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Development of lightweight mixes using ceramic microspheres as fillers

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Abstract

The present experimental study evaluates the physical and mechanical characteristics of lightweight mixes of uniform consistency having varying proportions of cement and ceramic microspheres. To further modify the physical and mechanical characteristics of the above mixes, supplementary chemical additives that generate stable bubbles in the paste and that endows the lightweight mixes with water-repellent property were introduced into the mix. The results of the study show the mixes made with ceramic microspheres fall in the category of low and moderate density lightweight concrete. The study also shows that, by introducing supplementary chemical additives into the mix, it is possible to generate ceramic microsphere-based lightweight mixes having a wide range of densities, compressive strengths and water-repellent characteristics.

Keywords: Ceramic lightweight aggregates; Physical properties; Fillers; Portland cement; Aggregates

1. Introduction

A number of economic and practical advantages can be derived by replacing normal high-density concrete (2200–2600 kg m^{-3}) made with natural hard rock aggregates with lightweight concrete of lower density (300–1900 kg m^{-3}) [1]. For normal high-density concrete, the self-weight of the element itself accounts for a major proportion of the total load on the structure. Selection and use of appropriate lightweight concrete result in load bearing elements of smaller cross-sections and corresponding reduction in the size of foundations. Occasionally, lightweight concrete can be used for construction on soils with lower load-bearing capacity [2]. Furthermore, with lightweight concrete, the formwork pressures are significantly lower than would be the case with normal high-density concrete and the total mass of concrete to be handled at site would be reduced with a consequent increase in productivity.

The density of a given concrete can be lowered by partially replacing the solid content of the mix with air voids. There are three possible locations of air voids in a hardened concrete: in the aggregate particles, the resulting aggregates being known as lightweight aggregates; in the hardened cement paste, the resulting concrete being known as cellular or foamed concrete; and between the normal coarse aggregate particles (fine aggregate being omitted), the resulting concrete known as no-fines concrete [3].

The lightweight aggregates conforming to BS 3797: 1990 [4] can be aggregates in their natural form (diatomite, pumice, scoria and volcanic cinders), or man-made aggregates manufactured from natural materials (clay, shale and slate), or from industrial by-products (aggregates manufactured from fly ash). The most important characteristic of the lightweight aggregates is their predominantly high porosity, which results in a lower apparent specific gravity. Ceramic microspheres manufactured from natural minerals offer an efficient and economic alternative in this respect—such lightweight fillers are already finding applications in a variety of formulated products such as paints, coatings, refractory materials and slip-resistant floors and composites. The ceramic microspheres, apart from lowering the bulk density of the formulated product, also act as an effective ingredient to improve the thermal, chemical and mechanical properties of the end product.

In the present study, an attempt is made to replace conventional aggregates with ceramic microspheres in

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mixes having Portland cement as the cementitious material. The main objective of the study is to elucidate the mechanical and physical characteristics of lightweight mixes by varying the proportion of cement and ceramic microspheres in the mix. In addition, an attempt is also made to further modify the physical and mechanical characteristics of the above mixes by introducing supplementary chemical additives such as aeration, foaming and water-proofing agents into the mix.

2. Experimental program

In order to understand the physical and mechanical characteristics of mixes having varying proportions of cement, ceramic microspheres and chemical additives, an experimental program, was carried out as described below.

2.1. Mix details

In the present study, five control mixes having varying Portland cement and ceramic microsphere contents were used. The Portland cement content in the five mixes was maintained at 30%, 40%, 50%, 60% and 70% by mass, respectively, and the remainder was ceramic microspheres. The water to solids ratio for each of the above control mix was adjusted to maintain an uniform consistency ($\sim$200 mm) by performing flow test in accordance with BS 4551 [5]. To further lower the bulk densities of the control mixes, an aeration agent in powder form, two foaming agents of different chemical bases in powder form and a liquid foaming agent were introduced into the mix as supplementary chemical additives (on the basis of one at a time). The aeration agent reacts with hydrated lime generated by cement hydration in the presence of moisture to generate bubbles of hydrogen gas, while the foaming agent generates stable bubbles during high-shear mixing. In order to improve upon the water absorption characteristics of the resulting lightweight mixes, a water-proofing chemical additive was also introduced in all the five mixes as resistance to water absorption is a functional requirement for lightweight elements such as lightweight masonry blocks [6]. To understand the effect on resistance to water absorption, the water-proofing agent was also introduced into the mix having one of the foaming agents in powder form.

Table 1
Physical properties of ceramic microspheres

Physical properties	Description
Form and colour	White free flowing microspheres
Nominal particle size	20–300 μm
Approximate mean particle size	130 μm
Relative density	700 kg m^{-3}
Bulk density	400 kg m^{-3}
Shell thickness	Approximately 10% of diameter
Melting point	1600–1800 °C
Hardness	6 Moh's scale
Thermal conductivity	0.10 W/m °C
Coefficient of thermal expansion	8×10^{-6}/°C
Water absorption	0%

Table 2
Chemical properties of ceramic microspheres

Chemical composition	Percentage by mass
Silica, SiO_2	55–60
Alumina, Al_2O_3	36–40
Iron oxide, Fe_2O_3	0.40–0.50
Titanium dioxide, TiO_2	1.40–1.60

2.2. Materials used

Normal Portland cement (ASTM type I) was the only cementitious material used in the mix.

The physical and chemical characteristics of the ceramic microspheres are presented in Tables 1 and 2, respectively. From Table 2, it is evident that the major chemical ingredients of the ceramic microspheres are silica and alumina—latter contributes for its higher melting point (1600–1800 °C) and lower coefficient of thermal expansion (8×10^{-6}/°C), both of which are of paramount importance for refractory applications. Ceramic microspheres are nonflammable and hence are fire-resistant. From Table 1, it is evident that the relative density (700 kg m^{-3}) and bulk density (400 kg m^{-3}) of the ceramic microspheres are significantly lower than those of conventional aggregates, which justify its selection for lightweight mix. Since the ceramic microspheres are hollow spheres (shell thickness: 10% of diameter) with partial vacuum inside the sphere, they act as natural barrier to heat transfer (thermal conductivity: 0.10 W/m °C), and hence they perform as an effective means of thermal insulation in the formulated products. Due to the higher surface hardness (6 on Moh's scale) of the ceramic microsphere, they can also withstand forces generated during rigorous mixing operations. As a consequence of having a spherical shape and smooth surface texture, the ceramic microspheres act like miniature ball bearings in the mix and impart better flow properties. Further, the nonabsorbent surface of the ceramic microsphere (water absorption = 0) together with their wide particle size distribution (20–300 μm) should be helpful in lowering the drying shrinkage properties of the resulting concrete.

Finely ground aluminium powder (dosage: 0.1% and 0.2% by mass of cement) having an average particle size of 40 μm and bulk density of 200 kg m^{-3} was used as an aeration agent.

To generate stable foam in the paste, three widely used foaming agents were used. Two were in powder form—sodium olefine sulphonate (A) and sodium dodecylbenzene sulphonate (B). The third one was a liquid foaming agent—polyoxyethylene alkyl ether sulfate (C). All the foaming agents were used by the same amount of 0.2%

by mass of cement. The water-proofing agent used was a finely ground calcium stearate ($Ca(C_{18}H_{35}O_2)$) at a dosage of 1.25% by total mass of materials. The water-proofing agent was also used in conjunction with the foaming agent B. The dosages selected for all the above chemical additives were based on the recommendations made by the respective manufacturers.

2.3. Test specimen preparation

The ingredients of the mix (Portland cement, ceramic microsphere and water) were collected in plastic pails (10 l) and were mixed using a hand-held power mixer (15 cm diameter stainless steel impeller) for at least 2 min. For those mixes having aluminium powder as an aeration agent, prior to wet mixing, the dry mix containing aluminium powder, cement and ceramic microsphere were thoroughly mixed. For those mixes containing foaming agent, the foaming agent was first added to the mix water and mixed for 30 s with a power mixer to generate the stable foam; the cement and ceramic microspheres were then added and remixed for another 2 min.

Soon after mixing, the mix was poured into a set of 100-mm steel cube molds and 25 × 25 × 250-mm steel prism molds. The control mixes without aeration and foaming agent were compacted manually by using a compacting bar. The mixes containing aeration or foaming agents were subjected to light tamping on the walls of the molds to ensure that no large air bubbles are trapped inside the mold. All the specimens were demolded 24 h after casting. In the case of mixes having the aeration agent, prior to demolding, the excessive material collected at the top surface of the mold due to expansion of the mix was scraped and leveled using a sharp tool. The demolded specimens were then stored in an open shaded environment, without exposure to sun or rain, until the day of the test.

2.4. Experimental procedure

The 100-mm cubes were tested in duplicate (unit test) for compressive strength after 8-day air curing in accordance with SS 78: Part A16: 1987 [7] at a loading rate of 0.20–0.40 N mm^{-2} s^{-1}. Prior to the test, the cubes were weighed in the as-received condition and their bulk density was estimated in conformity with SS 78: Part A14: 1987 [8].

The test for water absorption was performed in accordance to SS 214: 1979 [9]. The air cured (8-day) cubes (in duplicate) were dried for 72 ± 1 h in ventilated oven set at a constant temperature of 105 °C. On removal from the oven, they were cooled for 24 ± 0.5 h in a shaded environment. Soon after the cooling, each cube was weighed and immediately soaked in water maintained at 27 ± 2 °C for 30 ± 0.5 min. At the end of the 30-min immersion, the cubes were dried with a dry cloth as rapidly as possible until all the free-water on the surface was removed; the specimens were then weighed again. The water absorption for each cube was estimated by dividing the increase in weight of the cube due to water absorption after soaking in water (expressed in cm^3) by its volume.

The prism specimens cured for 8 days were used in duplicate for evaluating the modulus of rupture based on third-point loading conforming to ASTM C 78-94 [10].

In the present investigation, the mechanical and physical properties of the lightweight mixes were evaluated after 8-day air curing, although 28-day curing is generally considered to be more appropriate. However, in the present case, the selection of the 8-day air curing period appears to be more realistic because of the local practice of delivering the precast lightweight elements to the construction site after about a week's air curing in the plant. Further, the lack of storage place at the construction site leads to the normal practice of using the precast elements received from the plant immediately in the construction.

3. Test results and discussion

The physical and mechanical properties of the five control mixes containing 30%, 40%, 50%, 60% and 70% cement by mass and the balance with ceramic microspheres are presented in Tables 3–7. In addition to the above control mixes, the above tables also include the physical and

Table 3
An 8-day properties of mix with 30% cement + 70% ceramic microspheres

Mix type	Compressive strength (N mm^{-2})	Density (kg m^{-3})	Water absorption (%)	Modulus of rupture (N mm^{-2})
Control mix: 30% cement (by mass) and 70% ceramic microspheres (by mass) with water/solids = 0.75	2.60	655	24.34	0.60
Control mix + 1.25% calcium stearate	1.70	635	4.09	0.42
Control mix + 0.1% Al powder	2.60	620	–	–
Control mix + 0.2% Al powder	2.40	580	–	–
Control mix + 0.2% foaming agent A	1.41	550	24.16	–
Control mix + 0.2% foaming agent B	1.48	595	22.02	–
Control mix + 0.2% foaming agent B + 1.25% calcium stearate	1.68	640	2.52	–
Control mix + 0.2% foaming agent C	1.39	590	21.25	–

Foaming agent A: sodium olefine sulphonate (powder); foaming agent B: sodium dodecylbenzene sulphonate (powder); foaming agent C: polyoxyethylene alkyl ether sulfate (liquid). All dosages of chemical additives are by mass of cement except in the case of calcium stearate where it is by mass of total material.

Table 4
An 8-day properties of mix with 40% cement + 60% ceramic microspheres

Mix type	Compressive strength (N mm $^{-2}$)	Density (kg m $^{-3}$)	Water absorption (%)	Modulus of rupture (N mm $^{-2}$)
Control mix: 40% cement (by mass) and 60% ceramic microspheres (by mass) with water/solids = 0.65	4.40	770	22.39	1.48
Control mix + 1.25% calcium stearate	3.20	750	3.51	1.20
Control mix + 0.1% Al powder	4.30	700	–	–
Control mix + 0.2% Al powder	2.80	565	–	–
Control mix + 0.2% foaming agent A	3.06	615	21.81	–
Control mix + 0.2% foaming agent B	2.35	605	17.10	–
Control mix + 0.2% foaming agent B + 1.25% calcium stearate	4.00	735	2.54	–
Control mix + 0.2% foaming agent C	3.10	680	19.10	–

Foaming agent A: sodium olefine sulphonate (powder); foaming agent B: sodium dodecylbenzene sulphonate (powder); foaming agent C: polyoxyethylene alkyl ether sulfate (liquid). All dosages of chemical additives are by mass of cement except in the case of calcium stearate where it is by mass of total material.

mechanical properties for the corresponding control mixes blended with aeration and foaming agents and water-proofing chemical additive.

3.1. Role of ceramic microspheres as aggregates

From Tables 3–7, it is evident that as the proportion of cement (by mass) in the mix increases, the values of density, compressive strength and modulus of rupture also increase, while the water absorption decreases. Conversely, as the proportion of ceramic microspheres (by mass) in the mix increases, the density, compressive strength and modulus of rupture decrease, while water absorption increases with the proportion of ceramic microspheres in the mix. Since the ceramic microspheres have a relatively lower bulk density (400 kg m $^{-3}$) compared to cement, an increase in the proportion of ceramic microsphere by mass in the mix increases the specific surface (m^2/kg), and thereby increases the water demand to maintain the required consistency, the criterion used in the present mix design. Thus, the larger the proportion of ceramic microspheres in the mix, the larger is the water demand or water to solids ratio. As a consequence of the increased water to solids ratio, the capillary porosity increases while the compressive strength and modulus of rupture decrease. Furthermore, as a result of the higher capillary porosity, the water absorption also increases due to the greater accessible volume for the moisture to penetrate through the capillary pore network. This indirectly confirms the strong dependence of properties such as compressive strength, modulus of rupture and water absorption of lightweight concrete on water to solids ratio of the mix, as in the case of normal weight concrete.

The test results of the control mixes shown in Tables 3–7 emphasize that, by combining Portland cement with ceramic microspheres as aggregates, a wide range of construction materials with the 8-day compressive strength varying from 2.60 to 27 N mm $^{-2}$ and density of 655 to 1220 kg m $^{-3}$ could be designed.

3.2. Role of calcium stearate in reducing water absorption

From Tables 3–7, it is clear that when calcium stearate (1.25% by total mass) was introduced in all the control mixes, the amount of water absorption decreased significantly, by 70–85% compared to the corresponding mixes without calcium stearate. These results demonstrate the usefulness of calcium stearate in substantially enhancing the resistance to water absorption of lightweight mixes.

The introduction of calcium stearate has, however, a slight negative effect. The results show that with calcium stearate, compressive strength, density and modulus of rupture are all slightly lowered in magnitude compared to those of the corresponding control mixes without calcium

Table 5
An 8-day properties of mix with 50% cement + 50% ceramic microspheres

Mix type	Compressive strength (N mm $^{-2}$)	Density (kg m $^{-3}$)	Water absorption (%)	Modulus of rupture (N mm $^{-2}$)
Control mix: 50% cement (by mass) and 50% ceramic microspheres (by mass) with water/solids = 0.50	8.44	880	17.04	2.12
Control mix + 1.25% calcium stearate	8.00	830	3.32	2.00
Control mix + 0.1% Al powder	7.54	825	–	–
Control mix + 0.2% Al powder	2.70	610	–	–
Control mix + 0.2% foaming agent A	2.44	615	11.10	–
Control mix + 0.2% foaming agent B	2.45	625	12.03	–
Control mix + 0.2% foaming agent B + 1.25% calcium stearate	7.24	830	2.84	–
Control mix + 0.2% foaming agent C	4.53	700	10.50	–

Foaming agent A: sodium olefine sulphonate (powder); foaming agent B: sodium dodecylbenzene sulphonate (powder); foaming agent C: polyoxyethylene alkyl ether sulfate (liquid). All dosages of chemical additives are by mass of cement except in the case of calcium stearate where it is by mass of total material.

Table 6
An 8-day properties of mix with 60% cement + 40% ceramic microspheres

Mix type	Compressive strength (N mm $^{-2}$)	Density (kg m $^{-3}$)	Water absorption (%)	Modulus of rupture (N mm $^{-2}$)
Control mix: 60% cement (by mass) and 40% ceramic microspheres (by mass) with water/solids = 0.42	14.40	1060	8.30	3.42
Control mix + 1.25% calcium stearate	11.64	1030	2.43	2.70
Control mix + 0.1% Al powder	6.20	735	–	–
Control mix + 0.2% Al powder	5.00	680	–	–
Control mix + 0.2% foaming agent A	5.86	810	7.72	–
Control mix + 0.2% foaming agent B	5.14	750	7.98	–
Control mix + 0.2% foaming agent B + 1.25% calcium stearate	12.37	935	2.79	–
Control mix + 0.2% foaming agent C	6.00	810	8.12	–

Foaming agent A: sodium olefine sulphonate (powder); foaming agent B: sodium dodecylbenzene sulphonate (powder); foaming agent C: polyoxyethylene alkyl ether sulfate (liquid). All dosages of chemical additives are by mass of cement except in the case of calcium stearate where it is by mass of total material.

stearate. For example, the compressive strengths and modulus of rupture are lower by 5–35%, while densities are lower only marginally by 2.5–5.5%. Calcium stearate endows the lightweight concrete with water-repellent property through the process of generating hydrophobic layers on all possible surfaces. In the process of doing so, calcium stearate also forms hydrophobic layers on the surface of unhydrated and partially hydrated cement grains, and thereby isolates those cement grains from moisture causing a drop in compressive strength and modulus of rupture. This suggests that, in the process of building up resistance to water absorption, a small proportion of compressive strength and modulus of rupture are to be sacrificed. The observed drops in the magnitudes of density are too low and are attributed mostly to experimental errors.

3.3. Effectiveness of aluminium powder as aeration agent

In the tests reported here, finely ground aluminium powder at a dosage of 0.1% and 0.2% by mass of cement was used as an aeration agent. From Table 3, it is evident that when the cement content in the mix is lowest at 30% by mass, the addition of 0.1% aluminium powder by mass of cement to the control mix caused no change in the magnitudes of compressive strength, while there was a marginal drop in the density of the mix (5%) compared to the control. However, when the dosage of aluminium powder was increased to 0.2% by weight of cement, the drops in the magnitude of compressive strength (7.5%) and density (11.5%) were noticeable. When the cement content in the mix was at 40% by mass (Table 4), even a dosage of 0.1% aluminium powder to the control mix caused a marginal drop in compressive strength (2%) and a noticeable drop in density (9%) of the mix. However, when the dosage of aluminium powder was raised to 0.2% by mass of cement, the drop in compressive strength (36.5%) and density (26.5%) were significant compared to those for the control mix. For the mix having 50% cement by mass (Table 5), addition of aluminium powder by 0.1% by mass although showed noticeable small changes. However, an addition of 0.2% aluminium powder showed much pronounced drops in compressive strength (68%) and density (31.5%) compared to the control mix. For the mixes having 60% and 70% cement by mass (Tables 6 and 7), even a dosage of aluminium powder as small as 0.1% caused a pronounced drop in compressive strength and density compared to the control. By further raising the dosage of aluminium powder to 0.2%, the resulting changes to compressive strength and density of these two mixes were too small, out of proportions to the increase in the dosage of aluminium powder.

Table 7
An 8-day properties of mix with 70% cement + 30% ceramic microspheres

Mix type	Compressive strength (N mm $^{-2}$)	Density (kg m $^{-3}$)	Water absorption (%)	Modulus of rupture (N mm $^{-2}$)
Control mix : 70% cement (by mass) and 30% ceramic microspheres (by mass) with water/solids = 0.35	27.00	1220	7.5	5.68
Control mix + 1.25% calcium stearate	25.50	1200	1.80	5.20
Control mix + 0.1% Al powder	6.11	710	–	–
Control mix + 0.2% Al powder	5.83	700	–	–
Control mix + 0.2% foaming agent A	6.65	970	7.30	–
Control mix + 0.2% foaming agent B	4.47	815	7.20	–
Control mix + 0.2% foaming agent B + 1.25% calcium stearate	11.56	1040	2.01	–
Control mix + 0.2% foaming agent C	7.00	940	7.40	–

Foaming agent A: sodium olefine sulphonate (powder); foaming agent B: sodium dodecylbenzene sulphonate (powder); foaming agent C: polyoxyethylene alkyl ether sulfate (liquid). All dosages of chemical additives are by mass of cement except in the case of calcium stearate where it is by mass of total material.

These results suggest that, when the proportion of cement in the mix is greater than 50%, even a small dosage of aluminium powder (0.1%) added by mass of cement is effective in reducing the density and compressive strength substantially compared to the control. A further increase in the dosage of aluminium powder to 0.2% by mass of cement causes only a further marginal drop. However, for mixes having 40–50% cement by mass, addition of aluminium powder as low as 0.1% by mass of cement can only cause a marginal drop in density and compressive strength, whereas 0.2% aluminium causes a pronounced drop in the above properties compared to the control. For those mixes with least cement content of 30% by mass, addition of aluminium powder by 0.1% by mass of cement was nearly negligible to cause any noticeable change, although a dosage of 0.2% results in marginal changes in compressive strength and density. Thus, the dosage of aluminium powder required for causing changes to density and compressive strength of lightweight mixes is related to the cement content of the mix. This can be explained by the fact that the quantity of hydrogen gas evolved to form bubbles in the paste depends on the amount of hydrated lime liberated through hydration of cement.

3.4. Influence of foaming agents

Three foaming agents, two in powder form (A and B), and the third in liquid form (C) were used at a dosage of 0.2% by mass of cement. From the results shown in Tables 3–7, it is evident that when foaming agents A (sodium olefine sulphonate, powder), B (sodium dodecylbenzene sulphonate, powder) and C (polyoxyethylene alkyl ether sulfate, liquid) are introduced into the mix containing varying proportions of cement and ceramic microsphere, both compressive strength and density are reduced due to the formation of stable bubbles in the mix. However, irrespective of the type of foaming agent used in the mix, for each combination of cement and ceramic sphere, the magnitudes of compressive strengths remained nearly similar, but the foaming agent C in general caused relatively smaller reduction in both the density and compressive strength of the mix. It is also worth emphasizing that, despite the addition of foaming agents, the resistance to water absorption remained nearly unchanged compared to that of the control mix. This beneficial effect can be explained by the fact that, when foaming agents are introduced into the mix, they create stable and isolated bubbles, which are distributed in the paste matrix and these do not contribute to capillary porosity, and therefore water absorption remains almost unaffected.

The test results also show that the when foaming agent B is combined with calcium stearate and introduced into the control mix, there was negligible drop in compressive strength and density of the mix, for mixes containing up to 60% Portland cement. However, the resistance to water penetration was reduced dramatically in all cases compared to the control mix. This is a very significant property imparted to the concrete mix. Indeed, the calcium stearate appears to improve properties of the mix containing the foaming agent B alone, and helps to remedy the loss in strength induced by the foaming agent and restore it back to that of the control mix.

3.5. Overall comments

The results of the present investigation demonstrate that, with ceramic microspheres as aggregate, Portland cement and chemical additives as ingredients in the mix, it is possible to design a range of lightweight mixes having wide range of densities (550–1220 kg m^{-3}) and compressive strengths (1.39–27.00 N mm^{-2}). The majority of the mixes (except the control mix and the mix with calcium stearate in Table 7) having ceramic microspheres (Tables 3–7) meet the requirements of low and moderate density lightweight concrete with a compressive strength ≤ 17 N mm^{-2} and density < 1350 kg m^{-3} [11]. The threshold Portland cement content appears to be about 50% above which both compressive strength and density increase almost in proportion with the cement content.

4. Conclusions

The following conclusions are drawn from the present experimental investigation.

1. Lightweight mixes having a wide range of densities of 550–1220 kg m^{-3} and compressive strengths of 1.4–27 N mm^{-2} can be designed with a judicious combination of Portland cement, ceramic microspheres as aggregates and aeration/foaming agents.
2. Ceramic microspheres have a low bulk density of 400 kg m^{-3} compared to Portland cement and therefore are able to contribute to the low density of the mix. However, with increasing amounts of these aggregates, the water demand also increases leading to increased capillary porosity and lower resistance to water absorption.
3. The incorporation of calcium stearate as a waterproofing agent dramatically reduced the water absorption properties of the resulting lightweight mixes. However, process of generating hydrophobic surfaces within the mix lead to reductions in compressive strength and modulus of rupture.
4. When finely ground aluminium powder is used as an aeration agent, the amount required to effect changes in density is controlled by the amount of cement content in the mix. However, a reduction in density also causes a loss in compressive strength, and hence the amount of aeration agent used has to balance the density reduction with loss in compressive strength. In general terms, 0.1% by mass of cement should be adequate to obtain the desired changes in properties.

5. Foaming agents generally reduced both density and compressive strength, but the resistance to water absorption remained nearly unchanged compared to the control mix. This is due to the fact that they create stable and isolated bubbles, which are distributed in the paste matrix, and the bubbles thus formed do not contribute for the capillary porosity, therefore, resistance to water absorption remains unaffected.

6. A combination of a suitable foaming agent and calcium stearate caused negligible loss in density and compressive strength, but the resistance to water penetration was increased dramatically compared to the control mix. Calcium stearate as a water-proofing agent helped to improve the properties of the mix containing the foaming agent and remedy the loss in compressive strength.

7. The results of the present study show that incorporation of ceramic microspheres as aggregates and suitable chemical additives can produce low and moderate density lightweight mixes with a density <1350 kg m^{-3} and compressive strength of ≤ 17 N mm^{-2} with a high degree of resistance to water absorption.

References

[1] ACI 213R-87, Guide for Structural Lightweight Aggregate Concrete, ACI Manual of Concrete Practice: Part 1. Materials and General Properties of Concrete, Detroit, MI, USA, p. 27.
[2] J. Carmichael, Pumice concrete panels, Concr. Int. 8 (11) (1986) 31–32.
[3] P.K. Mehta, Concrete, structures, properties and materials, Englewood Cliff, NJ, 1986.
[4] BS 3797: 1990, Specifications for lightweight aggregates for masonry units and structural concrete.
[5] BS 4551: Part 1: 1998, Methods of testing mortars, screeds, and plasters: Part 1. Physical testing.
[6] Singapore Standard 271: 1983, Specifications for concrete masonry units (for non-load bearing applications), Singapore.
[7] Singapore Standard 78: Part A16: 1987, Testing concrete: Part A16. Method for determination of compressive strength, Singapore.
[8] Singapore Standard 78: Part A14: 1987, Testing concrete: Part A14. Method for determination of density of hardened concrete, Singapore.
[9] Singapore Standard 214: 1979, Specifications for pre-cast concrete kerbs, channels and dividers, Singapore.
[10] ASTM C 78-94: Standard test method for flexural strength of concrete using simple beam with third-point loading, Philadelphia, USA.
[11] A.M. Neville, Properties of Concrete, Addison Wesley Longman, England, 1997.