Development of a new thermally insulating and structural green concrete for lean constructions

Serina Ng[*a], Bjørn Petter Jelle[*,**]

[*]SINTEF Building and Infrastructure,
Department of Materials and Structures, NO-7465 Trondheim, Norway
[**]Norwegian University of Science and Technology (NTNU),
Department of Civil and Transport Engineering, NO-7491 Trondheim, Norway
[a]Corresponding author: serina.ng@sintef.no (e-mail), +47-93002055 (phone)

ABSTRACT

A new class of thermally insulating, structural concrete was designed and developed in-house. This was carried out by the fusion of current concrete/ mortar technology with aerogel granulates in an effort to produce a lean wall with both strength and thermally insulating properties. The target of this work is to achieve a material which has a compressive strength of 20 MPa, with a corresponding thermal conductivity as low as 0.1–0.2 W/(mK). Due to the Knudsen effect, aerogel decreased the thermal conductivity of the composites, but at the drastic expense of structural properties arising from its inherent brittleness and the development of gap spaces between the hydrophobic-hydrophilic interface of aerogel and concrete. Optimization of the mix designs, curing conditions, type of binders and additive employments improved the codependency. The research so far showed that such a goal is attainable even when increase sustainability efforts are met through incorporation of green construction materials.

Keywords: Thermal insulation, Compressive strength, Aerogel, Lean concrete, Green materials

1 INTRODUCTION

Thermal insulation has always been a demanding requirement in energy efficient constructions, particularly at locations with harsher and more extreme climates. To optimize thermal insulation resistance, new thermal insulation materials and solutions with low thermal conductivity values are being developed [1-3]. The current and most common practice is to utilize insulation materials in ever increasing thicknesses in the building envelopes. While this may achieve the immediate energy efficiency targets, very thick and multilayered building envelopes are less desirable due to many reasons, including but not limited to space challenges with respect to economy and useable floor area, transport volumes, refurbishment issues, architectural restrictions, material demands, existing and new building techniques, etc. This points to a need for a class of new materials which are both structural strong and thermally insulating. This article thus aims to give a review of the work performed in the development of such thermally insulating structural composites based on aerogel incorporation, and the way forward.

2 MATERIALS

The main materials for this series of work include:

- Cement with trade name Anlegg (Norcem AS)
- Hydrophobic aerogel (P100, Cabot Aerogel)
- Silica fume (SF, Grade 940U, Elkem Microsilica)
- Quartz fines (M4000, Sibelco AS)
- Calcined clays (based on smectite, CS and kaolinite, CK, Saint-Gobain Weber)
- Superplasticizers (Mapei AS)

The chemical compositions and loss on ignition (LOI) of all dry powders are given in Table 1. The resulting samples will thus possess very high contents of SiO_2, particularly when cement is replaced by calcined clay.

Table 1: Chemical compositions of cement, silica fume, aerogel and two calcined clays (wt.%).

[wt.%]	Cement	Silica fume	Aerogel	CK	CS
CaO	63.2	-	-	0.1	9.3
SiO_2	20.4	>90	>97	61.7	49.6
Al_2O_3	4.58	-	-	30.5	15.9
Fe_2O_3	3.56	-	-	3.5	8.1
MgO	2.26	-	-	0.4	3.2
SO_3	3.84	-	-	-	-
Na_2O_{eq}	0.71	-	-	3.3	4.2
LOI	2.14	<3.0	-	-**	-**

*Silica [(trimethylsilyl)oxy]-modified.
**Loss on ignition (LOI) not measured here.

3 METHODOLOGY

3.1 Recipe formulation and mortar casting

Aerogel-incorporated mortar (AIM) samples were prepared according to modification of the formulation and casting method reported previously [4, 5]. The water-cement-ratio (w/c) of the mortar systems varied from 0.2 to

1.7, depending on the requirement of the system. The main driving factors are optimization of initial mortar paste rheology and eventually good setting and hardening properties of the AIM samples, in balance with the employment of superplasticizers as rheology regulators. Calcined clay were employed as cement replacement of up to 65% by weight of cement according to their known pozzolanic effects [6], while fiber additions are up to 2%. The recipes for the different mixes discussed in this study can be found in our earlier work [5, 7-11].

The general mortar preparation is as follow: In a 2 liter Hobart mixer, all the dry powders of binders, quartz fines, silica fume and norm sand were first mixed together at low speed for 15 s. The required amount of superplasticizer was dissolved in water and the resulting solution was then added to the mix, marking the start of hydration. About ≈ 20 g of the superplasticizer solution was kept and added to the mix 5 min after initial wetting of the sample. Low shear mixing was continued till a total of ≈ 8 min where the mortar appeared to flow well before being subjected to high shear mixing for 1 min. Additional superplasticizers may be added to ensure a flowable mortar. The aerogel was subsequently folded and homogenized into the mortar mix manually to prevent excessive crushing. When well homogenized, the mortar was cast into the standard 10 x 10 x 160 mm metal moulds, vibrated and stored at 100 %RH (relative humidity) for 24 h before demoulding and curing in water or 100 %RH for 28 days before further analysis and characterization. The storage and curing temperatures were varied to investigate their effects [8].

3.2 Characterization of mortar prisms

Cured AIM samples were analyzed for their thermal conductivities, flexural and compression strengths. Mechanical strength properties of cured AIM samples were measured according to DIN EN 196-1 standard [12]. The thermal conductivity of cured concrete samples was determined by employing a Hotdisk Thermal Constants Analyzer of the type TPS 2500S. A transient plane source technique was applied [13] and the AIMs were measured using either the Kapton sensor with radius of 9.868 mm (#8563) or 3.189 mm (#5465). The conductivity measurements were performed with a heating power ranging from 0.1 to 0.7 W and a heating time ranging from 10 to 320 s. Scanning electron microscope (SEM) imaging was performed on polished samples precast in epoxy, employing both secondary electron imaging and backscattering, and energy dispersive X-ray spectroscopy (EDS) analysis with a Jeol JXA-8500F Electron Probe Micro Analyzer (EPMA).

All AIM samples were measured or prepared within 24 h after 28 days storage to minimize sample differences with respect to the hydration or moisture contents that may have occurred as a function of time.

4 RESULTS AND DISCUSSIONS

The neat cement mortar prism (0% aerogel) prepared at a w/c of 0.6 registered a compressive strength of 55.3 MPa and thermal conductivity of 0.97 W/(mK) after 28 days of curing. When aerogel was introduced, thermal conductivity decreased proportionally to compressive strength (Fig. 1, [6]). The decrease in thermal conductivity of the prisms can be attributed mainly to the network of nanostructure pores in the aerogel. In such nano-pores, the gas molecules present inside were located within the minute (nano-sized) space, resulting in Knudsen diffusion of the gas molecules which effectively reduced the thermal gas conduction of the material. However, due to the highly porous nature of aerogel, a degree of brittleness was introduced to the prism and the compressive strength hence decreased.

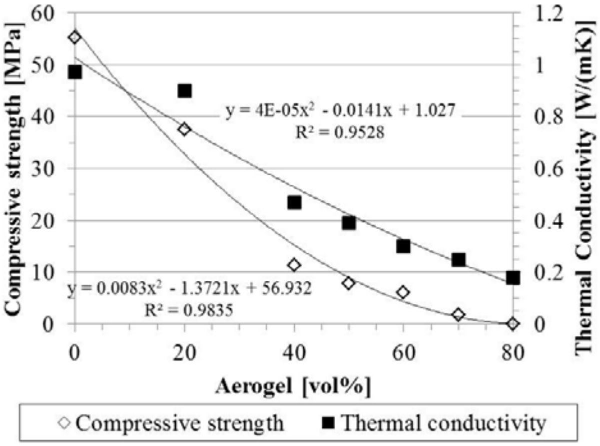

Figure. 1: Compressive strength and the corresponding thermal conductivity of AIM samples [6].

The lowest thermal conductivity attained was 0.18 W/(mK) at an aerogel loading of 80 vol% and compressive strength was < 1 MPa. With 70 vol% loading of aerogel, the thermal conductivity of the mortar prism increased almost 40 % to 0.25 W/(mK), with a low compressive strength of 1.7 MPa. Due to the low strength at range of desired thermal conductivities, further optimization methods were explored and they are discussed in the following:

4.1 Particle-matrix effect based on UHPC

The effect of improving the particle-matrix model was explored based on the concept of ultra-high performance concrete (UHPC), where a further add-on effect of low w/c was introduced. Here, it was found that when high amount of aerogel is present, the drop in mechanical properties of a UHPC system is much greater than that of the conventional cement-aerogel system (Figure 2), making it fall short of the 0.1–0.2 W/(mK) target. These effects can be attributed to the increased gap space (Figure 3, [7]), decreased binder/concrete ratio [9] and an imbalance in the particle/matrix ratio in the UHPC modified mortar system.

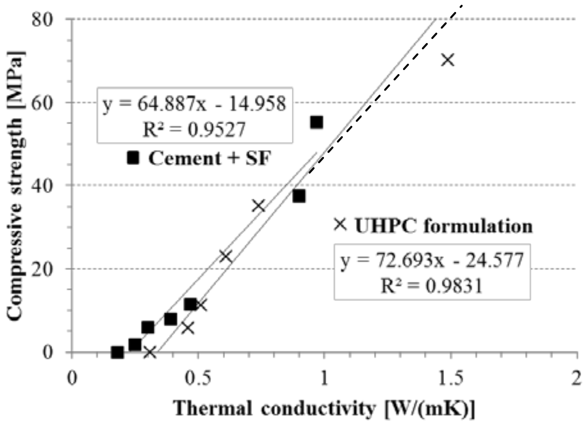

Figure 2: Correlation between thermal conductivity and compressive strength of AIM samples prepared from UHPC formulation (w/c=0.2) and cement (w/c=0.6) [7].

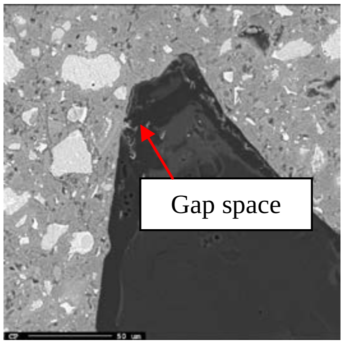

Figure 3: SEM images of AIM sample with 40 vol% aerogel. Magnification is 500x and scale bar is 50 µm [7].

Nevertheless, the fact that high compressive strength of up to 20 MPa was maintained at 50 vol% aerogel loading (thermal conductivity = 0.55 W/(mK)) demonstrated that thermal conductivity can be reduced by a factor of ~5, making the UHPC a desirable system for further exploration.

4.2 Effect of temperature and storage variations on UHPC based AIMs

As shown above, a stand-alone improvisation in the packing matrix was insufficient to significantly improve the strength and thermal conductivity combination of the composite material. When curing and storage effects were tweaked and optimized, up to 50% improvement in strength was achieved at a constant thermal conductivity value. For concrete samples possessing a similar thermal conductivity of ~0.2 W/(mK), the strengths of conventional versus enhanced samples were 8.3 MPa versus 12.6 MPa, respectively. Additionally, it was clearly demonstrated that an elevated temperature of curing at 80°C improved the correlation between thermal conductivity and comrpessive strength (Figure 4, [8]).

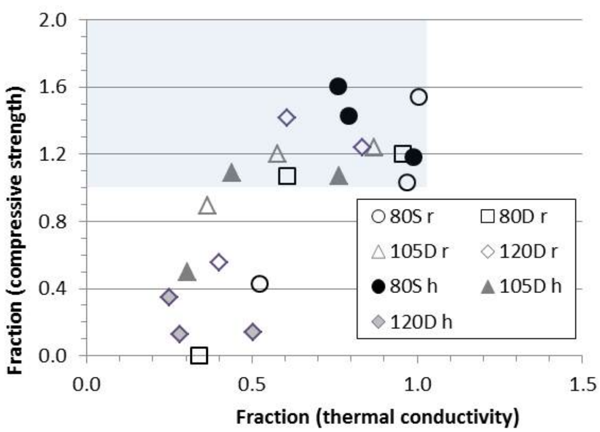

Figure 4: Correlation between fraction compressive strength and fraction thermal conductivity, variables = storing and curing conditions. Shaded area indicates AIM samples which perform better than the reference sample [8].

4.3 Effect of calcined clay as binder

Cement replacement was studied as binder makes up as the second largest quantity in the AIM sample. Calcined clay is a pozzolanic material, which is derived from the calcination of the abundant raw material clay. The most well-known of them is metakaolin. However, due to its high cost, pure metakaolin is not desirable as a mainstream cement replacement material. In this investigation, contaminated clays such as marl [14] were employed. It was found that ~10% improvement in thermal conductivity of the AIM samples could be achieved simply by partially replacing cement with calcined clays [6] due to the inherent lower thermal conductivity of calcined clays relative to cement. Further analysis of the clay based AIM systems displayed that there exist a threshold calcined clay content of 35% replacement for optimum correlation of the desired mechanical and thermal properties (Figure 5, [10]).

When calcined clay was used in place of cement, up to 2.5 times reduction in thermal conductivity was registered for AIM samples at similar strength level and as low as 0.07 W/(mK) was registered at an aerogel loading of 70 vol%.

4.4 Effect of fibers addition

The effect of additives, in terms of fibers was also explored. Up to 2wt.% of polypropyl fibers showed improvement in the strength to thermal property correlation (~10 %), attributing to the better packing ability of the matrix-aerogel as homogenization of aerogel and matrix is improved as polymer fibers acted as bridging systems in mediating the hydrophilic-hydrophobic interaction between matrix and aerogel [15].

However, when fibers are added to clay based AIM samples, this effect is not obvious, potentially due to the buffering effect of the clay on fibers.

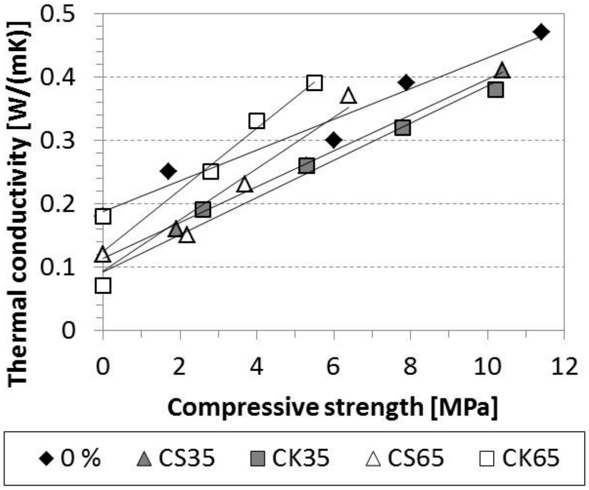

Figure 5: Correlation between thermal conductivity and compressive strength of mortar prisms prepared with and without calcined clay replacements (w/c=0.6) [10].

5 CONCLUSION AND OUTLOOK

As shown from the series of results here, we have come a long way to show the feasibility of thermally insulating, structural concrete. While the development of the structural insulating concrete is still an on-going investigation, the research so far demonstrated that concrete possessing thermal conductivity as low as 0.07 W/(mK) (corresponding thermal conductivity of < 2 MPa) or samples with thermal conductivities of ~0.2 W/(mK) and compressive strengths of ~20 MPa are possible. This signifies the possibility of realizing and actualizing the target of producing thermally insulating concrete with structural properties. The research development demonstrates the potential of producing a single composite material with both thermal insulation and structural properties which for on-site production can be employed in a freeform casting and aesthetic lean construction through advanced techniques such as e.g. 3D printing.

In house, we are continuing efforts to fine tune this composite material system. Further effort is also invested on nano-technological development, whereby one aspect is in the innovation of calcined clay systems. Exploiting the affinity of clays with cement and with polymers, there is currently on-going work exploring the possibility of organo-nanoclays with low thermal conductivity which can be incorporated into AIM samples, without affecting their mechanical properties [11].

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