Anti-Spalling And High-Strength Lightweight Aggregate Concrete

Cross-Reference To Related Application

This application claims the benefit of priority of Singapore Patent Application No. 10202012797R filed on 18 December 2020, the contents of it being hereby incorporated by reference in its entirety for all purposes.

Technical Field

The present invention relates to a composition for concrete, a method of preparing the composition and a concrete structure comprising the composition.

Background Art

More and more high-rise buildings are needed to cater for the rapidly growing demands of urbanisation. To overcome the challenges of construction speed, productivity and quality control, innovative construction methods such as modular construction has been encouraged in many countries. Since modular construction requires ease of transportation and assembly of the modular elements, a concrete of high-strength and lightweight is preferred.

Structural lightweight concrete is generally defined as a concrete having an equilibrium density between 1120 and 1920 kg/m^3 and a minimum 28-day compressive strength of 17.24 MPa (ACI 213R-03). It has been widely used because it makes use of local industrial waste that can be economically utilized and the reduction in concrete weight helps for easy removal, transport and erection of precast products. It also has many other advantages including lower thermal connectivity as well as maximized heat and sound insulation properties for its porous structure.

Structural lightweight aggregate concrete (LWAC) offers design flexibility and cost savings through the reduction of dead load and this greatly offsets the slightly higher cost of producing each unit of LWAC. Further, LWAC has better resistance under elevated temperatures as compared with normal strength concrete and as outlined in ACI 216.1, Code Requirements for Determining Fire Resistance of Concrete and Masonry Construction Assemblies, the thickness of slabs may be reduced which contributes to the further reduction of concrete volumes.

Using lightweight aggregates helps lower the self-weight, but at the same time, it may cause a sharp reduction in the compressive strength of concrete. Further, high-strength concrete is more susceptible to spalling and may result in lower fire resistance.

Spalling is the result of water entering concrete and forcing the surface to peel, pop out, or flake off. Explosive spalling occurs when fire-exposed concrete violently spalls, where entire cross-sections may be destroyed, thus substantially reducing the load-bearing capacity of a

construction. Therefore, explosive spalling at high temperatures must be effectively dealt with in order to maximise the benefits structural LWAC brings about.

Several mechanisms have been put forward to explain spalling of concrete exposed to fire, such as induced thermal stress (between the exterior layer and the interior of concrete) and vapor pressure. High temperatures can cause the water in the pore spaces of the concrete to vaporise, increasing the vapour pressure in the pores and inducing spalling on the exterior surface.

In recent years, it has been found that concrete porosity may be the underlying factor that adversely affects lightweight concrete's resistance to elevated temperatures. Porosity of a concrete is the measure of how much open spaces or voids are present and porosity is often linked to the permeability of the concrete. Permeability is the ability of fluid to flow through these voids and if these voids are well connected, a concrete is said to be highly permeable. It is important to note that it is possible for a porous concrete to not be significantly permeable and thus have a closed pore system if the open voids are not well connected throughout (Fig. 1A to 1D).

Usually, thermal crack patterns tend to follow a concrete's weakest zone, or the interfacial transition zone (ITZ). However, for the case of very porous lightweight aggregate concrete (LWAC), cracks tend to follow a path inside specifically porous aggregates (Fig. 1E). This leads to an uneven distribution of cracks in the concrete matrix. With the higher porosity leading to a higher moisture content inside the concrete, pore vapor pressure and thermal gradient increase. Spalling is worsened in concrete with lower permeability, where vapour cannot escape quickly enough.

In order to reduce explosive spalling, a concrete mix of low moisture content and high permeability is desired. The permeability of a concrete is primarily dependent on the hardened cement paste and voids between the aggregates. Therefore, the size of the voids is crucial. Larger voids increase permeability of the concrete and allow for more cement paste to be filled .

There is therefore a need for development of a concrete composition that overcomes or at least ameliorates, one or more of the disadvantages described above. That is, there is a need for a concrete composition that maintains all of the advantageous properties of a conventional lightweight concrete having high strength suitable for structural use, while preventing it from explosive spalling during fire exposure.

Summary

In an aspect, there is provided a composition comprising:

about 28 % to about 42 % by weight of a binder;

about 3 % to about 7 % by weight of cenospheres;

about 35 % to about 50 % by weight of sand;

about 8 % to about 13 % by weight of a lightweight coarse aggregate;

about 0.05 % to about 0.5 % by weight of a first fibre; and

about 1 % to about 4 % by weight of a second fibre,

wherein the total weight of the composition adds to 100 %.

In an example, the composition may further comprise water in an amount such that the water:binder ratio by weight is in the range of about 0.2 to about 0.3.

In another example, the composition may further comprise about 0.5 % to about 1 % by weight of a superplasticizer.

Advantageously, the composition as defined above may have the combined properties of anti-spalling, high-strength and lightweight due to a proportional mix of hybrid fibres in a high-strength lightweight concrete. Compared to other lightweight concretes, the composition as defined above may have a relatively high early strength and significantly higher modulus of elasticity even when cured in ambient air. More importantly, the composition as defined above may show better performance of flexure strength, ductility and workability. Further, the composition as defined above may resist explosive spalling while maintaining excellent mechanical properties during exposure to fire.

Advantageously, the composition as defined above may reach a 1-day strength of more than 26.7 MPa even at ambient air curing. This may facilitate the use of the composition in pre-fabricated or pre-cast construction materials, which are required to have sufficient strength to be transported out of the precast plants as early as 1 to 3 days after production.

Further advantageously, the composition as defined above may meet structural requirements of having a 28-day compressive strength of at least 40 MPa with air-dried density not exceeding 1850kg/m^3 by varying water to binder ratio and cenosphere to sand ratio.

Further advantageously, the Young's modulus of the composition as defined above may be much higher than that of commonly used lightweight concrete. The Young's modulus of the composition as defined above may be close to that of normal concrete, which is about 25-30 GPa. The high modulus of elasticity of the composition as defined above may be attributed to the strength of the matrix and its strong bond to the aggregates.

Advantageously, the two main reasons for spalling, that is pore pressure and thermal stress, may be effectively dealt with by lowering water content of the concrete mix and increasing the permeability of the concrete. The composition as defined above comprises a first fibre such as polypropylene (PP) which may melt in high temperature conditions to create channels or pore systems to allow for vapour pressure to escape, thereby preventing explosive spalling.

Further advantageously, the composition as defined above comprises a second fibre such as steel fibre, which may maintain the low density and high compressive strength of the composition as well as improve its ductility and workability.

Advantageously, the composition as defined above may not spall when subjected to high temperatures of up to 800 °C and the residual compressive strength after exposure to high temperatures at 800°C may still be as high as 28 %, which is considered to be of a better fire performance than normal concrete.

In another aspect, there is provided a method of preparing a composition as defined above, comprising the steps of:

a) mixing about 28 % to about 42 % by weight of a binder, about 3 % to about 7 % by weight of cenospheres and about 35 % to about 50 % by weight of sand to form a dry mix;

b) mixing a first volume of water with the dry mix to form a first wet mix;

c) mixing about 0.5 % to about 1 % by weight of a superplasticizer with a second volume of water to form a second wet mix;

d) mixing the first wet mix with the second wet mix to form a third wet mix;

e) mixing about 0.05 % to about 0.5 % by weight of a first fibre, about 1 % to about 4 % by weight of a second fibre, and about 8 % to about 13 % by weight of a lightweight coarse aggregate with the third wet mix to form the composition,

wherein step e) further comprises a step of soaking the lightweight coarse aggregate in soaking water before mixing with the third wet mix;

wherein the first volume of water in step b) and the second volume of water in step c) are mixed such that in combination, the water-binder ratio by weight of the composition is in the range of about 0.2 to about 0.3; and

wherein the total weight of the composition adds to 100 %.

Advantageously, the composition may be prepared using local industrial waste and may be a useful application to the local construction scene.

In another aspect, there is provided a concrete structure comprising the composition as defined above.

Definitions

The following words and terms used herein shall have the meaning indicated:

The term "lightweight coarse aggregate" as defined herein refers to construction materials comprising predominantly cellular and granular inorganic materials that have a bulk density of more than 200 kg/m^3 and less than 880 kg/m^3.

The word "substantially" does not exclude "completely" e.g. a composition which is "substantially free" from Y may be completely free from Y. Where necessary, the word "substantially" may be omitted from the definition of the invention.

Unless specified otherwise, the terms "comprising" and "comprise", and grammatical variants thereof, are intended to represent "open" or "inclusive" language such that they include recited elements but also permit inclusion of additional, unrecited elements.

As used herein, the term "about", in the context of concentrations of components of the formulations, typically means +/- 5 % of the stated value, more typically +/- 4 % of the stated value, more typically +/- 3 % of the stated value, more typically, +/- 2 % of the stated value, even more typically +/- 1 % of the stated value, and even more typically +/- 0.5 % of the stated value.

Throughout this disclosure, certain embodiments may be disclosed in a range format. It should be understood that the description in range format is merely for convenience and brevity and should not be construed as an inflexible limitation on the scope of the disclosed ranges. Accordingly, the description of a range should be considered to have specifically disclosed all the possible sub-ranges as well as individual numerical values within that range. For example, description of a range such as from 1 to 6 should be considered to have specifically disclosed sub-ranges such as from 1 to 3, from 1 to 4, from 1 to 5, from 2 to 4, from 2 to 6, from 3 to 6 etc., as well as individual numbers within that range, for example, 1, 2, 3, 4, 5, and 6. This applies regardless of the breadth of the range.

Certain embodiments may also be described broadly and generically herein. Each of the narrower species and subgeneric groupings falling within the generic disclosure also form part of the disclosure. This includes the generic description of the embodiments with a proviso or negative limitation removing any subject matter from the genus, regardless of whether or not the excised material is specifically recited herein.

Brief Description of Drawings

The accompanying drawings illustrate a disclosed embodiment and serve to explain the principles of the disclosed embodiment. It is to be understood, however, that the drawings are designed for purposes of illustration only, and not as a definition of the limits of the invention.

Fig. 1

[Fig. 1] refers to a series of schematic diagrams from the prior art indicated for reference only, showing the differences between porosity and permeability: (A) high porosity and low

permeability, (B) high porosity and high permeability, (C) high porosity and no permeability and (D) low porosity and high permeability, and (E) difference in fracture paths in lightweight and normal weight concrete.

Fig. 2

[Fig. 2] refers to photographic images of (A) the top view of over-compacted specimens, (B) bottom view of over-compacted specimens and (C1) bottom and (C2) top view of ideally compacted specimens.

Fig. 3

[Fig. 3] refers to a series of photographic images showing the explosive spalling of concrete having a W/B ratio of 0.42 without any PP fibre. (A) shows the general view after heating, (B) and (C) show a close-up view of the samples after spalling, and (D) shows a spalled sample compared to a sample before heating.

Fig. 4

[Fig. 4] refers to a photographic image showing the explosive spalling of concrete having a W/B ratio of 0.24 without any PP fibre.

Fig. 5

[Fig. 5] refers to a graph showing the compressive strength of LWAC with different fibre compositions (no fibre (reference), 0.2 vol% PP and 0.2 vol% PP + 0.5 vol% steel fibre) against age. Dotted line indicates rough estimation of compressive strength. In the figure legend, WB×× refers to water to binder ratio where ×× is in weight %; PP××ST×× refers to PP and steel fibre contents where ×× is in volume%; and A/S/W×× refers to ambient/steam/water curing where ×× are the number of days cured.

Fig. 6

[Fig. 6] refers to a graph showing the stress-strain relationship of reference specimens at 7 days.

Fig. 7

[Fig. 7] refers to a graph showing the stress-strain relationship of specimens containing 0.2 vol% PP at 7 days.

Fig. 8

[Fig. 8] refers to a graph showing the stress-strain relationship of reference specimens at 28 days.

Fig. 9

[Fig. 9] refers to a graph showing the stress-strain relationship of specimens containing 0.2 vol% PP at 28 days.

Fig. 10

[Fig. 10] refers to a graph showing the relative residual (mean) compressive strength after exposure to elevated temperatures.

Detailed Disclosure of Optional Embodiments

There is provided a composition comprising:

about 28 % to about 42 % by weight of a binder;

about 3 % to about 7 % by weight of cenospheres;

about 35 % to about 50 % by weight of sand;

about 8 % to about 13 % by weight of a lightweight coarse aggregate;

about 0.05 % to about 0.5 % by weight of a first fibre; and

about 1 % to about 4 % by weight of a second fibre,

wherein the total weight of the composition adds to 100 %.

The composition may be for a lightweight aggregate concrete (LWAC). A LWAC may be a lightweight concrete where natural aggregates may be replaced entirely or partially with aggregates containing a large number of voids.

Besides the improved functionality, the use of LWAC may be predicated based on the reduction of project cost.

LWAC may be generally perceived to have better fire performance than normal concrete at elevated temperature levels due to its lower thermal conductivity due to the presence of voids in the concrete. LWAC may have a lower coefficient of thermal expansion compared to normal concrete and this may be primarily due to the lower density. The lower thermal conductivity of the lightweight concrete may allow the concrete reinforcement to be better insulated at high temperatures, thus extending the structural life of the concrete.

Unlike other lightweight concretes such as no-fines concrete where fine aggregates may be omitted from the mix to create air-filled voids, or aerated concrete, where bubbles of gas may be entrained in a cement paste or mortar mix, LWAC, where natural aggregates may be replaced entirely or partially with aggregates containing a large number of voids, may be used in structural applications.

Binder

The composition may comprise about 28 % to about 42 %, about 28 % to about 30 %, about 28 % to about 35 %, about 28 % to about 40 %, about 30 % to about 35 %, about 30 % to about 40 %, about 35 % to about 42 %, or about 40 % to about 42 % by weight of a binder.

The binder may comprise cement and a pozzolanic filler.

The binder may comprise about 25 % to about 36 %, about 25 % to about 28 %, about 25 % to about 30 %, about 25 % to about 33 %, about 28 % to about 30 %, about 28 % to about 33 %, about 28% to about 36 %, about 30 % to about 33 %, about 30 % to about 36 % or about 33 % to about 36% by weight of cement.

The cement may be Portland cement CEM 52.5 (ASTM Type I), Portland cement CEM 42.5 (ASTM Type I), Portland Pozzolana Cement (PPC), Rapid Hardening Cement, Extra Rapid Hardening Cement, Low Heat Cement, Sulfates Resisting Cement, Quick Setting Cement, Blast Furnace Slag Cement and any mixture thereof.

One method for improving cement physicomechanical properties may be to introduce suitable supplementary cementing materials or fillers to the concrete mix. For instance, addition of small dosages of pozzolanic fillers such as silica fume may be one way of enhancing compressive strength of concrete.

The binder may comprise about 3 % to about 6 %, about 3 % to about 4 %, about 3 % to about 5%, about 4 % to about 5 %, about 4 % to about 6 % or about 5 % to about 6 % by weight of a pozzolanic filler.

Any material capable of binding calcium hydroxide in the presence of water may be a pozzolanic filler.

The pozzolanic filler may be selected from the group consisting of silica fume, microsilica, nanosilica, furnace slag, fly ash, glass powder, rice husk ash and any mixture thereof.

The pozzolanic filler may be silica fume. By adding silica fume, development of early strength of a lightweight concrete (of 7 days) may become higher than that of normal weight concrete. This may be due to improvement of the interfacial bonds between the lightweight aggregate and cement paste. Silica fume particles may surround each cement particle and fill up the voids with strong hydration products.

The pozzolanic filler may be ecological materials such as fly ash. Other than improving cement properties, pozzolanic fillers may aim to better control rheological properties of a concrete mix as well as reduce cement consumption.

Cenosphere

The composition may comprise about 3 % to about 7 %, about 3 % to about 4 %, about 3 % to about 5 %, about 3 % to about 6 %, about 4 % to about 5 %, about 4 % to about 6 %, about 4 % to about 7 %, about 5 % to about 6 %, about 5 % to about 7 % or about 6 % to about 7 % by weight of cenospheres.

Cenospheres may be used as a fine aggregate.

Cenospheres (CS) may be formed alongside ash during combustion of coal, wood, oil and domestic waste. The word cenosphere literally means "hollow sphere" in Greek since its cavity is filled solely with gas. Its spherical shape may make it highly workable. CS may be obtained as a result of granulation of a melted coal mineral and flushing of broken fine droplets with internal gases.

The specific composition and microstructure of CS may depend on coal composition and combustion conditions in a boiler combustion chamber, which may vary within the limits of 1400 - 17600°C. Very light fractions of CS may have very low bulk density of about 0.3 - 0.5 g/cm^3 and therefore may be accumulated within the surface layer of ash in settling tanks. CS may be predominantly made up of mullite, a rare silicate mineral that may be the only chemically stable intermediate phase in the SiO_2–$Al2O_3$ system. Hence, it may be highly inert and suitable as a filler.

CS may be added to the composition in the production stage, providing cement with new properties and lower cost. The spherical shape of CS may facilitate reduction in water requirement, heat of hydration and increases concrete strength. It has been established that CS may exhibit low thermal conductivity, high ultimate strength in compression and thermal stability. These properties, alongside its low density, may indicate CS to be a very suitable replacement to the usual lightweight aggregates.

CS may be a greener alternative to sand in concrete mixes. The presence of cenospheres may also increase the permeability of a concrete, which may negate the effects of explosive spalling.

The CS may be hollow or may comprise a void. One way of increasing permeability of the concrete may be to increase the amount of cement paste filled in the voids of the CS. Hollow CS may be filled up partially by cement paste, and this suggests that CS may be used to alleviate spalling effects to some extent.

The void of the CS as defined above may be partially filled with the binder. The void of the CS as defined above may become partially filled with the binder when mixed with the binder. The CS may be filled with the binder in a range of about 75 % to about 95 % by volume of the void of the CS. The CS may be filled with the binder in a range of about 75 % to about 80 %, about 75 % to about 85 %, about 75 % to about 90 %, about 80 % to about 85 %, about 80 % to about 90 %, about 80 % to about 95 %, about 85 % to about 90 %, about 85 % to about 95 % or about 90 % to about 95 % by volume of the void of the CS.

Sand

The composition may comprise about 35 % to about 50 %, about 35 % to about 40 %, about 35 % to about 45 %, about 40 % to about 45 %, about 40 % to about 50 % or about 45 % to about 50 % by weight of sand.

Sand may be used as a fine aggregate.

The sand may be silica sand, natural sand or river sand.

Silica sand may be a type of industrial sand, which may be used in construction applications in place of river sand. River sand may separately be used in lightweight concrete. In addition, quarry dust and other manufactured sand may also be used in the concrete mix.

The sand may have a particle size of less than 2 mm, less than 1.5 mm, less than 1 mm or less than 0.5 mm. The sand may have a particle size of at least 50 μm.

Lightweight Coarse Aggregate (LWCA)

The composition may comprise about 8 % to about 13 %, about 8 % to about 9 %, about 8 % to about 10 %, about 8 % to about 11 %, about 8 % to about 12 %, about 9 % to about 10 %, about 9 % to about 11 %, about 9 % to about 12 %, about 9 % to about 13 %, about 10 % to about 11 %, about 10 % to about 12 %, about 10 % to about 13 %, about 11 % to about 12 %, about 11 % to about 13 % or about 12 % to about 13 % by weight of a lightweight coarse aggregate.

Lightweight aggregates may be of natural (volcanic) origin. Pumice, scoria and tuff may be used as both coarse and fine aggregate. Other natural aggregates may include saw dust, rice husk and diatomite derived from remains of microscopic aquatic plants.

With the increase in demand and non-availability of natural lightweight aggregates, various techniques have been developed to produce them artificially. This may include aggregates prepared by expanding, pelletizing, or sintering natural raw products such as clay, fly ash, shale or slate, as well as from industrial by-products such as blast-furnace slag and bed ash. Foamed slag may be a lightweight aggregate suitably used in reinforced concrete. Sintered pulverised fuel ash aggregate may be used for a variety of structural purposes while expanded clays and shales may be capable of achieving concrete of considerable high strength. Other less common artificial aggregates may include exfoliated vermiculite, ciders, clinkers and breeze.

As indicated in ASTM C330/C330M, Standard specification for lightweight aggregates for structural concrete, bulk density of fine aggregate needs to be less than 1120 kg/m^3 and less than 880 kg/m^3 for coarse aggregate.

The lightweight coarse aggregate (LWCA) as defined herein may have a bulk density of less than 880 kg/m^3.

The LWCA may be selected from the group consisting of lightweight expanded clay aggregate (LECA), lightweight expanded shale aggregate, lightweight expanded slate aggregate, foamed slag, sintered pulverised fuel ash aggregate, and any mixture thereof.

The LWCA may be LECA. The raw material of LECA may be clay, which is abundant on a global scale. LECA may be a special type of pure natural clay that has been pelletized and fired at 1200°C in rotary kilns for 3 hours. The organic compounds in the clay may burn off and the yielding gases may force the clay pellets to expand to a honeycombed structure. The outer surface of each granule may melt and be sintered.

LECA may have an approximately round or potato shape and this may increase workability of the concrete due to ball bearing effect. The interior of LECA may comprise many inter-connected air cavities and this may contribute to the lightness of the concrete. LECA may also be highly inert with a natural pH value of nearly 7, and may have excellent thermal insulation and fire resistance due to its low thermal conductivity.

The stability of coarse aggregates already heated to high temperatures of about 1000 °C may also contribute to the better fire resistance of lightweight concrete over normal concrete.

It may be more economical to use LECA in LWAC as it may confer a higher strength to density ratio to the concrete than normal weight concrete (NWC). LECA may have a higher compression strength as compared to LWAC made with crushed lightweight bricks.

Prewetting the porous LECA expanded clay aggregate before usage may allow for better cement hydration process, leading to better control of the water to cement ratio as less water may be absorbed during mixing.

By increasing the pre-wetting time of the aggregate, the strength and the workability of the concrete may increase as well. The high workability of fresh concrete may be attributed to the localised high water content at the surface of these pre-wetted aggregates. The surface pores of the aggregate shell may absorb the water built-up at the cement-aggregate transition phase thus may result in lower water content at the transition zone. A good mechanical bonding between the cement and the aggregate interface may be observed. This loss of fluidity at the transition zone may suggest an increase in permeability of the lightweight concrete.

The LWCA may have a diameter in the range of about 4 mm to about 20 mm, about 4 mm to about 10 mm, about 4 mm to about 15 mm, about 10 mm to about 15 mm, about 10 mm to about 20 mm or about 15 mm to about 20 mm. The compressive and flexure strength of the concrete may decrease if lightweight coarse aggregates larger than 20 mm are used.

The LWCA may be LECA with a maximum size of about 8 mm.

Fibres

ACI 318: Building Code Requirements for Structural Concrete and Commentary defines modulus of elasticity as a function of density and compressive strength. Essentially, a lower elasticity value

for lightweight concrete may mean it is more flexible. Reduced stiffness may be beneficial, especially for structural lightweight concrete.

Addition of fibres to a concrete composite may have some beneficial effects on the specific toughness of the concrete.

First Fibre

The composition may comprise about 0.05 % to about 0.5 %, about 0.05 % to about 0.1 %, about 0.05 % to about 0.2%, about 0.1 % to about 0.2 %, about 0.1 % to about 0.5 % or about 0.2 % to about 0.5 % by weight of a first fibre.

The first fibre may be selected from the group consisting of polypropylene fibre, nylon fibre, rubberized fibre and any mixture thereof.

The rubberized fibre may be crumb rubber.

To directly counter the effects of (explosive) spalling, usage of polypropylene (PP) fibres may be most effective. PP fibre may melt when exposed to high temperatures such as during a fire to form extensive channels or a pore system, allowing for vapour pressure to escape out of the concrete.

Addition of PP fibres to concrete mass may therefore provide significant reduction of spalling.

The first fibre may be a monofilament cylindrical fibre.

The first fibre may have a length in the range of about 6 mm to about 20 mm, about 6 mm to about 9 mm, about 6 mm to about 12 mm, about 6 mm to about 15 mm, about 6 mm to about 18 mm, about 9 mm to about 12 mm, about 9 mm to about 15 mm, about 9 mm to about 18 mm, about 9 mm to about 20 mm, about 12 mm to about 15 mm, about 12 mm to about 18 mm, about 12 mm to about 20 mm, about 15 mm to about 18 mm, about 15 mm to about 20 mm or about 18 mm to about 20 mm.

The first fibre may have a diameter in the range of about 10 µm to about 40 µm, about 10 µm to about 15 µm, about 10 µm to about 20 µm, about 10 µm to about 25 µm, about 10 µm to about 30 µm, about 10 µm to about 35 µm, about 15 µm to about 20 µm, about 15 µm to about 25 µm, about 15 µm to about 30 µm, about 15 µm to about 35 µm, about 15 µm to about 40 µm, about 20 µm to about 25 µm, about 20 µm to about 30 µm, about 25 µm to about 35 µm, about 25 µm to about 40 µm, about 30 µm to about 35 µm, about 30 µm to about 40 µm or about 35 µm to about 40 µm.

The first fibre may be a monofilament cylindrical PP fibre having a length between 9 mm and 12 mm and a diameter between 15 µm and 30 µm.

The optimum PP fibre dosage may be 0.1 % by weight. At 0.24 W/B ratio, residual compressive strength after exposure to heat at 800°C may be at about 28%.

Second Fibre

The composition may comprise about 1 % to about 4 %, about 1 % to about 2 %, about 1 % to about 3 %, about 2 % to about 3 %, about 2 % to about 4 %, or about 3 % to about 4 % by weight of a second fibre.

The second fibre may be selected from the group consisting of steel fibre, glass fibre, carbon fibre and polyethylene fibre and any mixture thereof.

The second fibre may be steel fibre. Adding a small dosage of steel fibres may increase compressive strength and ductility of the concrete. Further, the usage of steel fibres may be effective in minimising degradation of compressive strength after exposure to elevated temperatures.

The presence of steel fibre in a hybrid fibre composite may minimise the negative effects of PP fibres on compressive strength.

Steel fibres may have different geometric properties of varying diameter, length and surface coarseness, and these properties may influence the anchorage and adhesiveness of the cement matrix. The steel fibre may be of a hooked shaped, a crimpled shape, may have a deformed end such as a cone shape at the end, or may be a deformed wire.

The second fibre may have a length in the range of about 30 mm to about 40 mm, about 30 mm to about 32 mm, about 30 mm to about 34 mm, about 30 mm to about 36 mm, about 30 mm to about 38 mm, about 32 mm to about 34 mm, about 32 mm to about 36 mm, about 32 mm to about 38 mm, about 32 mm to about 40 mm, about 34 mm to about 36 mm, about 34 mm to about 38 mm, about 34 mm to about 40 mm, about 36 mm to about 38 mm, about 36 mm to about 40 mm or about 38 mm to about 40 mm.

The second fibre may have a width in the range of about 0.5 mm to about 0.75 mm, about 0.5 mm to about 0.6 mm, about 0.6 mm to about 0.7 mm, about 0.6 mm to about 0.7 mm, about 0.6 mm to about 0.75 mm or about 0.7 mm to about 0.75 mm.

The second fibre may have a length of about 35 mm and a width of about 0.62 mm.

Water to binder (W/B) ratio

The composition may further comprise water in an amount such that the water:binder ratio by weight may be in the range of about 0.2 to about 0.3, about 0.2 to about 0.22, about 0.2 to about 0.24, about 0.2 to about 0.26, about 0.2 to about 0.28, about 0.22 to about 0.24, about 0.22 to about 0.26, about 0.22 to about 0.28, about 0.22 to about 0.3, about 0.24 to about 0.26, about 0.24 to about 0.28, about 0.24 to about 0.3, about 0.26 to about 0.28, about 0.26 to about 0.3 or about 0.28 to about 0.3.

The water to binder ratio may significantly affect important concrete properties such as rheology, mechanical properties, permeability and durability.

Early mechanical properties may be linked primarily to the water to cement (W/C) or water to binder (W/B) ratio of a concrete mix. Cement particles may react readily with water and form the first hydrates that may contribute to the strength of the cement paste. Other supplementary cementitious materials (SCM) such as fly ash may react at a much slower rate. The superficial hydrates on the surface of the cement particles may then react quickly with the SCM particles to form strong bonds. The concrete matrix may become even stronger when these SCM particles start to react with the lime liberated by the hydration of cement particles. Therefore, both the early and the long-term compressive strength of blended cements (cement with SCM) may essentially depend on the W/C or W/B ratio of the system.

The water-binder ratio as defined herein may confer the highest strength to the concrete. The optimum W/B ratio may be about 0.24 where high strength lightweight concrete of about 51.5 MPa at 28 days may be achieved. The corresponding density may be 1755 kg/m^3.

To achieve a W/B ratio of about 0.2 to about 0.3, the composition may comprise about 6 % to about 10 %, about 6 % to about 7 %, about 6 % to about 8 %, about 6 % to about 9 %, about 7 % to about 8 %, about 7 % to about 9 %, about 7 % to about 10 %, about 8 % to about 9 %, about 8 % to about 10 % or about 9 % to about 10 % by weight of water.

Superplasticizer

When cement particles react with water molecules, they may have a natural tendency to clump together into a floc and to trap water within. Water required for workability may then be unavailable and it may become necessary to increase the water dosage (water to cement (W/C) ratio or water to binder (W/B) ratio) to increase the workability. However, increasing the water content in a mix may create large capillary pores in the matrix which may decrease concrete compressive strength and durability.

With the introduction of superplasticizers (SP), it may be possible to drastically decrease the W/B ratio yet maintain workability due to the efficient dispersing properties of SP molecules.

The composition may therefore further comprise about 0.5% to about 1 %, about 0.5 % to about 0.6 %, about 0.5 % to about 0.7 %, about 0.5 % to about 0.8 %, about 0.5 % to about 0.9 %, about 0.6 % to about 0.7 %, about 0.6 % to about 0.8 %, about 0.6 % to about 0.9 %, about 0.6 % to about 1 %, about 0.7 % to about 0.8 %, about 0.7 % to about 0.9 %, about 0.7 % to about 1 %, about 0.8 % to about 0.9 %, about 0.8 % to about 1 % or about 0.9 % to about 1 % by weight of a superplasticizer.

The superplasticizer may be selected from the group consisting of sulfonated naphthalene formaldehyde condensate, sulfonated melamine formaldehyde condensate, acetone formaldehyde condensate, polycarboxylate ethers and any mixture thereof.

The superplasticizer may influence the set behaviour of the composition by acting as a water-reducer.

The superplasticizer may be based on a high molecular weight polymer resin. The superplasticizer may reduce the W/C or W/B ratio which means that the mechanical strength and wear and weathering resistance of the cement composition when set or hardened may be increased and shrinkage which causes cracking may be reduced. The superplasticizer may be added to the composition in the form of an aqueous solution (or water-based liquid) or as a dry-spray powder.

Compositions

There is provided a composition comprising:

about 28 % to about 42 % by weight of a binder;

about 3 % to about 7 % by weight of cenospheres;

about 35 % to about 50 % by weight of sand;

about 8 % to about 13 % by weight of a lightweight coarse aggregate;

about 0.05 % to about 0.5 % by weight of a first fibre; and

about 1 % to about 4 % by weight of a second fibre,

wherein the total weight of the composition adds to 100 %.

There is provided a composition comprising:

about 28 % to about 42 % by weight of a binder;

about 3 % to about 7 % by weight of cenospheres;

about 35 % to about 50 % by weight of sand;

about 8 % to about 13 % by weight of a lightweight coarse aggregate;

about 0.05 % to about 0.5 % by weight of a first fibre;

about 1 % to about 4 % by weight of a second fibre; and

about 6 % to about 10 % by weight of water;

wherein the total weight of the composition adds to 100 %.

There is provided a composition comprising:

about 28 % to about 42 % by weight of a binder;

about 3 % to about 7 % by weight of cenospheres;

about 35 % to about 50 % by weight of sand;

about 8 % to about 13 % by weight of a lightweight coarse aggregate;

about 0.05 % to about 0.5 % by weight of a first fibre;

about 1 % to about 4 % by weight of a second fibre,

about 6 % to about 10% by weight of water; and

about 0.5% to about 1% by weight of a superplasticizer;

wherein the total weight of the composition adds to 100 %.

Lightweight concrete cast based on the composition as outlined above may have a high 1-day strength of 28.2 MPa.

Method of Preparation

There is provided a method of preparing a composition as defined above, comprising the step of mixing: about 28 % to about 42 % by weight of a binder; about 3 % to about 7 % by weight of cenospheres; about 35 % to about 50 % by weight of sand; about 8 % to about 13 % by weight of a lightweight coarse aggregate; about 0.05 % to about 0.5 % by weight of a first fibre; and about 1 % to about 4 % by weight of a second fibre, wherein the total weight of the composition adds to 100 %.

The method as defined above may result in the preparation of a dry mix.

The dry mix may be thoroughly mixed to form a homogeneous mixture.

The method may further comprise the step of mixing about 6 % to about 10 % by weight of water with the dry mix.

The method may further comprise the step of mixing about 0.5 % to about 1 % by weight of a superplasticizer with the dry mix.

The water may be mixed with the dry mix first before mixing the superplasticizer therein.

Alternatively, the method may comprise the step of first mixing about 6 % to about 10 % by weight of water with about 0.5 % to about 1 % by weight of a superplasticizer to form an aqueous solution, and secondly mixing the aqueous solution with the dry mix.

There is also provided a method of preparing a composition as defined above, comprising the steps of:

a) mixing about 28 % to about 42 % by weight of a binder, about 3 % to about 7 % by weight of cenospheres and about 35 % to about 50 % by weight of sand to form a dry mix;

b) mixing a first volume of water with the dry mix to form a first wet mix;

c) mixing about 0.5 % to about 1 % by weight of superplasticizer with a second volume of water to form a second wet mix;

d) mixing the first wet mix with the second wet mix to form a third wet mix;

e) mixing about 0.05 % to about 0.5 % by weight of a first fibre, about 1 % to about 4 % by weight of a second fibre, and about 8 % to about 13 % by weight of a lightweight coarse aggregate with the third wet mix to form the composition,

wherein step e) further comprises a step of soaking the lightweight coarse aggregate in soaking water before mixing with the third wet mix;

wherein the first volume of water in step b) and the second volume of water in step c) are mixed such that in combination, the water:binder ratio by weight of the composition is in the range of about 0.2 to about 0.3, and

wherein the total weight of the composition adds to 100 %.

After the soaking step, the lightweight coarse aggregate may have a water content in the range of about 10 % to about 22 %, about 10 % to about 12 %, about 10 % to about 15 %, about 10 % to about 17 %, about 10 % to about 20 %, about 12 % to about 15 %, about 12 % to about 17 %, about 12 % to about 20 %, about 12 % to about 22 %, about 15 % to about 17 %, about 15 % to about 20 %, about 15 % to about 22 %, about 17 % to about 20 %, about 17 % to about 22 % or about 20 % to about 22 % by weight. After the soaking step, the lightweight coarse aggregate may have a water content in the range of about 15 % to about 17 % by weight.

The first volume of water in step b) and the second volume of water in step c) may be substantially the same volume.

The mixing steps a) to e) may each independently be performed in air at atmospheric pressure and at a temperature in the range of about 20 °C to about 35 °C, about 20 °C to about 25 °C, about 20 °C to about 30 °C, about 25 °C to about 30 °C, about 25 °C to about 35 °C or about 30 °C to about 35 °C.

The composition may be further cured in air or water at atmospheric pressure and at a temperature in the range of about 20 °C to about 90 °C, about 20 °C to about 40 °C, about 20 °C to about 60 °C, about 20 °C to about 80 °C, about 40 °C to about 60 °C, about 40 °C to about 80 °C, about 40 °C to about 90 °C, about 60 °C to about 80 °C, about 60 °C to about 90 °C or about 80 °C to about 90 °C.

Concrete structure

There is also provided a concrete structure comprising the composition as defined above.

The concrete structure may be a pre-fabricated structure.

The pre-fabricated structure is selected from the group consisting of a beam, a slab, a brick, a pipe, a pole, a vault, a tank, a well, a barrier, a wall, a column, a panel, stairs, a bridge, a containment vessel, a foundation, a floating structure and any combination thereof.

The pre-fabricated structure may be a containment vessel to protect ship fuel tanks or a kiln foundation.

The pre-fabricated structure may be a floating structure. The floating structure may be a floating slab. The floating structure may be used as a foundation for sheds, manufacturing workshops, houses or garages.

Examples

Non-limiting examples of the invention will be further described in greater detail by reference to specific Examples, which should not be construed as in any way limiting the scope of the invention.

Materials

Table 1 indicates the materials used in the concrete composition mix design of the present disclosure and their size, bulk density and specific gravity.

Table 1. Properties of the materials used in the mix design.

Material used	Size	Bulk density (kg/m^3)	Specific gravity, SG	Acquired from
LECA	3 to 8 mm	350 – 400	~0.45	ZQ Jinrui Ceramsite, Anhui, Huainan, China
Cenosphere	5 to 500 μm	300 - 500	0.4 - 0.8	Hebei Gator Chemicals Technology Co. Ltd, Shijiazhuang city, Hebei, China
River sand	62.5 μm to 2mm	1520 - 1680	1.6 - 1.7	River Sand, Inc., Cumming, Georgia, USA
Ordinary Portland cement. Grade 52.5*	0.1 to 250 μm	1000 - 1300	~3.15	Lafarge, Paris, France
Silica fume	≤ 1 μm	500 - 600	2.2 – 2.3	Elkem, Oslo, Norway
ViscoCrete® Superplasticizer (SP)	-	-	~2.1	Sika, Baar, Switzerland
Water	-	-	1.0	

Polypropylene (PP) fibres	12mm	-	-	Zhongding, Wuhan city, Hubei, China
Hooked steel fibres	35mm x 0.62mm (width)	-	-	Bekaert, Zwevegem, Belgium

* As stated in SS-EN 197-1: Cement – Part 1: Composition, specifications and conformity criteria for common cements.

Instrumentation And Methods

Compression Test

The compression test was carried out by using a compression machine (2000-3000 kN monobloc acquired from 3R, Montauban, France) in accordance with ASTM C39/C39M-20: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. ASTM C39 determines the compressive strength of cylindrical concrete specimens such as moulded cylinders and drilled cores. The minimum density of the tested specimen required was 800 kg/m^3. The specimen was placed exactly at the centre of the loading machine to ensure vertical loading with minimum eccentricity. Further, the specimen was placed onto a clean, flat plate to apply uniform loading onto the specimen. The protection door was shut tightly before commencement of the compression test to ensure safety. It was specified in ASTM C39/C39M that the loading rate should fall within 0.14 to 0.34 MPa/sec (65.9kN/min to 160.2 kN/min) for 100 x 200mm cylinders. In this disclosure, loading rate was selected to be 100kN/min.

Electric furnace

Before heating to test the spalling effects, 28-day old specimens in saturated-surface-dry condition were weighed at room temperature. To investigate spalling effects at elevated temperatures, the specimens were placed in an electric furnace (Nabertherm, Lilienthal Germany) under unstressed conditions and heated to 200°C, 400°C, 600°C, and 800°C, at a heating rate of 5°C/minute. When the target temperature was achieved, the maximum temperature was maintained at a constant for 5 hours to ensure that the specimens reached a thermal steady state. Then, the heated specimens were cooled down slowly to room temperature in the furnace.

When the specimens were cooled, they were taken out from the furnace and any superficial changes (i.e., colours, cracks, spalling, etc.) of the specimens were recorded. The specimens that were still intact (i.e. without spalling) were weighed again followed by crushing for compressive strength test.

To protect the interior of the electric furnace from possible explosive spalling, a make-shift steel cover was constructed.

Slump test

Slump test was carried out according to ASTM C143/C143M-15a: Standard Test Method for Slump of Hydraulic-Cement Concrete. Test equipment included a base pan (1m x 1m), standard steel rod, standard inverted cone, scraper and measuring tape. All the tools were pre-wetted with a thin surface layer of water before the test commencement to avoid unnecessary water absorption by the tools from the fresh concrete. The inverted cone was filled with fresh concrete up to about one-third of its volume and compacted by using a steed rod (tamped 25 times). The cone was then filled up to two-thirds of its volume and then compacted again. Lastly, the cone was filled to the brim and compacted. The excess concrete on top of the cone was scraped off. Subsequently, the inverted cone was lifted and allowed to slump. The decrease in height was measured with a measuring tape.

Deflection test using strain gauges

The deflection test was carried out using a 400-2000 kN compression machine (Instron, Norwood, Massachusetts, USA). A thin layer of adhesive was applied onto the concrete which provided a uniform surface for the strain gauge attachments. Strain gauges were applied on opposite sides of the cylinder. Special attention was needed during the placing of strain gauges as the strain gauge was very sensitive. The axis of the specimen was carefully aligned to ensure uniform loading. Apart from stress-strain curve, the maximum loading of concrete failure was obtained in this test.

Example 1: Preparation of the Initial Mix

Initial mix design

Key parameters such as water to binder (W/B) ratio and coarse aggregates to total aggregates (CA/TA) ratio were adhered to as indicated in the mix design outlined in Table 2.

Table 2. Initial mix design

Component	Mass (kg)	Proportion (kg/m^3)	Proportion (%)
Cement	3.05	534.90	39.00
Light Expanded Clay Aggregate (LECA)	1.00	175.38	12.79
Cenosphere	1.83	320.95	23.40
Portable water	1.46	256.05	18.67
Silica Fume	0.43	75.41	5.50
Superplasticizer (SP)	0.05	8.77	0.64

	W/B ratio	0.42
	CA/TA	0.35

Small dosages of polycarboxylate-based superplasticizer were added bit by bit to increase workability of the mix. Such small amounts of superplasticizer (by weight percentage) added allowed for reduction of the water to cement ratio without negatively affecting the workability of the mixture.

This preliminary mix design omitted the inclusion of any type of fibres as the primary aim was to firstly develop a high strength lightweight aggregate concrete (LWAC) with sufficient strength for structural applications.

Mixing

Before mixing was carried out, the LECA was soaked for at least an hour in water and excess water was drained away thoroughly. The components were also weighed out using an electronic balance with 0.001kg accuracy.

Moulds were tightened, oiled and placed near the mixer for placement. The inner surface of the mixing drum was pre-wetted with a minimal amount of water to ensure that the fresh concrete will have water content as accurate to the design mix as possible.

All the dry components were added first and mixed for at least a minute on low speed of 20 to 40 rpm to incorporate the dry mixture well. Water was divided into two portions and the first half of the water was mixed in at low speed for another minute. A required amount of superplasticizer (SP) was stirred into the remaining half of the water and mixed in at low speed to ensure even distribution of the SP into the mix. Mixing may be stopped here to check that no unincorporated materials were present at the bottom of the drum. To fully activate the SP, mixing was carried out for another 3 minutes at the same speed before adding in fibre (if any) and LECA. Mixing was halted after attaining an evenly mixed and cohesive mixture.

For experiments where only small batches of 3 to 4 cylinders were required, casting was carried out with a smaller benchtop laboratory mixer (120 plus pan mixer, Imer, Poggibonsi, Siena, Italy) .

For experiments requiring larger batches of 16 cylinders, a standard concrete pan mixer was used. Casting procedures remained the same.

Compaction

Hand compaction by rodding was adequate and no external machinery was required.

A test batch of specimens were compacted by vibration on a vibrating table (PE lab, Nanyang Technological University, Singapore) according to ASTM C 1170 – 91: Standard Test Method for Determining Consistency and Density of Roller-Compacted Concrete. After demoulding

and grinding, it was observed that a large amount of coarse aggregates floated to the top of the specimen.

As seen from Fig. 2A and 2B, compaction by a vibrating table resulted in uneven distribution of coarse aggregates throughout the specimen after demoulding and polishing as compared to an ideally compacted specimen (Fig. 2C) A possible explanation may be the lightness and roundedness of the LECA particles. Upon vibration on a vibrating table, the LECA easily floated to the top and this led to a structurally unsound specimen.

Hand compaction by rodding was carried out according to ASTM C31: Making and Curing Concrete Test Specimens in the Field instead.

For the chosen moulds of 100mm (diameter) by 200mm (height), the tamping rod was 9.53 mm diameter (+/- 1.59mm) and cylinders were filled in 2 layers (25 rods). The exterior of the moulds were tapped 10 to 15 times with a mallet or an open hand for each lift. The surfaces were then smoothed to ensure a compact and neat form conforming to the mould. The filled moulds were then covered with a plastic sheet to prevent water loss.

In accordance with ASTM standard procedure for making and curing concrete test specimens in the laboratory (ASTM C192/C192 M), de-moulding was performed 24 hours after casting and the cylinder specimens were transferred to a water tank for moist curing until their respective testing dates.

Example 2: Preliminary Test Results

The preliminary test results in Table 3 revealed some interesting findings.

Table 3. Compression test results for 100 % cenosphere (CS).

100 % CS	
No. of samples	4
Mean Density (kg/m^3)	1121
Mean 7-day compressive strength (MPa)	12.6

The very light density achieved suggested that it may be possible to produce a structural LWAC that can float on water. Structural LWAC has a 28-day air-dried density not exceeding 1920 kg/m^3 and 28-day compressive strength of more than 17 MPa (or in excess of 40 MPa for high strength LWAC). It is generally known that concrete strength at 7 days is at about 60 to 70 % strong.

This preliminary study showed that the initial mix had great potential for higher strength gain at early age as well as at 28-days. As understood from the relationship between strength and density in concrete, higher strength gain may be attained as density increases. The early age

compressive strength observed was far from adequate. The aim of this disclosure is to achieve a high strength LWAC (28-day compressive strength of more than 40 MPa) with considerable early age strength (1-day) of more than 20MPa.

To improve on the preliminary mix design, parametric studies were conducted to optimise the relevant concrete properties one at a time.

Example 3: Cenosphere Replacement

The first parameter tested was the amount of cenospheres. Sand-lightweight concrete comprises all of its fine aggregate as normal weight sand. Together with the common lightweight coarse aggregates, structural LWAC that meets the strength and density requirements may still be fulfilled. Some portion of the CS may therefore be replaced with river sand so that higher compressive strength is achieved. However, this comes at a cost of increasing concrete density as sand is much heavier than the same volume of CS.

However, it is worthy to note that good concrete mix design practices use a variety of aggregate sizes. The broader the particle size range is, the better the particles pack together. This can reduce the amount of cementitious materials needed, thus decreasing cost and environmental impact. It also improves material performance such as durability of the concrete.

A control specimen whereby all of the CS was replaced by river sand (0 % CS present) was cast for comparison. As seen in Table 4, it was found to have a dry density of 1901 kg/m^3 and a 7-day compressive strength of 37.7 MPa.

Table 4. Compression test results showing strength-density ratio for various replacement CS by sand

vol% of CS present as fine aggregate	**100 %**	**55 %**	**25 %**	**0 %**
No. of samples	4	3	3	3
Mean dry density (kg/m^3)	1121	1484	1635	1901
Mean 7-day compressive strength (MPa)	12.6	25.2	30.5	37.7

Replacement of CS by sand was done by volumetric replacement. CS has a specific gravity of about 0.6 while sand particles typically have a specific gravity of about 1.7. Dividing weight by density, it was observed that 1 kg of CS took up about the same absolute volume as 3 kg of river sand. The amount of other materials in the mix design remained the same. Water to binder (W/B) ratio remained the same at 0.42 as well. Table 5 shows the different combinations of CS and river sand (in mass) required after the respective volumetric replacements.

Table 5. Mass of CS and River sand used (kg) in the different mix designs.

vol% of CS present as fine aggregate	**100**	**55**	**25**	**0**
Cenosphere (kg)	1.83	1.00	0.46	-
River sand (kg)	-	2.50	4.17	5.56

As seen from Table 5, reduction of about half of CS so that 55 vol% was CS as fine aggregate and 45 vol% was river sand, had a dry density of 1484 kg/m^3 and a 7-day compressive strength of 25.2 MPa. Compressive strength doubled with an increase in dry density of about 32 %.

Subsequently, CS was reduced to a quarter of the amount of total fine aggregates present and a compression test revealed optimistic results. Dry density was at 1635 kg/m^3, with 7-day compressive strength at 30.5 MPa. Compressive strength increased by 142 % of the control specimens and this was coupled with an increase of 45 % in dry density.

Most lightweight concrete has an equilibrium (dry) density in excess of 1680 kg/m^3. Hence, the dry density recorded for 25 % CS replacement of 1635 kg/ m^3 was considered to be acceptable. Moreover, early strength of 30.5 MPa was considered to be an adequate 1-day strength.

Example 4: Water-Binder Ratio

Improved mix design with 0.24 water to binder (W/B) ratio is indicated in Table 6.

Table 6. Mix design with 0.24 W/B ratio

Component	**Mass (kg)**	**Proportion (kg/m^3)**	**Proportion (%)**
Cement	3.05	534.9	30.39
LECA	1.00	175.38	9.96
Cenosphere	0.46	80.24	4.56
River sand	4.17	731.32	41.54
Portable water	0.85	149.07	8.47
Silica Fume	0.43	75.41	4.28
Superplasticizer (SP)	0.08	14.03	0.80
	W/B	0.24	

Other than simply halving the amount of water required, the amount of SP was slightly increased from 0.64 % to 0.80 % to ensure good workability of the mix. As expected, 7-day compressive strength showed a significant increase from 30.5 MPa to 51.1 MPa. (Table 7)

Table 7. Compression test results for 25 % CS replacement at 0.24 W/B ratio

25% CS, 0.24 W/B ratio	
No. of samples	3
Mean Density (kg/m^3)	1755
Mean 7-day compressive strength (MPa)	51.1

High strength structural LWAC with optimistic (1-day) early strength could therefore be achieved.

Example 5: Polypropylene (PP) Fibre

Explosive spalling effects is worsened by increased water content in the mixture. Anti-spalling performance of the proposed mix design at both 0.24 W/B ratio and 0.42 W/B ratio was explored. 12 mm polypropylene (PP) fibres were added to the mixture to determine the optimum dosage of PP fibres required, specimens were placed in the electric furnace at 800°C and checked for possible spalling. The residual strengths were recorded as well.

At 0.42 W/B ratio

W/B ratio at 0.42 was expected to have a higher chance of explosive spalling due to the higher water content present. 0.2 vol%, 0.3 vol% PP and control (no PP added) were tested.. Specimens were heated to 800 °C and intact specimens were tested for residual strength. As expected, control specimens (Fig. 3A to 3D) spalled explosively. Table 8 shows that specimens containing 0.2 vol% and 0.3 vol% PP both exhibit anti-spalling properties and have the same residual (28-day compressive) strength. Table 8 also showed a trend in decreasing (7-day) compressive strength as the PP dosage increased. Thus, it can be concluded that 0.2 vol% PP can prevent structural LWAC from spalling.

Table 8. Compression test results with different PP fibre dosage after fire test at a W/B ratio of 0.42

25 % CS, 0.42 W/B ratio, 28-day fire test			
PP fibre dosage (kg/m^3)	2.0	3.0	NIL
At 800 °C			
No. of samples	4	3	3

Mean Density (kg/m^3)	1600	1588	1611
Mean residual 28-day compressive strength (MPa)	7.4	7.4	spalled
At ambient temperature			
No. of samples	4	3	3
Mean Density (kg/m^3)	1600	1588	1611
Mean 28-day compressive strength (MPa)	7.4	7.4	spalled

At 0.24 W/B ratio

At 0.2 vol% PP, specimens displayed a mean residual (28-day compressive) strength of 12.1 MPa with air-dried density of 1685 kg/m^3. Mean compressive strength was found to be 43.7 MPa at 28 days (see Table 9) and residual strength after the fire test at 800 °C was at 28 %. The control specimens also spalled explosively (Fig. 4). It was therefore found that even at this reduced W/B ratio, a minimum amount of 0.2 vol% PP was necessary to prevent spalling.

Example 6: Curing Conditions

The effect of curing condition on strength development was also investigated.

Reference batches containing 25 % CS and 75% sand were recast at the stated W/B ratio of 0.42 and 0.24 and cured in the different conditions listed in Table 9. The specimens were cured in ambient open air or water (containing calcium hydroxide at saturation). The compressive strength and density were then compared with those cured in steam.

Table 9. Properties of structural lightweight concrete in different curing conditions.

W/B ratio	Curing Conditions	Mean density (kg/m^3)	Mean compressive strength (MPa)
0.42	Ambient (air) curing for 28 days	27.7	1611
	Water curing for 28 days	34.7	1708
	Steam curing at 60°C at 3 days	32.2	1642
0.24	Ambient (air) curing for 28 days	49.0	1731
	Water curing for 28 days	57.7	1835
	Steam curing at 60°C at 3 days	51.5	1755

Table 10 indicates that curing in steam can effectively increase the early-age strength of concrete and the compressive strength of concrete measured is between that of air curing and water curing for 28 days. At both W/B ratios, compressive strength and density are lowest when the concrete is cured in open air.

In consideration of the minimum requirements and the practicality of structural lightweight concrete as precast elements, 0.24 W/B ratio cured in ambient (air) conditions was further adopted for this study.

Example 7: Optimised Mix

After optimising each parameter of the study, the final compressive results were tabulated in Table 10.

Table 10. Compression test results of final mix design.

25 % CS, 0.24 W/B ratio, 0.2 vol% PP		
Age	7-day	28-day
No. of samples	3	3
Mean Density (kg/m^3)	1719	1664
Mean compressive strength (MPa)	41.6	43.7

The final mix design is shown in Table 11.

Table 11. Optimised mix proportions of high-strength LWAC (in kg/m^3) (W/B ratio 0.24)

Cement	535
Silica Fume	75
Cenospheres	80
Silica Sands	731
Coarse Aggregates (1-8 mm)	175
Water	146
Superplasticizer	14
PP Fibres	2
Steel Fibres	39

Example 8: Progression of Compressive Strength

It is important to monitor the progress of compressive strength development to ensure the high strength lightweight concrete of the present disclosure is useful in the current precast and prefabrication climate.

Early concrete age of 1 day and 3 days are especially important as the moulded products at this stage must be strong enough to be assembled and moved around. This means that as soon as

the concrete is demoulded after 24 hours of curing, it should be strong enough to withstand handling and assembly. At around 3 days, the preassembled precast structures are expected to be transported onsite so that space in the precast factories can be freed up for the continuous production of precast products. Time is a predominant factor in construction and precast implementations are often the key in saving major project costs.

Key ages of 1, 3, 7 and 28 days were selected to monitor the key progression of strength at ambient conditions.

Addition of steel fibres (of up to 1 vol%) may increase compressive strength of concrete but may result in a concrete mix that is hard to work with. In consideration of workability in the presence of two different fibres, 0.5 vol% steel fibres were first selected to examine the possible effects in increased compressive strength. Hooked steel fibres were selected for use in the present disclosure.

As seen in Fig. 5, strength progression for specimens with no fibre were monitored for reference. Comparison of reference graphs with 0.2 vol% PP in Fig. 5 shows that the reduction of compressive strength as a result of PP fibre addition decreases as concrete ages. This may be due to the decreased hindrance effects of PP fibres due to low bond strength at an early age. Cement particles form rapid hydration products at the start. As time passes hydration slows down due to lesser cement particles available. As a result, the presence of PP fibres that disrupts C-S-H bond formation may become more significant.

It was observed that results at Day 1 were not very accurate, as compressive results of specimens with PP fibres should be lower than that of the reference specimens. This may be explained by the slight difference in ambient conditions. A day that is slightly more humid may lead to a slower drying rate and this may be significant to specimens tested just a day after casting. However, the unexpected increase was only by less than 5 % and was not found to affect the conclusion that 1-day strength of LWAC containing 0.2 vol% PP has adequate strength of $\geq$20 MPa.

Specimens containing 0.2 vol% PP + 0.5 vol% steel fibres displayed a possibility of gaining compressive strength higher than that of specimens containing only PP fibres. It can be observed from Fig. 5 that the 7-day (mean) compressive strength of 0.2 vol% PP + 0.5 vol% steel was slightly larger than that of 0.2 vol% PP and 0.2 vol% PP + 0.5 vol% steel at 28 days could achieve a compressive strength of 43.9 MPa.

Example 9: Stress-Strain Behaviour

As a supplementary test, a deflection test was conducted at ambient conditions to investigate any additional effects of fibres on the properties of the lightweight concrete. Specimens at key strengths of 7 days and 28 days were selected for the deflection test.

From Fig. 6 to 9, it can be observed that the addition of 0.2 vol% PP fibres had little effect on the elasticity of the lightweight concrete.

Example 10: Residual Compressive Strength

Residual compressive strength after exposure at given temperatures of 200 °C to 800 °C were plotted in Fig. 10. Residual compressive strength was expressed relatively to the compressive strength at ambient conditions, to illustrate strength loss after exposure to elevated temperatures.

Due to effects of spalling, residual compressive tests were not conducted for the control specimens from 400 °C upwards. Only the sample that was exposed to 200 °C remained intact and compressive test results found relative residual compressive strength to be almost 1.0. This was consistent with that for 0.2 vol% PP at 200°C.

From Fig. 10, it was observed that with an increase in temperature, residual compressive strength decreased. Temperatures below 400 °C showed specimens retaining about 80 % of compressive strength. The largest decline was recorded from 400 °C to 600 °C and the declination was the smallest from 600 °C to 800 °C. This possible plateauing after 800 °C may suggest the presence of a minimum compressive strength retained after exposure to even higher temperatures.

Industrial Applicability

The present invention may be used for structural elements prefabricated in a manufactory, especially for modular construction. The disclosed composition may be used in a fibre reinforced lightweight aggregate concrete (LWAC) in construction elements such as beams, slabs, bricks, pipes, poles, vaults, tanks, wells, barriers, walls, columns, panels, stairs, bridges, containment vessels, foundations and floating structures requiring better performance in terms of flexure strength, ductility and workability. The invention can also be used for casting structures in-situ and may be implemented in structures, such as underground structures including kiln foundations, which are required to be fire-resistant. The invention may also be useful in casting floating structures.

It will be apparent that various other modifications and adaptations of the invention will be apparent to the person skilled in the art after reading the foregoing disclosure without departing from the spirit and scope of the invention and it is intended that all such modifications and adaptations come within the scope of the appended claims.

Claims

1. A composition comprising:

about 28 % to about 42 % by weight of a binder;

about 3 % to about 7 % by weight of cenospheres;

about 35 % to about 50 % by weight of sand;

about 8 % to about 13 % by weight of a lightweight coarse aggregate;

about 0.05 % to about 0.5 % by weight of a first fibre; and

about 1 % to about 4 % by weight of a second fibre,

wherein the total weight of the composition adds to 100 %.

2. The composition according to claim 1, further comprising water in an amount such that the water:binder ratio by weight is in the range of about 0.2 to about 0.3.

3. The composition according to claim 1 or 2, further comprising about 0.5 % to about 1 % by weight of a superplasticizer.

4. The composition according to any one of claims 1 to 3, wherein the binder comprises about 25 % to about 36 % by weight of cement and about 3 % to about 6 % by weight of a pozzolanic filler.

5. The composition according to claim 4, wherein the cement is Portland cement CEM 52.5 (ASTM Type I), Portland cement CEM 42.5 (ASTM Type I), Portland Pozzolana Cement (PPC), Rapid Hardening Cement, Extra Rapid Hardening Cement, Low Heat Cement, Sulfates Resisting Cement, Quick Setting Cement, Blast Furnace Slag Cement and any mixture thereof.

6. The composition according to claim 4 or 5, wherein the pozzolanic filler is selected from the group consisting of silica fume, microsilica, nanosilica, furnace slag, fly ash, glass powder, rice husk ash and any mixture thereof.

7. The composition according to any one of the preceding claims, wherein the lightweight coarse aggregate is selected from the group consisting of lightweight expanded clay aggregate (LECA), lightweight expanded shale aggregate, lightweight expanded slate aggregate, foamed slag, sintered pulverised fuel ash aggregate, and any mixture thereof.

8.The composition according to any one of the preceding claims, wherein the lightweight coarse aggregate has a diameter in the range of about 4 mm to about 20 mm.

9.The composition according to any one of the preceding claims, wherein the sand is silica sand, natural sand or river sand.

10. The composition according to any one of the preceding claims, wherein the sand has a particle size of less than 2 mm.

11. The composition according to any one of claims 3 to 10, wherein the superplasticizer is selected from the group consisting of sulfonated naphthalene formaldehyde condensate, sulfonated melamine formaldehyde condensate, acetone formaldehyde condensate, polycarboxylate ethers and any mixture thereof.

12. The composition according to any one of the preceding claims, wherein the first fibre is selected from the group consisting of polypropylene fibre, nylon fibre, rubberized fibre and any mixture thereof.

13. The composition according to any one of the preceding claims, wherein the first fibre is a monofilament cylindrical fibre having a length in the range of about 6 mm to about 20 mm and a diameter in the range of about 10 µm to about 40 µm.

14. The composition according to any one of the preceding claims, wherein the second fibre is selected from the group consisting of steel fibre, glass fibre, carbon fibre, polyethylene fibre and any mixture thereof.

15. The composition according to any one of the preceding claims, wherein the second fibre has a length in the range of about 30 mm to about 40 mm and a width in the range of about 0.5 mm to about 0.75 mm.

16. A method of preparing a composition according to any one of claims 3 to 15, comprising the steps of:

a) mixing about 28 % to about 42 % by weight of a binder, about 3 % to about 7 % by weight of cenospheres and about 35 % to about 50 % by weight of sand to form a dry mix;

b) mixing a first volume of water with the dry mix to form a first wet mix;

c) mixing about 0.5 % to about 1 % by weight of a superplasticizer with a second volume of water to form a second wet mix;

d) mixing the first wet mix with the second wet mix to form a third wet mix;

e) mixing about 0.05 % to about 0.5 % by weight of a first fibre, about 1 % to about 4 % by weight of a second fibre, and about 8 % to about 13 % by weight of a lightweight coarse aggregate with the third wet mix to form the composition,

wherein step e) further comprises a step of soaking the lightweight coarse aggregate in soaking water before mixing with the third wet mix;

wherein the first volume of water in step b) and the second volume of water in step c) are mixed such that in combination, the water:binder ratio by weight of the composition is in the range of about 0.2 to about 0.3, and

wherein the total weight of the composition adds to 100 %.

17. The method according to claim 16, wherein after the soaking step, the lightweight coarse aggregate has a water content in the range of about 10 % to about 22 % by weight.

18. The method according to claim 16 or 17, wherein the first volume of water in step b) and the second volume of water in step c) are substantially the same volume.

19. The method according to any one of claims 16 to 18, wherein the mixing steps a) to e) are each independently performed in air at atmospheric pressure and at a temperature in the range of about 20 °C to about 35 °C.

20. The method according to any one of claims 16 to 19, wherein the composition is further cured in air or water at atmospheric pressure and at a temperature in the range of about 20 °C to about 90 °C.

21. A concrete structure comprising the composition according to any one of claims 1 to 15.

22. The concrete structure according to claim 21, wherein the concrete structure is a pre-fabricated structure.

23. The concrete structure according to claim 22, wherein the pre-fabricated structure is selected from the group consisting of a beam, a slab, a brick, a pipe, a pole, a vault, a tank, a well, a barrier, a wall, a column, a panel, stairs, a bridge, a containment vessel, a foundation, a floating structure and any combination thereof.