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Aerogel-incorporated concrete: An experimental study

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HIGHLIGHTS

- Replacing the natural aggregate with aerogel granules results in a lightweight and thermal insulating concrete.
- The properties of aerogel incorporated concrete can be modified by changing the aerogel content.
- Aerogel particles are stable during the hydration of cementitious materials.

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ABSTRACT

Lightweight concrete can be prepared by replacing the normal aggregate of concrete, either partly or totally, with lightweight materials. In this work, by incorporating silica aerogel particles into concrete matrix, we have successfully prepared a lightweight and thermal insulating concrete material, aerogel-incorporated concrete (AIC) [The term "aerogel-incorporated concrete (AIC)" is used in this work to describe a mortar or cement based material containing aerogel particles.], with a density of ~1.0 g/cm^3, a thermal conductivity of ~0.26 W/mK, and a compressive strength of ~8.3 MPa at an aerogel content of 60 vol.%. Moreover, the density, thermal conductivity, and the mechanical properties of AIC can be controlled by varying the aerogel content. Scanning electron microscopy observations reveal that the aerogel particles are stable during the hydration of cementitious materials, suggesting possibilities of combining aerogel and concrete materials for construction applications.

1. Introduction

Lightweight concrete has many important applications in modern construction and buildings due to its advantages such as higher strength/weight ratio and superior heat and sound insulation characteristics [1,2]. Lightweight concrete can be prepared, among others, by replacing the normal aggregate (i.e. sand and rock), either partly or totally, with lightweight aggregates such as pumice, diatomite, volcanic cinders, and perlite [3]. Since the introduction of lightweight aggregates into concrete introduces also possible interactions between the aggregates and the binder phase, depending on the nature of the aggregates employed, an intelligent design and selection of aggregates is obviously important for lightweight concrete for different applications.

Lightweight concrete usually possesses superior thermal insulation properties compared to conventional concrete due to the large amount of air void in the concrete matrix and/or in the lightweight aggregates [1]. This feature is especially relevant with regard to the energy efficient buildings, where achieving both the thermal insulation and the load-bearing feature with a unique material is very attractive [4]. For concrete, a low thermal conductivity requires in general the presence of voids within concrete, whereas for a high mechanical strength solid instead of void is needed. To meet this contradictory requirement, the application of thermal insulating aggregates with good mechanical strength is required to achieve lightweight and thermal insulating concrete. For example, expanded polystyrene (EPS), a low density (~50 kg/m^3) foam consisting of discrete air voids in a polymer matrix, has been widely studied for lightweight concrete [5–7]. So far, EPS concrete is commercially available with typically density of 95–750 kg/m^3, compressive strength of 2.9–5.8 MPa, and thermal conductivity of 0.23–0.26 W/mK, depending on dosage of the EPS materials [8]. It is worthwhile to note that mechanical properties of the EPS concrete are not satisfactory for many structural applications; moreover, the EPS concrete may suffer from its lack of fire-resistance. In this regard, other inorganic based lightweight materials with low thermal conductivity such as aerogel represent interesting alternatives [9,10].

Aerogel is a nanoporous material, typically made of silica, with 94–99% of the volume being air voids, resulting in extremely low density (3–100 kg/m^3 depending on the porosity), low thermal

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conductivity (0.003–0.02 W/mK, compared to 0.026 and 0.033 W/mK of air and EPS, respectively [11]), and good fire and acoustic resistance [12,13]. These characteristics make aerogel a perfect aggregate for lightweight and thermal insulating concrete. However, the application of aerogel in thermal insulating concrete has not been widely studied [9,10], probably due to the high manufacture cost of aerogel [14]. Ratke reported previously an aerogel concrete with interesting fire and sound resistance [9]. Kim et al. reported recently the insulation performance of aerogel cement prepared by mixing aerogel powder, methanol, and cement paste; thermal conductivity of aerogel cement with aerogel mass fraction of 2.0 wt.% was found to be decreased by maximum 75% of aerogel-free cement [10]. It is worth noting that, however, the use of methanol for construction purpose should be avoided in practice.

It is of fundamental interest to study aerogel-incorporated concrete (AIC) or cement based materials, where some interesting and useful properties may be achieved [9,10]. For example, the stability/durability of aerogel particles in concrete is worth studying since the alkaline environment during the hydration of cementitious materials may destroy aerogel (i.e., amorphous silica) through reactions analogous to the well known alkali-silica reaction (ASR) [15,16]. Obviously, the results obtained would be very helpful for the applications of aerogel materials in building sector. In this paper, we report an experimental study on lightweight and thermal insulating AIC; the correlation between aerogel content and the density, thermal and mechanical properties of AIC samples are discussed. We hope the AIC reported here may stimulate more research on both thermal insulating concrete and aerogel materials for construction applications.

2. Experimental procedures

2.1. Materials and specimens

AIC samples were prepared in a standard Hobart 2-litre mixer by adding cement, sand, silica fume, water, superplasticizer, and aerogel particles. The cement used in this study was a CEM I 52.5R (particle density: ~3140 kg/m^3) from Norcem AS Brevik, Norway; compositional details are reported in Table 1. Silica fume (Elkem Microsilica Grade 940, particle density: ~2200 kg/m^3) was added to modify the properties of cement. Superplasticizer (Dynamon SP130), a modified acrylic polymer solution for precast concrete from Rescon Mapei, Norway, was added during the stirring stage to increase cohesion and homogeneity of the concrete mixture. A natural sand from Finland (particle density: ~2600 kg/m^3) was selected by using sieve with size of 0.5–2 mm. Hydrophobic aerogel granules (ISOGEL 800, particle density: ~100 kg/m^3) were received from PCAS, France, with typical sizes of about 2–4 mm. Distilled water was used throughout the experiment.

Table 1
Chemical composition of CEM I 52.5 R.

Component	Percentage (wt.%)
CaO	64.16
SiO_2	20.37
Al_2O_3	4.58
SO_3	3.84
$CaCO_3$	3.8
Fe_2O_3	3.56
MgO	2.26
K_2O	0.47
Na_2O	0.40
P_2O_5	0.19
Cl^-	0.038
LOI	2.14

The water–binder (w/b) ratio used in this work was set as 0.4; the binder content was taken as the sum of cement and silica fume, where the amount of silica fume was 10.8 wt.% of the binder phase. The dosage of SP130 was 1 wt.% of the binder phase. The volume of aggregates (sand + aerogel) was 60 vol.% of the concrete sample. The air void was set as 2 vol.% for all samples. Details of the sample preparation are reported in Table 2.

Due to the lightweight and the hydrophobic nature of aerogel, a dry mixing process involving cement, silica fume, sand, and aerogel particles was applied first. Then, water was added slowly to obtain a uniform mixture with all aerogel particles having uniform coating of cementitious slurry. The superplasticizer SP130 was also added at this step to obtain a well-mixed paste. During the mixing, the fracture of some large aerogel particles was noticeable, especially with the presence of sand.

The well-mixed slurry was poured into in a stainless steel prism shaped mold (40 mm × 40 mm × 160 mm); an electric vibrator was employed for a short period (~3 s) to ensure good compaction as well as to avoid separation. The samples were kept sealed in their steel moulds at a water vapor saturated environment at room temperature for 24 h and then de-molded. Subsequently, the samples were maintained in the same water vapor saturated environment for 28 days. For each composition, three identical samples were obtained and thereafter characterized.

2.2. Characterization

Thermal conductivity of cured AIC samples was analyzed by using a Hotdisk Thermal Constants Analyzer (Model TPS 2500S). A transient plane source technique was applied [17,18] and a disk-type Kapton Sensor 5465 with radius 3.189 mm was used. The sensor, which acts both as heat source and temperature recorder, was sandwiched between the two pieces of samples. The measurements were made by applying a heating power of 0.315 W for 20 s. The temperature increase of the samples as a function of time was recorded to compute the thermal conductivity of the samples. The AIC samples were measured immediately after the curing process to minimize the effects of hydration or moisture content on thermal conductivities [18]. Different measurement configurations were employed and the reported data were the arithmetic mean of nine individual results.

Mechanical properties of cured AIC samples were analyzed according to UNI-EN standard [19]. The flexural tensile strength of prism (40 mm × 40 mm × 160 mm) was recorded by three–point bend test method with span of 100 mm and load speed of (50 ± 10) N/s. The final flexural tensile strength was the arithmetic mean of the three individual results. After the bend test, the obtained two fragments were subjected to compressive strength test with contacting surface of 40 mm × 40 mm. The load was applied vertically to the sample at a rate of (2400 ± 200) N/s. The final compressive strength was the arithmetic mean of the six individual results.

After the mechanical property test, the resulting small pieces with suitable sizes were collected and used for morphology characterization on a Zeiss Supra 55VP field emission scanning electron microscopy (FE-SEM). An amorphous carbon coating was applied on the surface of the samples before the SEM observation.

3. Results and discussion

3.1. Aerogel particles

The commercially available aerogel granules are usually several millimeters in size and are irregular in shapes, as shown in Fig. 1a.

Table 2
Mix proportions of the AIC (40 mm × 40 mm × 160 mm) (g).

Sample	Water	Cement	Silica fume	SP130[a]	Sand[b]	Aerogel	Aerogel fraction	
							(vol.%)	(wt.%)
2Ref	49.76	117.75	14.3	1.32	405.37	0	0	0
2A10	50.10	117.75	14.3	1.32	337.94	3.07	10	0.59
2A20	50.43	117.75	14.3	1.32	270.60	6.14	20	1.33
2A30	50.76	117.75	14.3	1.32	203.10	9.21	30	2.32
2A40	51.10	117.75	14.3	1.32	135.67	12.28	40	3.70
2A50	51.43	117.75	14.3	1.32	68.25	15.36	50	5.72
2A60	51.76	117.75	14.3	1.32	0	18.47	60	9.07

[a] Water content ~70 wt.%.
[b] Water content ~0.5 wt.%.