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Development of a cement-based lightweight composite

Abstract

This article addresses a mix design methodology for the development of a cement-based lightweight composite. A lightweight material produced from recycled glass is used as the lightweight aggregates. The mix design is developed applying the packing theory using the modified Andreasen and Andersen model to obtain the optimal target grading curve of all the solids in the mixture.

The properties of the designed composites, including the flowability and relative viscosity in fresh state, and the porosity, strength and thermal properties in hardened state are investigated. The porosity of the developed composites is studied by both modeling and experiments. Results indicate that there is a certain amount of internal closed pores in the composites, which contributes positively to a better thermal insulation property. The combined study on both mechanical and thermal properties of the composites shows a good balance. The developed composites have a quite low thermal conductivity while still retaining sufficient strength.

Introduction

Lightweight aggregates concrete (LWAC) has its roots in the ancient period about 3000 years ago when volcanic materials were used as lightweight aggregates [1]. Because of its many advantages such as low density, good thermal insulation and good fire resistance, LWAC has been widely studied and applied as both structural and nonstructural material recently. However, so far there is still no systematic study on LWAC regarding mix design methodology. Furthermore, there are usually two objectives to the design of the LWAC, either to achieve as low thermal conductivity or as low density as possible or to achieve as strong mechanical properties as possible, but so far no studies have been reported, to obtain a LWAC with a low density while retaining sufficient mechanical properties.

This article addresses the development of a cement-based lightweight composite, aiming at a good balance between a good thermal property such as a low thermal conductivity and sufficient mechanical property. Furthermore, the newly developed composites are economically attractive because of the low amount of cement used and little cost-intensive admixtures added.

Mix design concept

The mixes of the CLC are designed using a mix design tool applying the packing theory, i.e. the particle size distribution (PSD) theory [2]. Applying the PSD theory, the particles can be better packed, which results in an improved hardened properties as well as an improved workability since more water is available to act as lubricant between the particles [2]. In this mix design method, the modified Andreasen and Andersen (A&A) curve acts as a target function for the subsequent granular optimization of the individual materials [3]. The proportions of the individual materials in the mix design are adjusted until an optimum fit between the composed mix and the target curve is reached using an optimization algorithm based on the Least Squares Method (LSM).

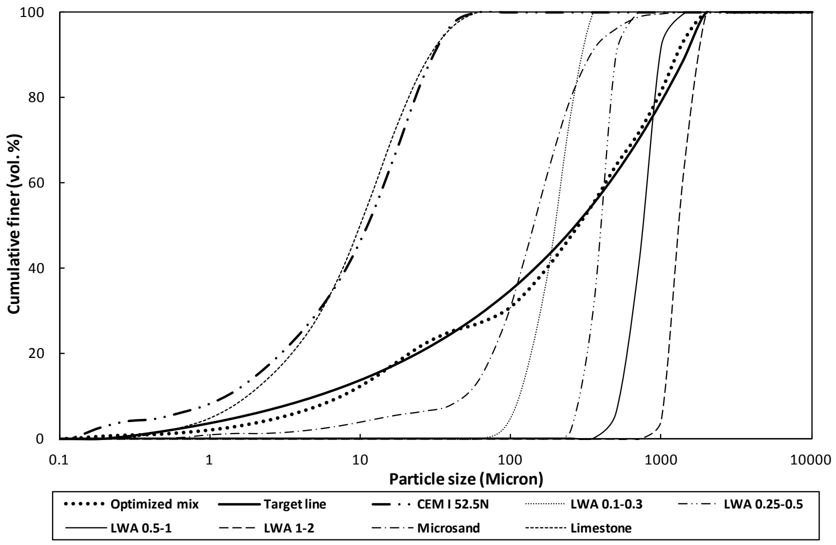

Fig. 1: PSDs of the used solids and the composed mix SCLC1 and target line.

Densities of lightweight concrete are strongly linked with its thermal properties. Neville [4] reported that there is an almost linear relation between the thermal conductivity and the density of lightweight concrete produced with different types of lightweight aggregates such as pumice, permite, vermiculite, cinders, expanded shale, and expanded slag. Loudon [5] also reported that, despite the effect of the type of the used lightweight aggregates, the thermal conductivity of lightweight concrete decreases when its density decreases. Therefore, here the effect of density on the investigated properties is taken into consideration. Two types of composites with different workability properties are developed here, which are self-compacting and conventionally vibrated, to investigate the influence of the water content and the used distribution modulus. As from [4, 6], the strength of concrete is related with the cement content in the matrix. Hence, the used cement content is set as a fixed, economically acceptable value just to minimize the effect of its dosage on the investigated targets.

Table 1: Dosages of the developed mixes.

Material	**SCLC1 (kg/m^3)**	**SCLC2 (kg/m^3)**	**VCLC (kg/m^3)**
CEM I 52.5 N	425.3	423.5	419.7
Limestone powder	111.9	259.6	0
Sand 0-4	0.0	0	407.0
Sand 0-1	0.0	95.6	0
Microsand	381.5	424.6	306.0
LWA 0.1-0.3	56.0	68.3	0
LWA 0.25-0.5	44.8	0	0

LWA 0.5-1.0	56.0	54.9	0
LWA 1.0-2.0	44.8	39.4	63.6
LWA 2.0-4.0	0.0	0	71.6
Water	250.9	230.3	159.4
Superplasticizer (% mass of cement)	1.0%	1.0%	0.8%
Water/cement ratio	0.59	0.54	0.38
Water/powder ratio	0.35	0.26	0.29
Distribution modulus	0.32	0.25	0.35

Therefore, applying the optimization algorithm, a preliminary design of the solid materials of three mixes is derived here. The designed grading line as well as the PSD of the used materials is shown in Fig. 1, using mix SCLC1 as an example, with the absolute amount of all the materials ready to be varied by adjusting the water content and superplasticizer (SP) dosage in order to achieve the desired flowability. The detailed fresh behavior analysis is presented in Yu et al. [7]. And the final mix design of the three abovementioned mixes are presented in Table 1.

The new composite in hardened state

The CLC is composed of lightweight aggregates, cement paste, sand, inert filler, and air. In the matrix, the porosity originates from both the internal porosity of LWA and from the porosity of the cement paste. Chandra and Berntsson [1] reported that the exchange of air and water during the water absorption test resulted in a rim of air bubbles in the interfacial transition zone (ITZ) of the lightweight aggregates concrete. However, this does not seem to occur here (see Fig. 2). So here the porosity of the interfacial transitional zone in the composite is assumed to be very small and therefore not considered in the calculation. A detailed calculation is presented in Yu et al. [7].

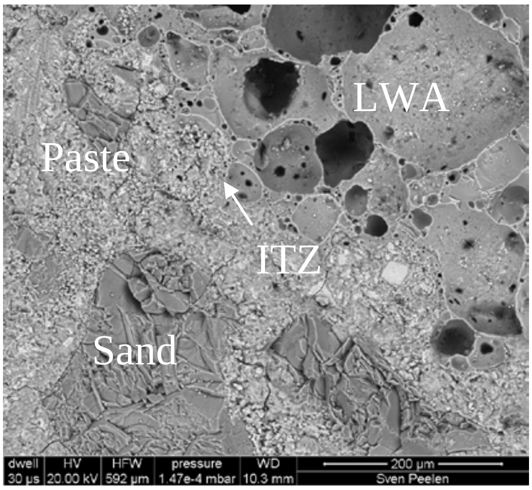

Fig. 2: SEM picture of the transition zone of VCLC.

The vacuum-saturation technique is applied to saturate the accessible pores with water, as this technique is referred to as the most efficient saturation method [8]. The test is carried out on 3 samples for each mix, following the standards [9] and [10]. A detailed description regarding the calculation is presented in Yu et al. [7].

Table 2: Results of the theoretical and measured water permeable porosity.

Mix	Porosity (%)	
	Theoretical	**Measured**
SCLC1	47.50	34.31
SCLC2	38.40	34.97
VCLC	42.01	30.65

The results are listed in Table 2. The measured water permeable porosities are similar for the two self-compacting composites (SCLC1 and SCLC2), 34.31% and 34.97% in average for SCLC1 and SCLC2 respectively; while for the VCLC it is slightly lower, 30.65% in average. Nevertheless, all the measured values of the permeable porosities are smaller than the calculated corresponding values. This indicates that some of the pores in the used LWA are closed and not accessible to water transport. The calculated total porosity of SCLC1 is larger than SCLC2 but their measured water permeable porosities are similar. It is shown that both SCLC1 and SCLC2 have very similar porosities contributed by the paste due to the similar water/cement ratios used in these two mixes. As can be seen from Table 1, 82.90 dm^3 LWA with the size of 0.25-0.5 mm are used in mix SCLC1 while zero in mix SCLC2, besides a similar amount of the used LWA in the fraction of 0.1-0.3 mm, 0.5-1 mm, and 1-2 mm in both SCLC, which results in the porosity difference of these two SCLC. This indicates that the used LWA with the size of 0.25-0.5 mm is quite water impermeable, and the pores inside the particles are mostly closed pores, and this is in line with the water absorption test results [3]. Another possible reason is attributed to the larger amount of the LWA 0.1-0.3 used in mix SCLC2. It can be seen that the particle sizes of fraction LWA 0.1-0.3 are very small (40% of the particles are smaller than 125 μm, as can be seen from Fig.1), which creates more chances to be interconnected through the permeable paste.

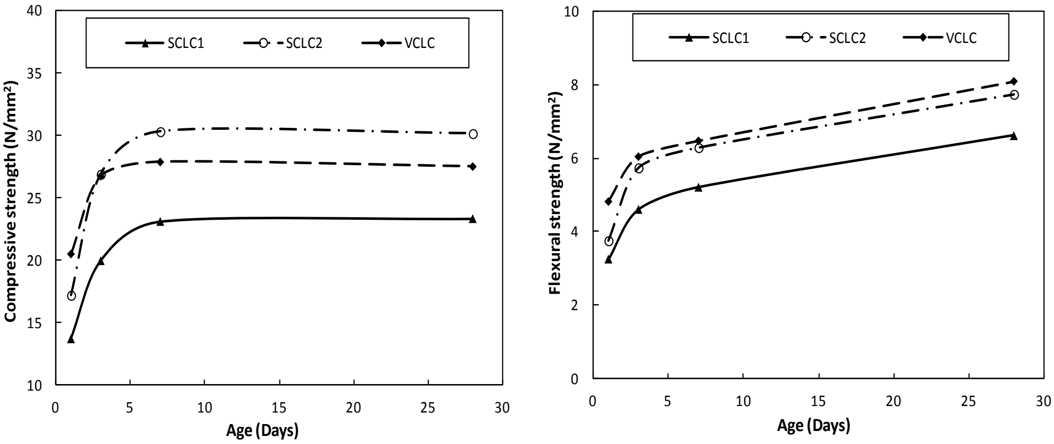

Fig. 3: Strength of the three lightweight aggregates composites (Left: compressive strength; Right: flexural strength).

The measured water permeable porosity of VCLC is the smallest, which can also be explained by the mix design. As shown in Table 1, only fractions of LWA with the large size of 1-2 mm and 2-4 mm are used in the mix design of VCLC. Therefore the interconnection possibilities between particles are reduced to some extent, and besides the water transport route is reduced also due to the small capillary porosity of the paste.

Fig. 3 shows the compressive and flexural strength development of the lightweight aggregates composites as a function of the curing age. All these three mixes have a similar feature of a quite fast early stage strength development. The compressive strength of the mixes SCLC1 and SCLC2 after 24 hours curing reaches 58.8% and 57.1% of their compressive strength at 28 days, respectively, while the compressive strength of VCLC reaches even 74.5% of its value at 28 days after 24 hours curing. This probably can be explained by the used lightweight aggregates. The porous structure of the used LWA allows absorption of water into their pores, so then the absorbed water can be used later for "internal curing" during the hardening process [1].

As discussed in the previous section, for lightweight concrete or mortars, the compressive strength is strongly linked with density, i.e. the compressive strength decreases with the decrease of the density. This relation is usually investigated using the so called structural efficiency, which is calculated from the ratio of the compressive strength at 28 days to the density, as listed in Table 3. It can be clearly seen that, although the compressive strength and densities of the three mixes are different from each other, the calculated structural efficiencies are very close to each other. This may be explained by the used cement content in the lightweight composites. As presented in Table 1, the cement content in the present study is kept at the same low level, around 420 kg/m^3, for all the three mixes.

Table 3: Compressive strength, density and calculated structural efficiency of the lightweight aggregates composites.

Mix	**Compressive strength (N/mm^2)**	**Density (kg/m^3)**	**Structural efficiency (N·m/kg)**
SCLC1	23.3	1280	18200
SCLC2	30.2	1460	20700
VCLC	27.5	1490	18500

Thermal behavior is a key factor in the development and application of lightweight concrete. Thermal behavior of lightweight aggregates concrete is related to its thermal conductivity and its density, which in turn is influenced by its pore structure, i.e. the air-void system, aggregates and the matrix [1]. The thermal conductivities of the three developed mixes are measured using the heat transfer analyzer (ISOMET Model 2104), as shown in Table 4. Here the samples are first dried in an oven at 105 °C until the mass becomes constant, and then cooled down to room temperature for executing the thermal conductivity measurement.

It can be seen that, with the increase of the density, the thermal conductivity of the two SCLC increases. ACI committee 213R-03 [11] and Topcu and Uygunoglu [12] reported that the relation between the thermal conductivity and density follows an exponential relationship, which reads as:

$$\lambda = a_0 \times e^{b_0 \times \rho} \quad (1)$$

where λ is the thermal conductivity (W/(m·K)), ρ is the density (kg/m^3), and a_0 and b_0 are parameters. ACI committee 213R-03 [11] proposed the values of 0.072 and 0.00125 for a_0 and b_0 respectively.

Table 4: Thermo-physical properties of the developed composites.

Mix	**Density (kg/m^3)**	**Thermal conductivity (W/(m·K))**
SCLC1	1280	0.485
SCLC2	1460	0.738
VCLC	1490	0.847
Reference*	2300	1.700

Using the experimental values from Table 4 for SCLC1, SCLC2 and reference self-compacting concrete, the values of a_0 and b_0 can be obtained employing the Solver function from Microsoft Excel$^{@}$, yielding a_0 and b_0 of 0.11 and 0.0012 respectively, with the coefficient of determination (R^2) of 0.99. It can be seen that the value of a_0 is larger than the recommended value from [11], but it is in line with the value reported by [12], who derived a_0 (0.1242) and b_0 (0.0011) also based on SCC lightweight concrete.

However, as already presented in [13], the thermal conductivity of a material is related not only to the porosity or density of the matrix, but also to the thermal conductivity and particle shape of all the materials in the matrix. Therefore, the proposed expression (Equation (1)) can only be used to estimate the relation between density and thermal conductivity, which is also in line with [1] and [5] who reported a significant influence of the LWA type on the thermal conductivity.

This is also confirmed by the thermal conductivity value of the VCLC, as listed in Table 4. With a similar density as SCLC2, the thermal conductivity of VCLC is 14.8% larger than that of SCLC2. This indicates that the expression (Equation (1)) is not suitable to compare concretes/mortars of different types; here the type means the design method. The larger thermal conductivity of the VCLC can be explained by the used mix design. Although the total porosity of SCLC2 and VCLC are comparable (See Table 2), it is obvious that the paste porosity of VCLC is much smaller, which is no surprise due to the low w_0/c_0 used in the mix of VCLC (see Table 1). This results in a much faster transport route for heat. Despite the fact that the internal porosity of LWA in VCLC is larger than that of SCLC2, the LWA in SCLC2 are better distributed because they are smaller, which contributes finally to the lower heat transfer rate.

Discussion

In the above sections, three mixes are developed and investigated. In order to study the effect of the density on strength and thermal conductivity, two self-compacting mixes (SCLC1 and SCLC2) and one vibrated mix (VCLC) are designed. Two mixes with self-compacting properties are designed applying different distribution moduli in order to study their influences.

The smaller distribution modulus applied in design of mix SCLC2 compared to that in SCLC1 results in a smaller porosity (See Table 2) due to the larger amount of inert fines used in that mix (See Table 1). This smaller porosity should theoretically lead to a larger strength, which is confirmed by the experimental results, as shown in Fig. 3, and to a larger thermal conductivity which is also confirmed by the value listed in Table 3. Therefore, the selection of a suitable q should be taken into consideration in order to obtain an optimal balance between strength and thermal conductivity.

SCLC2 and VCLC, designed following different distribution moduli and using different materials, have comparable densities. Surprisingly, these two composites have quite different thermal conductivities, which are in conflict with the well accepted opinion, i.e. the direct relation between the thermal conductivity and density (See Equation (1)). However, this finding confirms the analysis presented in [13]. The difference in the measured thermal conductivity between these two mixes can actually be explained from the permeable porosity (See Table 2), i.e. the small permeable porosity of VCLC leads to a larger thermal conductivity, and also by the distribution of the lightweight aggregate particles in the matrix.

Conclusions

This article addresses the development of a cement-based lightweight aggregates composite aiming at a good balance between a low thermal conductivity and good mechanical property. Based on the investigation presented above, the following conclusions are drawn:

- The results from the calculated porosity and the measured water-permeable porosity indicate that the used LWA have a certain amount of closed internal pores, which contributes a better thermal insulation of the developed composite;
- The developed composites have a very fast strength development, which is linked with the type of the applied LWA;
- The structural efficiency of lightweight composites are linearly related to their compressive strength, but no clear relations can be derived between the structural efficiency and the density;
- In the case of using same type of LWA, the thermal conductivity of cement-based lightweight composite is linked directly with its density;
- Selection of the finer LWA, which can be densely distributed in the matrix, leads to a lower thermal conductivity than selection of coarser LWA which are distributed with a lower density in the matrix.

Acknowledgements

The authors wish to express their gratitude the following sponsors: Bouwdienst Rijkswaterstaat, Graniet-Import Benelux, Kijlstra Betonmortel, Struyk Verwo, Attero, Enci, Provincie Overijssel, Rijkswaterstaat Directie Zeeland, A&G Maasvlakte, BTE, Alvon Bouwsystemen, V.d. Bosch Beton, Selor, Twee “R” Recycling, GMB, Schenk Concrete Consultancy, Intron, Geochem Research, Icopal, BN International, APP All Remove, Consensor, Eltomation, Knauf Gips, Hess ACC Systems, and Kronos (chronological order of joining).

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