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Implementation on a Preparation and Controlled Compaction Procedure for Waste-Fiber-Reinforced Raw Earth Samples

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Abstract: Earth bricks are a traditional eco-friendly construction material. In this study, harbor-dredged sediments were used along with hemp shiv to develop a brick manufacturing procedure and compaction techniques to produce durable earth bricks for the valorization of waste hemp shiv and dredged sediments. Prismatic specimens of size $4 \times 4 \times 16$ cm^3 were manufactured with Dunkirk sediments after analyzing their suitability for earth bricks according to the French standard for flexural strength test to observe the indirect tensile strength and impact of the compaction techniques on the strength of bricks. Crude bricks were manufactured with varying hemp shiv content from 0% to 5% by mass. Compaction techniques such as dynamic compaction, static compaction, and tamping were applied. The effect of hemp shiv content and compaction techniques was evaluated with a flexural strength test and the distribution of fibers in bricks. Grain size analysis of sediments with French and Spanish standards shows that the sediments granulometry is suitable for earth bricks. The flexural strength testing of bricks indicates that bricks with saturated hemp shiv have higher flexural strength. Earth bricks have maximum strength with dynamic compaction with 1% hemp shiv, which satisfies the adobe bricks tensile strength requirements that vary from 0.012 to 0.025 MPa (NZS 4298, 1998; NORMA E.080 (2017).

Keywords: dredged sediments; hemp shiv; reinforced mud bricks; compaction

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1. Introduction

Earth bricks are a low-cost building material and are widely used in developing countries. Nearly one-third of the world's population lives in earth buildings [1,2]. The importance of earth bricks is increasing due to high energy consumption and CO_2 emissions by construction materials such as concrete, cement, and fired bricks. The energy consumption of the building sector is 44% in France [3]. Thermal insulation is another problem associated with concrete and fired bricks. Therefore, thermally stable construction materials such as earth bricks with the minimum use of energy during their manufacturing process are helpful to limit environmental concerns.

Sediments are dredged from seaports and rivers. Dredged sediments are generally dumped in the sea or stored on land sites. Environmental concerns have forced authorities to use these sediments in different applications such as landfills, beach nourishments, roads, ceramics, etc. [4,5]. The mixing of fine dredged sediments with dredged sand increases the bearing capacity and makes the grain size distribution suitable for use as a base course material in road construction [6]. Dredged sediments can be used for manufacturing bricks by partially or fully replacing raw materials used.

For sediments reuse in crude bricks, analysis of sediments characteristics is essential, which helps to decide the suitability of sediments for crude bricks. In the case of polluted sediments, treatment of sediments becomes necessary before their use.

Sediments' suitability for crude bricks can be observed with Atterberg limits, optimum moisture content, and mineralogy [7–9]. The recommended limit for the plasticity index and liquidity limit for earth bricks are in the ranges of 16–18% and 32–46%, respectively [10]. The optimum moisture content of sediments helps to define molding moisture content. A higher amount of water causes shrinkage and decreases the tensile strength of crude bricks [11].

The minimum clay content for crude bricks in most of the applications is 5%, and the silt content varies from 10% to 25% for compressed earth blocks [10]. A higher percentage of clay produces shrinkage in bricks [12]. The organic matter, carbonate content, and pH of sediments are some of the other useful characteristics of sediments for their use in bricks [13].

Along with the sediments, natural fibers are another important raw material used for bricks reinforcement. Palm oil fibers, coconut fibers, banana fibers, hemp, jute, and sugarcane bagasse are some common waste fibers. The incorporation of these fibers with soil to make crude bricks has been studied by various researchers. [2,14–16]. Natural fibers increase the tensile strength, shear strength, durability, and improve the thermal insulation characteristics of bricks. Natural fibers reduce the density of the brick as well as minimize the shrinkage and cracks growth [17,18].

The fiber content used for crude bricks is taken by mass or by volume. The quantity of fibers used varies from 1 to 7% by mass depending on the type of fiber [14,19,20]. The higher quantity of fibers decreases the mass, density, tensile strength, and cohesion between the particles. Fibers prevent the spalling and distortion in crude bricks [18]. Fibers cluster inside the crude bricks, decreasing the brick's strength, and it is mainly associated with a higher fiber content and the mixing procedure [21]. The common range of natural fibers length is 2 to 10 cm. The length of natural fibers depends on the type of natural fiber and extraction procedure used [14,22].

Sediments and fibers are usually mixed with optimum molding moisture content to make crude bricks [23–25]. Increasing the fiber content also requires additional water to improve workability [13], as a higher fiber content reduces the dry density of sediments and fiber matrix and increases their optimum moisture content [26]. A higher amount of water makes the compaction and demolding of bricks difficult, while with low water content, friction between the soil particles is high and disturbs the compaction. The molding moisture content varies with the type of soil [27]. Axial shrinkage, cracks development, and a decrease in the tensile and compressive strength are related complications with a higher amount of molding moisture content [11,28].

The mixing of sediments and fibers is usually done with mixing machines. Mixed sediments are molded into different sizes of cubic and prismatic molds.

The compaction method has a significant influence on the compressive and tensile strength of crude bricks. The dynamic compaction of bricks increases the compressive and flexural strength of bricks by nearly 80% and 42%, respectively, when compared to reference samples without compaction [29]. The compaction of bricks decreases vertical deformation with applied load to the earth structure. It decreases permeability and increases the strength of earth blocks [24].

The compaction of bricks is followed by drying. Drying of bricks can be done by either sun drying or oven drying. Sun drying is an economical and eco-friendly method, and it takes a few days to a few weeks depending on the weather condition of a particular region [20,30].

Crude bricks characteristics include tensile strength, toughness, compressive strength, water absorption, density, and shrinkage. The flexural tensile strength of reinforced crude bricks ranges from 0.04 to 2.05 MPa [31]. The failure mechanism in unreinforced adobe materials is brittle. Fibers addition in crude bricks transforms their behavior to ductile, and the stress–strain curve becomes less steep [26,32]. Bricks failure under compression for unreinforced crude bricks is similar to the failure mode of concrete [33].

Fibers in mud bricks are distributed in transversal and longitudinal directions. The fibers' orientation and distribution depend on each fiber's length, the fiber content, the molding process, and compaction. The orientation of fibers is generally suitable with fibers of short length [34]. Fibers prevent bricks from spalling by holding the chunks of bricks. Longitudinal distribution of fibers is desired as it contributes substantially to the tensile strength of bricks [18]. Natural fibers have low thermal conductivity, and the addition of natural fibers decreases the thermal conductivity of crude bricks and makes them a suitable choice for bricks [14].

Crude bricks have also some drawbacks such as mechanical strength limitation, rapid weathering, durability, and fiber sensitivity to humidity and water [35]. The addition of binder and fibers treatment can help to limit these problems, but these materials have their own cost and environmental concerns. [36].

Earth bricks are usually made from soil mined from quarries and natural fibers from different plants such as date palm fibers, coconut fibers, banana fibers, jute fibers, sugarcane fibers, etc. [2,14–16,21].

However, there is limited work on recycling dredged sediments due to the complex nature of sediments i.e., the presence of contaminants and dehydration of sediments before their use. Sediments recycling in different applications such as concrete, fired bricks, roads, embankments, and earth bricks has become essential due to environmental regulations to dispose of these sediments. The recycling of sediments in adobe bricks is eco-friendly and valorizes dredged sediments along with plant waste.

The objective concerns the implementation of preparation under a controlled procedure to manufacture waste-fiber-based reinforced raw earth bricks to recycle waste-dredged sediments from Dunkirk port along with hemp shiv after analyzing their characteristics and suitability for bricks. The minimum use of energy and non-renewable resources for making crude bricks from dredged sediments makes them suitable as an ecological construction material.

2. Materials and Methods

2.1. Dunkirk Sediments

Sediments from Dunkirk port were used in this study. In Dunkirk port (north of France), 3 million tons of sediments are dredged annually [37]. The sediment's physical and chemical characteristics such as Atterberg limits, grain size, optimum moisture content, carbonate content, methylene blue value, etc. were determined with different tests by using French standards to use them in crude bricks. The grain size distribution of Dunkirk sediments was found with laser granulometry by using the French standard AFNOR NF X31-107 [38]. The clay, silt, and sand contents of these sediments are shown in Table 1, and their granulometric curve is shown in Figure 1.

Table 1. Dunkirk sediments characteristics.

Sediments	Clay (%)	Silt (%)	Sand (%)	$CaCO_3$ (%)	W_{opt} * (%)	OM * (%)	MBV * (g/100 g)	pH	LL (%)	PL (%)
DK	4.3	24.8	70.9	13.3	20.5	5.29	0.6	8.4	18.9	8.2

* OM = organic matter, W_{opt} = optimum water content, MBV = methylene blue value.

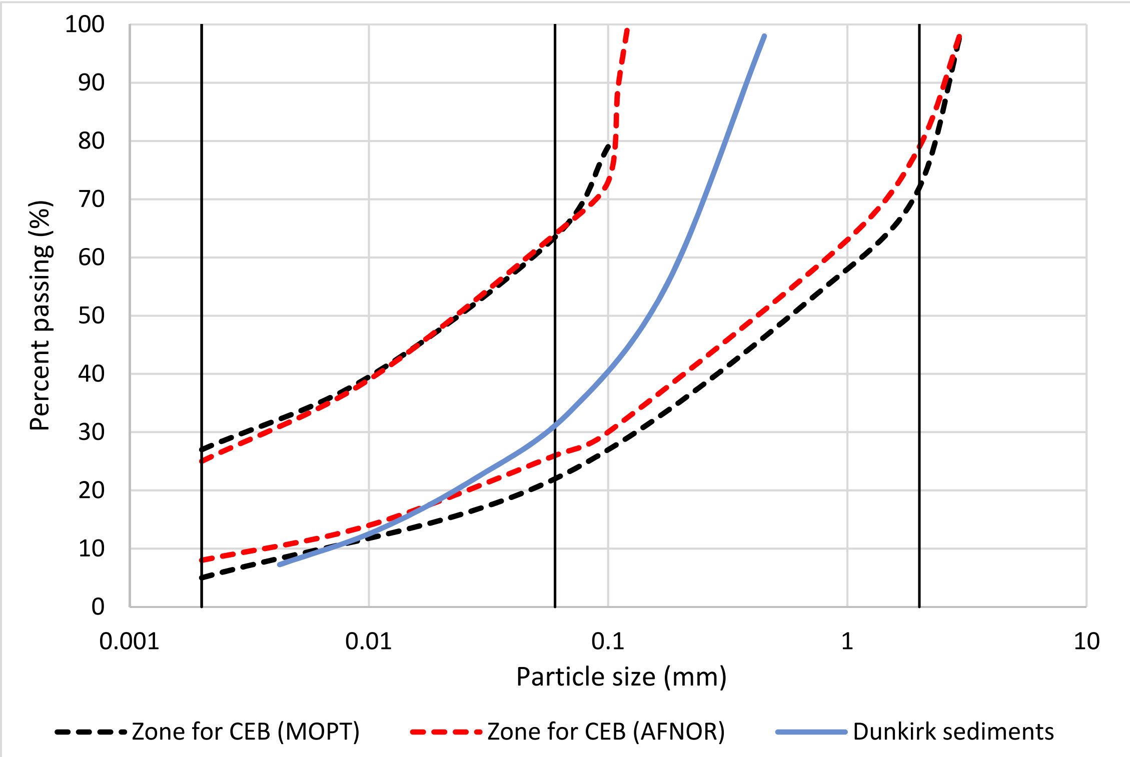

Figure 1. Sediments suitability for bricks. Note: CEB = compressed earth blocks.

Atterberg limits of sediments were found according to the French standard, AFNOR NF EN ISO 17892-12 [39]. The optimum water content was found with the standard Proctor test with a compaction energy of 600 kJ/m^3. Organic matter was found by burning the sediments at 550 °C according to the French standard, XP P 94-047 [40].

The carbonate content of sediments was found with the Bernard calcimeter method according to the French standard NF ISO 10694 [41].

Dunkirk sediment's characteristics determined by testing in the M2C lab Caen are summarized in Table 1.

Figure 1 is based on the French and MOPT standard, and it shows the sediment's suitability based on their grain size distribution for manufacturing crude bricks according to French standard [7] and Spanish standard, MOPT [42]. The red dotted line in Figure 1 shows the zone suitable for adobe bricks recommended by the AFNOR standard, while the black dotted line indicates the zone suitable for bricks recommended by the Spanish standard, MOPT. The recommended zones are based on the grain size of the soil. The Dunkirk sediments grain size distribution is plotted in blue color in Figure 1. It can be observed from Figure 1 that Dunkirk sediments lie within the zone recommended for adobe bricks, which means that their grain size distribution is suitable for earth bricks.

2.2. Hemp Shiv

Hemp shiv is a plant waste obtained from the hemp stalk. To use hemp shiv as a raw material along with Dunkirk sediments for manufacturing crude bricks, the characteristics of hemp shiv such as length, thickness, and water absorption were studied. The hemp shiv is shown in Figure 2A. The length and thickness of hemp shiv were found with ImageJ software. Hemp shiv was spread on a plain sheet, as shown in Figure 2B and treated with ImageJ software. Figure 2C shows the treated images of hemp shiv.

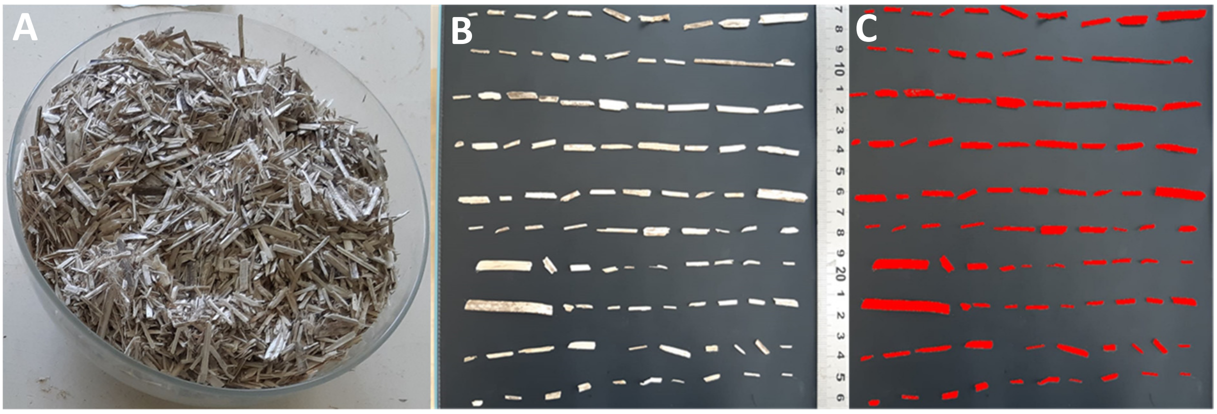

Figure 2. Raw hemp shiv fibers (**A**), length and thickness calculation of fibers (**B**,**C**).

Hemp shiv length varies from 2 to 20 mm. Hemp shiv length variation is shown in Figure 3A. Figure 3B shows the length and thickness distribution of both fine and coarse hemp shiv particles.

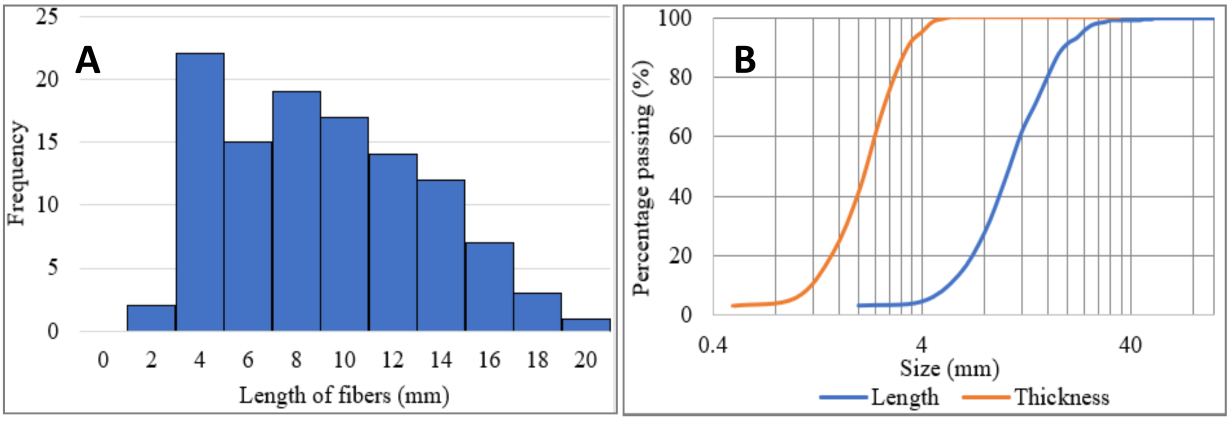

Figure 3. Length of hemp shiv (**A**), length and thickness distribution (**B**) of hemp shiv.

Water absorption is another important property of natural fibers for their use in bricks. The water absorption of hemp shiv was found by immersing the hemp shiv in distilled water for 48 h. Fibers were rotated in a perforated container, 100 times with two revolutions per second to remove the water on the surface of the fiber. The water absorption coefficient was measured at intervals of 30 min and 1, 4, 24, and 48 h to see the evolution of fiber water absorption.

The length, thickness, and water absorption of hemp shiv are presented in Table 2.

Table 2. Characteristics of hemp shiv.

Average Length (mm)	Average Thickness (mm)	Water Absorption (%)
11.7	2.24	298

2.3. Manufacturing of Crude Bricks

Crude brick manufacturing consists of mixing of sediment and fibers, molding, compaction, and drying. The manufacturing steps of bricks are explained in Figure 4. Figure 4A shows the raw material and electric mixer used for mixing, Figure 4B shows the mixing of sediments and hemp shiv, Figure 4C shows the dynamic compaction of bricks. Figure 4D shows the natural drying of bricks, and Figure 4E shows the tensile testing of bricks.

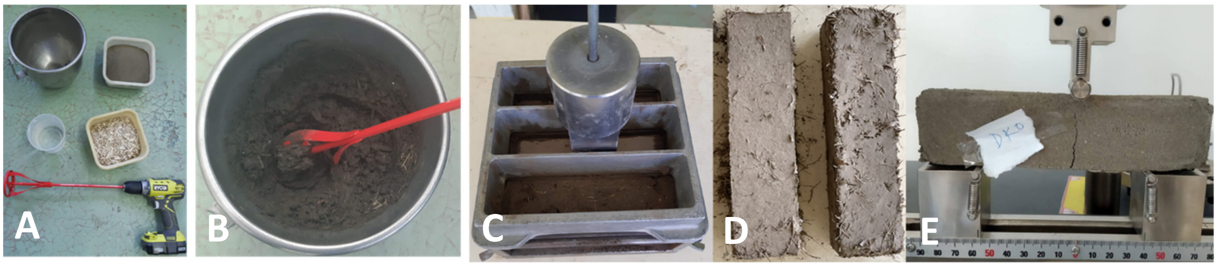

Figure 4. Raw materials (**A**), mixing (**B**), compaction (**C**), drying (**D**), and bricks testing (**E**).

Dunkirk sediments were dried in the oven for 24 h to remove water and humidity. Dried sediments were crushed, grinded, and passed through a 2 mm sieve. These sediments were mixed with dry hemp shiv content of 0%, 1%, 2%, 3%, 4%, and 5% by mass of sediments, which is a common range for natural fibers addition in adobe bricks [14,19,20]. Sediments and hemp shiv were mixed with optimum moisture content to make a homogenous mixture [11].

The water absorption coefficient of hemp shiv was respected to make a good mixture. Similarly, Dunkirk sediments were mixed with saturated hemp shiv to make bricks. In the case of saturated hemp shiv, hemp shiv was immersed in distilled water for 24 h to become fully saturated before their use.

Optimum water content found with the Proctor test was used as molding moisture content to mix sediments and hemp shiv, as it permits the optimal compaction. Distilled water was used to avoid the effect of water impurities.

The mass of hemp shiv was found with the mass of sediments and hemp shiv content by using Equation (1).

$$m_{\text{hemp shiv}} = \frac{m_{\text{sed}} * \%\text{hemp shiv}}{100} \quad (1)$$

where $m_{\text{hemp shiv}}$ = mass of hemp shiv, m_{sed} = mass of sediments, and $\%_{\text{hemp shiv}}$ = hemp shiv content.

Hemp shiv was mixed with sediment with molding moisture content. Molding moisture content was found with the standard Proctor test. The mass of water used for bricks was calculated with Equation (2) for dry hemp shiv.

$$m_{\text{water}} = \frac{m_{\text{sed}} * \%\text{ of water}}{100} + m_{\text{hemp shiv}} + \text{Ca} \quad (2)$$

where $m_{\text{hemp shiv}}$ = mass of hemp shiv, Ca = water absorption coefficient of fibers, and m_{sed} = mass of sediments. A mass of 450 g of dry sediments was used for each brick specimen according to the French standard, AFNOR EN 196-1 [43]. For saturated hemp shiv, Ca is taken as zero, as fibers are already saturated before their use.

The machine mixing of sediments and fibers allows making a homogenous mixture rapidly. Therefore, Dunkirk sediments mixing with hemp shiv was done with an electric mixer for 5 min. Initially, dry sediments are poured in a steel bowl, then hemp shiv was added, and finally, water was added. This sequence helps to avoid the clinging of wet sediments on the bottom of the bowl. The sediment's mixture was molded into prismatic specimens of size 4 × 4 × 16 cm^3, which is commonly used for mortar, AFNOR NF EN 1015-11 [44].

2.4. Compaction of Crude Bricks

The compaction of sediment mix was done with static compaction, dynamic compaction, and tamping. For static compaction, dynamic compaction, and tamping, wooden, steel, and polystyrene molds were used, respectively. For static compaction and tamping, the mold was filled to the top with one layer. While in the case of dynamic compaction, molds were filled into two layers.

Dynamic compaction of sediments mixture was achieved through falling mass with compaction energy of 600 kJ/m^3 i.e., normal Proctor energy. This energy is less than the energy applied by the hydraulic block-making machine, which applies a 1.6 MPa compressive load for the 30 s to compress the earth bricks [45]. Bricks in dynamic compaction were compacted in two layers with repeated strokes. Initially, the first layer was made by filling the mold with sediment mixture and compacted with the hammer and wooden plate at the top of sediments to achieve 2 cm height. Scratched and grooves were made at the surface of the first layer to make it rough, which increases the bonding between two layers. After compaction, each layer has an approximate length of 2 cm. To facilitate the compaction and energy calculation, the wooden plate at the top of the sediments mix used for compaction is divided into 4 parts with 7 zones, which show hammering patterns, as shown in Figure 5.

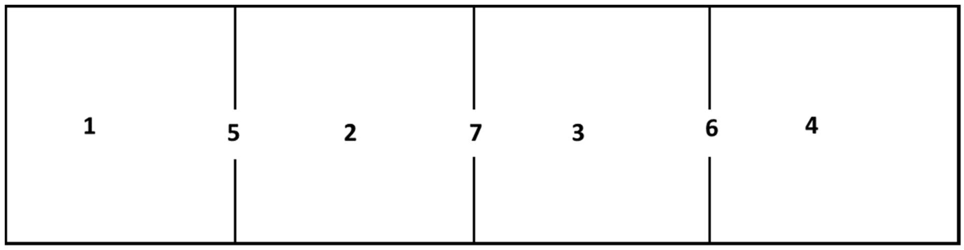

Figure 5. Compaction plane of mud bricks.

Dynamic compaction tool for crude bricks can be observed in Figure 6A.

Figure 6. Bricks dynamic compaction (**A**), sieve shaker (**B**), and static compaction(**C**).

Static compaction is a simple and easy compaction technique. For laboratory-scale testing, we have considered a 50 kg load for static compaction due to the better results and ease of handling after several trials between 10 and 50 kg load. Static load was applied for 4–5 h. In static compaction, it is difficult to control the final height of bricks. To attain the desired brick height, a thin layer of sediments mix was added at the top of the brick surface, and compaction load is applied again. The process is repeated until the desired height is achieved. In case of excessive height, the top surface is removed [21]. Crude bricks compaction through static loading is shown in Figure 6C.

Tamping of bricks was done manually. Polystyrene molds were filled with sediments and hemp shiv mix. A few millimeters thick layer of sediments was added at the top of the mold to meet height criteria as the height decreases with compaction. Ten strokes were applied to each brick specimen. The striking direction was changed after 5 strokes for uniform compaction; i.e., 5 strokes were applied from both ends of the bricks.

Shock table is another common compaction method. Due to the unavailability of the shock table, compaction was done with the sieve shaker machine. Crude bricks compaction by the sieve shaker machine can be seen in Figure 6B.

After compaction, the bricks samples were dried in the oven at 60 °C. Natural drying was also performed on some samples in the laboratory at room temperature (20 °C ± 2 °C) to observe the drying pattern. Oven drying of bricks takes 2–3 days, while air drying is achieved in two to three weeks depending on the weather condition.

3. Testing of Bricks

3.1. Flexural Strength of Bricks

A flexural strength test was performed on oven-dried prismatic earth bricks specimens of size 4 × 4 × 16 cm^3 with a three-point bending test to observe the flexural strength (indirect tensile strength) of bricks by using a Shimadzu AGS-X machine with a 50 kN sensor [46].

Bricks testing and the load–deflection curve for crude with dynamic compaction with 3% hemp shiv content are shown in Figure 7A–C. The propagation of rupture during the tensile strength test can be observed in Figure 7B. The testing and rupture surface for crude bricks from Dunkirk sediments is shown in Figure 7A,B. The behavior of the load–deflection curve is initially elastic; then, plastic stages come, and finally, the maximum load is achieved. Post-peak load decreases gradually, as observed in Figure 7C.

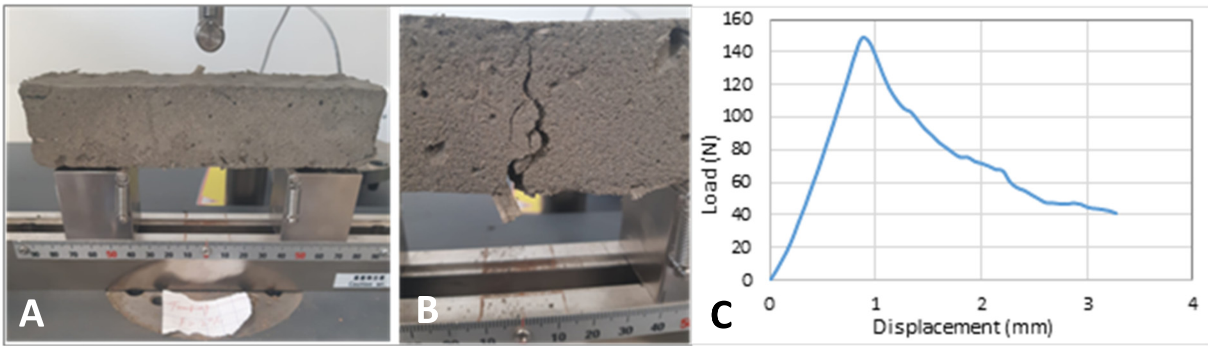

Figure 7. Crude bricks flexural strength test (**A**), brick failure (**B**) and load–deflection curve (**C**).

3.2. Toughness Index (I_5) of Crude Bricks

The post-peak load-bearing capacity of crude bricks increases with increasing fiber content. In the case of unreinforced crude bricks, the post-peak load-bearing capacity is zero, and failure occurs at point A in Figure 8. With the addition of fibers, the post-peak load-bearing capacity of composite materials increases. The toughness index (I_5) value for crude bricks was found with ASTM standard [47] with the help of Figure 8.

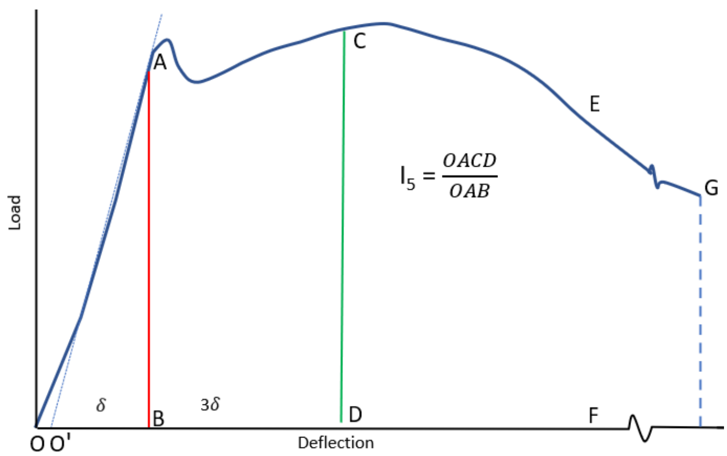

Figure 8. Toughness index calculation.

3.3. Fibers Distribution

Fibers distribution inside the crude bricks was observed by cutting the bricks into 4 cubes of size 4 × 4 cm^2 with an electric saw. Six cross-sections (1S2, 2S1, 2S2, 3S1, 3S2, and 4S1) were considered for fiber counting, as shown in Figure 9A. Each brick cross-section was gently brushed and moistened to remove dust and increase the contrast between the fibers and sediments. Brick cross-sections were scanned with the digital microscope (Keyence VHX 6000 model), as shown in Figure 9B. Finally, fibers counting was done with ImageJ software (Figure 9C).

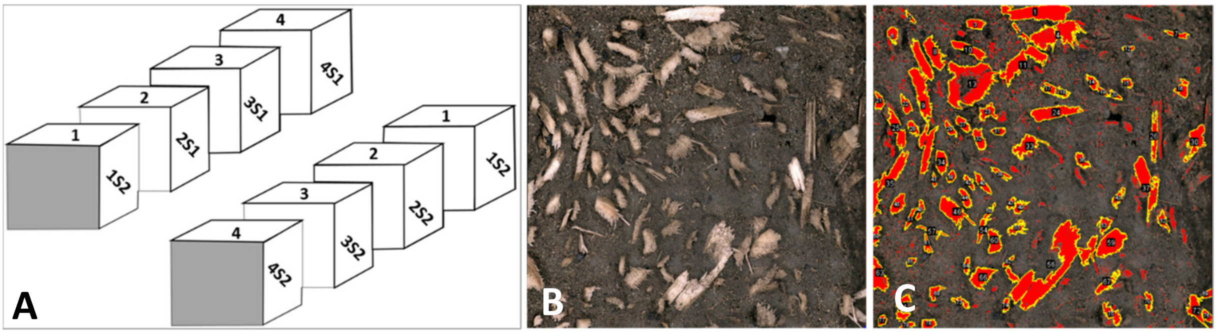

Figure 9. Bricks cross-sections (**A**), image scanning (**B**), and fiber counting (**C**).

Each was further divided into 4 layers of dimensions 4*1 cm^2 with 16 squares of size 1 cm^2, as shown in Figure 10.

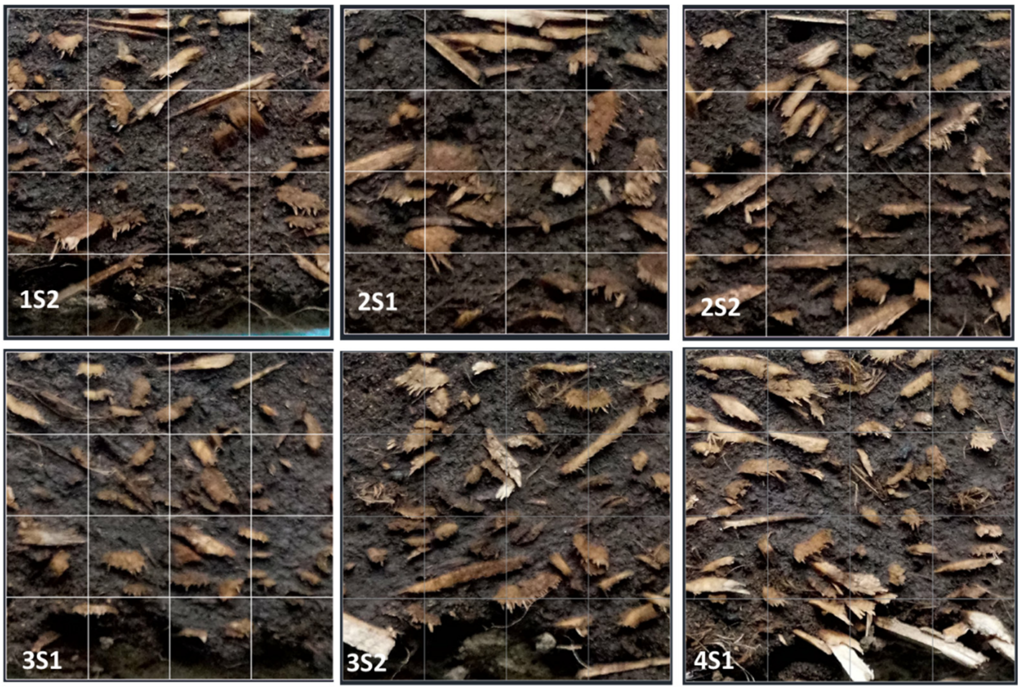

Figure 10. Cross-sections of dynamically compacted brick.

The area of fibers and number of fibers were found with ImageJ in each square through binarization. The following equation was used to find the area occupied by fibers in each square.

$$\text{Area occupied by fibers } (\%) = \frac{Area\ of\ fibers\ in\ a\ square}{Area\ of\ square} \times 100 \quad (3)$$

with the area of each square, the area occupied by fibers in each layer of dimension $4 \times 1\ cm^2$ was determined.

4. Results and Discussion

4.1. Manufacturing of Bricks

During sediments and fibers mixing, it was observed that in the case of dry hemp shiv, sediments, and a hemp shiv mixture, it is difficult to mold, compact, and preserve the shape of the specimen due to the high water content. Fibers water absorption is not simultaneous; on the other hand, water starts to evaporate quickly after compaction. Therefore, the fibers remain unsaturated, and there is excessive water, which makes brick manufacturing difficult.

The sediments and fibers mixture was molded into prismatic molds and compacted. Static compaction is achieved instantaneously with the static load. However, bricks were kept loaded for a few hours. In static loading, pores at the bottom part of the bricks were observed, which is the limitation of this method. The presence of pores is due to poor compaction in the case of static loading, as the compaction of bricks removes the voids in the bricks [48].

With dynamic compaction, upward fiber movements take place, which reduces each brick's tensile strength. On other hand, bricks with dynamic compaction are effectively compacted with fewer pores. Compaction with tamping seems unrealistic. When strokes are applied, the sediments mixture tends to come out of the mold. If the sediments mix has high water content, it goes out with splashes produced by strokes. Moreover, it is difficult to control the energy, as each manually applied stroke has a different energy. Furthermore, the energy of compaction changes from operator to operator. With compaction through the sieve shaker machine, fibers drift upward and are concentrated at the top surface of the brick specimen due to helical vibrations, which give undesirable fibers distribution. Fibers accumulation with a sieve shaker machine can be observed in Figure 11.

Figure 11. Fibers accumulation at the brick surface with a sieve shaker machine.

After compaction, bricks were dried in the oven at 60 °C. Bricks were dried until their mass variation was under 1%. In the case of oven drying, this limit was achieved in nearly 2–3 days, while for natural drying, this limit was achieved in approximately two weeks.

The drying of crude bricks made with dynamic compaction is comparatively faster than the bricks made from static compaction. The primary reason behind this is the water expulsion with hammering action in dynamic compaction.

During the drying process of bricks, evaporation of water takes place. Fibers in a sediments mix swell initially as they are saturated. After water evaporation, fibers shrink, causing small cracks to develop around the fibers. The development of cracks around the hemp shiv in mud bricks manufactured with Dunkirk sediments was observed with a microscope, and it is shown in Figure 12.

Figure 12. Microscopic image of hemp shiv inside the crude bricks.

4.2. Dry Density of Bricks

It was observed that the dry density of bricks decreases with increasing hemp shiv content. The typical range of dry density for adobe bricks ranges from 1800 to 2200 kg/m^3. The results of dry density crude bricks manufactured with Dunkirk sediments with stating compaction and dynamic compaction are shown in Table 3.

Table 3. Density values in static compaction (SL) and dynamic compaction (DC).

Amount of Fibers (%)	0	1	2	3	4	5
Dry density SL (kg/m^3)	-	1650.0	1547.6	1509.1	1433.4	1350.0
Dry density DC (kg/m^3)	1585.6	1549.4	1428.9	1478.3	1282.4	1329.1

The standard deviation for density results is around 11%. The average density values of the three brick samples for static and dynamic compaction are presented in Table 3.

The density results in Table 3 show that the density of materials decreases with increasing fiber content. This is because micropores are increased with higher fibers addition. The swelling of fibers during sediments mixing and shrinkage with drying leads to the development of micropores inside the bricks as shown in Figure 13. The development of micropores around the fibers decreases the cohesion between sediments and fibers, which have a negative impact on the strength of the bricks [49].

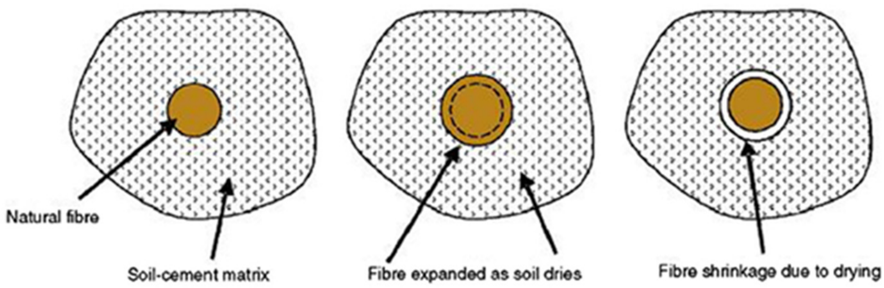

Figure 13. Fibers swelling and shrinkage in sediments matrix (Hejazi et al. 2012).

4.3. Flexural Strength of Bricks

The indirect tensile strength of bricks was found with a three-point bending test. The average tensile strength of three crude bricks samples manufactured with dry fibers through dynamic compaction (DC), static loading (SL), and tamping (T) are shown in Figure 14.

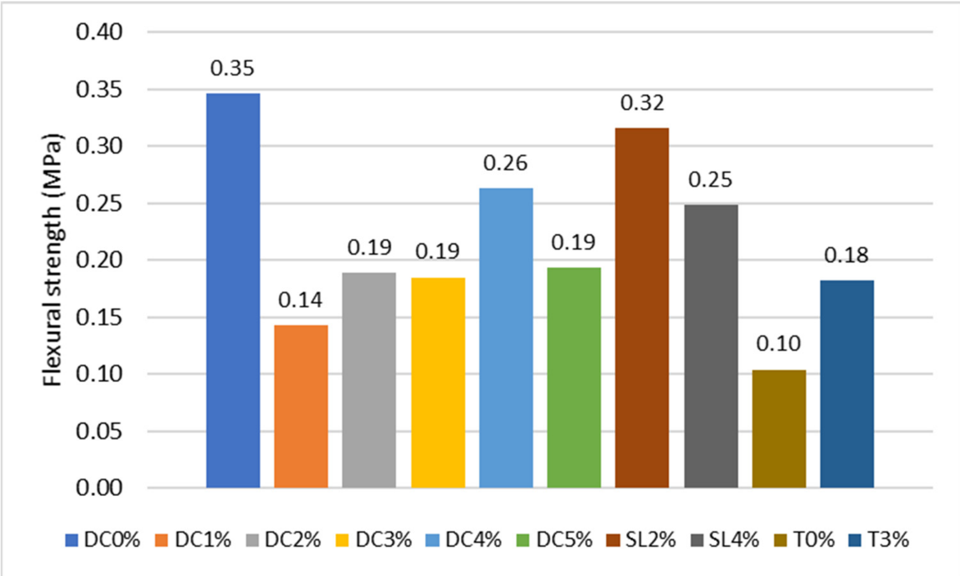

Figure 14. Flexural strength of bricks with dry fibers. Note: DCi: dynamic compaction of the sample with i (%) of fibers; SLi: static loading for sample with i (%) of fibers; Ti: tamping loading for sample with i (%) of fibers.

In case of dry hemp shiv use, there is excessive water in the sediments mix, which is added to accommodate the fibers' water absorption, but the absorption of the fibers is not simultaneous.

Bricks with static loading have high tensile strength, as shown in Figure 14. This is because it is easier to compact the sediments mixture by static loading, even if it is too wet. Water simply goes out in static loading. Dynamic compaction and tamping become very difficult if the molding water content is high. Preserving the shape of bricks becomes also difficult, and it affects the strength of bricks. Therefore, less strength can be observed with dynamic compaction and tamping in Figure 14.

For saturated fibers, compaction was done with dynamic compaction and static loading. Compaction through tamping is difficult, as the sediments mix tends to go out on applying strokes, and it is not possible to control the energy in manual tamping. Due to these reasons, the tamping test on saturated fibers was not performed. The average flexural strength results for three crude bricks samples manufactured with saturated hemp shiv with dynamic compaction and static compaction are presented in Figure 15.

Standard deviation for dynamic and static compaction is around 5%, while the maximum standard deviation of 10% is observed for tamping due to the manual procedure.

Bricks strength with dynamic compaction increases considerably with saturated fibers, while for static compaction, the increase in strength is small. The strength of bricks is maximum with dynamic compaction with 1% hemp shiv content. The tensile strength of bricks with dynamic compaction increases 39% from unreinforced bricks compacted dynamically with a 1% addition of fibers. The overall tensile strength of bricks is higher with dynamic compaction. The tensile strength of the fiber-reinforced adobe bricks varies with the type of sediments, clay and sand content, and fiber type and quantity. There is a lack of appropriate standards for adobe bricks [30]. However, the indirect tensile strength recommended in international standards varies between 0.012 and 0.025 MPa according to New Zealand and Mexican standards [50,51]. Figure 15 shows that with dynamic compaction, the indirect tensile strength of bricks is more than the minimum recommended strength.

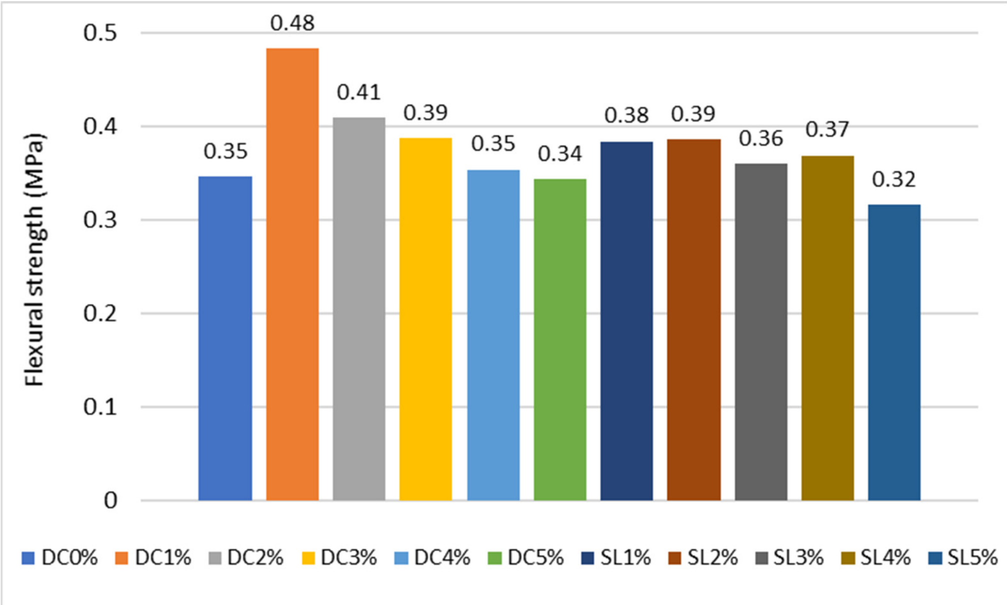

Figure 15. Flexural strength of bricks with saturated fibers. Note: DCi: dynamic compaction for the sample with i (%) of fibers; SLi: static loading for the sample with i (%) of fibers.

Table 4 shows the natural fibers used in adobe bricks, their percentage, and the tensile strength of bricks observed.

Table 4. Natural fibers used for bricks and tensile strength of earth bricks.

Fiber	Fiber Content (wt %)	Tensile Strength (MPa)	References
Jute	0.5–2	0.55–0.66	[52]
Seagrass	0.5–3	0.4–0.6	[53]
Straw	0.5	0.71	[54]
Sugarcane bagasse	0–1	0.29–0.89 *	[55]
Date palm waste	0–10	0.29–2.26	[56]

* CSEB = cement stabilized earth bricks.

4.4. Toughness Index (I_5) of Bricks

The toughness index of crude bricks increases with the addition of natural fibers as fibers transform the brittle behavior of unreinforced earth material into ductile behavior [26]. The toughness index values for the dynamic compaction of crude bricks are shown in Table 5.

Table 5. Toughness index for bricks with dynamic compaction.

Bricks	DC0	DC1	DC2	DC3	DC4	DC5
I_5	1	2.42	2.78	2.74	3.34	3.33

Note: DCi: dynamic compaction for the sample with i (%) of fibers.

4.5. Image Analysis

A brick made with 3% hemp shiv was divided into four parts with six cross-sections, as shown in Figure 9A. Each brick cross-section was divided into 16 squares of size 1 cm^2, as shown in Figure 10. The height of a brick cross-section is 4 cm, and it is divided into four layers of 1 cm. Each layer is further divided into four squares, as shown in Figure 16A. Fibers were counted in each square, and the area occupied by fibers in each square was calculated. The area occupied by fibers at different depths and squares with dynamic compacting and static loading is shown in Figure 16B,C, respectively.

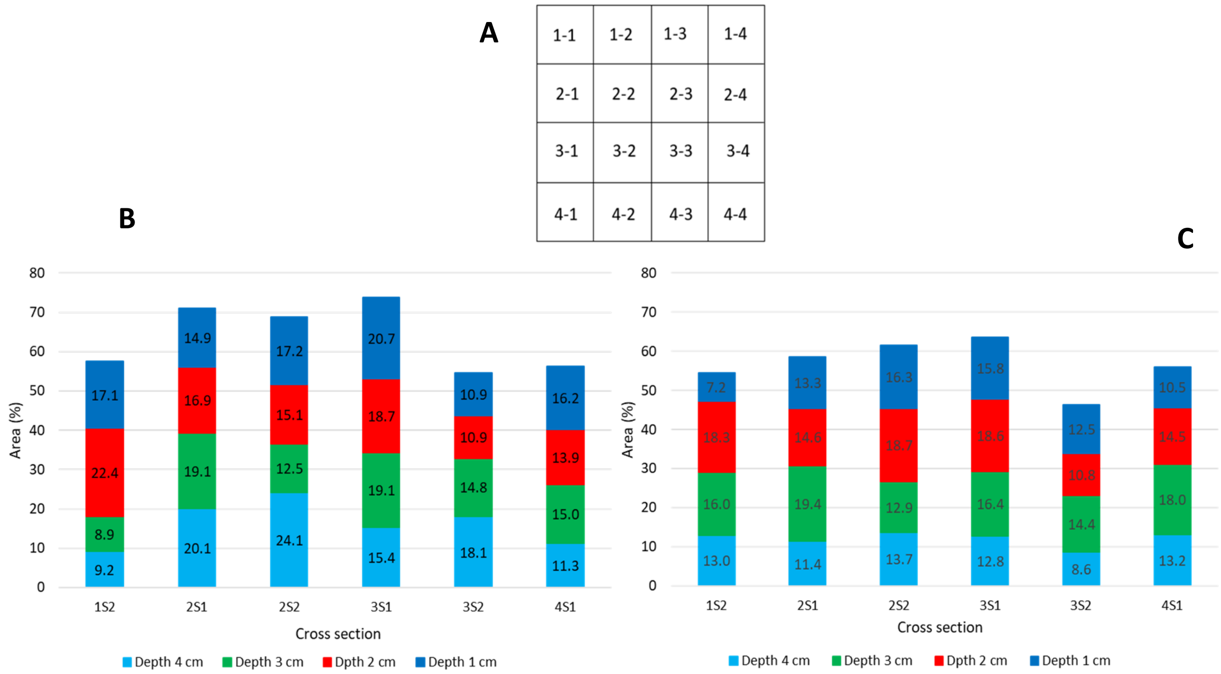

Figure 16. Division in 16 parts of a cross-section (**A**), areas occupied by fibers in dynamic compaction (**B**) and static compaction (**C**).

The average area occupied by fibers in dynamic compaction is 15.35%, and in static loading, it is 15.46%. The area occupied by fibers is nearly similar in both compaction methods as the quantity of fibers is the same.

The area occupied by fibers in the upper layer is higher in the case of dynamic compaction than the static compaction (Figure 16B,C). The upward movement of water due to compaction leads to the fiber's upward movement. This phenomenon is more apparent in dynamic compaction as water moves out due to falling mass on the sediments matrix. Similar observations were noted in coconut fiber reinforced mortar by Bui [48].

5. Conclusions

Dredged sediments from Dunkirk port and hemp shiv were used in manufacturing earth bricks after analyzing their characteristics. The grain size of sediments shows their suitability for crude bricks after French standard [7] and Spanish standards [42]. Crude bricks were manufactured with Dunkirk sediments by 0%, 1%, 2%, 3%, 4%, and 5% by mass with dry and saturated hemp shiv. Bricks were compacted with dynamic compaction, static loading, and tamping. It is observed that bricks with dry hemp shiv have lower strength due to the higher molding moisture content. Moreover, compaction by tamping deforms the shapes of the bricks, and it is difficult to control the compaction energy.

The mechanical testing of bricks shows that bricks have a maximum tensile strength at 1% fiber content with dynamic compaction that is 39% higher than that of the controlled sample with 0% hemp shiv. Fibers addition increases the tensile strength and the toughness of bricks and transforms the bricks into ductile material. Fibers distribution analysis shows that fibers occupy nearly 15% area of the brick cross-section with 3% hemp shiv. The tensile strength of bricks with dynamic compaction and saturated hemp shiv satisfies the minimum recommended limits, as it is superior to 0.25 MPa [50,51]. Therefore, it is possible to reuse uncontaminated harbor-dredged sediments in crude bricks with a minimum use of energy. Further analysis and experimental work are needed for the durability of bricks and the variation of results with the use of dredged from different locations.

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