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Characterization of the thermal behavior, mechanical resistance, and reaction to fire of totora (Schoenoplectus californicus (C.A. Mey.) Sojak) panels and their potential use as a sustainable construction material

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ABSTRACT

The extraction and use of construction materials generate an impact on the environment due to human activity. Facing these problems requires the development of new alternatives that support changes toward sustainable construction. The development of materials using natural resources creates an important opportunity to reduce the demand for energy, such as the energy used in manufacturing materials. This will contribute to the reduction of exhausting nonrenewable resources and waste production. The objective of this study is to develop a new kind of thermal insulation out of natural vegetation. In this case, using totora (Schoenoplectus californicus (C.A. Mey.) Sojak), which is an aquatic plant that grows in Lake Titicaca. Panels were made from both shredded and whole totora. These panels could be used to improve the thermal comfort inside houses in the high Andes region of Peru, where there are extreme variations in temperature.

Studies have demonstrated that one of the characteristics of this plant is its low thermal conductivity, which reveals its potential for insulation. Considering which variables exist that affect the thermal efficiency of an insulating material, flexural tests, air permeability, water vapor permeability, and fire resistance tests were done.

1. Introduction

Totora (Schoenoplectus tatora) is an aquatic plant that grows in Lake Titicaca. Its heat insulation properties have been known and utilized for a long time by the Uros people, who are indigenous inhabitants of Lake Titicaca [1]. Using ancestral techniques, the totora reeds are the principal and most abundant material used by the inhabitants to construct the floating islands in which they live, as well as their houses and boats [2]. The reed is used as fodder for cattle and part of the stem, which is off-white in color, is used as food for

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humans as well. When the reed is mature, it is used as raw material for handicrafts. For these reasons, this member of the cattail family is of great social and economic importance [3].

Peru has a mega-diverse climate, with 27 of the 32 climate types that exist in the world [4,5]. In the high Andes region, the natural and climatic characteristics are a cold, intertropical climate at altitude. It is rigorous and very cold, with temperatures at night during the winter reaching −10 °C and sometimes it can get as low as −15 °C with the climate phenomena known as frost. Frost is a reduction of room temperature at inferior levels to the point of freezing, causing the water or the steam that is in the air to freeze leaving ice formations on surfaces [6]. Year after year there is a high mortality rate due to respiratory illness caused by extreme temperature variations. However, this high death rate is not only caused by extreme weather but is due to inadequate thermal conditions in the homes as well [7–10].

This region of Peru also has high poverty rates. Most of the houses in the countryside are self-built without the materials or resources necessary to make the house a true refuge [11–14]. In this context, this study sets out to develop a natural thermal insulator using totora (Schoenoplectus tatora), which is resistant, durable, has apparent properties of low thermal conductivity, and grows in abundance in Lake Titicaca in the Peruvian Plateau [15,16]. In addition, the use of totora in the Puno region may be advantageous because it is a local, renewable, and biodegradable resource, as well as its environmental impact like costs of transport and production in comparison with other insulating materials on the market [17–21].

This type of heat insulation of vegetal origin would be biodegradable and have a reduced environmental impact. Also, one hopes that its production costs would be low since the totora plant grows in abundance and is renewable. As a result, it may have wider use in construction considering that, at the moment, totora is an undervalued raw material [22–25].

Some studies have shown the outstanding potential of totora as a building material. For example, Ecuadorian architect Juan Fernando Hidalgo [26,27] has published two studies that analyzed the characteristics of totora. At present, he uses it as the main material for the manufacturing of furniture and rugs. Also, initiatives for its use have been promoted, along with other materials, as part of a recent experimental design motivated by the government which is looking to improve the precarious housing conditions in the high Andes of Peru [28].

Nevertheless, to date, studies do not exist that analyze the ample mechanical and thermal properties of the plant. This analysis is necessary to compete in a market that is more and more specialized and technical, where the values of thermal conductivity are between 0.042 and 0.032 W/mK [29–31].

To initiate the experimental phase, it is necessary to confirm that totora (Schoenoplectus tatora) has sufficiently low thermal conductivity for it to be considered a thermal insulator. Therefore, the hypothesis considers that totora, specifically from Lake Titicaca (Schoenoplectus tatora), has good heat insulation properties [14,24,32]. As such, the objective of this study is to analyze the totora's thermal conductivity by developing rigid panels using whole and crushed reeds that are pressed together using a natural binding material and characterize them experimentally to determine their potential use.

Additional to the analysis of the thermal properties and to define the applicability of this material as a thermal insulator, the mechanical properties of flexural strength, the reaction to fire, and the permeability of water vapor and air are analyzed. Also, it is necessary to identify the type of binding material and its appropriate formula to construct the panels to obtain suitable thermal behavior, considering that the type of binding used will influence the cost and the environmental impact of the final product [33]. In addition, the transformation process may also reduce the advantages of this material. This study addresses these aspects and analyzes them to offer alternatives that harness and revalue the use of totora as a thermal insulator.

2. Experimental materials and methods

2.1. Materials

Two experimental models were elaborated with totora (Schoenoplectus Californicus (C.A. Mey) Soyak)), which is the principal material used in this project and was acquired from the Lake Titicaca Chulluni area in the city of Puno, Peru (15.81°S, 69.96°W). The totora was imported for this investigation (Fig. 1).

Biologically based products were used as binders, namely fish glue, bone glue, and gum arabic glue supplied by Kremer Pigmente GmbH & Co. KG. These renewable, natural raw materials are used in the restoration of wood and traditional carpentry, which makes them easily manageable, and they can be used in construction without health risks [34].

In the experimental stage, additives were used to improve two characteristics of the experimental models: their behavior to fire as well as insects and fungi. Additives were selected that could act as flame retardants and that had repellent properties to maintain fibers free of agents that degrade the material. The following substances supplied by Labbox Labware S.L. were selected.

Borax: It is part of a large family of salts derived from boric acid. In this case, sodium borate was used. It is a smooth white crystal that dissolves easily in water and is not harmful to the environment. If left out in the open, it dehydrates slowly. Due to its repellent properties, it is used as a pesticide to prevent insect attacks, eliminate weeds, and inhibit mold [35].

Potassium aluminum sulfate or alum: Alum refers to several isomorphous, solid sulfates composed of trivalent and monovalent metals, especially potassium aluminum and sulfate. It is used as a flame retardant for textiles, a rubber latex coagulation agent, and an astringent [36].

2.2. Formulations

In order to determine the appropriate formulations for the development of thermal insulating panels, various tests were carried out by mixing the cattail fibers with different types of binders (fish glue, bone glue, and gum arabic glue), and different percentages of

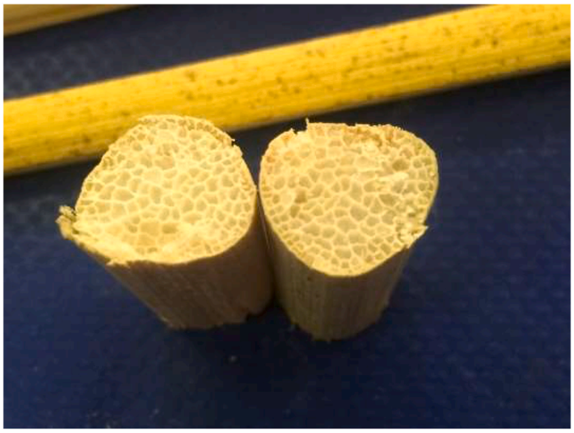

Fig. 1. Schoenoplectus tatora reed section (Aza-Medina).

water. The reference base weight was 10 g of crushed cattail fiber to achieve good workability of the composites during mixing. The amount of water varied.

In the case of alginate, the research carried out by Mariana Palumbo in 2015 [37] was used as a reference in which parameters for an adequate dosage had been established.

The experimental tests were to determine the most appropriate type of binder, the appropriate proportions between the fiber and other components, as well as the chemical compatibility between them. Finally, the formulations that allowed for adequate cohesion and those with the lowest thermal conductivity were selected.

Tables 1 and 2 show the formulations of fiber size, water, and binders (bone glue, fish glue, and gum arabic glue) that were considered.

Table 1
Unmixed fiber formulations.

Fiber size	Weight in grams			Formulation number
	Fiber	Binder	Water	
3.20 mm	10	10	52	01
1.19 mm	10	10	24	02
1.19 mm	10	8	22	03
fine fiber	10	10	24	04
fine fiber	10	12	22	05

Table 2
Blended fiber formulations.

Mixture of fibers	Weight in grams			Formulation number
	Fiber	Binder	Water	
3.20 mm	–	6	18	06
2.00 mm	4.0			
1.19 mm	3.5			
fine fiber	2.5			
3.20 mm	–	6	18	07
2.00 mm	2.5			
1.19 mm	3.5			
fine fiber	4.0			
3.20 mm	–	10	18	08
2.00 mm	4.0			
1.19 mm	3.5			
fine fiber	2.5			
3.20 mm	–	12	18	09
2.00 mm	2.5			
1.19 mm	3.5			
fine fiber	4.0			

2.2.1. Preparation and composition of the experimental models

Two types of experimental models with totora were developed. The first used crushed stems sifted to different particle sizes, as shown in Fig. 2. Next, different proportions of natural glues were added, which were gum arabic glue, bone glue, fish glue, and alginate. This was done following the proportions found in Table 1. The mixtures were used to form a panel using a metallic mold with wooden covers and a hydraulic press, as seen in Fig. 3.

The samples were compressed using approximately 0.5 kg/cm2 of pressure, which was maintained for 5 min until the desired thickness was obtained. Next, the samples were stripped and left to dry at room temperature for 48 h. Measurements from different parts of the dry samples were taken to obtain an approximated average of the sample as shown in Fig. 3.

In the second experimental model, the whole reeds of the totora were used. They were held together using different biological glues, which were gum arabic glue, bone glue, and fish glue. To produce the whole reed samples, the waxy outer layer of the stem had to be smoothed out with sandpaper because it prevented the binding agents from achieving the necessary union. The sandpapered stems were then covered with the selected binding agent and placed in a perpendicular direction, superimposing layers in alternating directions as seen in Fig. 4. The reeds were compressed using a hydraulic press with 0.5 kg/cm of pressure for 5 min and left to dry for 48 h (see Fig. 5).

Fig. 2. Sizes and sieves of shredded fibers.

Fig. 3. Process of crushing and compacting the fibers.

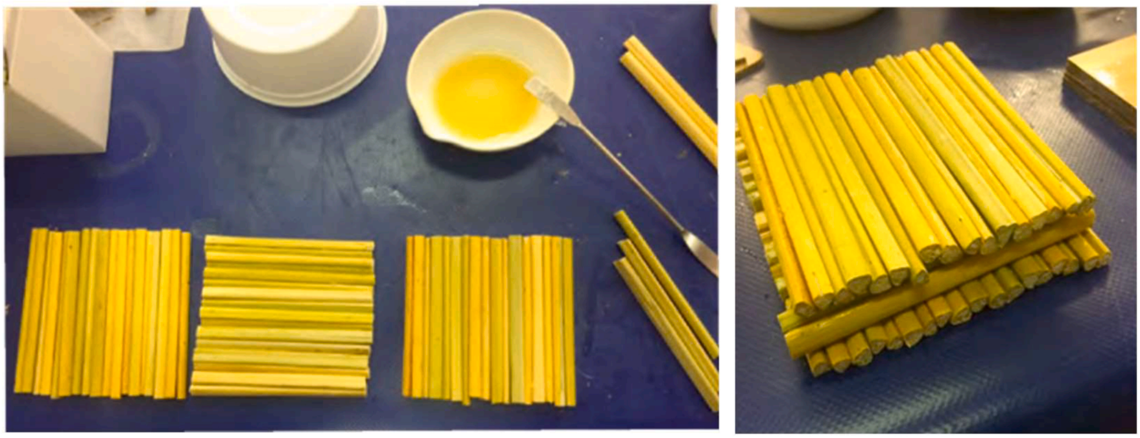

Fig. 4. Binding of whole cattail reeds.

Fig. 5. Process of pressing the whole reeds.

2.3. *Experimental methods*

2.3.1. *Thermal conductivity test*

The thermal conductivity (λ) and the diffusivity (α) of the samples of crushed and whole reeds panels were measured using a Quickline-30 Electronic Thermal Properties Analyzer based on the ASTM D 5930 Standard. It is made in the United States by Anter Corporation and uses a surface probe to measure thermal conductivity utilizing the transient hot-wire method. The equipment analyzes the findings of the transient temperature of the material with the variations of heat flow induced by electrical heating using a resistance heater that has direct thermal contact with the surface of the sample. The differences in the temperature on the surface of the samples are detected, as shown in Fig. 6. The measurements were taken at room temperature, indoors.

Twenty-five specimens of diverse characteristics, sizes, and thicknesses were analyzed. Two to four repetitions were made in some specimens to collect trustworthy data. The first measurements were taken when the specimens had dried at room temperature and the rest took place days later or when the samples had finished their drying process.

2.3.2. *Flexural test*

Zwick Roell equipment was used to carry out the flexural test, which was done at three points, defined by the ASTM D790 Standard. The feed mechanism is made up of two parallel supports for the test specimen and an actuator that applies pressure to the bending point in the center of the specimen between the supports. The speed of the test is 10/minute million and the separation between the strongpoints is 100 mm (Fig. 7). The test determines the minimum resistance of the specimen by using a stress-strain curve and the ASTM D638 Standard allows for the measurement of the flexural stress on the load-deflection curve using the testing machine's displacement transducer.

For this test, samples measuring 3.7 × 15 cm were placed on the surface and the exact thickness of each sample was measured with calipers so they could be registered in the testXpert III software. This process determines the maximum capacity that each specimen can support with a gradually increasing load during a short period of time.

Fig. 6. Thermal conductivity tests.

Fig. 7. Specimens that have undergone the test.

2.3.3. Behavior with fire

A radiator device outlined in the UNE 23.725–90 Spanish Standard was used to measure the time of ignition and the degree of extinction. Samples with a surface measurement of 3.7 × 3.7 cm and a thickness of 1.5 cm were placed on a metallic grid 3 cm below a 500 W heat source. The samples were taken away and put back after each ignition and extinction (Fig. 8). The most important parameters determined were the number of ignitions and the average value of combustion measured during the 5 min of testing.

Before being bound together, the whole reed specimens were immersed in a mixture of alum and borax with a ratio of 10:10. To speed up the drying time, the specimens were placed in an oven. This procedure was done to make the specimens less flammable since alum and borax act as flame retardants. The shredded fiber specimens were also immersed for a few minutes in the borax and alum mixture.

Before submitting the specimens to this process, it was necessary to obtain their initial weight. It was equally important to weigh the specimens after the test and obtain the percentage of mass loss due to fire (Fig. 9).

2.3.4. Water vapor permeability test

This test was taken according to the UNE-EN ISO 12572 Standard, which obtains the water vapor permeability of the totora specimens. A saturated solution of sodium hydroxide (NaOH) was used for the dry containers and a saturated solution of sodium sulfate (Na2SO4) for the damp containers. They were placed in an atmosphere with controlled conditions of temperature and humidity (23 ˚C and 45%) to generate differing water vapor pressure on both sides of the specimens. The samples were weighed regularly for five days until a progression in the change of weight of the samples was observed.

Fig. 8. A specimen being subjected to the radiator test.

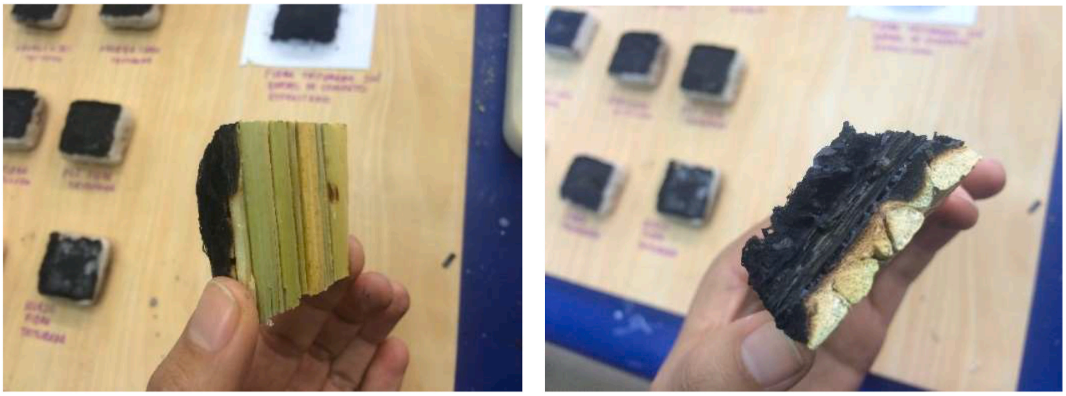

Fig. 9. Specimens after being subjected to the radiator test.

For the development of this test, transparent polymethyl methacrylate containers were used to contain the samples that measured 4 × 4 cm with a thickness between 1.5 and 2 cm, depending on the specimen. Two samples of each type are necessary, with their length, width, and weight measurements. The weight is a very important piece of data for obtaining results. A saturated solution of sodium hydroxide (NaOH) was placed in one and sodium sulfate (Na2SO4) in the other. The containers were closed with the specimens inside and modeling clay was used to seal the edges. This assured that all the water vapor will pass through the material as seen in Fig. 10.

2.3.5. *Air permeability test*

This test was done using criteria from the UNE-EN ISO 9237 International Standard. Its objective is to determine the air permeability of the different specimens. To obtain this, a method was applied that measured the speed of air (m3/h) passed through the sample with pressure tests.

This test was done by fixing the specimens to the opening (15 × 15 cm) of a support panel. To accomplish this, crushed fiber and whole reed specimens with the same dimensions were made. To measure the speed of the air, a thermal anemometer was placed alongside the backside of the panel. A compressor and a plastic cone fixed to the sample generated the necessary air pressure, as shown in Fig. 11. To process and compare the data, it was recorded every 5 s by a data logger that was connected to the anemometer.

Fig. 10. Prepared specimens for the water permeability calculations.

Fig. 11. Thermal anemometer and mounting system for the air permeability test.

3. Results and discussion

3.1. Thermal properties

Table 3 summarizes the thermal properties obtained for the samples analyzed. The results show that the smaller particles of crushed fiber specimens present a lesser value of conductivity and obtain better results. Throughout the process, very good results with the fiber have been obtained since it adheres very well with the binding agent, it does not require much water, and it has low conductivity and transmittance values with the average being (λ) 0.045 to (λ) 0.048. Concerning the whole reed specimens, similar thermal conductivity results were obtained with the average being (λ) 0.049 to (λ) 0.054. This is also a range of competent values [38].

In similar studies of the use of crop by-products (barley straw, corncobs, and rice husks), it was discovered that the thermal conductivity oscillates between 0.070 and 0.047 W/mK, which are considered to be acceptable values for thermal materials. However, they are only slightly superior to the typical values of commercially available products [39–41].

As observed in the graphs in Fig. 12, the thermal conductivity values of the whole stem board and the particle board specimens were analyzed with the T-Student test for independent samples. According to the results obtained, it is affirmed that there is no significant difference between the thermal conductivity values for both models ($t = -1.6882$, $df = 23$, p-value $= 0.1049$).

3.2. Flexural test

This test showed that there is a noticeable difference between the two models and the crushed fiber specimens have much less flexural strength than the whole reed specimens. The resistance of the crushed fiber specimens has a rank of 6–25 N/mm2 (standard force) and the samples with higher resistance are those that have been bound together with gum arabic glue (Fig. 13). Meanwhile, the whole reed specimens have a standard range of 240–320 N/mm2, demonstrating that the binding of the reeds and the fact that they were pressed together in alternating layers achieved a higher flexural strength. Therefore, this type of insulation can be used as a rigid panel that is easily manipulated, as seen in Fig. 14.

Table 3
A summary of the recorded thermal conductivity measurements.

Results of the tests carried out																
Dry measurements										**Calculus**	**Conductivity measurements**					
Sample	**Board type**	**Thickness (cm.)**				**a**	**b**	**mass 1 (g)**	**mass 2 (g)**	**ρ (kg/ m3)**	**λ(W/mk)**		**λ mean**	**α (10-6m2/ s)**		**α mean**
1	Particle Board	1,80	1,85	1,82	**1,82**	8,1	8,12	14,63	13,97	**125**	0,0484	0,0482	**0,048**	0,48	0,485	**0483**
2	Particle Board	1,81	1,81	1,8	**1,81**	8,08	8,12	12,93	12,33	**112**	0,0447	0,0465	**0,046**	0481	0,451	**0466**
3	Particle Board	1,7	1.71	1,69	**1,70**	8,05	8,09	16,49	15,16	**152**	0,0488	0,0477	**0,048**	0435	0,351	**0393**
4	Particle Board	2,10	2,25	2,35	**2,23**	8,20	8,18	17,16	11,78	**124**	0,0725	0,0482	**0,060**	0502	0,432	**0467**
5	Particle Board	1,81	1,79	1,81	**1,80**	8,22	8,15	11,83		**103**	0,0503	0,0501	**0,050**	0790	0,586	**0688**
6	Particle Board	1,65	1,80	1,75	**1,73**	8,15	8,20	11,87		**107**	0,0504	0,0491	**0,050**	0631	0,519	**0575**
7	Whole stem board	1,50	1,48	1,47	**1,48**	10,00	10,00	20,69		**218**	0,0495	0,0514	**0,050**	0391	0,387	**0389**
8	Whole stem board	1,50	1,46	1,49	**1,48**	10,00	10,00	20,17		**136**	0,055	0,0544	**0,055**	0414	0,433	**0424**
9	Particle Board	1,75	1,80	1,78	**178**	8,10	8,26	11,70		**98**	0,0541	0,0543	**0,054**	0646	0,450	**0548**
10	Particle Board	1,79	1,82	1,80	**1,80**	8,50	8,20	13,48		**107**	0,0577	0,0658	**0,062**	0555	0,393	**0474**
11	Particle Board	1,58	1,49	1,45	**1,51**	7,90	7,89	10,05		**107**	0,0487	0,0481	**0,048**	0498	0,478	**0488**
12	Particle Board	1,62	1,60	1,62	**1,61**	7,90	8,00	9,76		**96**	0,0454	0,0445	**0,045**	0534	0,510	**0522**
13	Particle Board	1,85	1,89	1,89	**1,88**	8,10	8,25	13,01		**104**	0,0481	0,0449	**0,047**	0519	0,407	**0463**
14	Particle Board	1,80	1,90	1,82	**1,84**	8,19	8,10	13,97	13,95	**114**	0,0501	0,0453	**0,048**	0670	0,418	**0544**
15	Particle Board	1,52	1,60	1,50	**1,54**	7,99	7,92	16,70	11,26	**171**	0,0519	0,0524	**0,052**	0395	0,382	**0389**
16	Particle Board	1,65	1,71	1,71	**1,69**	8,01	8,03	17,20	10,85	**158**	0,0512	0,0518	**0,052**	0548	0,559	**0554**
17	Particle Board	1,62	1,62	1,60	**1,61**	7,99	8,05	14,60	10,95	**141**	0,0518	0,0525	**0,052**	0452	0,509	**0481**
18	Particle Board	1,51	1,50	1,48	**1,50**	8,01	8,0	15,10	10,96	**157**	0,5210	0,0531	**0,053**	0476	0,479	**0478**
19	Particle Board	1,30	1,22	1,32	**1,28**	8,12	8,15	30,80	15,20	**364**	0,0620	0,0656	**0,064**	0310	0,423	**0367**
20	Particle Board	1,60	1,62	1,61	**1,61**	7,98	8,02	26,30	14,05	**255**	0,0560	0,0553	**0,056**	0424	0,317	**0371**
21	Particle Board	1,50	1,50	1,42	**1,47**	8,20	8,12	19,88	18,85	**203**	0,0605	0,0591	**0,060**	0382	0,367	**0375**
22	Whole stem board	1,50	1,47	1,48	**1,48**	15,00	15,00	26,30	24,24	**79**	0,0761	0,0727	**0,074**	0399	0,411	**0405**
23	Particle Board	1,49	1,51	1,50	**1,50**	23,50	14,50	110,90		**217**	0,0587	0,0586	**0,059**	0246	0,376	**0311**
24	Whole stem board	1,5	1,51	1,49	**1,50**	15,00	15,00	64,60		**191**	0,0593	0,0631	**0,061**	0320	0,332	**0326**
25	Particle Board	1,10	1,15	1,30	**1,18**	24,00	15,00	105,00		**246**	0,0644	0,0688	**0,067**	0293	0,583	**0438**

3.3. Behavior with fire: time of ignition and extinction

Table 4 summarizes the results obtained in the radiator test. Although all organic materials are combustible, totora behaves well with fire. When it is subjected to an external heat source, it displays a short duration of ignition due to a carbonized layer that is formed once it first ignites, which protects it from fire. It was observed that the material responded in a favorable way to the alum and borax treatments as well. The average time of ignition in these samples was less than 3 s, therefore, it is considered null.

Concerning the loss of mass, it is necessary to consider that the specimens had a refractory cement covering on their edges. This was done to avoid combustion at the edges where the fiber is exposed, which would add uncertainty to the test and affect the results. The whole reed specimens lose less mass than the crushed ones. Although the whole reed specimens ignite more, the combustion takes place on a superficial level whereas with the crushed fiber specimens the combustion occurs throughout.

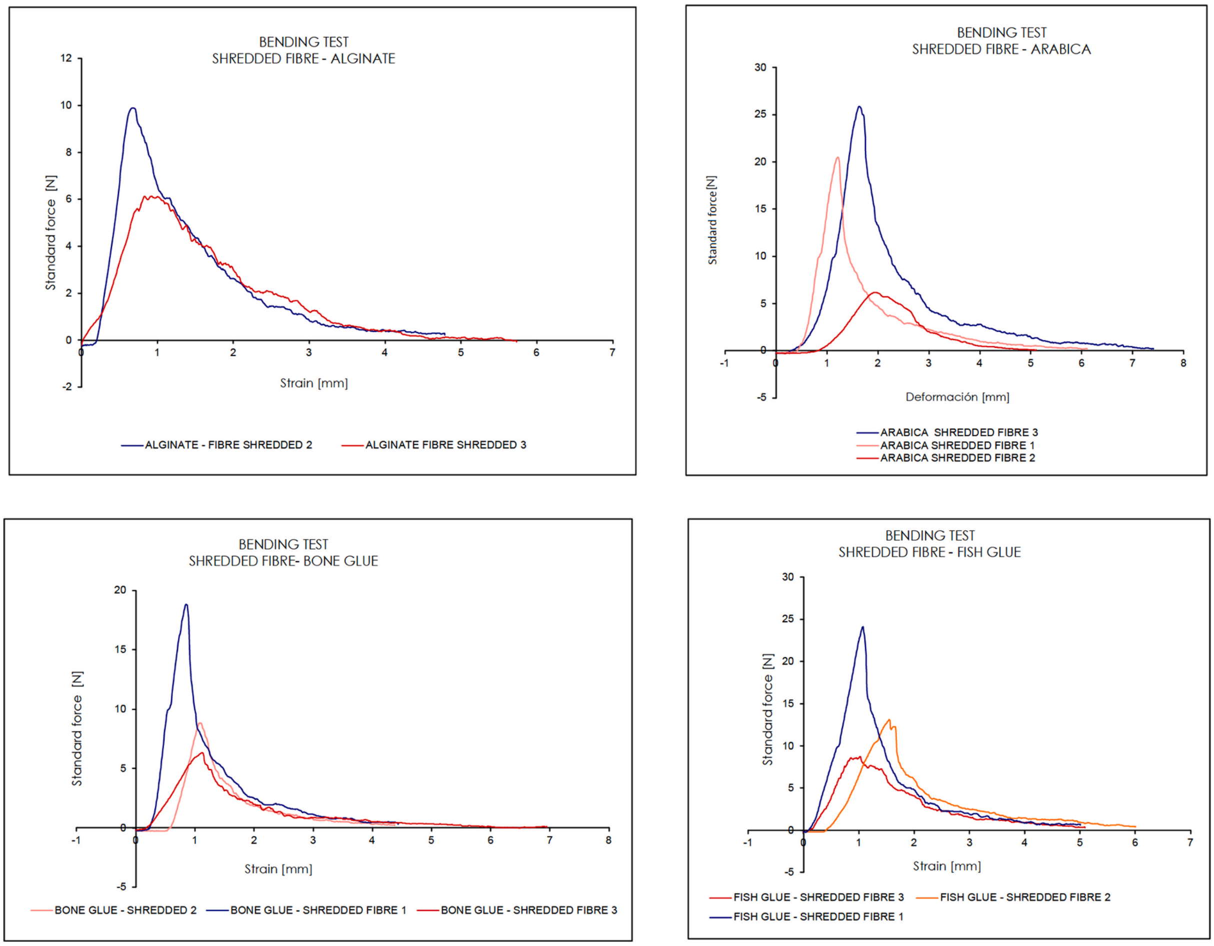

Fig. 12. Stress-strain curves for each type of shredded fiber specimen.

As observed in the graphs in Fig. 15, these data were analyzed with T-Student for paired samples, according to the result, it is affirmed that there is a significant difference between the initial and final mass ($t = 19.9$, $df = 12$, $p = 1.456e-10$). In the case of the samples without treatment and with treatment (alum and borax), the results were analyzed with T-Student for independent samples, according to the result it can be affirmed that there is no significant difference ($t = 1.3524$, $df = 11$, p- value $= 0.2034$).

3.4. Water vapor permeability test

The crushed fiber specimens obtained a good level of regression. The results obtained have an error between 10 and 20%, which is sufficient for analyzing the tendency and comparing results. However, the results for the whole reed specimens are much less trustworthy. More than likely, this is due to their greater level of resistance and the variation of mass registered in 5 days was too small to collect strong results. Even so, it is possible to draw conclusions. The average value of the factor of resistance to water vapor of the specimens with crushed fiber is between 3.8 and 4.9. No significant differences are observed according to the type of binder used. These are comparable values to other natural insulating materials like wood fiber, linen, and hemp. They are low if compared with polymeric foam, which presents factors of resistance between 20 and 70.

Table 5 shows the results obtained for the crushed fiber samples. The preliminary results indicate that the whole cane samples have less permeability with factors of resistance between 10 and 20, however, this must be confirmed in future research. At the moment, it would be possible to consider that they are more appropriate for indoor use than materials made with crushed fibers. However, it is necessary to create models that consider all the materials that make up the enclosure, the climatology, and the temperature indoors to determine the risk of condensation.

The difference in the weight of the specimens as the days went by allowed us to calculate the density of steam flow along the surface. Once this data was obtained, the values of permeability, the resistance to steam, the permeability of water vapor, and the factor of resistance of water vapor were obtained. Fig. 16 shows the data gathered during the test.

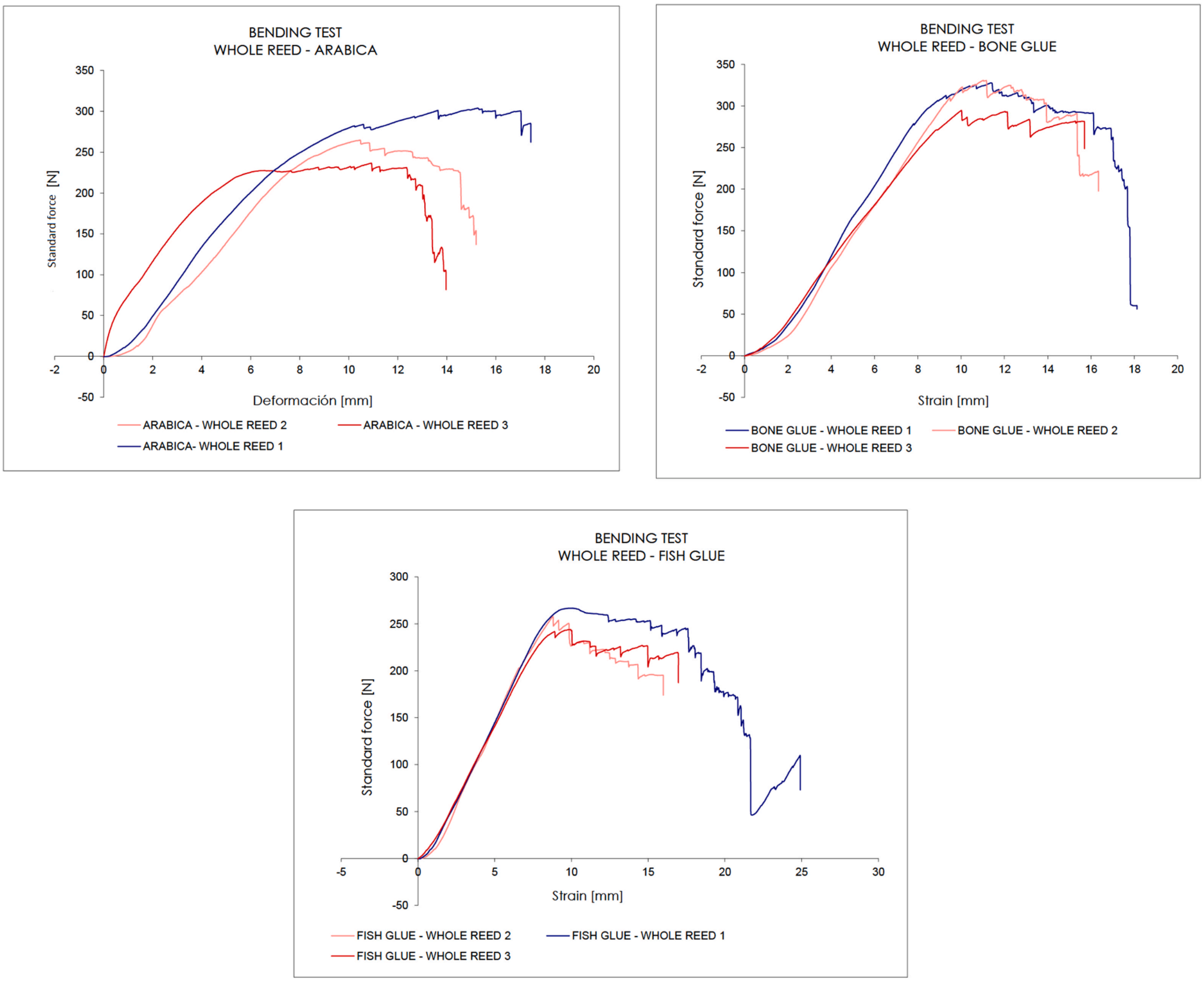

Fig. 13. Stress-strain curves for each type of whole reed specimen.

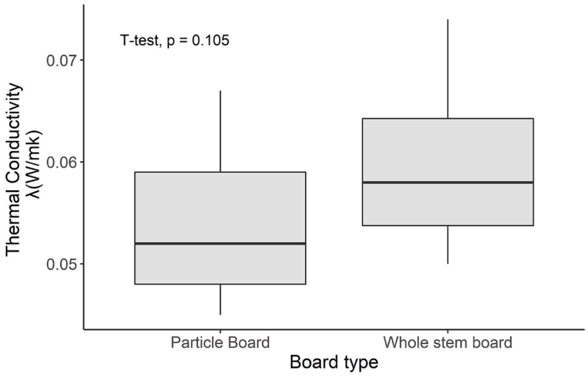

Fig. 14. Comparative graph of thermal conductivity values between particle board and whole stem board.

3.5. Air permeability

The behavior of specimens in this test was compared with *kesana* or totora mats that are handcrafted and used for the construction of houses on the Uros Islands [2]. The test specimens were also compared with the behavior of wood fiber, which is a more commercially available natural insulator.

To initiate this test, a mat or kesana was fixed to the measurement system to register its values of air permeability. The data was collected by a data logger and the values obtained oscillated between 17 and 38 m/s. This process was repeated for all the samples. As

Table 4
Radiator test results.

RADIATOR TEST RESULTS

N°	Specimen	Characteristics	Time 1° Ignition (s)	Number of Ignitions	Average duration (s)	Initial mass (gr.)	Final mass (gr.)	Loss (gr.)	Percentage %
1	WHOLE- ARAB 01	UNTREATED	6	14	4,0	11,05	8,35	2,70	24
2	WHOLE- BONE 01	UNTREATED	4	6	6,0	11,29	8,88	2,41	21
3	WHOLE- FISH 01	UNTREATED	6	10	5,4	7,85	5,98	1,87	24
4	FIBRA- ARAB 01	UNTREATED	11	0	0	9,61	6,58	3,03	32
5	FIBRE- ARAB 02	UNTREATED	10	1	3,0	10,03	6,98	3,05	30
6	FIBRE- FISH 01	UNTREATED	61	0	0	9,75	6,79	2,96	30
7	FIBRE- FISH 02	UNTREATED	45	5	3,0	11,23	8,39	2,84	25
8	FIBRE- BONE 01	UNTREATED	13	4	6,0	8,49	4,59	3,90	46
9	FIBRA- BONE 02	UNTREATED	11	1	3,0	10.66	7,80	2,86	27
10	WHOLE- FISH 01 - A	ALUM + BORAX	8	0	0	9,24	6,6	2,64	29
11	WHOLE- FISH 02 - A	ALUM + BORAX	7	0	0	9,97	7,22	2,75	28
12	FIBRE- ARAB 01-A	ALUM + BORAX	0	0	0	8,76	6,16	2,60	30
13	FIBRE- ARAB 02-A	ALUM + BORAX	0	0	0	8,46	6,40	2,06	24

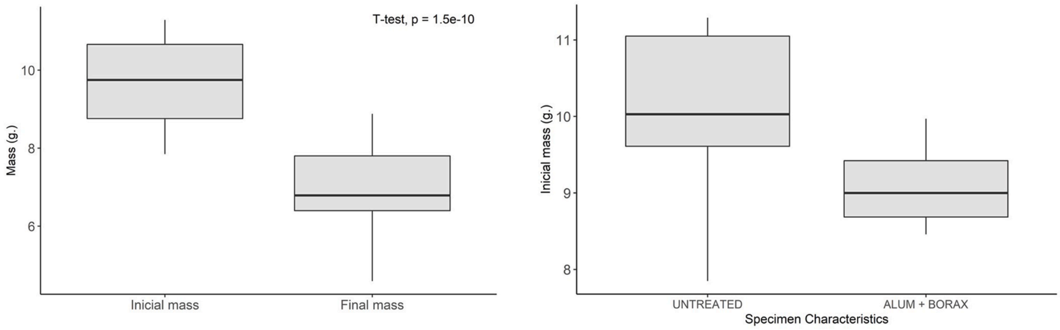

Fig. 15. Comparative graphs of loss of mass between the whole reed and crushed specimens with and without treatment.

Table 5
Vapor resistance factor (μ) of shredded fiber specimens.

Water vapor resistance factor μ

Fiber	NaOH		Na_2SO_4	
Fish fibers	3.9	±0.7 (18%)	4.4	±0.6 (14%)
Bone	4.5	±0.9 (20%)	4.9	±0.7 (14%)
Arabic	3.8	±0.4 (10%)	4.5	±0.4 (9%)

shown in Fig. 17, the whole reed specimens do not allow air to pass through easily. The data logger recorded values similar to what was found at the beginning of the test, which is between 0.05 and 0.07 m/s.

For the crushed fiber specimens, it is much easier for the air to pass through the surface, nevertheless, the values that have been registered are lower than the totora mats. The values are between 18 and 22 m/s as shown in Fig. 18. There was little difference detected in the behavior of the specimens according to the different types of binding agents used. They all behaved practically the same way.

With all the processed results, it can be concluded that the totora used as a whole reed panel presents better behavior than both the crushed fiber specimens and the totora mats. This occurs because the strong adhesion of the reeds does not allow for easy passage of air. This is shown in Fig. 19. If, on an individual basis, the behavior is compared with wood fiber (12–16 m/s) we see that the whole reed panels also greatly surpass their measurement of behavior (Fig. 20).

4. Conclusions

During the development of this project, several tests were performed to determine the behavior of totora as a natural thermal insulator. According to all the results obtained, it can be concluded that totora is a competent thermal insulator. The obtained values of thermal conductivity have been between (λ) 0.046–0.058 W/mK, which is within the rank of values of other commercialized materi-

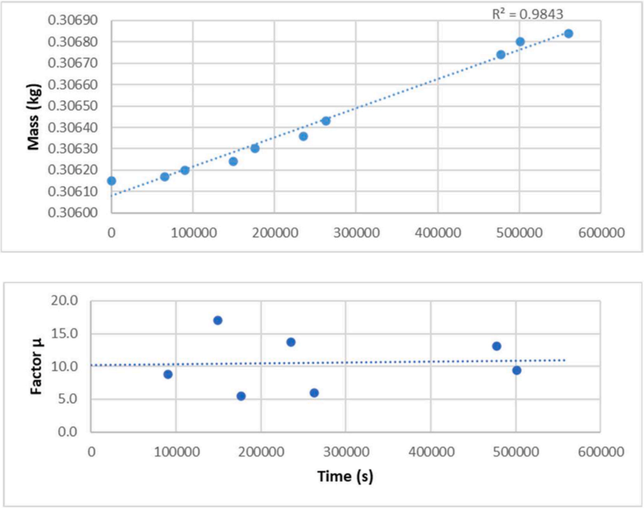

Fig. 16. Mass in (kg) and vapor resistance factor (µ) versus time, collected in the water vapor permeability test.

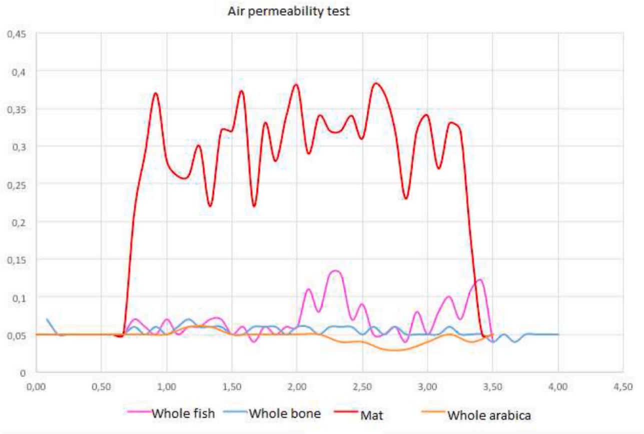

Fig. 17. Comparison of results between the mat and whole cattail reed specimens.

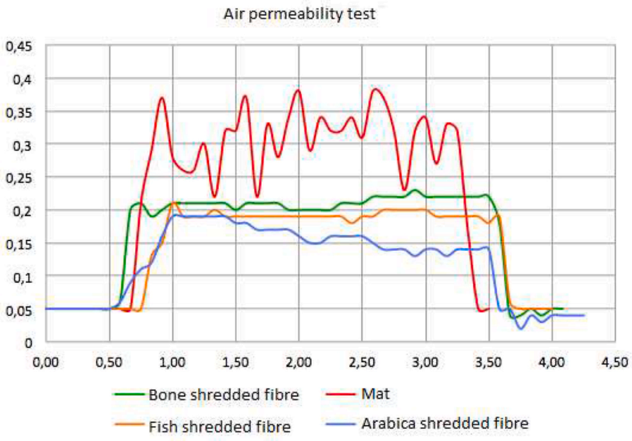

Fig. 18. Comparison results between the mat and shredded fiber specimens.

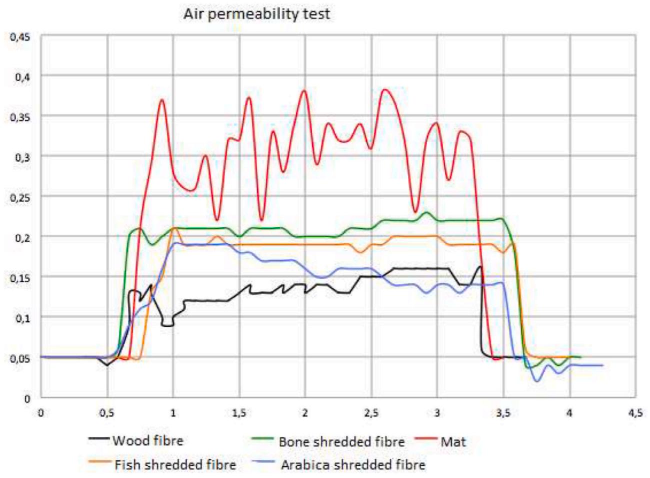

Fig. 19. Comparison of results between mat, wood fiber, and shredded fiber specimens.

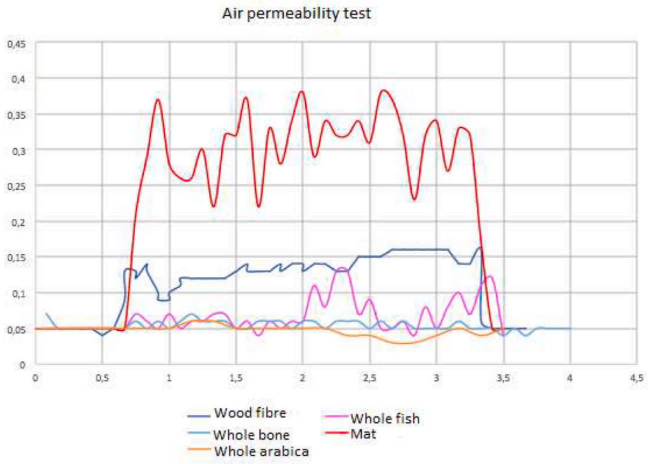

Fig. 20. Comparison of results between mat, wood fiber, and whole cattail reed specimens.

als of vegetal origin like linen with thermal conductivity of 0.037–0.047 W/mK, straw bales with 0.065 to 0.045 W/mK thermal conductivity, or wood fiber with 0.050 to 0.037 W/mK thermal conductivity.

Panels made with four types of natural binding agents (gum arabic glue, fish gum, bone gum, and alginate) have been compared with two different models: whole reed panels with and without sandpapering and crushed fiber panels with different-sized particles. The type of binding agent does not significantly affect thermal conductivity and the differences found in thermal conductivity are due to the size of the particles. The models with the best results were the specimens with the smallest particle size. In addition to being an easily renewable material, it is a good alternative to reduce the consumption of non-renewable resources. The necessary means for their manufacture are not intensive and could be implemented easily in the region.

The panels made from whole reeds have the advantage as they need less processing to transform the raw material and they also need less of the binder to be manufactured. Totora plants can measure up to 4 m in height with stems that do not have knots, which could permit a more consistent format in the panels. Nevertheless, disadvantages related to the manufacturing process exist because totora requires a more meticulous selection process in terms of the diameter of the reeds. The advantage is that this process is similar to the one already used by craftspeople who make totora mats.

The advantage of panels made with crushed reeds is they can be manufactured with the waste left over from manufacturing mats or other objects, which would provide greater use of the plant. Besides the development of formulations and the analysis of the thermal behavior of the material, a series of exploratory tests of other characteristics of the material for its use in construction have been made.

In order to assess the resistance of the material during installation, a flexural test was carried out. The results have verified that it is possible to develop rigid panels from the union of reeds with organic resins that can resist a maximum force of 331 N/mm2. The panel that presented the best results was the one that is made up of sandpapered whole reeds bound together with bone glue. Also, water vapor and air permeability have been determined. This provides useful data for future valuation of the risk of condensation that could take place from using this insulator in existing houses, as well as possibly contributing to the improvement of air infiltration of the protective surface material.

Another aspect that has been considered is the material's behavior to fire. The tests that compared the behavior of the material without being treated with alum or boric acid and the material that was treated show good results. The behavior of the material without treatment is better than polymeric foam because it extinguished itself. This behavior was improved in the treated materials, which show favorable results for treating the material with flame retardants. The treated materials showed better behavior with fire, managing to avoid full combustion with immediate moments of ignition and extinction. Although it is not possible to directly transpose the results obtained in the laboratory with the behavior of the material "on-site", the collected data allows for the comparison between different formulations and to establish an order of magnitude and tendencies in its behavior. In future research, this data will have to be valued in real situations.

All these tests show the potential of the material for use as thermal insulation in construction in the Puno region or in any place where this plant is located. Of the developed formulations, the whole reed panel is the one that presented a more favorable behavior overall. For this reason, future investigations will be to address the characterization and improvement of this formulation.

This study is an initial approach to the material and its possibilities, which is why an exploratory experimental campaign has been designed. A more in-depth study is necessary to characterize in a more detailed manner each one of the aspects addressed.

That would have to be accompanied by the characterization of the existing houses in the Puno region to evaluate (with numerical simulation and on-site tests) improvements that could be made with the implementation of this material in existing houses.

Finally, questions related to the economic, environmental, and social impact of possibly implementing an industry based on totora in the Puno region would have to be addressed in future investigations as well.

CRediT author statement

Aza-Medina: Conceptualization, Methodology, Writing- Original draft preparation, Validation, Formal analysis, Investigation, Writing –Review & Editing, Visualization, Project administration. Palumbo: Conceptualization, Methodology, Writing –Review & Editing, Supervision. Lacasta: Supervision, Visualization, Resources. González-Lezcano: Software, Visualization.

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.

Data availability

Data will be made available on request.

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