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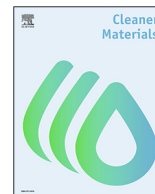
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## Reuse of harbour and river dredged sediments in adobe bricks

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### ABSTRACT

Dredged sediments from ports and rivers are treated as waste material. The disposal of waste sediments has environmental concerns and requires financial resources. Dredged sediments reuse in building material such as adobe bricks can provide an alternate solution to valorize and handle this waste material. Adobe bricks are eco-friendly construction materials manufactured with clayey soil and fibers. Natural fibers addition improves mechanical and thermal characteristics of adobe bricks.

In this research, a pilot study was conducted to manufacture adobe bricks from harbor dredged sediments and replicate the procedure to manufacture adobe bricks for river dredged sediments. Harbor sediments were taken from Dunkirk port, France. The physical and chemical characteristics of these sediments were analyzed. Sediments suitability for adobe bricks with grains size and Atterberg limit was discussed with different approaches. Bricks were manufactured by mixing Dunkirk sediments and saturated hemp shiv at different hemp shiv content. Sediments and fibers were mixed with a mortar mixer and molded into specimens of 4\*4\*16 cm<sup>3</sup>. Dynamic compaction was opted to compact the bricks. Drying of bricks was done in the oven at 40 °C. Finally, sediments mixing, molding and compaction procedures were derived and problems encountered during were discussed.

The procedure derived from Dunkirk sediments was implemented on Usumacinta River sediments to make adobe bricks with the addition of palm oil flower fibers (POFI). Characteristics of Usumacinta River sediments and palm oil flower fibers were found to use in adobe bricks. Palm oil flowers fibers were cut with a knife mill of grid-2 cm and grid-3 cm. Dunkirk sediments bricks manufacturing process was repeated to make bricks from Usumacinta sediments.

Laboratory scale manufacturing and testing of bricks from Dunkirk port sediments and Usumacinta River sediments allows to observe the valorization of dredged sediments in adobe bricks with mechanical perspectives. In this study, properties of bricks manufactured by both harbor and river dredged sediments such as tensile strength, toughness and fibers distribution inside the bricks were studied and compared.

### Introduction

Sediments are dredged from seaports, rivers and water channels for navigation, water flow and offshore activities. Millions of tonnes of sediments are dredged across the world. These sediments are treated as waste and dumped into the sea or stored on land sites. Sediment dumping in the sea causes environmental problems, especially for marine life. Similarly, land storage of sediments has leaching and cost issues. Sediments recycling in different applications is increasing nowadays due to the cost and environmental concerns (Rakshith and

Singh, 2017). Recycling polluted sediments is difficult and need prior treatment for their reuse. Furthermore, dewatering of dredged sediments is also necessary to use them (Boullosa Allariz et al., 2019).

Harbour and river sediments have been used in various sectors such as roads, backfill, retaining walls, cement clinker and bricks by different researchers (Siham et al., 2008; Anger et al., 2017; Manap et al., 2015). Sediments reuse in the building sector seems promising as it reduces the burden on natural resources and carbon emissions. The building sector in the world is increasing rapidly with concrete as the principal building material. Concrete is globally responsible for

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10% of worldwide carbon release (Ramakrishnan et al., 2021). Therefore, the use of dredged sediments in adobe bricks is important and provides eco-friendly construction material. Adobe bricks are one of the oldest construction materials and are widely used for construction activities in developing countries. Adobe bricks are environment-friendly and sustainable building materials with minimum CO<sub>2</sub> emissions. Less energy consumption, cheap and abundant raw material and easier recycling make them attractive building materials.

For sediments recycling in adobe bricks, physical and chemical characteristics of sediments are important. These characteristics include granulometry, Atterberg limits, chemical and mineralogical composition. Percentage of silt, sand and clay are also important factors for sediments suitability for bricks. Composition of silt, sand and clay can be modified by the addition of other types of sediments (AFNOR XP P13-901, 2001; MOPT - Ministerio de Obras Públicas y Transportes, 1992; Vasic et al., 2020).

Adobe bricks manufacturing consists of sediments mixing, molding, compaction and drying. Crushed sediments and natural fibers are mixed with molding moisture content.

Natural fibers are waste material and added in bricks due to the strength and durability limitation of crude bricks. Common natural fibers used in construction activities include coconut coir, straw, jute, palm fibers and sugar cane bagasse and others. Natural fibers use in composite materials such as concrete, mortar and crude bricks provide their eco-friendly use in construction materials (Bui, 2021; Parisi et al., 2015). Natural fibers act as reinforcement in composite materials. Natural fibers addition in composites increases the tensile strength of the composite material and transforms the brittle failure to ductile failure. The presence of natural fibers decreases the shrinkage and growth of big cracks in crude bricks during fast drying of bricks (ASTM E2392/E2392M-10, 2016). Natural fibers improve the thermal and hygroscopic characteristics of crude bricks by regulating humidity absorption and evaporation (Subramanian et al., 2021). Fibers characteristics such as tensile strength and shelf life are important for the strength of bricks and these properties can be improved by treatment of fibers. Fibers are added in crude bricks usually by mass or by volume (Calatan et al., 2016). Length of fibers is a useful parameter that significantly affects the quality of crude bricks. Recommended length of fibers for composite materials such as concrete in ASTM standard is around 25 mm (ASTM D7357 – 07, 2012). The distribution and orientation of fibers inside the matrix is also critical for the strength of bricks but is difficult to control the orientation of fibers inside the bricks. Fibers parallel to the brick cross-section contribute more towards the tensile strength of composite materials (Bui, 2021).

Water content used to mix sediments and fibers can be derived through Atterberg limits and optimum moisture content (Ramakrishnan et al., 2021; Li Piani et al., 2020). Higher molding moisture content reduces the strength of bricks while with lower moisture content, molding of the mixture becomes difficult. Sediments and fibers are usually mixed with a laboratory scale machine to make the homogenous mixture for experiments (Salih et al., 2018). The sediments mixture is molded into bricks of different sizes. Steel and wooden molds are commonly used for this purpose. Porcelain mold of size 4\*4\*16 cm<sup>3</sup> is generally used for laboratory-scale manufacturing of composite materials (Seifi et al., 2018; Bui, 2021). Molded sediments mixture is compacted to achieve good strength, improve the resistance of bricks against weathering and water absorption.

Compaction of bricks is usually done by static compaction, dynamic compaction, tamping and by vibrations. Rearrangement of soil particles takes place with the compaction of bricks, and voids are removed which increases the strength and density of soil. Crude bricks exhibit higher tensile and compressive strength with dynamic compaction (Binici et al., 2005). In the case of dynamic and static compaction, compaction energy is another useful parameter that influences the strength and density of crude bricks.

Soil stabilization in crude bricks is achieved by compaction or by the addition of stabilizers such as cement, gypsum and lime (Adam and Agib, 2001). Stabilized bricks samples after compaction are sun-dried or oven-dried. Sun-drying is the most economical and eco-friendly method, and it is possible in hot arid conditions. By drying the bricks, fibers inside the bricks also dry and their volume decreases due to shrinkage. Microcracks are developed around the fibers inside the bricks. Water repellent additives are helpful to minimize this effect (Ghavami et al., 1999).

The strength and characteristics of bricks are crucial for their use in construction material. Minimum design compressive strength for unreinforced adobe bricks varies from 0.3 to 1.4 MPa in different international standards used in Germany, Australia and India (Schroeder, 2012). French and Mexican standards recommend compressive strength of 1 MPa (AFNOR XP, P13-901, NORMA E.080). Tensile strength is another important property of crude bricks. The tensile strength of bricks with short fibers is usually higher than the tensile strength of bricks with long fibers (Bledzki and Gassan 1999). Tensile strength of crude bricks increases with fibers addition up to optimum fiber content. Minimum tensile strength recommended is 0.25 MPa in NZS standard while the Mexican standard recommends tensile strength of 0.012 MPa with three point bending test (NZS 4298, NORMA E.080). Higher quantity of fibers reduces cohesion between sediments. Some other important characteristics of bricks include water absorption, density, inundation and resistance against weathering. Density of crude bricks depends on sediments and fibers used, percentage of fibers and compaction energy applied.

Tensile and compressive strength of adobe bricks are considerably lower than concrete and fired bricks. Furthermore, crude bricks are vulnerable to weathering. Interaction with water reduces their strength and in case of inundation, bricks may lead to failure. Crude bricks have durability issues and weak seismic performance. Additives such as cement, gypsum and lime are sometimes used to increase the strength and durability of crude bricks (Mesbah et al., 2004). The use of additives increases the cost of crude bricks and the environment-friendly nature is affected.

This study focuses on the valorization of harbor and river dredged sediments and waste fibers in crude bricks as only a few studies have been conducted on the reuse of dredged sediments in crude bricks. Crude bricks were manufactured by waste sediments dredged from Dunkirk port and Usumacinta River. Dunkirk sediments are mixed with hemp shiv while Usumacinta River sediments are mixed with palm oil flower fibers to make crude bricks. Sediments and fibers characteristics were studied before their use in adobe bricks. Finally, bricks manufacturing was followed by the analysis of characteristics of adobe bricks such as tensile strength, bending stiffness, toughness and fibers distribution inside the bricks.

## Materials and methods

### Sediments

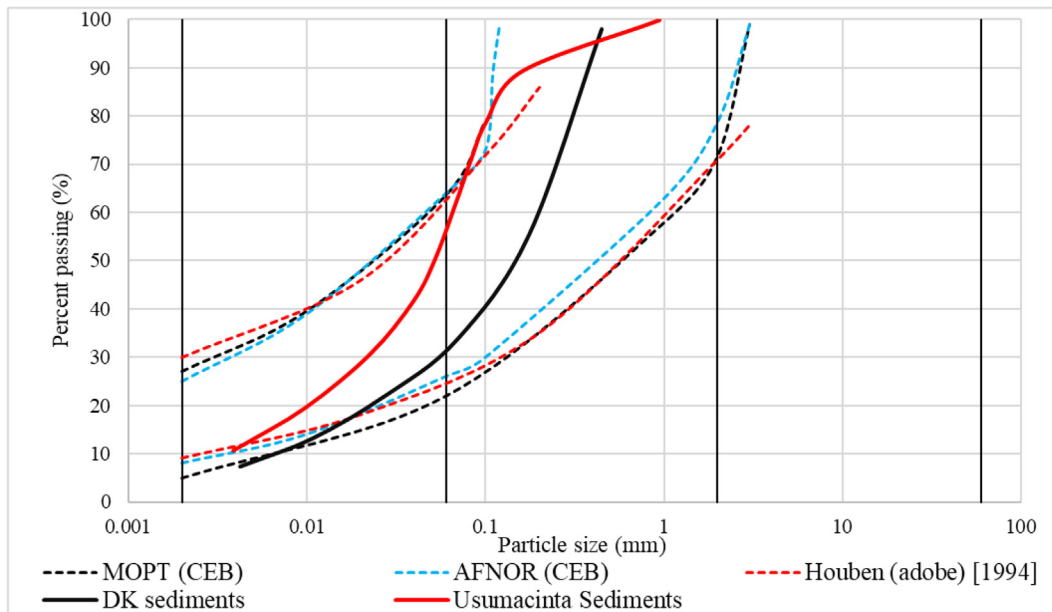
Harbour dredged sediments from Dunkirk port (France) and river dredged sediments from the Usumacinta River (Mexico) were used in this study. Physical and chemical characteristics of both sediments were found to use them in crude bricks.

Granulometry of sediments is an important parameter as it decides the sediment's suitability for crude bricks. Granulometry of Dunkirk (DK) and Usumacinta River sediments (USU) was found with laser granulometry according to French recommendations (AFNOR NF X31-107, 2003). The silt, sand, clay content and medium diameter of both sediments are shown in Table 1.

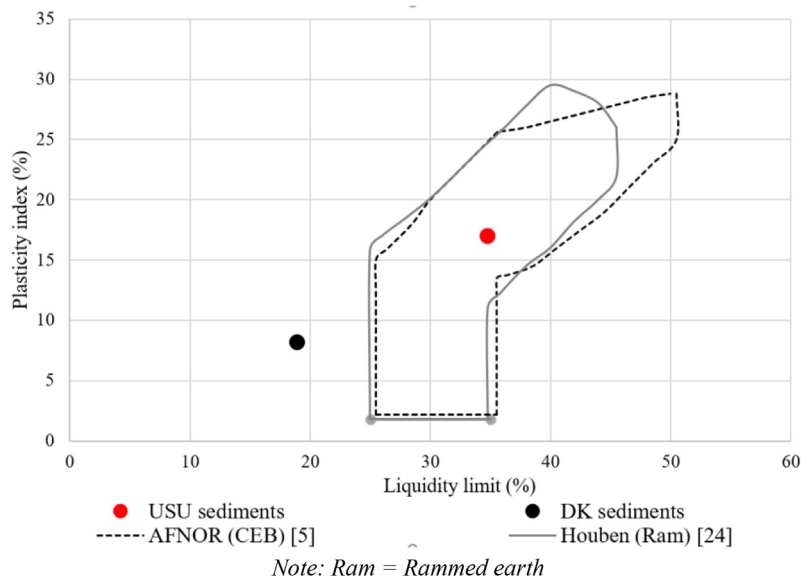
Sediments suitability with respect to granulometry for crude bricks with AFNOR standard (AFNOR XP P13-901, 2001) and recommended zones by Houben and Guillaud (1994) is shown in Fig. 1.

**Table 1**  
Silt, sand and clay content of Usumacinta and Dunkirk sediments.

Sediment	Clay (%)	Silt (%)	Sand (%)	D <sub>50</sub> (μm)
Usumacinta (USU)	5.90	41.30	52.80	51.85
Dunkirk (DK)	4.29	24.78	70.92	159.40



**Fig. 1.** Sediments suitability for crude bricks. Note: CEB = compressed earth blocks.



**Fig. 2.** Sediments suitability with respect to PI. Note: Ram = Rammed earth.

We can observe from Fig. 1 that Usumacinta River sediments and Dunkirk sediments are inside in the zones recommended for crude bricks. Sediments granulometry shows that these sediments can be used for manufacturing crude bricks. Atterberg limits of sediments were found as sediments molding characteristics are based on liquidity limit (LL) and plasticity limit (PL). Sediments suitability for bricks with Atterberg limits is shown in Fig. 2 with AFNOR standard (AFNOR XP

P13-901, 2001) and recommended areas by Houben and Guillaud (1994).

We can observe from Fig. 2 that Usumacinta River sediments (USU) are within the proposed zone while Dunkirk (DK) sediments are outside the zone suitable for manufacturing crude bricks due to low plasticity index and liquidity limit as these sediments have high sand content and low clay content.

Raw material along with mixing tools used for manufacturing crude bricks is shown in Fig. 3a and b. Fig. 3a shows the Dunkirk sediments and hemp shiv while Fig. 3b shows the Usumacinta River sediments and palm oil flower fibers used in this study.

Physical and chemical characteristics of Usumacinta River sediments and Dunkirk sediments useful for their use in bricks such as carbonate, optimum water content, organic matter, pH, Atterberg limits, solid particles density and specific surface area (SSA) were determined. Sediments characteristics are summarised in Table 2.

The specific surface area of Usumacinta River sediments was found with BET method. Specific surface area and solid particles density of Dunkirk sediments used in this study was calculated by Boulosa Allariz et al. (2019). and given by Wang et al. (2010), respectively.

### Fibers

Hemp shiv and palm oil flower fibers were used with Dunkirk and Usumacinta River sediments respectively to make crude bricks. Characteristics of hemp shiv and palm oil fibers were studied before their use.

Hemp shiv (Hs) is a waste material obtained from the hemp plant. The hemp shiv used in this study is taken from France. Hemp shiv is manufactured in Europe on industrial scale for different applications. In France, every year 51,000 tons of hemp shiv is produced. (Lenormand and Leblanc, 2020). The other plant biomass material used is palm oil flower fibers (POFl). POFI fibers are waste materials of palm oil empty fruit bunches after extraction of oil. POFI fibers are taken from the Tabasco state of Mexico. POFI fibers are not manufactured on industrial scale in Mexico and these fibers are treated as waste.

POFl fibers were cut with a knife mill with a grid of 2 cm and a grid of 3 cm length. Length distribution of hemp shiv and POFI fibers was studied with ImageJ software. As fibers obtained from knife mill are often grinded therefore length distribution and variation of POFI fibers were observed along with hemp shiv. Length of 100 random sizes POFI fibers and hemp shiv aggregates was measured with ImageJ software through binarization. Test was repeated three times to obtain precise values. Length distribution of hemp shiv and POFI fibers is shown in Fig. 4 and Fig. 5 respectively.

The average, maximum and minimum lengths observed for both types of plant aggregates are summarized in Table 3.

Tensile strength testing of palm oil flower fiber shows that these fibers have elastoplastic behavior which is common in natural fibers. Water absorption of fibers was found by immersing the fibers in water for 48 h. Water absorption, tensile strength and skeletal density of both POFI fibers and hemp shiv are shown in Table 4.

### Manufacturing of bricks

Crude bricks were manufactured with Dunkirk sediments and Usumacinta River sediments. Bricks manufacturing steps such as sediments mixing, molding, compaction and drying were performed. These steps are illustrated in Fig. 6.

Crude bricks were made with 1%, 2%, 3%, 4% and 5% plant biomass (hemp shiv and POFI fibers) while control specimens were manufactured with 0% plant biomass. The fiber content of 0% to 5% is commonly found in the literature for crude bricks (Salih et al., 2018). POFI fibers and hemp shiv were saturated for 24 h before their use as dry fibers water absorption is not instantaneous. Mixing of sediments, fibers and water was done with a laboratory mortar mixer for 10 min to make a homogenous mixture. Usumacinta River sediments were mixed with 0 to 5% POFI fibers by mass. Similarly, Dunkirk sediments were mixed with 0 to 5% hemp shiv by mass. For a specimen of size  $4 \times 4 \times 16 \text{ cm}^3$ , 450 g sediments are generally required (Afnor en 196–1, 2016). The following formula was used to calculate mass plant aggregates.

$$m_{\text{plant aggregates}} = \frac{m_{\text{sed}} \times \% \text{plant aggregates}}{100} \quad (1)$$

In this equation  $m_{\text{sed}}$  is the mass of dry Usumacinta and Dunkirk sediments (g),  $m_{\text{plant aggregates}}$  is the mass of POFI fibers and hemp shiv (g) and  $\% \text{plant aggregates}$  is 0 to 5% POFI fibers and hemp shiv. Molding moisture content was found with the standard Proctor test. Molding moisture content varies for Dunkirk and Usumacinta River sediments. For rammed earth blocks which is a type of crude brick, molding moisture content should not be less than 3% below optimum moisture content or 5% above optimum moisture content (NZS 4298, 1998). The following formula was used to determine the quantity of water necessary for the mixture.

$$m_{\text{water}} = \frac{m_{\text{sed}} \times \% \text{of water}}{100} + m_{\text{plant aggregates}} \quad (2)$$

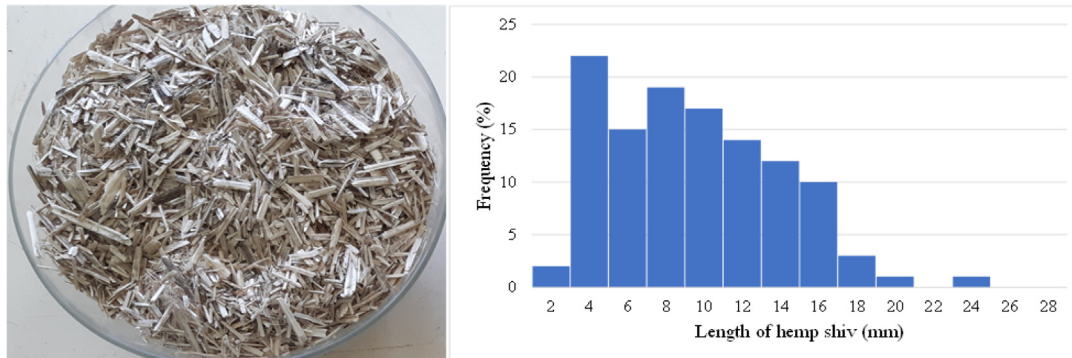


Fig. 3. Dunkirk sediments and hemp shiv (a), Usumacinta River sediments and palm oil flower fibers (b).

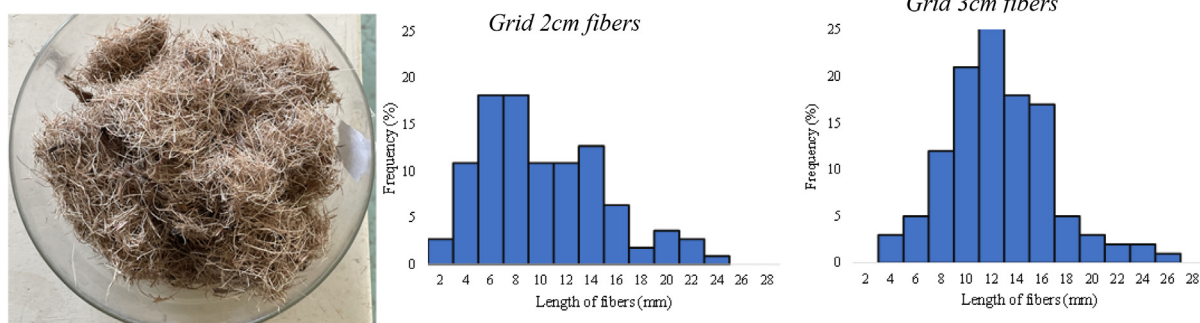


**Table 2**  
Usumacinta River and Dunkirk sediments characteristics.

Sediments	CaCO <sub>3</sub> (%)	W <sub>opt</sub> (%)	OM (%)	MBV (g/100 g)	pH	LL (%)	PI (%)	ρ <sub>sed</sub> (g/cm <sup>3</sup> )	SSA (m <sup>2</sup> /g)
USU	7.84	19.3	4.48	2.73	7.50	37.74	7.83	2.63	28.20
DK	13.34	20.5	5.29	0.60	8.39	18.92	8.20	2.53–2.58	14.33



**Fig. 4.** Length distribution of hemp shiv.



**Fig. 5.** Length distribution of palm oil flower fibers for grid 2 cm and grid 3 cm long fibers.

**Table 3**  
Length distribution of POFL fibers and hemp shiv.

Fibers	Average length (mm)	Maximum length (mm)
Hemp shiv	11.67	50.46
POFL (grid-2 cm)	9.50	24.05
POFL (grid-3 cm)	11.54	32.96

**Table 4**  
Characteristics of fibers.

Fibers	POFL	Hemp shiv
Skeletal density (g/cm <sup>3</sup> )	1.37	1.44–1.52*
Water absorption (%)	235	298
Tensile strength <sub>average</sub> (MPa)	29.27–334.60	960 +/-220 MPa**

Note \* Jiang et al., 2018; \*\* Thygesen et al., 2008.

In this equation  $m_{sed}$  is the mass of dry sediments (g),  $m_{plant aggregates}$  is the mass of POFL fibers and hemp shiv (g). As abovementioned, sediments and plant biomass mixture were molded into prismatic specimens of 4\*4\*16 cm<sup>3</sup> which are commonly used for mortar and concrete applications at laboratory scale (Afnor en 196–1, 2016). Bricks specimens were compacted in two layers. Dynamic compaction of crude bricks is an effective method and has been applied by different

researchers to compact the bricks (Bahar et al., 2004; Dormohamadi and Rahimnia, 2020). Crude bricks in this study were compacted with dynamic compaction with compaction energy of 600 kN.m/m<sup>3</sup> which is normally used for the Proctor test to get maximum density. Compaction was done with a miniature Proctor apparatus with a falling mass of 1.043 kg at a height of 17.8 mm (Hussain et al., 2020). After compaction, it is possible to remove the brick sample from the mold by opening the bolts. Finally, the bricks samples were oven-dried at 40 °C. Drying of bricks samples lasted for 3–4 days until their mass variation was below 1%. Crude bricks samples manufactured with Usumacinta Rivers sediments at 1%, 2%, 3%, 4% and 5% fibers addition by mass are shown in Fig. 7.

*Testing of mud bricks*

The flexural strength of crude bricks is an important parameter to observe the quality of bricks. Three-point bending test was used to find the indirect tensile strength of bricks according to ASTM standard (ASTM C1557-03, 2004). Shimadzu AGS-X model with a sensor of 50 kN at a displacement rate of 0.5 mm/min was used for the flexural strength test. We can see the testing and rupture surface of a crude brick sample in Fig. 8a in which load was applied perpendicular to the layers interface. Testing and flexural load–deflection behavior of a brick made with Usumacinta River sediments along with POFL fibers is shown in Fig. 8a and 8b respectively.

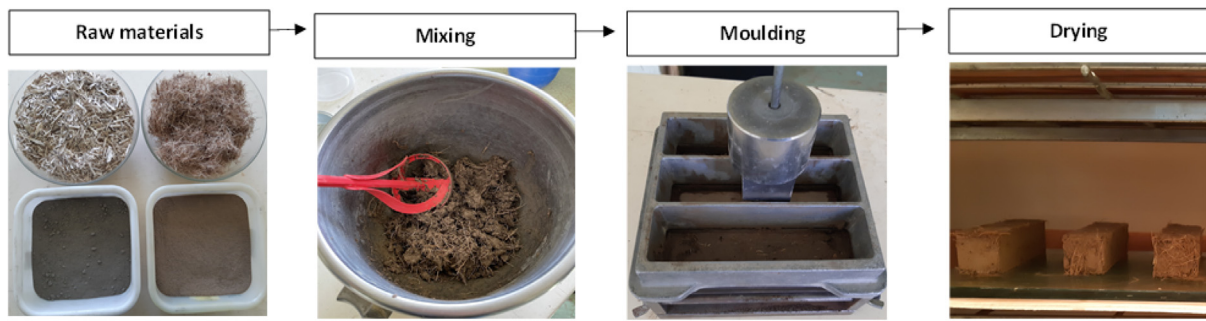


Fig. 6. Bricks manufacturing steps.



Fig. 7. Usumacinta River sediments crude bricks samples.

The failure mechanism of bricks in Fig. 8a indicates that crack initiates from the bottom of bricks and propagates upwards. The tensile load–deflection curves in Fig. 8b show that the tensile strength of bricks increases linearly before failure.

Toughness of both harbor and river dredged sediments was found with ASTM standard (ASTM C 1018 – 97, 1998). Toughness of bricks increases with fibers addition up to the optimum fiber content. The diagram to calculate toughness index ( $I_5$ ) is shown in Fig. 9.

Homogenous distribution and orientation of fibers are important for the strength of crude bricks. Fibers distribution in bricks was observed by ImageJ software. Crude bricks were divided into 4 parts with 6 cross-sections of size 4\*4\*4 cm<sup>3</sup>. Fig. 10 elaborates the 4 parts of brick with 6 cross-sections. Bricks parts at the corners have only one side where fibers are visible such as sides 1 and 4. In central parts of

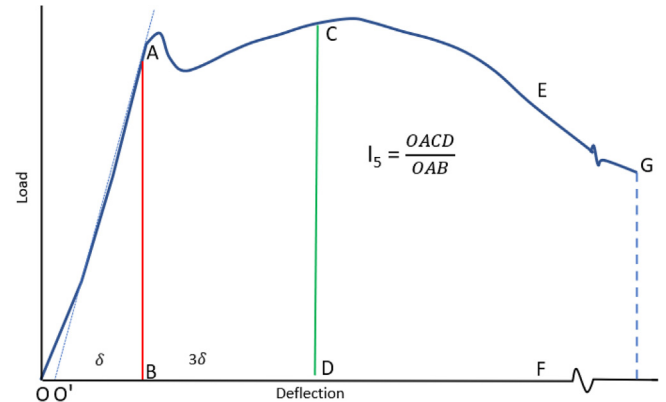


Fig. 9. Toughness index diagram after ASTM standard (ASTM C 1018 – 97, 1998).

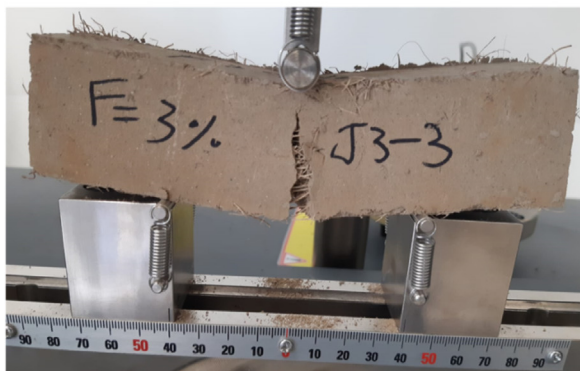
brick i.e. 2 and 3 fibers are visible on the front and backside such as 2S1, 2S2, 3S1 and 3S2. Each side corresponds to a cross-section. Digital microscope Keyence model VHX 6000, was used to make the image of each section. These images were treated with ImageJ software to observe the fibers distribution.

Results and discussion

Bricks manufacturing

During mixture preparation, prior hemp shiv and POFL fibers saturation allow us to respect the molding moisture content of sediments. Swelling of hemp shiv and POFL fibers takes place with saturation. In

a. Flexural strength test



b. POFL (G-2cm) fibers flexural load deflection behavior

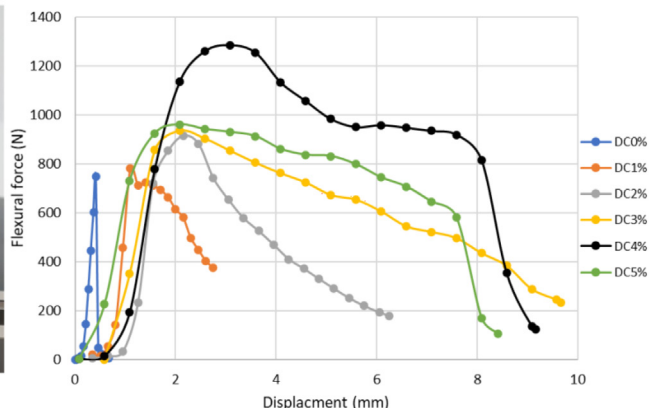


Fig. 8. Tensile strength testing and behavior of crude bricks (USU sediments and POFL fibers).

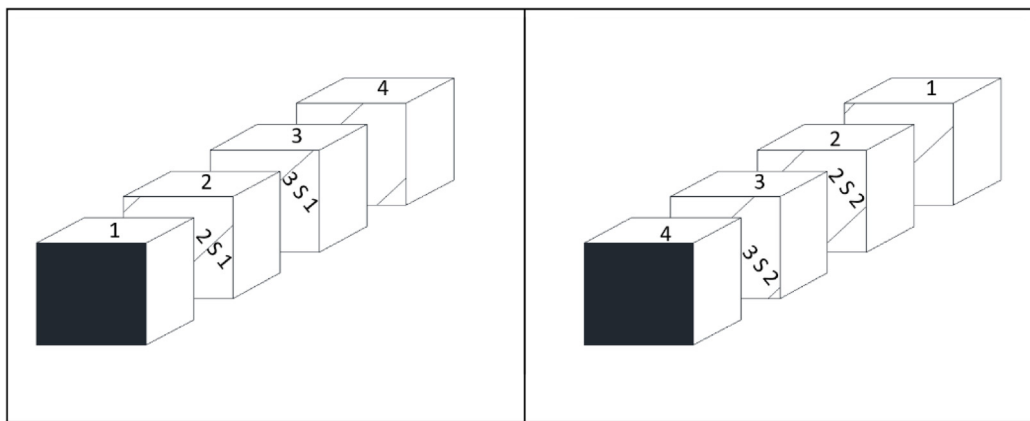


Fig. 10. Brick cross-sections.

Table 5  
Tensile strength of Usumacinta River and Dunkirk sediments bricks.

Sediment	Fibers content (%)	0%	1%	2%	3%	4%	5%
Usumacinta USU	$\sigma_t$ (MPa)- grid 2 cm	1.79	1.56	2.37	2.37	2.93	2.38
Usumacinta USU	$\sigma_t$ (MPa)- grid 3 cm	1.79	1.79	2.56	3.19	2.02	2.59
Dunkirk DK	$\sigma_t$ (MPa)- grid 2 cm	0.35	0.48	0.41	0.39	0.35	0.34

Note: Tensile strength values are overestimated as equation (3) is valid only for elastic behavior.

the case of dry hemp shiv and POFL fibers, water absorption by hemp shiv and POFL fibers is not instantaneous and the mixture remains too wet for molding. During the mixing of sediments and plant biomass, fibers clusters were observed and were manually broken and remixed in the case of POFL fibers. DK and USU sediments mixtures were compacted with dynamic compaction. Dynamic compaction of bricks prompts the upward movement of fibers which affects the homogeneous nature of the mixture.

Tensile strength

Tensile strength of adobe bricks was calculated with the following formula.

$$\text{Indirect tensile strength} = \sigma = \frac{1.5 * F * l}{bd^2} \tag{3}$$

Where F = flexural force, b = width of brick, d = height of brick, l = length of the supported span.

The average tensile strength of crude bricks with Dunkirk sediments and hemp shiv along with Usumacinta River sediments and POFL fibers of grid 2 cm and grid 3 cm is summarized in Table 5.

With increasing fiber content, the brittle behavior of bricks transforms into ductile behavior with increasing load-bearing capacity of bricks. It can be seen in Fig. 8b that bricks have brittle failure at 0% POFL fiber addition which changes into ductile with fibers addition.

Table 6  
Flexion stiffness of bricks.

Fiber content (%)	USU grid-2 cm (N/mm)	USU grid-3 cm (N/mm)	DK grid-2 cm (N/mm)
0	3080	3080	109
1	1913	2400	416
2	2287	2541	198
3	1335	1526.5	262
4	1185	965	182
5	1151	1051.5	269

From 0% to 5% POFL fibers addition, it is observed that bricks have maximum tensile strength for USU sediments bricks at 4 % fiber content of grid 2 cm long fibers and 3% for grid 3 cm long fibers. The tensile strength of bricks with grid-3 cm long POFL fibers is higher than the bricks of grid-2 cm long POFL fibers. Tensile strength of Usumacinta River sediments bricks with grid 2 cm and grid 3 cm POFL fibers at optimum fibers content increase 64 % and 79% from control samples with 0% fiber content respectively. Tensile strength of DK sediments bricks is maximum with 1% hemp shiv addition which increases 39% from the control sample. Dormohamadi and Rahimnia (2020) observed a 75% tensile strength increase for crude bricks compacted dynamically.

The tensile strength of bricks indicates that bricks with Usumacinta River sediments with POFL have higher strength than the bricks made with Dunkirk sediments and hemp shiv. Mineralogical composition, Atterberg limits, clay content of sediments, morphology and size of natural fibers used are a few reasons behind the low strength of Dunkirk sediments bricks (Bahar et al., 2004).

It can be observed from Table 5 that crude bricks with Usumacinta sediments and Dunkirk sediments have the tensile strength of more than 0.25 MPa which is recommended tensile strength by New Zealand standard, NZS 4298 (1998). The minimum tensile resistance recommended for adobe in Mexico with Brazilian tensile test is 0.08 MPa while with indirect tensile strength test minimum recommended value for adobe bricks is 0.012 MPa. Compressive strength recommended for adobe bricks in Mexican and French standards is 1 MPa (AFNOR XP P13-901, 2001; NORMA E.080, 2017).

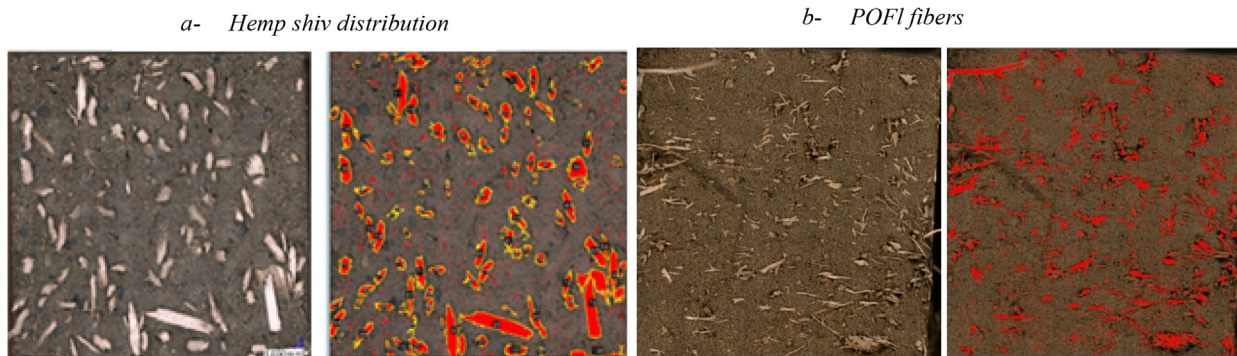
Fibers addition increases the tensile strength of bricks however, it has a negative impact on the compressive strength of adobe and composite material. During drying of bricks, fibers shrink and micro-cracks are developed around fibers. Bridging of these microcracks may lead to the formation of macro cracks which reduce the mechanical performance of bricks. As the size of these cracks is small, the development of macrocracks is not very common (Li Piani et al., 2020).

The USU and DK sediments bricks show satisfactory tensile strength. However, plant aggregates in bricks are sensitive to water



**Table 7**  
Toughness  $I_5$  index of crude bricks.

Fibers (%)	0	1	2	3	4	5
$I_5$ , USU grid-2 cm	1	3.95	4.02	4.38	4.24	4.73
$I_5$ , USU grid-3 cm	1	2.58	4.18	4.42	3.83	3.89
$I_5$ , DK grid-2 cm	1	2.42	2.78	2.74	3.34	3.30



**Fig. 11.** Hemp shiv and palm oil flower fibers distributed in a cross-section of the sample.

and humidity. Treatment of fibers increases the shelf life of fibers and reduces their hydrophilic nature. The use of binders such as cement and lime have a positive impact on the durability of bricks. As a recommendation in future studies, it is necessary to carry out medium- and long-term durability tests (wetting and drying, erosion test etc.).

**Bending stiffness**

Bending stiffness was calculated from flexural load–deflection curves. The average value of flexion stiffness is presented in Table 6. Table 6 shows that with increasing fiber content, stiffness decreases. Similar observations were made by Khouidja et al., (2021). This is because the peak value of the flexural load is achieved after high deflection with higher fiber content. The vertical rise of the load–deflection curve is gradual with increasing fiber content while it is sharp in the case of the controlled specimen with 0% fiber content.

The flexion stiffness of Dunkirk sediments is very low when compared with Usumacinta River sediments bricks. This is because the tensile strength of Dunkirk sediments bricks is also considerably lower than Usumacinta River sediments bricks and flexion stiffness increases with tensile strength.

**Toughness of bricks**

The toughness index for Dunkirk and Usumacinta River sediments bricks was found according to ASTM standard (ASTM C 1018 – 97, 1998). Results are presented in the following Table 7.

Toughness index is generally maximum at optimum fiber content and maximum tensile strength. Table 7 shows that a maximum toughness index is observed for grid-3 cm long fibers at 3% fiber content which is optimum fiber content. For grid-2 cm fibers and hemp shiv, toughness is increasing with fiber content but it is not maximum at the optimum fiber content. Heterogenous distribution of fibers inside the sediments mix, their length and orientation affect the toughness index of crude bricks.

**Fibers distribution**

Fibers distribution inside Dunkirk sediments bricks and Usumacinta River sediments bricks is illustrated in Fig. 11a and 11b respectively. Hemp shiv is thick and uniformly distributed across the brick

**Table 8**

The average number of fibers and area occupied by fibers in a crude brick cross-section.

Cross section	USU (POFl grid-2 cm)	USU (POFl grid-3 cm)	DK (Hs grid 2 cm)
Fibers number	280	272	98
Area (%)	6.45	6.71	15.34

cross-section while palm oil fibers are thin and their distribution is less homogenous. In Usumacinta sediments bricks, clusters of palm oil fibers can be seen in Fig. 11a.

As palm oil fibers are light and thin, their numbers are also high in each cross-section as we can see in Table 8.

The average number of fibers for six cross-sections of a crude brick with 3 cm long fibers is 272 fibers and they cover 6.71% area of a brick cross-section. In the case of 2 cm long fibers, the average number of fibers for a cross-section is 280 fibers and they occupy 6.46% area of a brick cross-section. The number of hemp shiv is less as these hemp shiv aggregates are thick and they occupy more area. Fibers are distributed in a longitudinal and transversal direction in the bricks (Bui, 2021).

**Conclusion**

This study is focused on the reuse of Dunkirk (DK) and Usumacinta River sediments (USU) with hemp shiv and POFl fibers respectively in crude bricks. Analysis of dredged sediments and plant biomass was done to find their characteristics. Mineralogy of Usumacinta River sediments shows that clay and silt content in USU sediments is higher than DK sediments. Furthermore, the morphology and size of particles show that POFl fibers are short with low width while hemp shiv is coarse aggregate material.

Bricks manufacturing steps such as sediments mixing, molding and drying were performed. Bricks were compacted with dynamic compaction with compaction energy of 600 kN.m/m<sup>3</sup> and oven-dried at 40 °C. Both harbor and river dredged sediments bricks characteristics and results were analyzed.

Tensile strength testing shows that adobe is a brittle material but the addition of natural fibers transforms it into ductile material. Fig. 8 shows that at 0% fiber content, there is no toughness in brick, and it starts to increase with higher fiber quantity.

Bricks with Usumacinta River sediments have maximum strength at 4% palm oil fibers addition with grid-2 cm fibers and 3% fibers content with grid-3 cm fibers. Bricks with Dunkirk sediments have a maximum tensile strength at 1% hemp shiv addition. Crude bricks with Usumacinta River sediments have higher tensile strength due to suitable USU sediments mineralogy and POFL fibers morphology.

Fibers distribution analysis shows that POFL fibers occupy nearly 6–7% while hemp shiv occupies 15.34% area of the brick cross-section. Crude bricks from both Usumacinta River sediments and Dunkirk sediments meet the minimum recommended tensile strength of 0.25 MPa according to standard NZS 4298 (1998) and NORMA E.080.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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