Thermal and mechanical properties of hemp fabric reinforced nanoclay-cement nanocomposites

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ABSTRACT

The influence of nanoclay on thermal and mechanical properties of hemp fabric-reinforced cement composite is presented in this paper. Results indicate that these properties are improved as a result of nanoclay addition. An optimum replacement of ordinary Portland cement with 1 wt% nanoclay is observed through improved thermal stability, reduced porosity and water absorption as well as increased density, flexural strength, fracture toughness and impact strength of hemp fabric-reinforced nanocomposite. The microstructural analyses indicate that the nanoclay behaves not only as a filler to improve the microstructure, but also as an activator to promote the pozzolanic reaction and thus improved the adhesion between hemp fabric and nanomatrix.

Keywords: Cement, nanoclay, hemp fabric, mechanical properties, microstructure, fracture toughness.

1. Introduction

Nowadays, in the building industry, natural fibres and nanomaterials have been gaining increasing attention due to two reasons. One is to develop ‘environmental-friendly materials’ through utilizing natural fibres as alternative to synthetic fibres in fibre-reinforced concrete [1-3], and another is to ‘improve the properties’ of Portland cement matrix by adding nanoparticles [4]. Recently, nanoparticles are used in polymer, ceramic and construction materials in order to produce nanocomposites that have superior physical and mechanical properties [5]. In the construction industry, several types of nanoparticles have been incorporated into concretes such as nano-$SiO_{2,}$ nano-Al_2O_3, nano-Fe_2O_3, nano-$ZnO_{2,}$ nano-$CaCO_3$, nano-$TiO_{2,}$ carbon nanotubes and nano-metakaolin in order to improve the durability and mechanical properties of concrete [6-9].

Natural and cellulose fibres are used in polymer and cement matrices to improve their tensile/flexural strength and fracture resistance properties [10, 11]. They are cheaper, biodegradable and lighter than synthetic fibres. Some examples of natural fibres are: cotton, sisal, flax, hemp, bamboo, coir, wheat straws and others [12-14]. On the other hand, one of the most effective techniques to obtain a high performance cementitious composite is by reinforcement with textile (fabrics), which are impregnated with cement paste or mortar. Synthetic (textile) fabrics such as polyethylene (PE) and polypropylene (PP) have been used as reinforcement for cement composites, in which fabrics are made of multi-filaments. This system has superior filament-matrix bonding which improve mechanical properties such as tensile and flexural strength better than continuous or short fibres [15-20]. In contrast, the use of natural fibre sheets and fabrics is more prevalent in polymer matrix when compared to cement-based matrix. For example, using cellulose-fibre sheets in epoxy or viny-ester matrix have resulted in significantly improved fracture toughness [5, 21].

Despite the advantages of natural fibres and fabrics and also nanoparticles, there are still obstacles which limit their applications in the cementitious composites. Firstly, for natural fibres, the interfacial bond between the natural fibre and the cement matrix is relatively weak and also the degradation of fibres in a high alkaline environment of cement matrix adversely affects the mechanical and durability properties of natural fibre reinforced cement composites [22]. Some researchers have recently recommended that much research is needed to overcome these disadvantages [23]. Secondly, for all nanoparticles, one of the major issues is that increasing the content of nanoparticles leads to reduction of some mechanical properties such as the flexural strength of cement paste [24].

However, little or no research is reported on using of natural fabrics and nanoparticles (e.g. nanoclay) as reinforcement in cement-composites. In this paper, nanoclay was utilised as partial replacement of cement at various contents to produce the nanocomposites and hemp fabrics (HF) were used as reinforcement to fabricate HF-reinforced cement nanocomposites. The underlying hypotheses of this research is to study the effects of different amounts of nanoclay on mechanical properties of HF-reinforced cement nanocomposites. The main aim of this study is to conclude the optimum content of nanoclay which enhances the properties of hemp fabric-reinforced cement nanocomposites. The microstructures of nanocomposites and HF-reinforced cement nanocomposites were also investigated using synchrotron radiation diffraction and scanning electron microscopy.

2. Experimental procedure

2.1. Materials

Hemp fabric (HF) and nanoclay platelets (Cloisite 30B) were used as reinforcements for the cement-matrix composites. The hemp fabric, as shown in Fig.1, was supplied by Hemp

Wholesale Australia Pty**.** Kalamunda, Western Australia. The chemical composition, and the physical properties and structure of hemp fabric are shown in Table 1 and 2, respectively [12, 16]. The nanoclay platelets (Cloisite 30B) used in this investigation are based on natural montmorillonite clay (hydrated sodium calcium aluminium magnesium silicate hydroxide $(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$). Cloisite30B is a natural montmorillonite modified with a quaternary ammonium salt, which was supplied by Southern Clay Products, USA. The specification and physical properties of Cloisite 30B are outlined in Table 3 [5]. Ordinary Portland cement (OPC) was used in all mixes. The chemical composition and physical properties of OPC are listed in Table 4 [2].

2.2. Sample preparation

2.2.1. Nanocomposites

In this study, the OPC is partially substituted by nanoclay with 1, 2 and 3 % by weight of OPC. The OPC and nanoclay were first dry mixed for 5 minutes in Hobart mixer at a low speed and then mixed for another 10 minutes at high speed until homogeneity was achieved. The cement –nanocomposite paste was prepared through adding water with a water / binder (nanoclay-cement) ratio of 0.48. The cement paste without nanoclay was considered as a control.

2.2.2. Hemp fabric-reinforced nanocomposites

Two layers of hemp fabric were used in hemp fabric-reinforced nanocomposites. The hemp fabrics were first soaked into the matrix in order to achieve a better penetration of the matrix in the openings of the fabrics. The fabrication of the hemp fabric-reinforced nano composite specimens was done in five steps. First, a thin layer of matrix was poured into the mould, then the pre-soaked hemp fabric was laid on top of it, then another layer of matrix was poured into the mould followed by another pre-soaked hemp fabric and the final layer of matrix. The total amount of hemp fabric in each specimen was about 2.5 wt%. The mix proportions are given in Table 5.

2.2.3. Curing and specimens

For each series, three prismatic plate specimens of 300×70×10 mm in dimension were cast. All specimens were demolded after 24 h of casting and kept under water for approximately 56 days. Five rectangular specimens of each series with dimensions 70×20×10 mm were cut from the fully cured prismatic plate for each mechanical and physical test [16].

2.3. Characterisation

2.3.1. High Resolution Transmission Electron Microscopy (HRTEM)

High Resolution Transmission electron microscopy imaging was done using 3000F (JEOL company) operating at 300 kV equipped with a 4×4 k CCD camera (Gatan). HREM is an imaging technique that creates images with atomic resolution. 3000F has excellent HREM performance including 0.195 nm point resolution and 0.104 nm lattice resolution. HRTEM was carried out at University of Western Australia. Nanoclay (Cloisite30B) powder was dispersed in ethanol inside small glass container by using ultrasonic device for 15 minutes. After that few drops of suspension were mounted onto copper grid and then kept to dry.

2.3.2. Synchrotron Radiation Diffraction (SRD)

Synchrotron radiation diffraction (SRD) measurement was carried out on the powder diffraction beamline at the Australian Synchrotron. The diffraction patterns of each sample were collected using a wavelength of 0.825 Å in the two-theta range of 8–52^{o}.

2.3.3. Scanning electron microscopy (SEM)

Scanning electron microscopy imaging was obtained using a NEON 40ESB, ZEISS. The SEM investigation was carried out in detail on microstructures and the fractured surfaces of samples. Specimens were coated with a thin layer of platinum before observation by SEM to avoid charging.

2.3.4. Thermogravimetric analysis (TGA)

The thermal stability of samples was studied by thermogravimetry analysis (TGA). A Mettler Toledo TGA 1 star system analyser was used for all these measurements. Samples with 25 mg were placed in an alumina crucible and tests were carried out in Argon atmosphere with a heating rate of 10^{o}C/min from 25 ^{o}C to 1000 ^{o}C.

2.4. Physical properties

Measurements of bulk density and porosity were conducted to determine the quality of nanocomposites. The thickness, width, length and weight are measured in order to determine the bulk density. The calculation for density was carried out by using the following equation:

$$\rho = \frac{m_d}{V} \qquad (1)$$

Where, ρ = density in (g/cm^3), m_d = mass of the dried sample (g) and V = volume of the test specimen (cm^3).

The value of apparent porosity P_S was determined using the Archimedes principle in accordance with the ASTM Standard (C-20) and clean water was used as the immersion water. The apparent porosity P_S was calculated using the following equation [25]:

$$P_S = \frac{m_s - m_d}{m_s - m_i} \times 100 \qquad (2)$$

Where m_i = mass of the sample saturated with and suspended in water, m_s = mass of the sample saturated in air.

For the water absorption test, the produced specimens were dried at a temperature of 80 °C until their mass became constant and then the mass was weighed (W_0). The specimens were then immersed in clean water at a temperature of 20 °C for 48 h. After the desired immersion period, the specimens were taken out and wiped quickly with wet cloth, and then the mass was weighed (W_1) immediately. The rate of water absorption (W_A) was calculated by using the formula:

$$\mathrm{W_A} = \frac{W_1 - W_0}{W_0} \times 100 \qquad (3)$$

2.5. Mechanical properties

Five specimens, measuring 70×20×10 mm, in each composition were used to measure the mechanical properties. Three-point bend tests were conducted using a LLOYD Material Testing Machine to evaluate the flexural strength and fracture toughness of the composites. The support span used was 40 mm with a displacement rate of 0.5 mm/min. The flexural strength σ_F was evaluated using the following equation:

$$\sigma_F = \frac{3P_m S}{2BW^2} \qquad (4)$$

Where P_m is the maximum load at crack extension, S is the span of the sample, W is the specimen thickness (depth) and B is the specimen width.

In order to determine the fracture toughness, a sharp razor blade was used to initiate a sharp crack in the samples. The ratio of crack length to thickness (depth) ($\frac{a}{W}$) was about 1/3. The fracture toughness was calculated using the following equation [26, 27]:

$$K_{IC} = \frac{p_m S}{BW^{3/2}} f(\frac{a}{W}) \tag{5a}$$

Where a is the crack length (mm) and $f(\frac{a}{W})$ is the polynomial geometrical correction factor given by:

$$f(\frac{a}{W}) = \frac{3(a/W)^{1/2}[1.99-(a/W)(1-a/W)\times(2.15-3.93a/W+2.7a^2/W^2)]}{2(1+2a/W)(1-a/W)^{3/2}} \tag{5b}$$

The impact strength of the composite was determined using, Zwick Charpy impact tester with 1.0 Joule pendulum hammer. Un-notched sampled were used to compute the impact strength using the following formula:

$$\sigma_I = \frac{E}{A} \tag{6}$$

Where E is the impact energy to break a sample with a ligament of area A.

3. Results and discussion

3.1. Characterisation

3.1.1. High Resolution Transmission Electron Microscopy (HRTEM)

HRTEM images for nanoclay (Cloisite 30B) are shown in Fig. 2 (a & b). The lower magnification image in Fig. 2a gives a general view of the nanoclay platelets. The high magnification image in Fig. 2b shows the layer structure of nanoclay platelets. It can be seen clearly that the distances between the nanoclay platelets were about 1.85 nm and thus this is evidence that the d-spacing of (0 0 1) planes in nanoclay layers were 1.85 nm as shown in Table 3 [21].

3.1.2. Synchrotron Radiation Powder Diffraction (SRD)

The synchrotron radiation powder diffraction (SRD) patterns of nanoclay, cement paste and nanocomposites containing 1, 2 and 3 wt% nanoclay respectively are shown in Fig. 3(a-e). International Centre for Diffraction Data (PDF-4 2013) database was used for phase identification. It is common that PDF is calculated according to Cu Ka wavelength (λ=1.5406A^o), but because synchrotron wavelength (λ=0.825A^o) was used in this study, PDF database was adjusted according to synchrotron wavelength. However, serial number of PDF and d-spacing which identify phases did not change but two-theta was shifted. Fig. 3a shows the SRD pattern of nanoclay. It has crystalline phase which refers to Montmorillonite-18A [$Na_{0.3}(Al,Mg)_2Si_4O_{10}OH_2 \cdot 6H_2O$] (PDF000120219). However, this phase was not detected clearly in nanocomposites. In Figs. 3b-e, three important phases can be seen: portlandite [$Ca(OH)_2$] (PDF 00-044-1481), dicalcium silicate [C_2S] (PDF 00-033-0302) and tricalcium silicate [C_3S] (00-049-0442). Moreover, there are two less important phases: Quartz [SiO_2] (PDF 000461045) and Calcite [$CaCO_3$] (PDF 000050586) [28, 29].

The composition of $Ca(OH)_2$ has a well-defined crystallized structure , it has five major peaks in the SRD pattern that corresponds to 2θ angle of 9.61°,15.23° , 18.06°, 24.71° and 26.56°. Although there are some overlaps of peaks and they have small intensities, dicalcium silicate (C_2S) has four major peaks that correspond to 2θ angle of 16.48°, 17.04°, 17.28° and 21.72° as well as tricalcium silicate (C_3S) has four major peaks that correspond to 2θ angle of 15.61°, 17.05°, 17.23° and 26.98°. However, generally, the addition of nanoclay reduced the intensities of $Ca(OH)_2$ crystals comparing to the control cement paste. In nanocomposite containing 1 wt% nanoclay, the intensities of $Ca(OH)_2$ crystals significantly reduced compared with control. This result indicates that an obvious consumption of $Ca(OH)_2$ crystals happens in the cement-nano composite mainly due to the effect of pozzolanic reaction in the presence of nanoclay and good dispersion of nanoclay in matrix which lead to produce more amorphous calcium silicate hydrate gel (C-S-H). This result is in agreement with the work done by Chang et al. [29] where the intensities of $Ca(OH)_2$ crystals were decreased by the addition of 0.6 wt% nano-montmorillonite into cement paste. On the other hand, for nanocomposites containing 3 wt%, there are insignificant effect. This may be attributed to agglomerations of nanoclay at high contents which lead to poor pozzolanic reaction. Overall, the results indicate that nanomatrix with 1 wt% nanoclay can consume more $Ca(OH)_2$ crystals and can improve the structure more effectively than 3 wt% nanoclay.

3.1.3. Thermal stability and properties

The thermal stability of samples was determined using thermogravimetric analysis (TGA). In this test, the thermal stability was studied in terms of the weight loss as a function of temperature in Argon atmosphere. The thermograms (TGA) of nanoclay, hemp fabric, cement paste, HF-reinforced cement composite and of HF-reinforced nanocomposites are shown in Fig. 4. The char yields at different temperatures are summarized in Table 6. For hemp fabric, it can be seen from TGA curve that the weight loss (%) between 285 and 375 ^{o}C is due to decomposition of cellulose. This result is in agreement with Rachini et al. [30] where the weight loss (%) of hemp fibres under Argon is in the range of 280-380 ^{o}C is due to cellulose decomposition. Concerning nanoclay, it can be seen from TGA curve that the weight loss (%) between 300-400 ^{o}C is due to decomposition of the ammonium salts on montmorillonite.

The TGA analysis show three distinct stages of decomposition in cement paste, HF-reinforced cement composite and HF-reinforced nanocomposites. The first stage of decomposition is between room temperature and 230 ^{o}C, which may be related to the decomposition of Ettringite and dehydration of C-S-H gel. The second stage of decomposition is between 420 ^{o}C and 500 ^{o}C, which corresponds to $Ca(OH)_2$ decomposition. The last stage of decomposition is between 670 ^{o}C and 780 ^{o}C, which correspond to $CaCO_3$ decomposition [31, 32]. In the first stage, HF-reinforced nanocomposites show slightly better thermal stability than cement paste due to resistance of nanoclay to the decomposition. In second stage, the HF-reinforced nanocomposites containing 1wt% show better thermal stability than all samples due to dense and compact nanomatrix through consumption of CH and formation of secondary CSH gels during pozzolanic reaction [33]. Whereas, HF-reinforced nanocomposites containing 3wt% show lower thermal stability than all cement paste and other HF-reinforced nanocomposites, in which this result confirms that slightly poor pozzolanic reaction has occurred and hence nanomatrix is less compacted. Moreover, HF-reinforced cement composites and pure nanoclay show lower thermal stability than others. At 800-1000 ^{o}C, HF-reinforced nanocomposites containing 1wt% show thermal stability slightly less than cement paste but better than other samples. From Table 6 at 1000 ^{o}C, the char residue of cement paste, HF-reinforced cement composite was about 76.08wt% and 59.99 wt%, respectively. The char residue of HF-reinforced nanocomposites containing 1, 2 and 3wt% was about 74.85, 70.86 and 67.62wt%, respectively. It can be seen that HF-reinforced nanocomposites containing 1 wt% performed better in thermal stability with higher char residue of 74.85 wt% than other samples. In similar study, Chen et al. [34] reported that addition of 10 wt% nano-TiO_2 into cement paste improved the thermal stability of nanocomposite, in which it was non-reactive filler.

3.2. Porosity and density

The porosity, density and water absorption values of cement paste, nano-composites, HF-reinforced cement paste and HF-reinforced nanocomposites are shown in Table 7. Generally the composites containing HF exhibited higher porosity and water absorption that these without HF. This could be attributed to the formation of voids at the interfacial areas between HF and matrices. However, Table 7 shows that the addition of nanoclay decreases the porosity and water absorption of these composites when compared to control cement paste and HF composites. For nanocomposites with 1 wt% of nanoclay, the porosity decreases by 20.6% and water absorption decrease by 23.5% compared to cement paste. Moreover, in HF-reinforced nanocomposites containing 1 wt% of nanoclay, the porosity and water absorption decrease by 16% and 18.8%, respectively compared to HF-reinforced cement composite. This indicates that nanoclay has filling effect in the porosity of cement paste composites with and without HF. This result is in agreement with the work done by Jo et al. [35] where the porosity of cement mortar is decreased by the addition of nano-SiO_2 particles. In Table 7, the addition of 1 wt% of nanoclay increased the density of control cement paste and HF-reinforced composites by 4% and 3%, respectively. This improvement demonstrated that cement composites with 1 wt% nanoclay yields more consolidated microstructure. However, the addition of more nanoclay leads to increase in porosity and decrease in density [36]. SEM examinations for the microstructure of nanocomposites containing 1 and 3 wt% nanoclay are shown in Figs. 5(a & b). The SEM micrograph for nanocomposites containing 1 wt% of nanoclay (Fig. 5a) shows that the structure is denser and compact with few pores. On the other hand, in Fig. 5b, the nanocomposites containing 3 wt% nanoclay shows more pores and microcracks which weaken the structure.

3.3 Mechanical properties

3.3.1. Flexural strength

Flexural strength of control cement paste, nanocomposites, HF-reinforced cement paste and HF-reinforced nanocomposites are shown in Table 8. In general, the incorporation of nanoclay in cement matrix led to a modest enhancement in flexural strength of all nanocomposites and HF-reinforced nanocomposites. The flexural strength of nanocomposites containing 1 wt% nanoclay is increased by 31.9% compared to control one. This improvement can be attributed to pozzolanic and filler effect of 1 wt% nanoclay which led to denser nanomatrix than the control cement matrix [7, 29]. The effect of nanoclay on the flexural strength of HF-reinforced cement composite can also be seen in Table 8. The flexural strength of HF-reinforced nanocomposites containing 1wt % nanoclay is increased from 6.9 to 8.8 MPa, about 28.5% increase compared to HF-reinforced cement composite. This could be attributed to good hemp fabric- nanocomposite matrix adhesion. An analogous research was done by Khorami and Ganjian [37] where cement matrix was reinforced with 4 wt% bagasse fibres and cement was replaced by 5% silica fume by weight. The flexural strength was increased by about 20% compared to control bagasse fibre-reinforced cement matrix in that study. They attributed this improvement to the pozzolanic and filler effects of very fine silica fume particles, which led to enhancement of the bond strength between the matrix and the fibres. However, the addition of more nanoclay than 1 wt% caused a marked decrease in flexural strength of nanocomposites and HF-reinforced nanocomposites containing 2 & 3wt % nanoclay in this study. This can be due to the poor dispersion and agglomerations of the nanoclay in the cement matrix at higher clay contents, which led to increase in porosity and decreased the bond between the fibres and the nanomatrix, [7, 38].

The load-midspan deflection curves for HF-reinforced cement composite and HF-reinforced nanocomposites are shown in Fig. 6. The HF-reinforced nanocomposites containing 1 wt% nanoclay shows highest flexural load. This is due to high fibre-matrix interface bond, which increases the maximum load capacity. On the other hand, the HF-reinforced nanocomposites containing 2 and 3 wt% nanoclay and HF-reinforced cement composite show low flexural load. This could be attributed to the increase in porosity which decreases the bond strength of fibre-nanomatrix adhesion.

3.3.2. Fracture toughness

The fracture toughness of control and nanocomposites with and without HF is shown in Table 8. In general, all composites containing HF showed significant improvement in fracture toughness. This enhancement is due to fracture resistance by hemp fabrics which resulted in increased energy dissipation from crack-deflection at the fibre–matrix interface, fibre-debonding, fibre-bridging, fibre pull-out and fibre-fracture [2, 14, 39, 40]. In case of nanocomposites, the fracture toughness of control cement paste and nanocomposites with 1, 2 and 3 wt% nanoclay was 0.35, 0.46, 0.42 and 0.39 $MPa.m^{1/2}$, respectively. It can be seen clearly that, the nanocomposites with 1wt% of nanoclay achieve highest fracture properties with improvement reaching up to 31.4%. The addition of nanoclay into HF-reinforced nanocomposites also increased the fracture toughness. The fracture toughness of HF-reinforced composites and HF-reinforced nanocomposites containing 1, 2 and 3 wt% nanoclay were 0.65, 0.81, 0.74, and 0.66 $MPa.m^{1/2}$, respectively. It can again be seen that the fracture toughness of HF-reinforced nanocomposites containing 1wt% nanoclay is increased by 24.6% comparing to HF-reinforced cement matrix. This is attributed to the fact that the nanoclay modified the matrix through pozzolanic reaction and reduced the $Ca(OH)_2$ content. Thus, good interfacial bond between the nanomatrix and the hemp fibres was achieved. In a similar study, Alamri and Low [41] reported that the addition of 1 wt% halloysite nanotubes (HNTs) into recycled cellulose fibres (RCF) /epoxy matrix significantly increased the fracture toughness by 38.8% compared to RCF-reinforced epoxy composites. However, facture toughness of nanocomposites and HF-reinforced nanocomposites decreased slightly with more nanoclay addition. This is attributed to the poor dispersion of high content of nanoclay into the matrix, which leads to increase in porosity and weaken the interfacial bond between the fibres and the nanomatrix [40]. Fig.7 shows the SEM micrographs of HF/matrix interface of HF-reinforced nanocomposite containing 1 and 3 wt% nanoclay after fracture toughness test. The examination of fracture surface of HF-reinforced nanocomposites containing 1wt% nanoclay shows good fibre-matrix interface as well as the presence of hydration products on the fibre surface indicating better fibre/matrix interface bond (Fig.7a). On the other hand, poor fibre-matrix interface, debonding of fibre and micro-crack are observed in HF-reinforced nanocomposite containing 3 wt% nanoclay (Fig. 7b), which revealed relativity weak matrix.

3.3.3 Impact strength

The impact strength can be defined as the ability of the material to withstand impact loading [27, 42]. As shown in Fig. 8 the presence of nanoclay enhanced the impact strength for HF-reinforced nanocomposites. The impact strength of HF-reinforced nanocomposites containing 1wt % nanoclay was 2.45 KJ/m^2, about 23% increase compared to HF-reinforced cement composite. This is due to good interfacial bonding between the fibres and the nanomatrix. But as clay loading increased, the impact strength decreased. For example, the impact strength of HF-reinforced nanocomposites containing 3wt % nanoclay was 2.25 KJ/m^2, about 13% increase compared to HF-reinforced cement composite. This reduction in impact strength at higher clay loading was due to the formation of clay agglomerates and voids which led to reduced fibre–nanomatrix adhesion. Alhuthali and Low [5] reported that the addition of 3 wt% nanoclay into recycled cellulose fibres (RCF) /vinyl ester matrix increased the impact strength by 27% compared to RCF-reinforced vinyl ester composites.

4. Conclusions

The effect of nanoclay on thermal, physical and mechanical properties of hemp fabric-reinforced cement nanocomposite has been investigated. The optimum content of nanoclay is found to be 1 wt%. SRD analysis and SEM micrographs showed that HF-reinforced nanocomposite containing 1 wt% nanoclay has denser microstructure than others, and thus this improvement led to enhance the hemp fabric-nanomatrix adhesion. In addition, the incorporation of 1 wt% nanoclay into the HF-reinforced nanocomposites improved the thermal stability, decreased the porosity and water absorption as well as increased the density, flexural strength, fracture toughness and impact strength when compared to the HF-reinforced cement composite. However, the addition of more nanoclay (> than 1 wt%) into the HF-reinforced cement composites adversely affected the thermal, physical and mechanical properties.

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Figure Captions

1. Structure of hemp fabric
2. TEM images of nanoclay (Cloisite 30B) at: (a) low magnification, (b) high magnification
3. Synchrotron Radiation Diffraction (SRD) patterns of: (a) nanoclay, (b) cement paste, (c) nanocomposites containing 1wt% nanoclay, (d) nanocomposites containing 2wt% nanoclay, (e) nanocomposites containing 3wt% nanoclay. Numbers indicate to: 1= Portlandite [$Ca(OH)_2$] phase, 2=Dicalcium silicate [C_2S] phase, 3=Tricalcium silicate [C_3S] phase, 4=Quartz [SiO_2] phase, 5=Calcite [$CaCO_3$] phase
4. TGA curves of nanoclay, hemp fabric (HF), cement paste, HF-reinforced cement composite and HF-reinforced nanocomposites
5. SEM micrographs of: (a) nanocomposites containing 1wt% nanoclay and (b) nanocomposites containing 3wt% nanoclay. Numbers indicate to: 1= [$Ca(OH)_2$] crystals, 2=pores, 3=C-S-H gel
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8. Impact strength as a function of nanoclay content for HF-reinforced composite and HF-reinforced nanocomposites

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Table 1

Chemical analysis of hemp [12]

	Cellulosic residue (wt%)	Pectin (wt%)	Hemicellulose (wt%)	Lignin (wt%)	(Wax, fat, protein) (wt%)
Hemp fibre	56.1	20.1	10.9	6	7.9

Table 2

Properties and structure of hemp fabric [12]

Fabric thickness (mm)	0.43
Fabric geometry	Woven (plain weave)
Yarn nature	Bundle
Filament size (mm)	0.04253
Number of filaments in a bundle	24
Bundle diameter (mm)	0.21
Opening size (mm)	0.3
Fabric Density (g/cm^3)	0.6
Modulus of elasticity (GPa)	38-58
Tensile strength (MPa)	591-857

Table 3

Physical properties of the nanoclay platelets (Cloisite 30B) [5]

Physical properties	
Colour	Off white
Density (g/cm^3)	1.98
d-spacing (001) (nm)	1.85
Aspect ratio	200-1000
Surface area (m^2/g)	750
Mean particle size (μm)	6

Table 4

Physical properties and chemical composition of OPC [2]

Properties/Compositions	OPC (ASTM Type I)
Physical properties:	
Specific gravity	3.17
Specific surface, Blaine (cm^2/g)	3170
Chemical analysis:	
SiO_2	21.10
Al_2O_3	5.24
Fe_2O_3	3.10
CaO	64.39
MgO	1.10
SO_3	2.52
Na_2O	0.23
K_2O	0.57
LOI	1.22

Table 5

Mix proportions of specimens

Sample name	Hemp fabric (HF) (wt%)	Mix proportions (wt%)		
		Cement	Nanoclay	Water/binder
NCC-0	0	100	0	0.485
NCC-1	0	99	1	0.485
NCC-2	0	98	2	0.485
NCC-3	0	97	3	0.485
NCC-0/HF	2.5	100	0	0.485
NCC-1/HF	2.5	99	1	0.485
NCC-2/HF	2.5	98	2	0.485
NCC-3/HF	2.5	97	3	0.485

Table 6

Thermal properties of nanoclay, hemp fabric (HF), cement paste, HF-reinforced cement composite and HF-reinforced nanocomposites

Sample	Char yield at different temperature (%)									
	100^{o} C	200^{o} C	300^{o} C	400^{o} C	500^{o} C	600^{o} C	700^{o} C	800^{o} C	900^{o} C	1000^{o} C
Nanoclay	98.76	98.52	90.81	79.02	75.64	74.75	72.35	71.68	71.01	70.64
HF	97.01	95.85	86.89	26.79	24.75	23.06	21.40	20.48	19.36	18.48
NCC-0	93.63	89.38	86.14	84.35	82.21	81.77	78.19	77.25	76.81	76.08
NCC-0/HF	94.61	91.41	81.02	76.85	75.58	74.21	67.08	61.69	61.02	59.99
NCC-1/HF	94.27	90.32	86.23	84.70	83.03	82.76	78.46	76.30	75.81	74.85
NCC-2/HF	94.77	90.80	86.52	83.82	81.47	81.34	77.15	72.18	71.76	70.86
NCC-3/HF	94.89	91.14	85.93	82.10	79.94	79.43	74.39	69.04	68.55	67.62

Table 7

Density, porosity and water absorption values for cement paste and its nanocomposites with and without HF

Samples	Density (g/cm^3)	porosity%	water absorption%
NCC-0	1.78	23.48	13.18
NCC-1	1.85	18.64	10.08
NCC-2	1.78	19.57	10.96
NCC-3	1.76	19.91	11.30
NCC-0/HF	1.66	27.21	16.40
NCC-1/HF	1.71	22.86	13.32
NCC-2/HF	1.64	25.45	15.45
NCC-3/HF	1.63	26.45	16.15

Table 8

Flexural strength and Fracture toughness of cement paste and its nanocomposites with and without HF

Samples	Flexural strength (MPa)	Fracture toughness (MPa.m$^{1/2}$)
NCC-0	5.43 ± 0.51	0.35 ± 0.02
NCC-1	7.16 ± 0.53	0.46 ± 0.03
NCC-2	7.06 ± 0.11	0.42 ± 0.05
NCC-3	6.76 ± 0.44	0.39 ± 0.02
NCC-0/HF	6.88 ± 0.52	0.65 ± 0.05
NCC-1/HF	8.84 ± 0.40	0.81 ± 0.08
NCC-2/HF	7.72 ± 0.26	0.74 ± 0.02
NCC-3/HF	7.07 ± 0.57	0.66 ± 0.09