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Influence of hemp shiv, cement, and water content on the properties of lightweight hemp composites produced using different sizes of hemp shiv

Murat Şahin[1]*

[1] Department of Civil Engineering, Yozgat Bozok University, Yozgat (Turkiye); murat.sahin@bozok.edu.tr
*Correspondence: murat.sahin@bozok.edu.tr

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Abstract: This study investigated the production and properties of lightweight hemp composites produced using waste industrial hemp stems cultivated in Turkey. Hemp stems were separated from their fibers and fragmented to obtain hemp shiv aggregates in the laboratory. Twelve mixtures were prepared with varied volumetric ratios of hemp: cement (H:C) and hemp: water (H: W) using different sizes of hemp shiv. The influence of mix proportions on the physical and mechanical properties of hemp composites were investigated. Besides, microstructure of hemp composites was examined. The hemp composites produced were in the apparent density range of 312 to 928 kg/m^3 and exhibited 0.20 to 1.24 MPa compressive strength. The water absorptions of samples were in the range of 3.47 and 8.50 kg/m^2.h$^{1/2}$. The apparent density and compressive strength of hemp composites decreased with the increase of H:C ratio, but this situation is the opposite for increase of H: W ratio and hemp shiv size. Besides, increase in H:C ratio or hemp shiv size caused higher water absorptions.

Keywords: Hemp composites, bio-composites, Turkish hemp stem, industrial hemp, compressive strength.

1. Introduction

The massive use of construction materials has caused rapid consumption of natural sources, enormous wastes, and high CO_2 emissions leading to serious environmental problems (Colinart et al., 2012). Thus, research on alternative construction materials with low environmental impact has gained more interest and importance (Orsini & Marrone, 2019). One such alternative material is bio-based building composites (Jones & Brischke, 2017) (also referred as bio-aggregate composites (Williams et al., 2018) or agro-concretes (Amziane, 2016) in which plant-based materials such as bagasse (Hernández-Olivares et al., 2020), bamboo (Ghavami, 2005), coconut (Kanojia & Jain, 2017), cork (Panesar & Shindman, 2012), corn stalk (Ahmad & Chen, 2020), flax (Benmahiddine et al., 2020), hemp (Jami et al., 2016), lavender (Ratiarisoa et al., 2016), palm shell (Huda et al., 2016), sunflower (Wadi et al., 2019), or wheat straw (Petrella et al., 2019) have been used as aggregate and mixed with a mineral binder such as cement (Çomak et al., 2018; da Gloria et al., 2021; Gourlay et al., 2017; Sedan et al., 2008), lime (Williams et al., 2017), hydraulic lime (Youssef et al., 2015), various pozzolans (Dinh et al., 2012; Walker & Pavia, 2012) or combination of these (Barbieri et al., 2020; Rahim et al., 2016). In recent years, there is a growing interest on the use of geopolymer binders for the production of plant-based composites (Korniejenko et al., 2018; Narattha et al., 2022; Sáez-Pérez

et al., 2021). Among these, hemp-based composites (hempcrete, hemp-lime composites or hemp concretes) have gained increasing interest owing to the high strength and durability of hemp stems since the development of hemp composites at the beginning of 19th century. Hemp composite typically includes high volume of hemp shiv, wooden part of hemp stalk, which is highly porous and lightweight unique component (De Bruijn & Johansson, 2013). Thus, hemp composites become a lightweight insulation material having excellent thermal (Hussain et al., 2019; Somé et al., 2018), acoustical (Degrave-Lemeurs et al., 2018; Kinnane et al., 2016), and hydric (Latif et al., 2015; Walker & Pavía, 2014) properties. In addition, hemp composites were found to be carbon-negative construction materials which store higher amounts of CO_2 than they emit through their service life (Arehart et al., 2020).

Properties of hemp composites are mainly governed by size, porosity and proportion of hemp shiv used, type and proportion of binder used, water content, mixing procedure, size and shape of specimen, compaction method used in production, curing type, and age (Delhomme et al., 2020; Niyigena et al., 2018; Pavía, 2017). A wide density range of hemp composites produced via casting, spraying, blocks, or prefabrication can be used in the non-load bearing structures such as wall infilling, floor and roof insulation or insulating plasters and renders (Arnaud & Gourlay, 2012). The density of hemp composite is 200-500 kg/m^3 for using in walls, floors, and roofs (Amziane et al., 2013). Thermal conductivity of hemp composites generally has a range of 0.06 to 0.13 W/m.K varying with the density and composition of the mixtures (Daly et al., 2012). A detailed review on the properties of hemp-based composites can be found elsewhere (Barbhuiya & Bhusan Das, 2022; Demir & Doğan, 2020; Jami et al., 2019; Sáez-Pérez et al., 2020).

Industrial hemp cultivation has become one of the important areas that have been revamped and started to develop with the new regulations in Turkey, since 2016 (Official Gazette of the Republic of Turkey, 2016). Thus, it is expected that there will be an increase in the amount of waste industrial hemp stems in the near future. This study is the base of a project on the production and investigation of various properties of hemp composites which aims to utilize waste industrial hemp stems cultivated in Turkey. It should be noted that there are no domestic hemp shiv aggregate producers in Turkey. Therefore, hemp shiv used in this study was obtained from raw hemp stems after retting process (removal of fibers from hemp stems) in the laboratory. In addition, a property known binder, Portland cement, was used instead of lime- or hydraulic lime-based binders to observe the influence of production parameters. Twelve mixtures were prepared with varied proportions. The influence of production parameters such as hemp:cement ratio, size of hemp shiv, and hemp:water ratio on the physical and mechanical properties of hemp composites are presented.

2. Materials and methods

2.1. *Materials*

An ordinary Portland cement, CEM I 42.5 R complying with TS EN 197-1:2012 (TS EN 197-1, 2012) was used as sole binder. The specific gravity and Blaine fineness of the cement are 3.08 and 3500 cm^2/g, respectively. The oxide composition of the cement determined with x-ray fluorescence spectroscopy is given in Table 1.

Table 1. Oxide composition of the cement used.

Oxide	%
CaO	61.83
SiO_2	18.37
Al_2O_3	5.41
Fe_2O_3	3.20
MgO	2.35
SO_3	3.52
K_2O	1.13
Na_2O	0.21
Free CaO	0.95
Loss on ignition	3.30

Hemp shiv without bast fibers was used as an aggregate. Industrial hemp stems were obtained from industrial hemp plants cultivated in Turkey. The process of retting of hemp stems (removing fiber from stems) is given in Figure 1. The hemp stems used were in 2.5 m to 5.0 height (Figure 1-a). First, they were sawed into 30 cm length using a universal cutting machine (Figure 1-b). Then, the hemp stems were put in a container with a size of 40x60x25 cm (Figure 1-c). The container was filled with water having a mass of 20 times of the mass of hemp stems. A ceramic tile covered with a plastic sheet was put on the hemp stems for keeping hemp stems inside the water (Figure 1-d). Hemp stems were kept in the container in the laboratory at a temperature of 21±2 °C and were regularly checked for a condition of easy removal of bast fibers. This condition was reached after 21 days. Consequently, removal of fibers from stems (manual defibration) was more effortless and rapid. It should be noted that the duration and method of retting operation directly affects the physicochemical properties of the hemp shiv (Arufe et al., 2021).

Figure 1. Retting process of hemp stems: a) Industrial hemp stems with various lengths, b) Sawing hemp stems in pieces of ~30 cm, c) Sawed hemp stems in container before retting, d) Retting of hemp stems in the water filled container.

Figure 2 shows the process of obtaining bare hemp stems. The hemp stems removed from the water filled container is given in Figure 2-b. The smooth surface of the hemp stems after removal of the fibers can be seen clearly in Figure 2-a. The hemp fibers removed from the hemp stems is given in Figure 2-c. In this study, only hemp shiv was used, and remaining fibers were oven dried at 60 °C for 24 hours and kept for a different project.

Figure 2. The process of obtaining bare hemp stems: a) hemp stems without fibers, b) hemp stems kept in water filled container for 21 days, and c) hemp fibers removed from the stems.

Hemp stems without fibers were chopped using a laboratory cutting mill after drying at 60 °C for 24 hours. At this stage, chopped hemp shiv can be defined as aggregates. Then, hemp shiv was screened using 1 mm, 4 mm, and 8 mm sieves, and categorized as fine, medium, and coarse according to their length and width. Figure 3 shows the three different sizes of hemp shiv used in the study. The thickness of the hemp shiv increased with the increase of their length and varied between 0.1 and 5 mm. The physical properties of hemp shiv aggregates were determined according to the recommendations of the RILEM TC 236-BBM (Amziane et al., 2017). The bulk densities of hemp shiv aggregates are given in Table 2. The water absorptions of hemp shiv aggregates are presented in Figure 4. The increase in hemp shiv size leads to the dramatic increase in its bulk density and water absorption.

Figure 3. Hemp shivs used in the study a) fine, b) medium, and c) coarse.

Table 2. Bulk densities of the hemp shiv used.

Hemp shiv size	Fine	Medium	Coarse
Bulk density (kg/m^3)	247	166	134

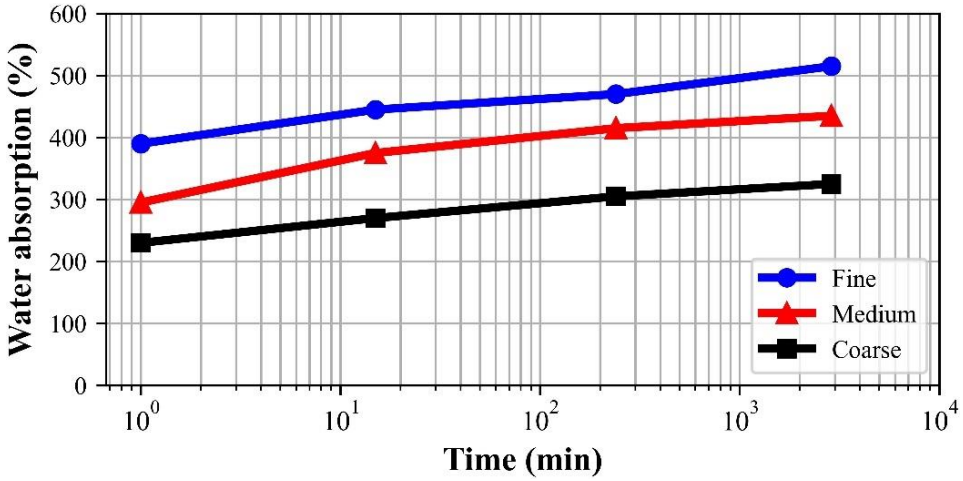

Figure 4. Water absorptions of hemp shiv aggregates used.

SEM analysis of hemp shiv aggregates is presented in Figure 5. A macro view of the hemp shiv aggregates used in the study is given in Figure 5-a. The longitudinal-sectional view is given in Figure 5-b and c. The micro fibrils on the surface can be seen, and these can positively affect the bond with binder and hemp shiv (Khorami & Ganjian, 2013). The SEM images of cross-sectional view of hemp shiv are given in Figure 5-b to f. The anisotropic honeycombed structure with different sizes of vessels can be seen clearly. The diameter of vessels varies between 10 to 100 micrometers. The thickness of the walls that separates the vessels is less than 1 micrometer. Overall, hemp shiv aggregates were found to be highly porous with a heterogeneous nature.

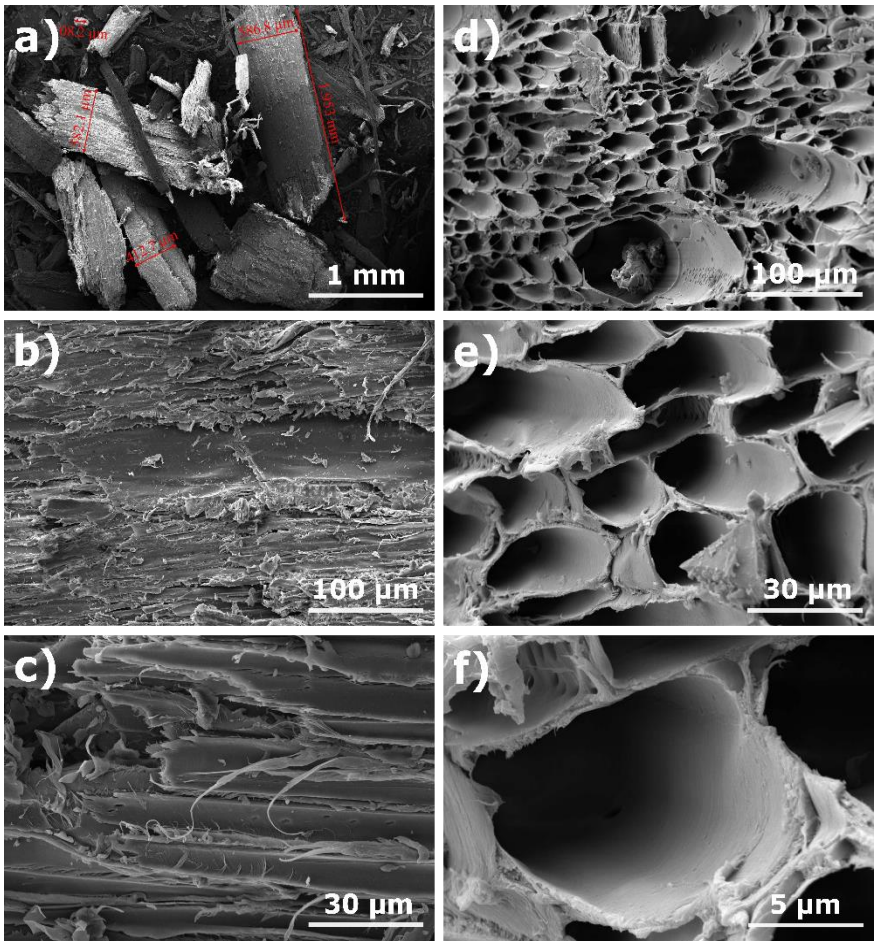

Figure 5. SEM images of hemp shiv: a) a macro view of fine hemp shiv aggregates (100x), b and c) longitudinal view of hemp shiv (800x and 400x), d, e and f) cross-sectional view of hemp shiv (1000x, 4000x and 15000x).

2.2. *Mixture proportions*

The mixture proportions used in this study is given in Table 3. In the design of mixture proportioning, volumetric ratios of ingredients were kept constant to observe differences of produced samples effectively. 12 different mixtures were prepared to explore the influence of hemp size, hemp:water and hemp:cement volumetric ratio on the physical, mechanical and microstructure properties of samples. The mixture identification of the produced samples indicates the size of the hemp shiv aggregate, volumetric ratios of hemp:cement and hemp:water. For example, HC6-HW3-C refers to the samples cast from the mixture with hemp:cement volumetric ratio of 6, hemp:water volumetric ratio of 3, and using coarse hemp shiv aggregates.

Influence of H:C ratios on the properties of hemp composites was investigated on Sample 1, 2, 3 and 4 produced using coarse hemp shiv aggregates. H:C ratios were varied between 4 and 47. In these mixtures, hemp shiv aggregate and water amount by weight and volume were kept constant, and cement amount decreased with increasing H:C ratio. Figure 6 presents the mixture proportion of a batch by volume and mass. Influence of the size of hemp shiv aggregates on the properties of hemp samples was investigated on two different sets of samples, Set 1 (Sample 10, 11 and 12) and Set 2 (Sample 3, 5, and 6), with H:W ratios of 2.5 and 3.0, respectively. The mixtures of these sample sets have same ingredient proportions by volume but are different by weight owing to the change in the bulk densities of hemp shiv aggregates. Influence of H:W ratio on the properties of hemp samples was investigated on three different sets of samples, set 1 (Sample 3, 7, 8, 9 and 10), Set 2 (Sample 5 and 11), and Set 3 (Sample 6 and 12), with hemp shiv grade of course, medium, and fine, respectively. The mixtures of these sample sets have the same amount of hemp shiv aggregates and cement by volume, and water amount by volume varied.

Table 3. Mixture Proportions.

No	MIX ID	Volumetric Ratio		Hemp Shiv Size	H:C:W Ratio (by volume)	H:C:W Ratio (by mass)
		H:C	H:W			
1	HC4-HW3-C	4	3.0	Coarse	1:0.75:0.33	1:5.8:2.5
2	HC5-HW3-C	5	3.0	Coarse	1:0.60:0.33	1:4.6:2.5
3	HC6-HW3-C	6	3.0	Coarse	1:0.50:0.33	1:3.9:2.5
4	HC47-HW3-C	47	3.0	Coarse	1:0.06:0.33	1:0.5:2.5
5	HC6-HW3-M	6	3.0	Medium	1:0.50:0.33	1:3.1:2.0
6	HC6-HW3-F	6	3.0	Fine	1:0.50:0.33	1:2.1:1.3
7	HC6-HW1.7-C	6	1.7	Coarse	1:0.28:0.59	1:3.9:4.4
8	HC6-HW2.1-C	6	2.1	Coarse	1:0.35:0.48	1:3.9:3.6
9	HC6-HW2.25-C	6	2.25	Coarse	1:0.48:0.44	1:3.9:3.3
10	HC6-HW2.5-C	6	2.5	Coarse	1:0.42:0.40	1:3.9:3.0
11	HC6-HW2.5-M	6	2.5	Medium	1:0.42:0.40	1:3.1:2.4
12	HC6-HW2.5-F	6	2.5	Fine	1:0.42:0.40	1:2.1:1.6

H: Hemp shiv, C:Cement, W:Water

2.3. *Mixture preparation*

The mixtures were prepared using a cement mixer. First, hemp shiv aggregates and 60 % of mixing water were mixed for 120 s. The chosen amount of cement was added to a bowl and mixed for 30 s. Then, the rest of the water which is 40 % of the mixing water, was added and mixed for 30 s. While the mixture was resting, the mixtures were scrapped from the sides and paddle in 30 s. Finally, further 150 s mixing was continued before casting. The total duration of mixing was 6 minutes. After mixing, mixture was immediately casted into cubes with a dimension of 50 mm x 50 mm x 50 mm in three layers and each layer was tamped 10 times. Samples were stored for one day at a temperature of 21±2 °C and relative humidity of 60±5 % and demolded. Samples were subjected to ambient curing at 21±2 °C and relative humidity of 60±5 % for 27 days. Figure 6 shows the preparation of hemp composite samples produced using coarse hemp shiv with hemp: cement ratio of 4, and hemp: water ratio of 3.0.

Figure 6. Preparation of hemp composite samples: a) weighted materials for mixture, b) hemp shiv mixed with 65% of mixing water, c) after addition of chosen cement amount, d) after mixing with the rest of water, e) casted samples in cubic molds, f) Casted samples named HC4HW3C.

2.4. *Methods*

The apparent density was determined using 50 mm cubic samples at the age of 28 days. The edge lengths of samples were measured with a digital caliper and volumes of samples were calculated. The ratio of mass to volume of sample's was presented as apparent density.

A 250 kN-capacity universal testing machine was used for compressive strength testing of samples. Three 50 mm cubic samples were used, and their average are presented as compressive strength. A loading rate of 30 N/s was used for the prevention of excessive loading. During the compressive test, a continuous deformation under compression load was observed for samples which made determination of strength difficult. Therefore, the failure loads were taken at a point where load-deformation curve ceases to be linear as described elsewhere (Walker et al., 2014).

The rate of water absorptions of samples were measured according to ASTM C1585 (ASTM C1585, 2013) with some modifications in sample size, timing, and conditioning. Three 50 mm cubic samples were used, directly after 28-days of curing at 21±2 °C and relative humidity of 60±5 %. In this test, only the bottom surface of the samples contacted with water of about 5 mm height. An insulation duct tape was used to seal sides of the samples to provide one-directional flow through the samples. The top surface of the sample was covered to prevent the evaporation of the absorbed water. The mass of the water absorbed was determined 1, 4, 9, 16, 25, 36, 49, 64, 81, 100, 126, 225, 425, 725, 1440, 2160, 2880, 5760, 7412, and 10080 minutes (up to 7 days) after the start of test. The water absorption was calculated as the increase in the mass of the test sample divided by the sample area and density water. The water absorption was calculated as follows in Equation (1).

$$I = \frac{\Delta m}{a.d} \quad (1)$$

where:
I: the water absorption, mm
Δm: the change in mass of the sample, g
a: area of the specimen, mm^2
d: density of water (g/mm^3)

Then, water absorption and square root of time ($s^{1/2}$) was plotted. The initial and secondary water absorptions were calculated from the linear regression analysis of the plot according to the recommendations of ASTM C1585-04. Finally, initial and secondary water absorptions were converted to $kg/m^2.h^{1/2}$ to compare to the existing literature.

Microstructure of samples were investigated by using scanning electron microscope (SEM) FEI, Quanta FEG 250. A piece with a dimension of about 1 cm was taken from the inner parts of the samples after their compressive strength determination. Prior to SEM, samples were oven dried at 40 °C for 24 hours and coated with gold-palladium in a high-pressure vacuum.

3. Experimental results and analysis

3.1. Microstructure

Figure 7 shows the SEM images of selected samples taken from hemp composites. It can be clearly seen from Figure 7-a to d that hemp shiv was well coated with cement paste. The longitudinal vessels of hemp shiv covered cement paste can be seen in Figure 7-a. Besides, there are also several unhydrated cement particles. This might be as a result of saccharides and organic acids from hemp shiv intervening with the hydration of cement (Guo et al., 2020; Wang et al., 2021). In Figure 7-b, voids on the longitudinal section of the hemp shiv can be seen. These voids might have been during the mixing, hence, in the raw hemp shiv no voids were observed in the longitudinal section. SEM analysis revealed the strong bonding at the cement paste and hemp shiv interface. This situation can be seen in Figure 7-c and d in which C-S-H products were formed around and over hemp shiv.

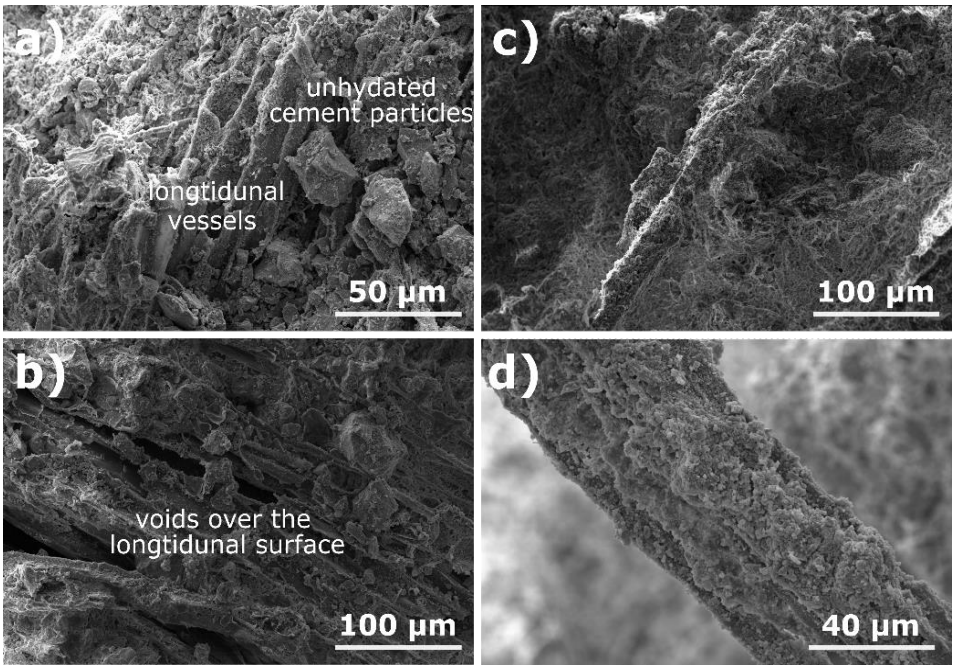

Figure 7. SEM images of hemp composites: a) transverse view of a section from Sample 2, b) longitudinal view of a section from Sample 9, c) a general view of section from Sample 11, d) a hemp shiv focused from Sample 12.

3.2. Apparent density

Figure 8.a shows the influence of hemp:cement ratio on the apparent densities of samples produced using coarse hemp shiv aggregates with hemp:water ratio of 3.0. Apparent densities of samples were in the range of 928-312 kg/m^3 for 4-47 H:C ratios. It is noteworthy to remind that with the increase of H:C ratio, the cement content decreases but the water and hemp shiv aggregate amount by volume were constant in the mixtures. Therefore, on account of increasing hemp shiv aggregate in the volume and decreasing cement paste weight in the samples, apparent densities of samples decreased with the increase of H:C ratio. The reduction in the apparent density of samples was about 66 % for the increase of H:C ratio from 4 to 47. The cement proportion decreased about 80 % and 90 %, while hemp shiv aggregate proportion increased about 133 % and 17 % by weight and volume with the increase of H:C ratio from 4 to 47, respectively. Therefore, it can be seen that apparent density is mainly governed by the volume of hemp shiv aggregates for these samples. Besides, the stickiness of mixtures decreased with increase of hemp content and decrease of cement content leading to the recovery of some compacted mixture. As a result, volume of samples increased with the increase of hemp content.

Influence of hemp size on the apparent densities of samples with hemp:binder ratio of 6 and hemp:water ratios of 2.5 (Set 1 – Sample 12, 11, and 10) and 3.0 (Set 2 – Sample 6, 5, and 3) are presented in Figure 8-b. The apparent densities of samples were varied between 596 and 856 kg/m^3. Apparent densities of samples increased with the increase of hemp size from fine to coarse regardless of hemp:water ratio, conflicting with the findings of (Arnaud & Gourlay, 2012; Stevulova et al., 2012). Arnaud and Gourlay (Arnaud & Gourlay, 2012) observed an increase in dry density with increasing size of hemp shiv. Stevulova et al. (Stevulova et al., 2012) reported higher density for composites produced using shortest hemp shiv among three different length of hemp shiv. In this study, the main reason of this behavior is the differences in the mixture proportions. The cement and water mass proportions increased about 11 %, and hemp shiv aggregate mass proportions decreased 40 % with the increase of hemp size from fine to coarse. It should be noted that an increase in the hemp size decreases both bulk density and the total surface area of hemp shiv. Thus, cement paste content around the surface of hemp shiv was relatively high for coarse hemp shiv than their counterparts with fine and medium hemp size grades. Furthermore, the stickiness of the mixtures increased, and samples with coarse hemp shiv were compacted relatively much more effectively than those with fine hemp shiv even though a similar compaction effort was applied.

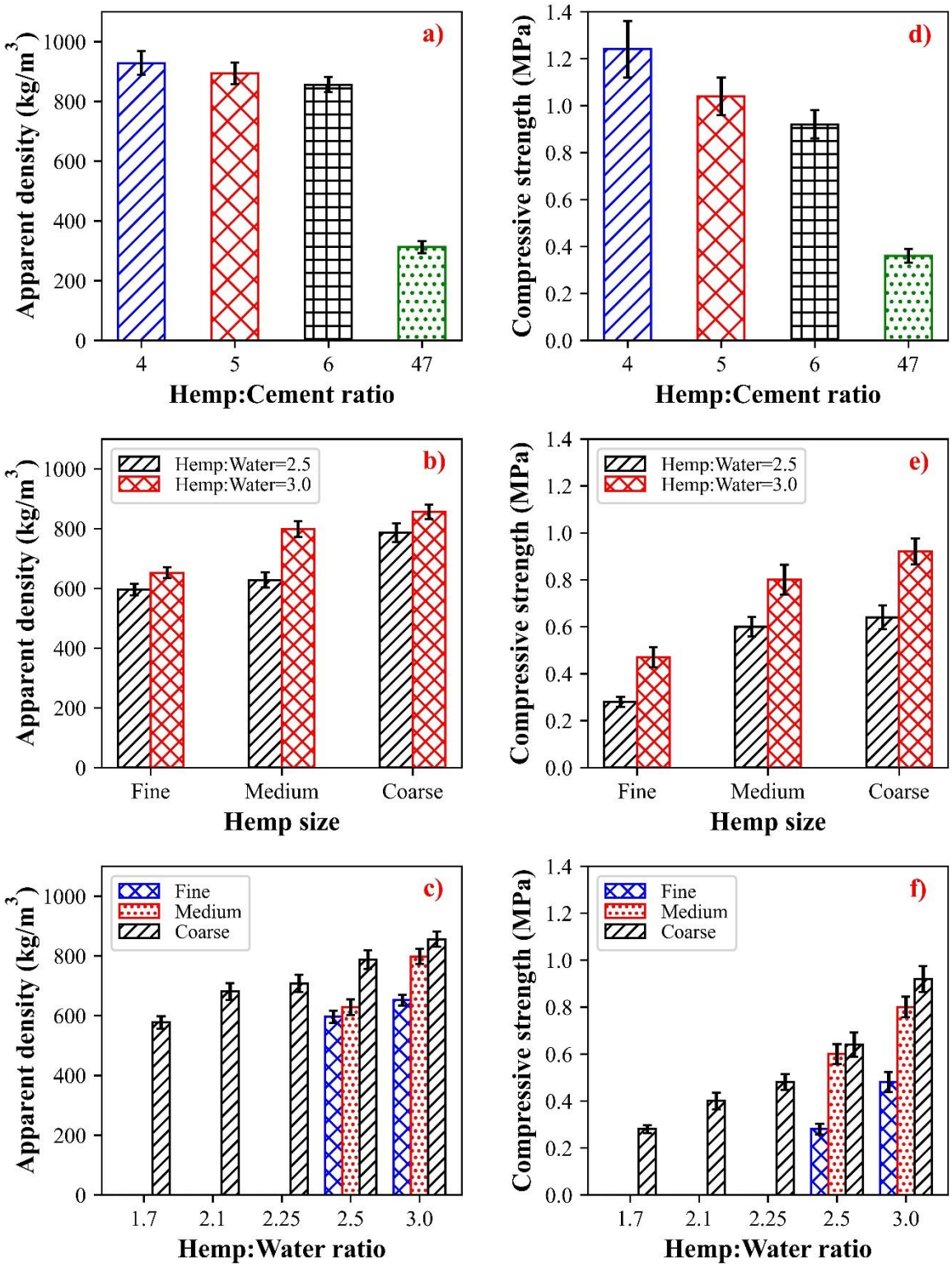

Figure 8. Influence of hemp:cement hemp:water ratio, and hemp size on the apparent density and compressive strength of hemp composites.

Figure 8-c demonstrates the influence of hemp:water ratio on the apparent densities of samples with different hemp sizes. The range of apparent densities of samples were found to be between 577 and 856 kg/m^3. It can be clearly seen that an increase in the H:W ratio leads to an increase in the apparent densities. The apparent densities of samples with H:W ratio of 1.7 were found to be about 48 % lower than those of samples with H:W of 3.0 produced using coarse hemp shiv. It should be noted that an increase in the H:W ratio by volume causes reduction in water/cement mass ratio leading to the increase in the mass of the cement paste. Therefore, apparent density of mixtures increases, consistent with the prior literature (Dhakal et al., 2017). Similar density reduction can also be seen between samples with H:W ratio of 2.5 and 3.0 produced using fine and medium hemp shiv. Apparent densities of samples produced using fine, medium, and coarse hemp shiv increased about 10 %, 27 %, and 9 % with the increase of H:W ratio from 2.5 to 3.0, respectively. In addition, the sharp rise in the apparent densities of samples produced using medium hemp shiv aggregates might be attributed to the advances in compactability of mixtures.

3.3. Compressive strength

Influence of hemp:cement ratio on 28-day compressive strength of samples produced using coarse hemp shiv aggregates with hemp:water ratio of 3.0 is presented in Figure 8-d. The compressive strengths of samples were varied in the range of 0.36 MPa and 1.24 MPa. There is an inverse relation between the H:C ratio and compressive strength of samples. The compressive strength of samples with H:C ratio of 4 was found to be about four-fold of those of samples with H:C of 47. Main reasons of this behavior might be a decrease in the cement content and an increase in the hemp content of samples with increasing hemp:cement ratio which also leads to a dramatic reduction in density. Arnaud and Gourlay (Arnaud & Gourlay, 2012) reported similar findings for hemp composites produced using different types of binders. Dramatic influence of the hemp increase on the strength was also stated elsewhere (Sonebi et al., 2015). It is also important to mention that with the increase of H:C ratio, fracture behavior of hemp composites became more ductile owing to the increase of hemp content which prevents binder's brittleness (Benfratello et al., 2013; Murphy et al., 2010).

Figure 8-e shows the influence of hemp size on 28-day compressive strength of samples with H:W ratio of 2.5 and 3.0. The samples produced had a compressive strength of 0.28 MPa to 0.92 MPa. There is a distinct increase in the compressive strength with the increase of hemp size regardless of the H:W ratio. The compressive strengths of samples produced using medium and coarse hemp shiv aggregates with H:W ratio of 2.5 are about 214 % and 229 % higher than their counterparts produced using fine hemp shiv aggregates, respectively. Similarly, with the increase of hemp size from fine to medium and coarse, the compressive strength of the samples with H:W ratio of 3.0 increased 169 % and 194 %, respectively. This behavior thought to be due to the increase of cement paste amount around the surface of hemp shiv as a result of dramatic decrease in the surface area of hemp shiv with increasing hemp shiv size. It is also important to state that the volume of hemp shiv is similar in these samples. There are different observations in the literature on the effect of particle size distribution and size of hemp shiv on compressive strength. Results of this research conflicts with the findings of Niyigena et al. (Niyigena et al., 2015) who obtained higher mechanical properties with the decrease of hemp particle size, but it should be noted that two different types of hemp shiv were used in that study. Stevulova et al. (Stevulova et al., 2013) found an increase in compressive strength with the increase of hemp particles. On the other hand, lower mechanical properties at early ages and higher final mechanical properties at later ages were reported for hemp composites produced with finer hemp shiv than those of coarse (Arnaud & Gourlay, 2012). Williams et al. (Williams et al., 2018) stated no correlation between particle size and compressive strength of hemp-lime composites.

The influence of hemp:water ratio on 28-day compressive strengths of samples with different hemp sizes are provided in Figure 8-f. The compressive strengths of samples were varied between 0.28 MPa and 0.92 MPa. Regardless of hemp size, compressive strengths of samples increased with the increase of H:W ratio. A substantial strength gain, about 130 %, was observed with the increase of hemp:water ratio of 1.7 to 3.0 for samples produced using coarse hemp shiv. In addition, strength gain was about 69 %, 34 %, 44 % for samples produced using fine, medium, and coarse hemp shiv aggregates with the increase of H:W ratio from 2.5 to 3.0, respectively. These might be as a result of decreasing water content of mixtures with the increase of H:W ratio, consistent with the prior literature (Mardani-Aghabaglou et al., 2020; Singh et al., 2015).

3.4. Relation between compressive strength and apparent density

Figure 9 presents the relation between 28-day compressive strength of samples and apparent density. A strong relation between the density and compressive strength is apparent, consistent with the prior literature (Elfordy et al., 2008). This relation becomes more obvious when some of the date is excluded (Sample 1, 4, and 11 – red diamond markers) as seen in the Figure 9.

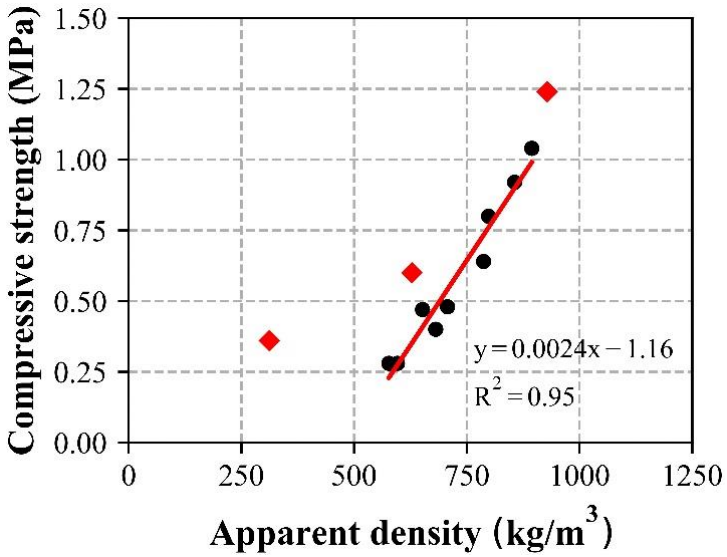

Figure 9. Relation between 28-day compressive strengths of samples and apparent density.

Compressive strengths of samples varied between 0.28 to 1.24 MPa in the apparent density range of 312 and 928 kg/m^3. There are explicit differences in the relation between apparent density and compressive for some of the samples. For instance, the apparent density of Sample 7 was 84 % higher than Sample 4 but Sample 7 exhibited the lowest compressive strength of about 0.28 MPa which is 22 % lower than Sample 4. This result may be expected owing to the higher water-to-cement ratio of sample 7, which was about two-fold of Sample 3. On the other hand, samples with higher apparent density exhibited the highest compressive strength, as expected. The compressive strengths of samples were found comparable in the similar range of density with those of hemp composites produced using cement in the existing literature (de Bruijn et al., 2009; Sassu et al., 2016). However, some studies reported much higher compressive strengths than strength range of this study using different binders and production methods in a lower density range. For instance, Sassoni et al. (Sassoni et al., 2014) reported 1.15 MPa and 3.04 MPa compressive strength for densities of 330 and 640 kg/m^3 hemp composites produced using MgO-based binders.

3.5. Water absorption

The initial and secondary rate of water absorption of samples, and apparent density of samples are presented in Figure 10. It can be seen from the results that the initial and secondary rate of water absorptions of samples were found to be quite different. There is no explicit relationship observed between the initial and secondary rate of water absorptions. To clarify, Sample 4 exhibited the highest initial and secondary water absorptions, and Sample 6 exhibited the lowest initial and secondary absorptions; however, there are much more differences in the relation of the initial and secondary water absorptions for the rest of the samples.

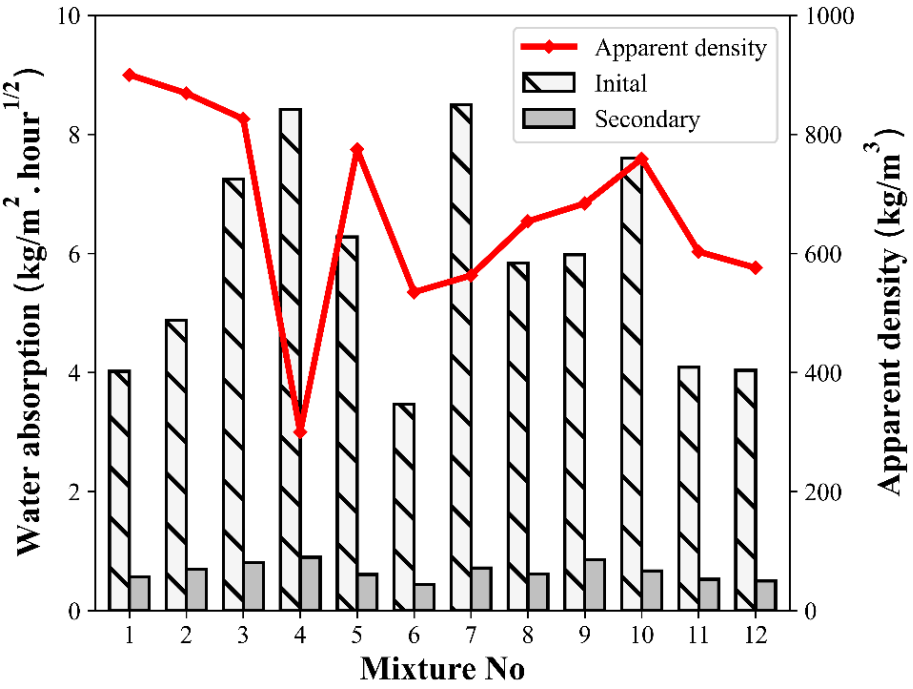

Figure 10. Relation between initial and secondary rate of absorption with apparent density.

The initial and secondary rate of water absorption of samples were in the range of 3.47 and 8.50 kg/m^2.h$^{1/2}$ and 0.44 and 0.90 kg/m^2.h$^{1/2}$, respectively. The ratio of initial to secondary absorption were varied between 7.0 and 11.8 for the samples. Table 4 provides the former research on water absorption of hemp composites of different densities produced with common binders which ranges from 0.8 to 9.0 kg/m^2.h$^{1/2}$. It is common to observe distinct differences in water absorption of hemp composites even if specimens are a similar density range. This can be explained by the differences in test conditions, curing regime, production methods, type of binder and hemp shiv used. Furthermore, the initial rate of water absorption of hemp composites produced were higher than those of cement-based composites (de Bruijn et al., 2009), owing to the use of a highly porous material namely hemp shiv in the production of hemp composites.

Table 4. Water absorptions of hemp composites from prior literature.

Reference	Density (kg/m^3)	Binder type	Water absorption (kg/m^2.h$^{1/2}$)
Walker and Pavia (Walker & Pavía, 2014)	360	Lime+GGBS/Metakaolin/NHL	2.65-3.37
Bruijn et al. (de Bruijn et al., 2009)	587-733	Lime, Lime+NHL, Cement	~2.30
Page et al. (Page et al., 2017)	250	Tradical (Commercial binder)	~1.80
	350		~2.10
	380		~2.30
	400		~0.90
Brzyski et al. (Brzyski et al., 2020)	377	Lime+Metakaolin	8.82
	382		7.27
Evrard (Evrard, 2008)	960	Tradical (Commercial binder)	4.42±0.27
Del Valle-Zermemo et al. (Del Valle-Zermeño et al., 2016)	600	Mg Phosphate Cement	~4.20
	697		~2.40
	1425		~0.80
Seng et al. (Seng et al., 2019)	446	Lime + Metakaolin	8.40

4. Conclusions and comments

This study investigated the production, physical and mechanical properties of hemp composites produced using hemp shiv aggregates obtained from Turkish industrial hemp stems. The following conclusions were reached:

1. The apparent densities of hemp composites varied from 312 to 928 kg/m^3. Hemp:cement ratio dominated the apparent densities of samples. The influence of hemp:water ratio and size of hemp shiv aggregates on the apparent density were found to be negligible.
2. Compressive strengths of hemp composites ranged between 0.20 and 1.24 MPa and governed by hemp:cement ratio and hemp:water ratio. In addition, sizes of hemp shiv aggregates were found be effective but not as hemp:cement and hemp:water ratios.
3. The initial and secondary rate of water absorption of samples were in the range of 3.47 and 8.50 kg/m^2.h$^{1/2}$ and 0.44 and 0.90 kg/m^2.h$^{1/2}$, respectively. The significant parameters for capillary absorption were found to be hemp:cement ratio and size of hemp shiv aggregates. An increase in these parameters has a negative effect on capillary absorption.
4. Lightweight hemp composites can be produced in a wide density range by turning waste industrial Turkish hemp stems into hemp shiv aggregates.

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