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Physical and mechanical properties of plasters incorporating aerogel granules and polypropylene monofilament fibres

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HIGHLIGHTS

- Experimental insulating plasters comprising lime, aerogel particles and polypropylene monofilament fibres are investigated.
- Replacing sand aggregate with aerogel significantly reduces both thermal conductivity and strength.
- Incorporating polypropylene fibres greatly improves flexibility and toughness.
- Incorporating aerogel granules in a plaster mix significantly improves vapour permeability.

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ABSTRACT

Growing concern over global warming in recent years has required buildings to become significantly more energy efficient. One of the main ways of achieving this aim has been through the use of innovative materials to facilitate improvements in levels of building insulation. This paper describes the use of aerogel granules as an additive material for lime-based plasters, with the objective of improving the thermal efficiency of buildings whilst maintaining or improving vapour permeability.

Five experimental lime composite mixes were prepared, with lime putty as the binder material and aggregate comprising differing proportions of standard sand and aerogel granules. Previous work had already confirmed very low strengths for plaster mixes containing aerogel granules alone as the aggregate material; therefore, polypropylene fibres were incorporated as a secondary additive material to improve the mechanical properties and reduce strength loss attributed to shrinkage and cracking.

The flexural strength, compressive strength, thermal conductivity and water vapour permeability of lime composite mortars containing different volume fractions of aerogel were determined. Microstructures were examined using scanning electron microscopy and transmission electron microscopy. The results showed that aerogel granules can be successfully incorporated into lime plasters to improve thermal efficiency. The addition of aerogel was also found to improve moisture vapour permeability. The inclusion of polypropylene fibres in aerogel plasters was effective in reducing shrinkage and cracking to acceptable levels. Experimental mixes exhibited a slight reduction in strength compared to standard plaster mixes, although this was compensated for by a high level of flexibility and toughness.

This work provides innovative information on utilising aerogel granules as an insulating plaster additive by addressing the issues of strength and flexibility, properties that are not normally associated with aerogel but which are of importance in a functional plaster material.

1. Introduction

Global warming continues to be one of the most challenging environmental problems we face today. Despite a growing number of climate change mitigation policies, total anthropogenic greenhouse gas emissions were the highest in history from 2000 to 2010 [1]. In the UK, the government is putting special emphasis on retrofitting and refurbishment of the existing housing stock in an effort to tackle this problem, as this offers the greatest potential for CO_2 reduction in the short to medium term. This will be an enormous challenge, with approximately 25 million homes requiring upgrading by the end of 2050 if carbon reduction targets are to be met [2]. One of the most promising ways in which buildings can be adapted to help meet these goals is through the use of state of the art insulation materials, and a highly insulating material in this respect is silica aerogel.

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Aerogel is most often incorporated into buildings in the form of blankets for loft insulation or boards for wall and ceiling insulation. However, insulating boards can be wasteful of material due to the requirement to be cut to size. Also, insulating boards have the disadvantage of requiring a flat surface for fixing onto. As a solution to these limitations, several organisations are developing plaster mixes that incorporate aerogel in granular form. One experimental product developed by Stahl et al. [3], comprised of a mineral and cement free binder and hydrophobised granular aerogel at up to 90% by volume, has achieved a thermal conductivity value of 0.025 W/mK. A similar composite material developed by Burrati et al. [4] reportedly achieved a thermal conductivity value of 0.05 W/mK with 90% aerogel by volume; the equivalent material without aerogel had a value of 0.5 W/mK. To date, however, there is only one known commercially available plaster that incorporates aerogel granules as the insulating element: the Fixit 222 Aerogel Insulating Plaster System. Fixit 222 is a highly developed product, comprising aerogel granules, light weight mineral aggregate, natural hydraulic lime, white cement and calcium hydroxide. Despite the use of cement and mineral aggregate, it still claims to achieve a thermal conductivity value of 0.028 W/mK [5]. These new plasters have significantly better thermal insulation performance than traditional cement or gypsum plasters with sand aggregate, which typically have thermal conductivity values of between 0.22 and 0.72 W/mK [6]. Interestingly, though, there appears to be no published information relating to strength or flexibility for any of these new insulating lime plaster materials. Two studies, involving cementitious mortars incorporating aerogel, which did investigate strength, reported compressive strength, flexural strength and thermal conductivity all reducing with increased aerogel content [7,8].

Aerogels are a special class of extremely low density, amorphous, mesoporous materials with a nanostructure. In the case of aerogels, the 'nano' designation refers to the size of the pores within the material rather than the actual particle size. Pore sizes in aerogels are generally between 5 and 70 nm and have a pore density of between 85 and 99.8% by volume [9], resulting in a very low thermal conductivity, a low gaseous conductivity and a low radiative infrared transmission, making them an extremely efficient insulating material.

An important property of aerogel for use in construction materials is its behaviour in the presence of water. There are several methods of manufacturing an aerogel, and the method used determines whether the finished product is hydrophilic or hydrophobic. Hydrophilic aerogels possess a large number of surface hydroxyl groups, making them extremely hygroscopic. When liquid water enters the pore structure, the surface tension of the water exerts strong capillary forces on the pore walls, causing collapse. This problem can be easily solved, however, by converting the surface hydroxyl groups (-OH) to non-polar (-OR) groups, where R is typically a methyl group [10].

Aerogel possesses a very high strength to mass ratio and can support up to 1600 times its own mass [11]; however, as manufactured, it is a brittle material, having a fracture toughness of only $\sim$0.8 kPa m$^{1/2}$. Although easily crushed, this does not destroy its porous structure; aerogel that has been ground into a powder occupies approximately the same space as the original sample, demonstrating that the pore structure of the material does not change significantly [12].

In addition to its low weight and lower space requirements, aerogel's higher durability makes it an attractive alternative to fibre and foam insulation materials [13].

Initial attempts during this investigation to incorporate aerogel granules with lime plasters resulted in high shrinkage and extensive cracking of the lime matrix. This work seeks to mitigate these problems through the incorporation of monofilament polypropylene fibres. These fibres have been used extensively in cementitious building materials, and are considered one of the most effective methods to reduce plastic shrinkage and cracking in mortars [14]. The effects of the volume fraction of polypropylene fibre on the mechanical properties of concrete was investigated by Rajguru R.S. et al. [15]. It was found that the flexural strength of test beams increased significantly with increased fibre content from 0.25% to 0.5%, but the rate of strength increase achieved by increasing fibre content from 0.5% to 1% was marginal. Work has also been carried out to investigate ways of improving the mechanical properties of aerogel by incorporating fibres into the actual aerogel structure itself to produce fibre-reinforced aerogel composites. It was found that composites could be produced that had a higher strength compared to non-reinforced aerogel, but sacrificed little thermal performance [16].

Whilst aerogel may have the potential to help reduce energy usage in buildings, it is also important to consider the properties of the binder material. Prior to the introduction of hydraulic cements, non-hydraulic lime putty was routinely used as a binder material for mortars, plasters and renders in building construction and has proved to be durable over many centuries [17]. It has a significantly lower environmental impact than that of the more commonly used Portland cement, which requires higher temperatures during production, and hence results in higher CO_2 output, than lime. But the case for lime as a low carbon material is strengthened further by the fact that it actually reabsorbs CO_2 whilst setting; a non-hydraulic lime putty can absorb nearly its own weight in CO_2 [18].

A further advantage of non-hydraulic lime is its long shelf life. It is common for manufacturers to recommend that, once opened, bags of lime are used within a specified time or discarded. In practice, practitioners may keep lime from a few days to one year depending on the storage conditions and risk of excessive hydration and carbonation within the bag. Non-hydraulic lime putty, however, can be stored for significantly longer due to the effectiveness of the milk-of-lime layer on the surface of the putty at preventing carbonation. The carbonation rate and plasticity of lime putty have been found to be still improving after periods in excess of five years [19].

The use of a lime putty as a binder is also advantageous for the recycling of materials. Hardened lime binder can be removed from masonry relatively easily, whereas the high strength bonding of cement mortars and renders can prevent recycling of materials, as it cannot be removed easily from brick and stone without causing damage.

An additional benefit to using lime is its superior water vapour permeability compared to modern commercial plasters [20]. When used as a render, the higher permeability of lime plaster helps moisture to escape from within the walls, preventing freeze thaw damage [21]. When used as a plastering material, its ability to release moisture helps to prevent mould formation and reduction in thermal resistance. Although there is little published data on the permeability of aerogel plasters, one study by Ibrahim et al. reported a figure of 5.1×10^{-11} kg/s m Pa for an experimental aerogel based external render [22]. This figure is significantly higher than was found in a study by Wang et al., where five commercially available gypsum plasters were found to achieve figures of between 1.62 and 2.53 kg/s m Pa [23].

Compared to other insulation materials such as glass and natural fibre, aerogel is still of higher cost. However, it should be noted that it is still a relatively new material for construction applications. As its use becomes more widespread, higher production quantities and economies of scale will help lower the cost [24]. Aerogel is the insulation material of choice for applications where the space available for insulation is limited but performance cannot be compromised. It is also noteworthy that over the service life