Hemp-Lime Concrete: A Green Alternative to Conventional CMU Construction

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Abstract — *This literature research presents a direct comparison between the hemp-lime concrete usually known as hempcrete, and the commonly used concrete unit blocks as an envelope building material. As in the recent decades thee has been an increased awareness of our impact in the environment and the implications to the natural resources, new construction methods and better performing materials are becoming available to improve our way of living while being environmentally conscious. Since there is no such thing as an environmentally perfect material, product selection for green buildings is therefore a process of evaluation and compromise, seeking the best overall solution for a given program and budget. Products and systems must demonstrate reduced life-cycle energy consumption, increased recycled content, and minimal waste products in manufacture, construction, use, and demolition.*

Key terms – *Hemp Lime Concrete, Concrete Masonry Units, Lime Binders, Portland cement.*

INTRODUCTION

In the recent decades there has been an increasing awareness of the impact that we humans have on the environment and the implications of our virtuous and limitless consumption of the natural resources. Global warming as a result of greenhouse effect and the energetic crisis has pushed us to seek new ways to build more efficient and sustainable construction.

As a result, researches for better performing green materials are emerging. With the decriminalization of cannabis in some states, among these materials is a new trend for the use of hemp in construction applications. Hemp shives when mixed with hydrated lime as a binder forms a solid mix with good mechanical properties and excellent thermal capabilities. Although hem lime concretes (HLC) at the time cannot be used as a load bearing material, the means to exploit its good properties are already on the market.

This literature research seeks to compare this "new" construction material to the conventional use of concrete masonry units in Puerto Rico.

PROBLEM STATEMENT

The ever increasing energy costs and the rise in ambient temperature associated with the tropics and global warming, have finally led home owners, designers and developers in Puerto Rico to seek new alternatives to control the associated costs of home ownership. If scaled, interior temperature control in a common household is one of the highest energy consumption devices, as Air Conditioners are habitually used. Although inverter technologies are available, thermal insulation losses greatly reduce energy and cost savings.

As it often happens, people resist changes, particularly when it comes to new construction methods. Recent researches and new construction trends are moving towards green materials as an alternative to conventional construction materials. These new materials are environmentally friendly, biodegradable, renewable and recyclable with the particular characteristic of being thermally and acoustically efficient.

RESEARCH DESCRIPTION

Unlike Portland cement and its derivate products like concrete masonry units (CMU) that have been widely studied, hemp-lime concrete (HLC) is relatively a new product. This literature research is intended to compare the known characteristics, advantages and constrains of HLC as a building envelope material versus the commonly used CMU. Both materials are being compared in their origin or manufacture, life cycle as a green or sustainable material, their characteristics or mechanical properties and thermal performance. With the limitation of HLC not being available for purchase in Puerto Rico, a cost comparison has been made considering the importation for batch material for a single project.

RESEARCH OBJECTIVES

Since recent legislation in Puerto Rico to decriminalize the use and cultivation of the cannabis plant for medical purposes, it is a possibility that the approval to grow industrial hemp will follow. Although the basic difference between medical cannabis and hemp mainly resides in the plant contents of Tetrahydrocannabinol (THC) that is the hallucinogen substance, in essence, the plant structure is the same.

As a by-product of hemp cultivation, the hemp shives or woody core of the stem when combined with lime as a binder has been successfully used across Europe and recently in the USA as a non-load bearing building material that can be used in exterior walls because of its excellent thermal and acoustical properties. Unlike threes, hemp is a rapid growing crop that can be harvested yearly. Since the shives are a by-product of the cultivation, it is a low cost material with zero carbon foot-print.

The purpose of this literature research is to compare the benefits and constrains of this Hemp-Lime Concrete (HLC) as a wall construction material versus the conventional use in Puerto Rico of Concrete Masonry Units (CMU). Although not limited by the approval of the aforementioned legislation, the import and use of hemp derived products is not criminalized. In this case, the hemp shieves could be transported to the island but at an increased cost.

LITERATURE REVIEW

"Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"- Our Common Future report, Brundtland Commission, 1987.

Green Conscience

In the recent decades there has been an increasing awareness of the impact that we humans have on the environment and the implications of our virtuous and limitless consumption of the natural resources. We have made some progress in limiting environmental pollution, but consumption of energy and other resources has climbed briskly, and we are continuing to release greenhouse gases at an ever-increasing rate.

This new green conscience is an abstract concept, which requires the inclusion of the terms: sustainability, ecology, and performance. Although there is a categorical relationship between the sub-terms, each category is nevertheless independent. For instance, a building can be sustainable but not ecological or green, whereas a green building must be a combination of sustainable, ecological, and performative. The level of greenness is determined based on the level of interaction of these three categories.

The American Society for Testing and Materials (ASTM) Subcommittee E50.06 on Green Buildings defines the term green building as "building structures … that are designed, constructed, operated and demolished in an environmentally enhanced manner." The green building movement seeks to identify building materials that minimize environmental impacts in their creation and use and minimize health risks to building occupants. But there is no such thing as an environmentally perfect material. Product selection for green buildings is therefore a process of evaluation and compromise, seeking the best overall solution for a given program and budget. Products and systems must demonstrate reduced life-cycle energy consumption, increased recycled content, and minimal waste products in manufacture, construction, use, and demolition. Such requirements have resulted in the introduction of mortar-less interlocking masonry systems and the renewed interest in the use of bio aggregate based building materials.

Recent researches have also led to the use of anthropogenic waste materials from each industrial process to be ingeniously consumed as inputs to other processes, while maintaining a sophisticated, carefully designed balance with the natural resources. Some of these new practices include the use of green materials or their combination (bio-composites) with these by-products to improve material performance. “Green” materials are so named because they are environmentally friendly, biodegradable, renewable, and recyclable. These come from plants, animals, or the earth. They are naturally occurring, and are suitable for building, as their use requires little construction knowledge. Since builders generally choose locally available materials, their associated embodied energies are relatively low.

Carbon Footprint

Carbon dioxide enters the atmosphere through burning fossil fuels (coal, natural gas, and oil), solid waste, trees and wood products, and also as a result of certain chemical reactions (e.g., manufacture of cement). Carbon dioxide is removed from the atmosphere (or "sequestered") when it is absorbed by plants as part of the biological carbon cycle.

The general understanding of zero-carbon buildings are that they involve “micro-generation”, adding renewable energy equipment like solar panels or reducing waste and water consumption. Energy efficiency, in terms of increasing insulation, is a very important part but until recently, there has been little concern about the methods and materials that are used to achieve this as long as energy consumption is reduced.

A recent awareness has been developed in which the nature of the materials and methods of construction are seen as equally important. It is general practice to use fossil-based materials to manufacture insulation when we are trying to reduce our consumption of fossil fuels, yet the insulation industry is dominated by products that are petro-chemical based or require a lot of energy to produce. To make matters even worse, the commonly used materials in everyday construction processes demand even more energy for their production.

Energy Consumption

Industrial development and population growth have led to a surge in the global demand for energy in recent years. During the decade of 2,000’s, this new demand, together with Middle East tension, the falling value of the U.S. dollar, dwindling oil reserves, concerns over peak oil, and oil price speculation triggered the 2000’s energy crisis, which saw the price of oil reach an all-time high. This effect directed the efforts of the government, industries and home owners to seek for alternatives to lower their energy consumption as an alternative to alleviate their economy as an initial and fundamental factor.

Although the installation of an energy system in a home represents a considerable percentage of the cost, energy retention efforts almost trifold the percentage of the energy expended in the average household. The amount of energy that can be retained, rather than dissipated, depends on several factors, many of which are architectural. These include the size, shape, style, orientation, and construction of the building, as well as the insulation, heating/cooling, and envelope systems within the building. Non-architectural factors include the location, local climate, and users’ preferences.

Thermal building insulation is essential for energy retention, which is one of the most important issues and oldest problems in the architectural field. Insulation fortifies the building against temperature fluctuations in the environment, reduces unwanted cold or heat, and affects an occupant’s budget significantly (positively or negatively). Up to 40 percent of the energy used to heat or cool a building is caused by air leakages, which continually drain additional energy in order to maintain a constant ideal indoor temperature. However, as much as 30 percent of this energy expenditure can be eliminated by proper insulation. Green insulation systems are adaptations of traditional systems, offering enhanced performance with the added benefit of being a sustainable and ecological solution to energy retention problems.

CMU Background & Properties

Masonry is one of the oldest forms of construction known to humans. The term generally refers to brick, tile, stone, concrete-block etc., or combination thereof, bonded with mortar. However, many different definitions of masonry are in vogue between the International Building Code (IBC 2009), ASTM E631 or other technical dictionaries. A commonality in these various definitions is that masonry essentially is an assemblage of individual units which may be of the same or different kind, and which have been bonded together in some way to perform intended function. Their main purpose of use is the construction of walls. Walls can be basically categorized as load-bearing or non-load-bearing walls, cavity walls, veneer walls, and solid walls. No matter the type of material used or the method by which the masonry wall is constructed, two components remain crucial: mortar and wall reinforcement.

Concrete masonry units (commonly referred to as CMU's) are made from a mixture of Portland cement (produced by pulverizing clinkers consisting essentially of crystalline hydraulic calcium silicates, and a small amount of one or more forms of calcium sulfate and up to 5% limestone and heated in a rotary kiln to high temperatures around 1,454ºC), aggregate (normal weight or lightweight), and water. They are available in a variety of shapes, sizes, configuration, strength, and colors. Because the properties of concrete vary with the aggregate type and mix proportion, a wide range of physical properties and weights are available in concrete masonry units. The weight class of a concrete masonry unit is based on the density or oven-dry weight per cubic of the concrete it contains.

Aggregate type, size, and gradation as well as water-cement ratio are important in determining the compressive strength of concrete masonry units. Manufacturers determine optimum ingredient proportions to obtain a balance among mold-ability, handling, breakage, and strength. For non-loadbearing CMU, compressive strength may be as little as 500 psi and still adequately serve its purpose. For loadbearing applications, CMU should have a minimum average compressive strength of 1,900 psi. Typically, compressive strengths range from about 1,000 to 3,000 psi.

CMU's can be made with aggregates that are light, medium, or heavy in weight. The heavy units are made with sand and gravel or crushed stone and can weigh more than 40 lbs. each. Lightweight blocks are made with coal cinders, slag, and other aggregates and might weight as little as 22 lbs. apiece. The lightweight units have higher thermal and fire resistance but also have higher moisture absorption.

In terms of thermal efficiency, a building material is normally judged by its resistance to heat flow. The material's R-value is a unit of measure for the rate of heat flow through a given thickness by conduction from one side to the other under laboratory conditions. **Table 1** shows average R values of common construction materials. Since the material R value relates to its unit weight, masonry is a poor insulator. In contrast, urethane insulation has a very high resistance because it incorporates closed cells or air pockets to inhibit heat transfer. The thermal resistance characteristics of CMU's vary with aggregate type and density. **Table 2** shows common R values for CMU and how it varies according to its unit weight.

To further understand this, heat flows from hot to cold. As the temperature rises on one side, heat begins to migrate toward the cooler side. For the heat transfer happen, the wall itself must undergo a temperature increase. This amount of thermal energy necessary to produce the increase is directly proportional to the weight of the wall. Since masonry is heavy, it can absorb and store heat and substantially retard its migration. This characteristic is called heat capacity. One measure of heat capacity is the elapsed time required to achieve equilibrium between inside- and outside-wall surface temperatures. The midday solar radiation load on the south face of a building will not completely penetrate a 12-in. solid masonry wall for approximately 8 hours.

The effects of wall mass on heat transmission are dependent on the magnitude and duration of temperature differentials during the daily cycle. Warm climates with cool nights benefit most. Seasonal and climatic conditions with only small daily temperature differentials tend to diminish the benefits. In the case of Puerto Rico, temperature ranges between 75°F to 85°F. Thus the effect of heat capacity can still be felt during the night time, hence the need of air conditioner particularly at night.

Table 1

Common Construction Materials R Values [1]

MATERIAL	R-value	MATERIAL	R-value	MATERIAL	R-value
1" mineral wool	3.70	3½" fiberglass	13.48	3" honeycomb	2.59
1/2" gypsum	0.45	½" mineral tile	1.19	3" isocyanurate	22.5
1/2" plywood	0.02	1" isocyanurate	7.50	3" polystyrene	12.0
1/8" floor tile	0.05	1" polystyrene	4.00	3" polyurethane	17.6
1/8" hardboard	0.09	1" wood core door	1.96	8" con. block	1.11
3/16" hardboard	0.14	6" fiberglass	19.00	insulated glass	1.65
5/8" gypsum	0.56	1" polyurethane	5.88	single glass pane	0.94

Table 2

CMU Walls R Values by aggregate weight [2]

R-Value of Insulated and Uninsulated Single-Wythe CMU Walls

Nominal Wall Thickness (in.)	Unit Cores	Concrete Unit Weight				
		60 pcf	80 pcf	100 pcf	120 pcf	140 pcf
4	insulated	3.36	2.79	2.33	1.92	1.14
	uninsulated	2.07	1.68	1.40	1.17	0.77
6	insulated	5.59	4.59	3.72	2.95	1.59
	uninsulated	2.25	1.83	1.53	1.29	0.86
8	insulated	7.46	6.06	4.85	3.79	1.98
	uninsulated	2.30	2.12	1.75	1.46	0.98
10	insulated	9.35	7.45	5.92	4.59	2.35
	uninsulated	3.00	2.40	1.97	1.63	1.08
12	insulated	10.98	8.70	6.80	5.18	2.59
	uninsulated	3.29	2.62	2.14	1.81	1.16

While not commonly used in residential applications in the island, there are insulation materials to enhance CMU walls performance. Christine Beall states in the book Masonry Design and Detailing that "in the thermal research conducted by the National Institute of Standards and Technology (NIST) and the National Concrete Masonry Association (NCMA), the effects of variable insulation location were studied. It was found that indoor winter temperature fluctuations were reduced by half when insulation was placed on the outside rather than the inside of the wall, and that the thermal storage capacity of the masonry was maximized. In cavity walls, performance in hot and cold climates is improved if the insulation is placed in the cavity rather than on the inside surface. Insulation location can affect the potential for condensation, so vapor flow as well as heat flow should be considered in optimizing wall performance".

Hemp-Lime Concrete Background & Properties

Hemp (Cannabis sativa) is a fast growing erect annual agricultural crop which produces only a few branches, usually at the top of the plant and grows to a height of between 5 and 13 feet. Hemp can grow without pesticide or agrochemical inputs, and sequesters large amounts of carbon dioxide (CO2) during the growing cycle. Its main difference when compared with medical cannabis it's the content of tetrahydrocannabinol (THC) that is the hallucinogen substance. Because the industrial hemp plant looks identical to the drug-producing strains, however, the growing of industrial hemp usually requires a special license from the government in non-prohibited states.

Its stem is thin and hollow, with a diameter of 0.15 to 0.8 inches depending on the conditions and the specific variety grown. Hemp fibers have high tensile strength and are advantageous for use in a number of products such as paper, textiles and natural fiber composites. Historically in non-banned countries, hemp shives were a by-product of the hemp fiber industry and were not used extensively. Hemp shives are the woody core parts of the hemp stalk, referring to their appearance and cellular structure, which resembles that of wood. It is this hemp shiv that is used in the production of HLC.

First used in France during the 1990's, HLC was developed as a light weigh material to restore historic buildings damaged in WWII. During the time, these buildings were repaired with cement but this created another problem since Portland cement does not allow the structures to breathe and mold and rotting issues became a common problem. On the contrary, since HLC uses lime as a binder, it allows the structure to breathe through its hygroscopic properties. Hemp Lime Concrete (HLC) is a bio composite material made from the hemp shives and a lime based binder which can be mixed and poured on site, similar to cast in place concrete, constructed into pre-cast panels or blocks.

Over time, lime has been used as a mortar in most historic buildings was made only with lime and sand. It did not contain any Portland cement. Lime mortars were strong and durable but cured slowly when compared to Portland cement by a process called carbonation. Mortars and plasters made from lime were vapor permeable in their finished state, which has important implications for the way the fabric of the building works: helping to manage humidity within the structure and thereby keeping the materials used con construct in good conditions. It is this property that makes it ideal to preserve the hemp shives in the bio-aggregate material.

The building lime is produced from calcium carbonate ($CaCO_3$), found naturally in quarried limestone, chalk, coral rocks or shell. The raw materials are burnt in a kiln, causing a chemical change to occur: carbon dioxide (CO_2) is given off, leaving behind calcium oxide (CaO) – a substance known as quicklime. Quicklime is a highly reactive material that produces a large amount of heat when mixed with water. Because of this reason, special precautions are required for handling and storage.

When quicklime is mixed with water in a process known as slacking, calcium hydroxide ($CaOH_2$) is produced. This is called "hydrated lime". This lime, when applied to a building in the form of mortar or plaster, will harden slowly by carbonation reacting with carbon dioxide from the air. Because of this end result, the process of transforming limestone to quicklime to hardening building lime is known as "lime-cycle". However, in reality the carbonated lime in the building is a very different substance from the original lime-stone, in terms of appearance and properties and especially in strength and hardness.

In order to prevent the process of carbonation to begin, lime putty is always stored under water until needed. It is from this substance that high quality lime mortars and plasters are made, and it can be diluted with water and or colored with natural pigments. The desirable qualities of lime putty improve with age, with the recommended minimum for production of quality mortar being one-month-old putty. Lime putty is commonly six-month-aged as standard.

To address these time constrains, special blends of hydrated lime with low concentrations of cement have been introduced to the market to assist in the early setting and drying of the material. Tradical HB and Batichanvre are some examples. Manufacturers claim that their engineered products, despite the addition of cement, the bulk of the material is lime-based and largely functions in the same way as lime.

Contrary to Portland cement that has been studied and evolved from over a century, HLC mixtures are virtually a new technology. Recent research and studies have proven that for the current knowledge of the material, its mechanical properties and levels of performance for load bearing capabilities are modest when compared to other construction materials. Laboratory test show a clear dependency of the level of performance on the volume concentration of binder. The higher the concentration, the greater will be the compressive strength. With low binder content, the compressive strength is around 29 psi (0.2 MPa). For intermediate proportions, it varies between 58 psi (0.4 MPa) and 116 psi (0.8 MPa), and for high content, it is 174 psi (1.2 MPa) (Amziane, 2013).

Thermal mass is a property that enables building materials to absorb, store and later release significant amounts of heat. For example, when outside temperatures are fluctuating throughout the day a large thermal mass within the insulated portion of a house can serve to "flatten out" the daily temperature fluctuations, since the thermal mass will absorb thermal energy when the surroundings are higher in temperature than the mass, and give thermal energy back when the surroundings are cooler, without reaching thermal equilibrium. This is distinct from a material's insulation value that reduces the building's thermal conductivity, allowing it to be heated or cooled relatively separate from the outside, or even just retain the occupant's thermal energy longer.

Appropriate use of thermal mass throughout structures can make a big difference to comfort and therefore energy consumption bills. Poor use of thermal mass can exacerbate the worst extremes of the climate and can be a huge energy and comfort liability. It can radiate heat all night as you attempt to sleep during a summer heatwave or absorb all the heat you produce on a winter night.

Studies show that HLC possess the characteristics of thermal mass with the added benefit of being lighter than concrete and other masonry building materials. This characteristic sets it apart from synthetic insulation materials that lack the capacity to store heat. Even when thermal mass is not a substitute for insulation, HLC possesses excellent R values as well.

Manufacturers claim that HLC buildings have excellent insulation properties of up to R25 when built to a recommended 12 inches [3]. This value is proportional to the wall's thickness. It ranges from R-25 at 12 inches to R-50 at 20 inches as shown in **Table 3**. The monolithic construction of HLC walls means that air leakage and draft is drastically reduced. Buildings stay warm in cold weather and cool in warm weather without a constant input of energy to be comfortable.

Table 3
Average R values of THC by thickness [3]

Average R Values of HLC	
Wall Thickness (in)	**R Value (ft²☉.°F.h/Btu)**
12	25
16	33
20	50

Other Hemp and Bio Aggregate Applications

In search to further develop existing materials and modify them to the actual needs, studies are being performed into blends of bio aggregates with cementitious binders. Hemp shieves have been used in cement mix designs to study the behavior, properties and life expectancy. Other mixes used over centuries in Europe ae also being studied. Straw bale construction has re-emerged successfully in France and England. Mixes of sawdust and concrete have (known as timber-crete) also been developed and studied.

METHODOLOGY

With the gathered information of both the CMU and HLC, a side by side comparison has been made. This comparison is limited to the available information on HLC and not over the complete spectrum of properties. Unlike cement derived products, there is still much to learn from hemp, lime and the combination of both.

Since speculations always come into play when limited information is available, efforts were focused where the speculation was. Only a handful of books related to HLC are available. Most of the manufacturer's claims are related to environmental concerns, carbon sequestration and thermal performance. Hence our comparisons starting points are manufacture and precedence of aggregates and binders and CO_2 emissions.

Much of the data obtained from the HLC manufacturers make the claim that their products have a negative carbon footprint. Literature shows that the claim is valid when the HLC is mixed in situ. Another point to consider for this claim is that after the structure has served its purpose and demolished, a proper recycling plan should be in place. If incinerated, the CO_2 will be released back to the atmosphere meaning that the sequestration was only temporary. On the other hand, if the material is deposited into a landfill, the carbon could be released as CH_4, which is far worse as a greenhouse gas than CO_2 [4]. With this said, if cast in place and the recycling process is done responsibly, HLC does provide a lower carbon foot print than CMU.

It should also be pointed that the Portland cement manufacture has greatly improved. Energy consumption for cement production has decreased 25% during the past 20 years, mostly as a result of more efficient equipment and production methods [2]. Cement accounts for only about 9 to 13% of the unit and this proportion can be reduced by substituting fly ash, which is a by-product of coal fired power plants.

CMU mechanical properties, in particular its compressive strength is far superior to HLC. This is a big step forward as the material is capable to bear the building loads. HLC has been commonly used with timber as the load bearing elements. Since the use of wood in Puerto Rico is not favorable, an alternative material could be a steel structure. Although HLC is nonflammable and capable of withstanding heat, further testing and compliance would be required in order for it to be used as fireproofing for the encased steel elements. For this particular scenario, CMU is capable to comply.

Thermal and insulation properties of HLC are far better when compared to CMU. If wall thickness is not an issue, HLC exhibit far better insulation properties (R-25@12”) against the CMU (R-1.11@8”). CMU performance can still be improved with the addition of an insulation agent but at an added cost.

Another important factor to consider when selecting between the two materials is the time required for the material to set. While CMU can be plastered once the mortar has cured in a matter of hours, HLC curing requires time and favorable weather conditions. About a month is required for the cast to cure before plastering can be made. This time is only required for the plastering process because forms can be removed right after compaction has been made. This is an important factor to consider in fast moving projects because of the costs involved, particularly with labor.

According to the costs provided by Hemp Technologies Collective in their page hemp-technologies.com, the cost for HLC per cubic feet is around $24.20 per cubic feet including labor costs. From their pricing list, the actual cost of material in that price is about $9.84 per cubic foot including an estimated shipping fee of $3.14 for the volume unit in a 2,230 cubic feet container (40ft). Taking into account that a typical HLC wall is 12” thick, this is the price for the square foot of wall as well. Even when deducting the freight charges, HLC is substantially more expensive than CMU at $6.70 per square foot of wall vs $1.36 per square foot of an 8” CMU block. It must be pointed out that in Puerto Rico; average household construction does not include insulation materials of any kind. In the long run, with the availability of local hemp materials and improved productions that lower the cost, these values might shift in favor of HLC since sooner or later we would be required by means of energy consumption to insulate our houses.

CONCLUSION

With more testing and research, the government approval for local hemp harvesting and the need of sustainability, HLC might prove to be a feasible alternative to Puerto Rico. It is clear that big marketing strategies are in play to promote HLC as a product around the globe and that more research is required in order to further develop the material to increase its mechanical properties. Only time will prove if the addition of Portland cement as an additive to the lime binder will not affect the hygroscopic characteristics of the lime and create deterioration to the hemp cellulose. Since it is a relative new material, there are several questions of its longevity and performance in real life conditions for the tropical weather.

On the other hand, CMU systems in Puerto Rico can also become technically sound as the means to improve the system thermal capabilities are already in the market. It is clear that this will initially increase the cost to the client but during the occupancy of the structure, there will be considerable savings in energy consumption. This would be aided if ceiling heights were to be increased as it used to be at the beginning of the century in the island.

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