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The Use of Hempcrete in Single-Family Home Construction

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Preface

This report is the fifth installment in a series of reports that describe alternative construction systems for single-family residential homes. The initial report, as a basis, described in detail the typical light-framed wooden structural system design process. That report was subsequently published as a book chapter[1]. The second report, which was also subsequently published as a book chapter,[2] described the design process associated with using a cross-laminated (CLT) structural system as an alternative to the traditional light-framed wooden system. In the second report, the same home designed in the first report was redesigned using the CLT structural system.

In the third report[3], the conventional design methods used by engineers to specify a cold-formed steel (CFS) framing system for a single-family residence was described. Once again, the same home designed in the first report was redesigned using both prescriptive and detailed design methods with an alternate CFS structural framing system.

In the fourth report,[4] prefabricated panelized construction was discussed as an alternative to site-built methods. Whereas the first three reports focused primarily on design-related topics, the fourth report introduces terminology and defines panelized construction as it relates to its

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[1] Jellen, A. C. and Memari, A. M., (2019). "Structural Design of a Typical American Wood-frame Single-family Home," Chapter in Book: *Structural Engineering for Buildings*, Editor: Giovanna Concu, IntechOpen, London, United Kingdom, Published online 5/11/19; pp. 1-28; DOI: 10.5772/intechopen.85929; https://www.intechopen.com/online-first/structural-design-of-a-typical-american-wood-framed-single-family-home.

[2] Jellen, A. C. and Memari, A. M., (2023). "Structural Design of a Single-Family Residential Dwelling Using Cross-Laminated Timber (CLT)," Chapter in Book: Sustainable Built Environment, IntechOpen, London, United Kingdom, Guest Editor: Ying-Fei Yang, Published 040523. 22p. ISBN: 978-1-83768-587-5. file:///C:/Users/amm7/Downloads/86770.pdf

[3] Jellen, A. C., and Memari, A. M., (2022). "Structural Design of a Cold-Formed Steel (CFS) Single-Family Home," Final Report, The Pennsylvania Housing Research Center, September 2022, 54 p. (142 p. incl. appendices).

[4] Jellen, A. C., and Memari, A. M., (2024). "The Essence of Panelized Construction," Final Report, The Pennsylvania Housing Research Center, Report No. 113, Submitted July 2024, 61 p.

parent fields of PPMOF and industrialized construction. Seven separate panelized systems are introduced and discussed in this report.

In this current report, the fifth in the series, hempcrete is introduced as a residential construction material. This report is also slightly different from its predecessors in that the four other systems discussed are primarily load-bearing systems, whereas hempcrete is typically utilized as a non-structural insulative infill material. In this report, hempcrete is described along with the various methods of its installation. In addition, a short structural study was performed to assess the current reported mechanical properties and estimate structural capacities at several critical residential connections.

Acknowledgements

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Disclaimer

The material presented in this report is for general public information on the subject, and the results of the study shall not be relied upon under any circumstances for any specific application or actual projects involving the materials, components, and systems mentioned without consultation by a licensed design professional experienced in the field. Anyone using the material in this report assumes all liability resulting from such use, and the authors, Penn State University, and PHRC ae not in any way liable for such use.

1. Introduction

1.1 Hemp as a Building Construction Material

The building construction industry is currently looking for ways to reduce both its energy use and its carbon footprint. A significant amount of energy is required to construct and operate both residential and commercial buildings. A significant amount of greenhouse gas emissions, primarily Carbon-Dioxide, have also been associated with the construction process and operation of buildings in the U.S. The National Renewable Energy Laboratory reports that buildings account for about 70% of electricity use, 40% of the total U.S. primary energy consumption and about 30% of operational greenhouse gas emissions (Goetsch and Deru 2022).

In addition to reducing the energy and carbon footprint, the construction industry is also continually looking for ways to effectively incorporate sustainable building products into mainstream construction. An understanding of our limited resources has developed over the last few decades, which has caused the industry to re-evaluate its current construction practices and use of traditional construction materials such as concrete, wood and structural metals (steel and aluminum primarily).

Concerns regarding the sustainability of our construction practices have prompted research and development of alternative construction materials/building systems. One such alternative building material currently under consideration in the construction industry is hemp. Hemp is currently used in hempcrete, hemp wood, fiberboards, wallboards, roofing materials, insulation, carpet, textiles, plastics, and hemp-oil based finishes. The focus of this report is on hempcrete used for homebuilding.

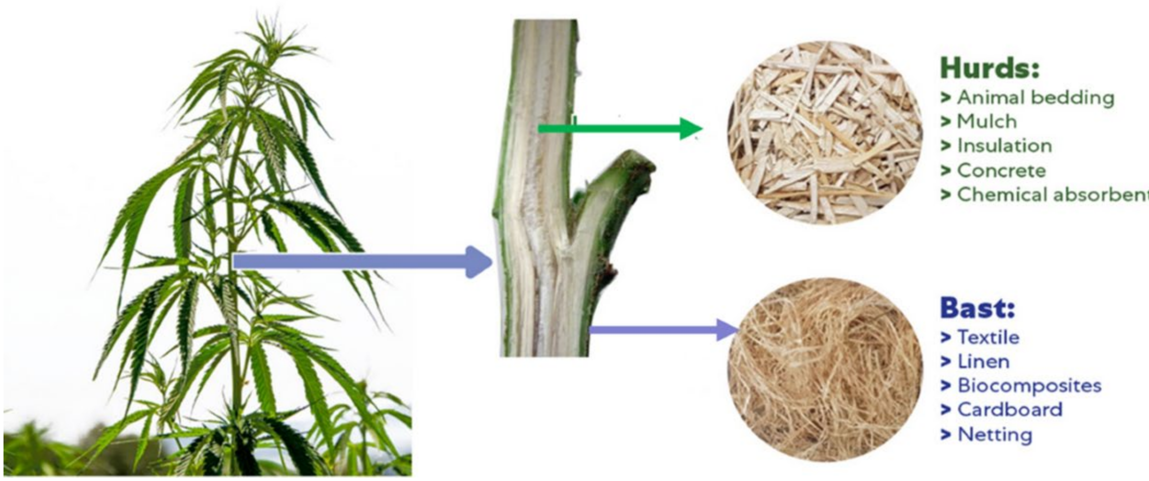


Figure 1. Parts of the Hemp plant (Tyagi et al. 2022) **.**

The industrial hemp plant is a non-psychoactive variety of the Cannabis plant and can be utilized in many ways as a cash crop. Figure 1 lists a few examples. The industrial hemp plant is a hardy plant that can be grown almost anywhere, and the entire plant can be utilized (Nelson 2018). As shown in Figure 1, the whole stalk of the hemp plant is typically utilized for the production of hemp-wood products (Farming 2021), whereas, the hurds are used in the production of hempcrete. The plant is ready to harvest in 100 to 120 days after it is planted. It can grow in new or old soil, can withstand frost and only requires a small amount of water (Zuabi and Memari 2021).

1.2 Hemp wood

One line of hemp products recently introduced to the construction industry is hemp wood. Hemp wood products are primarily used for interior residential applications. They are manufactured using the woody hurd fibers found in the stem of the hemp plant. Initially the stems are softened, the fibers are combed to align, and lastly the assemblage of fibers is compressed and adhered together using a strong adhesive (Ortiz 2024). Hemp wood can be made into flooring, as shown in Figure 2a, or also wall paneling. Hemp lumber, as shown in Figure 2b, is commercially available as an alternative to the traditional solid sawn wood typically used for interior trim applications. Some common uses of hemp lumber include interior trim, furniture or other similar non-structural uses ("HempWood Flooring" n.d.). Currently, hemp wood products are not used for structural applications. Hemp wood is a composite material and can be produced in a variety of sizes similar to other composite wood products, such as microlam or LSL boards.

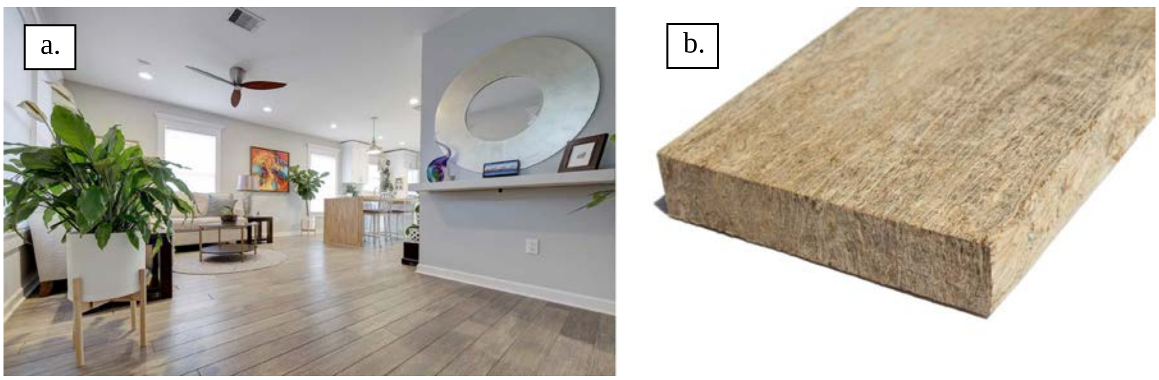


Figure 2. a. Hemp wood flooring installed in a living room b. hemp lumber ("HempWood Flooring" n.d.)**.**

2. Use of Hempcrete in Building Construction

Hempcrete is a cementitious building material made by combining hemp hurds, water and a binding agent together in specified ratios and in a specified quantity to produce a mixture that hardens into the shape that it is formed into. The conventional binding agent for hempcrete is a lime-based binder (Asghari and Memari 2024; Zuabi and Memari 2021). Lime binders typically are separated into hydraulic and non-hydraulic categories. Characteristics such as speed of set, structural integrity, vapor permeability and strength vary between categories; therefore, the selection of binder for the chosen application method is important. Hydraulic limes can have setting times of weeks or months and therefore are not appropriate for use in cast-in-place hempcrete applications. They may, however, in some instances, be suitable for precast or block applications (Stanwix and Sparrow 2021). The binding agent essentially serves to adhere the Hurd fibers together as shown in Figure 3a. Hempcrete is typically applied either by casting in place using forms, pre-casting into wall assemblies or blocks, such as the one shown in Figure 3b, or spray-applied directly on site (Mears et al. 2022). Lime mortar is typically utilized for joints when using blocks.

Conventional hempcrete mixture design has a fraction (say 1% to 10%) of the compressive strength of concrete (Zuabi and Memari 2021); however, it has good resistance to heat transfer (the approximate R-value is 1.5 to 2.0 per inch) due to the cellular composition of the hemp hurds and the presence of air gaps inside the cured mix (Asghari and Memari 2024). Because of its low compressive strength, the material is currently utilized mostly as non-load bearing infill for floor, roofs and walls. There are limited examples of hempcrete load-bearing systems that incorporate framing elements and experimentation with alternative binders to increase compressive strength; however, these topics will be discussed later in the report.

Figure 3. a. Close-up view of hempcrete (Gunderson 2022). b. Typical hempcrete masonry unit (https://therealdirt.com/wp-content/uploads/2019/05/hempcrete.jpg)

A major standpoint of the hempcrete industry is that it provides a construction material with a zero or negative carbon footprint; therefore, it offers a more environmentally friendly product in comparison to traditional building materials such as concrete. Figure 4 shows a hempcrete support agency's sell sheet, describing other claimed benefits of the material. Hempcrete manufacturer[5]Limetechnology claims that its Hemp-based walls system (Hemcrete) creates carbon-negative wall systems. The claim is that the Carbon-Dioxide absorbed (sequestered) in the growing of the hemp more than offsets that produced in the manufacture of the binder. Additionally, it claims that a large portion of the Carbon-Dioxide emitted in manufacturing of the material is reabsorbed as it cures and ("Tradical Hemcrete Embodied CO2," n.d.).

[5] http://www.americanlimetechnology.com/tradical-hemcrete/

Figure 4. Hempcrete sell sheet created by industry representative (August n.d.).

For the production of hempcrete, a lime binder traditionally has been preferred over cement, due to the abundant availability and lower Carbon-dioxide emissions associated with production of the lime (Asghari and Memari 2024). However, although the production of lime results in lower Carbon-Dioxide emissions, the overall embodied carbon levels and embodied energy levels are still high, due to the kiln involved in the production process. Unfired binders such as clay are sometimes used to reduce these levels (Haik, Meir, and Peled 2023).

Figure 5. Typical cement production facility (https://www.istockphoto.com/photo/concrete-or-cement-factory-gm177427859-21325165).

It is understood in the construction community that significant quantities of Carbon-Dioxide are released into the atmosphere during the production of cement. The cement industry is aware of this and has been taking an active role in confronting the issue and improving the process ("Roadmap to Carbon Neutrality" 2021). Due to its extensive use in the construction industry, cement is produced on a large scale in factories that typically run most, if not all, of the day (See Figure 5). Limestone, shale and marl are quarried as raw ingredients in the cement production process. These materials are sorted in appropriate proportions and run through a furnace to produce clinker, which is subsequently cooled, ground and packaged as cement, the binding ingredient in concrete (Engineering World 2022).

The Portland Cement Association (PCA) informs us that the production of clinker and cement is an energy intense process and results in the production of Carbon Dioxide as a biproduct. Approximately 60% of Carbon Dioxide is released during a chemical reaction that occurs when the raw ingredients are heated and transformed into clinkers. Approximately 40% of the Carbon Dioxide production can be attributed to the combustion process required to operate the furnace. According to the U.S. Environmental Protection Agency and PCA, the manufacture of cement accounts for 1.25% of U.S. Carbon-Dioxide emissions ("Roadmap to Carbon Neutrality" 2021). Although not insignificant, 1.25% is a relatively small percentage of the overall emissions. The various other aspects of construction and operations of buildings, both residential and commercial, when considered as a whole, contribute a much larger percentage (Leung 2018; Goetsch and Deru 2022).

3. Examples of Residential Hempcrete Construction Methods and Buildings

The use of hempcrete in buildings was developed in France in the 1980s as a potential means of retrofitting aging wattle and daub infill in medieval timber-framed buildings (Stanwix and Sparrow 2021). It has since developed into a form of construction that can be utilized in a variety of different building types. Hempcrete can be used in exterior walls, interior walls, floors and roofs to help designers provide a sustainable alternative to traditional building materials. Over time, hempcrete has been used in both modern and traditional buildings, as can be seen in Figure 6.

Figure 6. a. Example of a modern hempcrete home (Banks 2010) b. Example of a more traditional style home (Lotus 2024b).

Hempcrete is typically cast-in-place, precast, or sprayed-applied. Hempcrete is mostly utilized as non-structural infill requiring a structural backup wall or integral structural framing, such as shown in Figures 7 and 8. Although hempcrete does not act as the load-bearing element, it has been found that it can provide buckling resistance to embedded framing (Magwood 2022). Guide specifications (MasterFormat 2020) shown on Arcat.com (US Hemp Building Association n.d.) list Hempcrete under Division 7, which is thermal and moisture protection. Thermal resistance values of R 1.41 – R 1.94 per inch have been attributed to the material (Magwood 2022), which is better than most cementitious building materials, but could be problematic when considering the thickness of wall required to satisfy modern residential building codes. Advocates of hempcrete claim the thermal mass improves enclosure energy performance; however, dynamic modeling of heat flow is required to prove the beneficial effects (Stanwix and Sparrow 2021).

Hempcrete as an infill material offers several benefits when used in walls or roof or floor assemblies. Hempcrete assemblies, as infill, provide good thermal resistance, reduce thermal bridging, provide a high level of thermal mass, are vapor permeable, provide moisture storage capacity, have excellent fire resistance qualities, and furnish enhanced sound insulation (Zuabi and Memari 2021). Walls with these qualities can provide enhanced comfort, indoor air quality and safety to home occupants, if constructed properly.

Figure 7. Typical single-wall cast-in-place hempcrete construction application using proprietary forms (Hempcrete International 2013).

Figures 8 and 9 show examples of hempcrete being used for cast-in-place applications. In Figure 7, proprietary forms are being utilized to form the walls around the structural framing. Figures 8 and 9 show OSB being utilized as the form for the hempcrete mixture. Utilities required in the hempcrete walls are typically directly placed prior to casting or provisions such as conduits are installed to allow for later installation of utility branch lines. Holes and recesses for through penetrations can also be drilled after the material has set. It is important to be aware that the alkaline lime binder can potentially react with copper as well as other metals. To avoid this problem, any copper piping required to penetrate hempcrete assemblies should be installed in plastic conduits. An annular space should be provided around the copper piping as well, to prevent damage to the wall assembly due to thermal expansion of the piping (Stanwix and Sparrow 2021).

Figure 8. Typical double-wall cast-in-place hempcrete construction (see Figure 11) using temporary OSB shuttering (Matloff 2023).

It is difficult to fasten components directly to hempcrete walls; therefore, forethought and additional elements are typically required to support accessory items installed on the interior or exterior side. If the component is sufficiently light, wooden wedges can be pounded into the wall assembly after the mixture is set; however, if heavier items, such as radiators or cabinets, are required to be wall-mounted, then it is likely that blocking will be have to be positioned in the framing prior to casting the walls (Stanwix and Sparrow 2021).

Figure 9. a. Typical single-wall, cast-in-place construction using temporary OSB shuttering ("Hempcrete as a Building Material: Pros & Cons | Properties | Applications" 2019) b. Finished cast-in-place walls with forms removed (Gunderson 2022).

A structural support system, including provisions for lateral stability, is required for all hempcrete construction methods. Conventionally, platform framing methods using embedded light wood framing, or post-frame methods are used to construct the structural support system when using hempcrete infill. In many applications, the framing is cast directly in the hempcrete wall assembly, as shown in Detail 1 and 2 of Figure 10, as well as the center-stud and double-stud details shown in Figure 11. The details shown in the figures were adapted from various resources reviewed for the purposes of this report. IBC Appendix BL requirements were incorporated into the details where applicable. Notes associated with the building code requirements are listed below. The notes are only referenced in Figure 10; however, they are applicable wherever similar situations occur in other typical details:

1. Interior plaster finish shall have a vapor-permeance of 5 perms or greater.
2. Hemp-lime infill shall have an average moisture content less than 20% at a depth of 1.5-inches.
3. Membranes, not specifically allowed in the code, are prohibited between hemp-lime and plaster finishes.

4. Wood framing to be separated from plaster using a Grade-D building paper except where wood is naturally durable.
5. Install bridging across the juncture of dissimilar materials. Extend bridging 3-inches past juncture on all sides.
6. Bridging such as lath and the Grade-D building paper separation layer called for in Note 4 may be required depending on the sheathing type. Typical sheathings are wood fiber board and MgO board.
7. Provide minimum 1x2 horizontal anchorage rails installed at maximum 24-inch-on-center. Fasten with minimum one 8D box nail per stud.

Section can be mirrored such that the studs are positioned on the exterior of the assembly.

When using post-frame methods, it is common for the hempcrete mixture to function as a non-load bearing wall on the front, back or between the framing members. Figure 12 shows an example of a post-frame wall assembly with a hempcrete exterior layer that would function in this manner.

A building structure is shown in Figure 9b in which the forms have been removed after initial curing. As you can see in the figure, even though the walls are non-structural in nature, they still need to remain stable under their own weight. As mentioned previously, it is of chief importance to utilize the proper binder so the level of required stability can be achieved in a timely fashion.

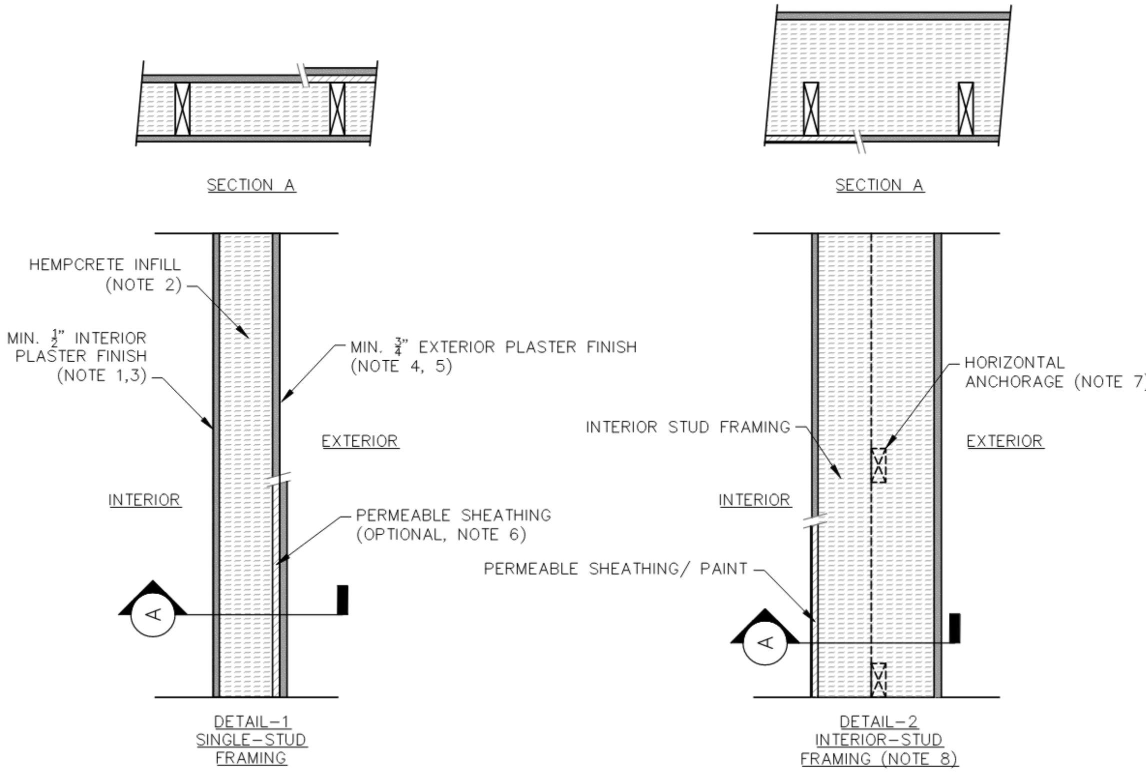


Figure 10. Two typical hempcrete wall sections.

Hempcrete exterior walls cannot be utilized as a below-grade wall assembly exposed to moist conditions, and, therefore, require a permanent foundation. As with most building materials containing organic substances, prolonged exposure to moisture can create opportunistic conditions for damaging molds and pests. The lime-binder provides some natural resistance; however, the hemp hurds are still organic and will deteriorate over time with long-term exposure to moist conditions. Hempcrete assemblies also have a large storage capacity for moisture and can wick and transport liquid water horizontally and vertically to more sensitive interior components such as wood framing and interior finishes. Hempcrete walls are vapor permeable, but not intended to be used for walls that are in direct contact with soils or moisture.

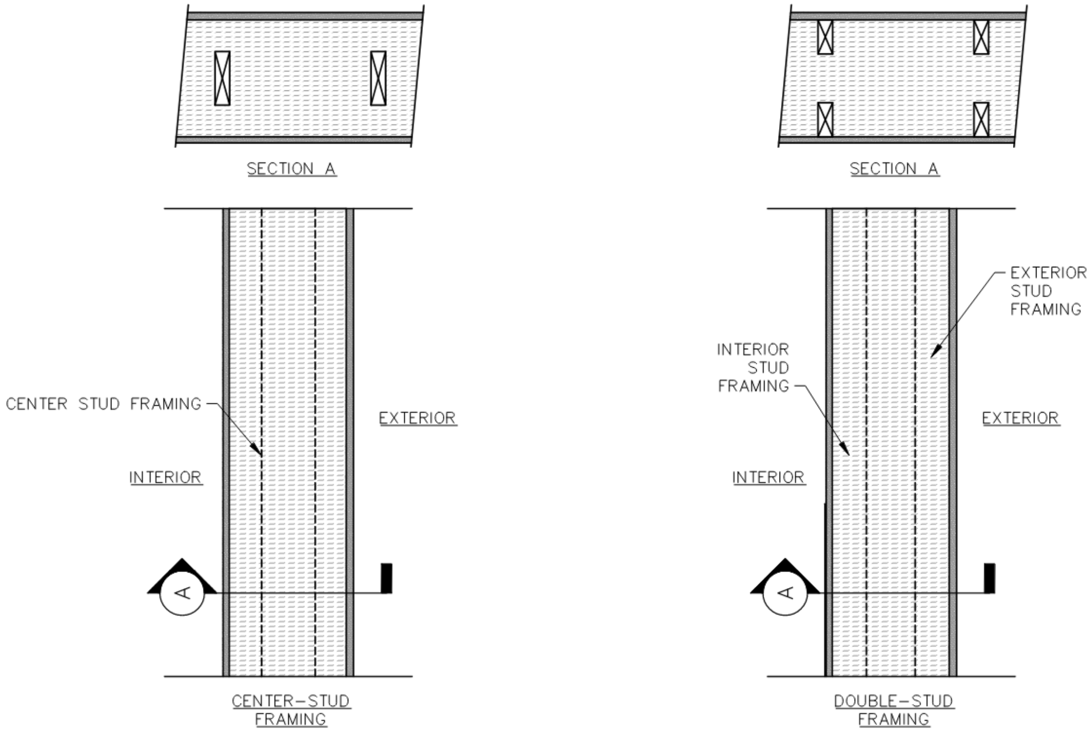


Figure 11. Two alternative hempcrete wall sections in which the position of the light-framed members varies in the assembly.

Traditional moisture resistant materials such as concrete and masonry are typically utilized to provide standard on-grade mat, crawlspace or basement type foundations. The base of the exterior hempcrete wall should be kept approximately 8 inches above the adjacent finished grade. Either the top of the foundation can be constructed to this height or a masonry or concrete plinth provided around the perimeter of the finished floor to elevate the hempcrete wall assembly (Stanwix and Sparrow 2021). Typically, a membrane functioning as a capillary break is placed between the base of the hempcrete wall and the foundation or plinth to prevent moisture from wicking up through the bottom of the wall. An example of a potential base-of-wall detail is shown in Figure 12.

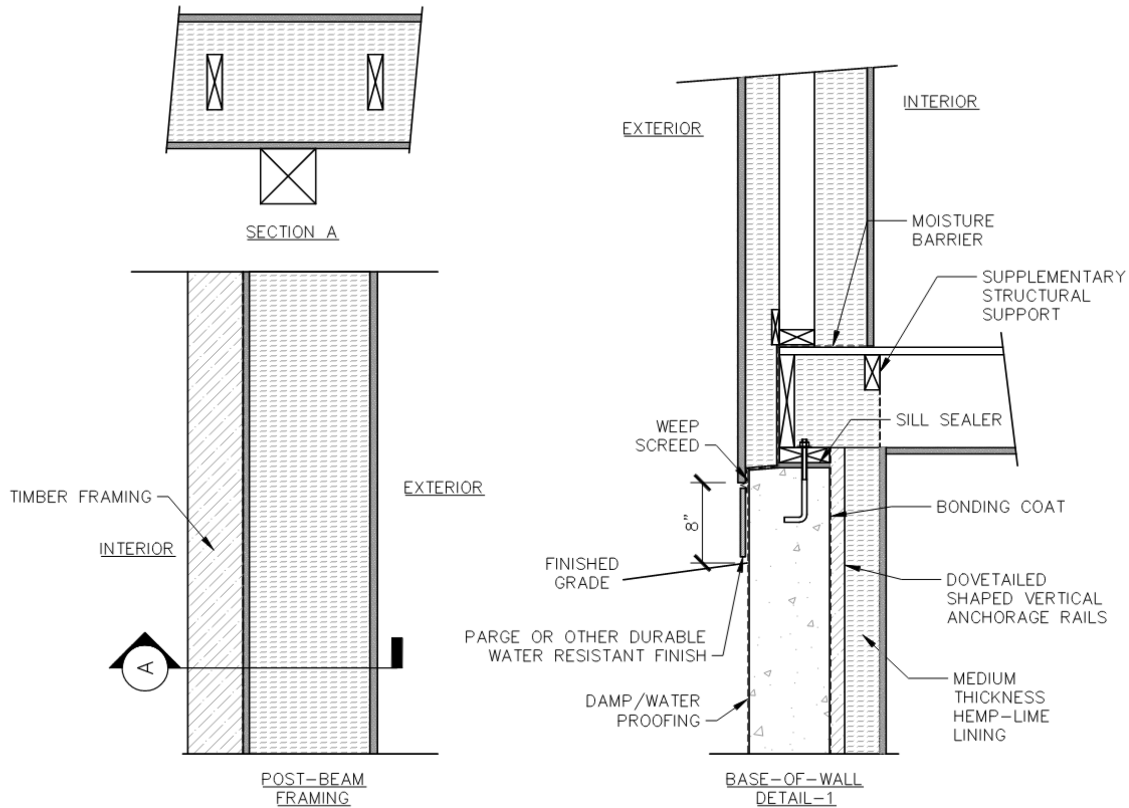


Figure 12. An example of a post-frame hempcrete assembly and an example of a potential base of wall detail.

The forms or shuttering used to construct cast-in-place hempcrete walls can be temporary or permanent in nature. OSB, plywood or similar materials can be utilized for temporary shuttering. ½” thickness can suffice in most cases, due to the lightweight nature of the material (Magwood 2022). OSB is not recommended for use as permanent shuttering due to its low permeability. Low permeability materials are not recommended due to the long drying time required for the wall assemblies. Wall assemblies typically take two-to-eight weeks to dry adequately for finish placement (Magwood 2022). Higher permeability materials such as the wood wool product shown in Figure 13 are recommended when permanent shuttering is required. The decision to use permanent shuttering as opposed to temporary shuttering is usually driven by labor savings; however, permanent shuttering application typically result in higher levels of embodied energy (Stanwix and Sparrow 2021).

Figure 13. Wood wool board product ("Wood Wool Board - a Complementary Natural Building Material" 2020).

Construction of the walls is completed from the bottom up. 24-inch-tall shuttering is placed, starting on the bottom of the wall. The hempcrete is mixed and placed, in 4-to-8-inch lifts, tamping between lifts to consolidate the material and fill any voids present (Magwood 2022). Subsequent lifts are placed until the top of the shuttering is reached. The hempcrete is then allowed to cure before removing the forms. Adequate curing could take anywhere from 30 minutes to 24 hours depending on the binding agent used (Stanwix and Sparrow 2021). After the first layer is adequately cured, the shuttering is removed and installed to form the next layer. This continues until the wall is completed. Typical wall thickness ranges from 10 to15 inches depending on the energy code and performance requirements of the wall (american lime technology, n.d.).

Figure 14. a. Hempcrete ceiling showing OSB temporary shuttering and furring keys (Stanwix 2010) b. Hempcrete roof insulation (“Hempcrete: Insulating Roofs” 2023).

In addition to its primary use as an insulative component in interior and exterior wall assemblies, hempcrete can also be cast into inter-story floor assemblies, subfloor assemblies, ceiling layers, or in between rafters as roof insulation. In these applications, as with wall applications, both temporary and permanent forms (shuttering) are utilized to contain the hempcrete. OSB, such as shown in Figure 14a, is often used as a temporary form. As with walls, vapor permeable components must be used when the shuttering is intended to be permanent. One example of a vapor permeable sheathing sometimes used in hempcrete structures is Magnesium Oxide Boards (MgO) (“Magnesium-Oxide Board Wall Assembly” n.d.). MgO boards, such as the MagPanel shown in Figure 15, are made with inorganic material and are known for their enhanced resistance to fire, mold, fungus, insects, mildew, moisture, and termites (“MagPanel Is New Alternative to Traditional Building Material” n.d.). The MagPanel can be used like a gypsum board in ceilings and walls, or as a subfloor or tile backer. Additionally, it can be used on the exterior as fascia, soffit or wall/roof sheathing. MgO panels typically are manufactured in standard sizes such as 4’x8’, 4’x9’ or 4’x10’. Not all MgO boards are equal. Both the permeability and the strength of the boards vary between manufacturers (Magwood 2022), so one should review the manufacturer data prior to selecting a product to ensure it will be appropriate for the application. Also, if the project goals include the reduction of environmental impacts, then one should consider that MgO board is a manufactured product and has moderate to high impact in many categories (Magwood 2022).

Figure 15. MagPanel Magnesium Oxide Board ("MagPanel Is New Alternative to Traditional Building Material" n.d.).

Figure 14a shows hempcrete being utilized in a ceiling. For ceiling applications, furring strips are installed perpendicular to the framing to provide keying action and support for the hempcrete ceiling layer. The layer is installed from above and can be installed as a single thin ceiling layer or be combined with another layer on top to provide additional insulation (Figure 14b). The ceiling layer is densified by tamping to improve durability and eliminate potential voids. The insulative layer is typically a low-density mix, which minimizes weight and increases insulative value. Inter-story floor-ceiling assemblies, such as the one shown in Figure 7, are constructed in much the same manner.

Hempcrete can be used as a sub-base or floor slab for on-grade applications (Figure 16, Detail 2); however, due to its organic nature, it is not intended to be in direct contact with soil or moisture. It should be noted that hempcrete assemblies are intended to be vapor permeable, therefore, a vapor barrier is not typically used in a hempcrete subfloor assembly (Stanwix and Sparrow 2021). Vapor permeable floor coverings, such as stone tiles, are typically installed as floor covering over hempcrete slabs to allow vapor to pass through the assembly. Figure 16 shows a typical application using natural floor covering, as well as how the top-of-wall detail might look.

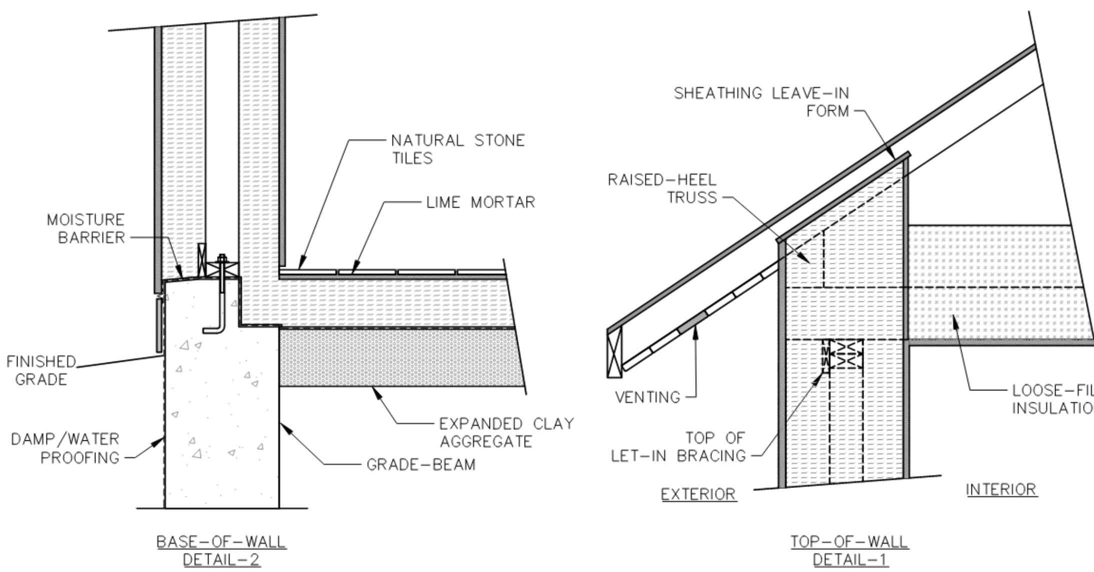


Figure 16. An additional example of a potential base-of-wall detail and an example of how the top of wall could be detailed when a light wooden framing system is used.

To prevent direct contact with moist soil, a separation layer, such as the black aggregate shown in Figure 17a, is installed beneath the hempcrete subfloor or slab. The separation layer must be free draining and prevent capillary action. Often a separation layer is placed upon a stone base, as shown in the figure, to provide additional stability and further remove the hempcrete from the moist soil layer. Both separation layers and hempcrete floors are on the order of 3-to-6-inches in thickness (Stanwix and Sparrow 2021). A binder-rich, dense mix is typically utilized for subfloor applications to increase its compressive strength. Note that this increase in density results in reduced thermal resistance, however. A finished hempcrete sub-base is shown in Figure 17b.

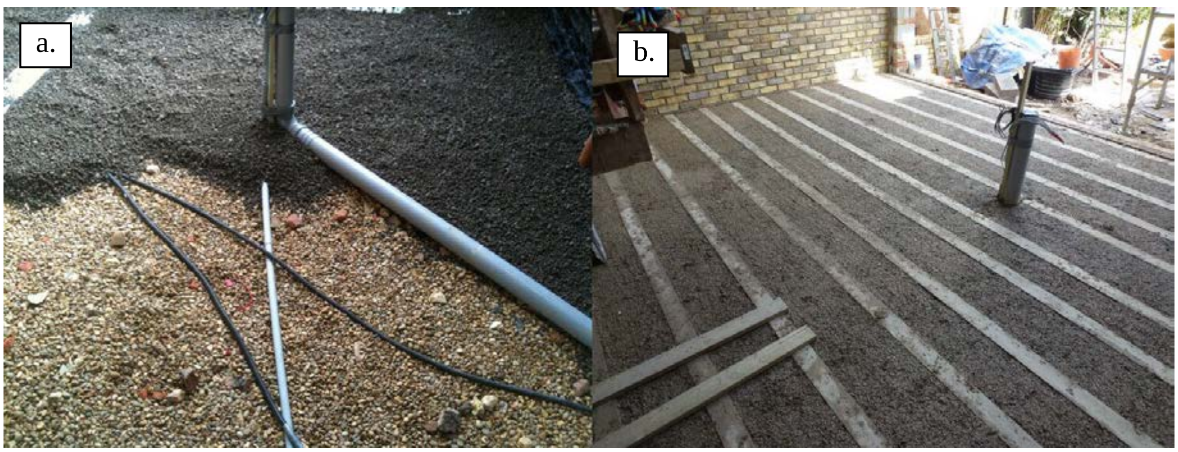


Figure 17. a. Light expanded clay aggregate base layer being placed over a small aggregate choke layer. b. Hempcrete subfloor cast over base layer (Stanwix 2012).

As mentioned earlier, another way to install hempcrete is to spray the material directly on the wall or floor-ceiling assembly. An example of a hempcrete spray-on application is shown in Figure 18, in which the contractor is using specialized equipment to apply the hempcrete mix to an exterior wall. Only one side of the wall assembly requires shuttering for this application type. In an article (Lotus 2024a), the founder of Americhanvre claims their spray-on method cuts manpower by 60% and dramatically reduces installation time. The same article goes on to say that the mix they use requires less binder, which is the expensive portion of the mix, and about half the water. The reduction in water cuts cure time to around 6-8 weeks (Lotus 2024a).

Figure 18. Americhanvre employee spraying hempcrete on an exterior wall ("Fiber Fort" n.d.).

Specialized equipment is required to spray hempcrete. Americhanvre utilizes the EREASY spray system (Figure 19b), which they exclusively license from a French Manufacturer ("Americhanvre" 2024). The hempcrete is mixed in the EZG Manufacturing Mud Hog, shown in Figure 19a, and fed to the EREASY equipment, which advances it to the spray nozzle for application. In their promotional video, ("Fiber Fort" n.d.) Americhanvre shows the hempcrete mixture being applied to an exterior wall. In the video, three laborers are required to apply the mixture. One is spraying, while another tends the material supply and air tubing to the nozzle. The third laborer distributes and smooths out the hempcrete application with a trowel. There does appear to be some material loss in the process; however, it looks like the level-of-loss could be minimized depending on the skill level and experience of the application crew.

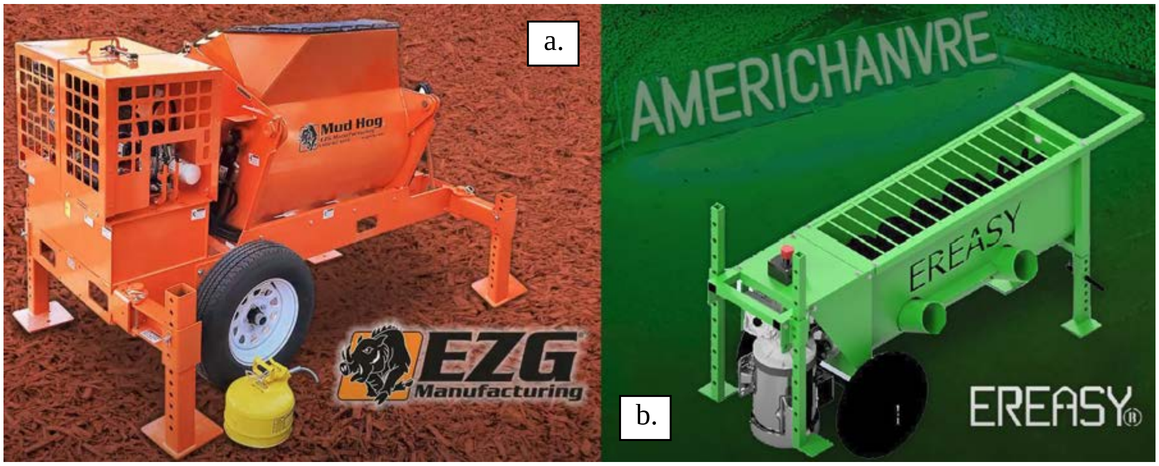


Figure 19 a. The Mud Hog material mixer b. EREASY hempcrete spray system (“Fiber Fort” n.d.).

In addition to the cast-in-place method and the spray-on method, hempcrete is also prefabricated into blocks or panels, which are delivered to a project location for installation and immediate finishing. The curing of the hempcrete along with the material mix can be controlled with greater precision in a factory environment. Also, the wait-time for the material to cure in the field is eliminated by choosing the factory-cured units. The ability to customize is reduced, however. With cast-in-place methods or spray-on methods, odd-shaped spaces and assemblies can be insulated with ease. The ability to accommodate a variety of wall, floor and ceiling geometries is one of the main advantages of hempcrete.

Figure 20. Premanufactured hempcrete block building under construction (Lotus 2021).

An example of a hempcrete block building is shown in Figure 20. Blocks can be prefabricated by individual contractors on a small-scale or manufactured on a large-scale. Hempcrete block manufacturer HempBLOCK USA offers two product lines: the HempBLOCK LB 300 load bearing system (Figure 21a) and the HempBLOCK Range solid veneer non-load-bearing system (Figure 21b) ("HempBLOCK" n.d.). The load-bearing system will be discussed later in the report.

The non-load-bearing system is used as an insulative substrate for exterior veneers, interior partitions and subfloors. The HempBLOCK Range installation guide informs us that the veneer blocks are installed in a running-bond pattern much like traditional masonry. The blocks are adhered to each other using a thin layer of HempBLOCK mortar. The blocks come in nominal 4", 6", 8", and 12" thicknesses. The insulative value of the blocks ranges from R8.6 to R26.3, respectively. One should note, however, that the block dimensions are nominal 12"x24" (Height x Length), which differs from traditional 8"x16" masonry geometry.

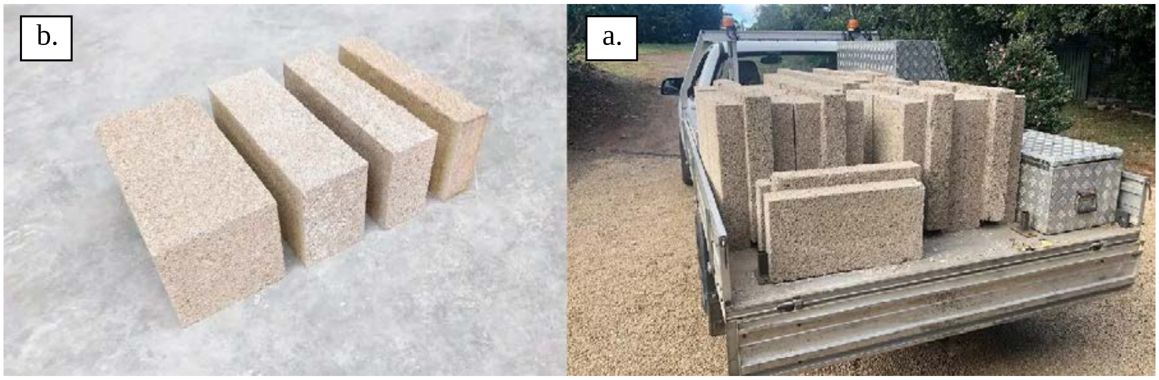


Figure 21. a. LB 300 load bearing system blocks ("HempBLOCK" n.d.) b. HempBLOCK USA Range solid veneer blocks.

Hempcrete can also be prefabricated into panels rather than blocks. Manufacturer American Lime Technology offers two prefabricated panel products (American Lime Technology, n.d.). The first is referred to as the Hemclad System. In this system, non-structural wood framing is utilized to contain the patented hempcrete material during fabrication. The panels, once cured, are hoisted into place and installed on a structural frame. Figure 22a shows the Hemclad panels being placed on a commercial building. The second panelized system is referred to as the Hembuild System. In this system, the structural frame is incorporated into the panel. Figure 22b shows the Hembuild panels being installed. Both panelized systems can be provided with varying degrees of prefabrication and finishes.

The prefabricated panelized system offers several benefits to users; however, they also have some potential disadvantages (Stanwix and Sparrow 2021). For instance, due to the factory production process and additional processed materials included in the panels, there are concerns about the life-cycle costs of the panels and the level of sustainability. Additionally, opportunities for thermal bridging and air leakage are introduced to the cladding system due to the added lumber and panel joints, respectively.

Figure 22. a. Installation of Hemclad panels b. installation of Hembuild panels on a commercial building ("Hembuild Pre-Cast Wall Systems" n.d.).

3.1 Hempcrete Wall Finishing Systems

To maintain vapor permeability, hempcrete assemblies are typically paired with natural finish systems such as lime and clay-based plasters or stone. A variety of other finishing systems can be utilized, but considerations for the hygrothermal performance must be given to maintain the breathability of the assemblies. When traditional systems like paint are used, additional manufactured components are often required, such as the MgO board shown in Figure 15. Additional components tend to increase environmental impact and monetary costs of the overall build.

The application of lime or clay-based plasters requires training and/or skilled craftsman experienced in the application of such plasters (Stanwix and Sparrow 2021). Clay-based plasters can be utilized on the interior; however, lime-based plasters are suitable for both interior and exterior application. Plasters can be mixed from raw ingredients or purchased as a premixed product. American Lime Technology offers a variety of premixed products for different applications ("Baumit Lime Stucco & Plasters" n.d.).

Plasters are typically applied directly to the hempcrete, such as shown in Figure 23a, without the need for an additional bonding layer. Plaster can be applied by hand as shown in the image or through the use of specialized spray-on equipment such as shown in Figure 23b. Any exposed wood or similar smooth surfaces will require the application of a mesh to provide a mechanical key and support for the plaster (Magwood 2022). Two-to-three coats of plaster, ranging in thickness from 1/8-to-3/8-inch, are typically applied as a finish. A lime wash or silicate dispersion can be applied afterwards to provide a finish color coat.

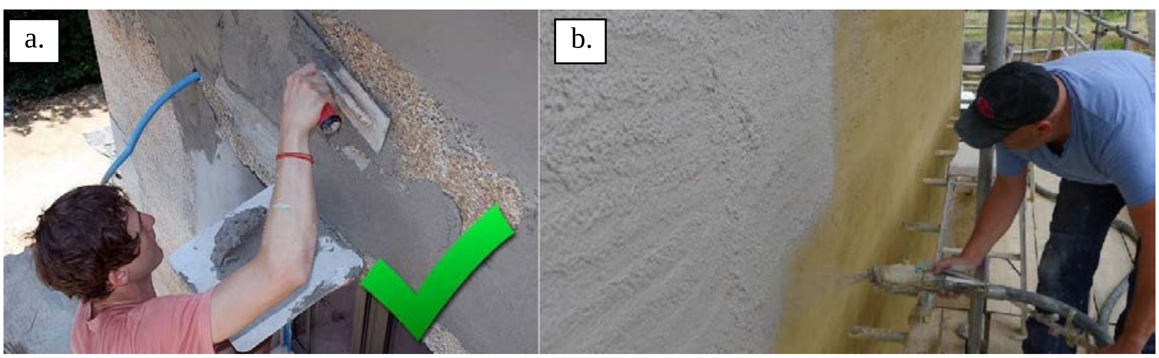


Figure 23. a. Hand application of a plaster base coat directly onto hempcrete substrate ("Hempsteads.Info" n.d.) b. spray application of plaster onto base coat ("Lime Plastering" 2015).

3.2 Building Code Regulations Applicable to Hempcrete Used in Residential Construction

In 2022, hempcrete was accepted for inclusion in the 2024 International Residential Code (IRC) as an allowable building material (HempToday® 2023). Regulations governing the use of hempcrete in one-or-two family dwellings and townhomes in low seismic areas were placed in Appendix BL (International Code Council (ICC) n.d.). The appendix limits the use of hempcrete to non-structural applications and appears to focus primarily on exterior wall assemblies. The appendix provides allowances for hand-cast construction, spray-applied, precast blocks, and panels; however, panels are required to be approved by a registered design professional. Select limitations for the use of hemp-lime assemblies are listed below:

1. Maximum height of one story above grade plane.
2. Maximum building height of 25 feet.
3. Braced wall panel lengths in accordance with Sections R602.10.3 and BL103.3.2.f

   This method is restricted to Seismic Design Categories A, B and C. Only Let-in Bracing Method (LIB) is acceptable, while solid sheathing is not allowed.
4. Maximum unit wall weight = 65 psf. Block-veneer limited to 50 psf.
5. Wall thickness between 3 inches and the thickness achieving maximum unit wall weight.
6. Metals in contact with hemp-lime shall be stainless steel or painted with an approved coating.
7. Acceptable water-to-binder ratio between 1:1 and 2:1, or in accordance with manufacturer’s recommendations.
8. Masonry or concrete walls lined with hemp-lime require anchorage (lining to substrate) according to Section BL103.6.7.
9. Moisture Control:

a. Water-resistive barriers (WRB) and vapor retarders are prohibited on hemp-lime walls (with some exceptions listed in the Appendix).

i. Horizonal surfaces exposed to water are an exception. They require a WRB and a minimum slope of 1:12.

ii. A moisture barrier is required between hemp-lime/exterior plaster and the foundation.

10. A vapor-permeable air-barrier is required on all interior and exterior surfaces.

    a. Plaster is an acceptable air barrier.

11. Hemp-lime and plaster require not less than an 8-inch separation from (above) exposed earth or paving.

12. Plaster finishes per BL104.3.

13. Ventilation is required for non-plaster finishes.

14. Walls with hemp-lime can be categorized as mass walls per IECC. R-values per inch are provided in Table BL106.2.

15. Compressive strength must be demonstrated in accordance with BL107.1.1. A minimum compressive strength of 29 psi must be demonstrated to prove the ability to hold plaster.

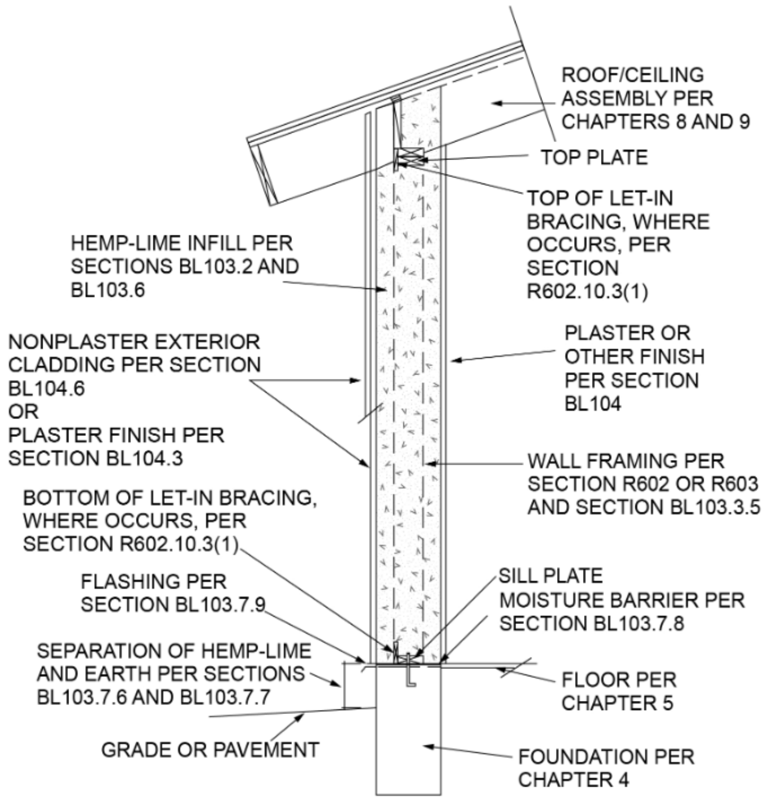


Figure 24. 2024 IRC Appendix BL Figure BL103.1(2) Typical hemp-lime with center stud framing.

Four typical hand-cast (cast-in-place) wall assemblies are described in the appendix, one of which is shown in Figure 24. The wall-section shown in Figure 24 represents a scenario in which the designer chooses to install the structural support framing in the center of the wall. No anchorage is required of the hemp-lime to the framing in this position. If the support framing is installed toward the exterior or interior of the wall-assembly, then anchorage (Bullet item 8), like that shown in Detail 2 (Figure 9), must be approved by a registered design professional. The appendix regulations place limitations on horizontal bracing without, however, prescriptively providing guidance on specification of the bracing.

3.3 Comments on the Performance and Durability of Hempcrete Assemblies

When selecting materials for building enclosure components, one must carefully consider whether the aggregate assembly will adequately perform all the building enclosure functions that will be required for the specific climatic region in which the building structure is located. The primary function of the building enclosure is to separate the interior environment from the exterior environment. It typically consists of the above-and-below-grade wall assemblies, the roof assembly and the base floor system. The enclosure typically performs four major functions: structural support; control of the flow of air, moisture, heat, sound, etc.; an aesthetically pleasing, durable finish; and, at times, the enclosure is required to distribute services and utilities throughout the building (Straube 2008).

Hempcrete assemblies have unique physical and mechanical properties that must be considered prior to specifying their use for a project. One that stands out is the vapor permeability of the wall assemblies and the need to maintain this permeability, both during the initial curing and during service. Another is the recommendation for natural finishes. Natural finishes are not appropriate or affordable for all projects. Regional considerations such as climate or precipitation should be understood prior to committing to hempcrete assemblies.

Hempcrete wall, roof and floor assemblies are able to provide a level of thermal insulation that can satisfy typical building and energy code requirements in various climactic regions (Memari et al. 2022; Shang and Tariku 2021). A study has shown that a hempcrete wall assembly, in comparison with a wood-frame wall assembly having similar thermal resistance, has similar heating and cooling energy performance in cold climates (Shang and Tariku 2021). The performance of the hempcrete wall assembly, however, varies slightly from the wood-framed assembly, due to its thermal mass properties and moisture buffering capabilities. The study shows that the hempcrete exterior wall assemblies tested have a slightly greater heating energy consumption (2.1% in Vancouver, 1.8% in Toronto) and reduced cooling energy consumption (34.6% in Vancouver, 37.4% in Toronto). The same study has shown that the moisture buffering capabilities of the hempcrete wall assemblies had a moderating effect on indoor humidity in the buildings. It was also shown that paint significantly limits the moisture buffering capability of the wall assembly. A study conducted on a hempcrete home constructed in New Castle, PA, reported, “Despite high outdoor humidity levels during hot summer weeks, the indoor relative humidity was always less than 60%” (Memari et al. 2022). The same study also reported a CO2 level below 1000 ppm throughout the monitoring period, highlighting the material’s ability to help maintain healthy air-quality parameters. The study showed marginal infiltration results (4.93 ACH50 with a 5.00 maximum limit) however, which could suggest air-sealing challenges associated with the wall assemblies, especially in retrofit situations.

The durability of hempcrete assemblies over time has been studied. Generally, the material is regarded as being resistant to mold and insects, due to the alkalinity of the lime. Hempcrete houses in France have existed for over 20 years without reported serious durability problems (Walker, Pavia, and Mitchell 2014). Due to the material’s high vapor-permeability and moisture storage capacity, some concerns have been expressed regarding the proliferation of microorganisms in hempcrete assemblies and their contribution to reductions in vapor-permeability and increases in thermal-conductivity over time. Studies have shown this to be unlikely due to insufficient nutrients, unsuitable environmental conditions, and PH variations over time. (Walker, Pavia, and Mitchell 2014; Marceau et al. 2017).

Age, seasonal exposure to the weather, and mix can affect hempcrete in a variety of ways. In one study reviewed, an accelerated aging protocol was applied to hempcrete samples in the laboratory in order to study the impact of aging on the microstructure of the material. During the study, the samples were subjected to repeated cycles of immersion in water, freezing and drying. Interestingly, the results showed that the porosity of hemp concrete increased, while the compressive strength and thermal conductivity of the material decreased due to changes in the microstructure of the material. Notably the compressive strength in the study was reported to have decreased by 56% (Benmahiddine and Belarbi 2022). A separate study also suggested that aging and the carbonation process can influence compressive strength (Walker, Pavia, and Mitchell 2014). Results from the same study have also shown that the binder type influences freeze-thaw resistance, as well as compressive strength. The study shows that freeze-thaw resistance is a function of the hydraulicity of the binder (the ability of the binder to harden in contact with water).

As highlighted above, it is also important to understand that hempcrete, while vapor-permeable and resistant to microbial growth, is not a material that can be exposed to moisture on a long-term basis. Hempcrete assemblies must be removed from exposure to significant amounts of rain or surface runoff. Providing adequate detailing to shelter the assemblies will help to improve the useful service life of hempcrete assemblies.

Lastly, the natural finishes typically utilized in hempcrete assemblies may not be appropriate for all regions. Walls exposed to a significant dirt load can be difficult to clean without additional finish coatings. Anticipated building movement in high wind regions or unstable ground conditions can also lead to the development of cracks in the rigid hempcrete assemblies. Additionally, vapor-permeable assemblies may not be desirable in all locations, especially if there are high regional moisture loads.

4. Structural Capacity of Hempcrete Building Components

Hempcrete is typically utilized as a non-structural insulative infill; however, the material's mechanical properties have been studied, and some effort has been made to determine ways to increase the compressive strength of hempcrete (Demir and Doğan 2020; Asghari and

Memari 2024; Walker, Pavia, and Mitchell 2014). Compressive strengths for hempcrete vary widely and depend on many factors, such as curing temperature, curing relative humidity, age, binder composition, binder type, hemp-to-binder ratio, and water-to-binder ratio. Increases in density of mix and percentages of Portland cement generally increase compressive strength. Age has been reported to both increase compressive strength, due to the carbonation process (Asghari and Memari 2024), and decrease compressive strength, due to changes in the microstructure of the hemp concrete (Benmahiddine and Belarbi 2022).

Both compressive strength and Young's Modulus are relatively low in hempcrete mixes, which generally makes hempcrete unsuitable for structural applications. Additionally, hemp-lime assemblages are flexible. This could be a positive attribute, if mechanical properties were improved; however, currently, the assemblages are viewed as unstable. One study commented that compressive strength should be in the range of 3-to-5 MPa (435-to-725 psi) and Young's Modulus increased significantly for consideration for structural applications (Asghari and Memari 2024). Comparatively, the nominal axial capacity for unreinforced masonry is capped at 0.80 f'_m, which for f'_m=1,500 psi would equal 1,200 psi. The nominal axial capacity of concrete is generally accepted as 0.85f'_c, which for concrete with a compressive strength of 3,000 psi would be 2,550 psi. Based on the approximate axial capacity of CMU and concrete, the range provided from the study of 435-to-725 psi seems to be reasonable.

Currently the compressive strength of hempcrete is adequate to support self-weight and its respective exterior/interior finish systems but significantly lower than what would be advisable for structural applications. The results of the compressive tests shown in Figure 25a range from 0.32-to-0.40 MPa (46.4 psi to 58 psi) after approximately one year of curing for the 6 different mixtures tested. In this study, ratios of raw mix ingredients (binder, hemp, water) were varied, along with binder composition. Another study summarizes a group of past studies, which presented compressive strengths ranging from 0.10-to-1.01 MPa (14.5 psi to 146.5 psi) (Demir and Doğan 2020).

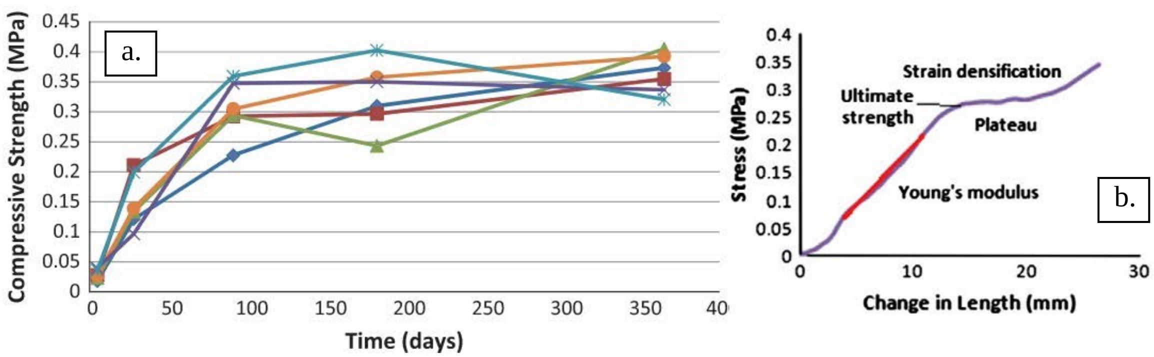


Figure 25. a. Hempcrete compressive tests reproduced from a study (Walker, Pavia, and Mitchell 2014) b. Typical hemp-lime concrete stress-strain behavior during compressive axial load reproduced from the same study.

Many factors contribute to the compressive strength of a hempcrete mixture. This is problematic from a quality control perspective, considering that for the most part, hempcrete is mixed in the field. The availability of commercial binder and mix recipes helps to improve the consistency of mix strength; however, the combining of the ingredients still occurs in an uncontrolled environment by labor forces of varying levels of expertise. This makes it difficult to assess the quality of the mixture without on-site testing for every project, which could be relatively cost-prohibitive for small residential projects.

Compressive strength is of principal interest in hempcrete structures, since hempcrete is typically used in walls, which generally resist axial loads; however, there are studies that report flexural strength as well. One group tested beam samples constructed with different mixes of hempcrete (Figure 25b) and determined that the flexural capacity of the tested mixes was between 0.13-and-0.20 MPa (18.9-to-29.0 psi) (Walker, Pavia, and Mitchell 2014). To put this into perspective, allowable bending stress for unreinforced masonry and concrete would be based on the modulus-of-rupture. The modulus-of-rupture associated with tensile stresses normal to the bed joints in running bond masonry installed using type M or S masonry cement is 38 psi. The modulus of rupture for concrete, however, is commonly taken as $7.5\sqrt{f'c}$, which for concrete with a compressive strength of 3,000 psi would yield a flexural strength of 411 psi (before application of any strength reduction factors). The flexural capacity is low for hempcrete; however, when comparing to masonry flexural strength, the difference is not large. This would suggest that, for use of hempcrete as structural walls, improvements in compressive strength are a bigger priority than improvements in flexural strength.

Figure 26. Typical flexural strength test (Walker, Pavia, and Mitchell 2014).

4.1 Structural Study of Hempcrete at Critical Residential Connections

To develop a better understanding of the performance of modern hempcrete subject to typical residential structural loads, a series of calculations was performed. A generic two-story residential building with hempcrete exterior walls was conceived for the purpose of estimating the structural demand at critical connections along the exterior wall. Figure 27 shows the plan view of the concept building and Figure 28 shows a section of the concept building.

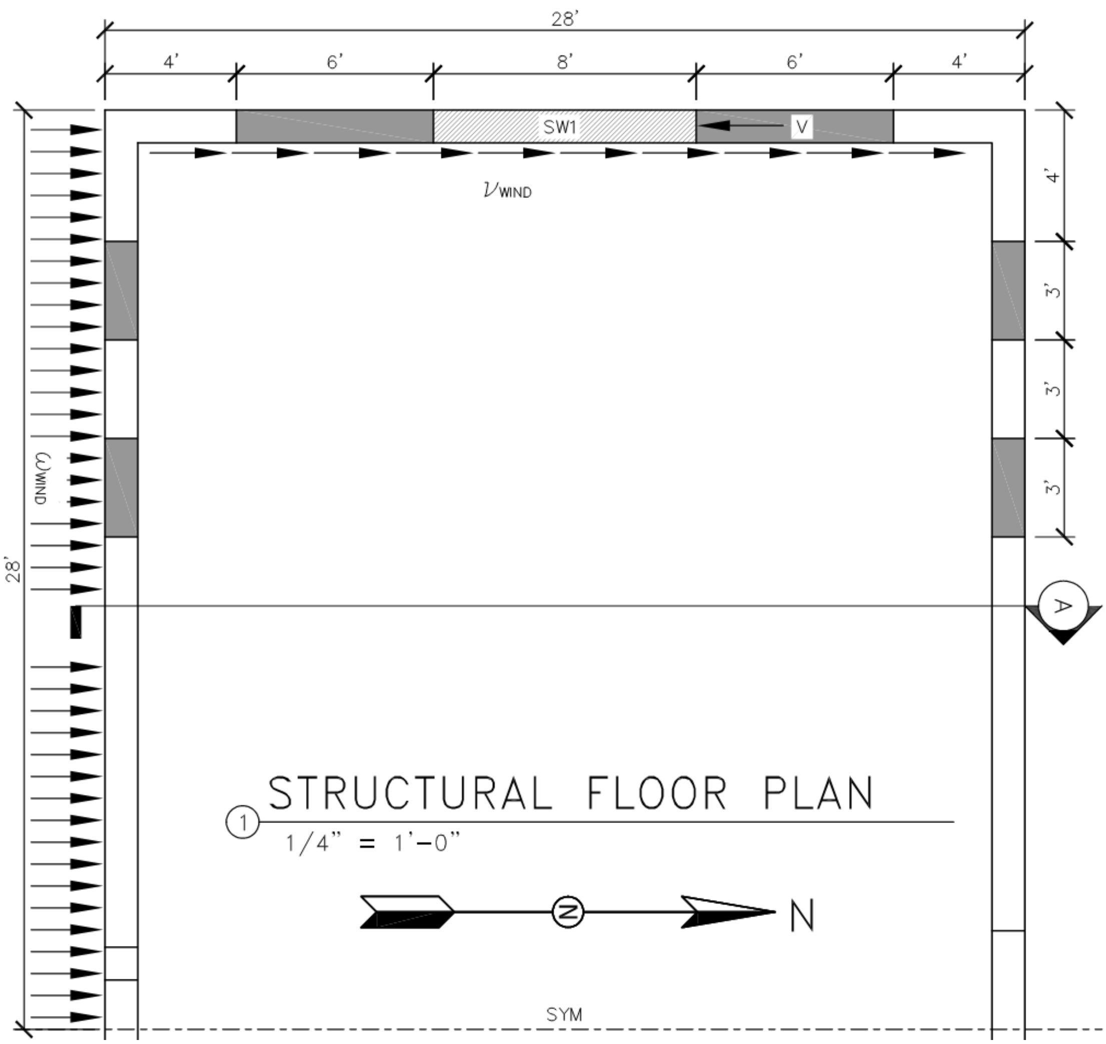


Figure 27. Conceptual floor plan utilized for structural study.

Hempcrete structural capacity was estimated at the defined critical interface points based on the limit-states developed for reinforced concrete design. Since there are no capacity prediction equations available for hempcrete, concrete design equations were considered, because they are well-established in structural engineering, and the hempcrete can be thought of as an extremely light-weight type of concrete, given its mixture (lime, as binder, hemp hurd as aggregate, and water) and its homogeneity. LRFD Methodology was considered, since the design equations taken from ACI 318 for concrete were primarily developed for use with this methodology.

To be clear, this is not an acceptable or common design practice for hempcrete walls, just a rough approximation for discussion purposes. The calculations were performed as an exploratory exercise to better understand the potential suitability of hempcrete as a structural material if mechanical properties were sufficiently improved. The exercise is also useful in developing a better understanding of where improvements are needed and the likely magnitude of the improvements required for hempcrete to function as a concrete-type structural material. The calculations and the resulting discussion are intended to be interpreted as a conceptual study and a guide for follow-up studies, which can be built upon in the future, when enhanced and increased strength are developed for the mixture.

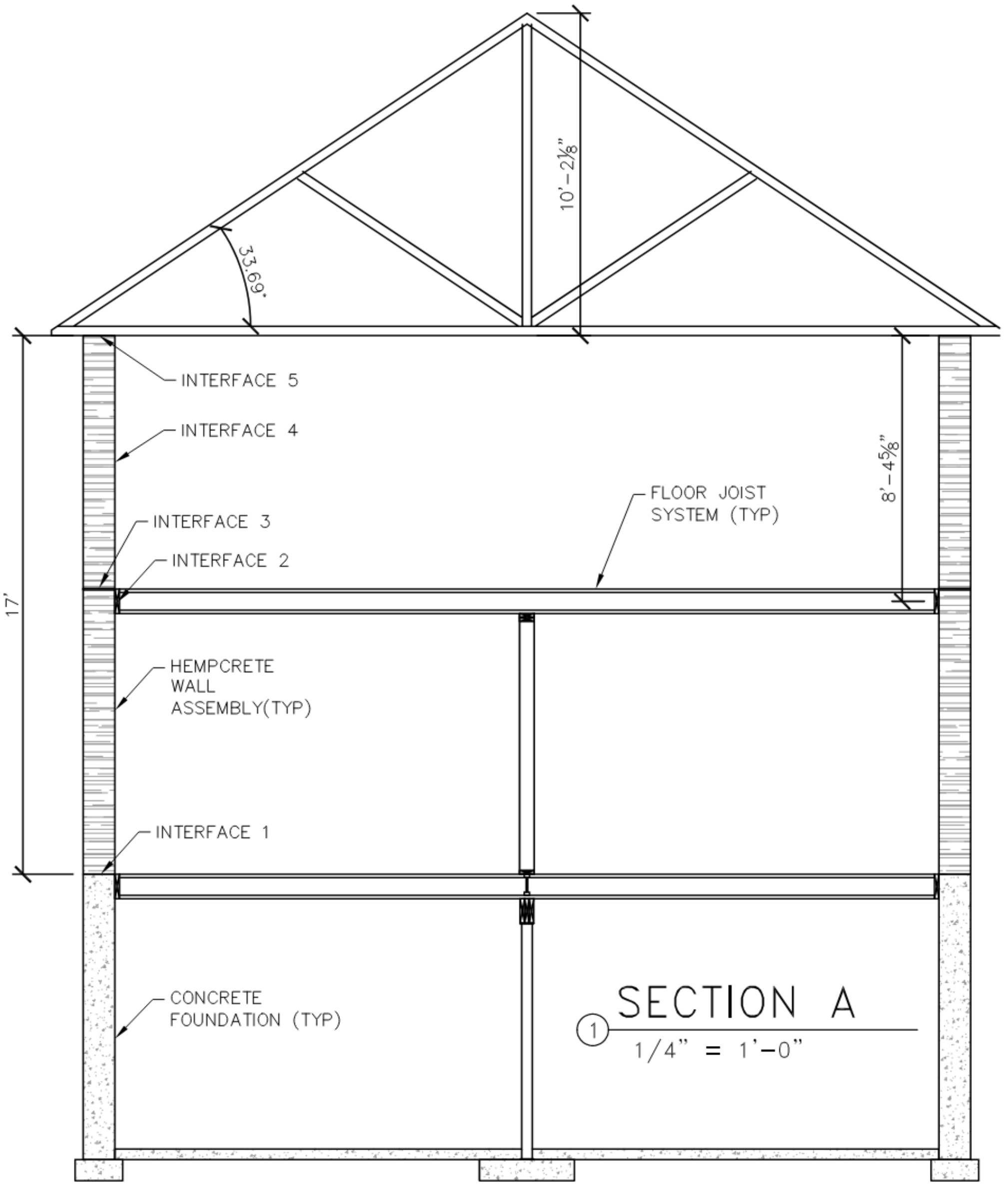


Figure 28. Conceptual building section utilized for structural study.

For the study, typical building connections were selected, and five interfaces were reviewed. Interface 1 is located at the base of the 1st-story wall where the wall meets the foundation. At this location, the material bearing-stress, due to self-weight and other conventional gravity loads, is at a maximum. Interface 2 is the anchorage of the 2nd-story ledger. This is the location of a critical shear-anchorage connection. Interface 3 is at the base of the 2ndstory wall, assuming a joint at this location. At this interface resistive force couples (opposing tension and compression forces located at opposite ends of panel) are required to stabilize 2nd-story shear-wall panels. Interface 4 is at the midpoint of the interior surface of the 2nd story wall. This is a location where maximum out-of-plane wall bending can occur. Lastly, Interface 5 is located at the top of the 2nd-story wall. At this location, trusses exert compressive pressure on the wall due to gravity loads. Additionally, the trusses require anchorage to resist uplift generated by wind forces at this location. Definitions of variables not defined in the calculations can be found in either the figures or in Appendix B. The following external loads were utilized for the study:

<u>Dead Loads</u>

$p_{dr} := 17\ \boldsymbol{psf}$ Roof Dead Load $p_{dfl} := 10\ \boldsymbol{psf}$ Floor Dead Load

$p_{dw} := 10\ \boldsymbol{psf}$ Exterior wood framed wall load per foot of height

$SG := 0.817$ Specific Gravity From (Zuabi and Memari 2021) $\gamma_{water} := 62.4\ \boldsymbol{pcf}$

$t_{wall} := 12\ \boldsymbol{in}$ Hempcrete wall thickness $\gamma_{d\_wall} := \gamma_{water} \cdot SG = 51\ \boldsymbol{pcf}$

<u>Live Loads</u>

$p_{l\_1} := 40\ \boldsymbol{psf}$ 1st Floor Live Load $p_{l\_2} := 30\ \boldsymbol{psf}$ 2nd Floor Live Load

$p_{l\_r} := 10\ \boldsymbol{psf}$ Attic Dead Load

<u>Snow Loads (From Enercalc)</u>

$p_s := 21\ \boldsymbol{psf}$

At Interface 1, the calculations suggest that the bearing capacity of the material would be acceptable to support typical residential single-family gravity loads. The gravity loads associated with a typical single-family residential dwelling are relatively low in magnitude. A 50-psi compressive strength (f'_c) was selected, based on the studies previously reviewed. It should be noted that conventional hempcrete can easily have this level of compressive strength. The low compressive strength appeared adequate when distributed over the 12-inch bearing area of the wall. Calculations for Interface 1 are as follows:

Investigate Pressure at Interface 1

$h_{wall} := 17\ ft \qquad W_{building} := 28\ ft \qquad W_{oh} := 1\ ft$

$f'_c := 50\ psi$ Estimate based on technical papers reviewed $\phi_{bearing} := 0.65$

Self-weight Only

$p_{self} := \gamma_{d\_wall} \cdot h_{wall} = 6\ psi \qquad p_u := 1.4 \cdot p_{self} = 8.4\ psi \qquad \phi R_n := \phi_{bearing} \cdot 0.85 \cdot f'_c = 27.6\ psi$

$p_u = 8.4\ psi\ < \phi R_n = 27.6\ psi$ Ok

Strength Load Combination (1): 1.2D+1.6L

$w_d := p_{dr} \cdot \left(0.5\ W_{building} + W_{oh}\right) + p_{dfl} \cdot \left(0.25 \cdot W_{building}\right) = 325\ plf \qquad p_d := \dfrac{w_d}{t_{wall}} + p_{self} = 8.3\ psi$

$w_l := p_{l\_r} \cdot \left(0.5\ W_{building} + W_{oh}\right) + p_{l\_2} \cdot \left(0.25 \cdot W_{building}\right) = 360\ plf$

$p_l := \dfrac{w_l}{t_{wall}} = 2.5\ psi \qquad p_{u\_1} := 1.2\ p_d + 1.6\ p_l = 13.9\ psi$

Strength Load Combination (2): D+1.6S+1.0L

$w_s := p_s \cdot \left(0.5\ W_{building} + W_{oh}\right) = 315\ plf \qquad p_{u\_2} := 1.2\ p_d + 1.0\ p_l + 1.6 \cdot p_s = 12.7\ psi$

$p_{u\_1} = 13.9\ psi\ < \phi R_n = 27.6\ psi$ Ok

At Interface 2, calculations suggest that the ledger anchorage has adequate capacity; however, this seems intuitively high, given the low compressive strength of the material. Only three shear limit-states are considered in ACI 318 Chapter 17: steel failure, breakout and pryout. At this connection, with anchor steel strength assumed to be adequate, only pryout is applicable. With a pryout failure (Figure 29), the concrete adjacent the lead surface of the anchor begins crushing, as an increasing amount of shear is applied. As the concrete crushes, the anchor begins to rotate, and an upward force is applied to the material above the embedded head of the anchor until a breakout failure occurs behind the anchor. Considering the low compressive strength of the material, it is not clear whether this type of failure would be able to occur. It is possible that the hempcrete failure modes may bear a closer resemblance to the dowel failure modes set forth in the wood design Yield Limit Equations. Testing would be required to investigate this possibility. The following are the calculations for Interface 2:

Investigate Anchorage Forces at Interface 2

$w_u := 1.2\ p_{dfl} \cdot \left(0.25 \cdot W_{building}\right) + 1.6\ p_{l\_2} \cdot \left(0.25 \cdot W_{building}\right) = 420\ \boldsymbol{plf}$

Assumptions:

1. Hempcrete behaves similar to concrete.
2. Steel strength limit state does not control.
3. Shear breakout not a consideration.
4. Condition B (No supplementary Reinforcement)
5. $\phi_{pry} := 0.70$

Estimate Pryout Strength

$d_{anchpr} := 0.625\ \boldsymbol{in}$ $\quad s_{anchor} := 36\ \boldsymbol{in}$ $\quad h_{ef} := 6\ \boldsymbol{in}$ $\quad A := 1.5 \cdot h_{ef} = 9\ \boldsymbol{in}$ $\quad C_{a1} := 4.25\ \boldsymbol{in}$

$V_u := w_u \cdot s_{anchor} = 1260\ \boldsymbol{lbf}$

$A_{Nc} := 2 \cdot A \cdot \left(A + C_{a1}\right) = 238.5\ \boldsymbol{in}^2$ $\quad A_{Nco} := 9 \cdot {h_{ef}}^2 = 324\ \boldsymbol{in}^2$ $\quad k_c := 24$ $\quad f'_c := 50\ \boldsymbol{psi}$

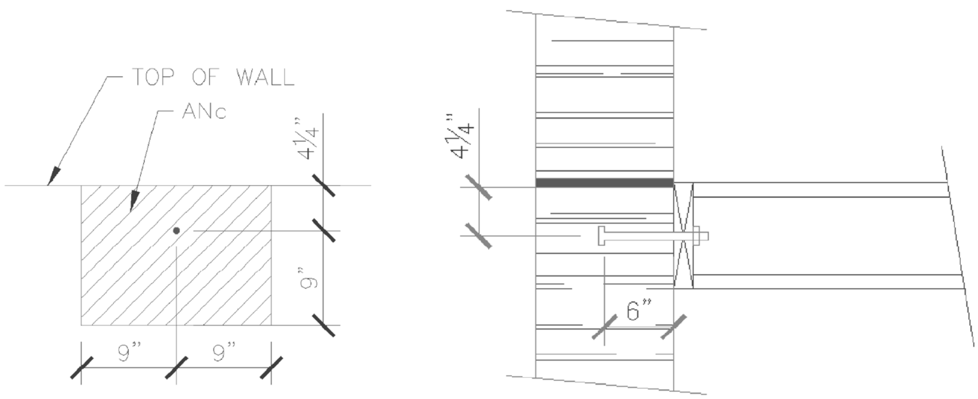


Figure a. Interface 2 Anc area and detail at anchorage connection.

$$N_b := k_c \cdot \sqrt{\frac{f'_c}{\boldsymbol{psi}}} \cdot \left(\frac{h_{ef}}{\boldsymbol{in}}\right)^{1.5} \cdot \boldsymbol{lbf} = 2494.2\ \boldsymbol{lbf}$$

$$\Psi_{edN} := 0.7 + 0.3 \cdot \frac{C_{a1}}{1.5 \cdot h_{ef}} = 0.842 \qquad \Psi_{cN} := 1.0 \qquad \Psi_{cpN} := 1.0$$

$$N_{cp} := \frac{A_{Nc}}{A_{Nco}} \cdot \Psi_{edN} \cdot \Psi_{cN} \cdot \Psi_{cpN} \cdot N_b = 1545.3\ \boldsymbol{lbf} \qquad k_{cp} := 2.0$$

$$V_{cp} := k_{cp} \cdot N_{cp} = 3090.6\ \boldsymbol{lbf} \qquad \phi V_{cp} := \phi_{pry} \cdot V_{cp} = 2163.4\ \boldsymbol{lbf}$$

$\phi V_{cp} = 2163.4\ \boldsymbol{lbf}$ >= $V_u = 1260\ \boldsymbol{lbf}$ Ok for spacing of 36" O.C.

Something else to be mentioned when discussing the applicability of concrete anchor design equations to hempcrete is that one of the design assumptions built into the anchor design equations is that "cracked concrete members have sufficient reinforcement to restrain cracking to acceptable widths under design loads." This assumption is immediately violated with hempcrete, due to the lack of reinforcement, and limits the potential application of the anchor equations to uncracked circumstances, which are difficult to predict. It should be noted that with conventional application of hempcrete, wood framing within the wall provides the needed structural support for the anchor. However, in this hypothetical case, the assumption is that the hempcrete alone functions as the structural material.

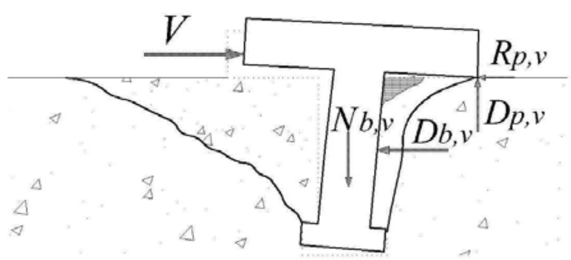


Figure 29. Concrete pryout failure mechanical model (Jebara and Hofmannn 2017)

At Interface 3, shear-wall SW1 on the western wall was investigated (see plan view in Figure 27). Calculations were performed to determine the force-couple generated by a north-south wind loading scenario. When wind load is applied perpendicular to the north or south wall, the load is transferred through the flexible roof diaphragm to the rigid shear wall segments along the eastern and western wall-line. Refer to the plan view for a description of the applied wind load. In this study, it is assumed that the connection of the shear-wall panels along the western wall is adequate to produce equal shear wall deflections in the panels; therefore, the shear is distributed to each segment based on relative rigidity. In this case, both the height and material thickness of the segments are equal, so the shear is distributed based on the length of the segment.

The calculations for Interface 3 are as follows:

Investigate the anchorage required at Interface 3 due to overturning of SW1 on the second floor

Assumptions:

1. No torsional diaphragm load.
2. Distribution of load based on rigidity. Model similar to concrete shear walls.
3. Flexible diaphragm.
4. Walls share lateral load based on their relative rigidity.

Calculate story shear at roof level

$h_2 := 8.39\ ft$ 2nd story wall height $h_r := 10.18\ ft$ Roof assembly height

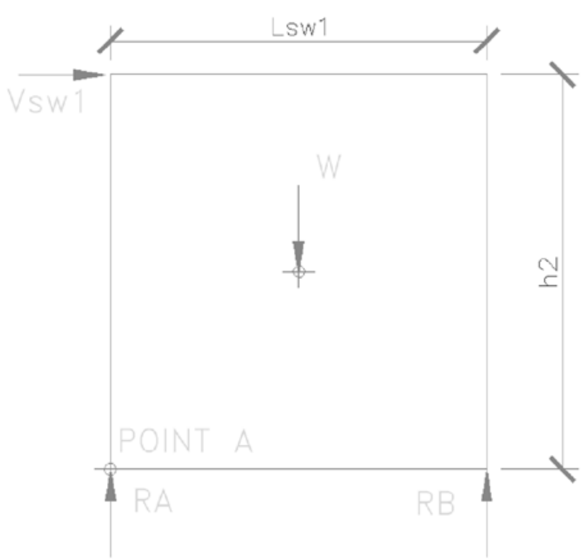
$L_{building} := 56\ ft$ $p_{wind} := 16\ psf$ (From Enercalc)

$w_{wind} := p_{wind} \cdot (0.5\ h_2 + h_r) = 230\ plf$ $P_{wind} := L_{building} \cdot w_{wind} = 12880\ lbf$

$L_{total} := 16\ ft$ Total length of shear wall on the western wall

$L_{sw1} := 8\ ft$ $v := \dfrac{0.5 \cdot P_{wind}}{L_{total}} = 402.5\ plf$ $V_{sw1} := v \cdot L_{sw1} = 3220\ lbf$ Shear Force to SW1

$P_{dw} := p_{dw} \cdot 0.5 \cdot h_r \cdot L_{sw1} + (\gamma_{d\_wall} \cdot t_{wall} \cdot h_2 \cdot L_{sw1}) = 3829\ lbf$ Dead Load on Wall



$W := P_{dw} = 3829\ lbf$

Evaluate LRFD LC : 0.9D+1.0W

$$R_b := \frac{0.9 \cdot W \cdot 0.5 \cdot L_{sw1} + V_{sw1} \cdot h_2}{L_{sw1}} = 5100\ lbf$$

$$R_a := W - R_b = -1271\ lbf$$

The application of wind loading resulted in a compressive force of 5100 lb. With a compressive resistance of 1326 lb, the difference between demand and capacity is significant. This is a clear example of why the low compressive strength of hempcrete is problematic when considering structural applications of hempcrete, and why wood framing members are currently used as the main structural load resisting system. Compressive failures are generally not ductile and are sudden. This is an undesirable trait in most civil structures, because sudden failures provide little to no warning prior to failure, which can be dangerous to any people in the vicinity of the structure.

The tensile resistance provided by the hempcrete for the cast-in-place anchorage was also inadequate. The calculated tensile demand was -1271 lb. The breakout capacity of the hempcrete was relatively close to the demand; however, the pullout capacity was only 188 lbs., due to the minimal bearing area of the headed anchor and the low compressive strength of the hempcrete. Given the low compressive and tensile capacity estimates at this interface, it would be safe to say that the hempcrete panels are currently unsuitable for shear wall applications without embedded wood framing to resist the applied loads. Furthermore, even if the compressive strength were to be improved, just like concrete, some sort of reinforcement would still be necessary for use in hempcrete.

At Interface 4 the out-of-plane bending capacity of the exterior wall was reviewed. As mentioned above, the bending or tensile capacity of hempcrete would be comparable to the allowable tensile stress for unreinforced masonry provided in the Building Code Requirements and Specifications for Masonry Structures. As suspected, there were no immediate concerns with the out-of-plane bending capacity considering the thicker wall. The calculated demand of 2.9 psi was significantly lower than the estimated capacity of 20 psi. 20 psi was used as an estimate based on the previous studies reviewed; however, 48 psi was calculated based on the concrete modulus-of-rupture design equation. This identifies another discrepancy between concrete design equations and tested hempcrete values. As mentioned above, if hempcrete were to have sufficient compressive strength as a structural material, reinforcement would still be needed as in reinforced concrete. Calculations for Interface 4 follow:

Investigate tension due to out-of-plane bending due to wind load at interface 4

1. Assume a joint at the second floor and a pinned-pinned restraint condition.
2. Assume similar to concrete behavior.

$p_{wind} = 16\ psf \qquad w_{wind} := p_{wind} \cdot 1\ ft = 16\ plf$ Vertical uniform load over a 1ft strip

$M := \dfrac{w_{wind} \cdot {h_2}^2}{8} = 140.8\ lbf \cdot ft \qquad I_{wall} := \dfrac{12\ in \cdot {t_{wall}}^3}{12} = 1728\ in^4$

$$\sigma_{t\_wind} := \frac{M \cdot t_{wall} \cdot 0.5}{I_{wall}} = 5.9\ psi$$

$$P_d := \left(p_{dr} \cdot \left(0.5\ W_{building} + W_{oh}\right) \cdot 1\ ft + \gamma_{d\_wall} \cdot t_{wall} \cdot h_2 \cdot 0.5 \cdot 1\ ft\right) \cdot 0.9 = 422\ lbf$$

$\sigma_{c\_d} := \dfrac{P_d}{t_{wall} \cdot 1\ ft} = 2.9\ psi$ Compressive pressure due to dead load at mid-height 2nd floor

$$\sigma_u := 1 \cdot \left(\sigma_{t\_wind} - \sigma_{c\_d}\right) = 2.9\ psi \qquad \phi_{bending} := 0.9 \qquad \sigma_n := 7.5 \cdot \sqrt{\frac{f'_c}{psi}} \cdot psi = 53\ psi$$

$\phi\sigma_n := \phi_{bending} \cdot \sigma_n = 47.7\ psi \qquad \sigma_u = 2.9\ psi$ <= $\phi\sigma_n = 47.7\ psi$ ok for out of plane bending

At Interface 5, both the bearing and the anchorage of a single truss were considered. It was assumed that the truss bears directly on the hempcrete wall and is anchored with a cast-in-place anchor like that used for the tension leg of SW1. The results of the calculation showed that the compressive demand of 1900 lbs. is greater than the estimated capacity of 497 lbs. The tensile demand of -47 lbs., however, was less than the estimated pullout capacity of -188 lbs. estimated for Interface 3. Calculations for Interface 5 follow:

Investigate Interface 5, truss bearing on top of second story wall

1. Assume truss bears directly on hempcrete.
2. Assume similar to concrete behavior.
3. Trusses spaced at 24 inches on center.
4. Investigate LC: 1.2D+1.6S+1.0L

$P_d := p_{dr} \cdot (0.5\ W_{building} + W_{oh}) \cdot 2\ ft = 510\ lbf$ $\quad P_l := p_{l\_r} \cdot W_{building} \cdot 0.5 \cdot 2\ ft = 280\ lbf$

$P_s := p_s \cdot (0.5\ W_{building} + W_{oh}) \cdot 2\ ft = 630\ lbf$ $\quad R_u := 1.2 \cdot P_d + 1.6 \cdot P_s + 1.0 \cdot P_l = 1900\ lbf$

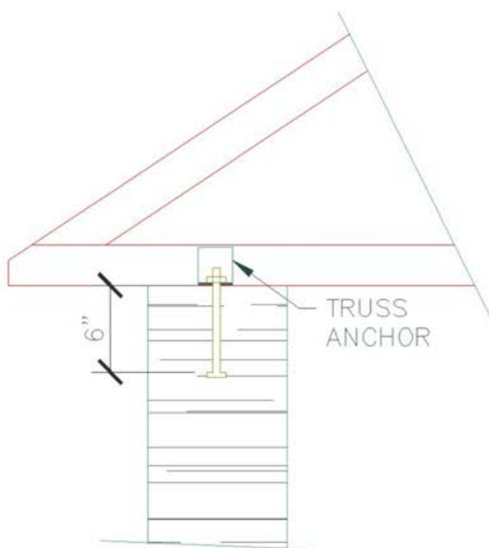
$\phi_{bearing} := 0.65 \quad A_b := t_{wall} \cdot 1.5\ in = 18\ in^2$

$\phi R_n := \phi_{bearing} \cdot 0.85 \cdot f'_c \cdot A_b = 497.3\ lbf < R_u = 1900\ lbf$ No good hempcrete crushes

$f'_{c\_req\_3} := \dfrac{R_u}{\phi_{bearing} \cdot 0.85 \cdot A_b} = 191.1\ psi$ Compressive strength required to satisfy demand

Maximum required compressive strength

$f'_{c\_req\_max} := \max\left(f'_{c\_req\_1}, f'_{c\_req\_2}, f'_{c\_req\_3}\right) = 338.2\ psi$



Investigate uplift on a single roof truss at the bearing

1. Assume cast-in-place anchorage similar to SW1.
2. Assume similar to concrete behavior.
3. Trusses spaced at 24 inches on center.
4. Investigate LC: 0.9D+1.0W

$p_w := -16\ psf \quad p_{w\_oh} := -29\ psf$

$P_w := p_w \cdot 0.5\ W_{building} \cdot 2\ ft + (p_{w\_oh})\ W_{oh} \cdot 2\ ft$

$P_w = -506\ lbf$

$P_u := 0.9\ P_d + P_w = -47\ lbf$

$\phi N_{pn} = 187.9\ lbf <= P_u = -47\ lbf$ ok for uplift anchorage

A summary of the results of the study is presented in Table 1. Estimating the capacity of critical connections proved to be a useful exercise. However, in at least two instances, the applicability of the concrete design equations was questionable (Pryout capacity at Interface 2 and the estimated modulus-of-rupture calculated for Interface 4). Generally, the study reinforced the consensus that the current mechanical properties of hempcrete are unsuitable for structural applications. The low compressive strength and lack of any reinforcement seem particularly problematic. The required compressive strength was calculated for those limit states that failed. The maximum compressive strength required out of all the failed limit-states reviewed was calculated to be 338.2 psi. This is close to the estimated range (435-725 psi) of compressive strengths (Asghari and Memari 2024) obtained for hempcrete structural applications using special additives presented in a previous study. Increasing compressive strength within this range seems like a reasonable goal for future research, based on this short study.

To recap, the low compressive strength resulted in obvious inadequacies at interface 3 and 5. The ledger anchorage check at interface 2 passed; however, the applicability of the failure modes to the material is in question at this location. The out-of-plane wall bending check passed at Interface 4 as well as the bearing check at Interface 1.

Table 1. Summary from study of the hempcrete capacity estimates at critical exterior wall interfaces/connections.

Interface	Limit State	Demand	Capacity (est.)
1	Bearing Pressure (self)	8.4 psi	27.6 psi
1	Bearing Pressure (strength)	13.9 psi	27.6 psi
2	Pryout	1260 lb	2163 lb
3	SW1 Compression Bearing	5100 lb	1326 lb
3	SW1 Anchor Tension Breakout	-1271 lb	-1048 lb
3	SWI Tension Anchor Pullout	-1271 lb	-188 lb
4	Bending (Strength)	2.9 psi	20 psi
5	Truss Compression Bearing	1900 lb	497 lb
5	Truss Anchor Tension Breakout	-47 lb	-188 lb

In general, the mechanical properties of hempcrete appear well suited for its current use as an insulative infill material. Significant improvement would be required to introduce a reliable stand-alone load-bearing hempcrete product. Currently, hempcrete assemblies appear as if they would be unstable and unpredictable if subjected to conventional external building loads. Part of the concern is the potential presence of cracks unaccounted for in the assembly. Introducing reinforcing to the material might help minimize crack widths and improve confidence in the material under structural loading, as is the case for reinforced concrete.

4.2 The Use of Hempcrete for Load-Bearing Building Construction Applications

As discussed above, hempcrete is not a load-bearing structural building material. One of two methods are currently used in practice when hempcrete is required for load-bearing applications. The first is to use precast blocks as forms, add steel reinforcement, and pour concrete into the cavities, creating a structural reinforced concrete framework within the insulative hempcrete forms. The second method is inserting steel or Fiber Reinforced Polymer (FRP) framing elements into the hempcrete block cavities and connecting the elements to create the complete structural framing system.

These load-bearing systems appear efficient in their use of structural material. The small, reinforced concrete or steel/FRP columns and beams are appropriate for the low magnitude loading typically experienced in single-family residential construction. The minimalistic embedded framing system creates thermal bridges and reductions in R-value where present; however, due to the efficiency of the framing and presence of thermal breaks, the effects could be minimized if designed properly. It is unclear whether the environmental impacts of these load bearing systems having concrete and steel elements would be greater in comparison to some of the wood-framed systems previously discussed.

Figure 30 shows an example of the first method in which reinforcement is installed into the cavities of the prefabricated block system. One benefit of using prefabricated hempcrete blocks is that the curing occurs prior to installation, so the long wait time at the construction site required for cast-in-place applications is eliminated. In the system shown in Figure 30, the tongue and groove blocks are cut to size using standard contractor equipment, such as handsaws or chainsaws, and dry-stacked to form the wall system. Reinforcing cages are constructed and concrete is poured to form columns and beams within special cavities provided in the product. As shown in Figure 30, temporary bracing is typically required to prevent block blow-outs and maintain wall plumbness.

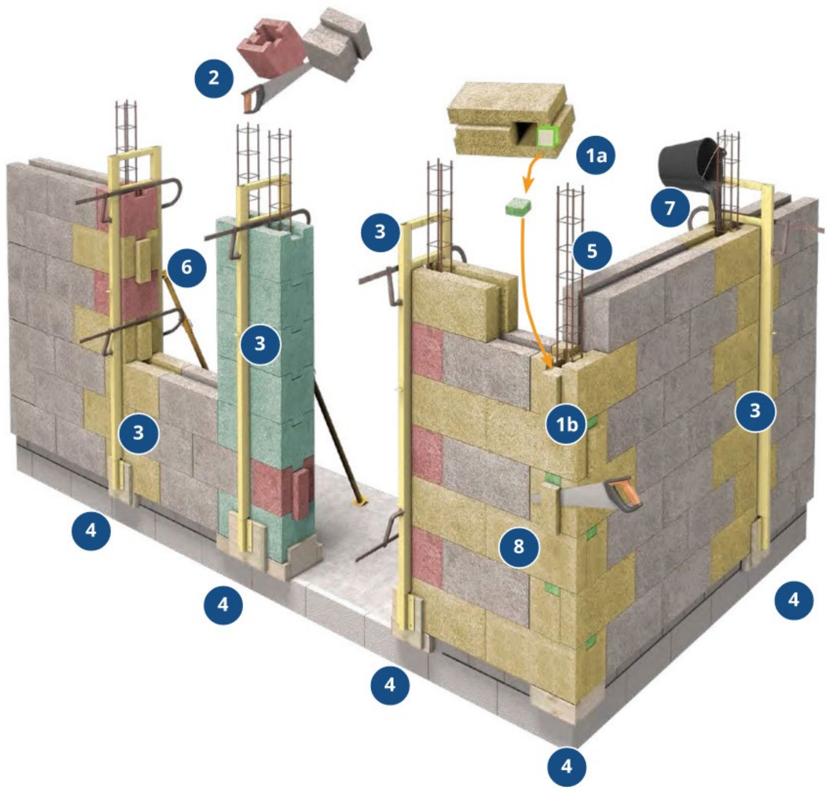


Figure 30. Hempblock USA Load bearing system.

Figure 31 shows an example of the second method of installation. This method is like the first method except that instead of reinforced concrete members, FRP or steel members are utilized for the framing. FRP members are shown in Figure 31a. Insulative infill is used around the FRP/steel members to fill in the annular space between the member and the block.

As can be seen in the image, connection components are required, along with solid members. The FRP connections shown in the image would not be as rigid as the reinforced concrete connections created using the first method. For the FRP example shown in Figure 31a, the HempBLOCK installation video shows that vertical truss members are installed to act as shear-walls to resist lateral loads from wind and earthquake. Another difference between the methods is that for both the FRP and the steel systems, column stubs (Figure 31b) are installed on the concrete slab or subfloor prior to installing the blocks. The stubs act as anchorage for the building.

Figure 31. a. FRP members inserted into HempBLOCK units b. Installation of FRP Column stubs (“LB 300 HempBlock-Load-Bearing System” n.d.).

5. Conclusions

Hempcrete is a versatile building material that can be utilized as an insulative infill for both residential and commercial structures. Hempcrete can be cast-in-place, sprayed-on or prefabricated into blocks or panels. Hempcrete has a proven history of success in residential construction and can, for the most part, be installed using common tools and without specialized work crews. Some buildings constructed with the material have been in service since the 1980s without significant issues. The main benefit of the material is that structures built with hempcrete assemblies typically have a lower environmental impact in comparison to traditional residential building systems.

Hemp is renewable and can be grown in a variety of environmental conditions, making it attractive as a building material. Hemp can be used as a cover crop to help regenerate soil during crop rotations, which adds to its usefulness. Additionally, the hurd component used in the production of hempcrete is also considered a waste product of the plant taken from the stalk. Other parts of the plant can still be harvested and used for other applications.

One of the primary benefits of hempcrete assemblies is their role in maintaining a healthy indoor environment. The material has both high vapor-permeability and high moisture-storage capacity, which help to maintain healthy indoor humidity levels throughout the year. The thermal resistance and mass of the assemblies are also relatively high for a cementitious product, which facilitates stable indoor temperature and reduces heating costs. Additionally, the assemblies provide good acoustic insulation along with excellent fire-resistance.

Hempcrete construction does have a few disadvantages, however. Hempcrete, although cementitious, should not be considered a viable alternative to concrete. Concrete is a very durable, dense, structural material and is well suited for use in wet environments. Concrete is reinforced and can predictably withstand tensile loads and maintain reasonable crack widths over time. Hempcrete, on the other hand, is not a stand-alone structural product. It has very low compressive strength and cannot be exposed to moisture for prolonged periods of time. It is unreinforced and cannot withstand significant tensile or compressive point loads, currently. The lack of reinforcement makes assemblies unstable and unpredictable without accompanying structural support. Although the material is generally known for its low-shrinkage properties, cracks or voids that develop in the assemblies for other reasons, such as poor installation practices or changes in the microstructure over time, can have negative effects on the strength of the material. Research from other professionals and the short structural study performed in this report suggest that significant improvements in the mechanical properties would be required for hempcrete to be used as a load-bearing material without the need for an independent structural support system. As discussed above, even with significant improvement in the mixture design to increase the compressive strength, some form of reinforcement for hempcrete is still needed in the absence of wood framing.

For the most part, specialized equipment or crews are not required to install hempcrete assemblies; however, there are certain pieces of equipment that should be purchased for cast-in-place or spay-on applications. A certain level of expertise is also required to accomplish successful installations. An example of important specialized equipment would be either the mud hog mixer or the EREASY spray system shown in Figure 19.

As for installation, expertise is required in the mixing process, as well as the plastering process. Proper selection of the proportions of the hemp (mixture design), binder, and water is initially important. Improper hemp selection can lead to degradation and pest issues over time. Selection of binder is critical; the binder type and the mix-ratio greatly affect both the mechanical properties of the material and the curing time. Commercial binders can improve chances of success for contractors who are not experts in the casting of hempcrete. In addition to mixture design considerations, it is important to have someone on-board with expertise in lime-plaster installation to install the interior and exterior finish systems. Lime-plaster is not installed in the same manner as gypsum plaster and requires skill to provide an attractive durable finish.

The main disadvantage of cast-in-place or spray-on hempcrete is the required curing time. A hempcrete cast in the field can take anywhere from two to 8 weeks to cure adequately such that the finish system can be installed. This could be problematic from two perspectives. Initially, it can impact the construction schedule; activities involving hempcrete assemblies are delayed until finishes can be installed. Secondly, the assemblies must be protected, and environmental conditions must be suitable for proper curing, which can be especially difficult in moist or cold conditions. Ventilation can be added to the wall assemblies to allow for early installation of finish systems, but at an added expense. As an alternative to cast-in-place construction, the precast block or panel can be utilized to allow for immediate installation of finish systems.

Lastly, hempcrete assemblies are thicker than traditional wood-framed wall assemblies. Hempcrete has good insulative value for a cementitious material; however, the R-value is significantly lower than conventional insulative materials, such as fiberglass or cellular foam. The R-values provided in IRC Appendix BL are between R1.2 and R2.10, depending on the density of the mix. So, for example, the 2021 IECC requires an R13 or R17 for an exterior mass wall assembly, depending on the position of the mass in the assembly, in Climate Zone 5A. This would require the hempcrete thickness, in a Climate Zone 5A wall assembly, to be anywhere from 6.5 to 14.5 inches thick. The energy code requirements generally lead to thicker overall wall assemblies that may not be able to be accommodated at all project locations.

Hempcrete, in summary, is a viable alternative construction material that can be utilized in residential wall, floor and roof assemblies. It has an established track record of successful installations and can offer advantages over traditional residential construction materials in certain applications. Although it has certain advantages, it also has noteworthy disadvantages, which have been discussed in this report. Continuing research to improve its properties and increased use in construction will help to clearly define appropriate economical uses for this unique construction material in the future.

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Appendix A – Additional Residential Hempcrete Details

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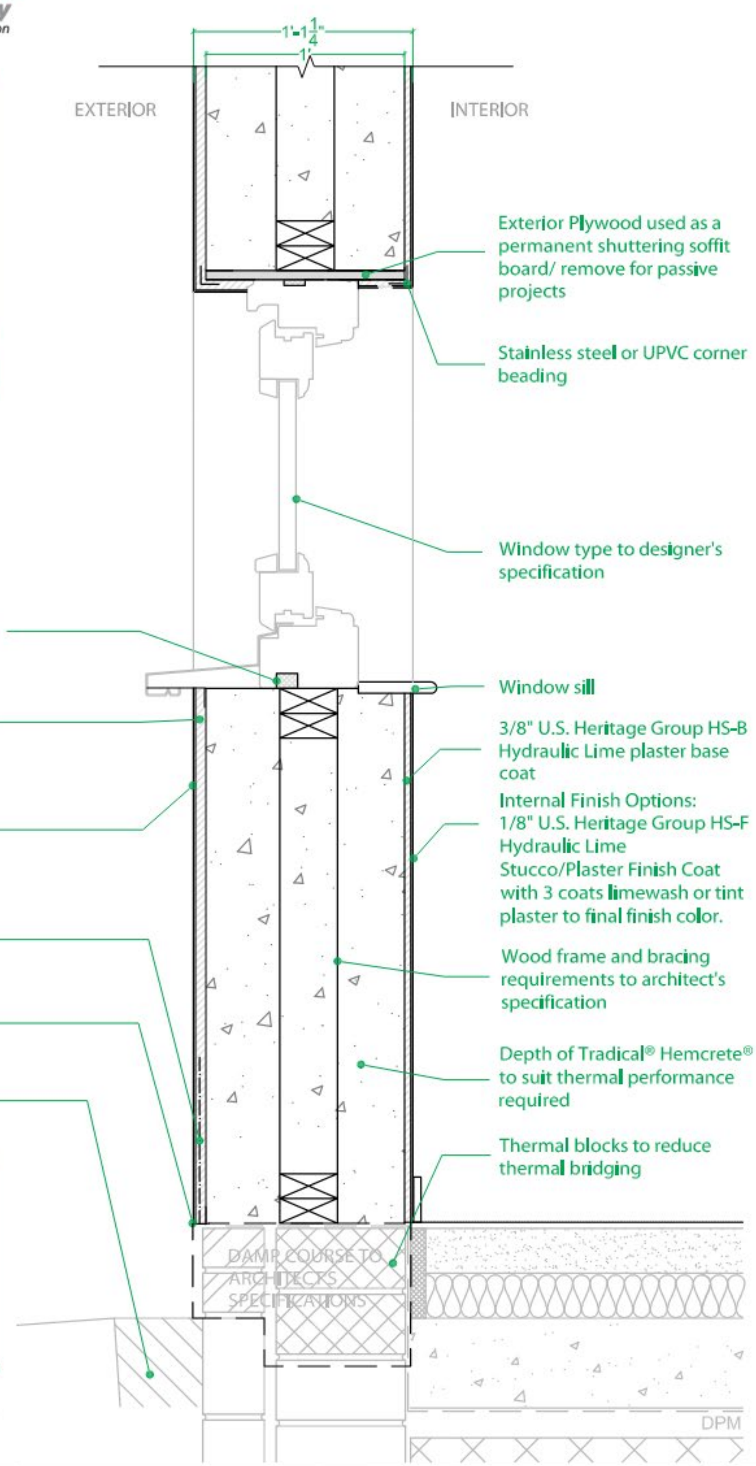
Details are INDICATIVE ONLY and need to be made project specific.

While reasonable care has been taken to ensure that the information included in this drawing was accurate at the time of issue, we reserve the right to change specifications at any time. Final detailing remains the responsibility of the designer due to site & client specific requirements.

Do not scale from this drawing.

Drawing to be read in conjunction with all standard series drawings

All structural fasteners to be non-ferrous, any galvanized fasteners to be painted with red oxide primer or bitumen paint.



Wall thickness (in.) Vs. R-value (ft²·°F·h/Btu)		
Approx. Wall Thickness	Hemcrete Thickness	Overall R-Value
11.25	10	26*
13.25	12	30*
16.25	15	35*

*Static R-value not adjusted for thermal mass or location

Tradical® hemcrete® Better-than-zero carbon

				DWN	CKD	
12.11	US Conversion	UK File Name				**Standard Wall Cross Section**
	ALT]TradHem]Render]STD_WALL_SECT	1_10_A4_LMT_2		JK	DW	Baumit Render on Tradical® Hemcrete® Internal Wood Frame

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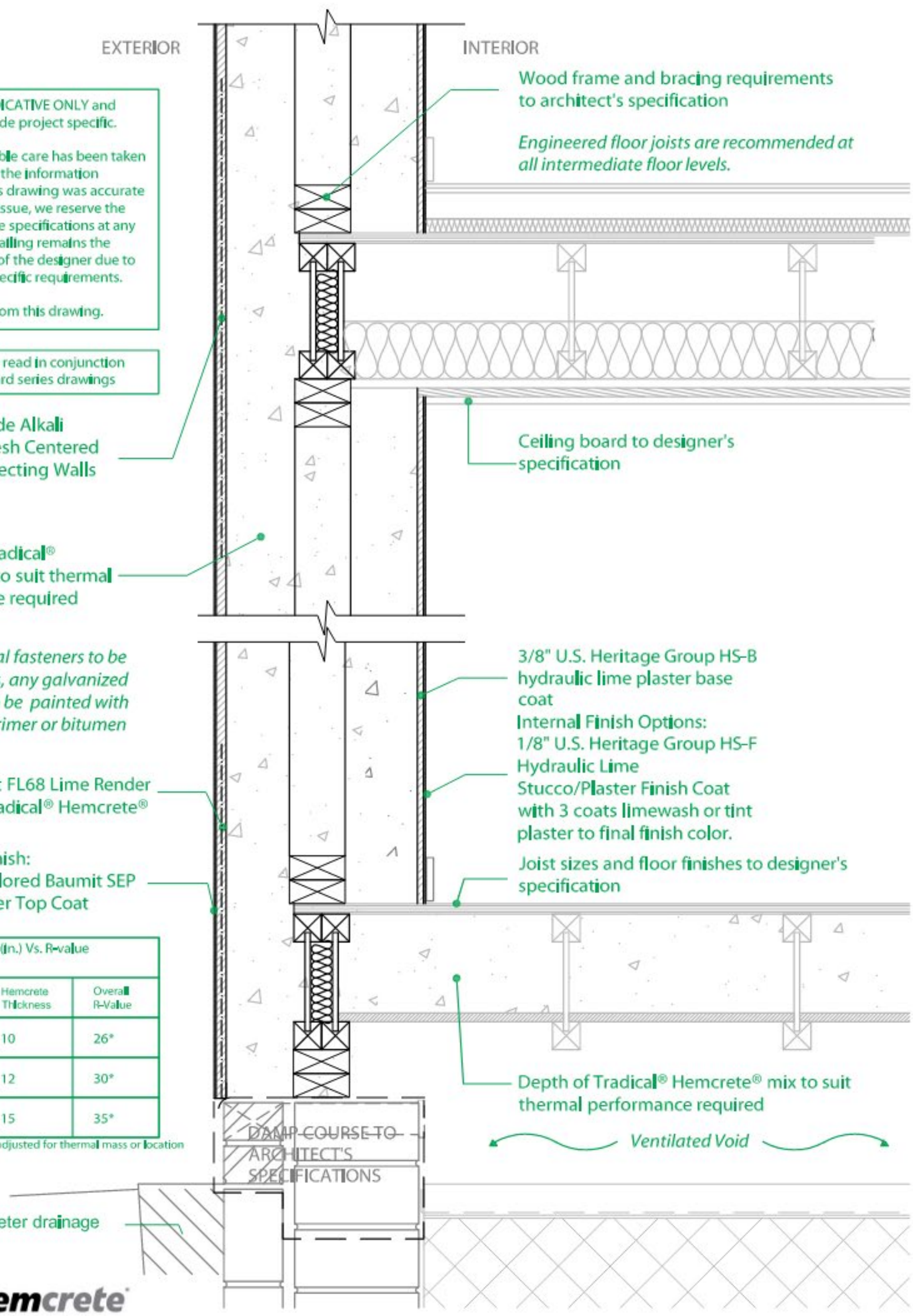
Details are INDICATIVE ONLY and need to be made project specific.

While reasonable care has been taken to ensure that the information included in this drawing was accurate at the time of issue, we reserve the right to change specifications at any time. Final detailing remains the responsibility of the designer due to site & client specific requirements.

Do not scale from this drawing.

Drawing to be read in conjunction with all standard series drawings



Wall thickness (in.) Vs. R-value (ft²·°F·h/Btu)		
Approx. Wall Thickness	Hemcrete Thickness	Overall R-Value
11.25	10	26*
13.25	12	30*
16.25	15	35*

*Static R-value not adjusted for thermal mass or location

Tradical® hemcrete® Better-than-zero carbon

12.11	US Conversion	US Conversion	DWN	CKD	
	ALT]TradHem]Render]MULTI_WALL_SECT	LT_H_1_06_SUF	JK	DW	

Multi-Story Wall Section

Baumit Render on Tradical® Hemcrete®
Internal Wood Frame

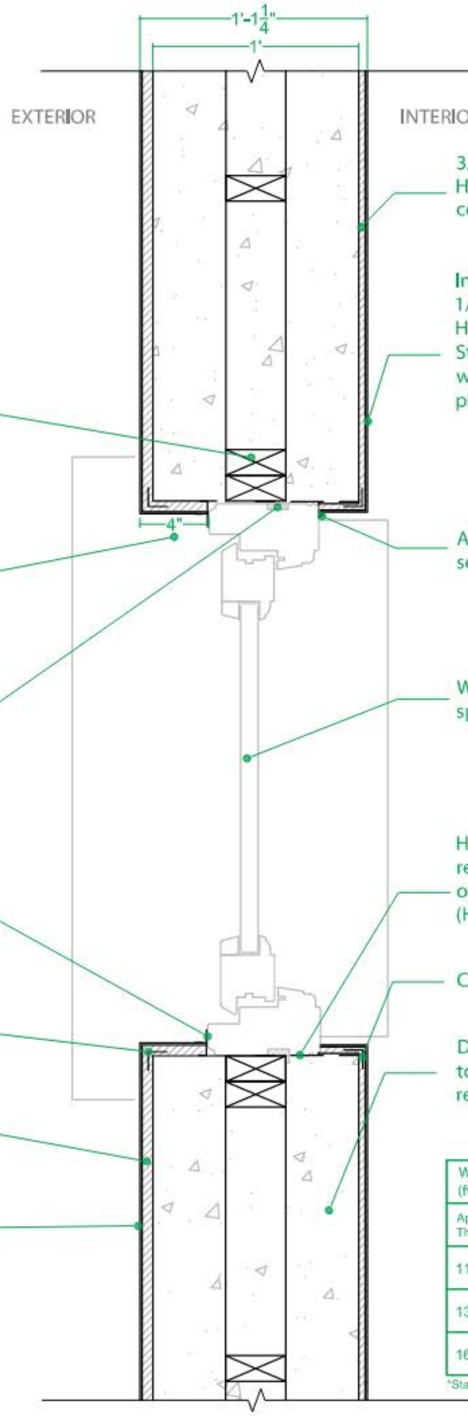
american lime technology
sustainable building innovation

Details are INDICATIVE ONLY and need to be made project specific.

While reasonable care has been taken to ensure that the information included in this drawing was accurate at the time of issue, we reserve the right to change specifications at any time. Final detailing remains the responsibility of the designer due to site & client specific requirements.

Do not scale from this drawing.

Drawing to be read in conjunction with all standard series drawings



All structural fasteners to be non-ferrous, any galvanized fasteners to be painted with red oxide primer or bitumen paint.

Wall thickness (in.) Vs. R-value (ft²·°F·h/Btu)

Approx. Wall Thickness	Hemcrete Thickness	Overall R-Value
11.25	10	26*
13.25	12	30*
16.25	15	35*

*Static R-value not adjusted for thermal mass or location

Tradical® hemcrete® Better-than-zero carbon

12.11	US Conversion	UK File Name	DWN	CKD	**Standard Window Plan**
	ALT]TradHem]Render]STD_WIN_PLAN	1_10_A4_LMT			Baumit Render on Tradical® Hemcrete®
			JK	DW	Internal Wood Frame

Standard Window Plan

Baumit Render on Tradical® Hemcrete®
Internal Wood Frame

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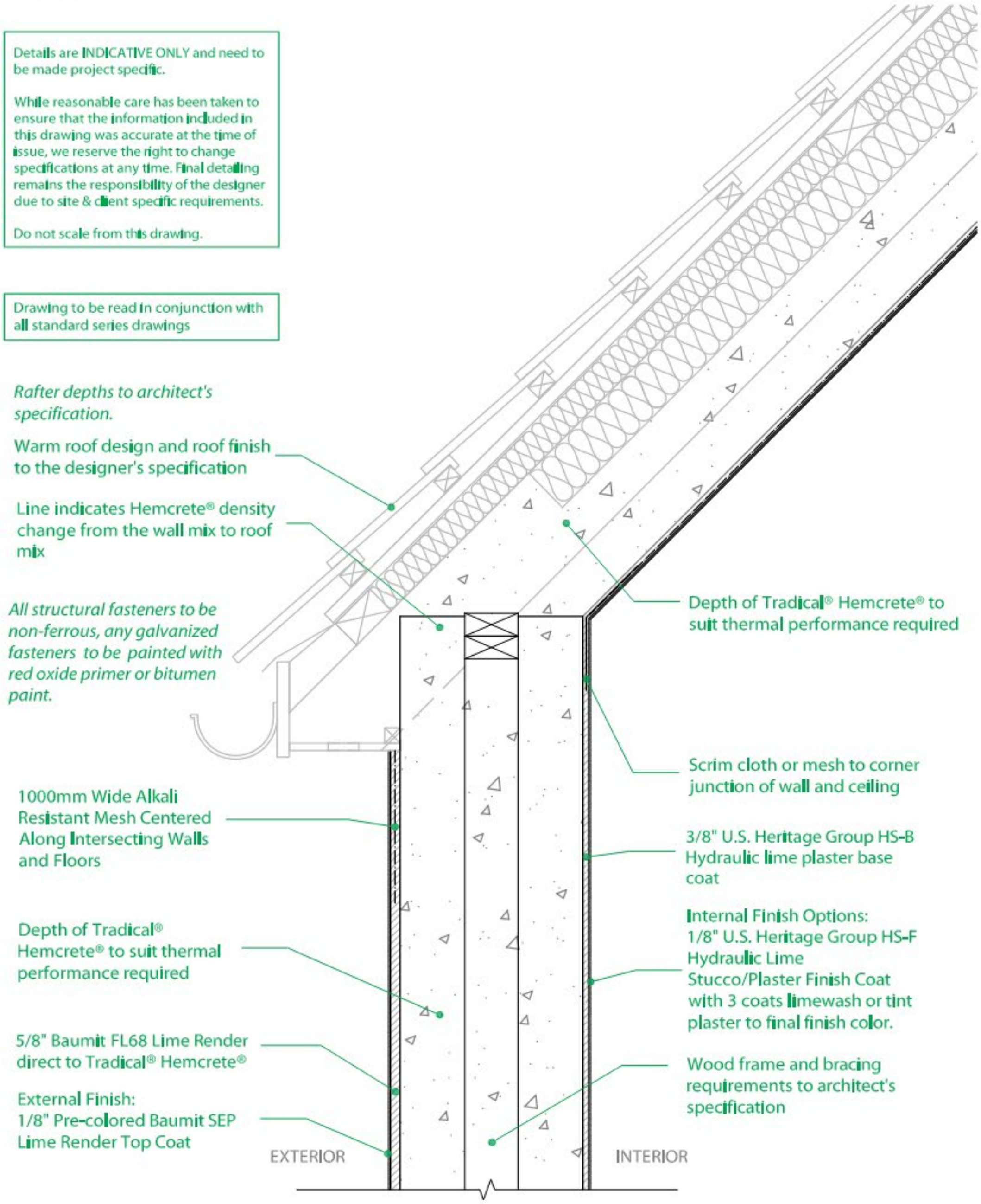

12.11	US Conversion ALT[TradHem]Render]TRAD_WRM_ROOF		UK File Name LT_H_1_05_WRF	DWN	CKD	**Tradical Warm Roof Section**
				JK	DW	Baumit Render on Tradical® Hemcrete® Internal Wood Frame

Appendix B – Structural Study Supplemental Documents

Definition of Variables Used in the Structural Study

Report Specific

h_{wall} = Height of the two-story hempcrete wall.

$L_{building}$ = Length of the concept building.

$W_{building}$ = Width of the concept building.

W_{oh} = Width of the roof overhang.

p_{self} = Self-weight pressure.

p_d = Dead load pressure.

p_{wind}, p_w = Wind pressure.

p_{w_oh} = Wind pressure on overhang.

p_l = Live load pressure.

w_d = Dead load per unit length.

w_l = Live load per unit length.

w_s = Snow load per unit length.

w_{wind} = Wind load per unit length.

P_{wind} = Wind force.

P_d = Dead load force.

P_l = Live load force.

P_s = Snow load force.

P_w = Wind load force.

p_u = Factored pressure.

w_u = Factored load per unit length.

σ_u = Factored pressure.

R_u, P_u = Factored force.

$d_{anchorpr}$ = Anchor diameter for pryout limit state.

s_{anchor} = Anchor spacing.

w_{wind} = Wind load per unit length.

M = Moment effect due to applied wind load.

I_{wall} = Moment of inertia of a 1 ft. wall strip.

ACI 318 (Refer to code document for more complete definitions of variables)

f'_c = Specified compressive strength of concrete.

$\phi_{bearing}$ = Strength reduction factor for bearing.

$\phi_{bending}$ = Strength reduction factor for bending.

ϕ_{bo} = Strength reduction factor for anchor tensile breakout.

ϕ_{po} = Strength reduction factor for anchor pullout.

ϕR_n = Design strength for bearing.

$\phi\sigma_n$ = Design strength for wall bending.

ϕN_{cb} = Design strength for anchor breakout strength.

ϕN_{pn} = Design strength for anchor pullout.

h_{ef} = Anchor embedment.

c_{a1} = Distance from center of an anchor shaft to the edge of concrete in one direction.

V_u = Factored shear load.

A_{Nc} = Projected concrete failure area of a single anchor, for calculation of strength in tension.

A_{Nco} = Projected concrete failure area of a single anchor, for calculation of strength in tension if not limited by edge distance or spacing.

k_c = Coefficient for basic concrete breakout strength in tension.

N_b = Basic breakout strength in tension of a single anchor in cracked concrete.

Ψ_{edN} = Factor used to modify tensile strength of anchors based on proximity to edges of concrete member.

Ψ_{cpN} = Factor used to modify tensile strength of post-installed anchors intended for use in uncracked concrete without supplementary reinforcement to account for the splitting tensile stresses due to installation.

ACI 318 (Refer to code document for more complete definitions of variables)

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$\phi_{bearing}$ = Strength reduction factor for bearing.

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This is a beta release of the new ATC Hazards by Location website. Please contact us with feedback.

The ATC Hazards by Location website will not be updated to support ASCE 7-22. Find out why.

ATC Hazards by Location

Search Information

Address:	state college pa
Coordinates:	40.7933949, -77.8600012
Elevation:	1151 ft
Timestamp:	2024-10-24T17:31:57.806Z
Hazard Type:	Snow

ASCE 7-16

Ground Snow Load .... 25 lb/sqft

The reported ground snow load applies at the query location of 1151 feet up to a maximum elevation of 1200 feet.

ASCE 7-10

Ground Snow Load ... 25 lb/sqft

The reported ground snow load applies at the query location of 1151 feet up to a maximum elevation of 1200 feet.

ASCE 7-05

Ground Snow Load .... 25 lb/sqft

The reported ground snow load applies at the query location of 1151 feet up to a maximum elevation of 1200 feet.

The results indicated here DO NOT reflect any state or local amendments to the values or any delineation lines made during the building code adoption process. Users should confirm any output obtained from this tool with the local Authority Having Jurisdiction before proceeding with design.

Please note that the ATC Hazards by Location website will not be updated to support ASCE 7-22. Find out why.

Disclaimer

Hazard loads are interpolated from data provided in ASCE 7 and rounded up to the nearest whole integer.

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ASCE 7-16 Snow Loads

DESCRIPTION: General Snow Loads

Flat Roof Snow Loads

Description : Main Roof Slope **per ASCE 7-16, Chapter 7**

Ground Snow Load, per Fig 7.2	25.00 psf	Roof Slope, Sec .7.3.4	33.69
Terrain Category	B (see ASCE 7-16 Section 26.7)	Roof Configuration	Monoslope
Exposure of Roof	Partially Exposed		
Ce : Exposure Factor, Table 7.3-	1.00		
Ct : Thermal Factor	Unheated and open air structures	pm, Minimum required	**0.00** psf
Risk Category, per Table 1.5-	**II**	pf, Calculated Snow Load per Equatio	**21.00** psf
Importance Factor, Is, Table 1.5-2	1.00	pf, Design Snow Load Max(pm min, pf cal	**21.00** psf

Sloped Roof Snow Loads

Description : Gable Roof Loads **per ASCE 7-16, Chapter 7**

pf : Snow Load	21.00 psf	Unobstructed & Slippery ?	No
Thermal Factor	1.20	Cs	1.00
Slope	33.69	ps, Calculated Sloped Roof Snow Loa	21.00 psf

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ATC Hazards by Location

Search Information

Address:	state college pa
Coordinates:	40.7933949, -77.8600012
Elevation:	1151 ft
Timestamp:	2024-10-24T17:30:41.976Z
Hazard Type:	Wind

ASCE 7-16

MRI 10-Year	76 mph
MRI 25-Year	80 mph
MRI 50-Year	86 mph
MRI 100-Year	92 mph
Risk Category I	100 mph
Risk Category II	110 mph
Risk Category III	117 mph
Risk Category IV	124 mph

ASCE 7-10

MRI 10-Year	76 mph
MRI 25-Year	84 mph
MRI 50-Year	90 mph
MRI 100-Year	96 mph
Risk Category I	105 mph
Risk Category II	115 mph
Risk Category III-IV	120 mph

ASCE 7-05

ASCE 7-05 Wind Speed	90 mph

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Please note that the ATC Hazards by Location website will not be updated to support ASCE 7-22. Find out why.

Disclaimer

Hazard loads are interpolated from data provided in ASCE 7 and rounded up to the nearest whole integer. Per ASCE 7, islands and coastal areas outside the last contour should use the last wind speed contour of the coastal area – in some cases, this website will extrapolate past the last wind speed contour and therefore, provide a wind speed that is slightly higher. NOTE: For queries near wind-borne debris region boundaries, the resulting determination is sensitive to rounding which may affect whether or not it is considered to be within a wind-borne debris region.

Mountainous terrain, gorges, ocean promontories, and special wind regions shall be examined for unusual wind conditions.

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ASCE 7-16 Wind Forces Chpt 28, Pt2 & Chpt 30, Pt2

DESCRIPTION: MWFRS Envelope and C&C

General Design Values

Calculations per ASCE 7-16

V : Basic Wind Speed per Sect 26.5-1 or 2	**103.0** mph	
User specified minimum design pressu	16.0 psf	
Occupancy per Table 1.5-1	II	All Buildings and other structures except those listed
Exposure Category per 26.7	Exposure B	
Topographic Factor Kzt per 26.8	1.00	

"Lambda" is interpolated between height tablular values.

Main Force Resisting System Valu

MRH : Mean Roof Height	17.0 ft
Roof Rise:Run Ratio	>7:12

Lambda MWFRS: per Figure 26. 1.00

Component & Cladding Values

Effective Wind Area of Component & Clad	72.0 ft^2
Roof pitch for cladding pressu	Gable Roof > 27 to 4
LHD : Least Horizontal Dimension	28.0 ft
a = max (0.04 * LHD, 3, min(0.10 * LHD, 0.4*MRH))	3.00 ft

Lambda Component & Cladding : per Figur 0.85

Design Wind Pressures

Horizontal Pressures . . .

Load Case # 1 . . .

Zone: A =	18.94 psf	Zone: C =	16.00 psf
Zone: B =	16.00 psf	Zone: D =	16.00 psf

Load Case # 2 . . .

Zone: A =	18.94 psf	Zone: C =	16.00 psf
Zone: B =	16.00 psf	Zone: D =	16.00 psf

Vertical Pressures . . .

Load Case # 1 . . .

Zone: E =	16.00 psf	Zone: G =	16.00 psf
Zone: F =	-16.00 psf	Zone: H =	-16.00 psf

Load Case # 2 . . .

Zone: E =	16.00 psf	Zone: G =	16.00 psf
Zone: F =	-16.00 psf	Zone: H =	-16.00 psf

Overhangs . . .

Load Case # 1 . . .

Zone: Eoh =	-16.00 psf	Zone: Goh =	-16.00 psf

Load Case # 2 . . .

Zone: Eoh =	-16.00 psf	Zone: Goh =	-16.00 psf

ASCE 7-16 Section 28.5.4 Minimum Design Wind Loads requires that the load effects of the design wind pressures from Section 28.5.3 shall not be less than a minimum load defined by assuming the pressures, ps, for zones A and C equal to +16 psf, Zones B and D equal to +8 psf, while assuming ps for Zones E, F, G, and H are equal to 0 psf.

DESCRIPTION: MWFRS Envelope and C&C

Component & Cladding Design Wind Press

*Design Wind Pressure = Lambda * Kzt * Ps30 pe*

Roof Pressures	Positive	Negative		Overhang Pressures	Negative	
Zone 1	16.000	-16.000	psf	Zone 1	-24.049	psf
Zone 1'	***	***	psf	Zone 1'	***	psf
Zone 2	***	***	psf	Zone 2	***	psf
Zone 2e	16.000	-16.000	psf	Zone 2e	-28.976	psf
Zone 2n	16.000	-21.127	psf	Zone 2n	-28.976499	psf
Zone 2r	16.000	-16.000	psf	Zone 2r	-24.049	psf
Zone 3	***	***	psf	Zone 3	***	psf
Zone 3e	16.000	-25.152	psf	Zone 3e	-32.795	psf
Zone 3r	16.000	-21.127	psf	Zone 3r	-28.976	psf

Wall Pressures

Wall Zone 4 :	16.000	-16.000	psf
Wall Zone 5 :	16.000	-17.641	psf

'*** : There is no value in Figure 30.4-1 Tabular Values