Agricultural Waste Fiber in "An Economy That is Restorative and Regenerative by Design"

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ABSTRACT: *This project investigates the use of grass fibers and how they can be used in "an economy that is restorative and regenerative by design", this is the definition the Ellen MacArthur foundation uses to define a Circular Economy. From an initial investigation by a graphic designer into the use of grass fibers for paper making a collaborative research initiative was established to analyze the properties of several grasses to better understand their structural strength and hydrophobic characteristics. Working with undergraduate research assistance from material science and fine and applied arts several perennial grasses and agricultural "waste" fibers were systematically studied. Initially meadow grasses were analyzed for their potential as an annual source of fiber for paper production as opposed to the clear-cut felling of trees for pulp. Following a couple of seasons of hands-on experimentation, the research became a more rigorous form of enquiry in which 10 plant types were studied down to the scale of a micron. In the process several preliminary findings related to tensile strength and hydrophobicity were discovered.*

In 2017 another form of inquiry was initiated to see if various grass fibers could be used in three dimensional constructs. This research focused on three grasses for the following reasons: corn stover, due to its ubiquity across the region in which the research was being conducted, miscanthus because it's a high yielding perennial rhizomic plant with a high lignin content, and the hurd from hemp because it has been used in wall construction since antiquity and provides a good base case for comparative analysis. In 2018, with the assistance of an undergraduate student and assistant professor in the department of Material Science and Engineering, the thermal resistance properties of these three different grasses were analyzed using the flat plate method. The results were very similar for the three grasses tested, with both miscanthus and corn stover slightly outperforming hemp with an average conductivity of 0.1 W/mK or an R value of 1.3 per inch.

In the spring of 2019, a three-foot tall mockup wall was constructed in the context of a graduate seminar class. The grass fibers which were milled to a somewhat uniform dimension, were mixed with hydrated and hydraulic lime, and tamped down into wooden formwork. Over time the lime binder hardens preventing the fiber from being affected by mold or insect attack.

In the summer of 2019, a Master of Architecture Research Assistant was appointed to develop construction drawings for permit approval to build two 14 ft. tall experimental walls. Over the following three months, with the help of two more research assistance, the two walls were constructed. Each wall contains three different mixes: hempcrete, a corn stover-lime mix, and a miscanthus-lime mix. The current phase of the research involves the analysis of the walls using thermal humidity sensors and thermal imaging. Research is also underway to replace the lime that is in the mix with a geopolymer material with better thermal and structural properties as well as a lower carbon footprint.

KEYWORDS: Thermal Performance, Miscanthus, Hemp, Circular Economy

INTRODUCTION

This paper presents the findings of an investigation into agricultural "waste" fibers and how they can be used in "an economy that is restorative and regenerative by design", this is the definition the Ellen MacArthur foundation uses to define a Circular Economy.

In 2012, with a desire to investigate if a more interconnected form of food production could be fostered in the industrialized agricultural landscape of America's mid-west, research got underway to see if mono-crop cultivation could be replaced with a fruit bearing perennial woody poly culture, interspersed with grazing crops and harvested meadow grasses. Within this more diverse landscape additional research opportunities opened. The meadow grasses were analyzed for their potential use as an annual source of fiber for paper production in contrast to clear-cut felling of trees for pulp. In the early years of the research several different native and forage grasses were explored to understand their properties and potential for use in paper manufacture. Following a couple of seasons of hands-on experimentation, the research became a more rigorous form of enquiry in which 10 plant types were studied down to the scale of a micron. In the process several preliminary findings related to tensile strength and hydrophobicity were discovered.

In 2017 another form of inquiry was initiated to see if various grass fibers could be used in three dimensional constructs. This research focused on three grasses for the following reasons: corn stover (from *Zea mays*), due to its ubiquity across the Midwest, Giant Miscanthus (*Miscanthus x giganteus*) because it is a high yielding perennial rhizomic plant, and the hurd from industrial hemp (*Cannabis sativa*) because it has been used in wall construction since antiquity and provides a good base case for comparative analysis.

1. METHODS

The research into the use of grass fibers in three dimensional constructs was carried out in an incremental manner. Initially a comparison was made of the plant fibers themselves. This was followed by experiments with the fibers in conjunction with a proprietary lime binder. Once the behavior of the different mixtures was understood the research moved on to determining the thermal conductivity of the different mixes by utilizing a fin equation. Once the conductivity, and subsequent thermal resistance had been determined, a small mockup wall was constructed. Following the construction of the mockup wall two demonstration walls measuring approximately 10ft wide and 14ft tall were constructed. Once the walls were completed thermal imaging was used to determine if actual performance matched with assumptions that could be drawn from the earlier conductivity testing.

1.1 Grass fiber analysis

No specific testing was carried out to determine the essential components of the plant fibers used in the conductivity studies, the mockup wall, or the demonstration walls, however data from peer-reviewed literature points to some general composition traits, with some variation based on where the plants were grown, in which soils, and when they were harvested. All three plant types are composed of cellulose, hemicellulose, woody lignin, extractables and ash. The approximate percentages of cellulose in each plant fiber are as follows: 39% for miscanthus, 41% for corn stover, and 44% for hemp hurds. The percentage of hemicellulose in each plant fiber are as follows: 19% for miscanthus, 31% for corn stover, and 25 to 33% for hemp hurds. The content of woody lignin in the three samples is probably the most varied and could possibly be of greatest concern. For hemp and miscanthus the range is from 19 to 24% while in corn stover it only accounts for approximately 6%. What corn stover lacks in lignin it makes up in extractables that account for 17% as opposed to only 0.3 - 4% for miscanthus and hemp. The final component ash ranges from 1% for Hemp, 3% for miscanthus and 4% for corn stover.

Grass-crete mix analysis
“Ideal fiber mix” as discribed in *Essential Hempcrete Construction*

% Mass fiber mix components, sorted by fiber length and width

	Width 1-5 mm			Width < 1 mm
	Length < 1 mm	Length 1 - 20 mm	Length > 20 mm	Length 1 - 20 mm
Ideal fiber mix	0.5%	75 - 90%	< 10 - 25%	—
Miscanthus*	—	95.8%	3.3%	0.9%
Hemp*	—	92.7%	1.0%	6.3%

*fine-sieved

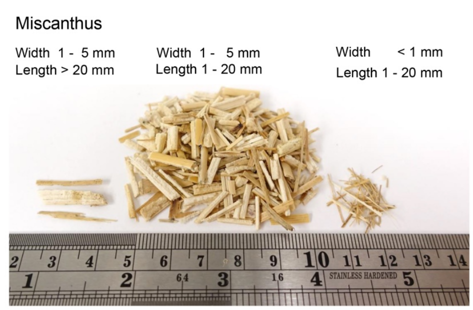

Figure 1: Fiber mix analysis. Source: (Lauren Kovanko 2018)

Although no testing of the essential components of the different plants was carried out, an analysis of the different sizes of material in each mix of chopped fiber was made. (see Fig. 1) This research was started before the 2018 United States Farm Bill removed industrial hemp, with THC content of less than 0.3%, from the list of Schedule 1 controlled substances, thus making it an ordinary agricultural commodity again, as it was in the 1950’s. With the prohibition in place sourcing locally grown hemp was a challenge. Since 2018 more US farmers have experimented with growing hemp but many still face the challenge of decortication and potentially separating 5 different commodities from the plant including seeds, bast fiber and hurds. For this research hemp hurds were imported from Europe where large processing plants have long been established. That said when it came to harvesting corn stover and miscanthus, the two plants we were most interested in researching as alternatives to hemp, machines readily available to any arable farmer could be used. (see Fig. 2). In the case of the corn stover, which is essentially a waste product of corn production, the combined harvester was set to cut higher than usual, leaving stalks of corn sticking approximately 2ft out of the ground. A second pass through the field with a different machine was then required to chop and collect the stover before being stored in super sacks to dry before being run through a hammer mill to provide a material with fibers close to the range described as ideal in the book Essential Hempcrete Construction (Magwood, 2016). The harvesting of the miscanthus was more straight forward, and since miscanthus is a perennial grass, a machine only need pass through the field once a year at harvest time to collect the fiber. The machine and processes are like those shown in figure 2, however miscanthus can be allowed to dry in the field prior to harvest, it can also be chopped finer at harvest time requiring only a small amount of sieving before use.

Therefore, from the perspective of smallest carbon footprint of the three grasses studied miscanthus would be best due to the minimal amount of mechanical power needed to process the material prior to use, and in this case the material traveled less than a mile from where it was harvested to where it eventually became part of the demonstration walls.

Figure 2: Harvesting corn stover. Source: (Author 2019)

1.2 Behavior of material

One of the behavioral nuances of hempcrete is its ability to store a great deal of moisture because of the porous structure in the hurds; "the moisture is adsorbed onto the large internal surface area of the plant fibers and absorbed into the cellular structure. This storage capacity is very helpful in allowing the material to take on moisture when it exists and to release it when conditions allow" (Magwood 2016. p6) Historically these types of materials have been used in what has been described as "breathable construction"; vapor permeable would be a better descriptive term, as when trying to maintain a desirable interior temperature uncontrolled air flow through a wall assembly is never a good thing. That said before these purported vapor permeable traits can be put to the test some familiarity and mastery is required to judge how much moisture in the form of water should be added to the mix of fiber, and lime binder. The recommended mix ratio is 4:1:1. Four parts fiber, one part lime binder and one part water per volume. In practice however, we found that the fiber from each type of grass would absorb water at different rates. Corn stover, probably due to its differences in essential components, would absorb more water than the other two grasses so we had to be careful that we did not add too much water to the mix. The initial samples made for the thermal conductivity tests did not have sufficient water and soon became crumbly during testing. Mixing small quantities is also more difficult to get consistency correct than larger batches. With practice we were able to mix the different types of fiber to similar consistency; something like the consistency of oatmeal. The accepted test for assessing a mix of fiber, lime and water is using gloved hands to form a ball. "If the ball can be squeezed into a coherent shape and maintains its integrity, the water ratio is in the right range" (Magwood 2016. p62) (see Fig. 3)

Fiber-crete mix analysis

% mass fiber mix components, sorted by type

	1	2	3	4
Hemp	6.0%	6.5%	30.2%	57.3%
Corn Coarse	10.2%	4.4%	52.7%	32.7%
Corn Fine	16.3%	2.0%	28.3%	53.4%
Miscanthus Coarse	3.9%	54.8%	41.3%	-
Miscanthus Fine	2.8%	45.2%	52.0%	-

Figure 3: Fiber composition and behavior. Source: (Lauren Kovanko 2018)

1.3 Thermal conductivity/resistance

A guarded hot plate (GHP) apparatus was designed to measure the effective thermal conductivity of cast "grasscrete" samples. The primary thermophysical principle that this apparatus exploits is Fourier's law, which shows that heat flux (heat transfer rate per unit area perpendicular in units of W/m^2) is proportional to the spatial gradient of temperature (in units of °C/m) with the proportionality constant being thermal conductivity k. The GHP directs heat unidirectionally by contacting a patch heater to one side of a given sample while contacting its other side with an ice bath. All other surfaces were insulated from the surrounding environment. Provided that heat loss through the surrounding insulation is insignificant, the one-dimensional form of Fourier's law can be used to determine thermal conductivity. This law can be expressed by the following equation: $q''_x = -k_{xx}\partial T/\partial x$, in which q''_x is the component of heat flux perpendicular to the heater, k_{xx} is the sample's thermal conductivity in the direction perpendicular to the heater's plane, T is temperature, and x is position.

$$k = \frac{P_e \cdot L}{A_c(T_H - T_C)} \qquad \text{(Eq. 1)}$$

Equation 1 is another way of expressing Fourier's law in which T_H is the temperature of the heater, T_C is the temperature of the ice bath, P_e is the known electrical power applied to the heater, A_c is the cross-sectional area of the sample, and L is the thickness of the sample. In our experiments the six samples tested each had A_c=11.8 inches (300mm) x 11.8 inches (300mm) and L=1.57 inches (40mm). These sample dimensions, along with the dimensions of the GHP and the type/size of insulation, were chosen to minimize heat loss from the apparatus.

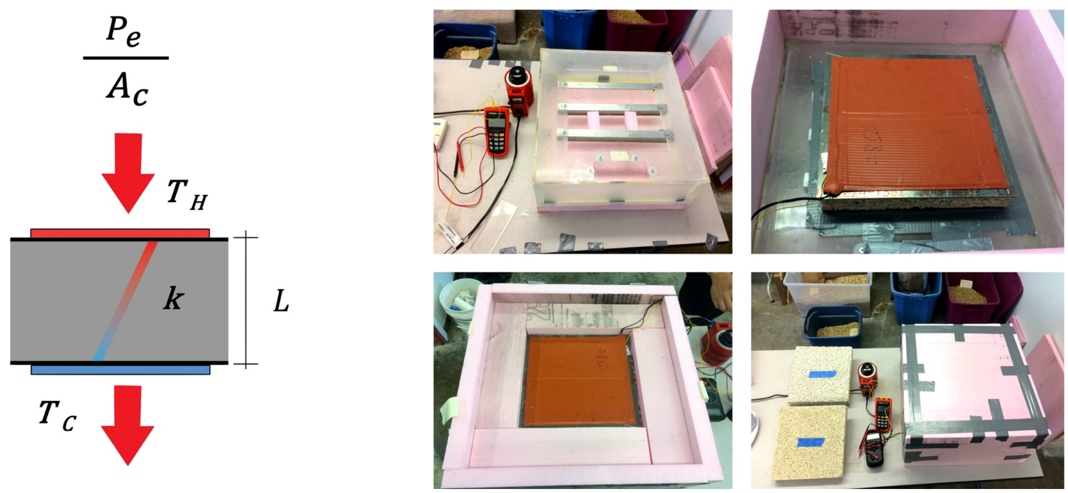

Figure 4: Thermal Resistance Testing Set-up. Source: (Kyle Smith and Author 2018)

To assure the validity of Equation 1 a quasi-one-dimensional model, a 'fin equation' (Bergman, Lavine, Incropera, and Dewitt, 2018), was used to account for potential heat loss from the sides of the sample. Using this approach, the following expression for the fraction of lost power was obtained as δ:

$$\delta \equiv \frac{P_{e,actual} - P_{e,ideal}}{P_{e,ideal}} = \left[m^* \frac{\left(\cosh(m^*) - \frac{T_C - T_\infty}{T_H - T_\infty}\right)}{\sinh(m^*)\left(1 - \frac{T_C - T_\infty}{T_H - T_\infty}\right)} - 1 \right] \times 100\% \qquad \text{(Eq. 2)}$$

Here, T_∞ is the temperature of the surroundings to which heat loss occurs and $m^* = \sqrt{4GsL^2/kA_c}$ is a non-dimensional parameter that depends on side length of the sample s 11.8 inches (300mm) and the net thermal conductance G (in units of W/m^2-K) through peripheral insulation and air beside the sample. For T_C=0°C, T_H=167°F (75°C), and T_∞=68°F (20°C), m^* must be less than 0.224 for the fraction of lost power to be less than 1%. Consequently, for a given conductance, thermal conductivity, sample cross-section, and sample side length, sample thickness must exceed a threshold value to assure heat loss of less than 1%: $L < 0.1\sqrt{kA_c/Gs}$.

Each sample was a mix of one of the three grasses being studied plus a lime binder. Small batches were mixed by hand with the addition of water and set in molds to dry for approximately two weeks before testing began. Six samples were created to see if particle size had an impact on thermal performance. Number 2 and 4 meshes were used to create a fine and a course mix sample for each of the three grasses being studied. Temperature was measured by securing thermocouple wires to steel plates on either side of the sample and connecting them to a thermoelectrical thermometer to record the temperatures on either side of the sample in °C. Each sample was tested three times with a gap of approximately 4 days before a test was repeated with the same sample. Each test took approximately twelve hours to approach steady state. The final heater temperature applied to each sample was typically 158-176°F (70-80 °C) as shown in Fig. 5.

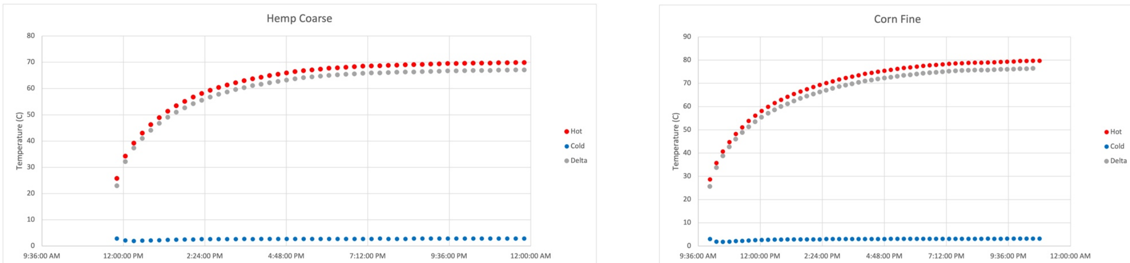

Figure 5: Temperature plots of hemp and corn samples. Source: (Cheng-Shen Shiang 2018)

Once three tests had been carried out on each sample the average thermal conductivity of each sample was calculated, this value was then converted into a unit more commonly used in construction: an R value. The outcome of the tests will be elaborated on in the results section of this paper, however, in brief no significant difference was detected between fine or course samples. Each of the three grasses performed very similarly with both miscanthus and corn stover slightly outperforming hemp with an average conductivity of 0.1 W/mK or an R value of 1.3 per inch.

1.4 Mockup and demonstration wall

Following the completion of the thermal analysis work began on a mockup wall. The wall was constructed in a seminar class to help understand what details would be needed when building larger demonstration walls. The mockup wall also provided an opportunity to mix larger volumes of material and gain experience in getting the mix consistency correct and develop the skills of tamping the material in movable formwork. It was envisioned that the first demonstration walls would be part of a retrofit of a small shed that needed repair on campus. With this in mind the mockup wall was built to reflect the construction of that building; 2x4 inch studs at 2ft on center sheathed with 0.75 inch boards. Inside of that envelope a 0.5 inch air cavity was created to allow the “grasscrete” materials to “breathe”. The corner section of the mockup was filled with hempcrete, in the middle section a corn stover-lime binder mix was used, miscanthus and lime binder was used in the final section. A 0.5 inch plaster coating was applied to the inside surface. The most significant lesson leant from building the wall was that working with “grasscrete” is labor intensive and time consuming. It was initially thought that the mockup wall would have only taken three or four seminar sessions to complete. As things turned out it took most of the semester to complete, soon after that campus authorities decided the small, shed structure should not be saved but demolished instead.

Figure 6: Mockup wall construction. Source: (Author 2019)

Although the opportunity to renovate a dilapidated shed did not come to fruition, towards the end of 2019 a more attractive prospect was presented to our research team. The farm manager, at a research facility focused on the use of miscanthus as a biofuel, approached us with the proposition that plans be developed to enclose one bay of an existing pole barn structure measuring 60ft by 40ft. Each demonstration wall would be approximately 10ft wide and 14ft tall. As this would essentially be new construction, we had the opportunity to develop our construction details further. The only given constraint was the outside of the wall had to match with the existing metal panels that clad the rest of the pole barn. The site was not particularly well drained, so a generous concrete upstand was installed to ensure the bottom of the walls never got damp. Between the structural poles 2x4 inch horizontal girts were installed for the vertical metal panels to be attached to, on the outside of the girts a moisture barrier, house wrap, was installed, typical agricultural building construction. Inward of the girts 0.5 inch Blue Ridge Premium Insulating Sheathing was installed, manufactured from recovered and recycled wood fibers this breathable sheathing was selected because of its vapor permeable characteristics which would allow any moisture in the wall to be able to migrate to the exterior of the assembly by passing through this sheathing to the air cavity created by the girts and the corrugation in the metal panels. Inward of the fiberboard 2x6 studs were set out on 2ft centers to provide something for the movable formwork to be screwed to. An improvement, that was not done in the mockup wall, was to cover the studs with a layer of “grasscrete” helping prevent thermal bridging through the assembly but also providing a more cohesive surface to plaster once the walls had been cast in place. A 30-gallon cement mortar pan mixer was purchased to allow for large batches of grass fiber, lime binder and water to be mixed. In a typical work session of approximately 3 hours the wall, which was 9 inches thick would grow by approximately 16 inches in height. The slow progress was in due in part to the team getting familiar with the process, and having to mix three different types of mixes in each wall: Hempcrete, “corncrete” and “miscanthuscrete”. Each wall took approximately twenty-five hours to cast including the time it took to raise the formwork between sessions, most of the time two people were working on the casting, one mixing the other on scaffolding tamping the material into the formwork. The team learnt to plaster for the first time and managed to apply a 0.75 inch plaster finish to both walls in three long days (approx. 30 hrs total).

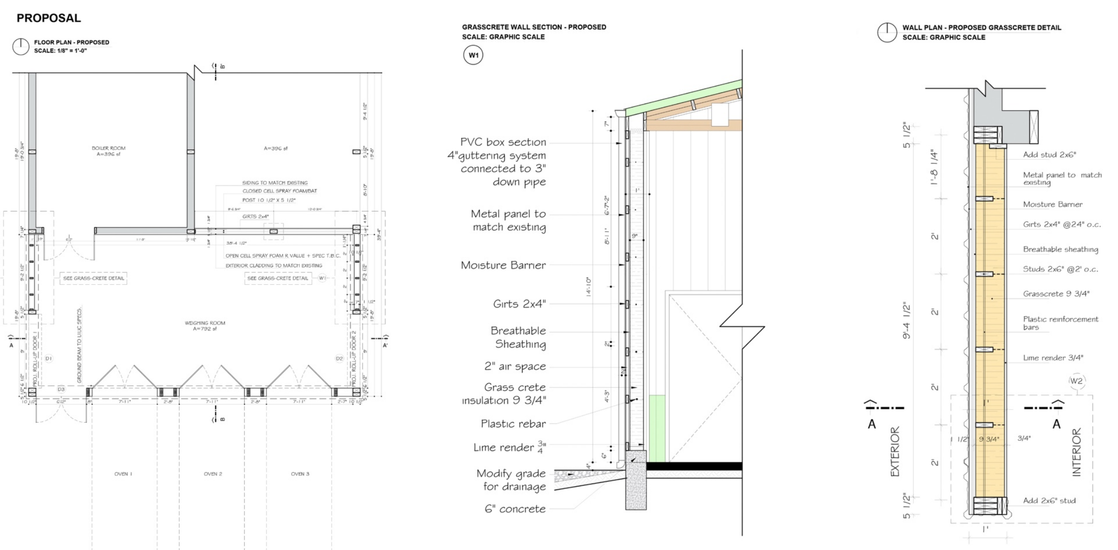

Figure 7: Mockup wall construction. Source: (Luis Felipe Flores Garzon and Author 2019)

2. RESULTS

The results from the investigation are as follows: As previously stated the thermal resistance testing provided very similar results for the three grass mixes that were studied. Figure 8 shows the results of the tests carried out on the course mix samples, as this was the type of mix which was eventually used in the demonstration walls. Thermal imaging of the demonstration walls was carried out once the walls were complete, plastered and allowed to dry. Thermal imaging photographs were taken on January 24th 2022 when outside temperatures were 28°F (-2.2 °C). The spot reading on the inside of the demonstration wall, which did not show much variation across its surface, read 55.6°F (13.1°C) see Fig 9. On January 31st 2023. six temperature and relative humidity sensors were set into the wall, two in each mix. Sensors were set in two locations, one near the back of the wall, 8 inch (203mm) in from the surface, the other set of sensors were positioned toward the middle of the wall, 4 inches in from the surface, inside and outside temperature and relative humidity data was also collected. Preliminary data was collected 1st February 2023 at 9.45am when the outside temperature was 18°F (-7.7 °C) and the interior temperature was 60°F (15.5°C). Although not conclusive, preliminary results clearly show the demonstration wall working as an insulator to the outside climate (see Fig 10)

Material	Test #	Conductivity K (W/mK)	Avg K	RSI per meter (mk/W)	Avg Rsi	R per inch (ft^2*f*h/BTU*in)	Avg R
Hemp Coarse	9	0.1290	0.1214	7.7518	8.2575	1.1215	1.1946
	15	0.1206		8.2932		1.1998	
	21	0.1146		8.7273		1.2626	
Corn Coarse	4	0.1110	0.1089	9.0069	9.1874	1.3030	1.3291
	10	0.1095		9.1299		1.3208	
	16	0.1061		9.4252		1.3635	
Miscanthus Coarse	5	0.1101	0.1108	9.0807	9.0397	1.3137	1.3078
	11	0.1164		8.5885		1.2425	
	17	0.1058		9.4499		1.3671	

Figure 8: Thermal resistance testing results. Source: (Cheng-Shen Shiang and Author 2018)

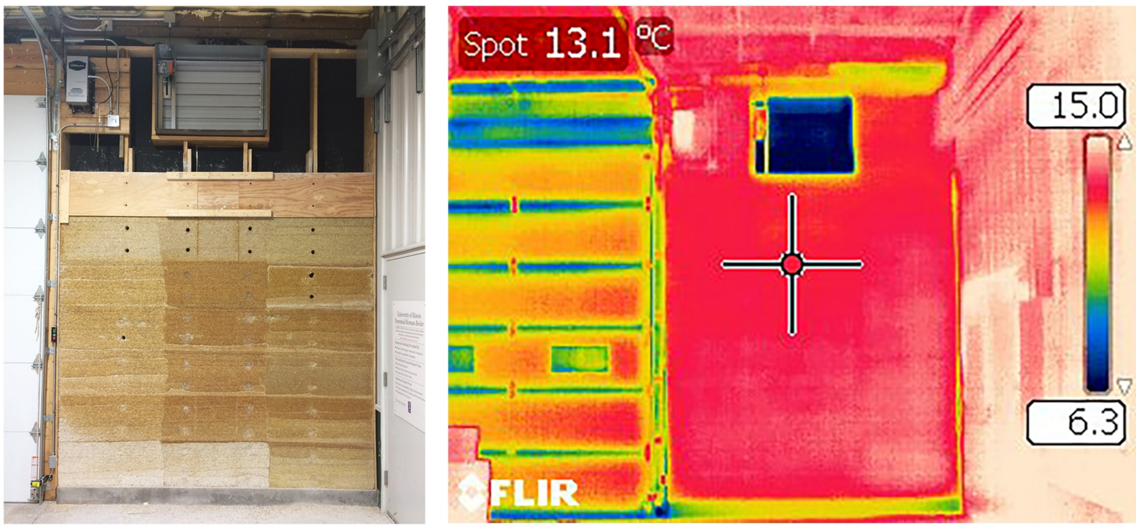

Figure 9: Demonstration wall near completion and thermal image after completion. Source: (Author and Yun Kyu Yi 2020)

2/1/2023 9.45am	Hemp	Miscanthus	Corn Stover
Outside	18.1°F (-7.7°C)	18.1°F (-7.7°C)	18.1°F (-7.7°C)
Back of Wall	34.5°F (1.4°C)	33.3°F (0.7°C)	31.9°F (-0.08°C)
Middle of Wall	43.5°F (6.4°C)	-	-
Interior	60°F (15.5°C)	60°F (15.5°C)	60°F (15.5°C)

2/2/2023 3.45pm	Hemp	Miscanthus	Corn Stover
Outside	43°F (6.1°C)	43°F (6.1°C)	43°F (6.1°C)
Back of Wall	41.0°F (5°C)	40.2°F (4.6°C)	40.5°F (4.7°C)
Middle of Wall	47.3°F (8.5°C)	-	-
Interior	60°F (15.5°C)	60°F (15.5°C)	60°F (15.5°C)

Figure 10: Preliminary in-wall sensor data. Source: (Author 2023)

CONCLUSION

The research to see if grasses, other than hemp, can be used as insulation materials in a wall assembly has been proven viable. In this study Giant Miscanthus (*Miscanthus x giganteus*), because of its essential components being very similar to hemp hurd, proved to be the most promising grass as an alternative to hemp. Giant Miscanthus also has the added advantages of being a perennial rhizomic plant that can dry in the field and requires only one mechanical process at harvest time to render the fiber ready for use as an insulation material in a wall assembly.

Corn stover also has it’s potential and further investigation may be needed. The material used in the demonstration wall may have been ground too fine in the hammer mill, or its essential components are not suitable for the application that was being tested. It was observed that the material would take on more water than the other two grasses, and when tamped into place it would compress more than the “hempcrete” and “miscanthuscrete”. It was also observed that as the material dried out horizontal cracks would form, cracks that had to be dug out and filled before the plaster finish was applied. It was initially intended that both the east and west demonstration walls would have the same samples in each, however, following the completion of the east wall it was decided not to use corn stover on its own in the second wall. Instead, the mixes that were used (right to left, see Fig 10) were hempcrete, “miscanthuscrete” and an even mix of corn stover and miscanthus with the addition of lime binder and water. It was noted that this mix with the combination of two grasses was easy to work and did not crack while drying out.

The preliminary data collected from sensors in one of the demonstration walls prove the “grasscrete” mixes are acting as insulators to the exterior climate. Further refinement of this instrumentation is required before the data can be used to build a WUFI (heat and moisture transiency) simulation of the demonstration wall assembly. However, by looking at the data collected at 3.45pm on 2/2/2023 there appears to be a time lag or thermal flywheel affect taking place, something that has been observed in similar constructions of this nature (Evrard, A., and De Herde, A 2005). If this is the case it will be very interesting to “move” the WUFI model to different climate zones to see where an assembly like this would perform best, locations with a significant diurnal swing would be likely candidates for further investigation. A further line of enquiry that is also in its early stage is the replacement of the lime binder with a binder with a lower carbon footprint and higher structural performance. The material under investigation is a geopolymer binder; a ceramic that sets at room temperature. From initial studies this material is promising and could lead to other, more time efficient methods of construction, and thus address the labor-intensive challenges of this form of construction.

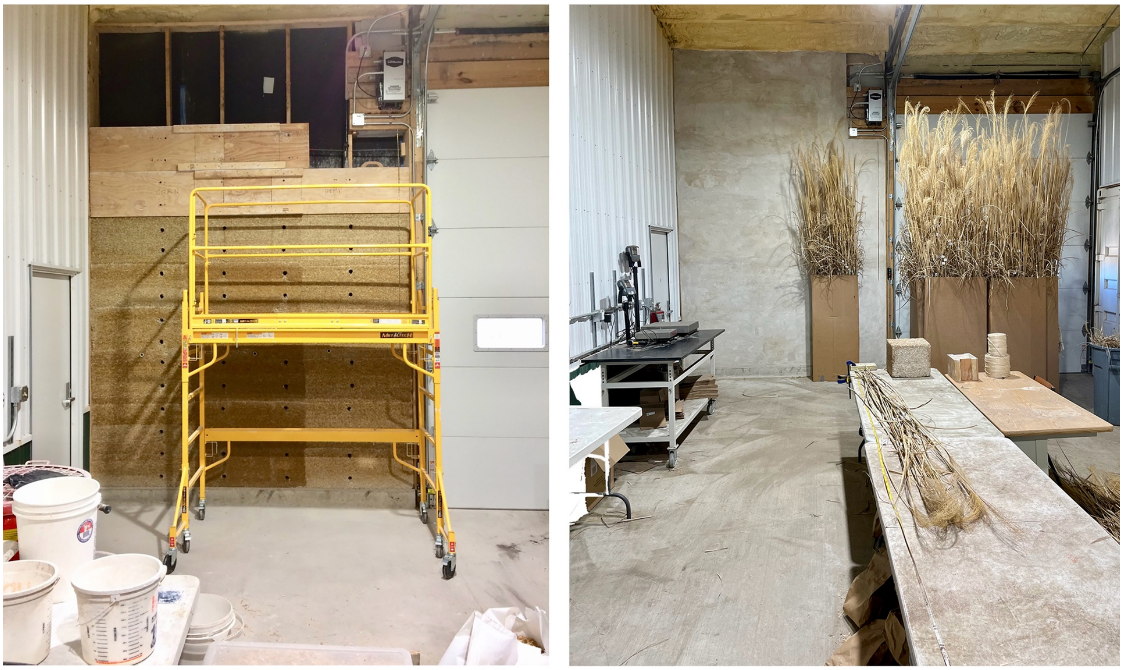

Figure 11: East demonstration wall under construction and complete. Source: (Author 2023)

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