aim of this article is to present the experiences with the laboratory development and subsequent field trials of an ultra-lightweight aggregates concrete, that could be used in the monolithic building concept. The materials development part includes the composition optimization as well as properties' assessment and heat release (temperature development) in concrete. The field trials are also described in this article and include the concrete production in a ready-mix concrete plant, casting a L-shape wall and evaluation of concrete properties. Finally, further challenges with the material are described and conclusions are drawn.

MATERIALS

Table 1. Properties of the used lightweight aggregates [5]

Size fraction	Bulk density [kg/m^3]	Specific density [kg/m^3]	Crushing resistance [MPa]
0.25-0.5 mm	300	540	> 2.9
0.5-1 mm	250	450	> 2.6
1-2 mm	220	350	> 2.4
2-4 mm	190	310	> 2.2
4-8 mm	170	300	> 2.0

The ultra-lightweight concretes analysed in this study are composed of expended glass lightweight aggregates (Liaver) of various size fractions, ranging from 0.25 mm up to 8 mm. The properties of the lightweight aggregates are summarized in Table 1. Various types of cements, supplied by ENCI HeidelbergCement Benelux, are used in this study, which include CEM I 42,5 N, CEM I 52,5 R, CEM II/A-LL 42,5 N and CEM III/C 32,5 N. Moreover, in several mixtures hard coal fly ash (Vliegasunie) is used as a supplementary cementitious material and limestone powder (Medenbach) as a fine filler. The characteristic of the cements, fly ash and limestone powder is presented in Table 2. A 3rd generation superplasticizer (Cugla LR 9400 or SIKA ViscoCrete 1020X) is applied to adjust concrete workability. The density of fresh concrete is adjusted either with an entraining agent (Cugla LBV-02 5%) or hollow polymeric microspheres admixture (MasterAir 150MHK, BASF).

Table 2. Chemical composition an specific density of the used binders and limestone powder.

	Composition [m%]						Specific density [g/cm^3]
Material	CaO	SiO_2	Al_2O_3	Fe_2O_3	SO_3	Na_2O_{eq}	
CEM I 42,5 N	67.20	21.40	4.40	0.30	3.10	0.48	3.10
CEM II/A-LL 42,5 N	67.50	18.50	4.00	0.30	2.74	0.42	3.10
CEM I 52,5 R	67.00	21.10	4.40	0.30	3.50	0.48	3.10
CEM III/C 32,5 N	44.30	31.20	9.60	0.60	3.60	0.60	3.00
Fly ash	2.60	60.40	24.40	7.60	0.30	0.60	2.33
Limestone powder	89.56	4.36	1.00	1.60	-	0.21	2.71

CONCRETE COMPOSITION DESIGN CONCEPT

The particle packing optimization helps to increase the packing density of all the solid ingredients in concrete. On the one hand, this optimization is especially important from the point of view of concrete's mechanical properties, as a minimized void fraction improves the strength. On the other hand, an increased void fraction is usually required in lightweight concretes to reduce their densities. Due to the latter, the particle packing models are usually not being used for the mix design of lightweight concrete as a high void fraction in such concretes is normally desired. Although this can be considered counter-intuitive, the approach of optimizing the ultra-lightweight concrete composition by applying the geometrical packing model can be successfully used, as demonstrated in [5]. In this approach a wide size range of lightweight aggregates (LWA) particles is used, so that a higher packing density can be obtained, increasing the mechanical properties of the concrete. At the same time, the densely packed LWA can still contribute to a low density and low thermal conductivity of the produced concrete, which results from their own very low densities.

The conceptual design and performance of ultra-lightweight concrete has been described in [5]. An algorithm based on the modified Andreasen & Andersen geometrical particle packing model [6] is employed for the mix design. This method has been already used to develop many different types of concrete, including SCC [7], zero-slump [8], or high-performance [9]. The modified Andreasen & Andersen model reads as follows:

$$P(D) = \frac{D^q - D_{\min}^q}{D_{\max}^q - D_{\min}^q} \forall D \in \left[D_{\min}, D_{\max}\right] \tag{1}$$

where: where $P(D)$ is a fraction of the particles being smaller than size D, D is the particle size, D_{max} and D_{min} represent respectively the largest and smallest particle size in the mix and q is the distribution modulus. In the process of concrete composition optimization, the deviation of the actual mixture grading curve from the target mixture grading curve (determined from Eq. 1) is minimized, by adjusting the proportions between the individual solid ingredients.

The ultra-lightweight concrete following this concept was developed in a laboratory scale, as described in [5]. Despite the outstanding properties of this concrete, such as an oven-dry density of about 650 kg/m^3, 28-days compressive strength of 10 N/mm^2 and thermal conductivity of 0.12 W/(m·K), the initial real scale experiments unveiled challenges with the heat development in concrete. It turned out that the monolithic test wall cast with ULWAC (based on Portland cement) developed very high temperatures during the first day after casting. The temperature within the massive concrete element significantly exceeded 100 °C, which was reflected by excessive steaming and severe cracking of the element. This confirmed that for a concrete prepared with highly insulating aggregates, a careful selection of binder type and content is of a great importance, as this determines the potential risk of overheating. Therefore, the next section focuses on further optimization of the ULWAC composition, taking into the account not only the mechanical and physicochemical properties but also the heat release upon the hydration of cements.

CONCRETE TEMPERATURE IN SEMI- AND FULLY-ADIABATIC MEASUREMENTS

In order to analyse the effect of different cement types and dosages on the temperature increase in concrete, the semi- and fully-adiabatic temperature measurements were performed on several concrete compositions. The fully-adiabatic test set up comprised of a tank filled with water, in which a sealed metal container was immersed. A polystyrene mold for fresh concrete (15 x 15 x 15 cm^3) was placed inside this container. An isolated thermocouple, embedded in the concrete mold, was connected to the adiabatic set-up steering unit, so that the temperature of the water jacket surrounding the metal container was steered to be equal to the concrete temperature. In this way, no heat released upon the cement hydration is lost in the system and the measurement is fully-adiabatic. The semi-adiabatic temperature measurement was performed by mounting a thermocouple in the middle of a polystyrene mold (15 x 15 x 15 cm^3), filled with fresh concrete. The cube was completely covered with polystyrene (wall thickness of 4 cm) and then stored at a room temperature (20 °C). For some mixtures tested within this study the semi-adiabatic temperature measurement is performed also in a larger scale, i.e. in a 40 x 40 x 40 cm^3 wooden mold (64 l), insulated from the sides and the top with a thick mineral wool fiber panels. This was done to closer simulate the construction side conditions, where the bulk of concrete is insulated by the formwork. All the variants of semi- and fully- adiabatic temperature measurements performed in this study are shown in Fig. 1.

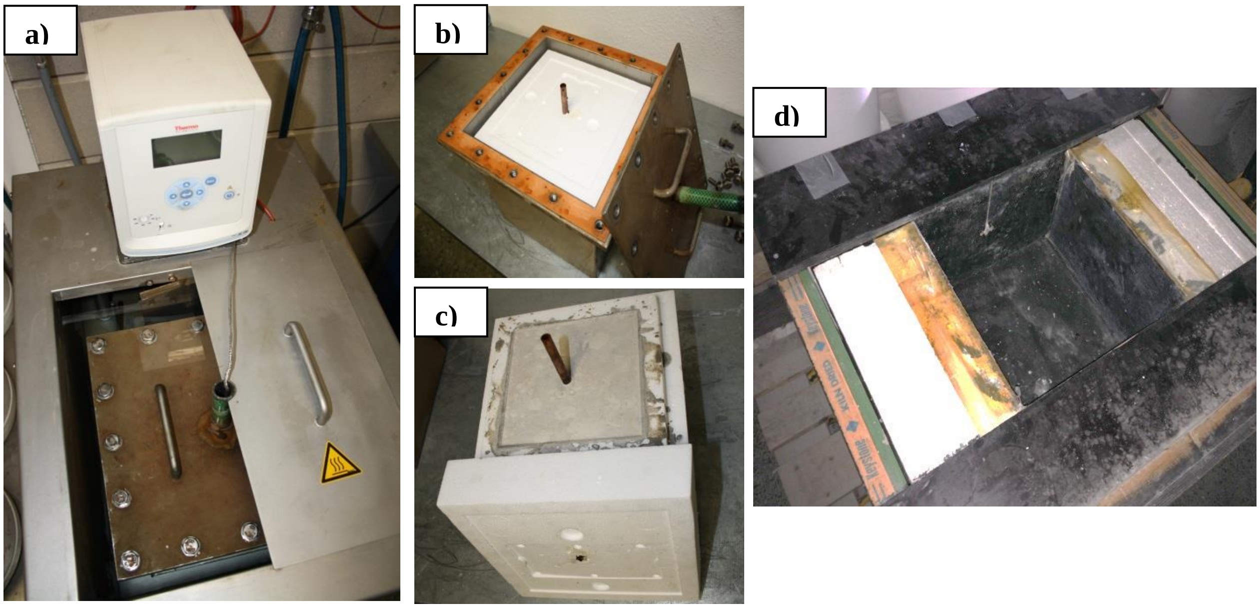

Figure 1. a) fully-adiabatic test set-up showing the water temperature steering unit and the metal container in water jacket, b) inside of the metal container embedded within the fully-adiabatic set-up, with the polystyrene mold filled with concrete, c) opened polystyrene mold (15 x 15 x 15 cm^3) used in the semi-adiabatic measurement and d) opened wooden mold (40 x 40 x 40 cm^3) used in the semi-adiabatic measurement.

Several concrete recipes were prepared in the laboratory for the temperature development measurements. The initial recipe was based on the previous studies [4,5] and then different cement types and contents were investigated, focusing on temperature development in the samples at different conditions. The investigated concrete compositions are summarized in Table 3. It can be seen that four types of cements were used and that the cement content varied, to analyse their influence on the temperature development.

Table 3. Concrete compositions investigated in the semi- and fully-adiabatic temperature measurements

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
Material	[kg/m^3]				
CEM I 42,5 N	500	-	-	-	-
CEM II/A-LL 42,5 N	-	500	400	-	-
CEM I 52,5 R	-	-	-	337	-
CEM III/C 32,5 N	-	-	-	-	500
Limestone powder	-	-	-	163	-
LWA 0.25-8 mm	155	155	160	155	155
Water	189	189	205	189	189
SP	1.20	1.20	1.20	1.20	1.20
Air entrainer	0.30	0.30	0.32	0.30	0.30

The fully- and semi-adiabatic temperature measurements were performed on small cubes (15 x 15 x 15 cm^3), on all five compositions shown in Table 3. Additionally, one semi-adiabatic measurement was performed on Mix 1 using a large cube (40 x 40 x 40 cm^3). The measurement results for the semi-adiabatic tests are shown in Fig. 2a and for the fully-adiabatic tests in Fig. 2b.

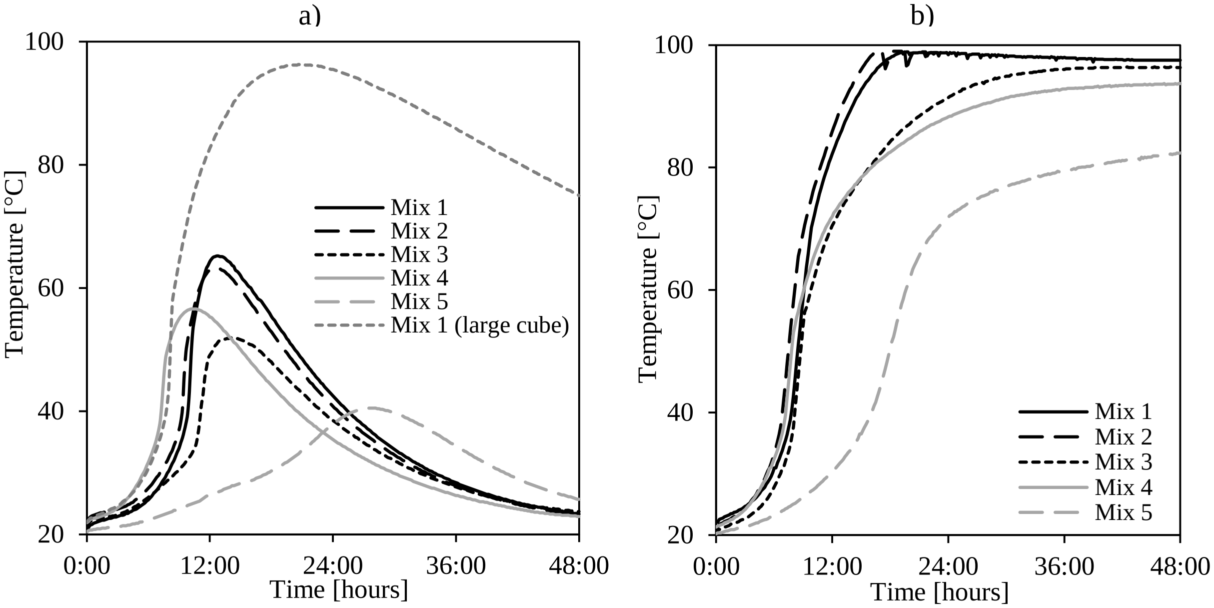

Figure 2. Test results for a) semi-adiabatic and b) fully-adiabatic temperature measurements in ultra-lightweight concrete.

It can be observed in Fig. 2 that both the cement type and content have a very strong influence on the temperature development as well as the maximum temperature reached in the concrete. The concretes with 500 kg/m^3 of cement (Mixes 1 and 2) developed the highest temperatures in both semi- and fully-adiabatic measurements. At this cement dosage, the Portland cement (Mix 1) and Portland limestone cement (Mix 2) generated the highest hydration heat, which lead to the maximum temperature of about 62 °C in the semi-adiabatic conditions and almost 100 °C in the fully-adiabatic conditions, both measured after about 12 hours from casting. The fluctuating temperature measured in the adiabatic conditions at around 100 °C (Fig. 2b), originated from the adiabatic test set-up thermal overload protection that shuts the heating system down for a few minutes as the water boiling point had been approached. In order to simulate a more massive concrete element, also a large cube was tested here in semi-adiabatic condition for Mix 1. As can be seen in Fig. 2a, the maximum temperature reached in the semi-adiabatic measurements in the large cube is far greater compared to the small cube, reaching about 96 °C after 21 hours from casting. Hence, it can be concluded that the large cube measurement reflects much closer on the real concrete construction, and explains well the previous field trials issues. Moreover, it can be seen here that the temperature reached within the core of a bulky concrete element is developed much closer to the fully-adiabatic rather than semi-adiabatic conditions.

For Mix 3, which contained 100 kg/m^3 cement less than Mix 2, the maximum temperature reached in both semi- and fully-adiabatic conditions is about 10 °C lower than for Mix 2. Although this difference is already significant, the reduction of the CEM II/A-LL content to 400 kg/m^3 does not seem sufficient to reduce the overheating risk of concrete prepared with this cement type. Even for Mix 4, in which only 337 kg/m^3 of Portland cement was used, the temperatures reached are very high (about 55 °C for semi-adiabatic and 90 °C for adiabatic measurements). Mix 5, contains of 500 kg/m^3 CEM III/C 32,5 N, which is composed of 87% ground granulated blastfurnace slag (GGBS) and only 11% cement clinker. It can be observed in Fig. 2 that Mix 5 developed much lower temperatures compared to all the other tested concretes. Moreover, the temperature rose at a much slower rate compared to other concretes, and this is caused by a slower hydration of GGBS compared to cement clinker. In the fully-adiabatic conditions a maximum temperature of about 80 °C was reached for Mix 5. Therefore, it was concluded that the CEM III/C 32,5 N is a good choice for the ULWAC production on a larger scale, as it can be expected that a maximum temperature reached for this cement would be substantially lower than for other cement types.

CONCRETE COMPOSITION FINE-TUNING

Table 4. Composition of ultra-lightweight concretes – recipe optimization for the field trials

	Mix 6	Mix 7	Mix 8	Mix 9
Material	[kg/m^3]			
CEM III/C 32,5 N	350	-	-	-
CEM I 42,5 N	-	350	350	350
Limestone powder	-	-	100	-
Fly ash	100	100	-	100
LWA 0.25-8 mm	232	232	232	232
Water	147	147	147	147
SP	2.0	2.2	1.9	3.3
Air entrainer	7.7	7.7	1.8	1.0

In order to fine-tune the concrete composition for the field trials, four mixtures were further prepared in the laboratory and their properties were analysed. These included fresh concrete (workability) as well as mechanical and physicochemical properties such as the compressive strength, dry density and thermal conductivity. The tests were done on a mixture based on CEM I 42,5 N cement, for which the concrete properties were earlier determined, as well as on CEM III/C 32,5 N cement, which was recommended from the heat release (temperature reached) investigations, presented in the previous section. A fixed cement content of 350 kg/m^3 was used here for all four recipes. This cement content was established based on the semi- and fully-adiabatic temperature measurements shown earlier, as the temperatures reached in concretes containing 400-500 kg/m^3 of cement were considered too high. To compensate for the lower cement content compared to the mixtures developed in the previous studies, fly ash and limestone powder were also used here to increase the binder/fines volume. It is assumed that the influence of fly ash on the maximum temperature is minimal, as the hydration heat of pozzolanic reaction of fly ash is about 4 times lower compared to the cement clinker hydration. An air entraining admixture was used to increase the air content (further reduced the density) and a superplasticizer to improve workability. The compositions of the investigated mixtures are presented in Table 4 and the obtained results are summarized in Table 5.

Table 5. Concrete properties

Property	Mix 6	Mix 7	Mix 8	Mix 9
Slump [mm]	247 (class S5)	205 (S4)	150 (S3)	23 (S1)
Flow [mm]	500 (class F4)	410 (F2)	370 (F2)	270 (F1)
Dry density [kg/m^3]	760	703	739	815
Thermal conductivity [W/(m·K)]	0.14	0.15	0.19	0.20
Compressive strength [MPa]				
1 day	0.6	3.5	6.2	6.0
7 days	10.3	8.0	9.3	10.4
28 days	10.2	7.9	8.9	12.0

As can be found in Table 4, the compositions of all the four recipes were similar, varying only in the binder/fines composition. Workability of the fresh concrete was adjusted based on visual observations, by adding the superplasticizer as well as the air entraining agent, for which the fresh concrete density was measured by collecting samples during the mixing. Here, a fresh concrete density of 750-800 kg/m^3 was the target. It has to be emphasized that the ultra-lightweight concrete of high consistency classes is very susceptible to segregation, which is due to the very low LWA density (as low as 300 kg/m^3). The entrained air, besides reducing the concrete density, has a very positive effect on improving the segregation resistance and fresh concrete stability. In order to reach the target fresh concrete density, a high dosage of air entrainer was required for Mix 6, as can be noted in Table 4. This is due to the known impact of fly ash on the air entraining agent, which tends to adsorb on the unburned carbon present in the fly ash, and in turn limits its efficiency. In Mix 7, the same addition of the air entrainer as in Mix 6 was used, however the obtained density was significantly lower. No fly ash was used in Mix 8 so a much lower air entrainer dosage was required to reach the target density. As the density of Mix 7 was considered too low, another recipe was tested (Mix 9), in which a lower air entrainer dosage was used.

As can be observed in Table 5, the recipe based on CEM III/C 32,5 N cement, has developed very good properties, including a low thermal conductivity (0.14 W/(m·K)) and a good compressive strength (over 10 MPa already after 7 days). Due to the cement type, the early strength of Mix 6 was low, reaching only 0.6 MPa after 24 hours of curing in the laboratory environment (20 °C). Nevertheless, it is expected that the early strength increase in a more massive concrete element would be much faster, as it would be accelerated by the elevated temperatures developed in the concrete.

Based on these results, Mix 6 was prepared in the laboratory in a larger volume (125 l) for additional tests, which included the elastic modulus, as well as semi- and fully-adiabatic temperature measurements and thermal conductivity. Due to the changes in the mixing procedure (mixer type, mixing intensity and duration, concrete volume), the air entrainer dosage was strongly reduced compared to the value given in Table 4 (from 7.7 kg/m^3 to 2.0 kg/m^3). Although the dosage was strongly reduced, the obtained mixture had a density of 684 kg/m^3, which was much lower compared to Mix 6. This gives an evidence that the dosage and action of the air entraining agent is in practice very difficult to control, which is most likely caused by interactions with the fly ash. Despite the low density, a number of samples were cast for further tests. The measured compressive strength of the mixture amounted to 0.3, 6.3 and 7.0 MPa after 1, 7 and 28 days respectively. These values are lower than shown in Table 5 for Mix 6, and can be explained by the low density. All the concrete compressive strengths measured in this study at 28 days are plotted in Fig. 3 against their dry densities. The obtained trend is very clear and shows directly the target density of concrete for a given compressive strength. It can be found in this figure that the compressive strength of 10 MPa corresponds to a dry density of 760 kg/m^3. The thermal conductivity values determined on concrete cubes was slightly lower than the value given in Table 5, and reached 0.135 W/(m·K), which can again be explained by the lower density. The elastic modulus, determined on ϕ15 cm x 30 cm height cylinders, amounted to 3.2 and 3.4 GPa after 7 and 28 days, respectively. These values are obviously lower than for conventional types of concrete, and are related to high porosity of the cement paste (entrained air) and lightweight aggregates as well as their low mechanical resistance. The fully- and semi-adiabatic temperature measurement were performed on both small and large insulated cubes, as described earlier and shown in Fig. 1. In the large cube, which can simulate the real conditions closer, three thermocouples were placed: one in the core of the cube, one at the side wall and one in between the two other. In this way, also the temperature gradient within the element could be registered. The measured temperatures are presented in Fig. 4.

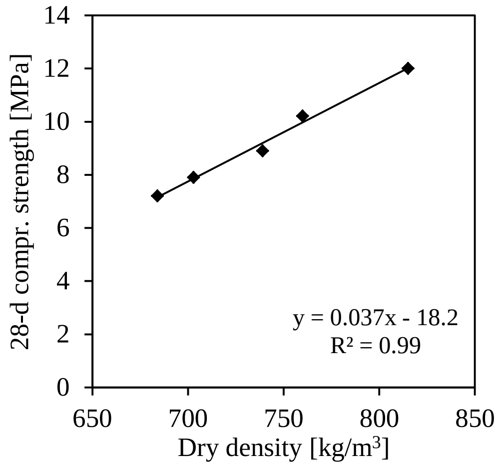

Figure 3. Compressive strength of concrete vs. the dry density

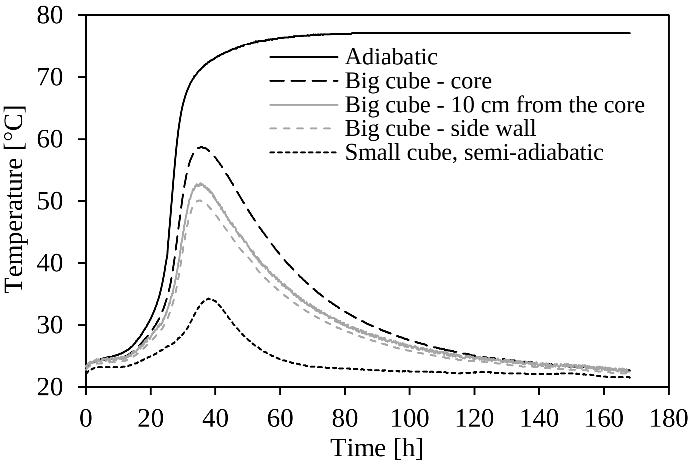

Figure 4. Temperature development measured in semi- and fully-adiabatic conditions for the optimized mix

It can be observed in Fig. 4 that the concrete temperature in the adiabatic conditions reaches about 42 °C after the first 24 hours, then 72 °C after 48 hours and 75 °C after 72 hours. The rate of temperature increase observed here is much slower compared to the results shown in Fig. 2, which already suggests that the hydration heat can be better released out of the optimized concrete and thus limit the maximum temperature reached in the real conditions. This is confirmed in the semi-adiabatic measurements performed on the large cube, as can be seen in Fig. 4. The maximum temperature reached in the core of the cube reached about 59 °C and about 50 °C at the external wall. Such temperatures as well as relatively small temperature differences within the element should on the one hand not provide the risk of element's overheating, and on the other hand, accelerate the early strength development for the otherwise slow system. Therefore, the laboratory research phase was ended here, with Mix 6 (Table 4) suggested for the field trial tests. It was also concluded that the conventional air entrainer admixture may deliver some issues, as it was found that it is difficult to control its effects due to the interactions with the fly ash.

FIELD TRIALS WITH THE ULTRA-LIGHTWEIGHT CONCRETE

As concluded from the laboratory research phase described before, the concrete recipe Mix 6 (Table 4) was selected for the field trials. However, in view of the difficulties with the air entraining agent control, it was decided to replace this conventional admixture with encapsulated air microspheres (MasterAir 150MHK, BASF). In this way, the stable air microspheres were introduced into the concrete, which are much easier to control and deliver a more predictable system. The field trials with the ultra-lightweight concrete consisted of mixing the concrete in a ready-mix concrete plant (Mebin, Tilburg, the Netherlands), transporting the concrete over a short distance with a concrete mixing truck and casting an L-shape test wall. The test wall had the dimension of 3.75 m x 3.75 m side lengths, 2.40 m height and 0.5 m thickness, with a horizontal window opening. Fig. 5a shows the test wall formwork. The concrete was mixed using a twin-shaft mixer in charges of 2 m^3 each. The total volume of the test wall amounted to about 8 m^3. After transporting, a concrete skip container was filled, transported with a crane over the formwork and poured inside in small charges. The process was repeated until the entire formwork was filled, while during pouring, the concrete was compacted with needle vibrators. Moreover, a vibrating motor was installed on the side of the formwork to intensify the vibration energy. In Fig. 5 several pictures from the field trials are presented, showing the concrete production process as well as the formwork and the ultra-lightweight concrete test wall.

Figure 5. Ultra-lightweight concrete test wall production: a) wall formwork, b) and c) concrete transportation and casting, d) compaction with a needle vibrator and e) demolded concrete wall with a window opening. Photo e) by Dolph Cantrijn.

Several technical difficulties occurred during the concrete production process. The main issue was related to mix segregation, which was significant especially in the first concrete batch. After that batch, the dosage of water and superplasticizer were slightly reduced. Nevertheless, obtaining the desired workability and mixture stability in the practical conditions were found challenging and this requires further attention in the future. It was concluded that the replacement of a conventional air entraining admixture with the air microspheres resulted in a mixture with a higher segregation tendency, as it is known that air entrainers have a very positive influence on mixture stability. Another experienced issue was related to the compaction – due to the low concrete density, the vibration energy could not be well dispersed in the concrete, resulting in a limited compaction efficiency, especially by using needle vibrators. The poor compaction resulted in the end in rather poor wall surface quality.

Several concrete cubes were cast from different concrete batches for the compressive strength tests. The measured average strengths amounted to 7.1 MPa after 7 days and 8.5 MPa after 28 days, which was lower than found earlier in the laboratory. This can be related to the segregation and stability issues.

The temperature reached in the test wall was recorded by BAS Research and Technology (the Netherlands), at several spots within the test wall, over a period of several days. With an outside temperature of about 12 °C during the first 24 hours after casting, the maximum temperature in the core of the wall reached about 32 °C and about 19 °C at the external side. During the following 24 hours, the outside temperature varied between 16 °C (daytime) to 8 °C (at night). In that time, the maximum temperature in the concrete was reached. A temperature of about 55 °C was measured in the core at about 35 hours from casting, whereas at the same time, temperatures of 32 - 42 °C were reached at the external side. From the 35th hour after casting on, the temperatures in the wall began to drop. Hence, these measurements confirmed the laboratory research on the binder type and dosage selection, showing that the used CEM III/C 32,5 N cement performed very well in terms of the hydration heat release and reached maximum temperature.

CONCLUSIONS

This study presents the laboratory development of a novel ultra-lightweight concrete followed by field trials. The presented results demonstrate that a material of outstanding properties can be produced. These properties include a moderate compressive strength (10 MPa) accompanied with an ultra-low density and very good thermal insulation properties (thermal conductivity of 0.14 W/(m·K)). Additionally, it has been shown that the selection of binder type and content plays a crucial role, as the cement type and dosage determine the risk of overheating and thermally-induced damage of larger concrete elements. It has been demonstrated that a concrete recipe based on CEM III/C 32,5 N cement can reach an outstanding performance, similar to the performance of the initial concrete recipes developed in previous studies that were mainly based on Portland cements. The temperatures measured in the semi- and fully-adiabatic conditions show that there is no excessive overheating. Instead, the temperatures reaching up to about 59 °C in the laboratory large volume semi-adiabatic measurements and up to 55 °C in the test wall, secure a faster reaction of otherwise very slowly reacting CEM III/C and fly ash system. The present study also revealed some practical issues with the material. These include the compaction efficiency as well as the difficulty with controlling the air entraining agent efficiency, which interferes strongly with the fly ash. It was found that when the conventional air entrainer is replaced with hollow polymeric microspheres, the stability and resistance against segregation are decreased. Despite these issues, it can be concluded that the ultra-lightweight concrete can soon be introduced to the concrete market, offering new possibilities to the architects, designers and structural engineers.

REFERENCES

[1] NEN-EN 206-1: Concrete - Part 1: Specification, performance, production and conformity (2001).

[2] T.A.M. Salet, Warmbeton - Constructieve materialeigenschappen (in Dutch). Report no BWK 2015/1566245, Eindhoven University of Technology, the Netherlands (2015).

[3] J.H. Köhne, Warmbeton – van laboratorium naar uitvoering (in Dutch). Press release (2014).

[4] Q. Yu, P. Spiesz, H.J.H. Brouwers, Ultra-lightweight concrete – Final report of project MA.12265, Eindhoven University of Technology, the Netherlands (2012).

[5] Q. Yu, P. Spiesz, H.J.H. Brouwers, Ultra-lightweight concrete: Conceptual design and performance evaluation. Cement and Concrete Composites 61 (2015), pp. 18-28.

[6] Hüsken G, Brouwers H.J.H. A new mix design concept for earth-moist concrete: A theoretical and experimental study. Cement and Concrete Research 38 (2008), pp. 1246-1259.

[7] Hunger M. An Integral Design Concept for Ecological Self-Compacting Concrete. PhD thesis. Eindhoven University of Technology, the Netherlands (2010).

[8] Hüsken G. A Multifunctional Design Approach for Sustainable Concrete with Application to Concrete Mass Products. PhD thesis. Eindhoven University of Technology, the Netherlands (2010).

[9] R. Yu, P. Spiesz, H.J.H. Brouwers, Mix design and properties assessment of Ultra-High Performance Fibre Reinforced Concrete (UHPFRC). Cement and Concrete Research 56 (2014), pp. 29-39.