Overview on bio-based building material made with plant aggregate

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Abstract

Global warming, energy savings, and life cycle analysis issues are factors that have contributed to the rapid expansion of plant-based materials for buildings, which can be qualified as environmental-friendly, sustainable and efficient multifunctional materials. This review presents an overview on the several possibilities developed worldwide about the use of plant aggregate to design bio-based building materials. The use of crushed vegetal aggregates such as hemp (shiv), flax, coconut shells and other plants associated to mineral binder represents the most popular solution adopted in the beginning of this revolution in building materials. Vegetal aggregates are generally highly porous with a low apparent density and a complex architecture marked by a multi-scale porosity. These geometrical characteristics result in a high capacity to absorb sounds and have hygro-thermal transfer ability. This is one of the essential characteristics which differ of vegetal concrete compared to the tradition mineral-based concretes. In addition, the high flexibility of the aggregates leads to a non-fragile elasto-plastic behavior and a high deformability under stress, lack of fracturing and marked ductility with absorbance of the strains ever after having reached the maximum mechanical strength. Due to the sensitivity to moisture, the assessment of the durability of vegetal concrete constitutes one of the next scientific challenging of bio-based building materials.

Keywords: Bio-based building materials; Vegetal aggregates; Sustainability; Physical properties; Life cycle analysis

1 Introduction

The concept of sustainable development dealt with locally is often linked to problems on a worldwide scale, such as global warming or the gradual exhaustion of resources. These two criteria constitute the points of no return for our civilization [1, 2]. The preservation of the environment is one of the principal features of sustainable development with the urge to reduce green house gas (GHG) emissions [2-6]. Total GHG emissions by economic sector in 2010 which includes the direct emissions were: 25% for electricity and building heat production, 6.4 % for construction buildings, 14 % for transport, 21 % for industry, 9.6% for other energy and 24% for Agriculture, Forestry and Other Land Use (AFOLU); and the indirect emissions were: 1.4 % for energy, 11 % for industry, 0.3 % for transport, 12 % for building and 0.87 % for AFOLU [7]. For its part, the construction sector finds itself facing significant challenges in terms of reducing GHG emissions and energy consumption [4, 5] by using alternative materials.

The estimation made in 2009 by the International Energy Agency (between 3.36 and 3.48 billion tonnes in 2015) for long-term evolution of the cement demands (used in construction) is already overcome with an estimated annual worldwide cement production in 2014 of 4.3 billion tonnes, i.e. an increase of 6.7 % from 2013. In summary, the construction sector battles four main impacts on the environment: its GHG emissions; its energy consumption; its consumption of natural resources; its waste production. As alternative, plant based materials have a valuable benefit for health, ecologic, comfortable habitat (moisture management, thermic and acoustic) and sustainable materials [8, 9]. Global warming, energy savings, and life cycle issues are factors that have contributed to the rapid expansion of plant-based materials for buildings, which can be qualified as environmental-friendly and efficient multifunctional materials. Concerning energy savings, most of thermal code in Europe requires that from 2020 on, all new buildings meet the positive energy criteria. This improvement of energy performance of buildings induces modifications in the distribution of environmental impacts (Figure 1), and places the manufacture of the building materials as the most important phase when the energy consumption decreases from 200 to 15 kWh/m²/yr [10, 11]. So, to reduce these impacts, it makes sense to go on moving towards plant-based materials, whose impacts are very limited, and can even be positive on the environment.

2 Development of agro-concretes

The introduction of a high concentration of bio-aggregate-building material in the construction design is the fundamental principle of this concept. The use of crushed hemp (shiv), flax and other plants associated to mineral binder represents the most popular solution adopted in the beginning of this revolution in building materials [8, 10].

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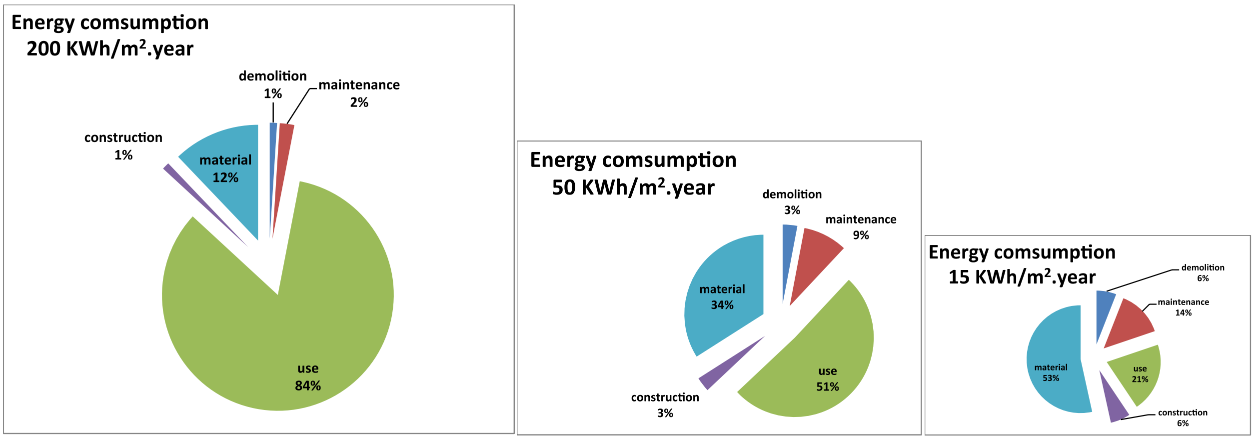

Figure 1. Distribution of environmental impacts between the different phases of a construction depending on its energy performances.

Around the main markets generated by a cereal or petroleum culture, there are a great many secondary markets springing up, which will facilitate as complete a value creation as possible. Such is the case, in particular, for hemp, for which the corners of the market are as varied as fibers for the automobile industry, foodstuffs for the grain or indeed the wood of the stem for construction [12]. The quantities and the sources available are abundant. Hence, vegetable biomass has a bright future.

3 What does the term "Agro-concrete" mean?

A concrete in the conventional sense of the word consists of a heterogeneous mix between a mineral binder and granulates (also mineral in origin) of graduated dimensions [3]. Similarly, that which we define as Agro-concrete will therefore consist of: "A mix between granulates from lignocellular plant matter coming directly or indirectly from agriculture or forestry, which form the bulk of the volume, and a mineral binder" [8].

Indeed, many projects aim to create construction materials using one or more forms of lignocellular matter as a reinforcement to the structure rather than as a lightweight aggregate with an insulating purpose. The materials used are generally fibers which serve to improve the traction resistance, ductility and post-fracture behaviour of composite concretes made in this way. More recently, projects used various sources of bio-aggregates, such as wood, coconut, sisal, palm, bamboo, or bagasse, etc. (Table 1). It is interesting to note that countries such as Brazil which have an exceptional range of flora have a wide range of fibers to experiment with, and research in this domain is very active [13, 14].

4 Properties of plant aggregate

Bio-based aggregate are coming from the stem of plants cultivated either for their fibers (hemp, flax, etc.) or for their seeds (oleaginous flax, sunflower, etc.) (Table 1). Owing to the structure of the stem of the plant they are made from, such aggregates are generally malleable, elongated and highly porous with a low apparent density. They are very different from the mineral aggregates typically used in concretes, for which there are standardised tools and techniques for characterisation. Amongst these, hemp shiv (the woody core of the stem of the hemp plant) is probably the most widely used in alternative or eco-friendly building materials in Europe and is also representative of most of the aggregate coming from the stem of an annual crop. This is usually mixed with a lime-based binder and the resultant bio-concrete is known as *hemp-lime*.

This kind of aggregate is a co-product of hemp industry that is renewable and produced in an annual cycle while the price of mineral aggregates is steadily increasing as resources become less readily available. The characterization of these aggregates, however, which is crucial to a proper understanding of the quality of the materials in which they are incorporated, requires adaptations to be made to the techniques usually employed for mineral aggregates, or the devising of new characterization procedures [63].

The hygroscopic behaviour of lignocellulosic plants is largely due to their hydrophobicity. Their complex architecture is marked by a multi-scale porosity in order to conduct the necessary fluids for their development (sap and water). Even after cutting and processing, this porosity continues to play its role and is therefore the main way of absorption of water following the Laplace laws. This absorption occurs mainly by conducting vessels or tracheids before the water spreads to the rest of the cells by diffusion through the cell walls and punctuation. The typical value of absorption is about 350 % [64, 66].

The bulk density of hemp shiv is linked to the porosity of the particles and to the inter-particular porosity. The bulk density of hemp shiv is measured in a cylindrical mould with a loose packing and without compaction. The typical value obtained is about 100 kg/m^3 [8, 13, 65]. The particle size distribution of bio-aggregate may be studied via sieving method and/or image analysis [8, 15].

Table 1. Overview of research into materials mixing mineral binders and lignocellular products for making of lightweight concretes.

Plant	Valuable material	Source(s)	Binder(s) used	Countries	References
Hemp	Hemp wood	Agricultural co-product	Tradical® PF70, hydraulic lime, methacholine/lime mix	France	[10, 15-22]
				Elsewhere	[23-27]
Flax	Shive, tow	Agricultural co-product	Portland cement, Cement + Sucrose	France	[28-30]
Wood (all types)	Sawdust, shavings	Sawmill waste	Portland cement, Cement/clay mix	France	[31-33]
			Portland cement	Elsewhere	[34, 35]
Sunflower	Stem	Agricultural by-product	Methacholine/lime mix	France	[10, 36]
Beetroot	Dried beetroot pulp	Food industry waste	Portland cement	France	[37]
Coconut	Shell	Food industry waste	Portland cement	Elsewhere	[38]
Durian	Shell	Food industry waste	Portland cement	Elsewhere	[38, 39]
Cork	Wood	Industrial waste	Portland cement	Elsewhere	[40]
Miscanthus	Stem	Co-product (ethanol)	Portland cement	France	[41]
Rice husk	Husk	Agricultural by-product	Lime	France	[42]
Corn Cob	Cob	Agricultural by-product	Cement	Portugal	[43]
Lavender	Straw	Agricultural by-product	Calcic lime	France	[44]
Dis	Stem	Wild plant	Cement	Algeria	[45]
Alfa	Fibres	Wild plant	BioPolymer	Algeria	[47]
Tipha, Catail	Stem	Wild plant	Methylene Diphenyl Diiso-cyanate binder	Senegal Germany	[48, 49]
Date palm	Fibres	Agricultural by-product	Cement	Algeria	[50]
Beet pulp	Pulp	Food industry waste	Cement/Lime	Nederland	[37, 46]
Durian, Rambutan, Pumello, Mangusteen	Peel	Agricultural by-product	Cement/Sand	Thailand	[38, 39]
Coir	Fibres	Agricultural by-product	Cement	India	[52]
Rape straw	Fibres	Agricultural by-product	Lime/Cement	France	[53]
Opuntia ficus-indica	Cladodes	Agricultural by-product	Resin	Italy	[54]
Sugar cane bagasse		Food industry waste	Cement / Soil	USA	[55]
Bamboo		Wild plant	Cement	China	[63]
Lechuguilla fibres		Wild plant	Cement	Mexico	[57]
Kenaf bast fibres		Wild plant	Cement	USA/Brazil, Malaysia	[58]
Wood shaves		Wild plant	Cement	Algeria/ France/Brazil	[59, 60]
Sulphite pulp fibres		Wild plant	Cement	Brazil	[61]
Eucalyptus kraft pulp		Wild plant	Cement	Australia	[62]

5 Binders

Various binders may be used to make construction materials based on granulates and fibers of plant origin. The choice is essentially made on the basis of the main properties sought (mechanical properties, thermal properties, etc.), which will depend on the material use (support, insulation, etc.), the manufacturing process (prefabricated in a factory, poured on site, projected ("shotcrete"), etc.) and on the construction location (indoors, outdoors, sheltered or otherwise) [68]. The choice may also be guided by financial considerations (e.g. local prices of materials) and environmental factors (CO_2 balance, for instance) [68].

Among the most commonly used materials, we find Portland cements and hydraulic or aerated lime, most often associated with pozzolanic additives such as fly ash, blast furnace slag and metakaolin [8, 65, 69]. We also find plaster for applications where it is sheltered from humidity. Certain commercial binders developed specifically for hemp concrete (hempcrete) are also obtained by mixing these different compounds: for instance, 70% slaked lime, 15% hydraulic lime and 15% pozzolana [8, 68].

6 Multiphysical Properties of Hempcrete

Hempcrete is a mixture, in very changeable proportions, of two very different components: a plant-based granulate and a hydraulic and aerated setting binder. It exhibits multi-physical behaviour which is unusual in the domain of construction materials. Indeed, the particles of hemp wood are characterized by a high degree of porosity which results in a high capacity to deform, absorb sounds and have hygrothermal transfer ability: this is one of the essential characteristics which set hempcretes apart from tradition mineral-based concretes for which the granulates are considered non-deformable. This difference has major effects on the performances of these concretes in all areas (acoustic, thermal [66], etc.), and of course, it has a direct impact on the mechanical properties of these innovative concretes [66, 67]. The aim of this part is to show why and how these concretes are distinguished from conventional concretes, and in particular to establish the properties of use and the characteristic values necessary for their use in construction.

6.1 Mechanical properties

As a mixture of plant particles and binder, hempcrete is an unusual construction material: the high flexibility of the aggregates in conjunction with the rigidity of the cement matrix leads to a non-fragile elasto-plastic behaviour. Thus, it is distinguished from other construction materials by a high deformability under stress, lack of fracturing and marked ductility with absorbance of the strains ever after having reached the maximum mechanical strength [66].

It is also helpful to highlight another peculiarity: the variability of the behaviour depending on the formulation enables us to adjust and optimize the performances of this material for diverse applications as a roof filling material, in walling or as flagging (Figure 2). Depending on the concentration of binder, three types of behaviours of hempcrete are observed. For small doses of binder, we have a material with poor mechanical strength and an elastic modulus of less than 5 MPa. The levels of deformation are very high (>15%) [8]. This material behaves like a sample of loose particles with bridges of binder connecting them. It is pre-destined for applications where thermal or acoustic insulation is important. For intermediary doses, the level of performance increases with the quantity of binder. The behaviour of the material becomes progressively more similar to that of materials with large doses of binder. The behaviour is guided by the binder matrix. For large doses of binder, the material is comparable to a continuous binder matrix in which the plant particles are buried. The mechanical performances increase and tend towards those of the pure binder. However, the high deformations that this concrete is capable of dealing with make it advantageous as a filling material. It can undergo differential compression, contraction or dilation with no apparent cracking [26].

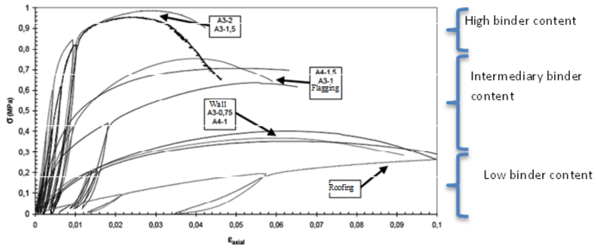

Figure 2. Influence of the dose of binder on the compressive strength of the hempcrete shaped by compaction (0.05 MPa) after 1 y of hardening, reproduced from [16].

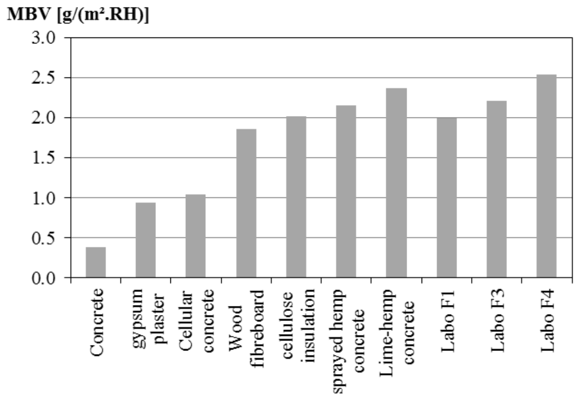

Figure 3. Review of Moisture buffer value of building materials, reproduced from [73].

6.2 Hygrothermal properties

The building of dwellings or renovation work including hemp-based materials often draw initial comments from users that are very positive in regard to the thermal and hygrothermal conditions. The particular reason behind this fact is their high porosity (between 70% and 80%) resulting in excellent insulating properties [72], see Fig. 4.

Hemp-based materials are considered as phase-change materials (PCM): the thermal behaviour reduces the amplitude of the variations in the ambient air temperature, whilst improving the thermal comfort by bringing down the surface heat of the material. Thus, the use of such materials is an excellent means of passively regulating the indoor temperature, and thereby decreasing the building's energy requirements [72]. In addition, the experimental results show a regulation of the relative humidity in the envelope because of constant exchanges of water vapour between the indoor and outdoor environments, modulating sudden changes in temperature. Hence, these materials are able to improve summer and winter comfort, and stabilize the indoor temperature between day and night, whilst preventing the phenomena of condensation and dampness on the walls [73]. Some examples of MBV value are given in Fig. 3 for concrete and cellular concrete from [74], gypsum plaster, wood fibreboard and cellulose insulation from [75], sprayed hempcrete (hemp concrete) from [73], lime-hemp concrete from [76], hemp lime concretes with increasing substitution of lime-based binder for sulphate-based binder (F1: 1/3 sulphate-based binder + 2/3 lime-based binder; F2: 1/2 + 1/2; F3: 2/3 + 1/3) [77]. These properties are also well summarised in reference [78].

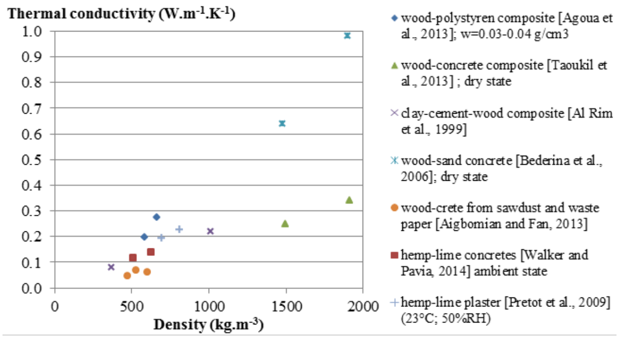

Figure 4. Thermal conductivity of bio aggregate based building composites (made of wood or hemp shiv).

6.3 Acoustic properties

Hempcrete is a material whose acoustic properties can vary greatly depending on the properties of its components and the way in which it is put to use [79, 80]. In particular, the results presented herein highlight that the parameters of installation have a far stronger influence than the properties of the components, with the apparent density of the material and the binder-to-shiv mass ratio playing an important part (Fig. 5). Thus, by combining these different parameters, it is possible to find the optimal formulation of a hempcrete for any given application.

6.4 Life Cycle Analysis of Hempcrete

Approximately 1.8 tons of CO_2 are sequestered for every ton of hemp shiv used [93]. One cubic meter of hempcrete uses 1000 litres of hemp hurds meaning that around180 kg of CO_2 dioxide will be locked up per 1 m^3 of wall in the hemp shiv [94]. Taking into account the CO_2 emitted for binder production and depending on the re-carbonation of the lime, 117 kg to 18 kg of CO_2 are sequestered into a one cubic meter of hempcrete [95]. This is equivalent to 6 to 38 l of fossil fuel using a CO_2 factor equal to 3.09 kg/l of fossil fuel.

In addition, according to the study published by [81] there is a favorable impact on the greenhouse effect; the hempcrete wall constitutes an interesting carbon absorber for a duration of at least 100 years, because it stores more CO_2 in its three carbon absorbers (i.e. the hemp shiv, wood and lime) than is emitted by its life-cycle (net balance of 35 kg CO_2 eq. stored over 100 years per m^2 of hempcrete wall) (Fig. 6). In time, the CO_2 stored in the organic parts of the wall will be restored to the atmosphere [8, 81].

6.5 Durability of bio-based materials

Because of their relatively recent development, few studies have focused on the durability of plant concrete until now [82, 92]. The aging protocols applied in laboratory and the analysed properties are diverse, making the comparison of obtained results very complex [83]. In addition, the aging times used are rather short, and significant variations of the material properties are perhaps not visible for these aging durations. The protocols implemented until now are focused on similar factors that could influence the material properties: temperature, relative humidity, immersion in water [85, 86] and potential microbiological growth [84]. This can lead to a physicochemical and microstructural modifications of the materials and therefore impact the performances of materials in a building.

An interfacial area of few dozen micrometers thick around plant aggregates can be observed in concrete [88]. In this area, the setting of the binder is inhibited or delayed by the extractable of shiv solubilised during the fabrication, or corresponding degraded products of shiv in an alkali environment. This interfacial transition zone is characterised by an increase of the porosity between the aggregate and the binder. These debonding areas can also be related to the vegetal dimensional changes depending on the material moisture content [87].

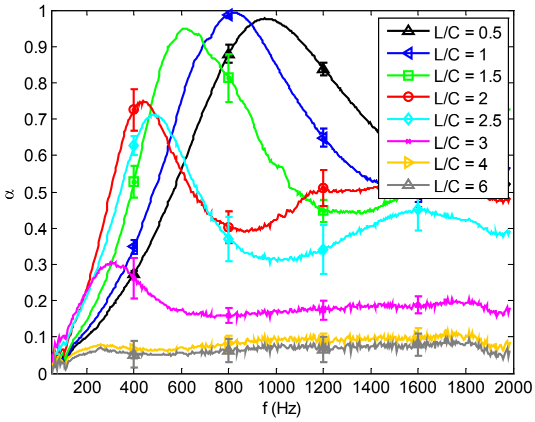

Figure 5. Sound absorption of hempcretes depending on the binder content [79. 80].

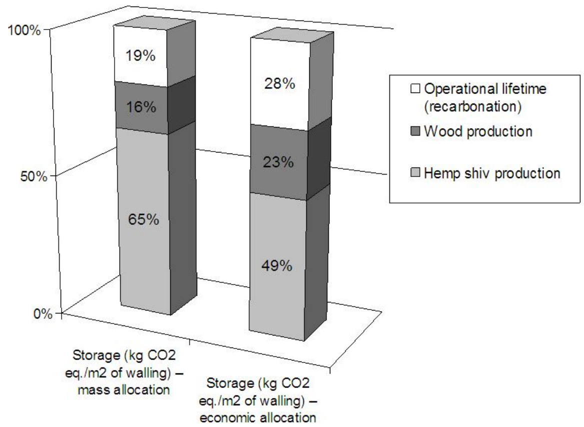

Figure 6. Distribution of the storage of CO2 between the three carbon absorbers in the banked hempcrete wall on a wooden skeleton, reproduced from [8].

Phenomena of degradation of the plant fibres can also be observed when a binder with highly alkaline pH is used [88, 89]. Then, degradation is due to lime crystallisation in the aggregate porosity or a partial or total dissolution of cellulose, hemicelluloses, and for certain kinds of plants, lignin, which leads to the embrittlement of concretes [90].

Some studies have shown that wetting/drying cycles, used to simulate natural variations of humidity, had an influence on the mechanical and thermal properties of hempcretes [84-86].

Finally, in some circumstances, as in the case of fibre-cement panels, fungi may also appear at the surface of materials. This fungal development can lead to changes in functional properties of materials, but also cause health problems by degrading the indoor air quality. Indeed, many studies [88, 89] have investigated the colonisation of different media by molds or fungi (walls, painting, wallpapering, wood, etc.). This development is possible whenever microorganisms have enough water. Fungal species most commonly isolated belong to the Penicillium, Aspergillus and Cladosporium types [91]. Colonisation of fungi and degrees of alteration depend on various factors such as support (nature, physico-chemical properties, surface, water content, pH), microorganisms and environmental conditions [91].

7 Conclusions

Bio-based building materials made with plant aggregates have a lot of potential in the market for construction materials worldwide. With modern building designs demanding ever increasing sustainability in construction and maitenance, efficiency in operating and carbon footprint reduction, bio-based building materials are able to help meet these demands. The material can be naturally grown in plentiful supply across countries with temperate climates, it offers improved insulation and absorbs carbon dioxide from the environment.

The unique selling point of bio-based building materials made with plant aggregate is its ability to effectively insulate a building, using a natural material. However, bio-based building materials typically exhibit a comparatively low mechanical strengths, which is reported in the paper. Due to this low mechanical strength, bio-based building materials cannot be commonly used as a material to form load bearing members of a building, however t well suited to form the fabric of a timber framed dwelling, or other modest timber frame constructions. Bio-based building materials can also be retro-fitted to a building by method of a prefabricated cladding sheet, which can be fixed to the exterior or interior of building, commonly large warehouses, to aid with insulation and carbon offsetting.

Bio-based building materials have proven to have both viability and marketability in the construction industry, despite their relative infancy as a material. As is to be expected with such a new material, limited research has been carried out as to how to best utilize it, particularly with regard to how to take advantage of its natural, low carbon, features as well as its mechanical capacity, i.e. its ability to carry load. These natural features reduce the carbon footprint of a building and improve the insulation, both thermal and acoustic. These features are the main focus of the argument to further research this material, and how it can best be used in the construction industry.

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