Development of low-carbon lightweight concrete using pumice as aggregate and cement replacement

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Abstract. An experimental investigation was conducted to develop a low-carbon lightweight aggregate concrete (LWAC) using naturally occurring aggregates and evaluate its mechanical performance. Lightweight aggregates used in structural concrete are commonly manufactured from recycled pulverised fuel ash or expanded clay, which require high temperatures during production. Additionally, the availability of traditional supplementary cementitious materials used in concrete, such as Ground Granulated Blast Furnace Slag (GGBS), is diminishing. Therefore, more environmentally friendly alternatives are required. Pumice, a naturally occurring lightweight stone formed due to the rapid cooling of magma from volcanic eruptions, poses a promising candidate for using as lightweight aggregate, whilst it might also exhibit pozzolanic properties that make it suitable as a cement replacement material. Therefore, the present study is focused on examining the development of low-carbon LWAC mixes with pumice as coarse aggregate and ground pumice as cement replacement. In addition, a novel recycled waste known as Lytash was trialed as a filler. This is a by-product of the manufacture of fly-ash based lightweight aggregates (commonly known as Lytag, which is in itself is a recycled by-product from coal fired power plants). The fresh and hardened densities of concrete were evaluated as well as the compressive strength (targeting a strength class LC30/33). It was found that lightweight aggregate concrete with a density of less than 1800 kg/m^3 was possible to achieve. Furthermore, the pozzolanic reactivity and X-Ray Diffraction (XRD) testing; as well as the 28 days compressive strength of samples tested revealed the potential of pumice powder to be used as a cement substitute. Embodied carbon calculations were also carried out accentuating the savings in carbon footprint that can be achieved with pumice aggregate and powder.

Keywords: Low-carbon concrete, Lightweight aggregate concrete, Pumice aggregates, Pumice powder, Cement replacement, Fresh and hardened densities

1 Introduction

Due to climate change and the contribution of cement manufacture to carbon emissions, there is an urgent need for low-carbon concrete solutions. Lightweight-aggregate concrete (LWAC) is a type of concrete that has gained popularity in structural applications, particularly in the construction of high-rise buildings, composite flooring systems and in situations where structural load and foundation size reductions are required. The use of lightweight aggregate is increasing due to its benefits in terms of material efficiency, thermal performance and the potential to reduce the embodied carbon of concrete structures.

Generally, the aggregate is the primary constituent that determines the final weight and density of lightweight aggregate concrete. LWAC should contain a suitable amount of lightweight aggregates, either manufactured or naturally occurring, with a density of less than 2000 kg/m^3. These are lower than normal-weight concrete densities, which are typically defined to be in the range of 2350-2500 kg/m^3. The commonly used lightweight aggregates are manufactured, often using energy intensive processes and the mixes contain high quantities of Portland cement to satisfy strength requirements and achieve the desired rheological properties (Kanavaris *et al.* [1]).

Pumice stone is a natural lightweight aggregate which is formed by the sudden cooling and solidification of molten volcanic matter (i.e. molten lava). Pumice aggregate's structure is also formed by bubble formation of minuscule air voids, as depicted in Fig. 1, when air in molten lava is trapped during cooling process. LWAC mixes generally contain low amounts of cement replacement materials as well as a higher total cementitious binder content than normal weight concretes. Therefore, it is necessary to enhance the lightweight aggregate concrete mixes for structural applications by increasing the cement replacement percentage usually using materials such as ground granulated blast-furnace slag (GGBS), fly ash and limestone. Also, fillers are used in concrete to reduce the amount of cement without lowering the strength whilst also improving the fresh properties of concrete such as workability. In the present study, a novel recycled waste material known as Lytash was used as a filler (it is a by-product of the fly-ash based lightweight aggregate Lytag, which in turn is a by-product of coal-powered electricity generation).

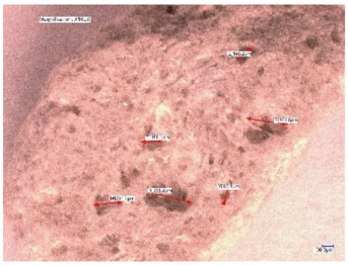

Fig. 1. Pumice aggregate porosity – optical microscopic photograph at 20x magnification

Several researchers have investigated the behaviour of lightweight aggregate concrete with respect to its fresh and hardened densities and mechanical properties. Most recently, in a study by Kanavaris *et al.* [1] the development of lightweight aggregate concrete mixes with lower embodied carbon dioxide emissions suitable for structural applications was investigated. In that study, fly-ash based lightweight aggregate concrete was examined with GGBS used as cement replacement. The study found that it was possible to utilize up to 60% GGBS replacement in the mixtures without negatively impacting their workability, density, or compressive strength. In other studies, [2-6], the benefits of adopting LWAC was highlighted, such as improved workability compared to normal weight aggregates concrete, continuous internal curing, and a steady increase in strength over time due to its high porosity and water absorption. It was also reported that LWAC has better thermal properties than normal weight concrete, so it is being used in thermal insulation to reduce the risk of thermal cracking.

2 Scope of work

The main aim of this study is to examine the structural behavior of low-carbon LWAC using pumice aggregate for structural applications [7-8] combined with the incorporation of pumice powder (with and without GGBS) as cement replacement and Lytash as filler. The aim is to produce LWAC mixes for structural applications with low embodied carbon, or at least comparable to the embodied carbon of normal weight mixes with supplementary cementitious materials. Achieving low-carbon lightweight concrete mixes will have provide sustainable solutions in relevant construction applications.

3 Materials and experimental procedure

3.1 Materials

The concrete constituents considered in this study were Portland cement, Pumice powder, GGBS, Lytash, Pumice aggregates, Lytag aggregates, Normal aggregates, natural sand, water and admixtures. CEM I 52.5 N and CEM II/A-LL 52.5 N conforming to BS EN 197-1:2011 [9] and GGBS conforming to BS EN 15167-1:2006 [10] were used. CEM I 52.5 N is ordinary Portland cement and CEM II/A-LL 52.5 N is Portland cement with limestone. Both of these cement types have the same strength classification, however CEM I 52.5 N mainly consist of clinker while CEM II/A-LL 52.5 N has 11-12% of limestone in addition to clinker. Lytag lightweight aggregate sizes used were 4/14 mm. It exhibits a particle density of 1350–1650 kg/m^3 and water absorption of 15% [1]. Pumice was used as lightweight aggregate exhibiting densities in the range of 1100 – 1350 kg/m^3 and water absorption of 17% which is more than that exhibited by Lytag aggregates. Normal 10mm aggregate was used which has water absorption of 2.1%. The sand considered was sharp 0/4 sand conforming to BS EN 12620:2013 [11] and has a water absorption of 0.7%. The pump aid admixture (Chryso Optima 100) conforming to BS EN 934-6:2019 [12] was utilized to enhance the concrete flowability and pumpability.

3.2 Experimental Procedures

The experimental procedures include the study of the pozzolanic behaviour and microscopic characteristics of pumice and the fundamental mechanical properties of LWAC. As pumice powder was used as cement replacement in the present study, pumice powder should exhibit certain reactivity to be considered as a credible concrete constituent. A ball mill was used to grind the granular pumice into powder form to a size of 63 to 300 µm. The determination of pozzolanic activity of pumice powder was determined using the Modified Chapelle test as described in Draft BS 8615-2:2018 [13]. The material is determined as pozzolanic if the consumption of $Ca(OH)_2$ is more than 700 mg of pozzolana. X-ray diffraction analysis (XRD) was also performed to investigate the crystallographic structure of the pumice powder whilst optical microscopic examination was conducted to study the external and internal structures of pumice stone. The concrete tests conducted were the flow test, fresh and oven dried densities and 28-day compressive strength. The flow test was performed in accordance with BS EN 12350-5:2019 [14] to achieve the flow of concrete in the region of 500mm to 600 mm for the concrete to be workable and pumpable. The fresh and oven dried densities were conducted as per the procedure in BS EN 12390-6:2019 [15] and BS EN 12390-7:2019 [16], respectively. The 28 days compressive strength tests were performed using cubes with 100mm width and cylinders with 100mm diameter and 200mm height in accordance with BS EN 12390-3:2019 [17].

3.3 Concrete mix design and process

The concrete mix designs developed were based on mixes developed in previous work by Kanavaris *et al.* [1] and in addition to GGBS and limestone, pumice powder (ground from pumice aggregates) and Lytash filler were also utilized to achieve low-carbon lightweight concrete for structural applications. The percentage of CEM I replacement with pumice powder and GGBS was 50 and 60%. Five lightweight aggregate concrete mixes were developed by using the pumice aggregate. Additionally, four concrete mixes were developed with Lytag aggregate concrete to understand the contribution of pumice aggregate and powder on concrete strength. The mix proportions are shown in Table 1.

3.4 Preparation of materials

The water absorption of pumice and Lytag aggregate measured was approximately 17% and 15%, respectively. Therefore, this may potentially complicate the mixing process and the control of the water content in the mix. According to previous research [1], it is preferable to soak the aggregates in water for 24 hours prior to mixing and to bring them to a saturated surface dry (SSD) condition just before mixing with other constituents. Prior to mixing, the pumice and Lytag aggregates were pre-soaked for 24 hours. In addition, the sand was oven-dried for 24 hours at 100°C before being mixed, and the additional quantity of water needed according to sand's absorption was added to the mix.

Table 1. Mix Design proportion

Mix ID	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
kg/m^3	**40% CEM II/A-LL 30% GGBS 30% Pumice powder**	**40% CEM I 45% GGBS 15% Pumice powder**	**40% CEM I 30% GGBS 30% Pumice powder**	**50% CEM I 50% GGBS**	**40% CEM I 60% GGBS**	**40% CEM I 60% Pumice powder**	**40% CEM I 60% Pumice powder with Lytash filler**	**40% CEM I 60% GGBS**	**40% CEM I 60% GGBS with limestone filler**
CEM	128	128	128	147	128	148	128	148	128
GGBS	96	144	96	147	192	-	-	222	192
Pumice Powder	96	48	96	-	-	222	192	-	-
Total binder content	320	320	320	294	320	370	320	370	320
Lytash or limestone	50	50	50	70	50	-	50	-	50
Sand 0/4 mm	831	831	831	828	831	846	831	846	831
Pumice aggregate 4/14 mm	683	683	683	698	683	-	-	-	-
LYTAG aggregates 4/14 mm	-	-	-	-	-	640	683	640	683
Normal aggregates 4/10 mm	-	-	-	-	-	-	-	-	-
Free water	142	142	142	136	142	164	142	164	142
Total water	147.57	147.57	147.57	144.28	150.31	172.46	150.31	172.46	150.31
Pump aid	3.75	12.62	11.25	4.25	8.45	10	10	10	10
Free w/b	0.44	0.44	0.44	0.46	0.44	0.44	0.44	0.44	0.44
Calculated theoretical density	2026	2026	2026	2026	2026	2030	2036	2030	2036

3.5 Mixing processes and casting of lightweight aggregate concrete

Firstly, the lightweight aggregate (Pumice/Lytag) on saturated surface-dry (SSD) condition was inserted in the mixer together with the oven dried sand and dry mix the aggregates for 1 minute. Then, the cementitious materials where in the mixer and dry mix the mixture for 1 min. This was then followed by adding the water and admixtures. The mixing was stopped after 2-3 minutes to conduct the slump-flow tests accordance with EN 12350-5:2019 [14] If the slump-flow value was less than the target, mixing was continued and additional admixtures were added, and the process was repeated until the target slump-flow was achieved.

4 Results and discussion

4.1 Pozzolanic behaviour, XRD and Optical microscopic test

The pozzolanic behaviour was studied using the Modified Chapelle test [13] for three different materials: Pumice powder, Lytash, and GGBS. The results are shown in Fig. 2. It is shown that GGBS is the highest pozzolanic material however this may be attributed to GGBS containing substantial amounts of $Ca(OH)_2$ [18]. Pumice powder and Lytash appear to exhibit pozzolanic behaviour as suggested by the high consumption of calcium hydroxide whilst XRD results indicated that pumice powder is mainly formed of an amorphous phase with a minor amount of quartz impurities.

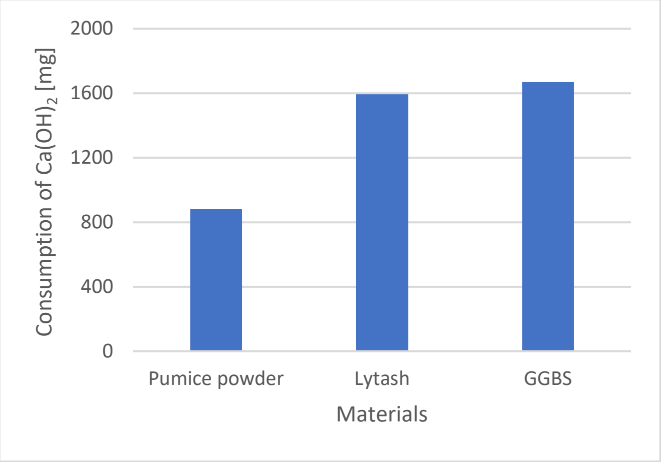

Fig. 2. Comparison of Modified Chapelle test for the materials considered in the present study

4.2 Flow tests

Due to the presence of cement replacement materials, the concrete mixture requires more water content for it to be pumpable and flowable. The presence of higher amount of GGBS and pumice powder along with Lytash filler makes it more challenging to achieve the required flow. In addition, the lightweight aggregates are very porous and absorb a large amount of water. A pump aid admixture was used to balance the water demand and make the concrete flowable and pumpable. The desired value of flow was in the range of 500mm to 600mm and the corresponding quantity of admixtures were added to achieve this flow value. It is noted that on some occasions, high admixture amounts were needed to achieve the required flow. Further investigations are required with respect to identifying suitable admixtures for combinations of Portland cement, pumice powder and GGBS.

4.3 Fresh and oven dried density

Fig. 3. depicts the results of the fresh and oven-dried density tests. The fresh density of lightweight aggregate pumice concrete mixes (Mix 1 to Mix 5) was in the region of 1900 kg/m^3 and the Lightweight aggregate Lytag concrete mixes (Mix 6 to 9) was in the region of 2000 kg/m^3. The oven-dry density of the pumice aggregate mixes (Mix 1 to Mix 5) was in the region of 1700 kg/m3, while the maximum permitted in this study was 1900 kg/m^3. It was generally observed that comparable densities can be achieved with pumice and Lytag aggregate whilst pumice aggregate could result in lower densities owing to its more porous nature compared to Lytag.

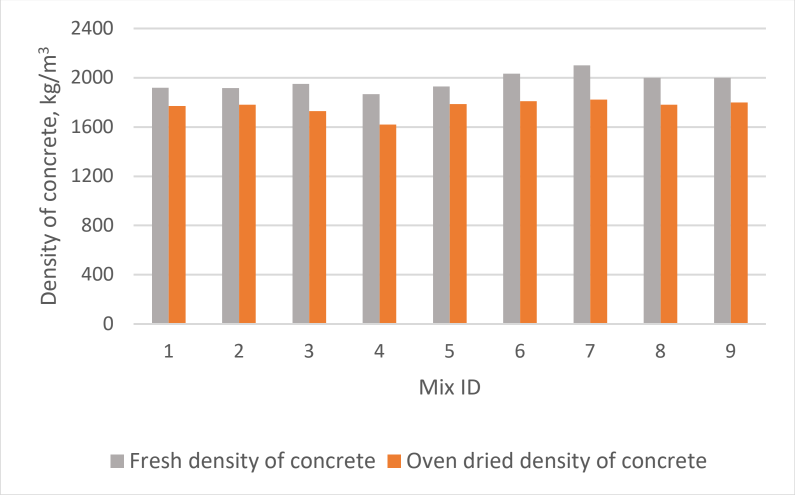

Fig. 3. Result for Fresh and Oven dried density of concrete for the developed mix design

4.4 Compressive strength

The results of the compressive strength of LWAC cube and cylinder specimens tested at 28 days are depicted in Fig.4. The results indicate that the compressive strength of the mixes investigated varies from 18 to 48 MPa which suggests that certain mixes may be suitable for lower strength lightweight aggregate applications, as the target was 40 MPa, to comply with the requirements of LC30/33. Nevertheless, it is demonstrated that is possible to utilize pumice powder as supplementary cementitious material as well as combined with pumice aggregate to produce low-carbon lightweight aggregate concrete. From the pumice powder and aggregate mixes, Mix (2) exhibited the higher strength, probably owing to the lesser addition of pumice powder. However, when compared to the control mixes (Mix 8 and 9) which were prepared with Lytag aggregate and GGBS replacement, the strength decrease for the pumice aggregate/powder mixes becomes more significant. This can be potentially attributed to the lower strength of pumice aggregates compared to Lytag. Regardless, for higher strengths, mixes with lower w/c could be considered.

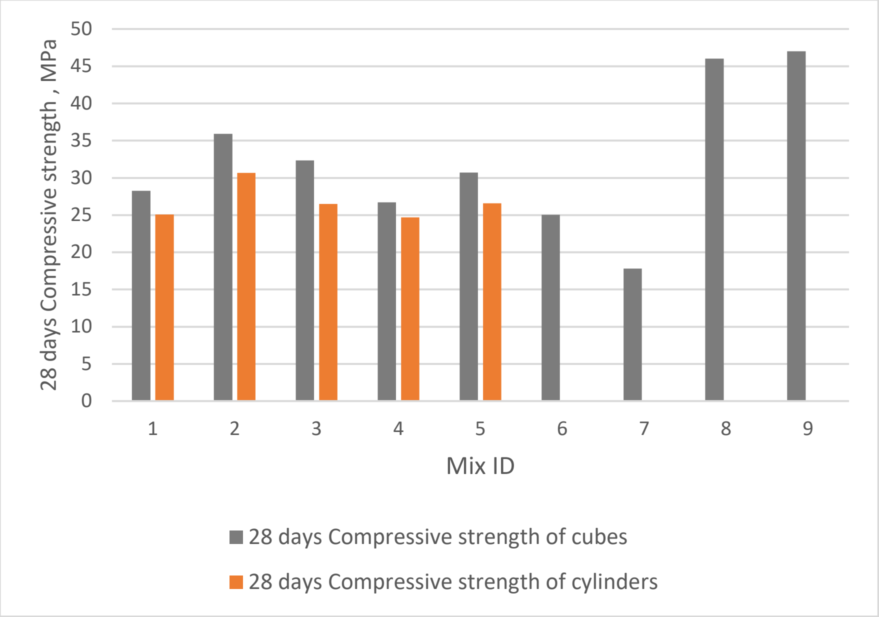

Fig. 4. 28 days measured compressive strength for the developed mix design

4.5 Embodied Carbon

The embodied carbon (life cycle stages A1–A3) of the LWAC mixes was calculated to examine the potential reductions in the carbon footprint of LWAC. Table 2. illustrates the embodied carbon values (‘carbon factors’) of each individual concrete constituent used in the calculations for the mixes in the present study [1, 19, 20]. The carbon factor for pumice powder was determined by adding the value of carbon emission from the energy used to grind pumice from ball mill with carbon factor for pumice stone.

Table 2. Embodied Carbon factors of each concrete constituent used in the calculation for the mix design in this study

Material	**Cradle-to-gate (A1-A3) GWP: kgCO$_2$e/t**	**Source**
CEM	846	[1]
GGBS	50	[1]
Pumice powder	38	[20]
Lytash	249	[1]
Sand 0/4 mm	4	[1]
Pumice 4/14 mm	2	[20]
Lytag aggregate	249	[1]
Water	0.000319	[1]
Pump aid	1670	[1]

The carbon emission analysis, shown in Fig. 5. revealed that the use of pumice aggregates and powder represent a promising alternative in LWAC, which can result in substantial carbon reductions. Particularly for mixes 1 to 5, the calculated embodied carbon was substantially low, and even lower that best practice low-carbon normal weight concrete, in which the A1-A3 emission can vary from 170-230 kgCO$_2$e/m^3. When compared to other mixes with manufactured lightweight aggregates, it is shown that further reductions in embodied carbon can be achieved.

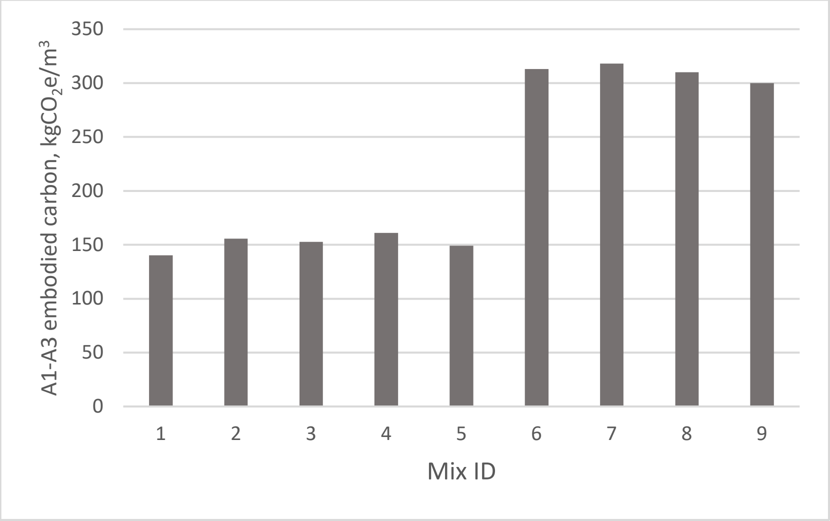

Fig. 5. Calculated embodied carbon for the investigated mixes

Currently, a shortage of GGBS has been experienced in the UK and is expected to become much worse by 2025 (concrete4change [21]). The decrease in availability of GGBS is due to the demand for low-carbon concrete usage in major projects around the UK. Therefore, more environmentally friendly alternatives are required for cement replacement. This study showed that pumice powder can be considered as a supplementary cementitious material and can be used in concrete. In addition, pumice aggregates [22, 23] can also be combined with pumice powder to provide a promising candidate for reducing the carbon footprint of lightweight aggregate concrete.

5 Conclusions

The present study was aimed at investigating the development of low-carbon lightweight aggregate concrete through the incorporation of pumice aggregates, pumice powder, GGBS and Lytash. The following conclusions can be made:

- Pumice aggregate can be used to produce structural lightweight aggregate concrete and represents a credible low-carbon aggregate alternative to manufactured lightweight aggregates.
- Pumice powder can be used as a supplementary cementitious material that can potentially aid the diminishing of availability of GGBS and fly ash.
- Lightweight aggregate concrete mixes were developed with pumice powder and combinations of Portland cement, limestone, GGBS, pumice powder and Lytash filler. It was demonstrated that structural lightweight aggregate concrete can be developed with these combinations.
- Through conducting embodied carbon calculations, it was demonstrated that is possible to achieve significant reduction in embodied carbon by considering pumice aggregate combined with and pumice powder as an alternative supplementary cementitious material.

6 References

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