

Original Article/Research

# Mechanical performance and durability of treated palm fiber reinforced mortars

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## Abstract

The performance of cement mortar reinforced with varying percentages of treated bundled date palm fibers is investigated to appraise their feasibility for structural and non-structural applications. The study first entailed the evaluation of two different alkali pre-treatments at varying concentrations by subjecting treated and untreated bundled fibers to tensile testing. The suitable pre-treatment was then adopted while casting cement mortar mixes. The physical properties of fresh mortar was studied through setting times and, for mortar mixes cured up to 28 days, through parameters such as drying shrinkage and water absorption. The unconfined compressive strengths, split tensile strengths as well as the flexural strengths of the cured mortar mixes at two different ages were undertaken to assess their mechanical properties; while the durability was gauged based on their sulfate resistance for up to a period of four months.

Observed stress–strain behavior under tension led to the choice of 0.173% Ca(OH)<sub>2</sub> as the preferred pre-treatment for the bundled fibers used in the mortar mixes. This was further supported by the microstructural examination on the hardened mortars which, revealed that the integrity of treated fibers remained intact within the cement matrix without hindering the hydration processes. Results also indicated that inclusion of fibers improves the flexural strengths as well as the sulfate resistance of the mortar mixes. However, the cylinder and cube compressive strengths decreased with the increase in treated fiber inclusion.

Although, the work reported in this paper was carried out on cement mortars, conclusions are expected to be relevant to fiber reinforced concrete employing treated natural fibers.

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**Keywords:** Fiber reinforced mortar; Durability; Date palm fibers; Mortars (materials); Mechanical performance

## 1. Introduction

Concrete and mortars made with Portland cement are known to be easy to form and relatively strong in compression but weak in tension, tend to be brittle and have poor impact strength and toughness. The weakness in tension could be overcome by the use of conventional rod reinforcement and to some extent by the inclusion of a sufficient volume of certain fibers (Mehta and Monterio, 1997; Neville and Brooks, 1990; Price, 1951).

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In concrete, fibers can be introduced as primary or secondary reinforcement. Fibers work as primary reinforcement in thin-sheet products in which conventional reinforcing bars cannot be used and includes no coarse aggregate and a matrix with markedly higher cement content than normal concrete. The fibers are used as primary reinforcement to increase both the strength and toughness of the composite. Fibers are also included in the matrix as the secondary reinforcement to control cracking induced by humidity or temperature variations or to provide post-failure integrity in the event of accidental overload or spalling ([Filho et al., 1999](#); [Bentur and Mindness, 2007](#)).

Reinforcing cement matrices with various fibers have been reported to resist rapid propagation of micro cracking under applied stress as well as the ability to withstand loads even after initial cracking, thereby improving toughness ([Yurtseven, 2004](#)). Furthermore, increase in the flexural strength of the fiber-cement composite up to 30% had been observed; however, fiber inclusion reduces the workability of the fresh concrete and mortars ([ACI Committee 544, 2002](#)).

Several fiber types in a variety of sizes, both manmade and natural, have been incorporated into cement based matrices which composed of paste, mortar or concrete. The choice of the most commercially significant types of fibers varies from synthetic organic materials such as polypropylene or carbon, synthetic inorganics such as steel or glass, natural organics such as cellulose or sisal to natural inorganic asbestos. Although, most of the developments involve the use of ordinary Portland cement; the use of high alumina cement, cement with additives such as fly ash, slag, silica fume, etc. to improve the durability of the composite or to minimize chemical interactions between the fibers and matrix have also been reported ([Bentur and Mindness, 2007](#)).

Natural fibers; either unprocessed or processed, have been used to reinforce cement based products in various applications around the world. These include materials obtained from different parts of plants. For example, fibers of jute, ramie, flax, kenaf and hemp are obtained from the stem whereas sisal, banana and pineapple are obtained from the leaf and cotton and kapok from the seed. Natural fibers are composites with a cellular structure including different proportions of cellulose, hemicellulose and lignin which constitute different layers ([Filho et al., 1999](#); [John et al., 2005](#)).

Natural fibers have a high tensile strength and a low modulus of elasticity; however, they have a high variation on their properties which could lead to unpredictable fiber-cement composite properties ([Swamy, 1990](#); [Li et al., 2006](#)). There are several studies on the evaluation of the use of different types of natural fibers in concrete and mortar applications. [Aggarwal \(1995\)](#) suggested that in countries where bagasse is substantially available, it can be used for the production of cement-bonded building materials, since the results obtained from the study showed that the developed composites meet most of the requirements

of various standards on cement-bonded particle boards and have high levels of performance even in moist conditions. Coconut fibers can also be used as reinforcement and to substitute sand in the development of composite reinforced coconut fiber. Moreover, increasing the content of coconut fiber increased the modulus of rupture and compressive strength of the composites up to a certain optimum composition. The composites manufactured with short coconut fibers and ordinary Portland cement matrix presented a significant reduction in toughness ([Abdullah et al., 2011](#); [Filho et al., 2000](#)). On the other hand, bamboo fiber is a satisfactory fiber for incorporation into the cement matrix, and does not vary greatly in flexural strength and fracture toughness values ([Coutts, 1995](#)). It is also proved that the composites reinforced with sisal fibers are reliable materials to be used in practice for the production of structural elements to be used in rural and civil construction, and improvement in flexural strength and splitting tensile strength was reported ([Filho et al., 1999](#); [Al Rawi and Al Khafagy, 2009](#)). Several other studies have been carried out on evaluating the behavior of cement composites with natural fibers from bamboo ([Ghawami, 2005](#)), sisal ([Filho et al., 2009](#)), coir ([Aggarwal, 1992](#)), vegetable origin ([Agopyan et al., 2005](#); [Toledo Filho et al., 2005](#)), etc.

Although natural fibers have some advantages like low density, less abrasiveness, and lower cost when compared to inorganic reinforcing fibers, they also have some disadvantages such as mechanical and thermal degradation during processing, poor wettability and high moisture absorption. Moreover, it is known that the natural fibers include high content of hydroxyl groups (OH) which causes the hydrophilic behavior. The hydrophilic behavior of fiber produces poor adhesion between fiber and matrix when the natural fiber is faced to develop composite material. This problem is mainly improved by several chemical treatment methods suggested by researchers. These methods range from being saline treatment, alkali treatment and treatment involving graft copolymerization of monomers. In order to modify and clean the surface of natural fiber, alkali treatment is one of the most common methods employed. Alkali treatment has been reported to decrease the surface tension and to improve the interfacial adhesion between the fiber and matrix. Furthermore, in the literature, several possible explanations can be found discussing the positive effects of alkali treatment on the properties and structure of natural fibers ([Tan, 1997](#); [Bledzki and Gassan, 1999](#); [Rong et al., 2001](#); [Aziz and Ansell, 2004](#); [Weyenberg et al., 2006](#); [Bachtiar et al., 2008](#); [Kriker et al., 2008](#); [Bachtiar et al., 2012](#); [Nordin et al., 2013](#)).

Date palm trees are native to the middle-east region; their fibers can be easily and abundantly found in countries like the State of Qatar. The idea of reinforcing concrete with date palm fibers was studied by [Kriker et al. \(2005\)](#). They had looked into the durability and mechanical properties of date palm surface fibers in hot-dry climate. They concluded that Male date palm surface fibers (MDPSFs) had the most tensile strength compared to other

types of date palm fibers. As the volume of fiber is increased in the concrete, more post-crack flexural strength and toughness coefficient were observed but at the same time a reduction in first crack and compressive strength was noted. Another research was launched by the same group to study the durability of male date palm surface fibers immersed in alkaline solutions which resulted in concluding that the durability of MDPSF reinforced concrete is poor (Rao and Rao, 2007). Also it was reported that the male date palm surface fiber had an average tensile strength and weak elastic modulus and the increase in percentage and length of the fiber in concrete has a beneficial effect on the ductile behavior (Kriker et al., 2005).

Hence, there is a need for further investigating properties of date palm fibers and understanding their contribution to the performance of cement–fiber composites.

## 2. Materials and methodology

The objective of this paper is to evaluate the performance of cement mortar reinforced with varying percentages of treated bundled date palm fibers so as to appraise their feasibility for structural and non-structural applications.

### 2.1. Materials

#### 2.1.1. Fiber sampling and extraction

Date palms are classified as male and female tree. While the female trees produce flowers, the male trees produce pollen. In this study, the female date palm leaves were used. According to the previous recent research (AlMaadeed et al., 2013), it is discovered that female leaves have better tensile properties. The date palm leaves were obtained from the female trees which are planted at the women campus of Qatar University. The female trees bear the date fruits. The bundled fibers (thickness 0.7–4 mm) were peeled out by means of scissors from date palm leaves and cutting them in lengths of 10 cm.

#### 2.1.2. Fiber pretreatment

The treatment of date palm fibers was performed by NaOH and Ca(OH)<sub>2</sub> solution immersion. The NaOH pellets used to prepare the solution were manufactured by the BDH Laboratory Supplies, U.K. and were of general purpose reagent category. Extra pure Ca(OH)<sub>2</sub> was used to prepare the second solution and was supplied by Riedel-de Haën, Germany.

#### 2.1.3. Mortar preparation

Sand (or fine aggregate) procured from the Qatar Sand Treatment Plant, having 2.73 specific gravity, unit weight (i.e. the weight per unit volume of a material) of 1.65 kg/l and water absorption of 2.15% and ordinary Portland Cement Type I supplied by Al Khalij Cement Company which conforms to BS EN 197-1 (BSI, 2000), were used in this study.

The mortar mixes used in this study have been detailed in Table 1. The volume fraction is defined as the volume of fibers divided by the volume of the composite (fibers and concrete), and typically ranges from 0.1 to 3.0%. In this study, the aim was to vary the volume fractions of the bundled fibers in the mix beyond 2.0%. However, while attempting to do so, during sample preparation, excessive separation of the mortar components was observed which pose difficulty in mix workability as well as in preparing and obtaining monolithic compacted samples. Hence, it was decided to limit the maximum fiber inclusion to 2.0%.

### 2.2. Experimental methods

#### 2.2.1. Fiber pretreatment

The bundled fibers were treated by immersing individually either in 2.0% of NaOH solution (based on recommendations from study performed by AlMaadeed et al., 2013) or 0.173% Ca(OH)<sub>2</sub> (as per room temperature solubility range). Additionally, for direct comparison, 0.173% of NaOH solution was also considered. The fibers were immersed in the solution for an hour and then placed in an oven at 60 °C for 3 h to dry. 10 cm length of treated fibers was then cut to prepare them for the tensile test.

#### 2.2.2. Fiber properties

Tensile test was performed using a Lloyd 1KN tensile tester to examine the elongation and maximum tensile load that can be applied to bundle palm leaf fibers (treated and untreated) of 10 cm length whose thickness ranged between 0.7 mm and 4 mm. The procedure specified in ASTM-D3822 (ASTM, 2007) was followed. A minimum of at least 10 replicates of treated and untreated fibers were tested. The tensile tester was equipped with a linear variable differential transformer (LVDT) to measure the corresponding deformation/strains and Young's stiffness modulus (E).

#### 2.2.3. Mortar and sample preparation

Sand, cement, water and treated palm fiber bundles were mixed to prepare the fresh mortar in a concrete mixer for four mixes with varying percentages (i.e. 0.0%, 0.5%, 1.0% and 2.0 wt.%) of treated date palm fiber bundles. The mortar was placed in molds to prepare four kinds of samples namely cylindrical, cubical, prism and shrinkage/sulfate bar whose dimensions are provided in Table 2. After 24 h, the samples were demolded, marked, dimensions taken and immersed in large drums filled with tap water at room temperature to cure.

#### 2.2.4. Physical properties of the fresh and hardened mortars

The setting time of the fresh mortar was recorded using a Vicat's apparatus in accordance to ASTM C807 (ASTM, 2008). The ASTM C1403 (ASTM, 2012b) method was followed to measure the water absorption of the hardened mortar after 7 and 28 day curing time. The sorptivity test method was based on the ASTM C1585 (ASTM, 2013a) and was used to determine the rate of absorption of water

Table 1  
Details of the mortar mix designs.

Mix No.	w/c <sup>a</sup>	Fiber inclusion (wt.%)	Sand content (kg/m <sup>3</sup> )	Cement content (kg/m <sup>3</sup> )
1 (control)	0.485	0.0	1197	400
2	0.515	0.5	1173	400
3	0.540	1.0	1157	400
4	0.550	2.0	1127	400

<sup>a</sup> w/c denotes water-to-cement-ratio.

Table 2  
Dimensions of mortar samples.

Sample type	Dimensions (mm)
Cube	50 × 50 × 50
Cylinder	100 × 200 (diameter × length)
Shrinkage/Sulfate Bar	280 × 25 × 25
Prism	160 × 40 × 40

by hydraulic cement concrete by measuring the mass increase of a disk specimen at 1, 5, 10, 20, 30, 60, 180, 240, 300 and 360 min time intervals when one surface of the specimen was submerged in 3–5 mm of water. The water absorption and the sorptivity tests were performed in triplicates. The change in length of the mortar bar samples was measured to identify the drying shrinkage according to ASTM C 596 (ASTM, 2009). Length comparator readings of the mortar samples were recorded on the 4, 11, 18, and 25 days of sample curing. Shrinkage results were based on observations made on six replicate specimens per mix.

### 2.2.5. Mechanical testing

Mechanical testing of hardened mortar samples after 7 and 28 days of curing tests was performed in triplicate. Cylindrical and cubical samples were subjected to compressive loading based on ASTM C 39 and C 109 (ASTM, 2012, 2012a), respectively; wherein the maximum load and stress at failure were recorded. The flexural strength of the prism samples was determined according to ASTM C293 (ASTM, 2010) by the three point bending test. The load at failure was noted and accordingly, the flexure strength of the sample was then calculated. The tensile splitting test of the cylindrical samples was performed as per ASTM C496/C496M (ASTM, 2011) by applying compressive force along the length of the specimen until failure.

### 2.2.6. Durability studies

The sulfate resistance of the mortar bars was determined according to ASTM C 1012 (ASTM, 2013a,b). The mortar bars were cured in lime water as per Section 9.2 of the aforesaid standard and then immersed in sodium sulfate solution. The length changes were measured using length comparators in the durations as provided in Section 9.4 of the standard. Six replicate specimens per mix were subjected to durability testing for a period of up to 4 months.

### 2.2.7. Microstructure analyses

The microstructure and crystallinity (viz. scanning electron microscopy and X-ray diffraction) of the various types of cured mortars reinforced with treated date palm fiber bundles were studied. FEI Quanta 400 Scanning electron microscope was used to study the microstructure of fibers and that of the hardened fiber reinforced mortars. SEM of samples was employed by firstly being dried and then mounted on an aluminum stub using a strong conductive double-sided adhesive tape.

X-ray diffraction was used to identify the crystalline phases and the corresponding orientation of various compounds in the 28 day cured fiber reinforced mortars. Rigaku Ultima IV 2-Theta-2-Theta type X-ray Diffractometer fitted with a copper anode diffraction X-ray tube operating at 40 kV and 40 mA was used in this study. The Peak Search and Qualitative Analysis software provided by Rigaku using JCPDS-ICDD library (PDF-2 Release 2007) was employed to identify the peaks of the raw XRD data.

## 3. Results and discussions

### 3.1. Fiber properties and choice of pretreatment

Tensile strength (TS) was chosen as one of the parameters to assess the performance of the treated and untreated fibers taking into account the maximum stress observed along with Young's modulus (E); which is a measure of the tensile stiffness of the fibers under service loads and is experimentally determined from the slope of a stress–strain curve.

In order to obtain meaningful comparison of the various fibers, both the strength and stiffness parameters were considered together. Therefore, a straightforward scatter plot in Fig. 1 indicates the relation between the TS and E. Results fell between the curves:  $40.00^*TS < E \text{ (MPa)} < 78.13^*TS$ . Moreover, it is seen from the figure that the majority of the points fall close to a single center line, represented by  $E \approx 56^*TS$ . Also, it can be observed that the data for 0.173% Ca(OH)<sub>2</sub> treated fibers display closer correlation with less variation compared to the aforesaid trend.

It can be inferred that the tensile strengths and stiffness properties of the fibers are generally better for those treated with Ca(OH)<sub>2</sub> than those treated with NaOH. Furthermore, Fig. 2 presents the stress–strain profiles for untreated and treated bundled fibers using 0.173% Ca(OH)<sub>2</sub>, 0.173% NaOH and 2.0% NaOH. It is evident that treated fibers experienced an overall loss in stress resistance when compared to the untreated fibers.

It is also observed that the stress–strain curves for 0.173% Ca(OH)<sub>2</sub> treated fibers displayed lesser variation and more consistency in comparison with the untreated fibers and NaOH samples treated at different concentrations. Furthermore, changing NaOH concentration from 2.0% to 0.173%; do make slight favorable difference in the tensile behavior of the bundled fibers.

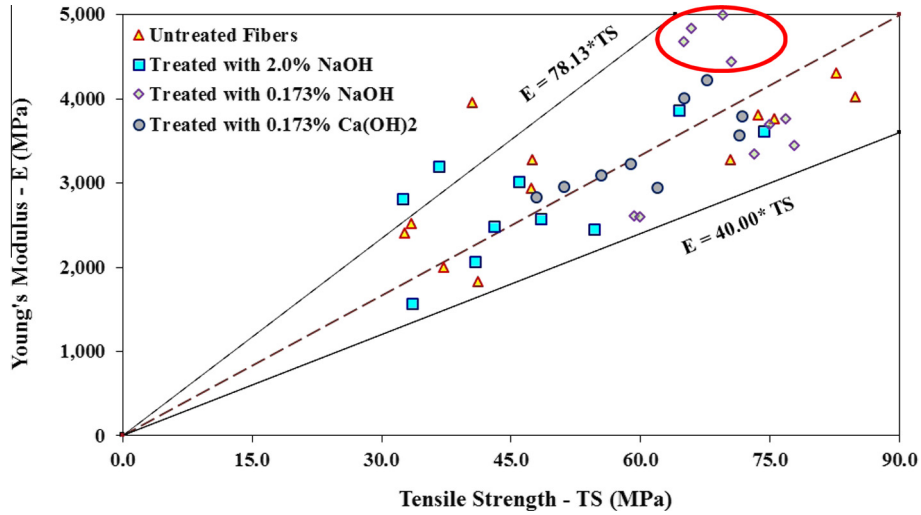


Fig. 1. Tensile Strength (TS) versus Young’s Modulus (E) relation for fibers with and without various treatments.

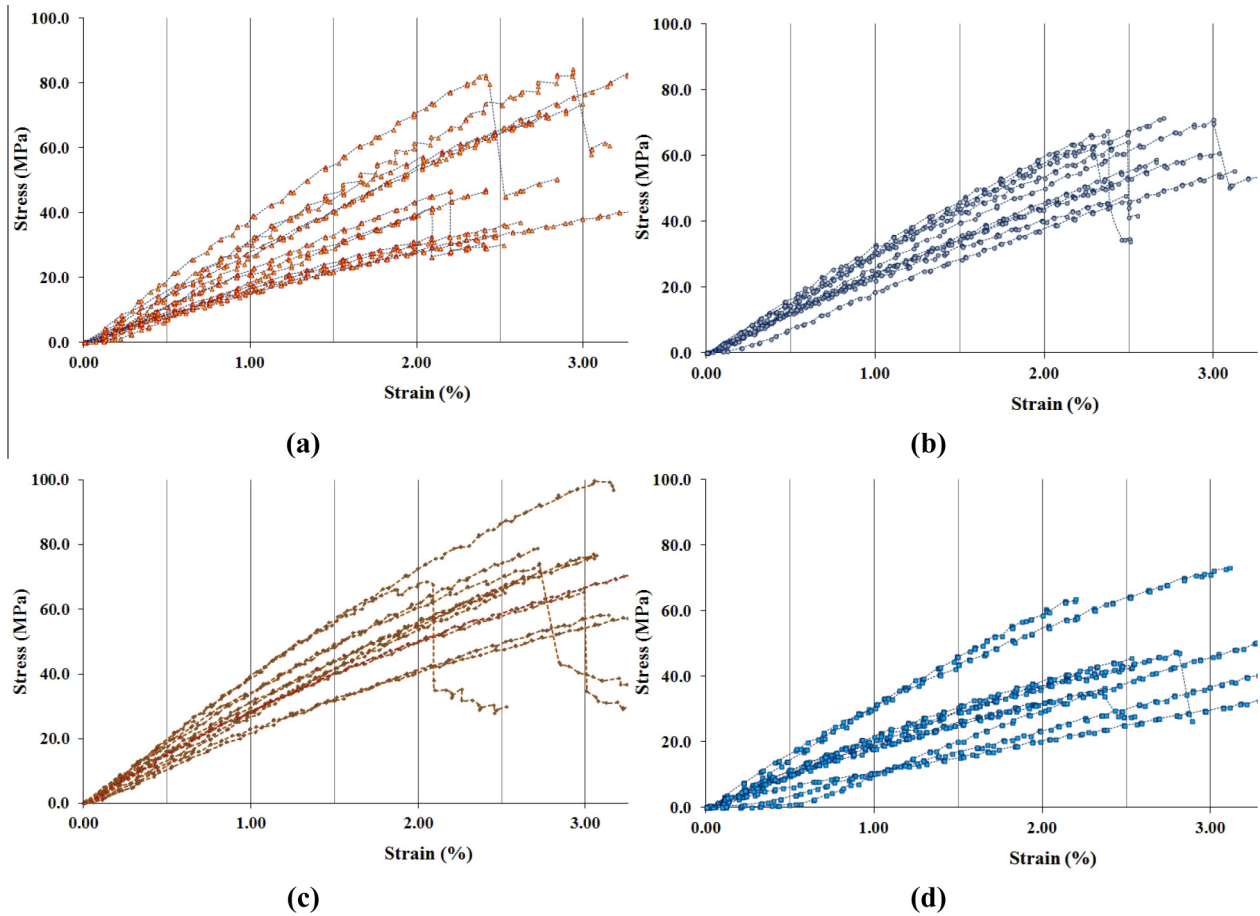


Fig. 2. Stress–strain profiles for (a) untreated bundled fibers, (b) treated with 0.173%  $\text{Ca(OH)}_2$ , (c) treated with 0.173%  $\text{NaOH}$ , and (d) treated with 2.0%  $\text{NaOH}$ .

Hence, it was decided to pursue only 0.173%  $\text{Ca(OH)}_2$  treatment for further investigations with mortar mixes, because the fibers displayed more or less uniform behavior.

Also, since cement hydration releases calcium hydroxide it is unlikely that fibers already subjected to the aforesaid pre-treatment will undergo further structural degradation.

Table 3  
Setting time test results of mortar samples.

Mix No.	Fiber Inclusion (wt.%)	Average setting times (h)	
		Initial	Final
1(Control)	0.0	3:00	4:00
2	0.5	3:15	3:55
3	1.0	4:25	5:00
4	2.0	2:20	2:45

3.2. Physical properties of the fresh and hardened mortars

The physical properties of fresh and hardened mortars were evaluated by performing the setting time, drying shrinkage, water absorption and sorptivity tests.

Table 3 shows the average setting times of the various mortar mixes tested. The overall trend seems to suggest that the setting times are prolonged with the increase in the fiber content. Although, with 2.0% of fiber inclusion, the setting time decreased; which could be due to water being absorbed by the excess fibers per se thereby making the mix set quickly.

Fig. 3 represents the results of drying shrinkage test for each mortar mix prepared in the study. It can be seen that all mixes containing varying palm fiber ratios show different shrinkage behavior. The rate of increase in shrinkage for all mortar, except the mixture including 2.0% palm fiber, was high up to 18 days which is a result of curing process, and after 18 days it can be noticed that palm fibers have effect in reducing shrinkage. Moreover, it can be observed from the figure that the mortars reinforced with 2.0% palm fiber (i.e. mix 4), which is the maximum ratio tested in this study, has the least shrinkage. This finding is in agreement with findings of Singh et al. (2010) which showed that a higher volume fraction, 4% of oil palm trunk fiber reduces shrinkage for different core diameters.

Water absorption and sorptivity test results for mortar mixes are presented in Figs. 4 and 5, respectively. The level of accuracy is shown in the figures by the error bars and was generally similar for all mixes with average and maximum values of 5.86% and 9.23% respectively. These figures indicate, that the mortar reinforced with 0.5% palm fiber

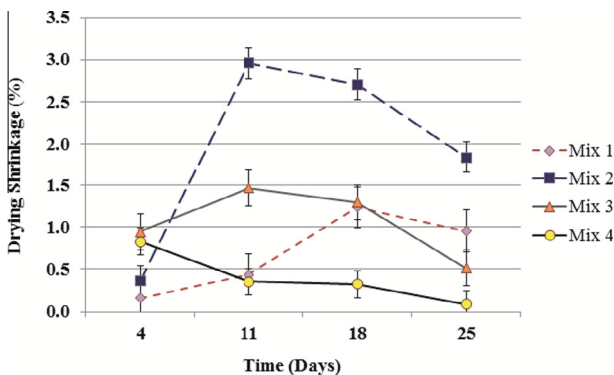


Fig. 3. Effect of palm fiber ratio on drying shrinkage.

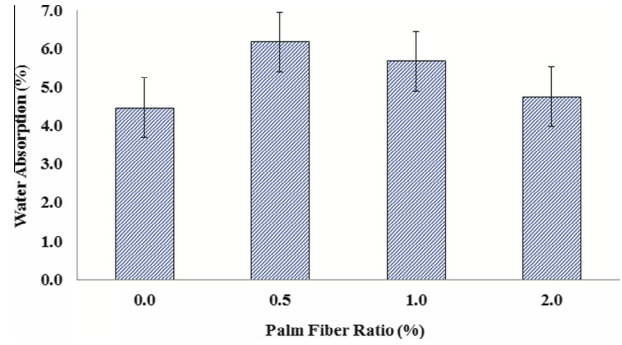


Fig. 4. Effect of palm fiber ratio on water absorption capacity of mortar samples.

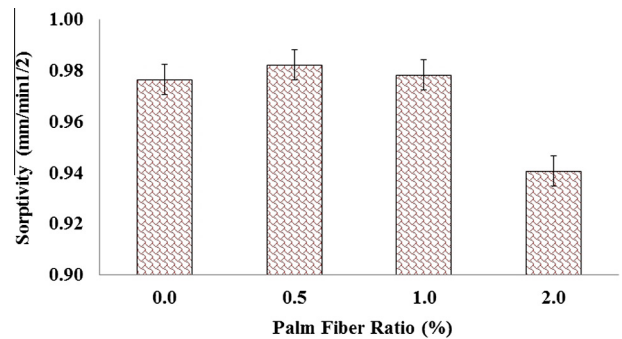


Fig. 5. Effect of palm fiber ratio on sorptivity of mortar samples.

has the highest water absorption capacity and water absorption rate whereas the lowest water absorption capacity and water absorption rate are given by the reference sample. For the mortar mixes reinforced with 1.0% and 2.0% palm fiber (i.e. mixes 3 and 4 respectively), it can be observed that the water absorption rate and capacity decreased with increasing weight percent of palm fiber. Although, these results differ from some published studies (Aggarwal, 1995; Abdullah et al., 2011; Abdullah et al., 2013), they are consistent with those of other studies (Ghavami, 1995; Filho et al., 2003; Bilba and Arsene, 2008; Savastano et al., 2001; Juárez et al., 2007; Parveen et al., 2012) and suggest that alkali treatment applied on natural fibers reduces the water absorption capacity by removing hemicellulose and lignin or by imparting hydrophobicity.

3.3. Mechanical testing

The mechanical test results including compressive strength, flexural strength and split tensile strength of mortars are presented in Figs. 6 and 7. For compression test, two types of samples were tested viz. 5 × 5 × 5 cm cubic samples and 10 × 20 cm cylindrical samples.

As seen in these figures, the compressive strength is slightly increased in value with low fiber content as compared with the control mix. High compaction between the fibers and the cement matrix was likely achieved

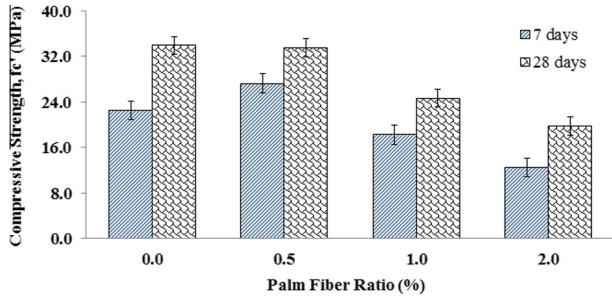


Fig. 6. The effect of palm fiber ratio on the compressive strength for cube mortar samples (the level of accuracy ranged between 3.53% and 15.22%).

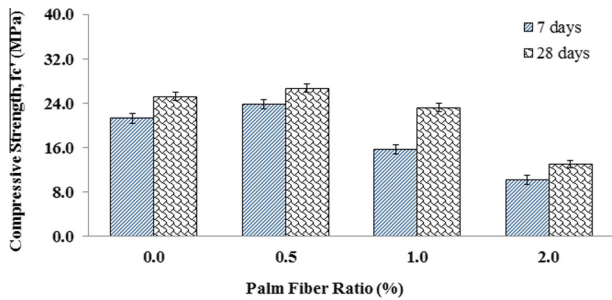


Fig. 7. The effect of palm fiber ratio on the compressive strength of cylinder mortar samples (the level of accuracy ranged between 3.53% and 15.22%).

leading to good homogeneity in mix with 0.5% fiber inclusion, and this finding corroborates with the findings of Ismail (2005) who showed that the compressive strength and bulk density slightly improved with low fiber content in the range of 0.3–1.5%. However, if the fiber content exceeds the value of 0.5%, the compressive strength of mortar samples decreases which also seems to be consistent with other studies (Shimizu and Jorillo Jr., 1992; Sorovshian and Khan, 1992; Islam et al., 2011; Awwad et al., 2011).

Fig. 8 represents the results of flexural strength test performed on 4 × 4 × 16 cm prism mortar samples. The estimated error ranged between 1.80% and 11.72%. The results corroborate the findings of compressive strength test results, i.e. flexural strength increases with lower fiber content, 0.5% and 1% as compared with the control mix, and decreases with higher fiber content.

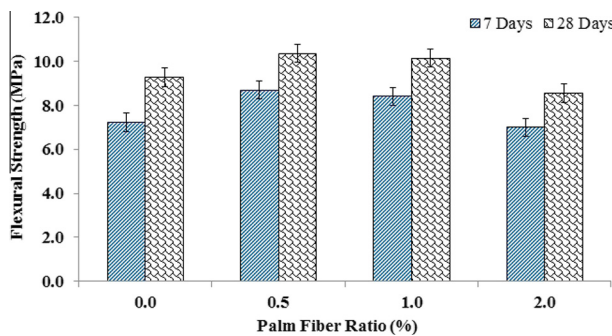


Fig. 8. The effect of palm fiber ratio on flexural strength of mortar samples.

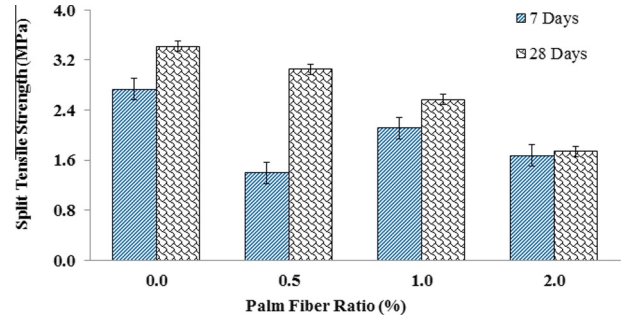


Fig. 9. The effect of palm fiber ratio on split tensile strength of mortar samples after 7 and 28 days (the level of accuracy varied between 3.28% and 17.86%).

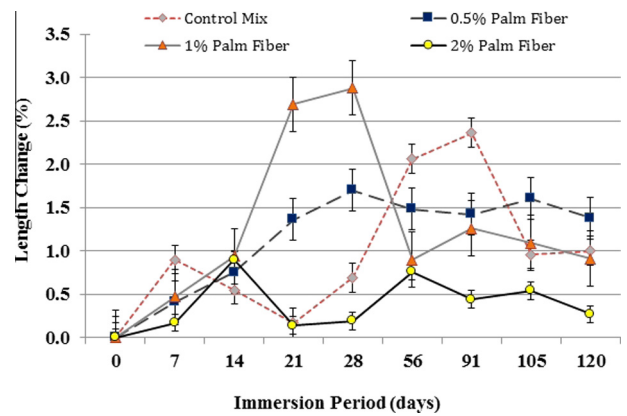


Fig. 10. Length change due to sulfate attack vs. immersion period.

The average splitting tensile strength at 7 and 28 days is shown in Fig. 9. Trend similar to compressive strength results was observed in this case. These results are consistent with those reported by other researchers which found that splitting tensile and flexural strength increases up to 1% of natural fiber volume (Ahmad and Ibrahim, 2010; Dawood and Ramli, 2011; Ahmad and Nurazuwa, 2008).

### 3.4. Durability studies

Fig. 10 presents the results of resistance against sulfate attack of conventional control mortar and palm fiber reinforced mortar samples in different ratios. The results are based on the average values obtained from six test specimens per mix. The highest length change at 120 days of immersion is observed in the control mix as well as mortar reinforced with low percentage of palm fiber (i.e. 0.5%); while, mixes with 1.0% and 2.0% appear to be more resilient to length changes. Hence, it can be inferred that higher inclusion of palm fibers within mortars offers better long term durability performance and advantage in resisting sulfate attack.

### 3.5. Microstructure examinations

Fig. 11 depicts some of the SEM micrographs obtained from this study which sheds some light on the tensile failure

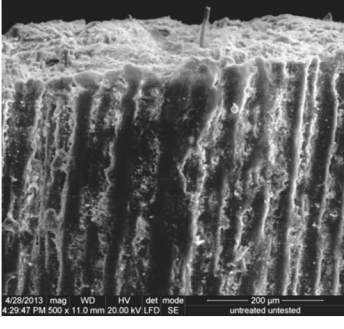
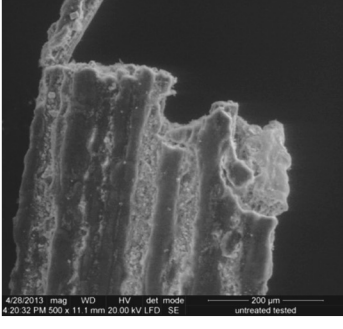
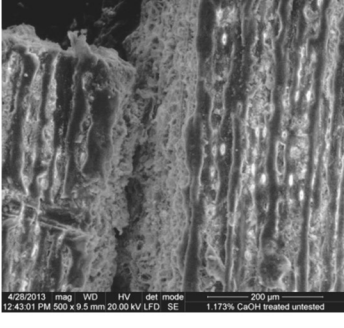
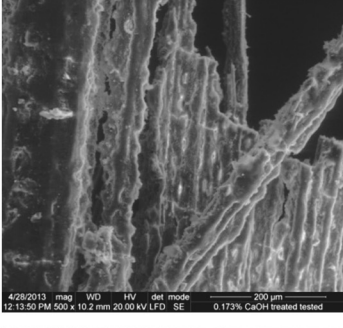
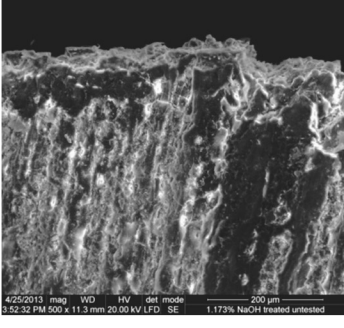
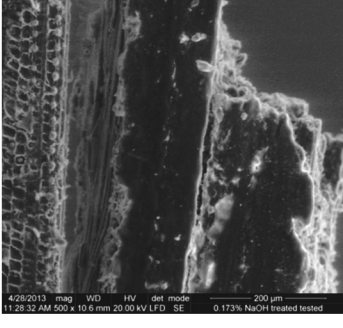
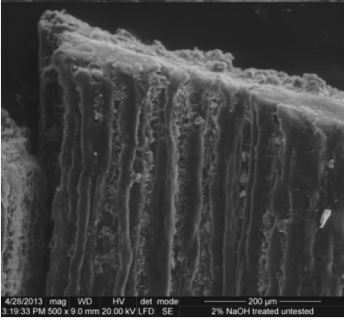
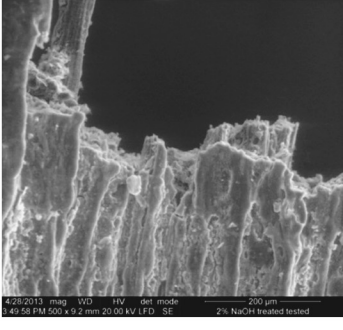
Specimen → Sample type	Untested	Failed sample undergone tensile testing
Untreated bundled fiber		
0.173% Ca(OH) <sub>2</sub> treated bundled fiber		
0.173% NaOH treated bundled fiber		
2.0% NaOH treated bundled fiber		

Fig. 11. Typical SEM micrographs for representative untreated and treated bundled fibers at ×500 magnification.

behavior of the treated and untreated bundled fibers. It can be observed that as the concentration of the treatment increased (i.e. 2.0% NaOH), the fibers became more brittle and this agrees with the tensile stress–strain profiles reported in the previous sections. Also, while comparing the failure morphologies of the 0.173% Ca(OH)<sub>2</sub> vs. the 0.173% NaOH, the contribution of the individual bundle fibers in resisting the tension is more conspicuous in the

former samples; a behavior that is considered favorable for mortar and concrete applications. This supports our choice of 0.173% Ca(OH)<sub>2</sub> treatment for mortar studies.

Typical SEM micrographs from the mortar mix cured up to 28 days have been presented in Fig. 12. The abundance of fiber bundles is observed to increase progressively with their inclusion in the mixes. Moreover, the treated fibers appear to remain intact within the cement matrix.

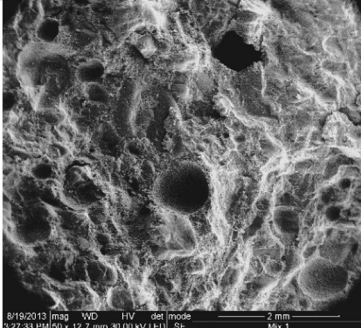
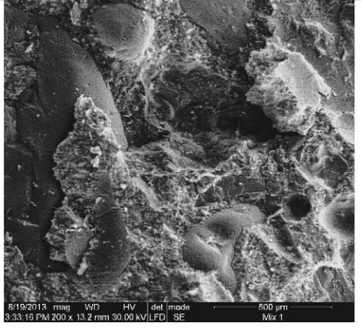
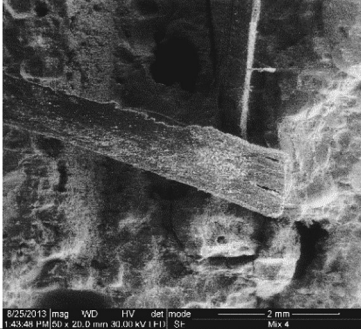
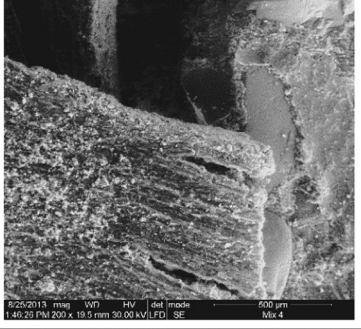
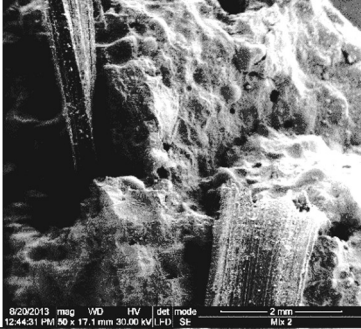
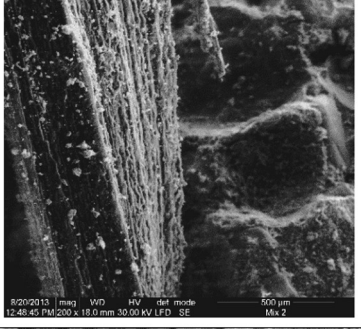

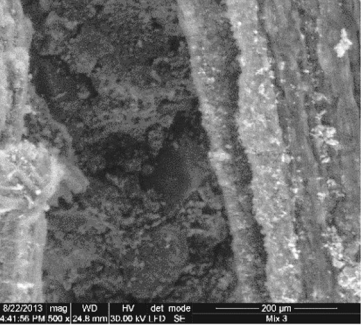
Magnifications Mix Details	50x	200x
<b>Mix 1- Control</b>		
<b>Mix 2 - 0.5% fiber</b>		
<b>Mix 3 - 1.0% fiber</b>		
<b>Mix 4 - 2.0% fiber</b>		

Fig. 12. Scanning electron micrographs of the 28-day mortar mixes (with and without fiber inclusion) at two different magnifications.

Also, the dense morphology of the CSH gel which is the product of complete hydration of cement is visible in the images indicating that the hydration progressed normally despite the inclusion of the fibers in the mixes.

X-ray diffraction of the mortar mixes cured up to 28 days has been compared in Fig. 13. Although some peaks of early hydration products such as portlandite (p),

ettringite (e) and gypsum (g) were observed, their relative intensities were significantly low again supporting the above argument that the treated fibers remained within the cement matrix without hindering the hydration processes. Calcite (c) peaks were observed which can be attributed to carbonation while the conspicuous peaks of quartz (q) can be attributed to the sand (i.e. fine aggregates)

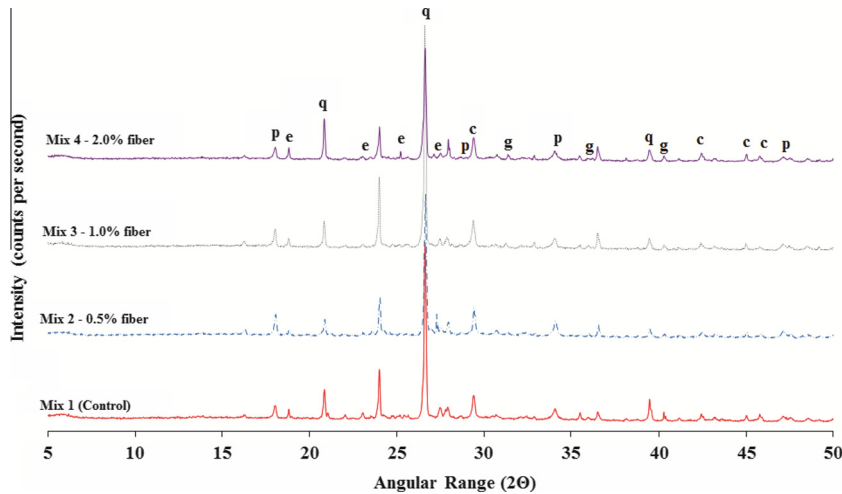


Fig. 13. X-ray diffractograms for mortar mixes (with and without fiber inclusion) at 28 days.

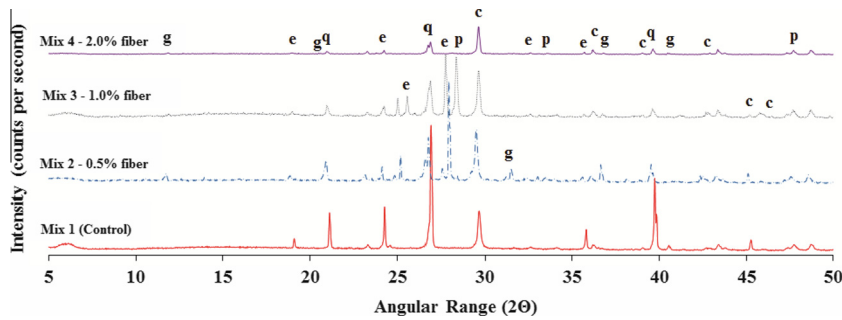


Fig. 14. X-ray diffractograms for mortar mixes (with and without fiber inclusion) subjected to sulfate attack at 120 days.

present in the mortar mixes. Hence, although the preferential orientation/crystallinity was slightly different, no phase change was observed between the mixes.

In contrast, X-ray diffraction of the mortar mixes subjected to sulfate attack was carried out and compared in Fig. 14. The samples collected for this analysis were obtained from mix specimens aged up to 120 days while being immersed in sodium sulfate solution. In addition to some of the phases reported earlier, presence of ettringite (e) and strong peaks of gypsum (g) especially at 11.6° 2θ were conspicuous which, are typical products formed as a result of sodium sulfate attack in cement mortars (Prasad et al., 2006). Weak peaks of portlandite (p) were also present; which could imply the possibility of conversion of calcium hydroxide into the aforesaid sulfate products. However, the overall trend seems to suggest that with increased fiber inclusion in the mixes, the intensities of products of sulfate attack became low thereby implying that such mixes offer better resistance to sulfate attack. This is in agreement with the previous observations that mixes 1.0% and 2.0% fiber inclusion are more resilient to length changes.

Nevertheless, it is recommended to investigate exposure times much longer than 120 days as well as higher sodium sulfate concentrations to better understand the deteriorating

effects on the mortar mixes as well as the influence of date palm fibers on improving the durability.

#### 4. Conclusions

The tensile performance of Portland cement mortars and concrete had been reported to be enhanced via the inclusion of certain fibers in sufficient quantities. Natural fibers such as those obtained are known to exhibit high tensile strength and a low modulus of elasticity despite high variation. Date palm trees are native to the middle-east region; their fibers can be easily and abundantly found in countries like the State of Qatar.

The results in this paper are based on laboratory experiments with four mortar mixes reinforced with varying percentages of treated natural date palm fiber up to 2.0%. For fiber inclusions greater than 2.0%, poor workability as well as difficulty in preparing and obtaining monolithic compacted samples due to excessive separation of mortar components was encountered. Hence, it is recommended that such date palm fiber inclusion in mortars to be limited to less than 2.0% by weight.

Fibers treated with 0.173% Ca(OH)<sub>2</sub> displayed better tensile strengths and stiffness properties than those treated with NaOH and hence, the former was chosen as preferred

pre-treatment for the bundled fibers used in the mortar mixes. This was further supported by the microstructural examination on the hardened mortars which, revealed that the integrity of treated fibers remained intact within the cement matrix without hindering the hydration processes.

The setting time of the mortar pastes was observed to be prolonged with the increase in the fiber content. Water absorption rate and capacity decreased with increasing weight percent of palm fiber in the mixes. Results also indicated that inclusion of fibers improves the flexural strengths. However, the cylinder and cube compressive strengths decreased with the increase in treated fiber inclusion.

Nevertheless, the results of the durability performance of the studied mixes clearly suggest that incorporation of 1.0–2.0% of date palm fibers improved the resistance of the mortar against sulfate attack. Also, the drying shrinkage performance of the mixes improved with increased fiber inclusion.

Based on this study, it can be concluded that inclusion of treated palm fibers in cement mortars do offer flexural strengths and durability performance improvements. However, these advantages come as a trade-off in the form of initial loss in workability and subsequent poor compressive strengths.

Although, the work reported in this paper was carried out on cement mortars, conclusions are expected to be relevant to fiber reinforced concrete employing treated natural fibers. Yet, for practical purposes, it is recommended to conduct thorough feasibility studies on the use of such natural fibers based on the actual application as well as the desired final properties of the resulting cement composites.

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