Sustainable Structures
ISSN: 2789-3111 (Print); ISSN: 2789-312X (Online)
http://www.sustain-dpl.com/journal/sust
DOI: 10.54113/j.sust.2024.000047

CASE STUDY

Design and construction of houses with Guadua cane and rice husk in Ecuador as an alternative to local development

Pedro José Rodríguez Gómez[a*], Adela María García Yero[b,*], Guberto Cánovas Riverón[c]

[a] Titular Professor, Universidad Técnica de Babahoyo, Babahoyo, Ecuador.
[b] Center for Study of the Conservation and Development of Structures, Universidad de Camagüey, Camagüey, Cuba.
[c] Center for Study for Business and Territorial Management, Universidad de Camagüey, Camagüey, Cuba.
[*]Corresponding Author: Pedro José Rodríguez Gómez. Email: pjrodriguez@utb.edu.ec

Abstract: The use of sustainable construction materials as a response to habitat problems is one of the urgent alternatives for Ecuador. The country has a high production of rice, an intensive crop that generates a high volume of polluting waste that is not efficiently managed, which causes damage to the environment. The purpose of the research was to design a sustainable construction system with the joint use of Guadua cane, of ancestral domain, and rice husk as components of a hybrid lightweight concrete. As a result, two houses were built in 1992 and 2020, respectively, validating the feasibility of the proposal. A flexible, resistant, sustainable system is achieved, which takes advantage of local resources, both traditional and alternative, that allow to give an answer to the habitat with a good aesthetic finish. It is an alternative for the local development of autonomous governments that allows the construction of decent, durable and comfortable housing, with the use of their own resources and in accordance with the country's traditions.

Keywords: Construction system; Guadua cane; rice husk; hybrid lightweight concrete; local development

1 Introduction

Today, the need to change production paradigms that contribute to environmental sustainability and conservation is increasingly recognized. Thus, the construction is a main sector in the transition to a world that takes advantage of the use of renewable sources, recyclable and less polluting materials. In 2019, this sector accounted for 35% of global energy consumption and were responsible for 38% of increased of carbon footprint into the environment [1].

In Latin America, the search for alternative construction materials has become relevant in the use of endogenous resources that mitigate the environmental impacts [2]. New technologies, the use of reinforcing materials, the combination of traditional, contemporary and recycled materials optimizes the performance of buildings [3], and generate sustainable construction practices. The above, together with good local development management, allows increasing employment, stimulating investments, the use of financial incentives and entrepreneurship as development options [1].

The need to use sustainable materials is recurrent in Ecuador. In the country, local sustainable architecture has a relevant role in the maintenance and rescue of identity values, the adaptation to local conditions, the use of endogenous materials with low energy consumption, with the consequent reduction of the environmental carbon footprint [4]. Hence, the ancestral experience in the use of

Received: 20 January 2024; Received in revised form: 10 August 2024; Accepted: 26 August 2024

Guadua cane and the exploration of other materials that respond to circular economy criteria in terms of local development.

Based on the analysis of existing studies about the sustainable construction materials, the purpose of this research was to design of a sustainable construction system with the joint use of Guadua cane and rice husk as components of a hybrid lightweight concrete to contribute to the solution of habitat problems in the Ecuadorian Costa region.

2 Traditional construction typologies for habitat in Ecuador with the use of Guadua cane

In Ecuador, the use of Guadua cane has been extended as a response to the housing problem, both in rural areas and in the cities. There is a lot research on the combined use of different techniques based on the potential of processing the material and its characteristics by virtue of its geographical location. Its use is associated with vernacular architecture, linked to traditional and local knowledge and, away from academia, in relation to the place where it is built [5].

In the region of the Ecuadorian Costa, the typology of the rural Guadua house or near the rivers is built as a palafitte, on a structure of feet and horizontal beams of wood, first as a framework of strips as a floor, while the horizontal beams are nailed to the Guadua cloths that close the house. A carpentry lining can be used as a termination and they are roofed with zinc tiles or with vegetable materials, this form is known as mat and chopped cane. When built in flooded areas, the first level can be used to store boats or gear; however, in rural areas that are not necessarily flooded, this level is used to protect animals, carry out productive activities, storage or visits [6]. (**Fig. 1**)

(a) Stilt houses with metal sheet roofing (b) Guadua cane houses (c) Guadua cane houses

Fig. 1 Typologies of Guadua cane houses in Ecuador: a Stilt houses between vernacular tradition and precariousness, with metal sheet roofing on the Babahoyo River; b and c Guadua cane houses in the city of Babahoyo, Ecuador.

In the cities the constructive typology is modified, it can reach two levels, although it can reach three. The articulation of arcades is appreciated, greater union with other materials such as wood or enquinche, the roofs preferably of zinc tiles or other alloys. The Guadua panels can be placed horizontally or vertically, the use of nails and pliers for the assembly, the strips of cane used as latillas or lianas for the joints. The first floor can be used as productive space for small businesses [7] (**Fig. 1**).

There are several governmental, institutional and private initiatives in the country that are committed to respond to habitat problems in a sustainable manner, in particular with the use of Guadua cane [8-9]. There are many examples of the versatility of bamboo and Guadua cane as construction materials [10-12]. However, despite the recognition of the need for their use, there is not always adequate management of their implementation from a local development perspective.

Experimentation and construction are limited to community or ad hoc proposals. In most cases, there is a lack of sustainability in implementation. The feasibility of their use from the local level is recognized, as they generate productive and social synergies, while adapting to the cultural and identity environment where they are built and with indissoluble links to tradition.

By using alternative construction materials as an option to traditional and contemporary materials with high energy consumption, solutions are achieved that take advantage of the government's interest at different levels of government, especially in its autonomous or local instances to implement sustainable responses to the demands of adequate and inclusive habitat, through the articulation of actions between the different actors and the community to achieve decent spaces that contribute to better life´s conditions.

3 Alternative sustainable building materials: Guadua cane, rice husk, hybrid lightweight concrete

In spite of the existence of a long tradition of Guadua cane and wood constructions in the Ecuadorian Costa region, they face functional and finishing problems due to the lack of a covering that protects them from anthropic and environmental risks, which implies the need for constant maintenance. The project of application of these new technologies is originated precisely to solve this aspect, to provide new elements to build houses, school classrooms, community centers, among others, in a functional and economic way, especially in the marginal urban and rural sectors of the areas.

The proposed and implemented construction system constitutes an alternative technology by using easily available materials (Guadua cane and rice husk) and giving the houses a safety and finish similar to those provided by conventional technologies.

3.1 Guadua cane

Guadua angustifolia Knuth (GaK), a grass belonging to the Bambusoideae family, like bamboo, has the ability to dissipate seismic energy, improve the structural behavior of buildings and be used as reinforcement or as a pure structural element [13-16]. It is a tropical subspecies, endemic to Central and South America, and its use as a construction material dates back to the pre-Columbian period, especially by the Mayas and the Incas [17]. It is also known in Latin America as "brava", "macho", "mansa", "caña" or "guadúa". In Ecuador it is a common crop that grows abundantly, especially in the Costa and Amazonian regions. It is known for its structural, physical and aesthetic properties, as well as for the diversity of construction and handicraft solutions, in addition to its sustainability and low cost compared to conventional construction materials [18].

It is recognizable by its green hue and the white band around the node and its thorns on the branches in the Ecuadorian varieties. It is very slender, fast growing and flexible, hence its widespread use in construction [19]. It is an easily renewable, ecological, natural and sustainable material, hence its capacity to produce biomass. It is estimated that the carbon fixation of Guadua angustifolia Knuth cane is 54.3 t, of which 10.8 t corresponds to the rhizome, representing 19.9% of CO_2 fixation, while 43.5 t, i.e. 80.1% corresponds to the aerial part of the plant, in a growth period of 6 years [20-21].

Its harvesting does not involve deforestation and it is capable of absorbing 30% more CO_2 than trees, hence its property of reducing the carbon footprint, as well as providing fresh, pleasant and safe environments. Its low cost makes it a material of easy accessibility and climate adaptability. Among its drawbacks in construction is its resistance to fire [22].

The use of Guadua sugarcane also offers economic and social advantages, as it reduces costs, generates jobs, strengthens community capacities, promotes the conservation of natural resources and preserves local cultures. Its cultivation does not require the use of chemicals or large amounts of water, and it is a natural replacement. Its transformation process as a construction material is simple, without the need for major technological changes [17].

The physical properties of Guadua cane guarantee its use as a construction material. Its density varies between 300 and 800 kg/m^3 depending on the age of the plant and the species. Its durability reaches 50 years depending on its location, environmental conditions and maintenance. Humidity varies between 10% and 20%, while porosity is between 60% and 80%. Its permeability is low, which guarantees a good resistance to water and humidity, hence its use in palafitic constructions, but better results are achieved after a drying process to reduce dimensional changes. Its fire resistance is good due to its low thermal conductivity (between 0.30 and 0.75W/mK, which places it within the range of concrete and wood) and its high silica content. As a perennial rhizomatous plant, it reaches a height between 6 and 20 m, its maximum diameter of 20 cm is used between 4 and 5 years after planting. Its best use for construction is reached in its mature cane stage, between 2 and 5 years, when it achieves its maximum resistance [23].

For its manipulation as a construction material, Guadua cane is sectioned into elements of variable size as required, which are subjected to a curing process that will allow its preservation from the attack of foreign agents, in addition to giving it a great consistency to withstand the different efforts to which it will have to respond (bending, traction of a ratio, modules of rupture and elasticity, effect of the water-cement ratio, effect of the intervention of additives, plastic flow, etc.). Advantage is taken of its flexibility and lightness, as well as its capacity to resist physical-mechanical stresses (compression, traction, bending and seismic behavior), its ability to absorb sounds, odors and high temperatures, its aesthetic qualities and versatility.

3.2 Rice husk

As a result of industrial production, polluting residues are generated with repercussions for human health and the environment that increase annually. Many of these wastes are the result of wasting or not taking full advantage of parts of agricultural production, such as corn stalks, rice and sugarcane straw, rice and coffee husks, as well as the bark of trees such as palms [24]. However, the reuse and recycling of agroindustrial production residues as construction materials is gaining ground every day, thus minimizing environmental impact [25-27].

One of the main economic sectors in Ecuador is rice production. In 2021, 340,281 hectares of rice were planted in the country, and 1,504,214 t of paddy rice were harvested, with the province of Guayas being the largest producer with a national share of 63%, followed by Los Ríos with 30% and by Manabí, Loja and El Oro. In 2021 itself, there was a 13% increase in production and a 9% increase in harvested area compared to the previous year. Despite this, it is not possible to speak of upward trends due to their fluctuating nature [28, 29].

Rice is a short-cycle grass (Oriza sativa) that requires large quantities of water for its production and is grown on all continents. As a result of its production chain, in addition to the marketable grain, the husk or hull is obtained, which is generally used to replace fuel in the drying process itself. It has a strong, woody and abrasive nature that guarantees its resistance to environmental factors [30].

The rice husk is canoe-shaped, with a rough, yellowish surface. Its length depends on the rice variety and ranges from 8 to 10 mm long by 1 to 2 mm wide, which corresponds to 30 to 40% of its length. It represents about one-fifth of the harvested product, but this may vary according to the variety of rice and the conditions of its production [31].

Rice husk represent a $^1/_5$ of the grain mass, it is composed of organic material: 50% cellulose, 25-30% lignin, 15-20% silica and 10-15% moisture, so it is not biodegradable. Its bulk density is small, between 90-150 kg/m^3 [32]. It has high porosity (54%) which helps to create air films that reinforce its insulating capacity, thermal conductivity (K) of 0.03605W/mK making it an efficient thermal insulating material; it does not burn easily due to the high incineration temperature, hence its fireproof behavior. It is highly resistant to moisture penetration and fungi, does not transmit heat easily, does not emit gases and is non-corrosive when in contact with steel, aluminum and copper. It naturally exhibits the properties required for isothermal materials, so it is used to thermally insulate walls, floors and roofs of houses [33-35].

The high concentrations of silica (SiO_2) in rice husks are highly polluting to human health and the environment. This concentration increases once calcined, until reaching values of 90% of silicon oxide of fine size and high reactivity. Because of this, it is possible to use it in the production of concrete as a partial substitute for Portland cement, as well as a source for preparing silicon (Si) based compounds [36].

Rice husk is used in the production of cement in different dosages, this addition is employed to improve the mechanical properties of mortars and reduction environmental impacts [37]. Its use is increasing in the manufacture of blocks for walls, lightweight panels, pavements, among others [36, 39]. Its use reduces the discharge of the husk into rivers and thus its pollution level. With these properties, it can efficiently contribute to the construction of housing and social works, as mass production, not only for the population with scarce economic resources, but can also be extended to other sectors and functions.

3.3 Hybrid lightweight concrete

The proposed hybrid lightweight concrete has rice husk as one of its main aggregates, after it has undergone a mineralization process to improve its strength, impermeability and lightness. The dosages depend on the structural element to be built. Its hybrid character is achieved by combining a Guadua cane mesh cut in the form of a slat of variable diameter tied by means of 4mm steel wire [40-44].

3.4 Problems with the use of rice husks in the Costa region of Ecuador

The main rice-producing areas in Ecuador are concentrated in the provinces of Guayas and Los Ríos, which belong to the Costa Region, located between the Andes Mountains and the Pacific Ocean. In the case of the region, environmental deterioration caused by contamination of water sources is increasing, particularly in Los Ríos province [36]. The case of the Babahoyo river in the city of the same name stands out, with sewage and wastewater from production processes such as agriculture, especially rice production waste, which not only clouds the water, but also contaminates it due to the degradation of the rice husk in the water, which releases silica among its components [33]. This causes not only the loss of fish and aquatic animal species, but also cancerous and other diseases among the inhabitants of the riverbanks (**Fig. 2**).

Fig. 2 Rice husk contamination of the Babahoyo river.

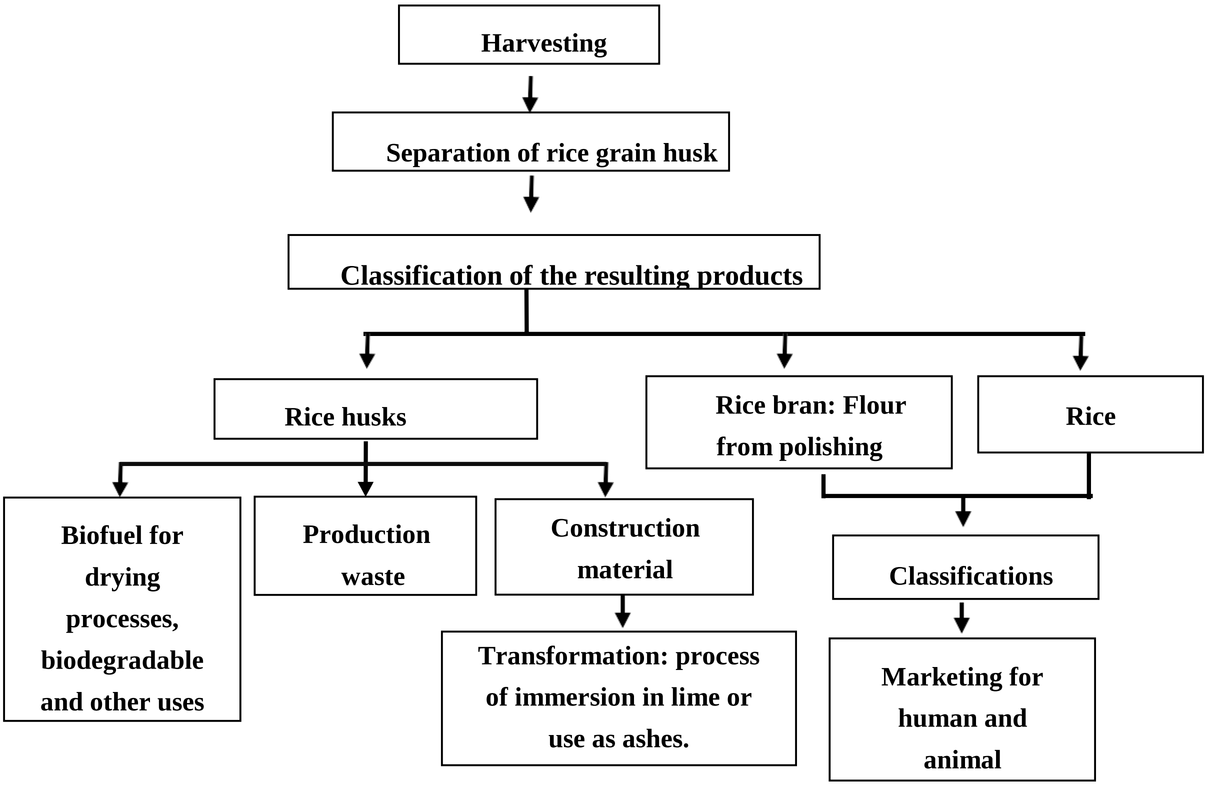

Fig. 3 Primary scheme of rice production and use.

In the Costa region, rice husks are one of the by-products or residues of the green paddy threshing process to obtain white rice and can be used as biofuel, especially in the grain drying process itself, in addition to being used mainly for bedding in poultry companies in the area, horse stables, concentrated animal feed and compost producers.

The rice production chain shows the different outlets for the products generated. It is worth noting the various options that the product has, and even so, it is insufficient to take advantage of them (**Fig. 3**). For every 5 tons of paddy that are milled, one ton of husk is generated. The usual practice of industrialists consists of direct burning of this residue in open spaces, generating environmental problems not only for the air, but also for the soil [34].

In many researchers was demonstrate the potential of using rice husk ash (RHA) as a pozzolanic material in lightweight concrete, by its capacity to increase compressive strength occurred between the levels of 10 and 15% RHA replacement in concrete for all cure durations [40]. In the case study, instead of the use of ash, which in itself in the burning process produces environmental impacts, rice husk is used, pre-treated before being incorporated into the lightweight concrete.

The versatility of Guadua cane and rice husks as construction materials is demonstrated by their properties and characteristics. However, despite the recognition of the need for their use, there is not always adequate management of their implementation from a local development perspective. Experimentation and construction are limited to community and specific proposals. In most cases, there is a lack of long-term sustainability in implementation. The feasibility of its use from the local level is recognized by generating productive and social synergies, while adapting it to the cultural and identity environment where it is built, with links to tradition, to achieve sustainable responses to the demands of adequate and inclusive habitat, through the articulation of actions between the different actors and the community to achieve decent spaces that contribute to the better life ́s conditions [33].

4 Design method of a construction system using Guadua cane and rice husk as components of a hybrid lightweight concrete for the Ecuadorian Costa region.

The research proposes a constructive system to promote access to a decent habitat, with a focus on equity, rooted in tradition and identity, and with sustainability criteria. It seeks to improve the access of families with medium and low resources, as well as the construction of essential services for the community. Energy efficiency, thermal insulation, the use of local resources, the use of renewable materials (Guadua cane) and the reuse of waste (rice husks), community participation, the application of traditional knowledge and the inclusion of circular economy criteria for endogenous development.

The design method corresponds to the adaptation of the Ecuadorian Guadua Structures Standard, which only contemplates constructions designed with whole cane and chopped cane elements, combined with other materials such as wood, steel and cladding. The standard does not include the design of a combined hybrid system of Guadua cane in structural function (as vegetal iron) with a lightweight concrete using rice husk among its components [42].

The allowable stresses (bending, tension, compression) were calculated from the characteristic value of the stresses for all the structural elements with Guadua.

$$f_{ki} = f_{0.05i}\left[1 - \frac{2.7\frac{s}{m}}{\sqrt{n}}\right] \tag{1}$$

Where: f_{ki}: Characteristic value of stress i; $f_{0.05i}$: Value corresponding to the 5th percentile of the laboratory test data at stress i; m: Average value of the laboratory test data; s: Standard deviation of the laboratory test data; n: Number of tests (20 minimum); i: Subscript depending on the type of stress (b for bending, t for tension parallel to the fibers, c for compression parallel to the fibers, p for compression perpendicular to the fibers, v for shear parallel to the fibers) [42].

This characteristic value varies depending on the stress. In this article, great importance has been given to the compressive and flexural stresses and the modulus of elasticity of hybrid lightweight concrete. We worked according to the Ecuadorian Standards when designing the structural elements and their subsequent construction, and we were able to validate the values obtained in the laboratory, in correspondence with the ranges established for this type of structures [41-43].

The allowable stress was calculated according to the designed elements, using the following formula:

$$f_i = \frac{FC}{F_s \cdot FDC} f_{ki} \tag{2}$$

Where: f_i: Allowable stress at stress *i*; *FC*: Quality reduction factor taking into account the differences between the laboratory test conditions and the actual conditions of the loads applied to the structure; F_s: Serviceability and safety factor taking into account various uncertainties; *FDC*: Load duration factor taking into account the GaK ultimate stresses; f_{ki}: Characteristic value of the stress at solicitation i [42].

The allowable stresses obtained in the laboratory were in correspondence with what is established by the Ecuadorian Standard for Guadua Structures, taking as an example the case of compressive strength parallel to the longitudinal axis are between 14 MPa and 21 MPa in tests performed at 28 days, with a load of 21 MPa [42].

The strength of the hybrid lightweight concrete used were determinate by the lab test. The design was validated in the construction of two houses, one in 1992 and the other in 2020 on the premises of the Technical University of Babahoyo. In the case of the first house, 10 tests were performed for each type of solicitation stress, while in the house built in 2020 and being in force the Ecuadorian Standard for Reinforced Concrete Structures of 2015, 20 tests were performed for each element as established [44, 45]. Tests were performed with different dosages to establish the suitable ones according to each type of elements and their functions, therefore, stresses. In all cases, parameters were found at 28 days that correspond to the ranges established by the Ecuadorian Standard [43].

The modulus of elasticity for the hybrid lightweight concrete was calculated at 28 days, where it reaches its highest values in compression, taking into account that it was designed to resist stresses produced by earthquakes, in accordance with the NEC-SE-DS. The formula was used:

$$E_c = 4.7\sqrt{f'c} \tag{3}$$

Where: E_c: Modulus of elasticity for lightweight concrete; f'_c: Compressive strength of lightweight concrete [42].

The hybrid lightweight concrete with rice husk is used in combination with Guadua cane lattices in the form of slabs that are joined with 8 mm steel trusses for the formation of panels for walls, as well as in the slabs of mezzanines and roofs, and also in the formation of columns, footing beams and enclosing beams. In all cases, the laboratory tests, according to the structural functions of the hybrid lightweight concrete, comply with the established ranges for compressive, flexural and tensile stresses [42]. In all cases, the laboratory tests, according to the structural functions of the hybrid lightweight concrete, comply with the established ranges for compressive, bending and tensile stresses [42, 44, 45].

To guarantee its resistance to earthquakes, the proposed design with this construction system must be a single-story building, although it can achieve two levels, provided that a reduction coefficient R equal to 2 is used [33, 43].

Laboratory tests were able to determine the strength of the hybrid lightweight concrete. The compressive strength for lightweight concrete with vegetable aggregates reaches values ranging between 100 and 150kg/cm^2 [33, 42]. While the standard establishes a minimum value for concrete mixtures between 17 MPa and 31 MPa, including those with fly ash or other artificial pozzolan, slag and silica fume admixtures, where the content of these should not exceed 25% [42]. In some cases, they can reach 5-6 mm/m shrinkage. Hybrid lightweight concrete with rice husk has, according to tests carried out, a volumetric mass between 400 and 900 kg/m^3, while with the use of other plant materials, according to the Ecuadorian standard, they reach a mass that varies between 500 and 1500 kg/m^3 [42].

The component elements of the designed construction system were subjected to laboratory tests to determine their resistance to the different stresses in the houses built in 1992 and in 20202, in order to validate the proposal [44, 45]. **Table 1** shows the results obtained in the tests of the 1992 house, located in the areas of the Technical University of Babahoyo, built with hybrid lightweight concrete, using rice husks and Guadua cane as vegetal iron [44]. The average results of the concrete tests at 7, 14 and 28 days were analyzed. In each case, 10 samples of the hybrid lightweight concrete were taken at each step of the construction process. As an example, the dosage of: 1 cement: 3 ripio (washed river sand-crushed gravel-stone-crushed gravel): 5 rice husks, as used for the columns, is shown. It is convenient to clarify that the ripio is extracted directly from the rivers, hence its final composition varies and it is only possible to identify it by means of laboratory tests, however, it is used in a traditional way in the area, in this case the Zapotal ripio was used.

Table 1. Strength and modulus of elasticity of hybrid lightweight concrete using rice husk as vegetable aggregate and Guadua cane as vegetable iron. Composition: 1 cement: 3 ripio: 5 rice husks

Time (Days)	Edification 1992		Edification 2020	
	Average Compression Test f'_c (MPa)	E_c (GPa)	Average Compression Test f'_c (MPa)	E_c (GPa)
7	16.97	19.36	17.16	19.46
14	19.42	20.71	18.54	20.23
28	23.64	22.85	23.44	22.75

The results were favorable, especially when compared to those established by the Ecuadorian Standard in force for lightweight concretes, considering as such those with a light aggregate with an equilibrium density between 1440 kg/m^3 and 1840 kg/m^3, as defined by ASTM and between 21 and 38 MPa. The maximum water/cement (w/c) ratio stipulated by the standard is 0.45 [42, 43].

The house built in 1992 has also demonstrated its anti-seismic effectiveness, durability and resistance. It was attested in 2016 after the earthquake occurred on April 16 with a magnitude of 7.8 Mw on the Richter scale [46], where its resistance was proven by not suffering damage, however, in most of the buildings in the affected areas cracks were observed in the walls, which do not compromise the stability of the structure. According to current Ecuadorian standards, traditional Guadua reed houses can last for fifty years [41]. In the case of the prototype built in 1992, it is in perfect constructive condition, and as part of the attention to its life cycle, scheduled maintenance has been carried out during the period, including painting, changes in carpentry and replacement of lighting fixtures.

In 2020, another house was built with this hybrid lightweight concrete construction system, on the area of the San Pablo farm in the Technical University of Babahoyo, which underwent the corresponding laboratory tests, as specified in the Ecuadorian Standard, already in force at this time. The results were satisfactory. In this case, 20 concrete tests were used for each element in each construction stage. As in the previous analysis, the results obtained from the samples of the columns were used as an example for this report, which allowed comparison with the one built in 1992. The proportion of the concrete mix was the same as the previous one, using river sand, stone and gravel from the same quarries and areas as the previous time, and cement of the same brand [42, 45] (**Table 1**).

The analysis shows that the structural elements increased their compressive strength until they exceeded the minimum values required by the standard and were in the range foreseen for traditional lightweight concrete [42].

The concrete tests were carried out with an average of 20 samples, in the second case, to each of the structural elements in the corresponding construction stages. The most favorable results were obtained at 28 days in both cases (210 and 140 kg/cm^2), with percentages exceeding 100%. The relevance of the use of hybrid lightweight concrete was demonstrated. Correspondences were observed between the values of the 1992 and 2020 buildings.

In all cases, the aggregates used in the preparation of lightweight concrete must comply with the specifications of the ASTM C330 [43].

4.1 Design of the structural elements of the construction system

4.1.1 Foundation

The design of the foundations took into account the type of soil, and worked with strip foundations, with reinforcing mesh in the areas where the columns are located. The foundations are formed by the bracing walls, plinths, and cliffs (replantillos). The buttress walls are made of lightweight concrete with rice husk in a 1:3:6 ratio (cement: ripio: rice husk), accord with the requirements of the Ecuadorian Concrete Standard, which establishes that when rice husk, slag or other additives are used, they should represent 25% of the mix [43] (**Table 2**).

The dimensions of the foundation were calculated in accordance with the regulations, in the same way as the rest of the structural components [42] (**Fig. 4**).

Table 2. Structural design of foundation components [42, 44, 45].

Foundation components	Compositions the hybrid lightweight	Compression Test f'_c (MPa)
Replantillos	1 cement: 3 washed sand	23.20
Plinths	1 cement: 3 ripio (sand-stone- crushed gravel): 6 rice husks	51.0
Bracing walls	1 cement: 3 ripio (sand-stone- crushed gravel): 6 rice husks	23.20

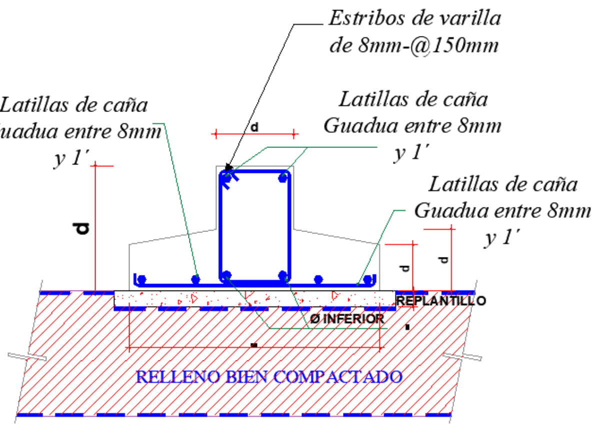

Fig. 4 Detail of foundation: plinth cutting.

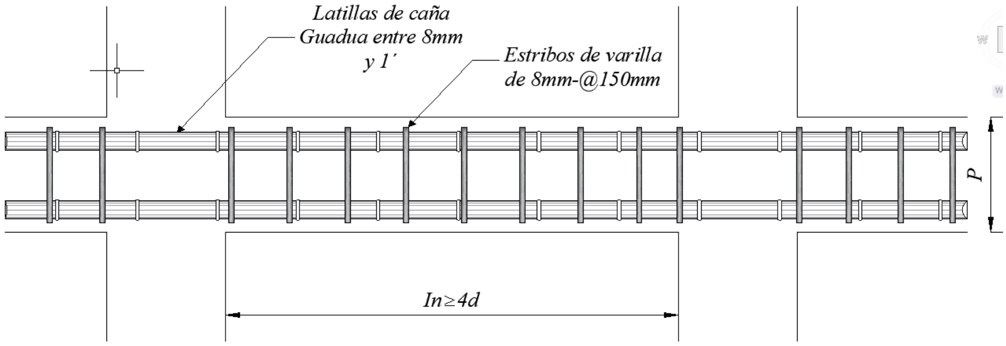

Fig. 5 Detail of enclosing beam: characteristics of bending elements [41-43].

4.1.2 Columns and enclosing beams

The columns, as well as the plinths and the enclosing beams, use hybrid lightweight concrete with rice husk and, instead of corrugated steel, Guadua cane is used in the form of 1-inch diameter latillas (bars), with steel stirrup reinforcement in one third of the column with diameters of 8 mm and 5.4 mm in the rest of the column. The proportion of lightweight concrete is 1:3:5 (cement: ripio: rice husk) (**Fig. 5**).

The design dimensions of the columns are 250mm × 250mm, they can reach up to 3 000mm in height and in the case of the enclosing beams, their dimensions are 250mm × 250mm, while the length depends on the dimensions of the spaces, but the spacing between supports ranges between 3 000 and 4 500mm [42].

In the design of the columns and beams, laboratory tests were carried out, obtaining at 28 days the optimum resistance to compressive stresses (f'_c) with an average value of 23.85 MPa for the columns and 23.40 MPa for the beams, in correspondence with the Ecuadorian Standards, which recommend a minimum f'_c of 17 MPa. The modulus of elasticity (E_c) is in the range for earthquake-resistant concrete structures, according to the Standard [41-43] (**Table 3**).

Table 3. Average design compression strength of columns and enclosure beams at 28 days, modulus of elasticity of the hybrid lightweight concrete used, 2020 building [33, 45].

Compositions the hybrid lightweight	Columns f'_c (MPa)	Columns E_c (GPa)	Enclosing beams f'_c (MPa)	Enclosing beams E_c (GPa)
1:3:5(cement: ripio: rice husks)	23.85	22.70	23.38	22.33

4.1.3 Roof slabs

Laboratory tests were carried out for the roof slabs, it is recommended to build only one level to achieve greater anti-seismic resistance. Twenty samples were used to determine the compressive and flexural stresses. A hybrid lightweight concrete was applied. In the case of the Guadua cane, the design included a latilla reinforcement with a width ranging from 8 mm to 1 inch, as a substitute for the traditional steel reinforcement. The resulting ideal ratio was 1:3:5 (cement: ripio: rice husk), the ripio consisted of a mixture of sand-stone-gravel crushed from Zapotal [43-45].

This structure is proposed as a ribbed slab; to achieve this, the blocks of the caissons will be cast on the slab formwork, which will be reinforced with chopped Guadua cane as a board on a wooden cartonry cage and cane shoring.

It should be noted that the selection of the roof slab will be based on the client's needs. If the proposed system is not used, it is recommended that light roofs that do not incorporate rigid elements, such as metal tiles, be used.

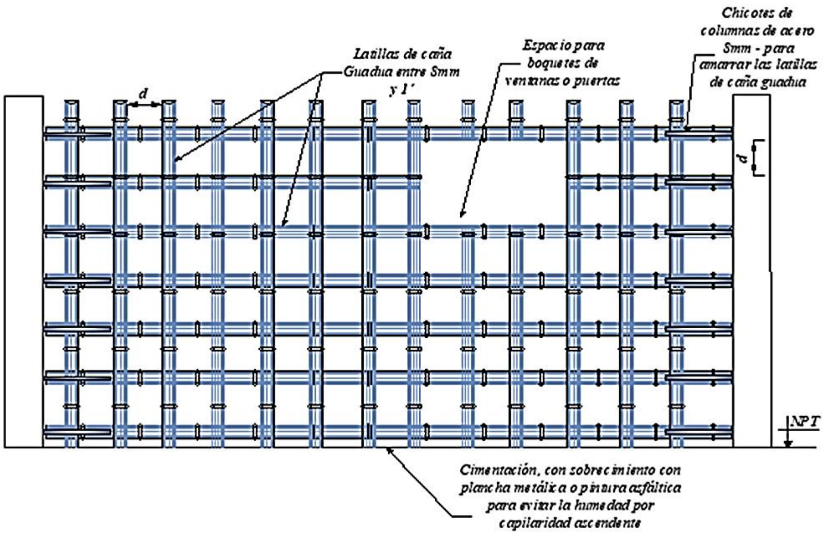

Fig. 6 Detail of structural design of the walls with the Guadua cane framing [45].

4.1.4 Walls

The walls can be worked with different materials, according to the availability and interests of the clients: with blocks manufactured in molds manually or by machine with the use of light concrete based on rice husk. Ceramic blocks can also be used: clay or conventional concrete blocks, wood panels for exteriors and interiors, or Guadua cane framing.

In the case of the walls, the traditional experience of tapial or bahareque is used in the proposals. They were designed as cast-in-place walls with Guadua plank formwork reinforced and fastened to the wood section in a vertical position, which facilitates a rough surface that allows its final finishing with different types of coatings as required by the clients. The use of asphaltic or metallic insulation between the foundation and the wall is foreseen to avoid rising damp that could affect its durability (**Fig. 6**).

The design of the wall framing is made with Guadua cane slats joined with steel wire and lightweight concrete with a 1:2:2:2 dosages (cement: sand: stone powder: rice husk), obtained after several laboratory tests (**Table 4**). This dosage, together with the use of Guadua, allows for greater impermeability and resistance, as well as better acoustic and thermal insulation performance [45].

Table 4. Design wall compression strength at 28 days and modulus of elasticity of hybrid lightweight concrete, 2020 building [33, 45].

Time(Days)	Compositions the hybrid lightweight	f'_c (MPa)	E_c (GPa)
28	1:2:2:2(cement: sand: stone powder: rice husk)	21.35	20.85

4.1.5 Architectural design of buildings

The design of the 1992 and 2020 buildings was accord with current Ecuadorian standards: NEC-SE-VIVIENDA: Housing up to 2 stories with spans up to 5m and the NEC-DR-BE: Andean Standard for design and construction of one and two story houses in cemented wattle and daub [47, 48].

Fig. 7 Prospective floor plan for housing built in 2020 in the San Pablo Farm, Technical University of Babahoyo, Babahoyo.

Fig. 8 Front view of the housing designed in 2020 for the San Pablo farm of the Technical University of Babahoyo, Babahoyo.

The buildings are located in the areas of the Universidad Técnica de Babahoyo and the institution's own San Pablo Farm. They have a functional distribution of one floor with living room (used as a multipurpose hall), bedrooms (two in the one built in 1992 and three in the one built in 2020), restrooms, kitchen, dining room, and in the last one built, spaces were also conceived for visitors' accommodation with bedroom, restroom and pantry, with a continuous doorway on two of its most unfavorable facades that minimize the effect of heat, while providing shade and creating a pleasant atmosphere(**Fig. 7** and **Fig. 8**).

5 Construction process

5.1 Selection and preparation of Guadua cane and rice husk as construction materials

To work Guadua cane as a construction material, traditional experience is used in the composition of structural elements and as a finishing material for false ceilings, light partitions between rooms, mats, for its aesthetic qualities. Rice husks contribute to reduce energy costs, reduce and optimize the use of Portland cement, reduce the weight of the construction and the effect of seismic forces. The use of both materials is facilitated by the compatibility of being plant components from the same species: *Gramineae*.

Guadua cane as a construction material should have a growth time between 4 and 6 years, when the plant reaches its optimum dimensions (between 6 and 20 m in height and a diameter of 20 cm) and maximum resistance. Cutting is recommended during the waning quarter moon stage. The selected mature canes should be cut at the level of the first lower node, the canes should be laid down without falling on the ground for six days to achieve a natural drainage of its liquid components. It must undergo a prior drying process to reduce moisture content and prevent fungal and insect (xylophagous) attack. With its use, transportation costs are reduced due to its lightness and easy handling, in addition to seeking proximity to the guadales of the construction sites [41, 48].

The cane will be sectioned into elements of variable sizes for different uses. Transport must be in vehicles whose size corresponds to the length of the culms; overloading of the culms during transport and storage must be avoided [41].

Because of its organic composition (cellulose, lignin and silica), Guadua must be compulsorily treated before its use as a construction material to guarantee its durability against possible insect and fungal attacks. This is done by impregnation with preservatives (borax, boric acid, sodium dichromate and copper sulphate), either by immersion, by pressure (Boucherie), by vinegaring (natural way, but which must be accompanied by another type of preservation) or by vertical diffusion [41].

According to the Ecuadorian Standard, the Guadua (GaK) used in construction must be dried until it reaches a moisture content equal to or lower than the equilibrium moisture content of the site (**Table 4**) [41]. Drying can be done in the air and takes an average of two to six months; it can be done in a kiln, similar to the industrial wood drying process, in approximately six days, but has the disadvantage that the cane tends to crack and bend; and finally, drying can be mixed, with a combination of the previous processes [33].

Table 5 shows the behavior of the equilibrium moisture content of the wood given by the Ecuadorian Standard for Guadua Structures, in relation to the province of Los Rios, in the region of La Costa, the area where the proposal has been validated. The culms after drying should reach, in these localities, a value equal to or lower than the equilibrium humidity, which guarantees resistance to insect and fungi attack [41].

Table 5. Average annual wood humidity equilibrium in Los Rios province's, adaptable to Guadua cane [41].

Locality	Average annual temperatura ℃	Relative humidity annual average%	Wood equilibrium humidity (annual average)%
Quevedo	24.40	83.60	18.80
Vinces	25.20	79.60	17.00
Babahoyo	25.50	85.20	17.90
La Clementina	24.30	85.20	19.50
Isabel María	25.00	80.60	17.40

The husk from the paddy rice production process is used. As a precondition for its use as a construction material, it must undergo a mineralization process. The purpose of this step is to neutralize those substances susceptible to cause fermentation or rotting, as well as to avoid incompatibility with cement and reduce impurities. Mineralization is carried out by immersion (hot or cold) in lime (a solution of sodium silicate and lime slurry with a lime concentration of 5%) or with cement.

In this proposal, immersion in lime slurry for 24 hours has been used most effectively. Immersion improves the physical and chemical properties of the material and provides greater stability for the preparation of lightweight concrete (**Fig. 9**). After immersion, maturation is performed to minimize subsequent shrinkage of the material in the concrete mix.

We worked with rice hulls obtained from the rice mills in the canton of Babahoyo, which reduces transportation costs. An analysis of the physical and chemical properties of the samples collected (16 from each rice mill) showed that they were highly impermeable, hydrophobic and did not burn easily, which demonstrates their fireproof nature (**Table 6**).

Fig. 9. Mineralization process of rice husk immersed in lime.

Table 6. Average physical and chemical properties of rice hulls from the rice mills of the canton of Babahoyo [44, 45].

Average porosity Total%	Average retention capacity of the H_2O%	Average density(g/mi)
65.45	24.78	0.11

5. Construction of foundations

The foundation complies with the dimensions and characteristics of the design. The interior structure with Guadua reed reinforcement in elements forming latillas with a variable width between ¼ and 1 inch, steel for the stirrups of 5.4 mm. The elements are fastened with annealed wire. The replantillos are a simple concrete base, without the use of rice husk, with a resistance of 140 kg/m^2, and a height of 50 to 70 mm, which is used as a base for the placement and concreting of the plinths, so that the irregularities of the ground are taken into account. Its use is mandatory according to the Standard, considered as a surcharge that must be properly waterproofed, in this case with a 2 mm thick metal plate covering the head of the surcharge to prevent rising damp [41, 42].

The plinths with a light concrete ratio of 1:3:5 (cement: gravel: rice husk) use a Guadua cane reinforcement in the form of latillas, with a width of ½ inch in the case of the plinths in one third of the column, with 8 mm stirrups and the rest of 5.4 mm (**Fig. 10**).

Fig. 10. Foundation preparation: a Construction of plinths and columns, b Placement and rectification of bracing walls, c Casting of the footing beam with lightweight concrete with rice husk.

Table 7. Average compressive strength of the foundation components, 2020 [33, 45].

Time (Days)	f'_c Replantillos (proportion 1:3) MPa	f'_c Plinths (proportion 1:3:5) MPa	f'_c Braced walls (proportion 1:3:6) MPa
7	16.28	16.67	16.87
14	18.44	18.64	18.54
21	21.18	20.60	21.48
28	23.44	23.64	23.54

The compression behavior of the foundation components was verified by laboratory tests with samples concrete tests, 10 in the 1992 building and 20 in the 2020 building. In both cases, the requirements of the Ecuadorian Standard were met, reaching and exceeding 110% of the requirements.

At 21 days, the recommended optimum resistance was reached. This ensures the stability of the construction. The highest values were reached at 28 days, in correspondence with those established in the design [41, 42, 44, 45, 48] (**Table 7**).

The elements follow the scheme of a traditional construction, but with the inclusion of rice husk as a component of lightweight concrete and its hybrid character is acquired with the use of Guadua cane instead of conventional steel.

5.3 Columns and enclosure beams

The columns and enclosure beams were built according to the project. Hybrid lightweight concrete was used, with a 1:3:5 ratio (cement: ripio: rice husk) and Guadua cane in the form of latillas, with 8 mm steel stirrup reinforcement (**Fig. 5**). In both buildings, four Guadua cane rods were used for reinforcement, in the case of the columns to take the compressive stresses, while in the beams, the bending stresses were taken from the columns (**Fig. 11**).

(a) Construction of the structure (b) Formwork (c) Column cast with hybrid light concrete

Fig. 11 Columns.

Laboratory tests for the columns and beams tend to the behavior predicted in the design. At 21 days they reach the maximum compressive strength as required by the Ecuadorian Standard, and exceed it by reaching 115% at 28 days. The modulus of elasticity was calculated in correspondence with the anti-seismic design and with the country's standards (**Table 8**).

Table 8. Average compressive strength of columns and enclosure beams, modulus of elasticity of the lightweight concrete used, 2020. Compositions the lightweight concrete: 1: 3: 5 (cement: ripio: rice husks) [33, 45].

Time (Days)	Columns f'_c (MPa)	Columns E_c (GPa)	Closing beams f'_c (MPa)	Closing beams E_c (GPa)
7	16.38	19.02	16.18	18.91
14	18.83	20.39	18.64	20.29
21	20.60	21.33	20.60	21.33
28	23.74	22.90	23.64	22.85

5.4 Roof slab

The 1992 building on the grounds of the Technical University of Babahoyo was designed and constructed with a ribbed roof slab, using caissons to achieve the ribs. The mold of the caissons was made with Guadua cane slabs duly traced. The reinforcement of the slab ribs, the upper reinforcements, solid beams and supports were made of Guadua elements, of variable width between 8 mm and 1 inch, placed and arranged in their position of maximum resistance, edgewise, tied with annealed wire, these elements were treated with preservatives.

Laboratory tests performed on 10 samples to determine the resistance to compressive and flexural stresses yielded favorable results as designed. The ratio used was 1:3:5 (cement: ripio: rice husk) [42, 44, 45] (**Fig. 12**).

This slab was replaced, in good condition, by metal tiles by institutional decision. There may also be other types of roofs according to the client's criteria. In the case of metallic tiles, the use of a false ceiling is recommended as a thermal and acoustic insulator, which can even be made of Guadua cane, due to its aesthetic characteristics and which allows to enhance the handcrafted work, typical of the country.

Fig. 12. Formwork for roof slab with the use of chopped Guadua cane, wooden quarters, round cane shoring, slab reinforcement with Guadua cane slabs and 6mm stirrups of the same material [34, 44, 46].

5.5 Walls and finishes

The walls were worked in situ, with Guadua cane board formwork, reinforced and fastened to a wooden section in a vertical position, as designed. The surfaces obtained facilitated the subsequent adherence of the finishes: plaster, fine plaster, ceramic (tiles or gress) (**Fig. 13**).

Fig. 13. *In situ* construction of the walls with hybrid lightweight concrete with rice husk and Guadua reed lattice. Based on the ancestral technique of bahareque or tapial.

On-site tests corroborated the design. Similar to the previous elements, the best response was obtained at 28 days and the parameters of the Ecuadorian Standard for Reinforced Concrete Structures and the Andean Standard for the design and construction of one- and two-story houses in cemented wattle-and-daub were met [42, 48] (**Table 9**).

If lightweight concrete blocks are used, it is necessary to apply laboratory test to know the appropriate dosages and responses to the different stresses, as well as the resulting physical and chemical characteristics. The proposed finishes are diverse, depending on the taste, availability and economic feasibility of potential clients.

Table 9. Wall compression resistance, 2020 [33, 45].

Time (Days)	f'_c (MPa)	E_c (GPa)
7	16.97	19.36
14	18.64	20.29
21	21.68	21.88
28	23.54	22.80

6 Final result

With the use of the hybrid light construction system with the use of rice husk and Guadua cane, as explained above, two houses were built on the grounds of the Technical University of Babahoyo in 1992 and 2020, indistinctly. Waste from rice production in the area and reeds from the Guadua fields near the city were used. The local labor force used were employees of the institution itself, previously trained in the handling of these materials and construction techniques, as established by Ecuadorian standards [41, 42, 43, 47, 48].

Due to the facilities offered by these ecomaterials, the construction cycle was completed satisfactorily, facilitated by the easy transportation, handling, storage and assembly of the elements that are part of the system created, all of which allowed optimizing labor, reducing costs compared to traditional housing. The houses built have a good aesthetic-functional finish, have seismic resistant capacity demonstrated in the 2016 earthquake in which it was not affected. Due to the characteristics of the materials used, adequate acoustic and thermal insulation is achieved.

As a result of this work, nearly 500 hectares of natural crops have been recovered and the planting of guaduales has increased in the area. Because of its capacity to sequester carbon due to its rapid growth, biomass production and self-regenerating properties, its potential as an eco-sustainable construction material has been demonstrated. Guadua cane reaches high percentages of biomass when used in proposals for sustainable constructions by storing carbon as biomass in the long term [49].

In Guadua angustifolia cane six years after cultivation, the contribution of the culm and rhizome to the biomass represents 90%, this carbon fixation is estimated at 54.3t, where 10.8t (19.9%) of the CO_2 fixation corresponds to the rhizome and 43.5t (80.1%) to the aerial part of the group [49]. An important aspect is that a construction system using materials of natural origin, such as rice husks and Guadua cane, and industrialized materials, such as cement, yields favorable energy data, with a reduction of about one third of the energy required for their use (28.7%), which places them in a position to save energy sources [50].

The cost of the house built in 2020 was $15,000, compared to the $18,000 proposed by the Ministry of Urban Development and Housing in 2022 for 56 m^2 of living space [49]. To which should be added its environmental sustainability due to the use of renewable resources and the achievement with this construction system of hybrid lightweight concrete with rice husk and Guadua cane of an adequate formal expression with links to tradition: the use of gable roofs, the portals that combine shade and solar control, versatility and identity in the functional approach, adaptation to climatic phenomena with less consumption of unsustainable construction materials (**Fig. 14**).

Fig. 14. View of the house built in 2020 on the San Pablo farm, belonging to the Technical University of Babahoyo.

This proposal seeks to improve the living conditions of low-income families through access to government subsidies and loans, the application of energy-efficient construction systems and technologies, and participatory methodologies through interaction between professionals and the community, as well as the articulation of public and private actors.

The house comfortably meets the minimum requirements established by the Ministry of Urban Development and Housing of Ecuador with the use of a construction system that allows for flexibility in design, reduced construction costs, use of eco-sustainable materials, easy assembly and the use of local resources. Its construction and durability validate the relevance of the proposal.

7 Conclusions

This paper introduces the structural design method of the component elements of a hybrid lightweight concrete construction system using rice husk and Guadua cane. It takes advantage of a review of the experience in working with Guadua cane and the potentialities of rice husk that allow its use as a construction material.

The use of Guadua cane in Ecuador is facilitated by its abundant presence and quality in the coastal region, in addition to using its advantages of being an eco-sustainable material, easy to transport and assemble and allows lower construction costs, in addition to taking advantage of local and national tradition and giving an identity response to the problem of habitat. Rice husks, when used as a component of lightweight concrete, increase the physical, chemical and mechanical characteristics of the mixture, while eliminating the polluting power it causes as waste from rice production.

From the analysis of the design and the implementation of the results it can be concluded that: a hybrid lightweight concrete is obtained that combines the use of natural materials such as rice husk as aggregate and Guadua cane as a substitute for steel, combined with industrialized materials such as cement. The result is a versatile, flexible, safe system that meets the requirements for different types of stresses as stipulated by the Ecuadorian construction standards for these elements.

In the case of the rice husk, it is used without the need to convert it into ash, which reduces the contaminating power resulting from burning, a 24-hour prior mineralization process is required to make its use as a construction material viable. The Guadua cane must also be pre-treated to protect it from environmental risks.

The strength and durability of the system has been demonstrated through structural design and validated in construction practice with a prototype that has been built for more than 30 years and was not damaged in the 2016 earthquake.

The architectural solution has demonstrated its functionality with adherence to tradition and identity, as well as its lower cost, better formal expression and safety than governmental responses. Its implementation is an option for local development by using endogenous resources, generating work synergies and meeting the needs of low-income sectors.

Acknowledgement

The writers gratefully acknowledgement Pedro José Rodríguez Vargas, Marcos Oviedo Rodríguez and Liliana Lara Suárez from the Universidad Técnica de Babahoyo, Ecuador for their helping.

Funding Statement

This work was supported by the Universidad Técnica de Babahoyo in the research and practical application project: “Lightweight concrete based on rice husks as the most important aggregate and use of vegetable iron (Guadúa cane) as a structural element to replace iron mineral”. The authors received no specific funding for this study.

CRediT authorship contribution statement

Pedro José Rodríguez Gómez: Research, Formal analysis, Writing – original draft. **Adela María García Yero**: Research, Conceptualization, Supervision, Formal analysis, Writing – original draft & editing. **Guberto Cánovas Riverón**: Supervision, Writing – review.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

References

[1] United Nations Environment Programme (2020). 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Nairobi. www.globalabc.org (accessed 2 August 2003)

[2] Hernández Zamora M.F., Jiménez Martínez S.I., Sánchez Monge J.I. Materiales alternativos

comooportunidad de reducción de impactos ambientales en el sector de la construcción. Revista Tecnología En Marcha 2021; 34 (2): 3-10. https://doi.org/10.18845/tm.v34i2.4831

[3] Goodrum P.M., Zhai D., Yasin M.F. Relationship between Changes in Material Technology and Construction Productivity. Journal of Construction Engineering and Management 2009; 135(4): 278-287. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:4(278)

[4] Calderón Maldonado T., Venegas Tomalá A. & Romo Zamudio C. (2023). Estrategias para la construcción sostenible de viviendas en la Asociación "Shuar Cultural Center" (Ecuador), adaptadas a su entorno rural. 593 Digital Publisher CEIT, 2023; 8 (1-1): 385-403. https://doi.org/10.33386/593dp.2023.1-1.1684

[5] Balseca L., Solórzano S., Bustamante H. Producción y comercialización de la caña *Guadúa* en la provinciade El Oro. Universidad Técnica de Machala. Conference Proceedings 2017; 1(1): 580-590. http://investi gacion. utmachala.edu.ec./proceedings/index.php/utmach (accesed 15 August 2023)

[6] Muentes W., Cedeño H., Cedeño T., Salvatierra G., Melgar C. Análisis de la vivienda vernácula de cañaguadúa Manabita del Ecuador y puesta en valor de su sistema constructivo en la vivienda contemporánea. Ciencia Latina Revista Científica Multidisciplinar Marzo-Abril, 2023; 7(2): 8291-8310. https://doi.org/10.37 811/cl_rcm.v7i2.5956

[7] Castro M., Barcia M.A., Labrado M.O., Chasing E.A. La guadúa que se corta: paisajes culturales ypatrimonio construido en la costa ecuatoriana (Manabí, Ecuador). Rev. Esp. Antropol. Amer. 2018; 48: 79-100. https://doi.org/10.5209/REAA.63691

[8] Sevillano Gutierrez E., Caimi A., Durzo S., Garnier P., Joffroy T, et al. Ficha de referencia detalladaEcuador Costa: culturas constructivas locales para la resiliencia y el desarrollo. CRAterre, 2017 https://www.researc hgate.net/publication/342877227_Ficha_de_referencia_detallada_Ecuador_Costa_culturas_constructivas_l ocales_para_la_resiliencia_y_el_desarrollo (accessed 6 August 2003)

[9] Amaluisa Peñaherrera M.A. Prototipo constructivo de vivienda con base en criterios de economía circularpara la Mancomunidad del Chocó Andino dentro del Distrito Metropolitano de Quito, Pichincha. Universidad Central del Ecuador. 2021. http://www.dspace.uce.edu.ec/handle/25000/23339 (accesed: august, 2023)

[10] Angulo V.L., Materiales alternativos sostenibles empleados en la construcción: una revisión de la literatura científica (Trabajo de investigación). Repositorio de la Universidad Privada del Norte 2018. https://hdl.hand le.net/11537/23755 (accesed february 2023)

[11] Dauletbek A., Xue X., Shen X., Li H., Feng Z., Lorenzo R., Liu K., Zea E., Yao L. & Zheng X. Lightweight bamboo structures – Report on 2021 International Collaboration on Bamboo Construction. Sustainable Structure 2023; 3(1): 000025. https://doi.org/10.54113/j.sust.2023.000025

[12] Mimendia L., Lorenzo R., Li H. An innovative digital workflow to design, build and manage bamboo structures. Sustainable Structure 2022; 2(1): 000011. https://doi.org/10.54113/j.sust.2022.000011

[13] Méndez Quintero M.A., Takeuchi Tam C.P., Li H. Structural análisis of a *Guadúa* bamboo bridge in Colombia. Sustainable Structure 2022; 2(2): 000020. https://doi.org/10.54113/j.sust.2022.000020

[14] Xue X., Zhou W., Sayed U., Feng Z., Li H., Li Y., Huang Z., Ashraf M., Lorenzo R. Design and construction of "Bamboo Cubic" façade with laminated lumber. Sustainable Structure 2023; 3(2): 000030. https://doi.org/10.54113/j.sust.2023.000030

[15] Sharma B., Gatóo A., Bock M., Ramage M. Engineered bamboo for structural applications. Construction Building Materials 2015; 81: 66-73. https://doi.org/10.1016/j.conbuildmat.2015.01.077

[16] Sierra L., Rojas J., Peña A., Takeuchi Tam C.P. Incidencia estructural de la esterilla de bambú Guadúa ante eventos sísmicos en muretes de mampostería republicana. Rev. Arquitectura Cuba enero-abril 2023; 44(1): 33-40. https://rau.cujae.edu.cu/index.php/revistaau/article/view/766 (accesed 6 august 2023)

[17] Delgado G. Ecologíay ambiente. Diseño y sustentabilidad en construcciones con caña Guadúa. Diseño, Arte y Arquitectura 2017; 1(2): 75-93. https://doi.org/10.33324/daya.v1i2.32

[18] Llumiquinga J.L. Calidad de la vivienda de caña guadúa en Ecuador: Área rural vs área urbana. Polo del Conocimiento 2023; 8(1): 1385-1409. https://polodelconocimiento.com/ojs/index.php/ (accessed 6 August 2003)

[19] Camino A.M. La caña guadúa en la provincia de Manabí y el litoral de Ecuador. Construcción con tierra. Tecnología y Arquitectura. Congresos de arquitectura de tierra en Cuenca de Campos 2010/2011. Valladolid. Universidad de Valladolid. 2011; 205-212. http://www5.uva.es/grupotierra/ publicaciones/digital/libro2011 /2011_9788469481073 (accesed 7 august 2023)

[20] Londoño X., Camayo G.C, Riano N., López Y. Characterization of the anatomy of Guadúa angustifolia (Poaceae: Bambusoideae) culms. Bamboo Science and Culture 2002; 16 (1): 18-31. http://www.maderinsa.c om/guadua/Anatomia.pdf (accessed 7 August 2003)

[21] Ramírez A.D., Torres D., Peña P., Duque-Rivera J. Life cycle assessment of greenhouse gas emissions arising from the production of glued and pressed wall panels derived from Guadúa Angustifolia Kunth (bamboo) in Ecuador. WIT Transactions on the Built Environment 2014; 142: 447-457. https://www.witpress.com/elibra ry/wit-transactions-on-the-built-environment/142/29805 (accessed 13 August 2003)

[22] Cevallos C. La caña Guadúa y su uso en la arquitectura de la tierra: Intervención en la arquitectura vernácula y la arquitectura contemporánea en varios cantones de la Provincia de Manabí, Ecuador. Universidad de Valladolid. Escuela Técnica de Arquitectura 2020. http://uvadoc.uva.es/handle/10324/44384 (accessed 13 August 2003)
[23] Calle Chuinda W.M., González Redrován T.J., Alvarez Vera M.S. Analysis of Guadúa cane as a sustainable construction material for the development of ecoturism in the Ecuadorian Amazonas. Revista Religación octubre-diciembre 2023; 8 (38): 1-21. http://doi.org/10.46652/rgn.v8i38.1109
[24] Velasco Muñoz J.F., Aznar Sánchez J.A., López Felices B., Román Sánchez I.M. Circular economy in agriculture. An análisis of the state of research based on the life cycle. Sustain. Prod. Consum. 2022; 34: 257-270. https://doi.org/10.1016/j.spc.2022.09.017
[25] Arroyo R. La Economía circular como factor de desarrollo sustentable del sector productivo. INNOVA Research Journal 2018; 3(12): 78-98. https://doi.org/10.33890/innova.v3.n12.2018.786
[26] Arowojolua O., Ibrahimb A., McDonald A. The effect of including biomass on the rheological and pozzolanic properties of Portland limestone cement – case study. Sustainable Structure 2023; 3 (1): 000024. https://doi.org/10.54113/j.sust.2023.000024
[27] Guo A., Sun Z., Feng H., Shang H., Sathitsuksanoh N. State of the art review on the use of lignocellulosic biomass in cementitious materials. Sustainable Structure 2023; 3 (1): 000023. https://doi.org/10.54113/j.sust.2023.000023
[28] Ibarra A., Molina J., Crespo B., Pozo M., Ramírez L. Análisis de la cadena agroalimentaria del arroz en Ecuador. Pol. Con. 2023 (Edición núm. 82); 8 (5): 3-21. https://doi.org/10.23857/pc.v8i5
[29] Corporación Financiera Nacional B.P. Ficha sectorial arroz. 2023. https://www.cfn.fin.ec (accesed 10 apryl 2024)
[30] Vargas J., Alvarado P., Vega-Baudarit J., Porras M. Caracterización del subproducto cascarilla de arroz enbúsqueda de posibes aplicaciones como materia prima en procesos. Revista Científica 2013; 23 (1): 87-102. https://dialnet.unirioja.es/descarga/articulo/5069938 (accesed 10 apryl 2024)
[31] Cruz Pérez J.C., González Ruiz J.E., Perdomo González L. Valoración del uso de la cascara de arroz comomaterial termoaislante en la fundición de piezas de acero. Minería y Geología 2020; 36 (4): 465-482. http://scielo.sld.cu/scielo.php?script=sci_arttext&pid=S1993-80122020000400465&lng=es&nrm=iso (accesed 10 apryl 2024)
[32] Singh B. Rice husk ash in waste and supplementary cementitious materials in concrete. Woodhead Publishing 2018. https://doi.org/10.1016/B978-0-08-102156-9.00013
[33] Rodríguez Vargas P.J., Oviedo M., Rodríguez Gómez P.J., Lara L. La estructura de edificaciones en base aluso de la cascara de arroz (concreto ligero) y la utilización de la caña Guadúa (hierro vegetal). Imp. "Don Gonzalo", Babahoyo, Ecuador, 2016
[34] Mafla A. Uso de la cascarilla de arroz como material alternativo en la construcción. Rev. Uniminuto 2009; 4(6): 74-78. https://doi.org/10.26620/uniminuto.inventum.4.6.2009.74-78
[35] López J., Cazorla X., Zambrano G., Chancusig W. La economía circular de los desechos generados porlagramínea de arroz frente al efecto ambiental. Rev. Pol Con. 2021 (Edición núm. 56); 6(3): 874-900. https://doi.org/10.23857/pc.v6i3.2411
[36] Llanos O., Ríos A., Jaramillo C., RodríguezL. La cascarilla de arroz como alternativa en procesos de descontaminación. Producción + Limpia July/Dec 2016; 11(2): 1560-160. http://dx.doi.org/10.22507/pml.v11n2a12
[37] Silva F.G., Liborio J.B., Helene P. Improvement of physical and chemical properties of concrete with Brazilian silica rice husk (SRH). Rev. Ing. Construcc. 2008; 23(1): 18-25. http://doi.org/10.4067/S0718-50732008000100002
[38] Jarre C., Piug R., Zamora-Ledezma C., Zamora E. Caracterización preliminar de la ceniza de cáscara dearroz de la provincia de Manabí, Ecuador, para su empleo en hormigones. Revista Técnica de la Facultad de Ingeniería Universidad del Zulia 2021; 44(1): 44-50. https://www.redalyc.org/articulo.oa?id=605772532007 https://doi.org/10.22209/rt.v44n1a06
[39] Iturralde X., Hernández A. Biofiltarción de aguas residuales de industrias arroceras de San Jacinto de Yaguachi, Ecuador mediante cascarilla de arroz. Revista Iberoamericana Ambiente & Sustentabilidad 2022; 5, e271. https://doi,org/10.46380/rias.vol5.e271
[40] Suárez Silgado S.S., Calderón Valdiviezo L., Betancourt Quiroga C. Life cycle análisis and economic evaluation of cement and concrete mixes with rice husk ash: application to the Colomnian context. Materiales de Construcción 2021; 74, e 353: 1-17. https://doi.org/10.3989/mc.2024.350723
[41] Ministerio de Desarrollo Urbano y Vivienda (MIDUVI). Normas Ecuatorianas para la Construcción. 2017. CÓDIGO NEC-SE-GUADÚA. https://www.habitatyvivienda.gob.ec/wp-content/uploads/downloads/2017/04/NEC-SE-GUADUA-VERSION-FINAL-WEB-MAR-2017.pdf (accesed 12 february 2023)
[42] Ministerio de Desarrollo Urbano y Vivienda (MIDUVI). Normas Ecuatorianas para la Construcción. 2015. CÓDIGO NEC-SE-HM Estructuras de hormigón armado. https://cicp-ec.com/documentos/NEC_SE_HM_

Hormigon_Armado.pdf (accesed 12 february 2023)
[43] Ministerio de Desarrollo Urbano y Vivienda (MIDUVI). Normas Ecuatorianas para la Construcción. 2016. CÓDIGO NEC-SE-DS: Cargas Sísmicas. Diseño Sismo resistentes. https://www.obraspublicas.gob. ec/wp-content/uploads/downloads/2016/04/MTOP_NEC-SE-DS.pdf (accesed 12 february 2023)
[44] Rodríguez J. Informe de resistencia de los materiales de la construcción de edificación en la ciudadela Universidad Técnica de Babahoyo, utilizando el concreto ligero a base de cascara de arroz como el agregado más importante y con el hierro vegetal caña Guadúa como elemento estructural del reemplazo del hierro mineral. Consultoría Lab./Mec./Soils y Hormgns. Construcción y Fiscalización de Obras Civiles. Agosto de 1993 (Ecuador)
[45] Rodríguez J. Informe de resistencia de los materiales de la construcción de edificación en los predios de la granja San Pablo de la Universidad Técnica de Babahoyo, utilizando el concreto ligero a base de cascara de arroz como el agregado más importante y con el hierro vegetal caña Guadúa como elemento estructural del reemplazo del hierro mineral. Consultoría Lab./Mec./Soils y Hormgns. Construcción y Fiscalización de Obras Civiles. Agosto de 2020 (Ecuador)
[46] Instituto Geofísico Nacional. Informe Sísmico Especial N. 18-2016. https://www.igepn.edu.ec/servicios/noticias/1324-informe-sismico-especial-n-18-2016 (accesed 12 apryl 2024)
[47] Torres B., Segarra M., Bragança L. El bambú como alternativa de construcción sostenible. Extensionismo, Innovación y Transferencia Tecnológica- Claves para el desarrollo 2019; 5: 389-400. https://doi.org/10.30972/eitt.503787
[48] Ministerio de Desarrollo Urbano y Vivienda (MIDUVI). Normas Ecuatorianas para la Construcción. 2023. CÓDIGO NEC-SE- VIVIENDA: Viviendas de hasta 2 pisos con luces de hasta 5 m. https://www.habitatyvivienda.gob.ec/wp-content/uploads/2023/03/12.-NEC-SE-VIVIENDA-parte-1.pdf (accesed apryl 2024)
[49] Red Internacional para el Desarrollo del Bambú y el Ratán. NEC-DR-BE: Norma Andina para diseño y construcción de casas de uno y dos pisos en bahareque encementado. 2017. https://www.habitatyvivienda.gob.ec/wp-content/uploads/downloads/2017/03/Bahareque-Encementado.pdf (accesed apryl 2024)
[50] González Calderón A. & Guerrero Baca L.F. Bajareque tecnificado. Evaluación de energía incorporada y emisiones de CO_2 en comparación con la edificación convencional. Viviendas y Comunidades Sustentables 2022; 11: 9-21. https://doi.org/10.32870/rvcs.v0i11.177