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ScienceDirect

Soils and Foundations 58 (2018) 462–480

www.elsevier.com/locate/sandf

Effect of compaction method on the undrained strength of fiber-reinforced clay

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Received 17 December 2016; received in revised form 8 December 2017; accepted 27 December 2017
Available online 9 March 2018

Abstract

The use of discrete fibers in reinforcing soils is of interest to the geotechnical engineering community. Two limitations exist in experimental studies involving fiber-reinforced clays. First, fiber-reinforced clay specimens are generally prepared in the lab using conventional "impact" compaction, whereas the compaction of clay systems in the field typically involves "kneading" action. Second, the majority of tests reported in the literature use synthetic fibers to the exclusion of other types. This paper addresses these limitations through an experimental triaxial testing program that: (1) supplements the scarce data available in the literature on the undrained load response of clays reinforced with "natural" fibers and that are compacted by "kneading", and (2) assesses the capacity of the experimental procedures that involve "impact" compaction to produce responses that are relevant to actual field conditions. Results from 73 unconsolidated undrained triaxial tests indicate that the percent improvement in the undrained strength of the fiber-reinforced clay is highly dependent on the compaction method, with specimens that are prepared using impact compaction yielding improvements up to three times larger than identical specimens prepared by kneading. This discrepancy in the behavior can be traced back to differences in the fiber orientation distributions between specimens that were compacted by impact and kneading.

Keywords: Ground improvement; Fiber-reinforced clays; Compaction; Hemp fiber; Shear strength; Unconsolidated-undrained test

International Geotechnical Classification Numbers: D06; D10; K14

1. Introduction and background

The potential use of discrete fibers in applications involving the reinforcement of soils in earth retaining systems, pavement systems, earth slopes, and compacted clay liners and cover systems is garnering more attention and acceptance in the geotechnical community (Najjar et al., 2013; Hejazi et al., 2012; Sadek et al., 2010, among others). Fiber-reinforced soils were used successfully on more than 50 embankment slopes in the United States between the year 1990 and 2006 (Gregory, 2006).

The fibers traditionally investigated in research settings consist primarily of synthetic fibers. In the past decade, sustainability concerns have significantly impacted the fields of construction engineering and materials. The current drive to use renewable resources in construction is significant

Peer review under responsibility of The Japanese Geotechnical Society.
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https://doi.org/10.1016/j.sandf.2018.02.013
0038-0806/

Nomenclature

L_F	length of the fiber
w	water content, in percentage
η_F	aspect ratio, defined as the ratio of the length to the diameter of the fiber (L_F/d_F)
$\chi_{F,w}$	gravimetric fiber content defined as the ratio of the weight of fibers to the dry weight of soil, in percentage
σ_3	confining pressure, in kPa
γ_d	dry unit weight of the soil, in KN/m^3
σ_d	deviatoric stress, in kPa
$\rho(\theta)$	generalized fiber orientation distribution function
$\bar{\rho}$	average volumetric concentration of the fibers
θ	fiber orientation angle with the horizontal
P	ratio of the volume of fibers having orientations within an angle $\pm\beta$ from the horizontal to the total volume of fibers
N_V	number of fibers crossing vertical planes
N_H	number of fibers crossing horizontal planes

(Hejazi et al., 2012; Mitchell and Kelly, 2013). Several studies have explored the use of natural fibers such as coconut, palm, straw, bamboo, and cane fibers to reinforce soils. Results indicate that natural fibers could provide soils with added shear strength and ductility.

Gregory (2006) reports that clayey soils constitute the real potential for the practical and extensive use of fibers in geotechnical applications. To date, several experimental studies investigated the response of clays reinforced with discrete fibers (e.g. Maher and Ho, 1994; Nataraj and McManis, 1997; Prabakar and Sridhar, 2002; Li and Zornberg, 2005; Gregory, 2006; Punthutaecha et al., 2006; Tang et al., 2007; Akbulut et al., 2007; Ozkul and Baykal, 2007; Abdi et al., 2008; Chandra et al., 2008; Attom et al., 2009; Viswanadham et al., 2009; Al-Mhaidib, 2010; Jiang et al., 2010; Babu and Chouksey, 2010; Maheshwari et al., 2011; Amir-Faryar and Aggour, 2012; Plé and Lê, 2012; Pradhan et al., 2012; Jamei et al., 2013; Maliakal and Thiyyakkandi, 2013; Mirzababaei et al., 2013; Qu et al., 2013; Anagnostopoulos et al., 2014; Najjar et al., 2014; Wu et al., 2014).

Output from published studies points to common findings in some aspects of behavior. Most studies conclude that the inclusion of fibers generally leads to an increase in the shear strength of the composite. For a given aspect ratio (fiber length/diameter), the strength increases with fiber content up to certain point, beyond which the improvement in strength reaches an upper limit, and in some cases starts to decrease. Decay in strength gain at high fiber contents is believed to be due to the presence of increasing numbers of fiber-to-fiber contact, rather than fiber-to-soil contacts. For a given fiber content, an increase in the fiber aspect ratio leads to higher strengths up to certain values of aspect ratio beyond which loss of strength, or stability in strength, is observed.

An investigation of the scope and findings of previous studies leads to two possible shortcomings and/or limitations. The first limitation is that fiber-reinforced clay specimens are prepared in the laboratory using conventional "impact" compaction methods (Proctor), although compacted clay systems in the field are typically constructed using equipment that produces high shear strains/"kneading" action (e.g. sheep's-foot rollers). A question could be raised as to whether fiber-reinforced clay samples prepared using "impact" compaction will produce reliable representations of actual field conditions.

The second limitation is that the majority of the tests reported in the literature involve synthetic fibers. From the above-referenced 27 experimental studies, only 8 involved natural fibers. It could be argued that additional emphasis and further studies on clays reinforced with "natural" fibers are needed.

The work presented in this paper aims at addressing the above two limitations by designing and implementing a comprehensive experimental program that investigates the load response of natural clay reinforced with natural fibers (hemp in our case) and prepared using "kneading" and "impact" compaction techniques. The testing program consists of a series of unconsolidated globally-undrained (UU) triaxial tests, where various parameters (fiber length, fiber content, compaction water content and confining pressure) are varied aside from the compaction method.

The UU test setup allows for an effective quantification of the degree of improvement in the undrained shear strength of the compacted clay for applications involving short-term stability (foundations, slopes, landfill covers, etc.). The UU triaxial test has been utilized for decades to investigate the strength of compacted clays (Olson and Parola, 1967; Daniel and Olson, 1974; Liang and Lovell, 1983; Mun et al., 2016, among others). The UU test setup allows for examination of the roles of the initial hydraulic conditions (the initial matric suction and degree of saturation) and compaction effects (potential changes in soil structure when a soil is compacted wet or dry of optimum) on the undrained shear strength (Mun et al., 2016). To this end, the scope of this paper was limited to short term stability.

It is worth noting that concerns related to the potential degradation of natural hemp fibers in the long term are not addressed in this study. Focused and comprehensive research studies are needed to characterize the durability of natural fibers that are embedded within a soil matrix. Such an endeavor is beyond the scope of this paper.

2. Laboratory testing program

A total of 73 unconsolidated globally undrained triaxial tests were performed on compacted clay specimens with a diameter of 71.5 mm and a length of 142 mm. Fiber-reinforced specimens with a diameter of 70 mm or greater, and a height to diameter ratio of 2, are likely to eliminate any possible fiber size effects (Zornberg 2002; Ang and Loehr 2003; Jamei et al. 2013).

Standard Proctor compaction tests (5 point tests) were conducted on the clay to define the full compaction curve and determine the optimum moisture content and the corresponding maximum dry unit weight. Once the compaction characteristics of the clay were determined (optimum water content was ~19%), three water contents (14%, 18%, and 20%, corresponding to initial degrees of saturation of ~50%, 80% and 95%, respectively) were selected to represent different states of compaction.

The clay was reinforced with fibers with lengths of 20 mm or 40 mm, representing average aspect ratios of 50 and 100, respectively. Gravimetric fiber contents of 0% (control sample), 0.5%, 1.0%, and 1.5% were adopted in the experimental program. The sample preparation techniques included impact compaction and compaction by kneading. Compacted specimens were subjected to UU-triaxial testing at a strain rate of 1% per minute. The confining pressure was varied from 20 kPa to 200 kPa to represent stress states that are indicative of high overburden pressures (embankments and backfill behind walls) or low confining pressures (localized repair of shallow slope failures and landfill covers). Failure was defined as the deviatoric stress at 20% strain or as the maximum observed deviatoric stress, whichever is larger. This assumption is in line with published studies related to similar tests and similar materials (Yang et al., 2011; Jamei et al., 2013; Maliakal and Thiyyakkandi, 2013).

The parameters corresponding to each test, together with the test results, are presented in detail in Tables 1 and 2: 64 tests were conducted on control clay and Hemp-reinforced clay, and 9 additional tests were conducted on specimens of clay that were reinforced with Polypropylene fibers to allow for comparison with the results observed for Hemp-reinforced specimens.

3. Materials

The materials used in this experimental study are a clayey soil termed henceforth "natural clay", Hemp fibers, and polypropylene fibers.

3.1. Natural clay

The soil used in this study was excavated from a construction site in kfarselwan, Lebanon. Specific gravity, sieve analysis, hydrometer, Atterberg limits and standard Proctor compaction tests were conducted to characterize the soil. Standard procedures proposed by the American Society for Testing Materials (ASTM) were implemented. The index properties are presented in Table 3 and the grain size distribution curves are presented in Fig. 1. The soil is classified as an inorganic clay of low plasticity (CL) as per the unified soil classification system (USCS). The clay has a plasticity index of 14% and a fines content of around 55%. The clay fraction within the fines is around 35%. The results of the standard Proctor test indicate a maximum dry unit weight of around 16.8 KN/m^3 and optimum moisture content ~19%.

It should be noted that although the soil is classified as "clay", it includes a high percentage of sand. The presence of sand is expected to affect the volumetric change tendencies and the shear strength of the soil; however, it is still expected to act as a clay given its small coefficient of consolidation (c_v) which was reported by Rayyis (2015) to range from 3.3×10^{-4} to 6.6×10^{-4} cm^2/sec based on 1-D consolidation tests. These c_v values are typical of clays comprised of the clay mineral "illite" (Robinson and Allam, 1998). As a result, the clay was treated as a typical low plasticity clay which will exhibit undrained behavior for short-term stability conditions. The choice of this soil was intentional as it represents natural "non-ideal" and/or "synthetic" soils.

3.2. Natural Hemp fibers

Hemp fibers are natural fibers that originate from the plant Cannabis Sativa, which is legally planted in different countries including Spain, China, Japan, and France, and is used in several industries. A preliminary feasibility study done by the United Nations Development Program and the Lebanese Ministry of Agriculture shows that the cost to locally produce industrial hemp is $79 per 1000 m^2 of non-irrigated lands (Awwad, 2011). The potential use of these fibers could provide sustainable solutions to a number of geotechnical and materials applications.

Hemp fibers were supplied as "long fibers" (see Fig. 2a). The fibers were soaked in a sodium hydroxide solution (NaOH) at 6% by weight for 48 h in order to remove all organic impurities. Soaking fibers in sodium hydroxide solution constitutes an alkali treatment that improves bonding between the fiber surface and the soil leading to a more efficient soil/fiber interface interaction. After treatment, the fibers were washed with water and left to dry. The fibers were then cut manually to lengths dictated by the predefined experimental program. The hemp fibers have a rectangular cross section with a relatively uniform thickness of about 0.13 mm and a relatively variable width.

Table 1
Test series 1, samples compacted by constant kneading effort.

Test no.	Compaction Method	Number of layers	Compaction effort per layer	Target w (%)	σ_3 (kPa)	Fiber Type	$\chi_{F,w}$ (%)	L_F (mm)	Actual w (%)	γ_d initial (KN/m^3)	γ_d before shearing (KN/m^3)	σ_d at failure (kPa)	Impr. (%)
1	Kneading	5	10 psi, 25 T	14	20	–	–	–	14.3	14.3	14.7	150.0	–
2	Kneading	5	10 psi, 25 T	18	20	–	–	–	18.3	15.8	16.2	153.1	–
3	Kneading	5	10 psi, 25 T	20	20	–	–	–	20.1	16.4	16.8	149.0	–
4	Kneading	5	10 psi, 25 T	14	100	–	–	–	13.4	13.9	14.3	335.8	–
5	Kneading	5	10 psi, 25 T	18	100	–	–	–	18.3	15.6	16.1	256.9	–
6	Kneading	5	10 psi, 25 T	20	100	–	–	–	20.3	16.1	16.5	207.1	–
7	Kneading	5	10 psi, 25 T	14	200	–	–	–	14.7	14.3	15.2	540.5	–
8	Kneading	5	10 psi, 25 T	18	200	–	–	–	16.9	15.5	16.1	351.5	–
9	Kneading	5	10 psi, 25 T	20	200	–	–	–	19.3	16.9	17.4	248.3	–
10	Kneading	5	10 psi, 25 T	14	20	Hemp	0.5	20	14.2	13.8	14.3	134.1	−10.6
11	Kneading	5	10 psi, 25 T	18	20	Hemp	0.5	20	18.2	15.3	15.7	159.0	3.9
12	Kneading	5	10 psi, 25 T	20	20	Hemp	0.5	20	19.9	16.6	16.9	136.8	−8.2
13	Kneading	5	10 psi, 25 T	14	100	Hemp	0.5	20	14.5	14.0	14.3	340.0	1.3
14	Kneading	5	10 psi, 25 T	18	100	Hemp	0.5	20	18.7	15.3	15.8	266.9	3.9
15	Kneading	5	10 psi, 25 T	20	100	Hemp	0.5	20	19.9	16.5	16.9	199.0	−3.9
16	Kneading	5	10 psi, 25 T	14	20	Hemp	1	20	14.5	13.8	14.1	145.6	−2.9
17	Kneading	5	10 psi, 25 T	18	20	Hemp	1	20	17.8	15.3	15.6	161.0	5.2
18	Kneading	5	10 psi, 25 T	20	20	Hemp	1	20	20.1	15.5	15.9	142.7	−4.2
19	Kneading	5	10 psi, 25 T	14	100	Hemp	1	20	14.2	13.7	14.2	363.5	8.2
20	Kneading	5	10 psi, 25 T	18	100	Hemp	1	20	18.1	14.4	14.8	285.0	10.9
21	Kneading	5	10 psi, 25 T	20	100	Hemp	1	20	19.6	15.2	15.7	244.6	18.1
22	Kneading	5	10 psi, 25 T	14	100	Hemp	1.5	20	14.0	12.6	13.3	387.5	15.4
23	Kneading	5	10 psi, 25 T	18	100	Hemp	1.5	20	17.4	14.2	14.8	313.5	22.0
24	Kneading	5	10 psi, 25 T	20	100	Hemp	1.5	20	20.1	14.8	15.4	273.4	32.0
25	Kneading	5	10 psi, 25 T	14	20	Hemp	1	40	14.9	14.0	14.5	254.4	69.6
26	Kneading	5	10 psi, 25 T	18	20	Hemp	1	40	17.8	14.8	15.1	210.8	37.7
27	Kneading	5	10 psi, 25 T	20	20	Hemp	1	40	20.3	16.4	16.8	179.6	20.5
28	Kneading	5	10 psi, 25 T	14	100	Hemp	1	40	13.1	12.4	13.0	400.5	19.3
29	Kneading	5	10 psi, 25 T	18	100	Hemp	1	40	17.5	15.0	15.5	321.8	25.3
30	Kneading	5	10 psi, 25 T	20	100	Hemp	1	40	19.3	15.0	15.6	247.2	19.4
31	Kneading	5	10 psi, 25 T	14	200	Hemp	1	40	14.3	13.9	15.1	605.4	12.0
32	Kneading	5	10 psi, 25 T	18	200	Hemp	1	40	17.8	15.2	16.0	389.5	10.8
33	Kneading	5	10 psi, 25 T	20	200	Hemp	1	40	20.3	15.2	16.3	252.6	1.7
34	Kneading	5	10 psi, 25 T	14	20	Hemp	1.5	40	13.6	13.1	15.3	261.5	74.3
35	Kneading	5	10 psi, 25 T	18	20	Hemp	1.5	40	17.0	13.9	14.3	185.2	21.0
36	Kneading	5	10 psi, 25 T	20	20	Hemp	1.5	40	19.7	15.6	16.0	168.6	13.2
37	Kneading	5	10 psi, 25 T	18	20	Polyp.	0.32	25	17.9	15.3	15.7	153.0	−0.1
38	Kneading	5	10 psi, 25 T	18	100	Polyp.	0.32	25	18.6	15.5	15.9	285.1	11.0
39	Kneading	5	10 psi, 25 T	18	200	Polyp.	0.32	25	18.4	15.6	16.4	417.8	18.9
40	Kneading	5	10 psi, 25 T	18	20	Polyp.	0.65	50	18.4	16.3	16.7	131.6	−14.0
41	Kneading	5	10 psi, 25 T	18	100	Polyp.	0.65	50	16.3	16.2	16.8	262.0	2.0
42	Kneading	5	10 psi, 25 T	18	200	Polyp.	0.65	50	17.7	15.7	16.6	342.2	−2.6
43	Kneading	5	10 psi, 25 T	18	20	Polyp.	0.65	25	18.1	16.7	17.0	169.0	10.4
44	Kneading	5	10 psi, 25 T	18	100	Polyp.	0.65	25	18.5	16.0	16.7	228.0	−11.2
45	Kneading	5	10 psi, 25 T	18	200	Polyp.	0.65	25	18.3	15.8	16.8	304.5	−13.4

w: water content; σ_3: confining pressure; $\chi_{F,w}$: fiber content, given as percentage by weight of dry soil; L_F: fiber length; γ_d initial: initial dry unit weight before testing; γ_d before shearing: dry unit weight of the sample after the cell pressure application stage (compression of air voids), prior to shearing stage; σ_d: deviatoric stress reached at failure; Impr.: Improvement in deviatoric stress at failure, in percentage; T: tamps; 1 psi = 6.89 kPa.

Table 2
Test series 2, Identical samples compacted by impact and kneading.

Test no.	Compaction method	Number of layers	Compaction effort per layer	Target w (%)	σ_3 (kPa)	Fiber type	$\chi_{F,w}$ (%)	L_F (mm)	Actual w (%)	γ_d initial (KN/m^3)	γ_d before shearing (KN/m^3)	σ_d at failure (kPa)	Impr. (%)
46	Impact	3	14 T	14	20	Hemp	–	–	13.8	15.3	15.8	188.5	–
47	Impact	3	17 T	14	20	Hemp	1	40	14.5	15.1	15.5	409.0	117.0
48	Impact	3	14 T	18	20	Hemp	–	–	17.4	16.6	17.1	164.4	–
49	Impact	3	17 T	18	20	Hemp	1	40	18.2	16.9	17.3	363.0	120.8
50	Impact	3	14 T	20	20	Hemp	–	–	19.4	16.9	17.3	136.8	–
51	Impact	3	17 T	20	20	Hemp	1	40	19.8	16.5	17.1	221.4	61.8
52	Impact	3	14 T	14	100	Hemp	–	–	14.1	15.4	15.8	434	–
53	Impact	3	17 T	14	100	Hemp	1	40	14.5	15.2	15.6	798.4	84.0
54	Impact	3	14 T	18	100	Hemp	–	–	17.8	16.7	17.0	289	–
55	Impact	3	17 T	18	100	Hemp	1	40	17.5	16.6	17.1	470.7	62.9
56	Impact	3	14 T	20	100	Hemp	–	–	19.6	16.9	17.6	165.1	–
57	Impact	3	17 T	20	100	Hemp	1	40	19.4	16.8	17.3	273.6	65.7
58	Impact	3	14 T	18	200	Hemp	–	–	18.1	17.1	17.5	302	–
59	Impact	3	17 T	18	200	Hemp	1	40	18.0	16.1	17.0	541.2	79.2
60	Kneading	5	15psi, 25 T	14	20	Hemp	–	–	14.3	14.8	15.1	149.6	–
61	Kneading	5	20psi, 25 T	14	20	Hemp	1	40	13.5	14.7	15.4	269.5	80.1
62	Kneading	5	15psi, 25 T	18	20	Hemp	–	–	17.8	16.9	17.5	182.1	–
63	Kneading	5	20psi, 25 T	18	20	Hemp	1	40	18.4	16.5	16.9	245.6	34.9
64	Kneading	5	15psi, 25 T	20	20	Hemp	–	–	19.4	17.0	17.5	132.9	–
65	Kneading	5	20psi, 25 T	20	20	Hemp	1	40	19.3	16.8	17.4	179.6	35.1
66	Kneading	5	15psi, 25 T	14	100	Hemp	–	–	14.3	15.1	15.4	373.7	–
67	Kneading	5	20psi, 25 T	14	100	Hemp	1	40	13.6	14.7	15.0	474	26.8
68	Kneading	5	15psi, 25 T	18	100	Hemp	–	–	18.4	16.6	17.1	304.1	–
69	Kneading	5	20psi, 25 T	18	100	Hemp	1	40	17.3	16.3	16.7	383	25.9
70	Kneading	5	15psi, 25 T	20	100	Hemp	–	–	19.5	17.1	17.6	197.6	–
71	Kneading	5	20psi, 25 T	20	100	Hemp	1	40	19.6	16.9	17.3	213.7	8.1
72	Kneading	5	15psi, 25 T	18	200	Hemp	–	–	17.5	16.8	18.1	312.0	–
73	Kneading	5	20psi, 25 T	18	200	Hemp	1	40	17.5	16.2	16.9	376.8	20.8

w: water content; σ_3: confining pressure; $\chi_{F,w}$: fiber content, given as percentage by weight of dry soil; L_F: fiber length; γ_d initial: initial dry unit weight before testing; $\gamma_d$before shearing: dry unit weight of the sample after the cell pressure application stage (compression of air voids), prior to shearing stage; σ_d: deviatoric stress reached at failure; Impr.: Improvement in deviatoric stress at failure, in percentage; T: tamps; 1 psi = 6.89 kPa.

Table 3
Material properties of the clay.

Clay property	Batch #		
	1	2	3
Liquid limit, LL, %	35	33	34
Plastic limit, PL, %	22	19	20
Plasticity index, PI, %	13	14	14
Sand, %	46	46	46
Silt, %	37	35	32
Clay, %	17	19	22
% Fines	54	54	54

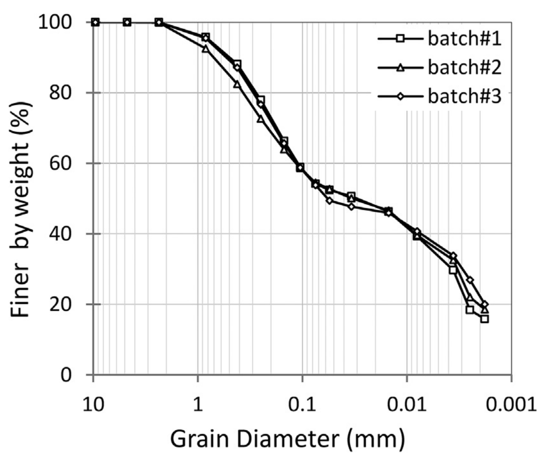

Fig. 1. Grain size distribution curves of the clay.

A statistical analysis of a random set of 250 fibers indicated an average width of 0.65 mm and a standard deviation of 0.42 mm. A total of 20 fiber tensile strength tests indicated an average ultimate tensile strength (UTS) of 276 MPa and an average modulus of elasticity of 21.7 GPa. The properties of the hemp fibers are summarized in Table 4.

3.3. Synthetic polypropylene fibers

Polypropylene fibers were supplied with a manufacturer's data sheet summarizing their properties/specifications. The polypropylene fibers used in this study are shown in Fig. 2b. Their mechanical properties are presented in Table 4.

Table 4
Material properties of the fibers.

Fiber property	Fiber type	
	Hemp	Polypropylene
Specific gravity	1.4	0.91
Ultimate tensile strength, MPa	276	570–660
Elastic modulus, GPa	21.7	–
Thickness, mm	0.13 (mean)	0.051
Width, mm	0.65 (mean)	1.12
Equivalent diameter, mm	0.41 (mean)	0.51
Length, L_F, mm	20, 40	25, 50
Aspect ratio, η	49, 98	49, 98
Gravimetric content, $\chi_{f,w}$, %	0.5, 1, 1.5	0.32, 0.65
Volumetric content, $\chi_{f,v}$, %	0.55, 1.1, 1.51	0.55, 1.1

4. Specimen preparation

The natural clay was oven dried, crushed, and sieved through a number 10 sieve (mesh opening size of 2 mm). The dry clay was initially mixed with water and the fibers were then added gradually and mixed manually to ensure a homogenous mix with a random distribution of fibers. It should be noted that the fibers were added at a prescribed percentage by weight of dry soil, the weight of dry soil the same among all samples. The mixture was then sealed and left aside for three to four hours to allow for water content homogenization.

The mix was then transferred to a split mold with a height of 210 mm and an internal diameter of 71.5 mm and compacted in batches/layers with the preset method (impact or kneading) and energy. Different compaction efforts/energy were adopted to achieve the target initial dry unit weights. After compaction, the specimen was extracted from the split mold, trimmed to the required length, and assembled in the triaxial cell. The advantage of using a split mold was to ensure that the compacted clay

Fig. 2. Fibers: (a) Hemp fibers and (b) Polypropylene fibers.

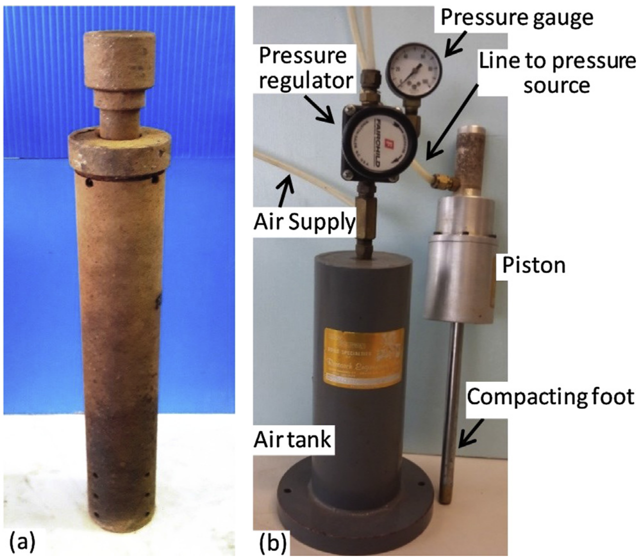

Fig. 3. Tools: (a) The standard Proctor hammer and (b) The kneading pneumatic compactor.

specimen could be removed from the mold with minimal disturbance.

Specimens that were prepared by "impact" were compacted using the standard Proctor hammer (Fig. 3a). The specimens prepared by "kneading" were compacted using the kneading pneumatic compactor developed at UC Berkeley as a modified/improved version of the Harvard Miniature Compactor (Fig. 3b). The basic difference/improvement of this device in comparison to the Harvard Miniature Compactor is that the foot/tamper is loaded by air pressure instead of a spring force. The use of the Proctor "impact compaction" technique in the laboratory is consistent with the use of conventional impact/roller compaction equipment in the field, while the use of the kneading pneumatic compactor is considered to be a more realistic representation of the "kneading" compaction by sheep's-foot rollers in the field.

5. Program and sequence of tests

The testing program included two series of tests. In the first series, control and hemp-reinforced specimens were compacted by kneading and 36 UU-triaxial tests were conducted for the range of test parameters presented in Table 1. This series aimed at reproducing the construction procedures usually implemented in the field. In the control specimens of Series 1, specimens were prepared by mixing the required water content with a fixed mass of dry clay prior to compaction by kneading at a constant energy. For fiber-reinforced specimens of series 1, the same mass of dry clay was mixed with fibers at a given gravimetric fiber content, which was taken as a function of the mass of dry clay. The same kneading energy was used as in the case of control clay. The purpose behind maintaining the same energy was to investigate the effect of the presence of fibers on the compaction curve of the clay.

Based on the results of the first series of tests, the combination of the reinforcement parameters (fiber length and fiber content) which produced the most consistent improvement in the load response was identified and used as a basis for the second series of tests (Tests 46–73 in Table 2) where specimens were prepared by impact compaction and kneading to reach identical dry density states. This made a one-to-one comparison between the two techniques possible.

The triaxial tests conducted in this study were "globally undrained" in the sense that all drains to and from the sample were closed during the application of confining pressure and shearing (typical UU-triaxial tests, ASTM D2850). The term "globally undrained" indicates that the global water content of the sample was not allowed to change during the tests; however, local internal drainage and volume change could occur during shear given the unsaturated nature of the compacted clay and the presence of natural fibers in the soil matrix.

Since short-term stability considerations are the main concern in this study, all samples were tested "as-compacted", with different degrees of initial saturation. The cell chamber was allowed to exchange water with an outer burette which was monitored during all the stages of the test to determine global volume changes. The volume changes recorded in the cell pressure application stage are corrected to take into consideration the cell expansion due to the application of confining pressure.

During shearing, the axial load was measured using a load cell and the deformation of the specimen was measured using an LVDT (Linear Variable Differential Transducer). A data acquisition system recorded the data at small time increments (every 5 s). Right cylinder area corrections were adopted in calculating the deviatoric stress from the axial force readings. Similarly, the volume change readings were corrected to take into consideration the penetration of the loading piston into the triaxial cell during loading. Volumetric strains were then calculated as the ratio of the corrected volume change to the volume of the sample. It should be noted that results from duplicate tests showed an acceptable level of repeatability, with a maximum difference of 5% in the measured deviatoric stress at failure.

6. Test results and analysis

Results include an analysis of the mode of failure, a description of the stress-strain relationships for the reinforced and control specimens, and an analysis of the degree of improvement in the globally-undrained shear strength.

6.1. Test series 1 – compaction by kneading

The objective of the first series of tests is to investigate the behavior of fiber-reinforced clays that are compacted

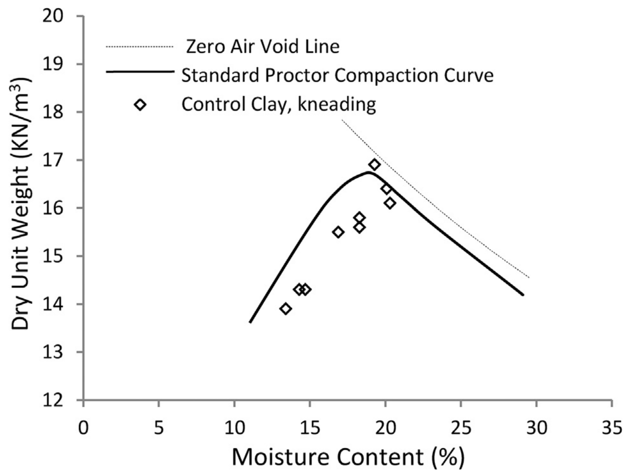

Fig. 4. Dry unit weights of the control samples compacted by kneading (Series 1).

using kneading with a pneumatic compactor. As a first step, the standard Proctor compaction curve of the unreinforced soil (no fibers) was established (Fig. 4). A calibration exercise was then initiated to determine the number of layers, number of tamps per layer, and tamping pressure required to produce control clay specimens at 90% of the standard Proctor maximum dry unit weight using the pneumatic compactor. The calibration exercise indicated that control clay specimens should be prepared in 5 layers with a kneading effort per layer of 25 tamps, at 10 psi (69 kPa) rod pressure. The resulting dry unit weights of the control clay specimens are shown in Fig. 4 and are consistent with the target 90% dry unit weight from standard Proctor compaction tests. It should be noted that this same energy was then used in compacting all fiber-reinforced clay specimens.

Thirty-six (36) control and hemp-reinforced clay specimens were tested to investigate the effect of changing the fiber reinforcement properties (fiber length or aspect ratio and fiber content) on the response of hemp-reinforced specimens.

The variations of the deviatoric stress and the volumetric strain with axial strain for control clay specimens and specimens reinforced with 20 mm-long hemp fibers are presented in Fig. 5 for cases involving compaction water contents of 14%, 18% and 20%, respectively.

For the control clay specimens, the stress-strain response was affected by the compaction water content (initial degree of saturation) and the applied confining pressure. The deviatoric stresses at failure were found to be relatively sensitive to the confining pressure, particularly for specimens prepared dry of optimum. This sensitivity could be attributed to (1) the compression of air voids in the partially saturated specimens that were compacted dry of optimum and (2) the composition of the soil which includes more than 45% sand. Although the triaxial tests that were conducted were globally undrained, global dilative (for 20 kPa) and compressive (for 100 kPa) volumetric strains were measured during shear. The magnitude of the volumetric strains decreased for the higher water contents with higher initial saturations.

For fiber-reinforced specimens, results of the tests conducted at the lowest confining pressure of 20 kPa indicate that the inclusion of fibers had a negative (or null) impact on the stress-strain response, particularly at relatively low strains. However, the addition of 1.0% fibers suppressed the dilative tendency particularly for the relatively unsaturated specimen (14% water content), where the volumetric strains at failure decreased from about 4% (control case) to 0.5% (reinforced specimen). This ability of the fibers to restrain dilation at low confining pressure has been reported by others (Punthutaecha et al., 2006; Abdi et al., 2008; Viswanadham et al., 2009; Al-Mhaidib, 2010). This reduction can be attributed to the resistance offered by fibers to expansion through clay–fiber contact (Viswanadham et al., 2009).

For the tests conducted with 20-mm hemp fibers at a confining pressure of 100 kPa, some improvement (upto 8–30%) in the deviatoric stress was observed particularly at relatively high axial strains. For specimens compacted dry of optimum, improvement was observed at axial strains exceeding 15%. The measured volumetric strains show a tendency for additional contractive volume change in specimens reinforced at a relatively high fiber content compared to control specimens. These increases in the contractive volumetric tendencies with fiber content were more significant in the fiber-reinforced specimens compacted wet of optimum (high degree of saturation).

The results of the tests conducted with short fibers (20 mm) indicated that reinforcing the clay with 0.5% fibers by weight did not lead to any improvement in load response. As a result, the specimens prepared with 40-mm long fibers were tested only with fiber contents of 1.0% and 1.5%. The results pertaining to the case of 20 kPa confining pressure are presented in Fig. 6.

The stress-strain curves indicate that the specimens reinforced with 1% fibers exhibited an improved response compared to the 1.5% case, particularly at small strains and low compaction water contents. For specimens prepared with hemp at $\chi_{F,w} = 1\%$, maximum improvements of 70% were observed in the deviatoric stress at failure for the case with a water content of 14%. The improvement decreased systematically to 38% and 20% as the water content increased to 18% and 20%. Increasing the fiber content from 1% to 1.5% resulted in an insignificant increase (from 70% to 74%) in the improvement level for the case of w = 14% and in a drop in the improvement levels (from 38% and 20% to 21% and 13%) for water contents of 18% and 20%, respectively. This indicates that the threshold fiber content for the hemp-reinforced clay could be between 1.0% and 1.5%.

With regards to the volumetric response, an analysis of the measured global volumetric strains on Fig. 6 shows a

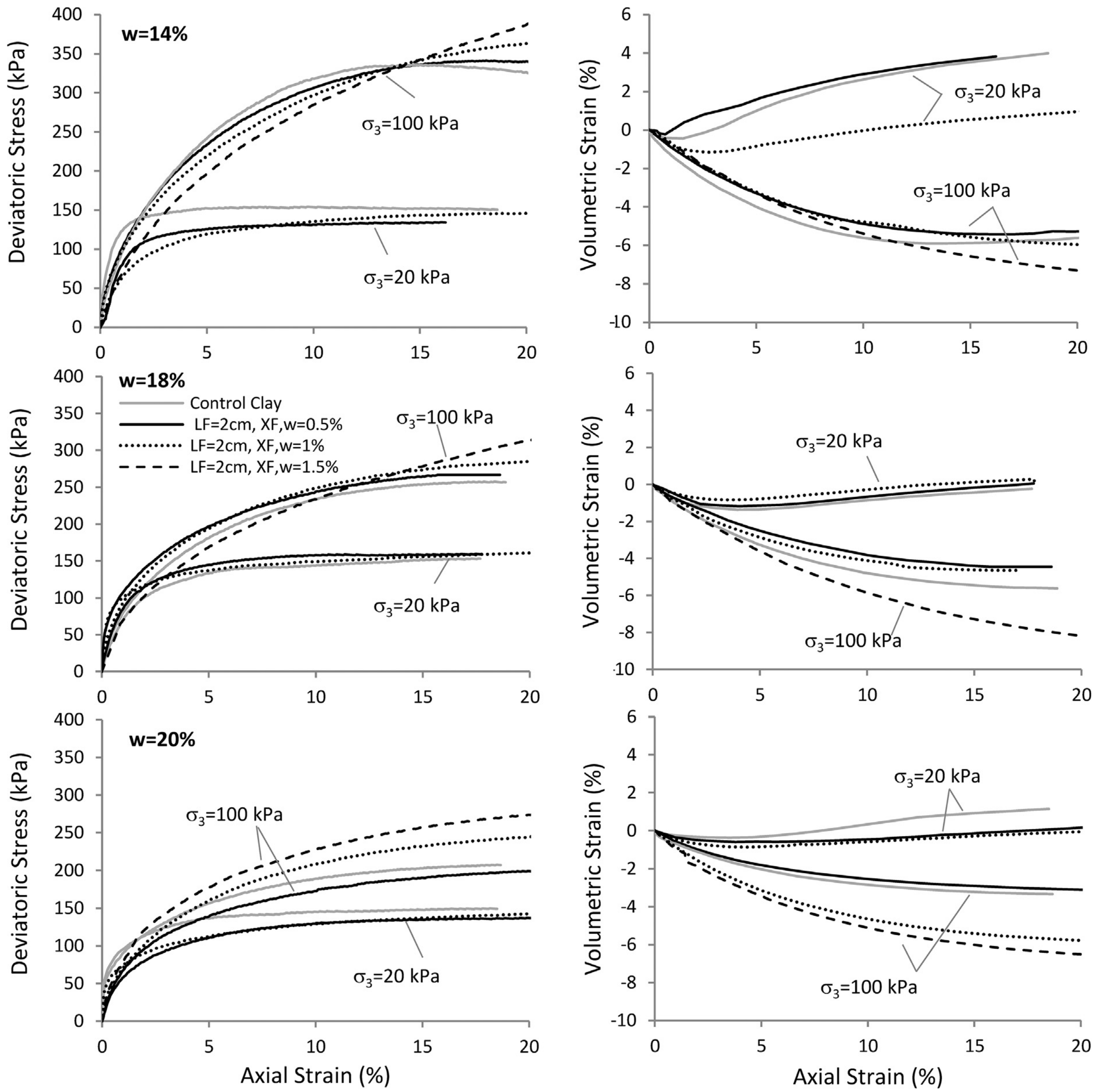

Fig. 5. Variation of stress and volumetric strain with axial strain (Hemp fibers, $L_F = 20$ mm, Series 1).

tendency of fibers to restrain expansive volume changes at all water contents. This effect increases as the fiber content increases and as the water content decreases.

Based on the results of the tests conducted at 20 kPa, a decision was made to adopt a fiber content of 1% and to investigate the effect of confining pressure on the observed response as portrayed in Fig. 7. Results indicate a systematic and consistent improvement in the deviatoric stress at failure at all confining pressures. The percent improvement in the deviatoric stress appears to decrease for the higher confining pressure and the higher compaction water content adopted. The smallest improvements were witnessed for clay specimens that were compacted wet of optimum and were accompanied by consistent increases in the contractive volumetric strains as compared to the control specimens. It should be noted that the general trends observed for specimens tested at the confining pressure of 200 kPa were in line with the trends reported for the 100 kPa cases (see Table 1).

Results of the first series of tests (kneading) indicated that the most efficient combination of fiber length and fiber content was found to be 40-mm and 1%. To compare the observed improvement levels to other published results, an effort was made to collect published data that are limited to (1) unconsolidated undrained triaxial tests, (2) volumetric fiber content that is around 1.0%, (3) compaction water content that is close to optimum, and (4) confining pressure in the range of 20–200 kPa. The published tests that met the above criteria are presented in Fig. 8.

The results in Fig. 8 indicate that the average percentage improvement for specimens compacted by kneading at 18% and 20% water content was significantly lower than the

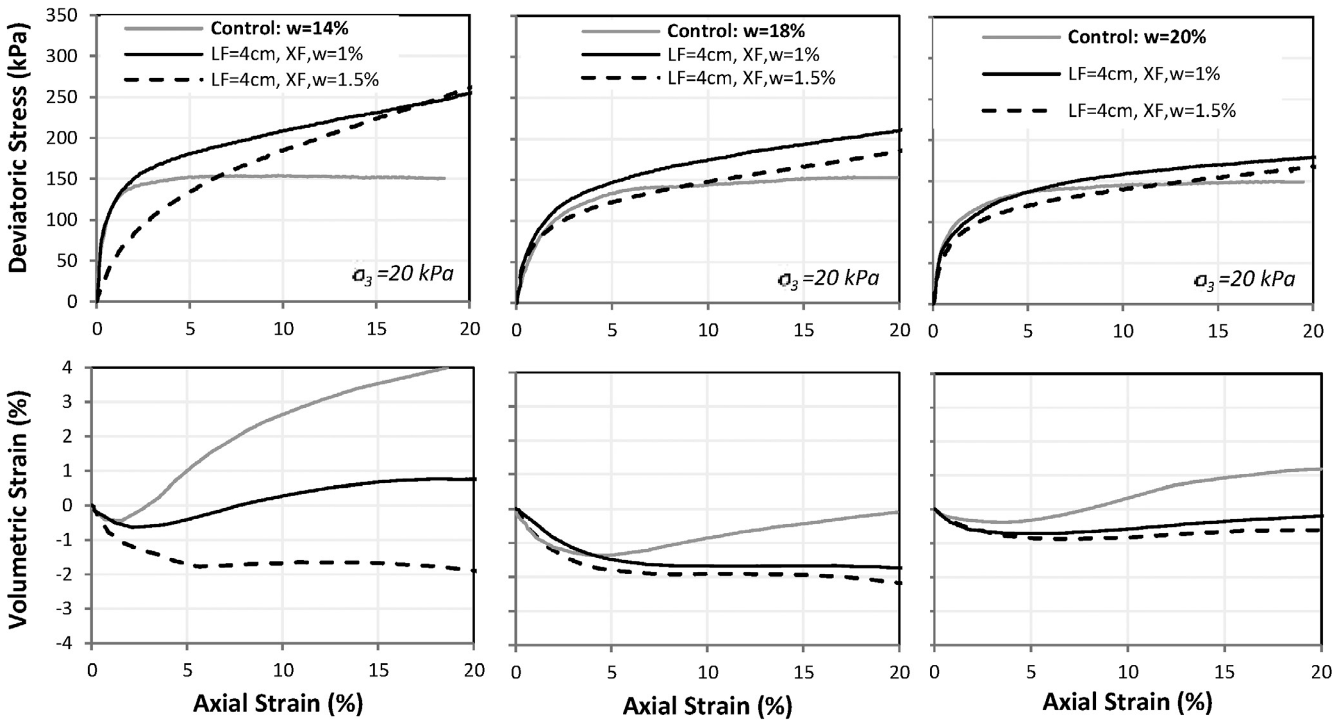

Fig. 6. Variation of stress and volumetric strain with axial strain (Hemp fibers, $L_F = 40$ mm, Series 1).

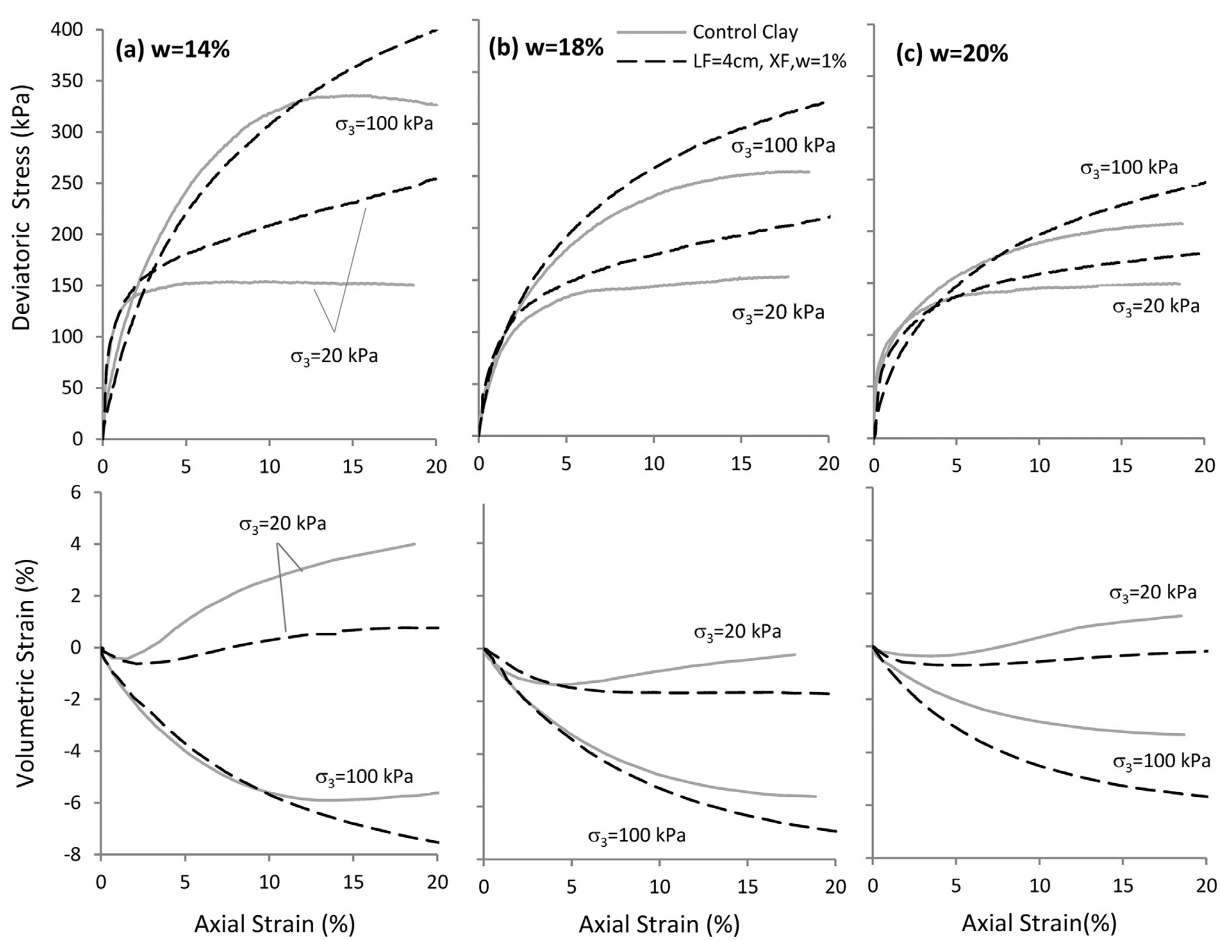

Fig. 7. Stress-strain and volumetric strain response (Hemp fibers, $L_F = 40$ mm, $\chi_{F,w} = 1\%$, Series 1).

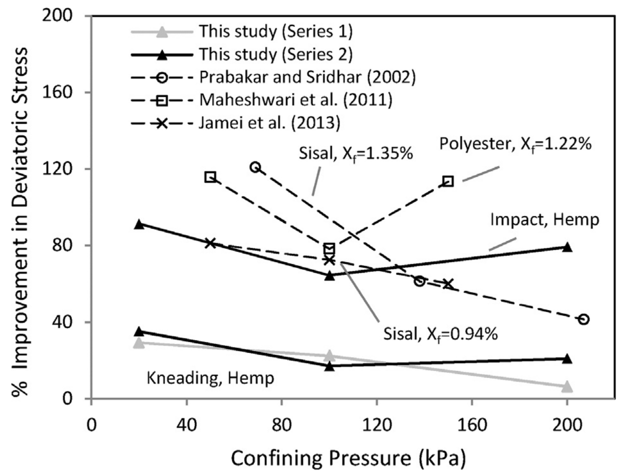

Fig. 8. Comparison with published results (Series 1 & 2).

range of improvements reported in the literature under similar conditions. However, it must be noted that the samples in this study were prepared by kneading, whereas the samples in the reported studies were prepared by impact compaction. To investigate the reasons for the relatively low effectiveness of the fibers, the initial dry unit weights of the fiber-reinforced specimens tested in Series 1 were determined and plotted in Fig. 9a. The data indicates that although the kneading effort was calibrated on the control clay specimens to yield dry unit weights of 90% of the standard Proctor unit weights, the dry unit weights of the fiber-reinforced specimens were actually much lower, with differences of up to 2 kN/m^3. The first hypothesis is that it is likely that the relatively low to moderate effectiveness of the fibers can be attributed to the reductions observed in the initial dry unit weight of the fiber-reinforced specimens compacted by kneading.

A second plausible hypothesis that could explain the relatively low improvement levels relates to the nature and characteristics of the natural hemp fibers. To isolate the effect of the type of fiber on the response, a supplementary series of UU-tests (Tests 37–45 in Table 1) were conducted on the same soil with polypropylene fibers. Results did not show any improvement in strength over the identical clay samples mixed with hemp fibers. It could thus be concluded that the relatively low improvement in load response witnessed for hemp-reinforced clay specimens could not be primarily attributed to the nature and properties of the hemp fibers.

A third possible consideration in explaining the relatively low to moderate effectiveness of the fibers is the compaction method. The specimens were prepared by kneading rather than impact, unlike the majority of the tests reported in the literature. Previous research on the permeability of clay liners indicates that the structure of the compacted clay could differ significantly between "impact" methods and "kneading" methods (Harrop-Williams, 1985; Benson et al., 1994; Omidi et al., 1996). This is particularly important for clays that are reinforced with fibers, since the fibers are expected to affect the response/behavior of the clay during compaction and may result in important differences in the orientation of the fibers and in the structure and behavior of the composite.

To investigate the validity of hypotheses 1 (effect of dry unit weight) and 3 (effect of compaction method), a comprehensive series of tests (Series 2) was designed and implemented whereby the compaction energy for both "kneading" and "impact" compacted specimens was varied to achieve identical dry unit weights for both control and fiber-reinforced specimens. The target dry unit weights were chosen to be consistent with 100% of the standard Proctor compaction unit weights for the control clay. This allowed for a one-to-one comparison between identical specimens that had more-or-less similar initial water contents and dry unit weights but were prepared using different compaction methods. To our knowledge, this attempt to compare the response of identical fiber-reinforced specimens prepared by kneading and impact compaction is the

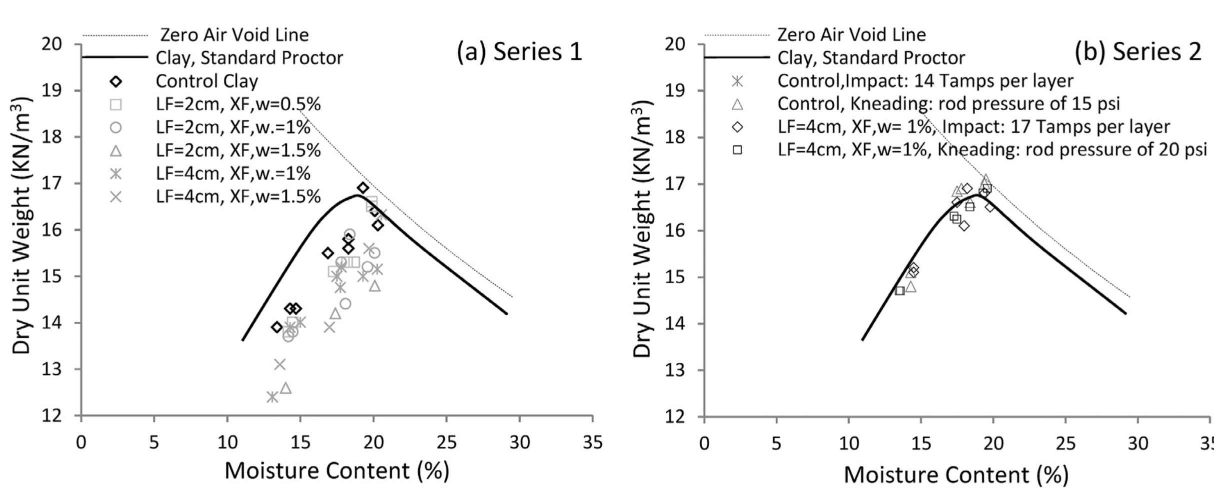

Fig. 9. Dry unit weights of the control and Hemp-reinforced samples: (a) constant kneading energy, Series 1 and (b) calibrated kneading and impact energy, Series 2.

first in the literature. The results and analysis of Series 2 tests are presented in the following section.

6.2. Test series 2 – modified kneading vs. impact compaction

To bring the dry unit weight of the control clay and fiber-reinforced specimens up to the standard Proctor unit weight of the control clay, the "kneading" compaction effort was modified by increasing the rod's pressure to 15 psi (103 kPa) for control clay specimens and 20 psi (138 kPa) for fiber-reinforced clay specimens. For specimens prepared with impact compaction, the number of hammer drops per layer was 14 for the control clay specimens and was increased to 17 drops for the clay reinforced with Hemp fibers. To reduce the number of tests to be conducted in Series 2, the tests were limited to specimens reinforced with 40 mm long fibers at a gravimetric fiber content of 1%, for which maximal improvement effects were observed in Series-1.

The initial dry unit weights and water contents of the fiber-reinforced specimens that were compacted by impact and by kneading are presented in Fig. 9b. The results indicate that the calibrated compaction efforts for both compaction methods produced consistent and comparable compaction characteristics. This indicates that any observed differences in the measured stress-strain and volumetric strain responses are solely related to the method of compaction and not to any other unit weight-related factor.

The variation of the deviatoric stress and volumetric strain with axial strain is shown in Figs. 10 and 11 for specimens prepared using kneading and impact compaction. For tests conducted at a confining pressure of 20 kPa, results on Fig. 10 indicate that control specimens that were prepared by impact compaction (grey solid lines) exhibited a strain softening response that was slightly more pronounced than that of their identical counterpart specimens which were compacted by kneading (grey dotted lines). This was more evident for the specimens compacted dry of optimum.

Despite some slight differences in the response of the control clay specimens at relatively small strains, the deviatoric stress at large strain was very similar in the two compaction methods. This behavior is expected to be linked to differences in the structure and orientation of the clay particles in the two compaction methods. For a given compaction water content, kneading is known to produce a more dispersed and oriented clay structure compared to impact compaction, which produces a structure with relatively more random/flocculated clay particles. The difference in structure affects the load response at small strains, but is expected to be less significant at larger strains

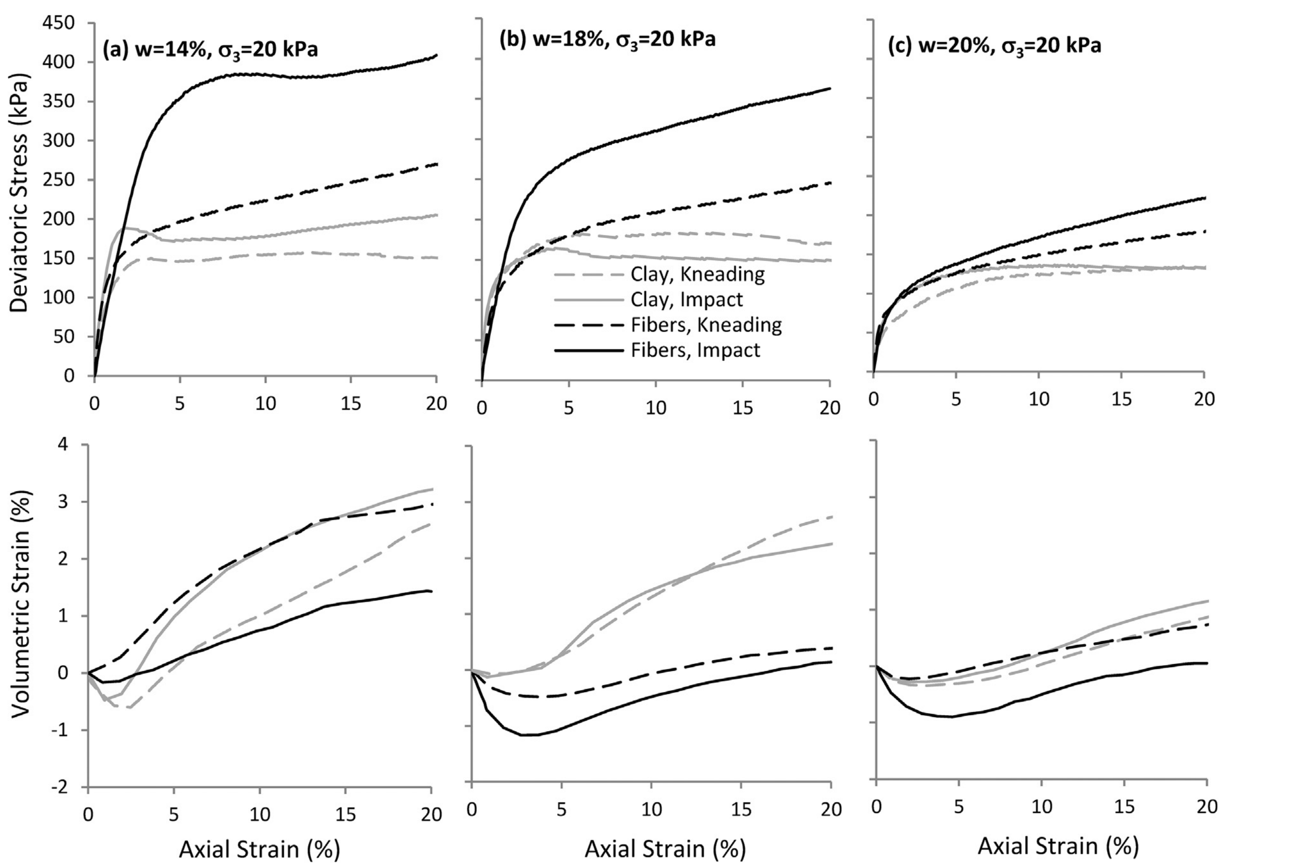

Fig. 10. Triaxial tests results on samples compacted by impact and kneading to the same dry unit weights, $\sigma_3 = 20$ kPa (Hemp fibers, $L_F = 40$ mm, $\chi_{F,w} = 1\%$, Series 2).

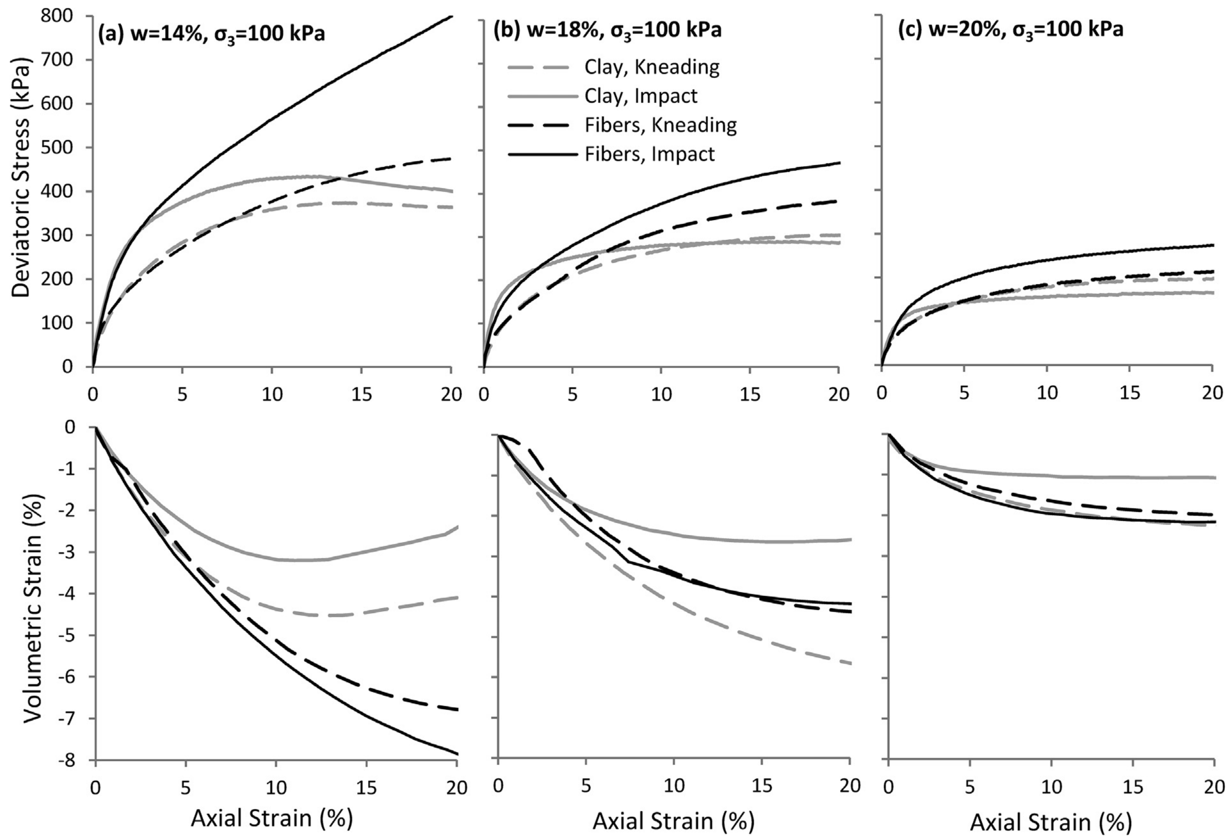

Fig. 11. Triaxial tests results on samples compacted by impact and kneading to the same dry unit weights, $\sigma_3 = 100$ kPa (Hemp fibers, $L_F = 40$ mm, $\chi_{F,w} = 1\%$, Series 2).

where the clay particles in both compaction methods tend to orient during shearing.

Unlike the control clay specimens, specimens that were reinforced with 40-mm long fibers at a fiber content of 1% exhibited clear differences in load response for the two compaction methods for a confining pressure of 20 kPa. Specimens that were prepared using impact compaction consistently showed a superior stress-strain response compared to their identical counterparts which were prepared using kneading. Nevertheless, specimens from both compaction techniques exhibited ductility in the stress-strain response. The volumetric strain response showed that fibers in specimens that are prepared using impact compaction were more efficient at arresting and reducing the dilative tendency of the clay.

For the tests conducted at a confining pressure of 100 kPa, the results in Fig. 11 show similar trends to the tests conducted at 20 kPa. Small differences in the globally undrained shear strength were observed for the control clay specimens while significant differences were observed for the fiber-reinforced specimens, with the specimens prepared using impact compaction exhibiting higher deviatoric stresses then the "kneaded" specimens, particularly at larger strain levels. In addition, the strain softening response witnessed in the control clay specimens was replaced by a strain hardening response upon the addition of fibers.

Pictures showing the mode of failure for the control and the fiber-reinforced clay specimens prepared using impact and kneading compaction are presented in Fig. 12. The pictures indicate that the fibers arrested the shear plane that formed in the control clay specimen that was prepared using impact compaction and prohibited failure along that potential failure plane. For the specimen that was prepared using kneading, the development of a shear plane was not observed in the control clay specimen which showed signs of significant bulging. The addition of fiber to this sample reduced the degree of bulging and resulted in a more uniform deformation along the length of the specimen.

Fig. 13 shows the total stress Mohr circles at failure and the bilinear representations of the total stress Mohr-Coulomb failure envelops for the control and fiber-reinforced specimens prepared at a water content of 18% by kneading (Fig. 13a) and impact (Fig. 13b). An analysis of the data on Fig. 13 leads to the following observations:

- The total stress Mohr-Coulomb failure envelop for the control clay is only slightly affected by the compaction method, both at the low and high pressure ranges. In the lower pressure range, cohesive intercepts of 50 kPa

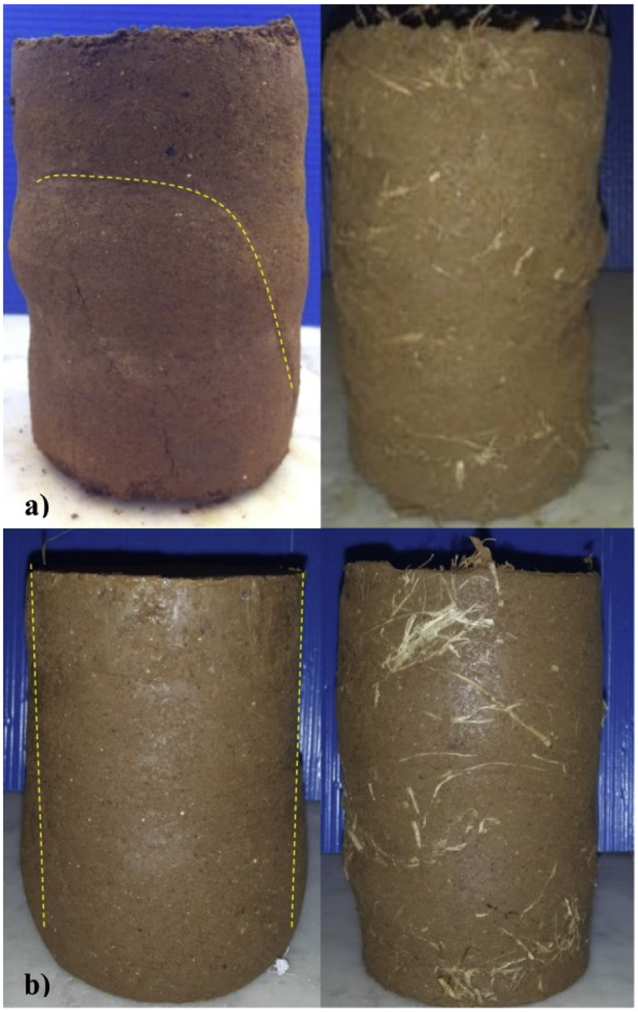

Fig. 12. Failure modes of samples compacted by (a) impact and (b) kneading to the same dry unit weights (w = 18%, Series 2).

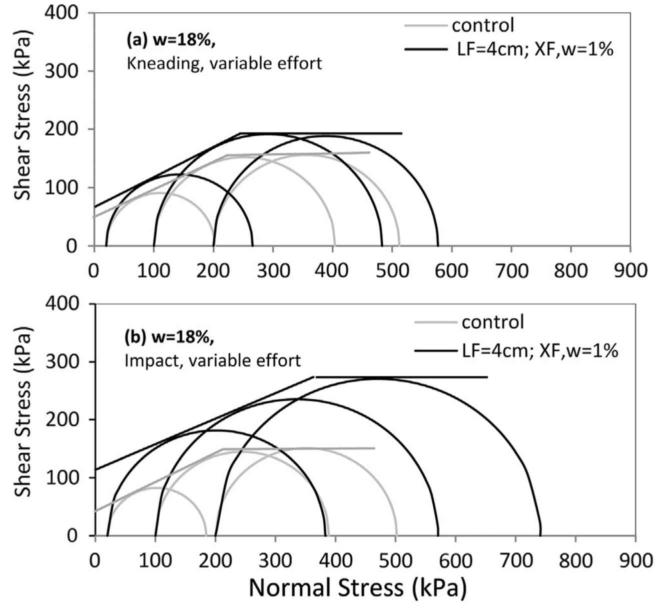

Fig. 13. Mohr circles at failure for samples compacted by (a) kneading and (b) impact to the same dry unit weights (Hemp fibers, $L_F = 40$ mm, $\chi_{F,w} = 1\%$, w = 18%, Series 2).

and 40 kPa are observed for specimens compacted by kneading and impact, respectively with corresponding friction angles of 24.2° and 26.3°.

- For fiber-reinforced specimens, the total stress friction angle in the low pressure range is marginally affected by the compaction method (25.6° for kneading and 24° for impact), while the cohesion intercept is significantly affected (68 kPa for kneading and 110 kPa for impact) by the compaction method.
- In the high pressure range, the failure envelop flattens for control and reinforced clay specimens resulting in undrained shear strength values that are independent of the confining pressure. The undrained shear strength is observed to increase from around 150 kPa in the control specimens to about 195 kPa and 275 kPa for the fiber-reinforced specimens prepared by kneading and impact, respectively.

It could be concluded that the method of compaction has a direct impact on the total stress Mohr-Coulomb envelop of fiber-reinforced clays. The specimens prepared by impact exhibit a higher cohesive intercept and a higher undrained shear strength in the high pressure range.

It should be noted that the bi-linear failure envelopes observed in Fig. 13 are expected for unsaturated clay specimens sheared in UU-triaxial settings. In the low pressure range, increasing the confining pressure compresses the air voids and the fabric of the unsaturated clay resulting in an increase in the shear strength of the soil. When the confining pressure is high enough, volume decreases during the test may be large enough to result in almost complete saturation (Weitzel and Lovell, 1980). Hence, any further increase in confining pressure merely increases the pressures in the pore water, but neither the effective stresses nor the shear strength of the soil are changed. This process ultimately results in a flat failure envelope upon complete saturation. Such flat envelopes are observed in the UU-triaxial tests conducted on initially saturated clay specimens.

The measured deviatoric stresses and the computed percentage improvement in the deviatoric stresses at failure are plotted versus the compaction water content in Fig. 14 for the clay specimens prepared by impact and kneading. Results are shown separately for confining pressures of 20 kPa and 100 kPa. Results indicate that the globally undrained shear strength of the control clay is more-or-less insensitive to the method of compaction, irrespective of the compaction water content. For specimens reinforced with fibers, increases in the deviatoric stresses at failure were consistently observed for all compaction water contents. The increase in the deviatoric stress was more pronounced in specimens compacted by impact compared to specimens prepared by kneading.

An analysis of the percent improvement in the undrained shear strength at a confining pressure of 20

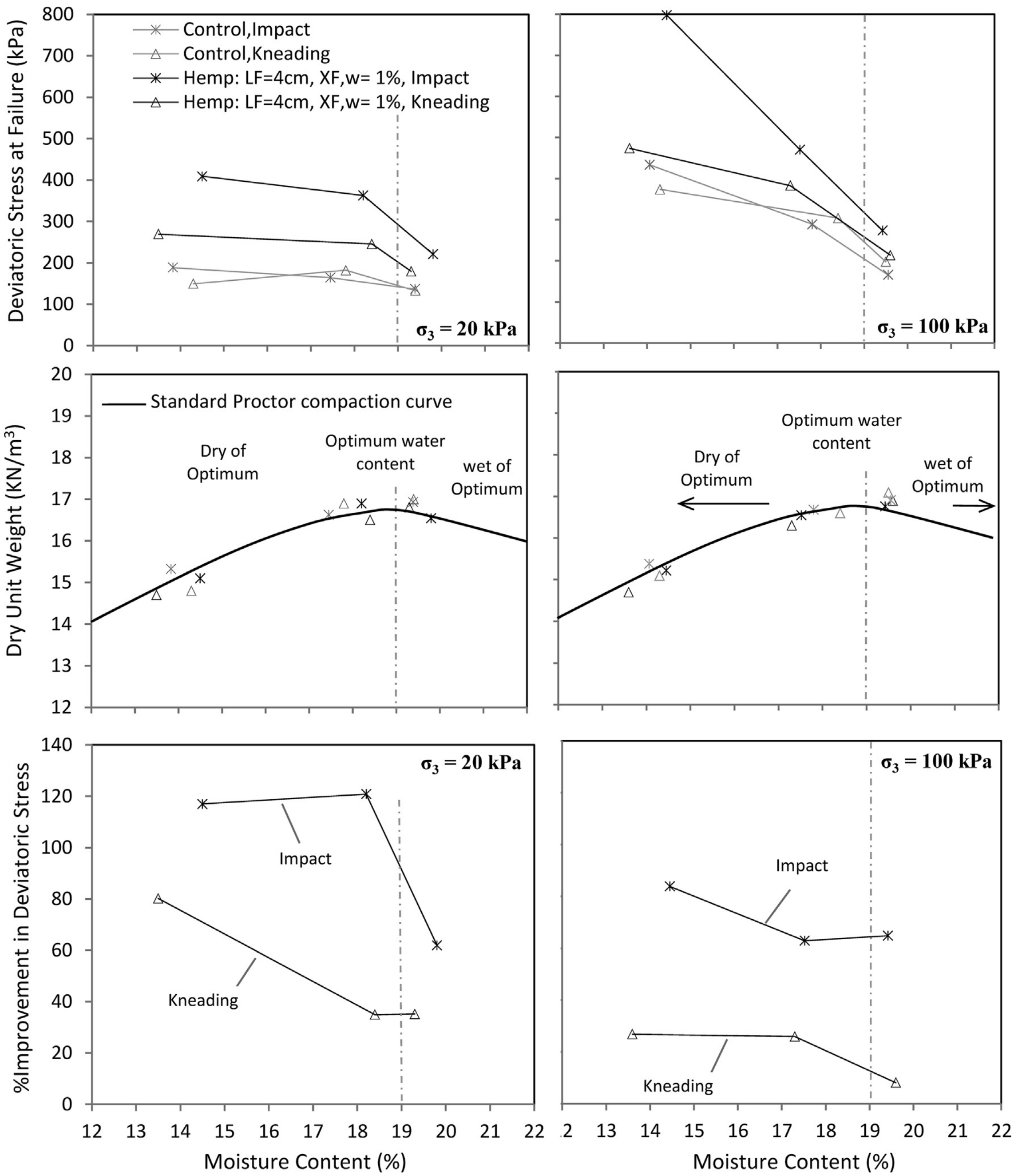

Fig. 14. Variation of the deviatoric stress and its percent improvement versus moisture content (Hemp fibers, $L_F = 40$ mm, $\chi_{F,w} = 1\%$, Series 2).

kPa indicates that specimens compacted by impact exhibited improvements in the order of 120% for the cases with water contents of 14% and 18%. This improvement decreased to about 62% as the compaction water content increased to 20%. The corresponding improvements in the specimens prepared by kneading were much lower reaching values of 80%, 35%, and 35% for water contents of 14%, 18% and 20%, respectively. For the tests conducted at a confining pressure of 100 kPa, the improvements were lower, with the specimens prepared by impact showing improvements ranging from 65% to 85% compared to 8% to 26% for the corresponding kneading tests.

A comparison between the percentage improvements in undrained strength in Series 2 tests and those published in the literature is presented in Fig. 8. Average percentage improvements for specimens compacted around optimum (18% and 20%) are included in the figure and indicate that the results for the "impact compaction" cases are in line with published results in the literature, whereas percent improvement observed in the "kneading" cases is much lower.

It can be concluded with confidence that the method of compaction has a major effect on the degree of improvement in the globally undrained strength for fiber-reinforced clays. For the clay and fiber used in this study, the percentage improvement in the undrained shear strength of fiber reinforced clays compacted near optimum is observed to be more than three times higher in specimens prepared using impact compared to identical specimens that were prepared using kneading to the same dry density. This finding is significant because it indicates that the results of the majority of the laboratory tests in the literature may be overestimating the degree of improvement expected in fiber-reinforced soil in practical field applications where compaction is generally conducted using field equipment that uses kneading as the main compaction technique. The majority of laboratory scale experimental studies for fiber-reinforced soils use impact compaction techniques in the testing programs.

The reduction in the effectiveness of the fibers in the specimens prepared by kneading compared to the samples prepared by impact compaction could be attributed to several factors. The first factor is related to differences in the orientation of the fibers within the clay matrix. Although randomly-oriented fibers were targeted, the resulting fiber orientations in the two compaction techniques may differ, possibly affecting the load response of the composite. Several studies have indicated that impact compaction using tamping is more likely to produce oriented rather than random fibers. The second factor may have contributed to a reduction in the fiber efficiency in samples prepared by kneading is the relatively large shear strains which are imparted to the clay-fiber mixture during compaction. These large shear strains may have damaged the fibers by increasing the likelihood of the kinking or even rupture of the fiber during compaction.

7. Effect of compaction method on fiber orientation distribution

Diambra and Ibraim (2014) proposed a constitutive model for fiber-reinforced cohesive soil. On the experimental level, Diambra et al. (2007) presented a procedure for determining the distribution of fiber orientation in cylindrical sand specimens reinforced with flexible fibers. The procedure is applicable for cases where the fiber orientation could be assumed to have a vertical axis of symmetry as is the case in the triaxial test specimens utilized in the current study. The experimental procedure is tied to a theoretical generalized fiber orientation distribution function $\rho(\theta)$ (Eq. (1)) which represents the volumetric concentration of fibers in an infinitesimal volume dV with an orientation angle θ with the horizontal such that:

$$\rho(\theta) = \bar{\rho}(A + B|\cos^n \theta|) \tag{1}$$

In Eq. (1), $\bar{\rho}$ is the average volumetric concentration of the fibers ($\bar{\rho} = Vf/V$), defined as the total volume of fibers (V_f) per sample volume (V), and A, B and n are constants linked by:

$$B = \frac{1 - A}{\int_0^{\pi/2} \cos^{n+1}(\theta) d\theta} \tag{2}$$

Within a sample with fiber orientation distribution described using Eq. (1), the ratio (P) of the volume of fibers with orientations within an angle $\pm\beta$ from the horizontal to the total volume of fibers is given by:

$$P = \frac{1}{2\bar{\rho}} \int_{-\beta}^{\beta} \rho(\theta) \cos(\theta) d\theta \tag{3}$$

Diambra et al. (2007) states that the fiber orientation distribution in Eq. (1) requires two of the constants A, B and n to be specified. This can be done by adjusting A and n such that the theoretical predictions of the number of fibers crossing vertical and horizontal planes will closely match the actual number of fibers intersecting vertical and horizontal planes cut through a sample in the laboratory. Mathematical expressions for the number of fibers crossing vertical (N_V) and horizontal (N_H) planes are presented in Diambra et al. (2007). It should be noted that the parameter "n" needs to be an integer. The procedure can be simplified even further by assuming $A = 0$, meaning that no fibers have a vertical orientation, so that only n needs to be calibrated with the experimental data.

The experimental procedure recommended in Diambra et al. (2007) for estimating the number of fibers crossing horizontal and vertical planes in frozen fiber-reinforced sand specimens was adopted with minor variations given the differences in the soil type (clay versus sand). Four hemp-reinforced specimens were compacted at a water content of 18%, reinforced with 1% hemp fibers by weight, and used as a basis for the fiber orientation distribution analysis. Two samples were compacted with the standard Proctor hammer and two using the kneading pneumatic compactor. These specimens were prepared to be identical to the specimens used in the UU-triaxial tests conducted in the Series 2 tests to allow for an investigation of the effect of fiber orientation on the resulting shear strength response.

Following compaction, the samples were cut in the vertical and horizontal directions using a very sharp rigid cutter custom-fabricated for the purpose of the tests. Given the cohesive nature of the soil and the nature of the fibers, there was no need to freeze the specimens prior to cutting them. Three horizontal cuts were made to produce three slices/disks of soil each being around 3.5 cm thick. Note that 1.5 cm thick horizontal slices were scraped from the top and bottom of the specimens. For the vertical and horizontal cut planes, fibers intersecting an area 2 cm × 2 cm on the cut plane were counted visually. As per the recommendations of Diambra et al. (2007), counting was repeated for different area locations on each cut plane while ensuring that the areas did not overlap. However, the area locations were kept away from the sample edges.

Representative pictures showing vertical and horizontal cuts taken from specimens compacted by impact and kneading are shown on Fig. 15a and b, respectively. The images show the 2 cm × 2 cm areas used to calculate the number of fibers intersecting the horizontal (N_H) and ver-

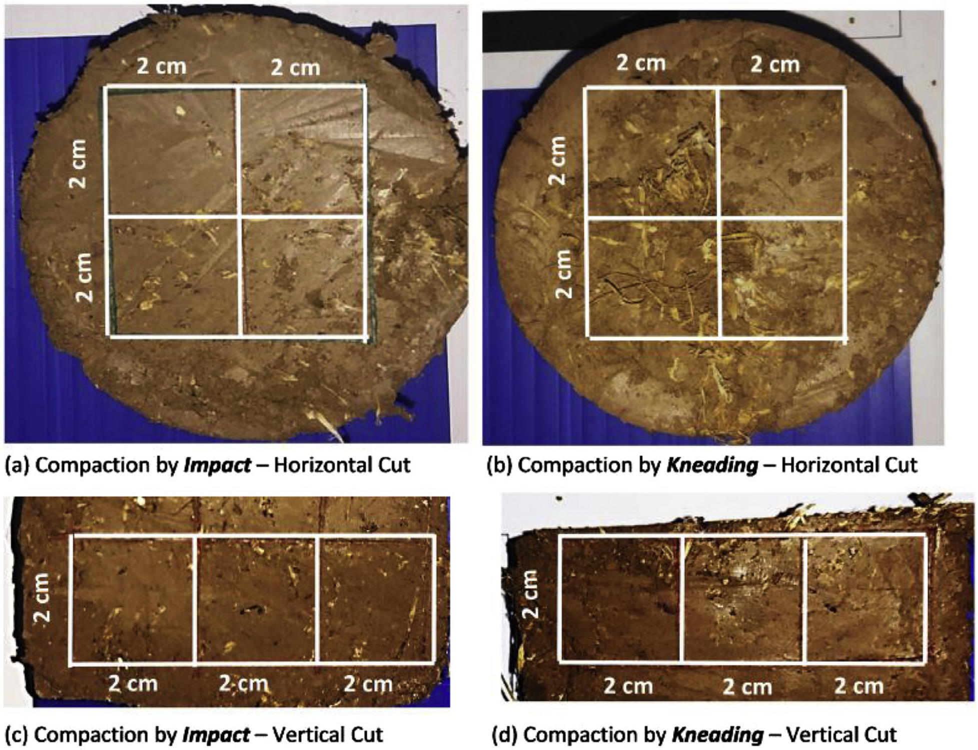

Fig. 15. Samples of vertical and horizontal cuts through Hemp-reinforced clay specimens that were compacted by Impact and Kneading.

Table 5
Average numbers of fibers intersecting 20×20 mm area and their respective N_V/N_H ratios.

Sample	Fabrication method	Average number of fibers intersecting 20 mm × 20 mm area			Orientation parameters			Analytical prediction		
		N_V	N_H	N_V/N_H	A	n	B	N_V	N_H	N_V/N_H
1	Impact	21.0	14.5	1.45	0	2	1.50	22.5	15.1	1.49
2	Impact	22.0	13.1	1.68	0	3	1.70	22.9	13.5	1.69
3	Kneading	17.8	23.4	0.76	0	−1	0.64	16.3	25.6	0.64
4	Kneading	20.5	21.0	0.98	0	0	1.00	20.2	20.2	1.00

tical (N_V) cut planes. It should be noted that image processing was used to count the number of fibers crossing these planes. The average values of (N_H) and (N_V) and the corresponding ratio between N_V and N_H were calculated for the four specimens and summarized in Table 5. Interestingly, results show that the ratio N_V/N_H is significantly affected by the method of compaction, with recorded N_V/N_H values ranging from 1.45 to 1.68 for specimens compacted using impact and 0.76 to 0.98 for specimens compacted using kneading. It was concluded that for specimens compacted using impact, fibers crossing vertical planes are more than fibers crossing horizontal planes while the opposite is true for specimens compacted using kneading. These differences can only be associated with differences in the fiber orientation distribution as a result of differences in the compaction methods. In a general sense, it could be argued that compaction using impact led to a preferred near-horizontal orientation which is more pronounced than the cases involving kneading compaction.

To quantify the distribution of the orientation of hemp fibers, an analytical fiber orientation distribution model that was proposed by Diambra et al. (2007) was used and the parameter n in Eq. (2) was calibrated such that the analytically-predicted and experimentally-measured N_V, N_H and N_V/N_H ratio closely match. The results of the matching are presented in Table 5 and indicate that n values of 2 and 3 are required to fit the measured results of the specimens compacted by impact while n values of -1 and 0 are required to fit the results of the specimens compacted by kneading. These best-fit n values can be used to plot the fiber orientation distributions as represented by the variation of $\rho(\theta)\ \cos(\theta)/\bar{\rho}$ with the fiber orientation angle θ (radians) as shown on Fig. 16. Diambra et al. (2007) state that the function$\rho(\theta)\ \cos(\theta)/\bar{\rho}$ is analogous to a probability density function for the fiber orientation, with the area beneath the curves between $\theta = 0$ and $\theta = \beta$ representing the proportion of fibers (P) orientated within $\pm\beta$ from the horizontal (Eq. (3)).

The results in Fig. 16 indicate that for hemp-reinforced specimens that were compacted using impact, 88.3 to 92.4% of the fibers are expected to be orientated within $\pm 45°$ from the horizontal. On the other hand, the fiber ori-

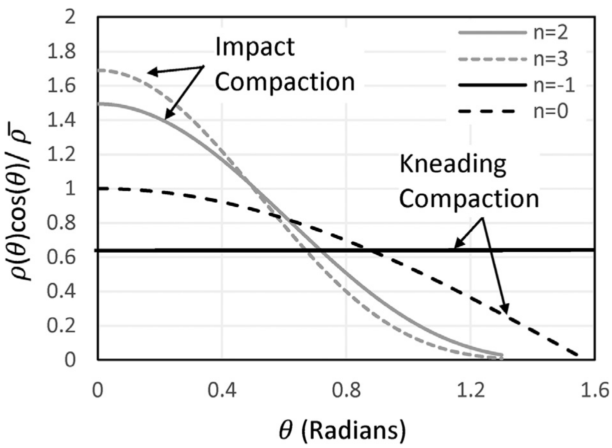

Fig. 16. Differences in the fiber orientation distributions (Eq. (1)) for specimens that were compacted by kneading and impact.

entation distribution curves of the specimens compacted using kneading indicate that only 50% to 70% of the fibers are expected to be orientated within ±45° of the horizontal. Also, it could be observed that 68.7% to 74% of the fibers are predicted to be orientated within 30° from the horizontal for impact-compacted specimens, compared to 33–50% for the specimens compacted using kneading.

The results presented above should be analyzed in the context of published results on the orientation of fibers in fiber-reinforced soils. For the fiber-reinforced sand specimens that were analyzed by Diambra et al. (2007) and which were compacted using moist tamping, results pointed to a preferential horizontal fiber orientation, with nearly 97% of fibers with an orientation that lies within ±45° of the horizontal. Ozkul and Baykal (2006, 2007) also reported that fiber-reinforced clay specimens that were compacted using both Standard and Modified Proctor tests showed preferential alignment of fibers in the horizontal direction. They also report that although the strength anisotropy occurring from this preferential orientation was not studied, the general alignment of fibers (estimated to be mostly within ±45° of the horizontal plane) is favorable for the improvement of shear strength because it does not coincide with the plane of maximum shear strain expected in triaxial tests.

In our study, both impact-compacted and kneading-compacted hemp-reinforced clay specimens showed a preferential horizontal fiber orientation. However, results of the fiber-orientation experiment that was conducted (Table 5 and Fig. 16) show that the horizontal preferential orientation was less in the specimens compacted by kneading. These observations may explain the relatively smaller improvements in the undrained shear strength for fiber-reinforced specimens that were compacted by kneading in comparison to those compacted by impact. It was thus concluded that the method of compaction affects the fiber orientation distribution and the resulting efficiency of the fibers by increasing the shear strength of fiber-reinforced clays.

8. Conclusions

The following main conclusions can be drawn from the results of the 73 UU triaxial tests conducted in this study.

First, natural hemp fibers which are abundantly available in many countries (Bouloc, 2013) were proven to be effective in increasing the globally undrained shear strength of a natural CL clay. Important degrees of improvement were recorded in the undrained shear strength of fiber-reinforced clay specimens as compared to their unreinforced counterparts, particularly for specimens compacted by impact and reinforced with 4 mm-long fibers. The inclusion of hemp fibers added ductility to the mode of failure by arresting the development of shear planes and reducing concentrated bulging in control clay specimens. The added ductility was reflected in the stress strain response where strain softening behavior in control clay specimens was replaced with strain hardening behavior in fiber reinforced specimens.

Second, optimum fiber reinforcement properties for the hemp and soil were found to consist of 40-mm long fibers mixed with soil at a fiber content of 1.0%. It is worth noting here that this conclusion is specific to the soil conditions and reinforcement parameters/characteristics analyzed in this research project.

Third, the percentage improvement in the undrained shear strength was found to be highly dependent on the compaction method. Fiber-reinforced clay specimens prepared using impact compaction yielded consistently larger improvements than those witnessed in identical specimens prepared by kneading. In the majority of cases studied, the percentage improvement was more than 3.0 times larger in specimens compacted by impact.

An experimental investigation targeting the orientation distribution of fibers within the compacted clay showed that both impact-compacted and kneading-compacted hemp-reinforced clay specimens showed a preferential horizontal fiber orientation. However, the horizontal preferential orientation was less in specimens that were compacted by kneading leading to the conclusion that the method of compaction affects the fiber orientation distribution and the resulting efficiency of the fibers in increasing the shear strength of fiber-reinforced clays.

This observation is significant since it indicates that experimental studies that use impact compaction may yield unconservative estimates of undrained shear strength that may not be representative of field compaction conditions, which predominantly involve kneading.

Acknowledgements

The authors would like to acknowledge the support of the Lebanese National Council for Scientific Research and the American University of Beirut Research Board for funding this research program.

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