Title: Alternate to Concrete

Introduction

Concrete has been used by humans since ages– its basic ingredients dating back to ancient Egypt. After water, it is the second-most utilised substance on Earth. Approximately, three tons of concrete are consumed by every person each year. It is used globally in building applications like bridges, roads, runways, pavements, and dams. Concrete is used not only for basic infrastructure construction. The building of the Burj Khalifa skyscraper relied on a highly viscous concrete mixture that doesn't harden before it can be pumped to the top of the tower and forms a strong and robust final product. And Japan's construction industry has developed ultra-strength concrete samples to build its earthquake-proof bridges. It needs no additional fireproofing treatments to meet stringent fire codes and performs well during both natural and manmade disasters. Buildings constructed with cast-in-place reinforced concrete can resist winds of more than 200 miles per hour and the impact of flying debris. As a concrete building has a life-span of 150 years, it reaches its end because it has no further use rather than a structural failure. In addition, it is UV-resistant and water-proof [1-2].

The main ingredient of concrete is cement. As it is instrumental for the construction activity, it is tightly connected to the global economy. Its production is growing by 2.5 percent annually, and is expected to increase from 2.55 billion tons in 2006 to 3.7-4.4 billion tons by 2050. Australia itself produces up to of 26 mm. cubic of concrete every year. However, the cement industry accounts for about 5 percent of the global carbon dioxide discharges. Also, approximately 3-4% of concrete produced by concrete batching plants is wasted. Cement manufacturing is highly energy and discharge intensive process as extreme heat is needed. For example: Producing a ton of cement consumes 4.7 million BTU of energy, equivalent to about 400 pounds of coal, and releases nearly a ton of CO_2 [1-3].

The aim of the project is to find a suitable replacement of concrete in terms of sustainability and structural strength on a commercial-scale.

Cement and Concrete Production

Cement is a binder ;it binds with sand and gravel (aggregate) to form concrete.
Cements used in construction are often lime or calcium silicate based .The process releases carbon dioxide directly and indirectly. Carbon dioxide is released during the production of clinker (cement constituent) which involves heating calcium carbonate in a rotary kiln (directly). Also, CO_2 is produced during calcination which involves heating limestone to decompose it into calcium oxide and CO_2. This process releases 50% of all CO_2 discharges from cement production [3-4].

$$CaCO_3 + heat \rightarrow CaO + CO_2$$

[4]-Reaction of the calcination
Afterwards, the clinker is removed from the kiln to cool, grounded to a fine powder, and added to a small amount of gypsum to create Portland cement. Masonry cement is generally used after Portland cement. As it requires more lime than the former cement type, it results in more CO_2 discharges [4]. Numerous chemicals are added to the cement mixture to act as plasticizers, accelerators, dispersants, and water-reducing agents called admixtures. These additives are used to increase the workability (ability of a fresh concrete mix to fill the mould properly with the desired vibration and without reducing the concrete's quality) of a cement mixture still in the non-set state, the material's water accumulation and to decrease the amount of water necessary to obtain workability and cement needed to create strong concrete. Structural concrete contains one-part cement to two parts fine mineral aggregate to four parts rough mineral aggregate. These amounts are varied to achieve the strength and flexibility. Aggregates improve the formation and viscosity of the concrete paste and enhance its structural performance. To form concrete, add water to the cement and aggregate. The resulting calcium silicate hydrates form an extended network of bonds which bind together the solid aggregate [4-5].
Full mixing of concrete is important to make it uniform and high-quality. After mixing, the placing and compaction of concrete must be done side-by-side. Placing is done so that separation of various components is avoided, and full compaction is done to eliminate all air bubbles. Then it must be cured so that it doesn't dry too quickly. Its strength is influenced by its moisture level during the hardening process (as cement solidifies, concrete shrinks). If the concrete does not shrink, tensile stresses form, failing the concrete. To mitigate this issue, it must be kept damp as it sets and hardens [4-5].

Reinforcement of concrete-

Concrete is a brittle material that performs well in compression but not in tension due to its low tensile strength. Reinforcement in concrete is used to take in these tensile forces so that cracking does not weaken the structure. For many years, steel has been used as a reinforcement for concrete slabs that have to take on some loading. The direct stress (tensile or compressive) transmits from concrete to steel interface via the bond between them due to friction. Steel is a highly ductile material (deforms without losing its toughness) and is non-brittle due to its high tensile strength(2000MPa). Its Young's Modulus is equal in both tension and compression ($2.0 – 2.1 \times 10^5$

N/mm^2) i.e. increase/decrease in length of the steel bar on pulling/pushing would be same. The coefficient of thermal expansion of concrete and steel is almost the same ensuring the bond is strong during thermal expansion, thus preventing bond failure. If not same, the bar undergoes the same strain or deformation under the load [6].

Synthetic fibres are not a substitute for steel in structural concrete but help in dropping the incidence of small cracks within the slab by the plastic shrinkage and settlement during the curing process. They are often used together with the steel fabric. The fibres are mainly polypropylene or polyester filaments and come in various lengths for different applications. Along with better crack mitigation, the addition of fibres to a concrete mix improves impact resistance and hardness, reduce aggregate separation and bleeding occurrence whilst the curing process, reduce permeability after curing and increase frost and fire resistance in the finished slab [6].

Hazards of cement and concrete-

Cement can cause grave wounds by skin or eye contact, or inhalation. Severity of injury depends on length, level of exposure and personal sensitivity. Hazardous substances in wet concrete include:

- alkaline compounds like lime (calcium oxide) that are corrosive to human tissue
- small amounts of crystalline silica which is corrosive to the skin and can damage lungs
- small amounts of chromium that causes allergic reactions
- cement dust released while bag clearance, or concrete cutting can also irritate the skin [7].

Environmental Hazards-

Air pollution- Some aggregates used for concrete production have turned out to be sources of radon gas. When uranium mine tailings were used as concrete aggregate, discharges increased but natural stone also gives out radon. The industry's heavy dependence on coal leads to high discharges of CO_2, nitrous oxide and sulphur oxide. For every ton of cement produced, 1.25 tonnes of CO_2 are released into the atmosphere. Global cement production accounts for more than 1.6×10^9 tonnes of CO_2 discharges from all human activities. Based on estimates, total particulate (dust) discharges of 360 pounds per ton of cement were released. Discharges of sulphur-based gases like SO_2 are produced from sulphur content of both the raw materials and the fuel. Nitrous oxide discharges are determined by fuel type and combustion settings [7].

Energy-Energy consumption is a major environmental alarm with cement and concrete production. It is one of the most energy exhaustive of all industrial manufacturing process. Including direct fuel use for mining and transporting raw materials, about 1,758 kWh is released for every ton of cement. Energy used for concrete production is better than that for cement, as the other components of concrete (sand, crushed stone, and water) are much less energy intensive [7].

Water pollution-At the plant, wash water (water contaminated with concrete) from equipment cleaning is often disposed into setting ponds where the solids are settled out. Some returned concrete also goes into settling ponds to wash off and recover the aggregate. Lime is a major component of cement and is found in all concrete products. It dissolves in water to produce a basic solution that will burn and kill fish, insects and plants. Water that encounters unset concrete or concrete dust quickly increases in basicity and will be highly toxic to aquatic life [7].

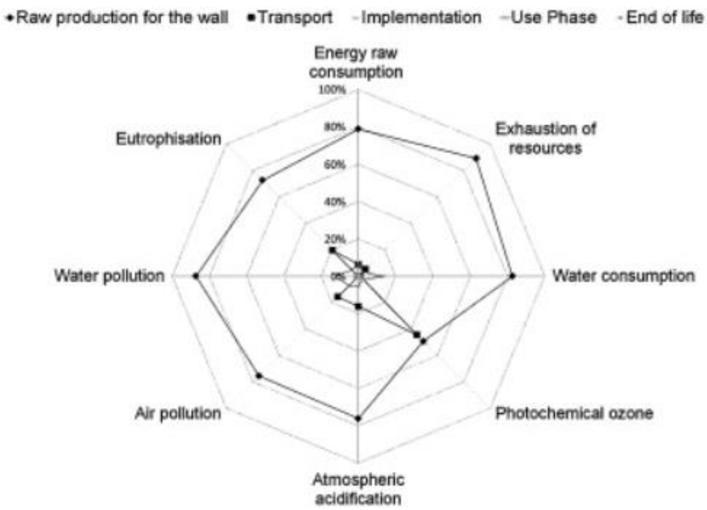
Alternative to concrete

Hempcrete-

Hempcrete is a bio-composite made of the inward woody part of the hemp plant mixed with a lime-based binder. The hemp cores(shiv) has a high silica volume which allows it to bind well with lime. This feature is unique to hemp among other natural fibres. The binder base can be hydrated lime, natural hydraulic lime or both. In some cases, a small fraction of cement and/or pozzolanic binder is added to speed up the hardening process and improve the mechanical resistance. By the action of lime, hemp shives slowly mineralize, becoming inactive and decreasing the risks of rot and mould formation. It also makes hempcrete pest-resistant. The final product is solid but light, durable and with good insulation. Hemp, as any crop, is considered a carbon negative material, because during its growth it takes in CO_2 from the atmosphere. The CO_2 captured from the air via carbonation will be stored into the hempcrete block throughout its lifetime and may further improve its environmental profile. When used in constructions, hempcrete mixtures can easily absorb or release water vapour from the air and have a good vapour permeability ($3.2x10^{-11}$ kg/m.s.Pa). These quantities allow a better control of thermo-hygrometric surroundings in the internal environment, decrease the risk of vapour condensation and increase thermal comfort. Its thermal conductivity is approximately 0.1 W/m.K and its moisture buffer value is 2.15 g/(m^2%HR). The performances and properties of hempcrete materials depend on the binder, on the quality and length of the hemp shives and on their proportions in the mixtures. It also has less toxicity unlike concrete and it is not abrasive to the skin [8].

Life cycle assessment of hemp concrete wall-

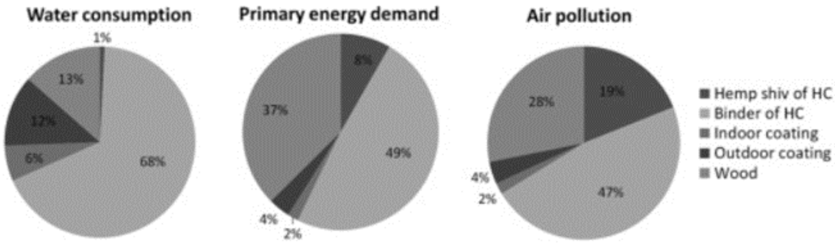
Life Cycle Assessments (LCA) are scientific studies that assess the environmental impact of products, processes or activities from beginning to end. In this report, the outcomes of the Life Cycle Assessment (LCA) from beginning to end of a sprayed hemp concrete wall (with a load-bearing timber structure) will be observed. The phases considered are construction of wall, transport of materials from production site to construction site, implementation, use phase and end-of-life. The figure below shows contribution of each phase for each environmental indicator, except for the climate change indicator [8].



[8]- Contribution of production, transport, implementation, use phase and end-of-life to environmental impact.
Raw material production causes the largest input to environmental impact, with values over three-fourth for all the environmental indicators, except for photochemical ozone that reaches only half of

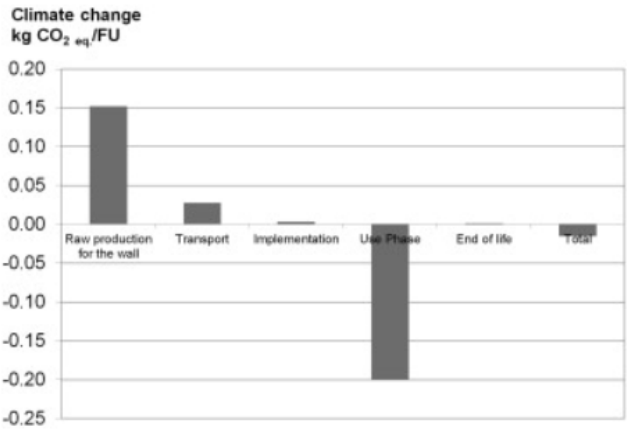
the impact. Material transport is the second contributor. Among environmental indicators, photochemical ozone is the highest, almost half. It is related to fuel consumption and emission of pollutants to the air. To the contrary, transport has a low effect on water consumption and water pollution. The use phase is the least important contributor to environmental impacts with between 5 and 15% of total impact. This result is mainly due to the regeneration of the coatings that involves prime raw materials and water. Lastly, implementation has an insignificant impact because the energy consumption for mixing and spraying the hemp concrete is low by contrast with the energy required to produce the materials. Likewise, the impacts of the end-of-life are low because they are only related to transport to a landfill [8].

The figure below shows the contribution of each component of the wall: wood, coatings and hemp concrete.



[8]- Distribution of production impacts between the different materials in hempcrete.

Among the many raw materials, the binder accounts for the highest impacts (49% of primary energy, 68% of water consumption and 47% of air pollution). Also, binder manufacture needs high-temperature cooking (900–1000 °C for the lime). The binder has also the greatest effect on water consumption due to the hydrated lime manufacturing procedure. This product is attained by hydration of quicklime which needs large quantities of water. Air pollution due to the binder is related to the cooking that releases fumes because of combustion of fossil energy. The coatings are the second contributors to water consumption, but they show only a small effect on primary energy demand and air pollution. The preparation of coatings requires high water content. Also, the coatings are usually made of sand and are thick, so they require little binder and hence little energy. Finally, hemp shiv is the third significant contributor to primary energy demand and air pollution due to the fuel consumption of agricultural equipment and transport. Their effect on water consumption is insignificant [8].

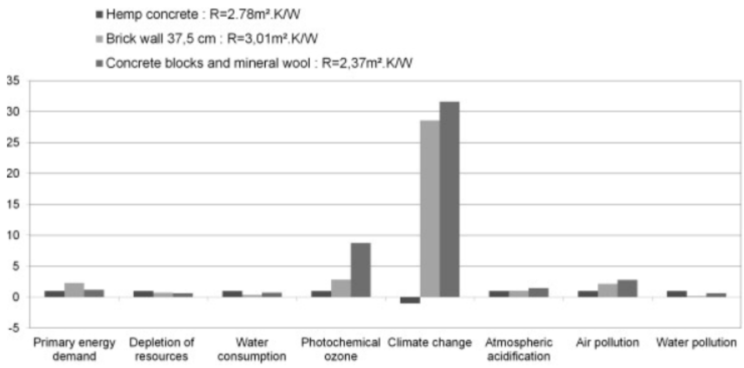


[8]-Impact on climate change for different phases.

The figure above depicts the effect on climate change for different phases. The environmental effect on climate change accounts for the emitted greenhouse gases. Production and transport have the greatest discharges. During the use phase, hemp concrete and coating binders take up carbon dioxide through the carbonation process. Also, there is nearly no effect on climate change as no material rotting is accounted for during landfilling. Finally, the worldwide balance of the climate change indicator is positive due to photosynthesis and carbonation [8].

Comparative analysis of environmental impact of concrete, timber and hempcrete walls-

The figure below shows environmental effects of different building materials standardised by the results obtained for hemp concrete.

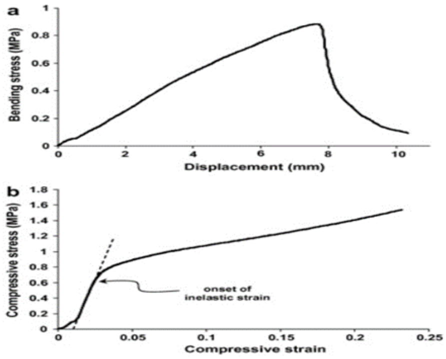


[8]-Environmental impact of different materials.

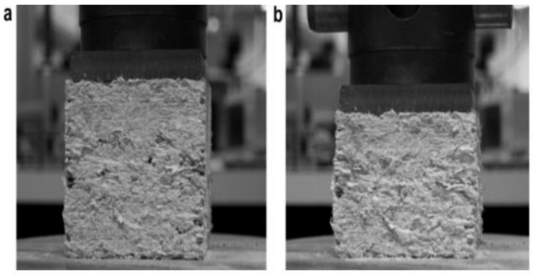
For the exhaustion of resources and the atmospheric acidification indicators, the values are alike for the three walls. For the water consumption and water pollution indicators, the value is the least for the brick wall as production of the brick that needs small quantity of water. Also, this wall is executed with narrow joints that requires less water than mortar joints. From a water pollution point of view, the factory does not emit process water in the external environment, excluding the vapour from the drying and cooking of brick. For primary energy demand, the brick demonstrates the highest impact largely due to the production phase. The energy used for the production is provided from recycled waste to generate energy. So only the transport of waste is accounted for primary energy consumption. For the concrete blocks, there is also an energy recapture from waste to produce cement. For discharges in the atmospheric air, the concrete block has the highest impact while the hemp concrete has the lowest one. These discharges are due to the production process and the transport. The main inconsistency between the products appears on climate change. The hemp concrete wall exhibits lower impacts than the other building products due to carbon sequestration and carbonation [8].

Mechanical properties-

Mechanical properties are calculated by bending and compression. Typical bending and compression loading curves are shown below for hempcrete. Compression strength was determined at the onset of inelastic strain and flexural strength was found from the maximum load. Beneath this point, an apparent Young's modulus was determined by calculating the maximum gradient of the stress–strain graph [9].



[9]-Bending and loading curves of a hempcrete block.



[9]-Compaction of material before(a) and after(b) the test.

Hempcrete has very low compressive strength (1/20 to that of concrete), elastic modulus and flexural strength which does not make it appropriate as a direct load bearing structural material. The particles in it can take up water and deter the hydration process of the binding materials and thus result in a lower overall strength. Another crucial property of hempcrete observed from the compression tests was the large deformation it can undergo after reaching the ultimate load. This shows hempcrete has a quasi-ductile behaviour unlike the sudden brittle failure associated with concrete due to which it could be reused in the same form without much affecting it structural properties. Hence, it is resistant to crack under movement and is suitable in seismic zones. Its behaviour depends on its composition and compaction during manufacturing. Slight compaction leads to a low resistance to compression unlike with the usual building materials. In the considered range, compacting directly brings about large improvements in compression resistance, but does not affect the stiffness of the material, which remains relatively low [9-10].

[10]-Material properties of lime hempcrete (LHC) and other building materials.

Material	Young's modulus E (MPa)	Compressive strength σ (MPa)	Density ρ_{norm} (kg/m³)	Thermal conductivity λ_{norm} (W/m·°C)
Steel	210000	350–1000	7500–8500	52
Concrete	20000	12–80	2300	1.5
Cellular concrete	1000–2500	5	420–1250	0.14–0.23
Brick	10000–25000	25–60	1300–1700	0.27–0.96
Wood	230–20000	$4_{\perp}$ - $34_{\parallel}$ [1]	350–900	0.12–0.3
LHC (wall mix)	24	0.4	445	0.17

[1] ⊥ perpendicular to the wood grain, ‖ parallel to the wood grain.

As density of hempcrete is less than that of water, it can float on water and is lightweight. Also, the density is affected by water quantity. For higher water content the density decreases due to volume of voids. But this has a good effect on compressive strength as strength is more for less density [9-10].

Feasibility of hempcrete (HC) as building material-

Parameter	Hempcrete	Concrete
Constituents	Hemp shives and binder	Cement, aggregate and admixtures
Cost	Higher than concrete as its cultivation is illegal.	Lower than hempcrete due to its conventional use.
Density	Lower than water, hence it is lightweight	Higher than water, hence it is heavier than hempcrete.
Limitations in mechanical properties	Low compressive strength, elastic modulus and other mechanical properties.	Low tensile strength.
Ductility	It is a quasi(almost)-ductile structure.	It is a brittle structure.
Greenhouse discharges	Lower than concrete as hemp takes up carbon and stored into the block throughout its life.	Very high due to discharges from cement production.
Insulation	Very good insulator with thermal conductivity of 0.1 W/mK	Poor insulator with thermal conductivity of 1.8 W/mK
Passage of water vapour	Good vapour permeability of 3.2×10^{-11} kg/m s Pa.	Low vapour permeability of approx. 1.52×10^{-12} kg/m s Pa.
Energy Consumption	It is low as hemp cultivation needs little fertiliser and no pesticides.	High as cement production requires heating of raw materials at high temperatures.
Water consumption	Higher than concrete due to the binder production and cultivation.	Lower than hempcrete due to water reducing agents.
Resistance to water	Must be protected against too much water.	Completely water resistant.
Toxicity	Low toxicity and can easily be handled.	High toxicity.
Biodegradability	It is biodegradable and adds lime and organic matter to the soil.	Not biodegradable.

[1-10]-Comparative analysis of the properties of hempcrete and concrete

As hempcrete cannot be directly used as a structural material, the buildings methods with HC use a load-bearing structure (mainly timber structure) [10].

Tamping- The boards, for example plywood sheets, are briefly attached to both sides of a load-bearing timber structure, creating a mould that is filled with HC. The HC mix is tamped to avoid huge air voids in the material. It should not to be tamped too hard, as the material produced would have inferior thermal insulation properties. On the other hand, the tamping must be hard enough to eliminate large air voids. Two hemp homes have been constructed in Haverhill, UK, using the tamping method. Reports by the British Building Research Establishment have concluded that the qualities of these hemp houses are at least equal to those of traditional constructions [10].

Spraying- Plywood sheets are attached to one side of the load-bearing timber structure and the HC is sprayed uniformly onto these boards. The HC stays satisfactorily to the boards to stay in place [10].

Blocks-A load-bearing timber frame is established. The blocks have holes that fit exactly over studs on the framework. All blocks are placed on the frame and then the wall plate is fitted. In France several houses have been constructed with these blocks [10].

Hemp cultivation is illegal in places like UAE, Japan and China to name a few as it is related to cannabis. However, it is an unfounded bias, as hemp is different from marijuana in function, cultivation and application. In fact, it contains less than 0.3 % of THC, the chemical accountable for marijuana's psychological effects. For this reason, it is expected to cost about seven to ten percent more than conventional methods as the demand is more than the supply. The Australian Industrial Hemp Alliance was formed in 2015 to address these misconceptions and fund industrial hemp-based business developments in pharmaceutical research and development, clothing and textile, and building-related products. In 2017, Western Australia had constructed its first hemp home in just eight months and Canberra's first hemp home had won the title of the 2018 HIA Australian GreenSmart Home. About 24 hemp homes exist in Australia and 50 in the USA till now. The material was developed in the 1980s in France, with its roots going back ages not only to homes as far away as Japan but also to Merovingian bridges in ancient Gaul. They were also used in the clay plasters in Ellora Caves, Maharastra, India where no pest activity was found and the temperature and humidity fluctuation inside the caves was very less. The hemp plaster survived for 1500 years in the cave. Hundreds of buildings use hempcrete in Europe and Canada ;a seven-story office tower in France, a Marks and Spencer department store in the United Kingdom, and even a home built by Prince Charles [11-12].

According to the Australian Bureau of Statistics, over the next 13 years (2013 to 2026), Australia's population is most likely to increase by 4 million people to 27.2 million. If current demand trends with population growth go on, by 2056 the Australian industry must produce about 210 million tonnes aggregate, 14 million tonnes cement and 37 million cubic metres concrete per year. To mitigate the negative consequences of concrete on the environment, it must be replaced gradually with hempcrete [13].

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