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DEVELOPMENT OF LIME BASED, LOAD-BEARING MATERIALS FOR WALL CONSTRUCTION

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Construction of buildings in the UK is traditionally done using building materials such as concrete blocks, bricks and less so, timber. Although timber is a sustainable product, concrete blocks and bricks require a lot of energy input during fabrication, concrete especially being a large producer of CO_2 during its manufacture. Reducing energy consumption either domestically or industrially is an important part of achieving the UK Government's legally binding commitment to reducing greenhouse gas emissions by at least 80% (relative to 1990 levels) by 2050. New, low embodied energy construction materials are urgently required to enable the construction industry to revolutionize and drastically decrease its carbon footprint. The constituents of the materials investigated were selected based on low embodied energy criterion. To achieve this, lime was selected as the base material with hemp (fibers and shives) and PVAc used as additives. Specially selected nanomaterials were used as fillers. The constituents were combined in a manner, which led to different materials being developed, all exhibiting different characteristics. One characteristic was strength (load bearing) to eliminate the use of timber studding during construction. The results show that the highest strengths were achieved by mixing 10 wt. % hemp fiber, 4 wt. % nanozinc oxide and 12 wt. % PVAc at a 0.4 W/L ratio, yielding 17.7 MPa in compression and 7.3 MPa in flexure.

Keywords: Nanomaterials, Compressive and flexural strength, PVAc, Hemp fibers and shives.

1 INTRODUCTION

In order to reduce the environmental impact of buildings, there is a requirement to not only reduce energy use during occupancy, but also use eco-friendly materials with low embodied energy but with high performance characteristics for energy conservation. Concrete and bricks are very common building materials but have an adverse impact on the environment due to the levels of CO_2 produced during the manufacturing process. Reducing energy consumption either domestically or industrially is an important part of achieving the UK Government's legally binding commitment to reducing greenhouse gas emissions by at least 80% (relative to 1990 levels) by 2050. Therefore, the construction industry needs to revolutionize and push for specification of materials, which have a low environmental impact. Lime is considered a relatively low impact material but its strength is normally insufficient for the loads it is subjected to as a free standing material. The main objective of this paper, therefore, is to change the lime-based material from a non-loadbearing to a loadbearing material. The flexural strength should be similar to the flexural strength of cement mortar (4.0 MPa) and the compressive strength must be more than the minimum value of a loadbearing construction material, this is typically 3-5 MPa (De Bruijn *et al.* 2009), or 3.0 MPa for moderate strength mortars and about 4.0 MPa for high strength mortars as given by Swan and Bonora 2017. Aho and Ndububa (2015) reported a flexural strength of 4.0 MPa for a 1:2 cement: sand mix which also meets the criterion for a load bearing material. Ideally, it should be lightweight in comparison to concrete or brick.

A series of experiments were conducted to determine the impact of different nanomaterials such as nanosilica ($nSiO_2$), nanoclay (nclay), nanofibrillated cellulose (nFc), nanozinc oxide (nZnO) and expanded graphite (EG) on the mechanical strength (flexural and compressive) of lime composite properties. Furthermore, hemp shives (HS), polyvinyl acetate (PVAc), hemp fibers (HF) and fiber glass (FG) were also used to determine their effects on the mechanical strength properties. The impact of these components on other properties such as thermal conductivity, porosity, shrinkage, water absorption and water vapor permeability of lime was also studied but is outside the scope of this paper (O'Flaherty *et al.* 2019). SEM images were taken of many specimens to obtain a better understanding of the composition of the fibers and lime matrix. In this paper, the focus is on the mechanical properties (flexural and compressive strength) due to their importance in construction materials.

2 METHODOLOGY

The specimens were divided into groups, with each group focusing on a different nanomaterial such as nanosilica (nSiO2), nanoclay (nclay), nanofibrillated cellulose (nFc), and expanded graphite (EG), which were added to lime matrix. The percentage of nanomaterial was varied to find the optimum percentage, which gave the highest flexural and compressive results. Fiber glass, hemp fibers and PVAc were also added to the lime nanocomposites to determine their influence on strength. A food mixer was used to mix lime binder (NHL5) with nanofillers and water for 5 minutes at low speed and 15 minutes at quick speed. There are a number of common methods used in the dispersion of nanomaterials before adding them to a matrix, those being magnetic stirring in water or solvent, sonication and surfactant agent (Agubra *et al.* 2013). In this work, the nanofillers were stirred by magnetic plate with deionized water then added to the mixer following the recommendations given elsewhere (Bensadoun *et al.* 2011). The hemp fibers or shives were blended with dry lime and then the water and nanomaterials were added. The optimum water lime binder ratio was conducted by a flow rate device. The mortar was placed in a conical mold and allowed to free fall after 15 raise/drop cycles. The spread of mortar diameter had to be 160 mm for the optimum water lime ratio. The percentage of water binder ratio firstly was 0.5 W/L and the mortar spread was within the standard limit. The water lime ratio was then decreased to 0.4 W/L, which too, was within the limit.

To ensure full compaction, the on-site placing method was followed where a 'mortar-board' type tamping tool was used to compact the materials. This technique worked quite well despite the low workability (future work will investigate the use of a plasticizer to increase workability). The molds were 40 mm x 40 mm x 160 mm as shown in Figure 1. A total of 13 specimen groups were cast with varying percentage of nanomaterials. Specimens were demolded after five days and stored for a further 23 days to give a 28 days age at testing. All samples were stored at 20 °C and 60 % RH throughout the curing period.

The compressive and flexural strengths were determined on an Instron 3367 as shown in Figure 2 in accordance with BS EN 1015-11 (1999). The ruptured flexural strength samples were then tested in compression by sandwiching them between two steel 40 mm x 40 mm x 5 mm thick steel plates, the test area being taken as 40 mm x 40 mm as specified by the test standard.

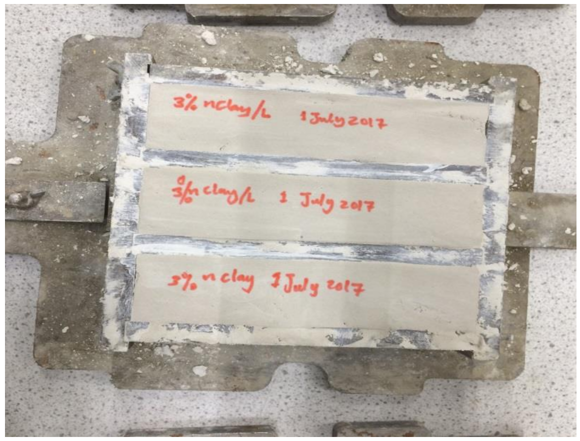

Figure 1. Molds of 40 mm x 40 mm x 160 mm with nanocomposite specimens (3% nClay).

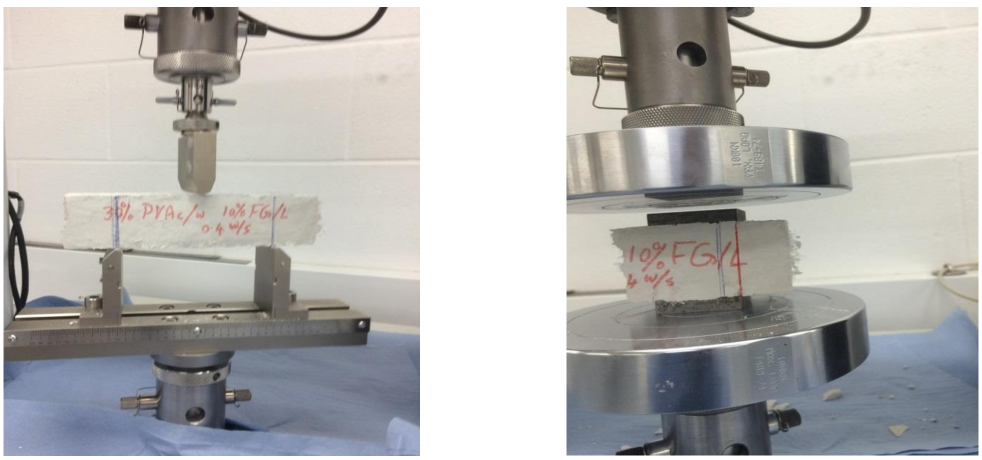

Figure 2. Flexural (left) and compressive (right) strength testing.

3 FLEXURAL AND COMPRESSIVE STRENGTH TESTS RESULTS AND DISCUSSION

The flexural and compression test results for all groups of specimens are presented in Table 1. Referring to Table 1, the specimen group number is given in Column 1. The percentage and type of nanofiller is given in Column 2. The water/lime ratio (W/L) is given in Column 3 and is generally 0.5 except for the last two specimen groups (12 and 13) which were manufactured with a lower 0.4 W/L ratio. The range of compressive strengths obtained for each specimen group is given in Column 4 along with the number of specimens tested per group to give the range and mean compressive strength (Column 5). This is repeated for the flexural strengths in Columns 6 and 7.

3.1 Control Specimens (Pure Lime)

The flexural and compressive strength results for the control specimen groups are given in Table 1. Referring to Table 1, the average compressive strength of the control samples (Specimen Group 1) was 2.9 MPa (range 1.8 - 4.2 MPa) whereas the average flexural strength was 1.1 MPa

Table 1. Summary of test results for compressive and flexural strength.

1 Specimen Group No.	2 % Filler	3 W/L ratio	4 Range of compressive strengths (MPa) (No. of samples in brackets)	5 Mean compressive strength (MPa)	6 Range of flexural strengths (MPa) (No. of samples in brackets)	7 Mean flexural strength (MPa)
1	0 % pure lime	0.5	1.8 - 4.2 (10)	2.9	0.2 - 3.0 (8)	1.1
2	2 wt. % $nSiO_2$	0.5	1.9 - 3.7 (4)	2.8	0.2 - 0.8 (3)	0.4
3	4 wt. % nSiO2	0.5	2.5 - 2.9 (4)	2.7	0.2 - 2.1 (3)	0.9
4	0.5 wt.% nclay	0.5	2.6 - 3.4 (4)	2.9	0.3 - 0.3 (3)	0.3
5	1 wt.% nclay	0.5	2.6 - 3.3 (4)	2.9	0.5 - 0.7 (3)	0.6
6	2 wt.% nclay	0.5	3.3 - 3.8 (4)	3.6	0.6 - 0.7 (2)	0.7
7	5 wt.% nFc	0.5	2.2 - 2.5 (4)	2.3	0.3 - 0.4 (2)	0.3
8	7 wt.% nFc	0.5	2.2 - 2.5 (3)	2.3	0.8 - 0.8 (3)	0.8
9	5 wt. % FG	0.5	1.9 - 4.9 (6)	3.4	1.5 - 3.1 (5)	2.2
10	10 wt. % FG	0.5	10.2 - 11.5 (3)	10.7	3.1 - 4.6 (2)	3.9
11	15 wt. % FG	0.5	5.6 - 7.3 (3)	6.7	1.6 - 2.5 (3)	1.9
12	4 wt. % nZnO	0.4	0.6 - 0.9 (4)	0.7	0.6 - 0.7 (2)	0.6
13	10 wt.% HF, 4 wt.% nZnO, 12% wt. PVAc	0.4	14.4 - 19.7 (6)	17.7	6.7 - 7.7 (3)	7.3

(range 0.2-3.0 MPa). These results were achieved at 0.5 W/L. They are clearly weak in flexure in comparison to the flexural strength of cement mortar (4.0 MPa) as given by Aho and Ndububa (2015).

The mean compressive strength of 2.9 MPa is just about at the minimum limit for load bearing materials (e.g., 3-5 MPa, De Bruijn *et al.* 2009). Some specimens had cracking due to shrinkage and it may be that these cracks contributed to low failure loads, especially when the cracking was near the mid-span of the prisms.

3.2 Nanosilica (Nsio2)/Lime Nanocomposite Specimens

Referring to Table 1, two groups of specimens are presented with nanosilica added as a nanomaterial. Specimen Group No. 2 has 2 wt. % of nanosilica added as a nanofiller whereas Specimen Group No. 3 has 4 wt. %. Referring to Specimen Group 2 (Table 1), the average compressive strength was 2.8 MPa but when the quantity of nanosilica increased to 4 wt. %, the average compressive strength decreased slightly to 2.7 MPa. With regards to the flexural strength results, the 2 wt. % $nSiO_2$ exhibited strength of just 0.4 MPa whereas the 4 wt. % specimens averaged 0.9 MPa. However, this was influenced by an unusually large flexural strength for one of the test specimens, which yielded a flexural strength of 2.1 MPa. This value is suspect and if omitted, the average flexural strength would broadly be in line with the 2 wt. % samples. A possible reason for the low flexural strength of $nSiO_2$/lime nanocomposites was due to cracking as a result of drying shrinkage as shown in Figure 3.

From the test results, it can be concluded that the $nSiO_2$/lime nanocomposite specimen groups with either 2 or 4 wt. % $nSiO_2$ nanofiller yield similar results but overall, there has been a decrease in strength compared to the Control samples.

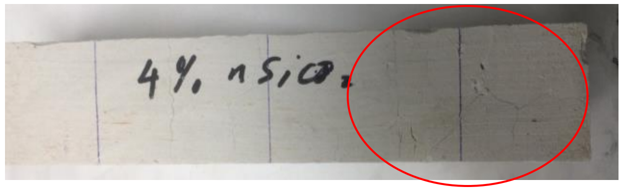

Figure 3. Shrinkage cracking of the nanosilica specimen (circled).

3.3 Nanoclay/Lime Nanocomposite Specimens

The nanoclay/lime nanocomposites have three different dosage percentages (Specimen Groups 4-6, Table 1). Samples dosage of 0.5 wt. % and 1 wt. % nclay both exhibited an average compressive strength of 2.9 MPa. When the percentage increased to 2 wt. % nclay, the compressive strength increased to 3.6 MPa. The corresponding flexural strengths were all low, 0.3, 0.6 and 0.7 MPa respectively.

3.4 Nanofibrillated Cellulose Nfc/Lime Nanocomposites

A total of seven specimens containing nanofibrillated cellulose were tested for compressive and flexural strength as shown in Table 1 across Specimen Groups 7 and 8. Four specimens were dosed with 5 wt. % nFc giving an average compressive strength of 2.3 MPa and flexural strength of 0.3 MPa (Specimen Group 7). The remaining three samples (Specimen Group 8) had an nFc content of 7 wt. % and yielded a similar compressive strength of 2.3 MPa. The flexural strength increased, however, to 0.8 MPa.

3.5 Fibre Glass/Lime Nanocomposites

Table 1 shows that the 5 wt. % FG sample (Specimen Group 9) had an average compressive strength of 3.4 MPa and an average flexural strength of 2.2 MPa. The 10 wt. % FG (Specimen Group 10) yielded a relatively high average compressive strength, 10.7 MPa, and a higher average flexural strength, 3.9 MPa. For 15 wt. % FG (Specimen Group 11), the compressive and flexural strength values were 6.7 MPa and 1.9 MPa respectively. The inclusion, therefore, of fiber additives has led to an increase in strengths compared to the nanofiller additives as would be expected.

3.6 Nanozinc Oxide/Lime Nanocomposites

Specimen Group 12 (Table 1) included 4 wt. % nZnO and a slightly reduced W/L ratio of 0.4. It yielded very low strengths, the average compressive strength was only 0.7 MPa whereas the average flexural strength was 0.6 MPa which again is a low value for this property.

3.7 Hemp Fibres/PVAc nZnO/Lime Nanocomposites

Referring to Table 1, the mix of 10 wt. % HF, 4 wt. % nZnO and 12 wt. % PVAc nanocomposite (Specimen Group 12) were tested but again with a decreased W/L from 0.5 to 0.4 W/L. The average compressive strength for this composite was 17.7 MPa, which is about 3.5 times the upper strength limit of the load bearing material. The average flexural strength was also the highest at 7.3 MPa, which is approaching double the minimum strength of a cement mortar (4.0 MPa) and about the same as the flexural strength of concrete (about 7 MPa). Therefore, it is clear that the addition of PVAc has had a beneficial effect on the strength of this nanocomposite.

4 DISCUSSION AND CONCLUSIONS

It was noticed during testing of Specimen Groups 9, 10 and 11 that the failure of the fiber glass was by pulling out under flexural load, which may mean that the flexural strength can be increased if the adhesion between the fibers and lime increases. As a result, polyvinyl acetate (PVAc) was added to the specimens at 12 wt. % of the mixture, which also contained 10 wt. % hemp fibers and 4 wt. % nZnO (Specimen Group 13). The aim was to increase the adhesion and subsequently the strength. This was achieved by adding PVAc as shown in Figure 4 for Specimen Group No. 13. The results were 17.7 MPa and 7.3 MPa compression and flexure respectively.

Although Specimen Groups 10 and 11 did show promise from the point of view of load bearing characteristics, all other specimens yielded relatively low strengths, which would render them unsuitable as a load bearing construction material.

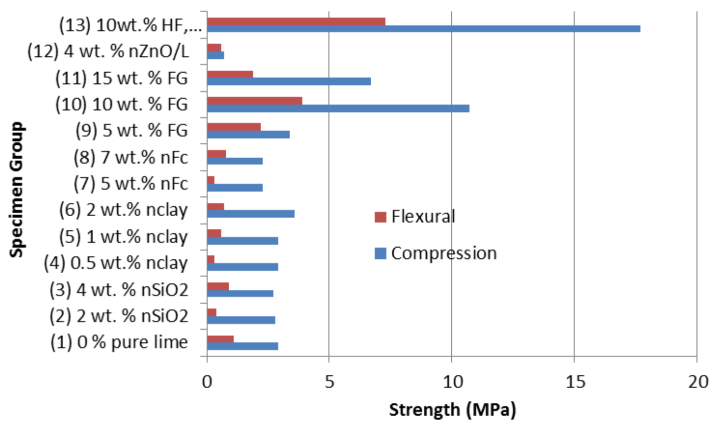

Figure 4. Average compression and flexural strengths.

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