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Reducing the carbon footprint of lightweight aggregate concrete

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Abstract

Lightweight aggregate concrete (LWAC) is a special concrete type with density of no more than 2200 kg/m^3. Lower densities than normal weight concrete (2400-2500 kg/m^3) are achieved using lightweight aggregates, which may originate from by-products of industrial manufacture such as fly ash, for example Lytag. Currently there is an increasing demand for LWAC for the construction of lightweight composite flooring systems, particularly in commercial buildings. Despite the well-recognized issues and challenges associated with the carbon dioxide (CO_2) emissions from cement production, LWAC still contains high quantities of Portland cement (Type I or CEM I) as well as high quantities of total cementitious materials content. This has been primarily utilized to attain a certain workability and pumpability, as well as to not compromise the strength development. As such, the carbon footprint of LWAC is generally higher than that of normal weight concrete, owing also to the carbon intensive lightweight aggregates. In this work, several alternative lightweight aggregate mixes were optimized to maximize Portland cement replacement and reduce the total cementitious materials content without compromising the strength, workability and pumpability of a standard, to Eurocode 2, LC 30/33. The developed mixes contained up to 60% of ground granulated blast-furnace slag, as well as limestone powder, which resulted in a reduced carbon footprint compared to the conventional LWAC mixes. It was possible to reduce the Portland cement content by approximately 40%, the total cementitious materials content by 22% and embodied carbon (life cycle stages A1-3) by 12% compared to the initial, conventional LWAC mixes.

Keywords

Lightweight aggregate concrete, carbon footprint, low carbon concrete, ground granulated blast-furnace slag

1. Introduction

Lightweight aggregate concrete (LWAC) is a special concrete type with density of no more than 2200 kg/m^3. Lower densities than normal weight concrete, which normally exhibits a density of 2400-2500 kg/m^3, are achieved using lightweight aggregates. These may originate from by-products of industrial manufacture, such as fly ash or from processing naturally forming materials, such as clays. While clays can be sintered to form expanded clay aggregate, the final aggregate product itself does not exhibit particularly high compressive strength, hence, is considered suitable for low strength concrete applications, e.g., < 20 MPa [1,2]. On the other hand, lightweight aggregate products from sintering fly ash, such that of Lytag [3] shown in Figure 1, exhibit higher strength and are, therefore, considered more appropriate for structural concrete applications requiring medium strength concretes.

Figure 1: *Lightweight coarse aggregate based on sintered fly ash (Lytag) [3]*

Lytag-based lightweight aggregate concrete (LWAC) has been relatively extensively used in the UK, and particularly London, in the construction of composite floors for high-rise buildings. In general, LWAC can offer several benefits in building construction, such as the reduction of permanent actions (loads), potential to decrease the size of foundations, savings in material quantities, improved fire protection and thermal insulation and others. However, the common drawback of LWAC is that it typically uses high quantities of cementitious materials and relatively low Portland cement substitutions with supplementary cementitious materials (SCMs), such as fly ash or ground granulated blast-furnace slag (GGBS), which results in LWAC having a relatively high carbon footprint. This is potentially attributed to: a) concerns of not meeting the required strength on 28-day due to the inherently lower strength of LWAC compared to normal concrete, b) concerns over loss of workability and pumpability which are fresh properties of fundamental importance in transporting, pumping and placing LWAC over considerable height and c) lack of previous knowledge in the developments of LWAC with relatively high percentage of SCMs.

This study, therefore, focuses on the development of more environmentally friendly LWAC mixes to be used in structural applications, without compromising the strength and workability requirements of pumpable LWAC.

2. Materials, methods and concrete mixes

The materials used in this study were Portland cement (CEM I), GGBS, limestone powder, coarse 4/14 lightweight aggregate (Lytag) and ordinary 0/4 sand. High-range water-reducing admixture (HRWRA) was used for achieving the required workability and a small dosage of pump-aid was also incorporated for pumpability retention.

The experimental programme involved the preparation, casting and curing of concrete cubes which were subsequently tested for concrete strength and oven-dry density at 28 days after casting. Fresh properties of concrete were also measured, such as fresh concrete density and flow.

The aim was to produce LWAC concrete with maximum oven-dry density of 2000 kg/m^3 and with a minimum compressive strength of 40 MPa. This corresponds to the requirements of LC30/33 LWAC strength grade in accordance with Eurocode 2 and EN 206 [4,5]. The target slump flow was set as 600 mm.

The mixes were design in such way so that the boundaries of current practice are pushed beyond normal. The chosen reference/control mix contained 50% GGBS and 410 kg/m^3 total cementitious materials content. This is somewhat optimistic for current practice, where it is more common to see 40% GGBS replacements or even lower during winter months. In any case, subsequent mixes were designed with higher GGBS concrete, as high as 60%, lower total cementitious materials content, as low as 320 kg/m^3, and even with added limestone powder. The mix designs are shown in Table 1.

Table 1: *Mix proportions of the developed mixes*

	SSD Mix proportions (kg/m^3)						
	1. Control 50% GGBS	2. Modified-1 50% GGBS	3. Modified-2 50% GGBS	4. Modified 60% GGBS	5. Modified 50% GGBS, limestone-1	6. Modified 50% GGBS, limestone-2	7. Modified 60% GGBS, limestone
CEM I	205	175	169	148	155	147	128
GGBS	205	175	169	222	155	147	192
Limestone filler	--	--	--	--	60	70	50
Sand 0/4mm	809	869	870	846	825	828	831
Lytag 4/14mm	588	633	655	640	675	698	683
Free water	200	168	157	164	150	136	142
HRWRA	1.65	3.29	4.74	4.23	4.51	5.40	5.06
Pump aid	0.41	0.23	0.26	0.26	0.40	0.40	0.37
Free w/c	0.49	0.48	0.46	0.44	0.48	0.46	0.44
Calculated density (kg/m3)	2009	2020	2020	2020	2020	2026	2026

3. Results and discussion

As mentioned earlier, the key properties to be investigated are that of flow, oven-dry density and compressive strength. The target flow of approx. 600 mm was achieved for all mixes through adjusting the addition of the admixtures. It was noted that the mixes with limestone powder required a slightly higher admixture dosage to attain the target flow, as it is known that limestone tends to reduce the workability of the concrete as the fines content increases. The oven-dry density values are shown in Figure 2. The target density of less than 2000 kg/m^3 was achieved for all of the investigated mixes. It is noted that although the corresponding standard permits densities of up to 2200 kg/m^3 for lightweight aggregate concrete, the target density in the present study was 2000 kg/m^3 for weight optimisation in structures.

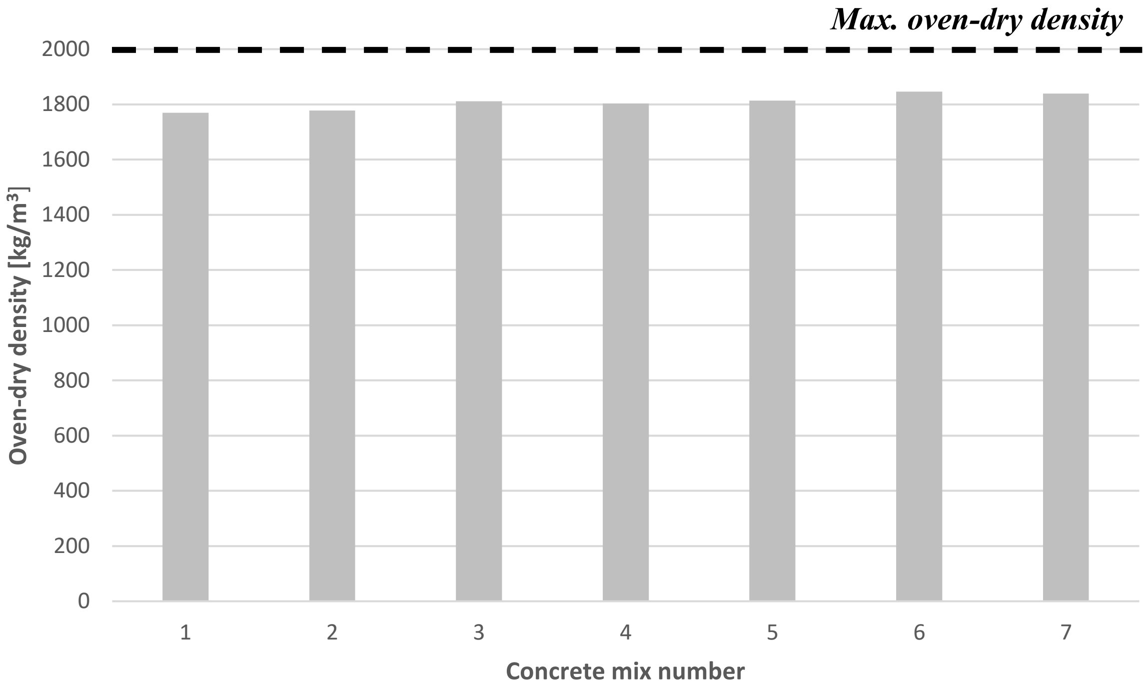

Figure 2: *Oven-dry densities of investigated mixes*

The 28-day cube compressive strength results are shown in Figure 3. It appears that all concrete mixes could achieve the target strength of 40 MPa at 28 days after casting except for the second mix by 2 MPa. This may be potentially attributed to a not low enough water-binder ratio, as mix 3, which had less binder content and lower water-binder ratio than mix 2, achieved the target strength. Most notably, the last four mixes also achieved the target strength which increases confidence on the use of low carbon lightweight aggregate concrete. With reference to mixes 4 (60% GGBS) and 7 (60% GGBS + limestone), the embodied carbon of these mixes was approximately 15% lower than the reference mix. Furthermore, results also indicated savings in total cementitious materials content that can be adopted in LWAC, as this was reduced by 22% compared to the reference mix, which results in both carbon savings but also cost optimisation. Finally, the Portland cement content in the mixes was ultimately reduced by even 40%, without adversely affected the workability, pumpability, strength and density of the LWAC developed.

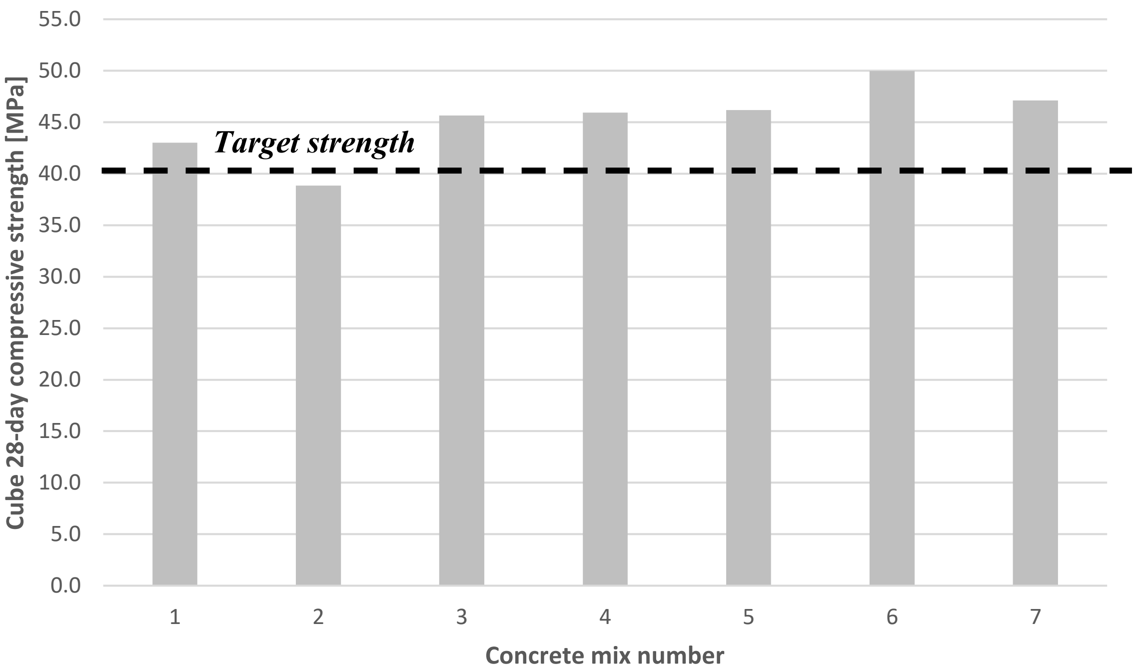

Figure 3: *28-day cube compressive strengths of investigated mixes*

The embodied carbon (life cycle stages A1-A3) of the LWAC mixes considered are shown in Figure 4. The embodied carbon of mix 1, the control Lytag LWAC mix, is 347 $kgCO_2e/m^3$, and the breakdown of embodied carbon by constituents is shown in Figure 5. Mixes 4 and 7 have the lowest embodied carbon, 308 and 304 $kgCO_2e/m^3$, respectively, due to the higher proportion of cementitious material that is GGBS (60%) compared to the others (50%) in addition to the overall reduction of cementitious content. The reductions in overall cementitious content appear to achieve a 6-7% reduction in embodied carbon, and the increase of GGBS proportion from 50% to 60% achieves a further 6-7% reduction. These reductions applied across a whole building can therefore result in 100s or 1000s tons of CO_2e emissions saved, solely due to an improved LWAC mix design.

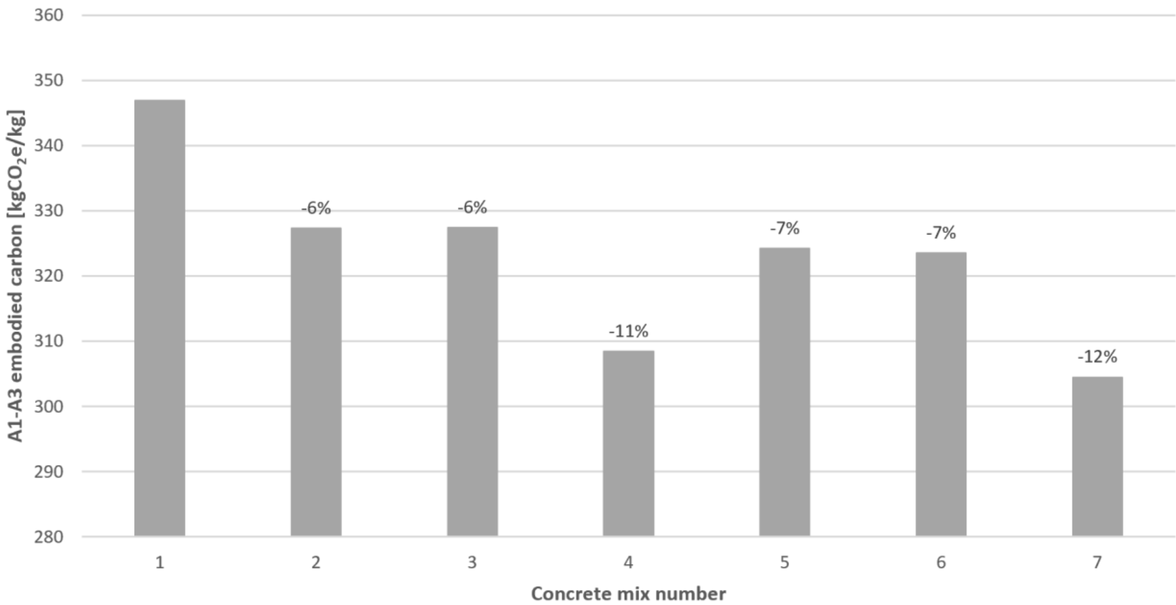

Figure 4: *Embodied carbon for each mix design*

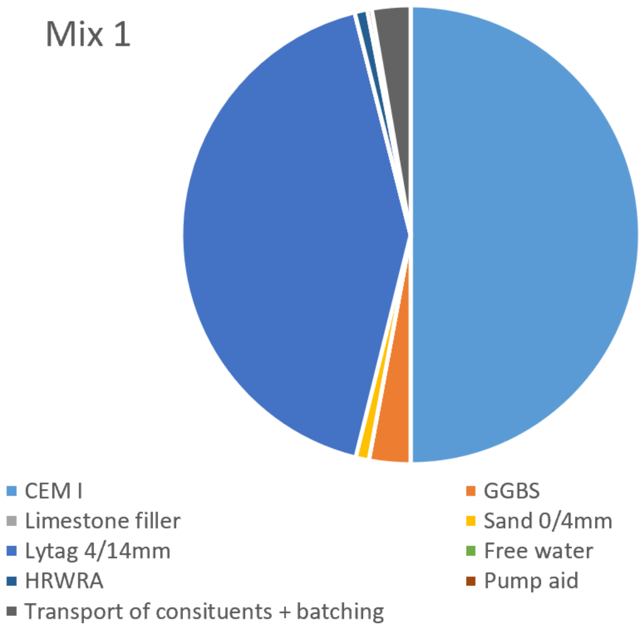

Figure 5: *Breakdown of embodied carbon by constituents for Mix 1*

4. Summary and outlook

This research investigates the potential of producing more environmentally friendly lightweight aggregate concrete (LWAC) mixes. So far, based on the obtained results, the following remarks can be made:

- It was generally found that with limestone addition, greater amounts of chemical admixtures were required to achieve the target flow (approx. 600 mm). This was also the case for decreasing the w/c ratio, something that was anticipated.

- Structural LWAC of grade LC30/33 can be developed with various proportions of supplementary cementitious materials.
- It was possible to reduce the Portland cement content by approximately 40%, the total cementitious materials content by 22% and embodied carbon by 12% compared to the initial, conventional LWAC mixes.

The next steps currently involve a cost analysis of the developed mixes as well as, further refinement of mix proportions to include more supplementary cementitious materials and the investigation of additional mechanical properties relevant to structural design.

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Conflicts of interest

The authors declare no conflict of interest.

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