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Reducing the embodied carbon of lightweight aggregate concrete for structural applications

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Abstract

This study investigated the development of lightweight aggregate concrete (LWAC) mixes with lower carbon footprint suitable for structural applications. The production of LWAC prerequisites the replacement of the normal weight coarse aggregate with a lightweight aggregate. In the present study, Lytag was considered which is a good quality lightweight aggregate manufactured from fly ash. LWAC for structural applications usually contains high CEM I content owing to the requirements for workability, pumpability and strength. Consequently, the carbon footprint of LWAC is generally higher than that of normal weight concrete. In this study, LWAC mixes of LC30/33 class were developed and contained up to 60% of ground granulated blast-furnace slag (GGBS), as well as limestone powder and their fresh and mechanical properties were assessed experimentally. It was found that the embodied carbon of the investigated mix could be reduced by up to 40% when compared to neat CEM I LWAC mixes containing Lytag aggregates and to 20% when compared to a LWAC mix that would be generally used in current practice in the UK containing 40% GGBS. It was also possible to reduce the CEM I content in the investigated mixes by approximately 40% compared to what would have been normally used.

Keywords chosen from ICE Publishing list
Concrete technology & manufacture, Sustainability, Composite structures

1 Introduction

The plethora of construction methods, types of structures and concrete material requirements often result in the development of special concrete types, next to the ordinary concrete ones. Amongst others, lightweight aggregate concrete (LWAC) is a special concrete type which has gained popularity in structural applications particularly in the construction and specification of high-rise buildings, composite flooring systems, situations where load reduction in structures is required or even in cases where foundation size reduction is preferred. LWAC also exhibits better thermal properties than normal weight concrete and thus, it is also used for thermal insulation or even for the reduction of thermal cracking risk. LWAC should exhibit a density of not more than 2200 kg/m^3 (Soutsos and Domone, 2017), although the commonly seen LWAC could be in the region of 2000 kg/m^3. In any case, these are significantly lower than the densities of normal weight concrete, which are generally known to be in the region of 2350 - 2500 kg/m^3.

The main constituent that decides the final weight and density of LWAC is the aggregate itself; LWAC should contain an adequate quantity of artificial or natural lightweight aggregate with density of less than 2000 kg/m^3.

There are several potential sources of lightweight aggregate that can be used in concrete. These can be differentiated to naturally occurring and artificial/manufactured lightweight aggregates. Naturally occurring lightweight aggregates include pumice and diatomite, whilst artificial/manufactured lightweight aggregate is produced after processing naturally occurring materials, such as clays, or waste by-products, such as fly ashes and slags (Neville, 2011; Alexander and Mindess, 2005). To an extent, it could be considered preferable to use waste materials from industrial applications as this contributes to waste utilisation and reducing the depletion of natural resources.

Particularly for the UK market, the commonly employed lightweight aggregate technology in the production of lightweight aggregate concrete is that of Lytag (Lytag, 2017) which is manufactured through sintering of fly ash, a by-product from coal-fired power plants. In this technology, the fly ash is transformed into small round pellets, which are then heated to 1,100°C. This creates a very hard pellet with a honeycombed internal structure of interconnecting spaces. These hard pellets can then be used as a lightweight aggregate which is up to 50% lighter than natural aggregate.

This type of lightweight aggregate is generally preferred due to the higher concrete strengths that can be achieved when compared to other types of lightweight aggregates, e.g., expanded clay aggregates, which are known to be more suitable for lower strength concrete applications (< 20 MPa [Ahmad *et al*., 2019; Vijayalakshmi and Ramanagopal, 2018]). As a result, generally, Lytag aggregate is frequently used where LWAC applications are required. However, LWAC traditionally encompasses a higher carbon footprint than normal weight concrete. While this is partially attributed to the carbon footprint of the manufactured aggregate itself, the higher carbon footprint of LWAC stems also from lack of concrete mix optimisation with emphasis on sustainability. More specifically, LWAC generally contains relatively small quantities of cement replacement materials (CRMs), such as ground granulated blast-furnace slag (GGBS) and fly ash, due to their adverse effects in the concrete strength gain rate and negative implications with flowability and pumpability of LWAC. Furthermore, to also satisfy flowability and pumpability requirements, LWAC usually contains higher total cementitious binder content when compared to normal weight concrete.

LWAC have been examined by several researchers who studied its mechanical properties and structural performance and compared those of normal weight aggregate concrete, such as Lambert, 1982; Gerritse, 1981; Finn, 1987; Collins and Sherwood, 1995; Bilodeau *et al.*, 2004; The Concrete Society, 2006; Chen et al., 2010; Badogiannis and Kostovos, 2014; Dias-Da-Costa *et al.*, 2014 and Grabois *et al.*, 2016. It was generally reported that LWAC is more workable than its counterpart with normal weight aggregates and that due to its high porosity and water absorption, it has better continuous internal curing and steady increase of strength over time. However, due to LWAC modulus of elasticity being lower than normal weight equivalent (by about 30% on average), this leads to higher creep, deflection and prestress losses (although creep can play an advantage in counteracting internal or external restraint stresses). LWAC has also been reported to exhibit better insulation properties (imposed temperature stresses lower by about 50% on average compared to normal weight aggregate concrete). Furthermore, Sin et al (2011) carried out tests on cracking and determined that LWAC result in narrower and higher number of cracks as compared to normal weight aggregate concrete, which could indicate a higher energy dissipation of LWAC. Chen et al., 2010; Badogiannis and Kostovos, 2014; examined the dynamic and cyclic structural behaviour of LWAC in order to use the material in earthquake resistant design applications (to take advantage of its low mass). Lambert (1982) carried out comprehensive experimental studies on fly ash LWAC investigating both the material properties (mainly in compression) and the structural behaviour using beam specimens and the study largely underpinned Lytag as a recycled construction material suitable for structural applications.

Historically, the use of natural lightweight aggregates predates the Romans (The Concrete Society, 2006) who also used LWAC as a structural material utilising natural pumice aggregates in the construction of the Pantheon and the Coliseum. One of the early successful applications of LWAC in the UK was in marine structures during World War I such as ports and jetties and pontoons as well as off-shore structures and bridges such as Westminster and Kingston bridges (The Concrete Society, 2006). A notable case of the application of LWAC is also the cantilever roof of the Twickenham Grandstand built by Bobrowski & Partners (Clarke 1993).

2 Research significance

Specifying, producing and using low carbon concretes is of ever-increasing importance. Current construction practice does not necessarily encompass optimised lightweight aggregate concretes for structural applications with improved carbon footprint. LWAC mixes commonly contain relatively small quantities of CRMs and generally exhibit higher total cementitious binder content than normal weight concretes. It is, therefore, necessary to optimise LWAC mixes for structural applications through increasing the Portland cement replacement levels with CRMs, such as GGBS as well as through reducing the total cementitious binder content, while achieving the required performance in terms of density, strength and flowability/pumpability.

3 Materials and experimental procedures

The experimental programme focused on improving the carbon footprint of LWAC for structural applications. This was investigated through the optimisation of the mix design for an LC30/33 LWAC mix, which is one of the most frequently specified LWAC strength classes to EC2, particularly in the UK.

3.1 Materials

The concrete constituents considered in this study were Portland Cement, GGBS, limestone, natural sand, Lytag lightweight aggregate, water and admixtures. CEM I 52,5 N and GGBS confirming to BS EN 1997-1:2011 (2011) and BS EN 15167-1:2006 (2006) were supplied by Hanson whilst limestone powder (calcium carbonate) confirming to BS 7979:2016 (2016) was supplied by Omya.

Sharp 0/4 sand conforming to BS EN 12620 was also supplied by Hanson with a water absorption of 1%. Lytag lightweight coarse aggregate was a 4/14 aggregate supplied by Lytag and exhibits a particle density of 1,350 to 1,650 kg/m^3 which is significantly less compared to normal weight aggregates which commonly exhibit particle densities in the region of 2,600 kg/m^3. Due to its porous nature, Lytag aggregates also exhibit high water absorption, i.e., 15%, an element which has to be taken into account in concrete mix design and constituent preparation, as it is going to be discussed in the Section 3.1. The water absorption reported herein agrees with existing literature (Kwasny et al. 2012) although even higher values have been reported for fly ash based lightweight aggregate (Litsomboon et al. 2009).

Two concrete admixtures complying to BS EN 934-6:2019 (2019) were considered in this study and both where supplied by Chryso: a High-Range Water Reducing Admixture (Chryso Optima 76) and a pump aid one (Chryso Optima 100); owing to the requirements for lightweight aggregate concrete to be sufficiently flowable and pumpable.

3.2 Experimental procedures

The experimental procedures considered in this study focused on the fundamental concrete properties that LWAC should exhibit in order to be used in structural applications. The challenge in this particular study was to achieve such LWAC performance with Portland cement replacement levels and binder contents as high and as low as possible, respectively, which to the authors' best knowledge, is not generally attempted due to the LWAC mixing and casting processes and general performance complications (e.g. setting time, bleeding, strength development). The properties considered for testing included: (a) Workability-pumpability through slump flow tests, (b) fresh and oven-dry density and (c) 28-day compressive strength. The slump-flow test was conducted in accordance with BS EN 12350-8:2019 (2019) whilst fresh and hardened density was assessed in accordance with BS EN 12350-6:2019 (2019) and BS EN 12390-7:2019 (2019) respectively. The compressive strength at 28 days since casting was assessed with 100 mm cubes in accordance to BS EN 12390-3:2019 (2019).

3.3 Concrete mix designs and processes

The aim was to investigate LWAC mixes suitable for structural applications and therefore, the target strength class considered was LC30/33, as previously mentioned. The 28-day target mean strength of LC30/33 is approximately 40 MPa and this was also the 28-day target strength considered in this study. The mixes were designed in such way so that the oven-dry density would consistently be in the region of 1800-1900 kg/m^3. Controlling the density of LWAC in the desired ranges is of great importance in order for LWAC to maintain its lightweight characteristics. The difficulty with developing usable LWAC mixes for structural application lies within the requirements for high workability which in return requires high binder contents. On the same time, due to the inherently lower strength of the Lytag aggregate compared to natural aggregates, the strength of LWAC may be lower than that of normal-weight concrete for the same water-binder ratios (w/b) and total cementitious materials contents, which prevents specifying higher than normal GGBS contents.

The mixes considered contained at least 50% of CEM I replacement with GGBS and the purpose of the study was to modify them accordingly in order to optimise the total binder content and GGBS replacement levels and achieve further carbon footprint reduction. Limestone fines were also considered where appropriate with the aim of increasing the powder content (required for workability) without having to increase the binder content. The derived mix proportions are shown in Table 1. The quantities of admixtures required were determined during mixing through adjusting the dosage in accordance with the target slump-flow value.

As Lytag is highly porous, it exhibits high water absorption, as previously indicated. This makes the mixing process and controlling of water content in the mix more complicated. It was found in this study that it was best to pre-soak Lytag in water for 24 hours prior to mixing and bring them in saturated surface dry (SSD) condition just before mixing with other constituents. This is different to other methods which involve pre-soaking the aggregate in water for 30 minutes before mixing or oven-dry them and adding the water to be absorbed by Lytag in the mixer during mixing. Nevertheless, the latter method was also tried and was resulting in highly flowable mixes with increased risk of bleeding and segregation. This was due to the fact that although Lytag has high water absorption, it does need certain time to absorb the foreseen water and the time during mixing is not enough for the excess water to be absorbed by Lytag. It is, therefore, suggested that Lytag is pre-soaked for at least 24 hours prior to mixing. Similar behaviour was also observed in other studies, such as (Kwasny et al. 2012).

Lytag and sand were inserted in the mixer first and dry-mixed for approximately 30 seconds. This was the followed by the addition of CEM I, GGBS, limestone and water. After approximately 2 minutes of mixing, the admixtures were progressively added at small, controlled increments. Mixing continued for 30 to 60 seconds and stopped for conducting the slump flow tests. If the slump-flow value was below the target, mixing was continued with adding extra quantity of admixtures and this process was repeated until the target slump-flow was achieved. The prepared LWAC mix was cast into 100 mm single steel cube moulds (3 for strength and 3 for oven-dry density for each mix) and was consolidated using tamping rods. The samples were left to cure in room environment conditions while covered with plastic sheeting and with damp hessian for 1 day, whilst after that period they were demoulded and submerged in a water tank set at 20 °C, where they were left to cure until tested.

Table 1. Developed mix designs for LC30/33

Mix ID	SSD Mix proportions (kg/m^3)						
	1. Initial 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
Total binder content	410	350	338	370	310	294	320
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/b	0.49	0.48	0.46	0.44	0.48	0.46	0.44
Calculated theoretical density (kg/m3)	2009	2020	2020	2020	2020	2026	2026

4 Results and discussion

This section discusses the findings from the experiments on fresh and oven-dry densities, workability and strength of the mixes developed as well as an evaluation of the carbon footprint improvement achieved as a result of this investigation is provided.

4.1 Fresh and oven-dry density

The results from the fresh density tests are shown in Figure 1. It is important to assess whether the measured fresh concrete density matches the theoretical/calculated one in order to gain confidence that constituents have been added correctly and the water content is the expected one. It will also give an indication of the differences between fresh and oven-dry densities in terms of evaporable water. As it can be seen from Figure 1, the measured fresh concrete densities match the calculated ones.

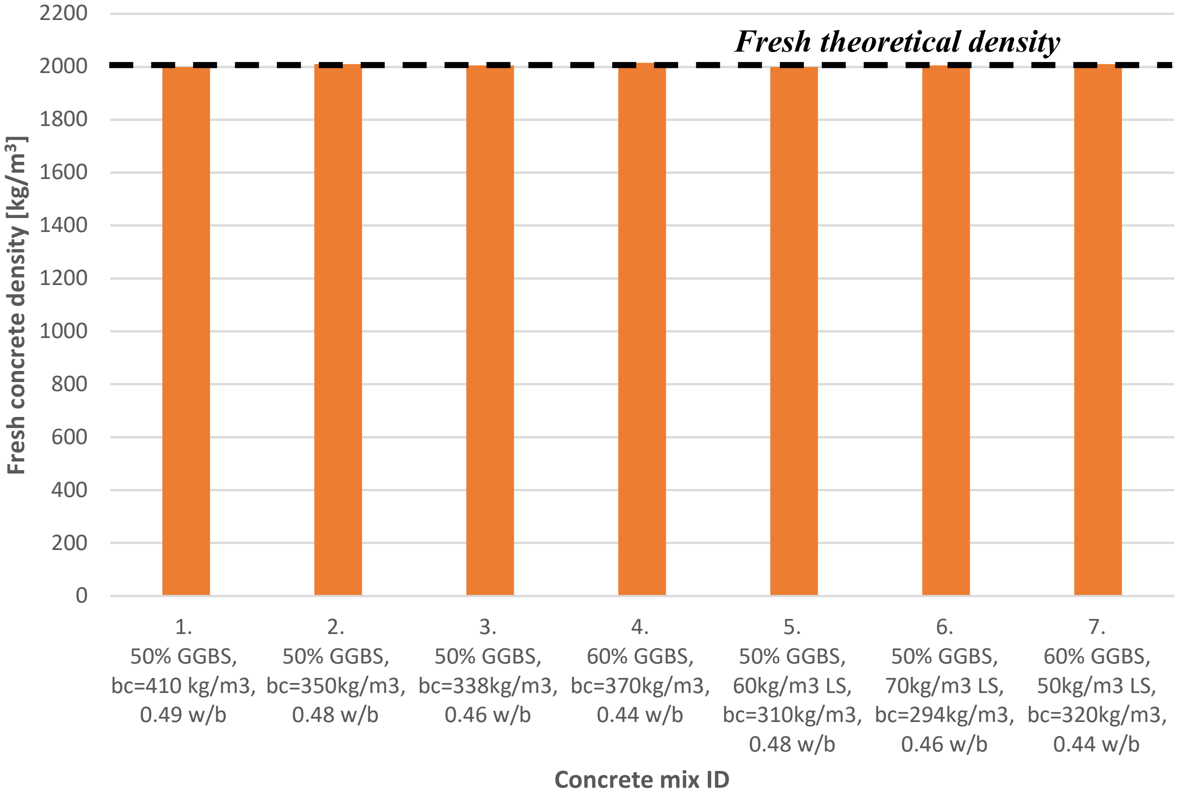

Figure 1. Fresh concrete density results for the developed mixes (bc: binder content; LS: limestone; w/b: water-binder ratio)

Results from the oven-dry density tests are shown in Figure 2. The target oven-dry density of the LWAC mixes was in the region of 1800 kg/m^3 whilst the maximum permitted in this study was 2000 kg/m^3. This was somewhat lower than those reported in e.g. (Kwasny et al. 2012) where Lytag lightweight aggregates were also used and hardened densities ranging from approx. 2000 to 2150 kg/m^3 were achieved; however, the target density of a LWAC is adjusted in accordance with the weight requirements for a possible application. In any case, it was found that the mixes developed are well within the target densities and can be classified as lightweight concretes, in accordance with the corresponding standard. The difference between the measured fresh and oven-dry concrete densities, correspond to the amount of water absorbed by Lytag and sand prior to mixing (they were brought in SSD condition) as well as the unbound water that was not consumed by cement hydration and was evaporated after oven drying at approximately 100 °C.

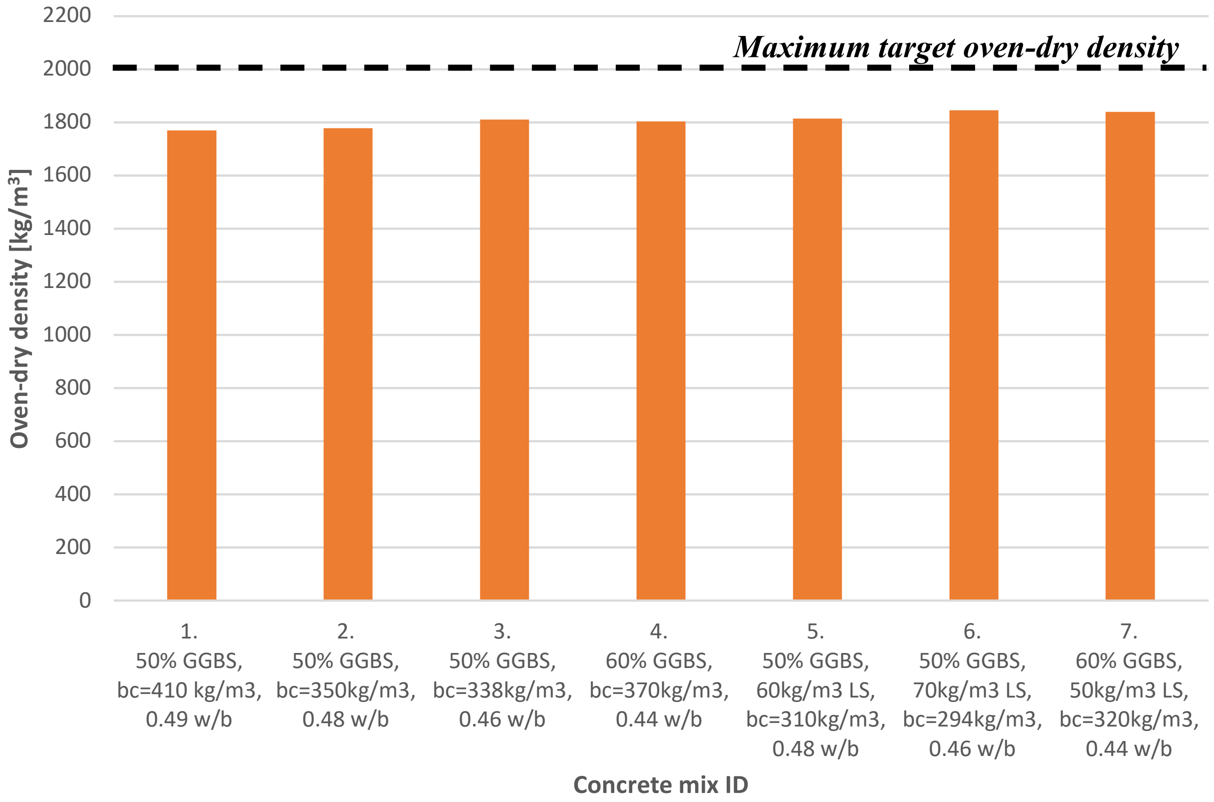

Figure 2. Oven-dry concrete density results for the developed mixes

4.2 Fresh properties

Attaining consistently a defined slump-flow performance was also important in the development of the LWAC mixes herein, as this determines the usability and pumpability of the mixes developed. The target slump flow class was set at 600 mm (SF1 class to BS EN 206 (2013)) after discussions with manufacturers and concrete producers. With lower w/b and, lower paste volumes and higher GGBS contents, the process of achieving sufficient slump to allow for pumping becomes more challenging. Furthermore, limestone fines tend to increase the water demand of the mix that may further reduce workability-pumpability. The target slump-flow value was achieved through adjusting the dosages of admixtures used, with final dosages as shown before in Table 1, whilst there was no apparent risk for segregation or excessive bleeding observed, in contrast to what was observed in (Solak and Tenxa-Abril, 2019; Solak et al. 2020). The slump was expectedly affected adversely as the water-binder ratio decreased higher dosages of admixtures were required to meet the target slump as previously described. Also, the mixes with limestone required the highest dosage of admixtures as water demand increases with limestone and GGBS addition (Alhozaimy et al. 2009; Kanavaris, 2017; Soutsos, 2017; Soutsos, 2020).

4.3 Compressive strength

The 28-day compressive strength results are shown in Figure 3. It appeared that all concrete mixes could achieve the target strength of 40 MPa at 28 days after casting with the exception of the second mix, which fell 2 MPa below the 40 MPa target. This may be potentially attributed to a not low enough w/b, compared for example with mix 3, which had less binder content and lower w/b than mix 2 and achieved the target strength. Most importantly, the last four mixes also attained the 28-day target mean compressive strength something that increases confidence on the use of low carbon lightweight aggregate concrete. The last four mixes (mixes 4 to 7) incorporated the highest GGBS content whilst mixes 5 to 7 also included limestone powder in order to reduce the total cementitious materials content. The mixes investigated achieved consistently the target mean strength requirement for LC30/33 (40 MPa) which is encouraging in terms of using higher GGBS contents and limestone powder in LWAC for structural applications. Particularly mixes 6 and 7, which exceeded that requirement, encompass the potential to be qualified for higher strength LWAC classes, such as LC35/38 or LC40/44. LWAC mixes of similar w/c ratio but consisting rather of neat CEM I investigated in (Nadesan and Dinakar, 2017) also developed comparable strengths to the mixes considered herein. It is worth noting that results also indicated savings in total cementitious materials content that can be adopted in LWAC, as, for example, this was reduced by 22% compared to the initial mix (mix 1), which results in both carbon savings but also cost optimisation. Finally, the Portland cement (CEM I) content in the mixes was ultimately reduced by even 40%, without adversely impacting the workability-pumpability, density and compressive strength of the LWAC mixes developed.

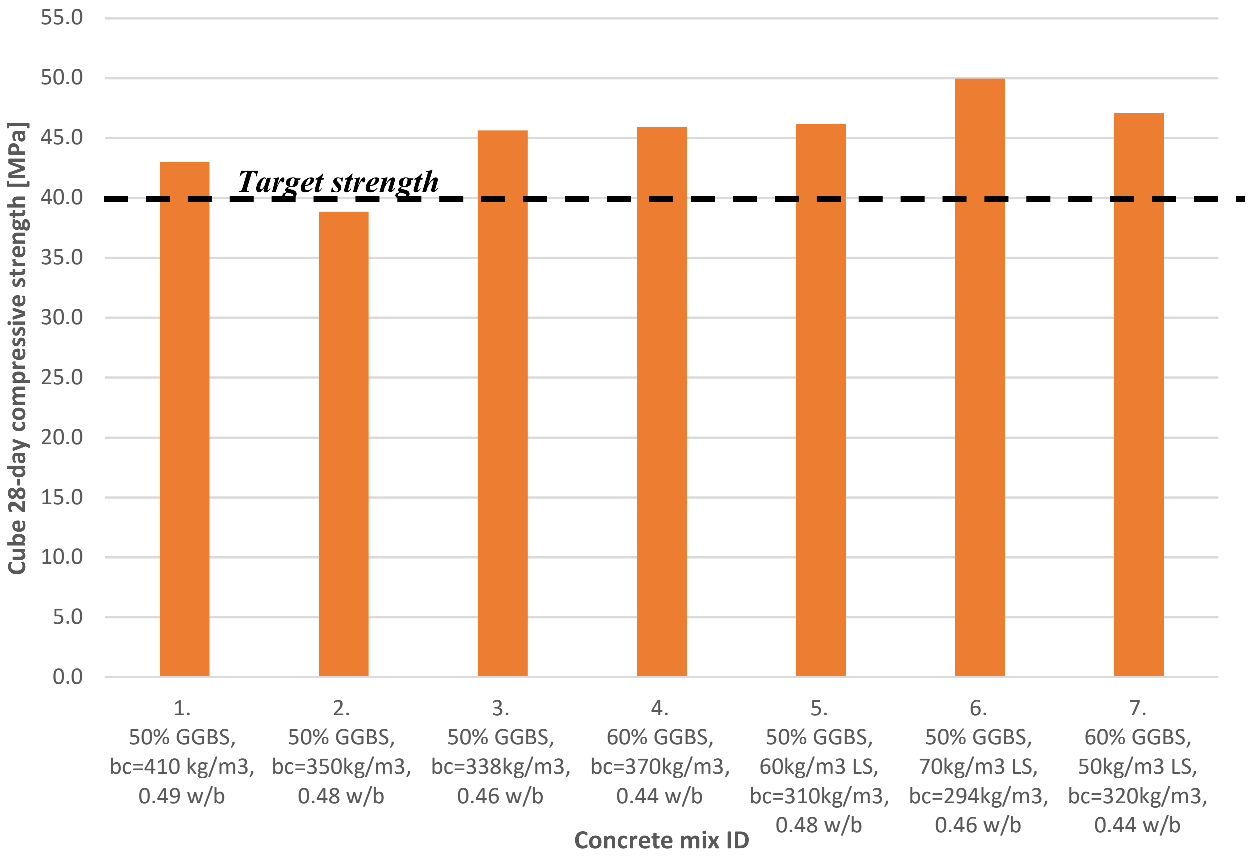

Figure 3. 28-day measured compressive strength of investigated LC30/33 concretes

4.4 Embodied carbon analysis

The embodied carbon (life cycle stages A1-A3) of the LWAC mixes developed was calculated in order to demonstrate the potential reductions in carbon footprint of LWAC arising from this study. The embodied carbon values (carbon factors) of each individual concrete constituent used in the calculations for the LWAC mixes developed in this study are shown in Table 2. The carbon factors are used in conjunction with the LWAC mix proportions to derive the embodied carbon of the mixes developed. To demonstrate the carbon reduction achieved from this investigation with respect to the development of LWAC mixes, the carbon footprint of the developed mixes is calculated, plotted and compared to that of a LWAC mix with 100% CEM I (without any addition of a supplementary cementitious material, such as GGBS), as shown in Figure 4. It is noted that this 100% CEM I “reference” mix is fictitious and has not been part of the experimental campaign of this study, hence, it is not included in the table of mixes investigated herein (Table 1). It merely serves the purpose of comparing the developed mixes with a hypothetical 100% CEM I mix, with 400 kg of binder per m^3. It becomes apparent that significant reductions in carbon footprint can be achieved with the investigated mixes and the reduction can reach the magnitude of 40%. It is worth noting, however, that a comparison of the carbon footprint of modern concrete mixes to 100% CEM I mixes may not be particularly representative of the current practice in the construction sector. It may be seen that in several cases any new concrete technology or binder is compared against 100% CEM I mixes and as a result, the carbon footprint savings of a corresponding concrete/cement technology seem quite significant. However, while 100% CEM I mixes are produced and used in many places worldwide, this is particularly the case in developing countries that have limited to none cement replacement materials available. For countries which maintain a higher availability of cement replacement materials, such as the UK, it seems prudent to compared the carbon footprint of each mix/technology under question to that regarding as “business-as-usual”, which are concretes that are normally specified and used in construction. To put this in perspective, in UK specifically, the use of GGBS in concrete has been widespread for several years. With particular reference to LWAC, what would be regarding as “business-as-usual” would be a LWAC mix containing 40% GGBS. Therefore, the mixes investigated herein are compared against a 40% GGBS LWAC mix in terms of carbon footprint, as shown in Figure 5. The apparent reduction in carbon footprint, now becomes rather smaller when compared to 100% CEM I concrete. Nevertheless, the reduction reaches the magnitude of 20% which can still be considered as much beneficial. These reductions if applied across a whole building can potentially result in 100s or 1000s tons of CO_2e emissions saved, solely due to an improved LWAC mix design.

Table 2. Embodied carbon values (carbon factors) of each individual concrete constituent used in the calculations for the LWAC considered in this study

Material	**Cradle to gate (A1-A3) GWP [kg CO_2e/tonne]**
CEM I	846[*]
GGBS	50[**]
Limestone filler	80[*]

Sand 0/4mm	4[#]
Lytag 4/14mm	249[##]
Water	3.19E-04[###]
HRWRA	1880[#]
Pump aid	1670[#]

[*] (MPA, 2019)

[**] Average from (MPA, 2019; ICE database, 2019; Ecocem, 2018)

[*] (MPA, 2019)

[#] (ICE database, 2019)

[##] (Aggregate insustries, 2016)

[###] of negligible GWP and can be considered as 0 kg CO2e/tonne after (Rawaz et al. 2018; ecoinvent 3.7.1, 2020)

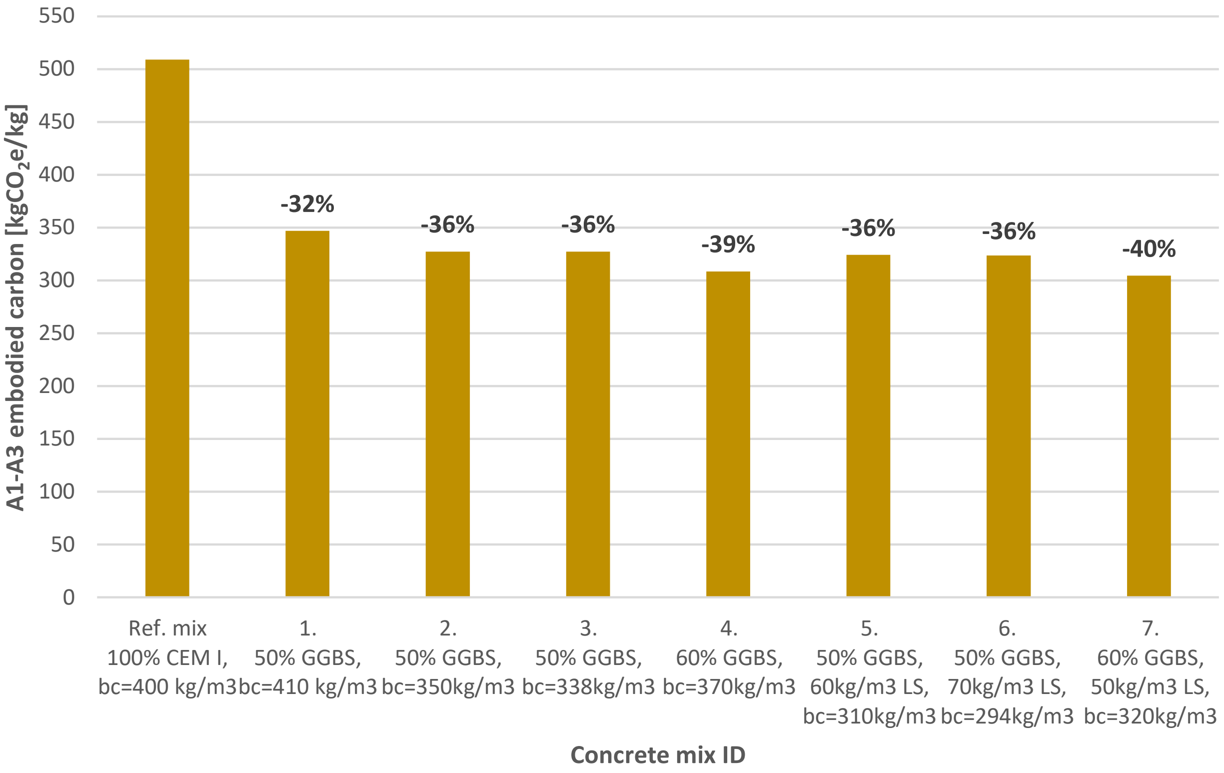

Figure 4. Calculated embodied carbon of the LWAC mixes investigated herein and demonstrated carbon footprint reductions compared to a neat CEM I LWAC mix

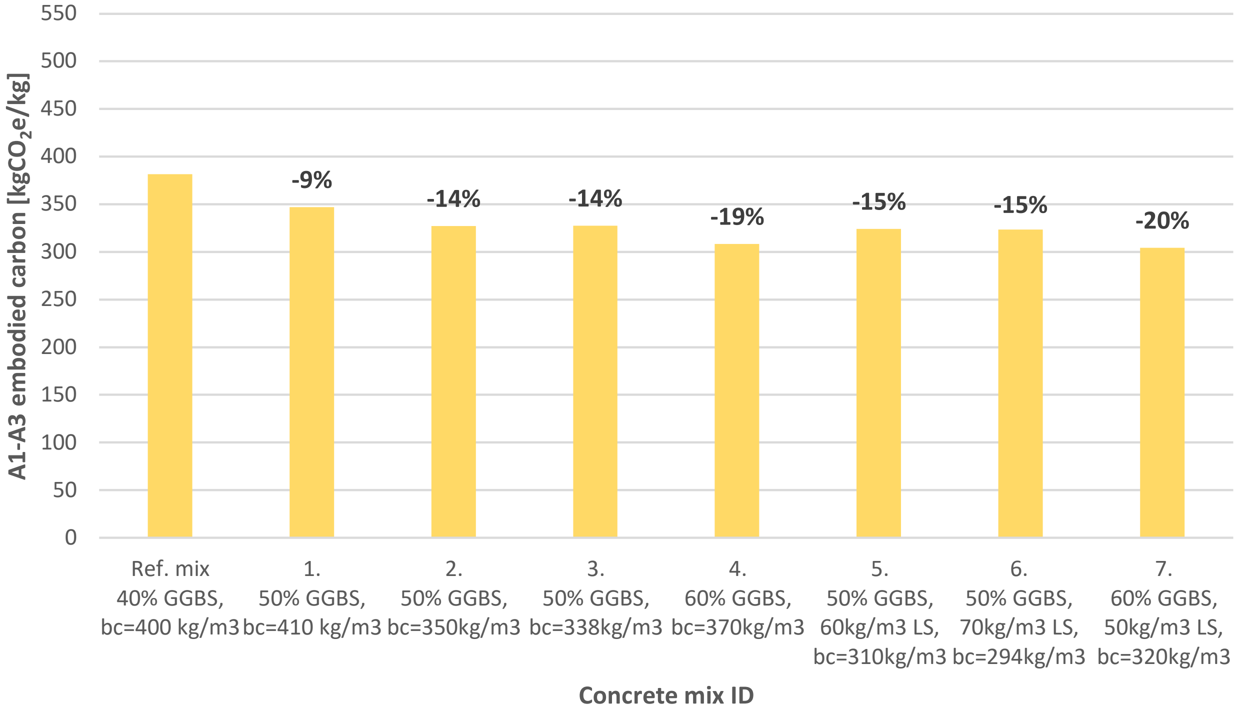

Figure 5. Calculated embodied carbon of the LWAC mixes investigated herein and demonstrated carbon footprint reductions compared to a 40% GGBS LWAC mix

What also needs to be mentioned and taken into consideration when calculating embodied carbon figures and exploring low carbon concrete options is the availability of the corresponding industrial by-products that are used in concrete. The present research considers improving the carbon footprint of lightweight concrete consisting of fly ash – based aggregates, with increasing the GGBS addition in the mix (amongst other techniques, such as limestone powder addition and reduction of total cementitious materials content). Nevertheless, GGBS is known to be diminishing globally. As reported in (UN Environment et al. 2018) the availability of GGBS has decreased from 17% of cement production in 1980 to only 8% in 2014. This decrease in availability is expected to be exacerbated in the upcoming years, owing to changes in steel and iron production as well as due to coincident demand for GGBS for concrete use in major projects across Europe. For UK specifically, there are indication that local GGBS production is not adequate so that the nation-wide GGBS demand is satisfied and therefore, GGBS needs to imported from elsewhere, either Europe or even China (DBEIS); something which has already been taking place during the past decades but for rather relatively small material quantities.

Equally for Lytag aggregate, its availability will be influenced by the closing of coal-fired power plants in the UK and Europe; however, it may be anticipated that current fly ash deposits will suffice to produce this type of lightweight aggregate for several upcoming years.

5 Conclusions

This study investigated the development of low carbon LWAC concrete mixes suitable for structural applications. Based on the findings of the study, the following conclusions can be drawn:

- The Portland cement (CEM I) content in a LC30/33 LWAC mix can be minimised with mix optimisation and GGBS addition.
- It was possible to used up to 60% GGBS replacement in the mixes without adversely affecting workability, density and compressive strength at 28 days since casting.
- Limestone addition resulted in higher admixture demand than non-limestone containing mixes for achieve 600 mm of slump flow value.
- The improved LWAC mixes developed herein resulted in carbon footprint reduction in the magnitude of 40% if compared to 100% CEM I LWAC mixes with Lytag aggregate and 20% if compared to 40% GGBS LWAC mixes with Lytag aggregate.
- The CEM I content in the improved LWAC mixes was reduced by approximately 40% compared to conventional LWAC mixes containing GGBS and Lytag aggregate.

Work is continuing with focus on cost analysis on the developed mixes as well as further refinement of mix designs to include higher quantities of cement replacement materials of different nature (e.g., fly ash) and also further investigations on the mechanical properties relevant to structural design.

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Conflict of interest

The authors declare no conflicts of interest.

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