BREE 495 - Engineering Design 3 - Dr. Chandra A. Madramootoo

Light Transmitting Aircrete (LTA): A Composite Approach

Authors: Intisar Syed Mahmood [redacted] Bao Chau Bui [redacted]

Bioresource Engineering Department, McGill University,

Ste-Anne-de-Bellevue, QC, H9X 3V9, Canada.

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Abstract

This project conceptualizes a concrete wall with concrete blocks that are as heat resistive as foam insulation, light transmissive enough to read a book, and has the strength to become structural walls of a medium sized household. Precedence has been set by the creation of concretes such as LiTraCon which uses optic fibers in order to create a light transmitting, structural concrete, bringing in sunlight as an ambient light source. The flaw in this technology is the necessity in precasting, not to mention that LiTraCon is not an insulating concrete. We propose Light Transmitting Aircrete (LTA) blocks which are as versatile as standard concrete masonry unit. Light transmission through multiple LTA blocks are achieved by using clear plastic embedded epoxy resin mortar. With an optic fiber area density of 9%, an LTA block alone has the capacity to achieve around 640 lux illumination from the wall on a sunny day. 640 lux represents an appropriate amount of light for reading purposes. However, stacked in double, the light transmittance percentage is squared reduced to tenths of a percent. The compressive strength of LTA is around 3 MPa after 8 days, but the projected 28 day cure strength is 4.56 MPa, while minimum necessary compressive strength of Aircrete to build a 2.7m wall is 2.9 MPa. With a thermal conductivity of 0.36, a 4” thick LTA has an R value of 1.64 while a foam board insulation is rated at R5. The conductivity can be reduced further by adjusting the Aircrete mixture ratio. The high cost of optic fibers puts the small-scale production of LTA at 51.76 CAD per block, but a high-volume production reduces it closer 19.91 CAD. Though expensive, we hope to prove the viability of Aircrete in real world application, such that upon any future cost improvements, the design will be considered a norm in concrete construction.

Table of Contents

1. Introduction

1.1. Background

Concrete is synonymous with modern infrastructure and architecture. With its high durability and versality, it is an integral part of construction projects worldwide. According to the International Energy Agency (IEA), buildings are the largest energy consuming sector globally and account for over 30% of final energy consumption (IEA, 2017). As a result, energy saving building materials are paramount in promoting sustainable development. It becomes an imperative to reimagine the world's most ubiquitous building material, concrete, and innovate on its composition and manufacturing to reduce energy consumption and ensure sustainability.

1.2. Problem Definition

Currently, there is a demand for energy savings in the form of increased natural light such that electrical power usage is lowered. In new and retrofitted buildings, there is an increasing trend towards a greater window to wall ratio (Cao et al., 2016). Although glazing is quintessential in a building's reception of sunlight, industry buildings codes in the US such as *ASHRAE* 189.1-2014 and *ASHRAE* 90.1-2016 recommend less window glazing due to structural safety compromise and lowered insulation values. Alternative ways to capture, transport and deliver natural lighting into buildings are necessary, and this is where light transmitting concrete (LTC) technology is proposed. LTC such as fiber optic embedded LiTraCon are costly, and production is tedious and time consuming compared to regular concrete. In addition, LTC blocks (LTCB) are not sold as standardized blocks, but is precast. A more versatile design and production system is needed.

1.3. Vision Statement

Our vision statement is:

"We strive to use rigorous scientific tests and techniques, and combine it with artistic design, to offer structural light transmitting concrete wall that is as pleasing to look at as it is practical"

Our client is the Biomass Production Laboratory in Macdonald campus under the supervision of Dr. Mark Lefsrud, as well as Cemex S.A.B de C.V. and Innotech in association. We are mentored by Dr. Mark Lefsrud and his M.Sc student, Sam Bilodeau.

1.4. Goal

As such, we propose a novel light transmitting concrete wall composition with insulative and strength properties. Embedding light transmitting properties into concrete will also promote its usage in decorative aesthetic applications. Furthermore, to assure lateral stackability and reduce costs, we propose the production of standardized blocks and accessible means of light transmissivity.

1.5. Limitations

Due to its primarily aesthetic nature and unproven properties, we will not be evaluating the energy savings generated from light transmitting concrete composite wall. However, previous studies on light transmitting concrete embedded with optic fibers have quantified the lighting energy savings being between 25-50%

(Ahuja and Mosalam, 2017; Al-Kurdi et al., 2014). Instead, we will be focused on the optimizing the relevant material properties and manufacturing process, and the economy of small-scale production of the light concrete blocks. In addition, using resin as mortar is an uncommon practice, and its structural implications will only be evaluated through experiment.

1.6. Applications

Previous iterations of light transmitting concrete focusing on optimizing the light transmission and decorative aspects have been constructed primarily in European infrastructure. For example, in a public square in Stockholm, Sweden, the square's sidewalk is coated in light transmitting concrete made by LiTraCon (Gahrana et al., 2018). During the day, it looks like a regular concrete sidewalk, but there are lights embedded under the sidewalk which light up at night time. This is possible due to the utilization of light transmitting concrete with an additional artificial light source. Additionally, in eastern Europe, a renovated Bank of Georgia headquarters buildings was made using light transmitting concrete combined with light emitting diode (LED) wall panels to give additional lighting elements and create a more aesthetic architectural style (Gaurao and Swapnal, 2015). This light transmitting concrete was manufactured by a company under the name LUCEM. In general, light transmitting concrete is designed for use on exterior and interior walls to capture, transport and emit natural or artificial lighting. Specifically, its usage in fine architecture is encouraged due to the aesthetic look of this variant of concrete (Bajpai, 2014). Its utility rests upon its ability to bring in additional natural or artificial light to its surroundings whether in an office setting to increase human comfort, in exterior applications to increase nature lighting in a tunnel designed for cars or even in contemporary artistic displays requiring lighting and symbolic shadow aspects. Furthermore, it can be used as a façade material or for cladding of walls including partition walls, stairs or decorative tiles.

Subsequently, as previously briefly outlined, in the context of the design project, there are three main material properties to be optimized, compressive strength, thermal insulation and light transmission. Depending on the results of these properties, there will be a wider range of possible applications for the designed product. Previous iterations of light transmitting concrete will be studied to propose further refinement in its structural and insulative potential which is usually not a focus of these designed products.

2. Literature Review

2.1. Existing Products

2.1.1. LiTraCon

Light transmitting concrete was first postulated in 2001 by Hungarian architect, Aron Losoncz, and successfully manufactured as LiTraCon in 2003 using optic fibers oriented parallel to light incident. Total internal reflection occurs within the fiber, allowing light information to travel long distance without loss despite changes in direction (Zielinska and Ciesielski, 2017). Light transmitting concrete made with optic fiber achieves light transmittance without compromising on compressive strength due to optic fibers acting as added reinforcement. Using optic fibers of 1.5 mm diameter, spacing of 10 mm, parallel orientation and 1.43% optic fibers, the compressive strength of light transmitting concrete was found to be 34.16 N/mm^2 compared to 26.52 N/mm^2 for *standard concrete (Altlomate et al., 2016). In the same conditions, the maximum light passing through the cubes was 75.53 lux after 28 days of curing (Altlomate et al., 2016). In another experimental study, light transmitting concrete was produced using optic fiber percentages between 0% to 8% and replacing fine aggregates with glass crystals (Git and Kewate, 2017). Compressive and flexural strength was found to be increasing with higher percentage of optic fiber (Git and Kewate, 2017). Another study found that compressive strength of light transmitting concrete peaked at 4% optic fiber with reflection of 250 lux (Sawant et al., 2014). Accordingly, the trademarked light transmitting concrete produced by LiTraCon also uses 4% optic fiber. The properties for a block size of 600 mm by 300 mm with a varying thickness 25-500 mm include: density 2100-2400 kg/m^2, compressive strength of 50 N/mm^2 and tensile strength of 7 N/mm^2.

2.1.2. Polymeric Cement

Polymer concrete is prepared by mixing polymer resin as a binder such as polyester or epoxy with aggregate mixture. Some of its advantageous properties include high compressive strength, chemical resistance, corrosion resistance and rapid curing (Bedi et al., 2014). For example, it has been shown replacing sand with fly ash by 15% can improve compressive strength by 30% in polyester polymer concrete (Rebeiz, 2004). In addition, polymer concrete has also been considered as a replacement for conventional concrete structures undergoing repair. Having high acid, salt and freeze-thaw resistance leads to increased service life for polymer concrete (Allahvirdizadeh, 2011). Similarly, polymer concrete can also be reinforced with glass or steel fibers. Addition of glass fibers 0-4% by weight increases the strength and toughness of polymer concrete (Bedi et al., 2014). Therefore, polymer-based concretes are compatible with glass and plastic fiber optics and may yield light transmitting properties. Although the concept hasn’t been explored in depth, it may be possible to embed light transmission in polymer concrete. An alternative way of viewing light transmitting polymer concrete is the idea of introducing a translucent polymer-based resin admixture. One experimental study examined the idea of using crushed fine aggregates, silica fumes and polycarboxylate superplasticizers. However, light transmission was minimal and blocked by the mixing of the layers creating opacity (Pilipenko et al., 2018).

2.1.3. Aircrete

Aircrete and Autoclaved Aerated Concrete (AAC) is a type of lightweight aerated concrete. Aircrete, also known as aerated concrete, is produced by combining foam to a cement slurry while AAC involves further admixtures and is autoclaved to create a lower density concrete significantly lower than Aircrete

(H+H UK, 2018). Due their light weight workability, construction productivity is increased. Aircrete and AAC are highly effective insulator due to their porosity with thermal conductivities of 0.15-0.17 W/mK corresponding to blocks of density 620 kg/m3 (Ahmed et al., 2004). Unfortunately, increased insulation is correlated to decreased compressive strength. For the same block, the compressive strength is 4.0-4.5 N/mm2 (Ahmed et al., 2004). With density of 400 kg/m3, the thermal conductivity is 0.10 WmK and compressive strength 0.5-1.0 N/mm2 (Hamad, 2014). Furthermore, Aircrete is non-combustible and limits flame propagation thus providing excellent fire protection (Limbachiya and Kew, 2011). Aircrete and AAC offers good resistance to penetration of moisture and is resistant to freezing and freeze-thaw damage due to the isolated structure of its spherical pores (Limbachiya and Kew, 2011). Due to its lowered compressive strength, Aircrete is regulated to be used in only low-rise buildings (Hamad, 2014). There is minimal literature involving fiber reinforced Aircrete, one study proposed the use of natural fibers through a section within Aircrete. Due to the aeration of Aircrete, natural fiber did not significantly increase the compressive strength (Garbis, 2013). Adding fibers within Aircrete may modify its porous structure and advantageous properties. Due to a lack of experimental results, it is unclear how embedding optic fibers to achieve light transmitting properties within Aircrete may change the material.

2.1.4. Porous Concrete

Porous concrete mixtures do not vary from standard concrete except for varying proportions of admixture. Fine aggregate content is significantly reduced, and coarse aggregates content is increased to achieve open interconnected pores in the resulting concrete. In porous concrete, higher cement content tends to result in better strength properties and lowered porosity and permeability (Mahalingam, 2016; Kia et al., 2016). The study's experimental results indicate an optimal aggregate to cement ratio of 4:1 for two types of aggregates. Aggregates exhibited a porosity of 22-23%, compressive strength of 10-12 N/mm and permeability of 12-16 mm/s (Mahalingam, 2016). Trademarked light weight aggregates such as Poraver, a recycled expanded glass, have been used in porous concrete mixed at the Biomasss Production Lab. Poraver acts as a thermal and sound insulator and is available in sizes varying between 0.04 mm and 4 mm (Stanton, 2016). Another study showed the compressive strength of porous concrete can be increased with adding 30% fly ash yielding in 4.14 MPa (Sun et al., 2017). In same study, porous concrete with 150 mm thickness and a density of 600 kg/m3 was able to achieve a heat conductivity coefficient of 0.116 W/mK, 12% water absorption and maximal compressive strength of 4.37 MPa (Sun et al., 2017). In fact, light weight concrete such as porous concrete is a good way to reduce the amount of heat transfer due to lower reported thermal conductivity k-values (Asadi et al., 2018). As for embedding porous concrete with reinforced fiber, one experimental study found that the addition of cured carbon fiber composite yielded in improved mechanical properties, workability and infiltration rates (Rangelov et al., 2016). Though the use of optic fibers for light transmittance in concrete is recommended for fine aggregates, it may be possible to incorporate in porous concrete as well.

2.2. Patents

LTC has two major categories; embedded optic fiber concrete and concrete which substitutes limestone-based cement with polymers such as plant-based resin. The patents found in junction to light transmitting concrete primarily consists of methods to mold the initial mix, rather than the content of the admixture. This is to say that predominantly, the mold construction and structure are subjected to patents.

For instance, Patent No. CN105818252 shown in Appendix 4, is a mold construction which offers strategically placed holes to weave optical fibers through and fasten them together (Guohui et al., 2016). Similarly, as shown in Appendix 2, patent No. CN101234510 shows a set up involving versatile positioning of trays to constitute a mold which offers an adjustable grouting groove position (Yangliang, 2008). In addition to mold structure, patent No. CN207044385 demonstrates a robotic arm and rail apparatus which threads optic fibers through two lateral plates, as seen in Appendix 1 (Jun et al., 2018). Even among the 20 or so patents detailing fiber arrangement methods found in WIPO, patent No. CN102758496 is particularly unique (Appendix 3). This patent uses an optic fiber bundle and applies static electricity to spread the ends of the bundle, which are then attached to quick drying cement plates. The plates constitute two opposing ends of a concrete mold (Wen et al., 2012). The creativity of this design is in the application of electricity to spread the fibers throughout one side of the mold, because it replaces tedious manual work. The design also bundles up the fibers and wraps them in an anti-corrosive coating, making this design one of a kind accounting for optic fiber damage from the alkalinity of concrete.

The patents overall demonstrate the importance of orienting optic fibers within concrete. Furthermore, the patents themselves state their inventions to be a way to expedite light transmitting concrete production process, which is indicative of the fact that fiber orientation process is the most problematic step.

2.3. Standards

In addition to referring to internationally recognized standards and specifications on concrete formulations and building codes for material properties, it is important to consider scientifically validated testing standards championed by organizations such as the American Society for Testing and Materials International (ASTM). Concerning light transmission testing, it was based on ASTM D1494-12 Standard Test Method for Diffuse Light Transmission Factor of Reinforced Plastics Panels. ASTM D1494-12 details the recommended apparatus, a transmissometer, and testing procedures used in light testing methods. Specifically, a transmissometer is made of three primary components including a light source, a photometer consisting of a photocell and galvanometer and a testing cabinet (ASTM, 2012). It is important to use the correct testing specimen dimensions and consider appropriate distances between the light source and light measuring component known as a photometer. Additionally, these components must be isolated from the surrounding environment to prevent ambient light interference that would falsify the results. The results obtained from the experiment must also be repeatable and reproductible to prevent reliability issues. Finally, the test specimen thickness must be significant enough to be representative of life scale models. Using these principles, a transmissometer was specifically designed in the context of the design project for light transmitting testing purposes. For scientific validity and project feasibility, it was important to use the principles of the standard while adapting to the specific purpose of analyzing samples representative of an alternative concrete product.

Many standards and research professionals were consulted regarding the thermal insulation test which proved to be the most challenging. The considerations and recommendations of the following standards were examined: ASTM C1363-11 Standard Test Method for Thermal Performance of Building Materials and Envelope Assemblies by Means of a Hot Box Apparatus, ASTM C177-19 Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus, and ASTM C1044-16 Standard Practice for Using a Guarded-Hot-Plate Apparatus or Thin-Heater Apparatus in the Single-Sided Mode. In ASTM C1363-11, the notion of using hot boxes to measure thermal resistance of specimens is outlined with the two main modes of heat flow including convective heat transfer and radiation heat transfer defined over a set period for the experiment. Relevant parameters to consider over a timeframe include the heating and cooling capacity of the apparatus, the air circulation patterns and velocity, internal heat storage capacity of the test chamber equipment, the thermal diffusivity and resistance of materials in the chamber construction, the testing specimen geometry, thermal diffusivity and resistance and finally, its heat storage capacity (ASTM, 2011). Most importantly, the uncertainty of results is noted due to transient effects due to residual moisture change, latent heat effects and the onset of convection within specimen which will increase the time required for the stability stage of the experiment. Furthermore, ASTM C177-19 details the design of a guarded hot plate apparatus which comprises of a cold plate, testing specimen, guarded hot plate with auxiliary insulation and additional cold plate (ASTM, 2019). Concerning the hot plate and cold plate specifications, they are defined by a temperature differential meaning one plate is at a higher or lower temperature than the other. To properly insulate the experiment, the interspaces between the hot and cold surface assemblies should be insulated meticulously. Due to the discontinuous surfaces area shapes that may be present, it may be more appropriate to use powder or fibrous insulation material such as vermiculite for example. Precautions should also be taken to minimize erratic voltages variation in the thermocouples to prevent temperature gradient increase due to inhomogeneous wiring. Unfortunately, there are limitations present in this testing method due to the presence of contact resistances, vacuum conditions uncertainties and the amount of rigor needed in selecting appropriate sample thickness as the heat transfer process is dependent on specimen thickness. Finally, ASTM C1044-16 is a companion to ASTM C177-19 in some respects such as the use of a guarded hot plate apparatus in single sided mode (ASTM, 2016). However, ASTM C1044-16 is more general, encompassing and recommending alternative apparatuses with similar working principles such as a thin-heater. Again, the importance of the potential error due to the heat flow gap inherent to the testing design is emphasized. This gap causes differences in temperature profiles that may not be due to the materials properties, but due to the experimental set up. Thermal transmission equations and calculations are outlined which take into consideration variables such as surface area of the hot plate, heat flow, thermal conductance, resistance, conductivity of the specimen, thickness of the specimen and surface temperatures of the hot and cold plates. In accordance with ASTM C177-19, caution must be exerted when selecting a testing specimen thickness.

Moreover, as an aside, structural materials testing was based on previous experience obtained within the learning curriculum of the Department of Bioresource Engineering at McGill University. Small cylindrical samples are recommended for testing purposes to minimize stress accumulation on the edges of the sample and not being as representative. Small sample sizes are required to fit into the testing cabinets of the machines available on campus. In the context of analyzing materials properties, the Instron from the Engineering Materials Laboratory and Universal Testing Machine from the Machine Shop was utilized under the guidance and supervision of relevant machinery and equipment technicians. These tests were based on past iterations investigating compressive strength and related properties such as load capacity on other materials such as steel or biomass.

2.4. Comparison with Other Products

2.4.1. Glass

Glass is known as an excellent medium for light transmission with minimal to adequate structural and insulative properties depending on the mounting structures present. For example, windows are commonly made from glass and the use of proper sealant to prevent air leakage. In fact, glazing typically refers to the addition of glass panels and windows. Glass is generally shaped into thin panels and the use of double layer panels with an air vacuum is found in residential or commercial building to increase insulation properties. Though load bearing capacities and structural integrity of the glass panels can be increased with the use of steel mounting, frames and fixtures, it is generally not considered high strength material and is susceptible to cracks. Light transmission through glass is practically transparent and even in color tinted decorative glass types, light transmission is usually 60% to 90% (Pilkington Glass Handbook, 2010). Since light transmission depends on the uniformity and continuity of the surface area of glass and the presence of specialty coating, there does exist glass types with only 10% light transmittance. Overall, light transmission in glass is characterized by the amount of incident light, wavelengths transmission, coating types, orientation of the parallel planes and the thickness of the glass (Guardian Glass, 2019). Surface treatments or bulk properties present on glass types such as stained glass, frosted glass, glossy or matt surfaces can decrease light transmission ratio by scattering or absorbing incident light. Concerning the light transmission mechanisms, there is a Fresnel reflection off each glass surface, an amount of light absorbed, and light scattered from surface roughness. Light transmission measurement accounts for the Fresnel reflection and absorption though may not necessarily consider light scattering effects. Light transmission also depends on maintenance as glass products are prone to dust particulate and condensation accumulation when air is stagnant and leaks frequently. Regular maintenance of glass surfaces is recommended for optimal light transmission and long-term operation and allow for inspection of potential cracks and scratches. Specialty glass types are varied and include annealed glass, heat strengthened glass, tempered glass, laminated glass, insulating glass, patterned glass, tinted glass including some glass application configured for high strength utilization for safety purposes such as hurricane glass or security glass (Pilkington Glass Handbook, 2010). Furthermore, glass windows are also used to increase solar heating for indoor occupants. In fact, the solar heat gain coefficient expressed as a value between 0 and 1 used to rate windows performance is generally 0.86 for uncoated clear glass of 3mm (Guardian Glass, 2019) with 0.84 being from a direct solar transmittance glass and 0.02 being an indirect gain from convection heat transfer and reflective radiation effects. High solar heat gain coefficients mean higher natural solar heating potential. Low U-value mean better insulative properties and accounts for glass center, edges losses and frame performance and will range from 0.2 to 1.2. Air leakages from frame irregularities and discontinuities from glass glazing ranges between 0.1 and 0.3 for R-value and these air leakages can result in increased heating and cooling costs. Due to excellent light transmission, a high level of solar heat gain and structural integrity using frames and fixtures, glass has traditionally been used in greenhouse applications. However, it is relatively expensive to use in large quantities depending on glass quality and can be technically difficult to shape or repair due to challenging workability. Glass is also considered an occupational health and safety hazard when it cracks as shattered glass easily punctures through the epidermis and causes bleeding. Overall, glass has a long history of use as windows and it is difficult to find a replacement for its excellent light transmission and thermal conductivity properties. Structural and insulative properties of glass are not its strength though can be modulated with specific design considerations such as coating additives or steel mounting, Due to high costs and technically challenging workability, its strongest contender for light transmission is plastic.

2.4.2. Plastic

Firstly, it is important to note that optic fiber is made of either plastic or glass therefore technically, the light transmitting mechanism is still derived from these conventionally used materials. Plastic optic fiber was chosen over glass optic fiber due to lowered costs for our design purposes especially regarding economic optimization. Plastic comes in many forms including polystyrene, polycarbonate, polypropylene and more. Generally, plastic is considered to have a lower thermal conductivity than glass with values ranging from 0.35 BTU/ft h °F to 0.69 BTU/ft h °F for polypropylene and polycarbonate (Omnexus, 2019). For comparison, glass is about 1.82 BTU/ft h °F therefore plastic is a better insulator. In fact, plastics are poor heat conductor because they have almost no free electrons available for heat conduction. In general, amorphous plastics between 0 to 200℃, the thermal conductivity values are between 0.125 to 0.2 W/m K (Omnexus, 2019). Due to their insulative nature, we find plastics commonly used in everyday products and components such as in drinking cups, food containers and as insulative material on buildings. Usually in solid or fibrous form, plastics also come in many different colors, levels of opacity and are easy to shape and manufacture. For example, 3D printing technologies rely on plastic fibers due to their versality and relatively low cost in bulk quantities. However, there are environmental and health concerns with the use of plastic due to a certain health risks including the endocrines disrupters which affect living organisms' hormones especially susceptible and vulnerable populations such as children, marine life or as choking hazards to small animals. Due to the widespread use of plastic, there is an immense amount of plastic waste generated. Though plastics are generally considered recyclable products, managing the significant amount of plastic waste can be challenging and often ends up polluting valuable land and water. Subsequently, plastic is not typically considered a load bearing material, but specialized plastic products do exist. Overall, monolithic thermoplastics have low strength and low stiffness and are therefore not suitable for load bearing structural applications (TechLink, 2019). Advanced plastic composites are laminated with reinforcing fiber fibers creating a polymeric matrix with two-dimensional reinforcement. However, this reinforcement does not necessarily translate to multidimensional tolerance. In general, regular plastics can still be structural stronger than glass because they are manufactured with more thickness as they are not susceptible to cracking and shattering failure as glass products are. For example, a 60 in round plastic folding table has a load capacity of 1000 lbs (TechLink, 2019). Subsequently, plastics are highly advantageous for their light transmission properties and may be on par with glass depending on the type of plastic. For example, colorless Plexiglas sheets made for visible light transmission can reach up to 92% light transmission with measured haze effects around 1% (Arkema, 2000). Plexiglas sheets transmits visible range lengths between 400 nm to 700 nm on the electromagnetic spectrum. However, light entry critical angles are crucial in the use of plexiglas. In fact, if an incident light interacts with the air interface at the critical angle, 42.2° off normal, the light will not be transmitted and will be completely reflected at the Plexiglas sheet at an equal angle opposite to the angle of incident (Arkema, 2000). Due to these constraints, plastics are not recommended for large scale windows applications and may look rather opaque due to incident angles and surface matrix issues. Additionally, plastic windows are not as aesthetically pleasing as glass windows and can scratch and yellow over time. Despite this, in greenhouse applications, polycarbonate is gaining popularity over glass due to primarily, lower initial and maintenance costs. Besides providing better insulation than glass, polycarbonate is also stronger and lighter than glass increasing its workability (Garden Buildings Direct, 2017). Furthermore, plastics are resistant to shatter and are more resilient to impacts from random projectiles such as stones and recreational balls. Since plastics are manufactured with greater thickness than plastic, they also provide better light diffusion than glass and therefore light will be spread out more evenly for optimal plant growth. If ultraviolet (UV) light protection is needed, plastic is more advantageous than glass as polycarbonate is a natural UV filter. Overall, plastics are easier to shape than plastics are available in many sizes for quick, low-cost, customized installation frames.

2.5. Alternate Designs and Mentor Consultation

2.5.1. P-N Junction Possibilities

Upon consultation with our mentor Sam Bilodeau, a Masters' student in the Biomass Production Lab whose work focuses on alternatives forms and uses of concrete, the idea of a concrete block mimicking the structure of a light emitting diode (LED) was suggested. Electroluminescence in LEDs is achieved through the p-n junction interface incorporating two semiconductor materials with P-type and N-type properties. P-type side contains an excess of electron holes while N-type contains an excess of electrons. Diodes allows for current to be primarily conducted in one direction and made of two terminals, an anode and cathode. When an electrical current is applied to a diode containing a P-N junction, electrons recombine with the electron holes and release energy in the form of photons. To make a concrete block light generating like an LED, a P type and N type material would need to be incorporated and stabilized within the mixture. In addition, an electrical current would need to be conducted through the P-N junction. Conductive concrete has been previously produced by adding electrically conductive components such as steel shavings and carbon particles (Tuan, 2016). Concrete with embedded thin film photovoltaic cells to generate solar energy has been made by researchers at the Swiss Federal Institute of Technology of Zurich. Cement is an electronically conducting material which can be transformed into a P-type by adding short carbon fibers or N-type material with short steel fibers (Chung, 2003). A junction can be made by pouring dissimilar cement side by side (Chung, 2003).

2.5.2. Phosphorescence

During a meeting with our mentor Dr. Lefsrud, it was suggested the incorporation of phosphorescence within concrete be researched. Phosphorescence is a type of photoluminescence. Photoluminescence occurs when molecules absorb energy such as light energy and are raised to a higher energy level. When returning to a lower and stable energy level, photons are released. Though phosphorescence is related to florescence, it is distinct due to the fact it does not immediately re-emit the radiation it absorbed. Phosphorescence materials require high energy light usually ultraviolet and last longer than fluorescence. Glow-in-the-dark cement paste has been produced by adding photoactive materials into the cement and altering the cement's microstructure to permit passage of UV rays (Avalos, 2016). Subsequently, phosphorous the element glows in the dark due a chemiluminescent process as it reacts with oxygen in the air. A mechanism for stable phosphorous relay is needed to continue the reaction across a material. Phosphors are solid materials that emit light when excited by radiation in an electroluminescent reaction with direct conversion of electric energy into visible light with no generation of heat. Concrete luminescent sealant has been made using a mixture of soy methyl ester polystyrene and strontium aluminate (Wiese et al., 2014). Strontium aluminate is a phosphorescent powder that releases luminescence gradually after being excited by light. Luminescent concrete was produced by doping phosphors into raw concrete materials (Zhao et al., 2013). Results shows that with increased phosphor dosage, concrete compressive and flexural strength decrease with uniformly mixed phosphor distribution (Zhao et al., 2013).

2.5.3. Transparent Acrylic Rods

The idea of using acrylic rods instead of optic fibers was discussed with our mentor to offset the high costs of optic fibers. In fact, total light transmission in acrylic rods is 92% with an averaged measured haze of only 1% (Arkema, 2000). However, if light passing through encounters an air interface at critical angle 42.2 deg off the normal, it will be completely reflected (Arkema, 2000). In one experimental study which compared the use of acrylic rods to optic fiber arranged parallel, the light transmitting ability of acrylic rods was almost equal to the use of optic fiber (Kim, 2017). Smaller diameters of acrylic rods due to increased density were found to be more successful at transmitting light compared to larger diameters (Kim, 2017). In another application, concrete was embedded with acrylic rods and fishing line to transmit light. Fishing line is nylon-based material with high resistance to shear and strain forces. The combination of acrylic rods and fishing line was shown to successfully transmit light when arranged parallel (Baggaley et al., 2016). In general, there are very few studies documenting the use of acrylic rods and impact in light transmitting concrete.

3. Concept Generation

3.1. Design Criteria

Aesthetic. The design light transmission features must be aesthetically pleasing to promote its usage in artistic and decorative purposes. *Standard concrete has a reputation for being ugly and grey, light transmitting concrete should be interesting and fun to observe.

Novel. The design must be innovative and novel. It must re-imagine the possibilities of and propose fresh perspectives on concrete as a building material.

Safe and Ease of Production. Production method of light transmitting concrete must be simple and easy to understand. One of the greatest strengths of standard concrete that has enabled its widespread use is its ease of production. Safe manufacturing conditions are important to protect the workers. Nontoxic materials should be prioritized to ensure the final product is not a toxicity threat.

Block Stackability. Block stackability is important to ensure stability of a concrete wall. Blocks must be able to stack without compromising the integrity of their structure. This also allows for efficient manufacturing through expedited production of blocks.

Light Stackability. Incident light should be received, transported and emitted through the individual blocks in addition to light transmission between multiple blocks due to the use of a transparent mortar medium. Losses are inevitable between the mortar and block interfaces though should be minimized as much as possible.

3.2. Design Parameters

Light Transmission. Adding light transmitting properties to a concrete wall can yield energy savings by increasing the amount of natural lighting in a building. Light transmission will also increase the aesthetic appeal of concrete. We will consider a theoretical concept of workable light intensity for this purpose, where a minimum workable light is a typical light intensity required for a 10-year-old to be able to read, which is achieved with a 40W bulb (Louie, 1986). Assuming the bulb is incandescent, 1W translates to about 16 Lumens, thus a 40W bulb will produce 640 lumens (Office of Energy Efficiency & Renewable Energy, n.d.). Let us consider that 640 lumens is being transmitted from a wall of $1m^2$, then the lux is also 640. Given that daylight is around 10,752 lux, % transmittance required to achieve 640 lumens is 6% (Recommended Light Levels, n.d.). This value is of course different for an overcast day, when the %T must be 60%. For simplicity, we will consider a 6%light transmittance to be a minimum criterion for the light transmitting concrete.

Thermal Insulation. By ensuring thermally insulative properties in a concrete wall, power consumption regarding HVAC requirements can be reduced. Insulation is vital for indoor settings where conditions must be kept stable for human well-being.

Insulation is quantified by R value. R value of a material represents the resistance to heat flow through a given width of a material. It is measured in °F*ft*hr/BTU or m^2*K/W, which represents a change in temperature required to transmit one unit of heat through a unit area over time (Calculate and Measure R-Values, 2012).

The relative insulating performance of a material can be predicted by its air pocket content and specific Heat value (C_p), where C_p represents the energy required to increase a material's steady state temperature by 1 K. The presence of trapped air, air pockets, represents a solid material's resistance towards convective heat transfer, which makes materials with air pockets a good insulator (Limbachiya et al., 2011). In addition, the entrapment of air, which has a low density, is beneficial also because vacuum has an excellent insulating characteristic. This is because vacuum does not permit heat transfer by means of conduction and convection.

Insulation property of concrete depends highly on its density, as a high density of concrete indicate a lack of air pockets. Aircrete is a good insulator for this very reason; they are highly porous, though to different degrees.

As a fair baseline of comparison, let us consider rigid 1" insulation foam boards available at hardware stores such as Homedepot. The FOAMULAR CodeBord Extruded Polystyrene Rigid Insualtion (24 x 96 x 1 inch) is a very typical rigid insulation foam board and it has an R value of 5. Concrete blocks of densities less than 40 pcf are likely to also exhibit R5, which translates to R/inch of less than 1.25. The issue with concrete of 50 pcf or below is that they are considered to be as weak as 100 psi and are used primarily for solely insulation to begin with. Meanwhile, Autoclaved Aerated Concrete walls can rank at R values as high as 7.5, and a density of 400 kg/m^3 (Limbachiya et al., 2011). The lightest specimen of porous concrete available at the Biomass Production Laboratory in Macdonald campus is comprised of Poraver aggregates. Poraver based light weight concrete can achieve densities as little as 52.8pcf for a sample with strength of over 1000 psi (Stanton, 2016). However, such a piece would likely have an R value of just over 3.5, based on Appendix 9, which is far less than the maximum R value of AAC at 7.5. Non-autoclaved Aircretes can have thermal conductivities as low as 0.11 W/(mk) which translates to a 4" concrete block R value to be around 5 (H+H UK Limited, 2019). As AAC manufacturing is difficult, the thermal conductivity and resistivities achieved by Aircretes are more realistic goals for this project. Therefore, given a block width of 10cm (4"), the concrete blocks made for this project should obtain an R value of 5 to be comparable to industrial Aircretes and 1" foam insulation boards.

Compressive Strength. Standard concrete is known to have good compressive strength which makes it a useful building material. The higher the strength of the concrete wall designed, the more versatile it is. Depending on the strength properties obtained and their adherence to building codes, the concrete wall designed can be used in exterior and interior walls, facades, partitions, divisions or decorative and artistic applications.

Compressive design specification as per ASTM C90 requires concrete masonry units (hollow concrete structural blocks) to have a compressive strength of 2000 psi (ASTM C90-00, 2002). Meanwhile, a High Strength Grade AAC has a strength of 1058 psi (Designing a Building with Aircrete, n.d.). This project desires to follow the precedence set by ASTM C90 for structural concrete and to match the compressive strength currently being achieved and applied to construction with Aircretes (Appendix 8) and AAC. In order to prove that the rated psi is sufficient, a theoretical test was carried out. This test assumes that our light transmitting concrete blocks are made for a structure of less than 21.5 m in height. If the height is fully achieved by the LTCBs only, this wall is exactly 100 LTCB tall. The wall weighs 378.4kg being comprised of AAC, or 2270.4 kg comprised of standard concrete. Adding 100 layers of 1cm thick polyurethane resin mortar increases the weight of the walls by 44 kg. Given that the LTCB has a vertical face surface area of 0.044m^2, the weight of the walls alone exerts on itself a maximum pressure of 1213.64 psi for standard concrete, and 74.82 psi for AAC. The validity of this theoretical test is in the nature of compressive strength, which is merely a vertical force being applied perpendicularly to the object. In this test, the compression is achieved by the weight of the wall directed perpendicularly to the block, which is how it is designed to bare the load. Hence, the experiment demonstrates that for a moderate sized building of around 20m, following the precedence of requiring structural concrete blocks to have a compressive strength of 2000 psi, and for AAC to have more than 1058 psi, is indeed satisfactory. In addition, for the H+H Celcon building guide for non-autoclaved aerated concrete, the weakest of the Aircretes used for wall constructions must have a minimum compressive strength of 2.9 MPa, or about 400 psi. For the scope of this project, AAC is desirable but difficult to manufacture, thus regular Aircrete will be the focus. Therefore, though compressive strengths of above 1000 psi as achieved by AAC is desirable, anything above 400 psi should be acceptable for our product.

3.3. Design Proposals

Cement Types for Strength Comparison. Portland cement is the most commonly used type of cement used in concrete. Its primary ingredient is limestone which is widely available and low cost. As a hydraulic cement, it hardens when reacting to water and allows concrete mixture to bind, become load-bearing and have strength properties. Portland cement derivatives include Portland blast-furnace slag cement and Portland fly-ash cement. Slag cement made using ground granulated blast slag is typically used when a lower heat of hydration is required. Slag cement also offers better sulphate and chloride resistance. With slag cement, early strength of concrete is weaker, but ultimate strength over time is higher. Fly ash cement is made using fly ash which is a pozzolanic material which produces cementitious properties. Fly ash cement is an economic alternative to ordinary Portland cement and re-uses an industrial by-product. Strength wise, early and ultimate strength is maintained in fly ash concrete.

Criteria	*Portland Cement*	*Slag Cement*	*Fly-Ash Cement*
Overall Strength	++	+	++
Low Cost	+	++	++
Low Emissions	-	0	+

Table 1: Cement Types Comparison

Criteria	*Crushed Quartz*	*Perlite*	*Vermiculite*	*AAC*	*Porous Concrete*
Insulation	++	++	+	+++	+++
Accessible Material	+	++	++	+	++
Low Cost	-	+	+	-	++

Table 2: Insulation Performance Considerations Comparison

Criteria	*Optic Fiber*	*Phosphorescence*	*LED*
Accessible Materials	++	+	-
Ease of Production	+	-	--
Current drawn	+	+	-
Time constraint	+	+	--

Table 3: Light Transmission Modes Comparison

Criteria	*Polyurethane Resin*	*Epoxy Resin*	*Clear Silicone*
Transparency	++	++	+
Safety	--	-	-
Accessible Material	+	+	+
Load bearing	++	++	--
Durability	0	+	+

Table 4: Mortar Type Comparison

Criteria	*Drexel*	*Suave Shampoo*	*Seventh Generation*	*Dawn Ultra 4x*
Cost	++	+	+	+
Safety	--	+	+	+
Foam Quality	++	+	+	+
Accessible	--	-	-	++

Table 5: Foaming Agents for Aircrete Production Comparison

Criteria	*Structural Concrete*	*Porous Concrete*	*Aircrete*
Compressive Strength	++	-	+
Thermal Insulation	-	+	+
Optic Fiber Compatible	+	-	+

Table 6: Comparison between Concrete, Porous Poraver Concrete, Aircrete Block

Insulation Modes Comparison. Insulation by adding aggregates with insulating properties and by increasing porosity in the concrete structure was considered. Aggregates examined include crushed quartz, perlite and vermiculite. Crushed quartz is a colorless mineral with silicon dioxide as its main component. Due to silica having a low thermal conductivity, crushed quartz makes an excellent insulator. Perlite and vermiculite are two common soil additives in horticulture. They are produced by heating ores thus expanding them and creating bubbles within the particles. Perlite has higher air porosity than vermiculite and both have been previously added to concrete mixtures to yield insulation properties. Another way to incorporate insulation into the design would be creating a concrete structure with high porosity such as Autoclaved Aerated Concrete (AAC) or Porous Concrete. While AAC creates pores in its structure during a unique aeration process in manufacturing, porous concrete relies on an increased proportion of coarse aggregate for porosity. Pores in AAC tends to be isolated and those in porous concrete may be connected. Higher porosity is related to higher insulation in both cases.

Modes of Light Transmittance Comparison. Three modes of potential light transmission in concrete were examined. Light transmitting concrete with embedded optic fiber which transmits light through the concrete block without any loss due to total internal reflection. Optic fiber orientation is parallel to the concrete and distributed uniformly. Optimal density of optic fiber was found to be around 4% without hindering on compressive strength properties. Additionally, adding phosphorescence to the design was also considered. Phosphors such as strontium aluminate are solid materials that emit light when excited by radiation in an electroluminescent reaction with direct conversion of electric energy into visible light and no generation of heat. Phosphors powder can be added to cement or mortar to produce light. Finally, the third mode explored was the concept of creating an light emitting diode (LED) out of a concrete block by creating a P-N junction. This requires the use of electrical current to generate light and local electrical source and storage. Conceptually, it is postulated creating a P-N junction by positioning two differing cement mixtures is possible since cement can be made conductive.

Mortar Types for Comparison. Three transparent mortar types were considered for the design including polyurethane resin, epoxy resin, clear silicone. Polyurethane is a polymer made from organic units bonded by carbamate links. It is commonly used to seal concrete and has good abrasion resistance, which is a benefit in transmitting uninterrupted light. Due to its organic nature, moisture, temperature and UV cause it to react and deteriorate over time. Clear silicone is also used as a sealant in concrete to fill in gaps. Though not as transparent as polyurethane, it is an inorganic substance suitable for outdoor and indoor conditions. However, clear silicone is more expensive, but has a significantly longer service life. Thirdly, epoxy resin was also examined as mortar as it is compatible with the granular nature of concrete. Color can be added to epoxy resin and exposure to UV may yellow it over time. It is considered more suitable for indoor conditions. Epoxies should only be applied on materials with similar mechanical strength properties. Epoxy resin is a hard material with low flexibility like most concrete, but as per ASTM C476, mortars of equal or higher compressive strength than concrete is desirable.

Foaming Agents for Aircrete Production Comparison. Selecting a proper foaming agent is quintessential for optimal foam density and Aircrete production. Without a high-quality foam that is long lasting and firm, it will dissolve and cause the Aircrete to collapse (DomeGaia, 2018). Automatic or manual foamers can be used for foam production. Commercial foaming agents have a detergent base and the foam generated is like higher end dishwashing detergent such as Seventh Generation or Dawn Ultra 4x. In fact, if a dishwash detergent is used, it should have good degreasing capacities. Shampoo with a good proportion of sodium lauryl sulfate such as Suave Essentials have similar proportion to degreasing detergent. Unfortunately, many of these products are only available in the United States and may not be easily accessible in Canada. Subsequently, it is possible to use commercial protein based foaming agents such as Drexel Foam Concentrate to produce similar high-quality foam. However, Drexel is toxic and proper safety precautions must be taken to mitigate the health risks. Additionally, these products vary in price and additional costs will be incurred to shipping and tax import expenses. Shaving cream foam has been suggested due to its low collapsibility though its usage and performance has not been extensively studied experimentally previously and is riskier to use.

Comparison Between Blocks Types. Standard concrete is traditionally made from Portland cement, water, fine and coarse aggregate such as rock and sand. It is known for its good compressive strength making it suitable for structural applications. In larger scale applications, additional reinforcement such as steel rebar is required to counteract its low tensile strength. Concrete is known for its gray opaque appearance ubiquitously found in urban concrete jungles. Moreover, it is a good thermal mass and therefore known as a heat conductor. Concrete can absorb, and store heat energy and it takes a significant amount of heat energy to modulate the temperature of high-density materials like concrete. Subsequently, the aggregates proportion in concrete can be replaced with large aggregates such as Poraver expanded glass aggregates to create a porous white opaque concrete. Poraver is known to be thermally insulating and very light weight due to its expanded structure which create air pockets within the aggregate. Using large aggregates size also increases the air pockets within the concrete matrix to create a more porous structure capable of insulating. Furthermore, porous concrete made from Poraver is not generally designed or recommended for structural applications requiring high load capacities and compressive strength. Finally, Aircrete is known to be a good insulator due to the air pockets created by the foam aggregates. Aircrete can be structural if the foam density selected is high enough though it is not as structural as traditional concrete (H+H UK, 2018). Due to its light weight, it is easy to work with though its manufacturing can be challenging due to proper foam generation. Quality foam should not collapse and have an adequate density measurement. By applying quality checks at each step, Aircrete production can be optimized. Additionally, light transmission by embedding plastic or glass optic fibers has been previously experimentally demonstrated in structural concrete according to scientific literature. There is a risk of fiber slippage, but generally it is compatible with concrete formulations. Fiber reinforced porous concrete does exist but is rare and integration with Aircrete is even rarer with no previous published instance of optic fiber embedding available. According to the experimental samples conducted in the context of the design project, fiber optic had low capability with porous concrete made from Poraver and was highly compatible with Aircrete formulations therefore being selected as the final design as light transmitting Aircrete (LTA) blocks with light stackability properties.

3.4. Design Selection

The design recipe was selected in accordance with optimizing the three design parameters light transmittance, strength and insulative properties. Comparative charts were made to examine potential recipes with selected context appropriate design criteria and limiting factors that would hinder its feasibility. To account for a lack of experimental results for some applications and provide a possible alternative post testing for redesign, a second recipe selection was made to complement certain properties.

The design recipe is: Portland cement is recommended for balanced strength properties and ease of access to materials. Insulating properties will be based on either Porous Concrete or Aircrete. In fact, both yield insulating porosity and there is a precedent for research on porous concrete at the Biomass Production Lab. Light transmittance mode will be primarily the use of optic fibers due to its proven effectiveness and technical simplicity compared to the other modes proposed.

Phosphorescence through the admixture of phosphor powder will serve as accompaniment to promote novelty of the design. Finally, epoxy resin is selected as a mortar due to its transparency and compatibility with concrete. Polyurethane resin mortar is also interesting to evaluate through tests due to its load bearing capacity and transparent properties.

3.4.1. Structural Light Transmitting Block

Ingredient	Quantity	Specifications
Structural Block Sizing (cm)	44.0 x 21.5 x 10.0	Portland cement is used. Sand passing through a 1.18mm size sieve is used as fine aggregate. Tap water is suitable. Plastic optic fiber is recommended.
Optic Fiber Spacing (cm)	1.00	
Optic Fiber Diameter (cm)	0.75	
Optic Fiber Density (% of total mass)	4.00	
Optic Fiber Mass (kg)	0.90	
Cement Mass (kg)	5.76	
Water Volume (L)	2.30	
Fine Aggregate (kg)	14.40	
Water to Cement Ratio	0.40	
Cement to Aggregate Ratio	0.40	

Table 7 Structural Light Transmitting Block

3.4.2. Porous Light Transmitting Block

Ingredient	Quantity	Specifications
Porous Block Sizing (cm)	44.0 x 21.5 x 10.0	Portland cement is used. Poraver retained on the 4.75 mm size sieve is used as coarse aggregate. Tap water is suitable. Plastic optic fiber is recommended.
Optic Fiber Spacing (cm)	1.00	
Optic Fiber Diameter (cm)	0.75	
Optic Fiber Density (% of total mass)	4.00	
Optic Fiber Mass (kg)	0.96	
Cement Mass (kg)	4.54	
Water Volume (L)	1.36	
Coarse Aggregate (kg)	18.17	
Water to Cement Ratio	0.30	
Cement to Aggregate Ratio	0.25	

Table 8 Porous Light Transmitting Block

3.4.3. Aircrete Light Transmitting (LTA) Block

Ingredient	Quantity	Specifications
AAC Block Sizing (cm)	44.0 x 21.5 x 10.0	Portland cement is used. Tap water is suitable. Plastic optic fiber is recommended.
Optic Fiber Spacing (cm)	1.00	
Optic Fiber Diameter (cm)	0.75	
Optic Fiber Density (% of total mass)	4.00	
Optic Fiber Mass (kg)	0.15	
Cement Mass (kg)	2.37	
Water Volume (L)	1.26	
Foam (g/L)	5.00	
Total Foam (g)	47.28	
Water to Cement Ratio	0.53	

Table 9 Aircrete Light Transmitting (LTA) Block

3.4.4. Transparent Mortar with Phosphorescence Powder

Transparent Mortar Specifications	Phosphorescence Powder Specifications
Epoxy resin will be tested due to lower costs and ease of accessibility.	Phosphor powder could be strontium aluminate (Wiese et al., 2014). Manufacturer recommends a powder to sealant ratio by mass of 10:6

Table 10 Transparent Mortar with Phosphorescence Powder

3.4.5 Structural and Porous Light Transmitting Concrete Procedure

Firstly, a level clay mount is made on which a mold to cast concrete in is placed. Fiber optics are cut and placed in the desired orientation. Concrete is mixed with water, specified aggregates and cement before pouring it into the mold. After the concrete has cured for 28 days, the clay mount is removed. Extra fiber is trimmed, and sandpaper can be used to polish light transmitting concrete.

3.4.6 Aircrete Light Transmitting Concrete (LTA) Procedure

Firstly, the foaming agent must be diluted with water. Aircrete machine is then set up and connected to an air compressor. Pressure must be monitored to achieve adequate foam mass. Mix water, cement with the foam injection mixer to form Aircrete. Similarly, to previous concrete blocks, a level clay mount is made on which a mold to cast concrete in is placed. Fiber optics are cut and placed in the desired orientation. Aircrete is then poured into the mold and clay mount is removed. Extra fiber is trimmed, and sandpaper can be used to polish light transmitting concrete. Once blocks have been made, they will be stacked and linked using transparent mortar doped with phosphorescent powder.

4. Proposed Design

4.1. Product Architecture

The product we propose is light transmitting Aircrete (LTA) intended to be stacked in multiple layers and connected with a transparent resin mortar. A layer indicates one concrete block, so a multilayered composition has multiple blocks stacked width-wise (Appendix 5). LTA will be solely made into concrete blocks rather than bespoke precast. Light transmitting concrete in its existing forms are available as precast, but it is not common to find the products sold in the common concrete block units such as Concrete Masonry Units (CMUs). The benefits of bricks and CMU production is the high degree of repeatability in production in order to reduce cost and propose higher production efficiency (DentonVacuum, 2019). We will be employing a standard CMU size of the dimension 440mm x 215mm x 100mm for the LTA thus, all future references to an LTA block will have this size. Though concrete masonry units (CMU) are hollow, for our application, the block will be solid, because solid block permits the optic fibers be placed and oriented more easily.

LTA blocks are unique in having insulating and structural property. Though these properties are ideal, there are potential drawbacks. Firstly, Aircrete is more expensive to produce than regular concrete. Furthermore, optic fiber embedding within Aircrete is thus far unheard of, preventing any research on precedents. Also, potential degradation of optic fibers within concrete, and fiber slippage due to lack of adherence to the cured concrete matrix may pose a problem. Degradation of fiber is a known phenomenon in concrete due to the alkaline environment present in concrete, but as demonstrated in patent CN102758496, damage can be mitigated by using fiber coating (Yang et al., 2016).

In application, the LTA blocks will be stacked using transparent mortar. We propose a transparent mortar composed primarily of polyurethane or epoxy resin due to its casting convenience. To save costs and curing time, we propose that the resin be mixed heavily with clear plastic or glass fragments. We hypothesize that the addition of clear plastics or glass fragments should still produce a mortar with significant transparency and light transmissivity because clear objects embedded in transparent mediums with similar index of refractions appear largely transparent (Carroll, n.d.). In practice, this is very similar to mixing pebbles into cement mortars in building walls.

The light transmitting characteristics of optic fibers allows for a smaller prototype to be made for testing. Optic fibers have minimal light losses; thus, the size of the block is largely irrelevant in assessing light transmittance. Furthermore, the insulation and strength values can be evaluated with smaller samples, because they are material properties irrespective of the size. Therefore, the prototypes produced for this project are not full-sized.

The embedding of optic fibers is tedious as discussed previously in the Literature Review. Although it is not necessarily used to place the fibers in the prototype used for this project, a novel method of fiber placement inside concrete is proposed to entertain cost reduction. Typically, fibers are woven end to end within a mold, onto which concrete is poured. Here, we are proposing that the optic fiber should be bundled into an amorphous spool and placed inside the concrete. The guiding hypothesis that when the concrete sample embedded with the amorphous spool is sliced into multiple pieces, each piece will have ample light transmissivity, though with some losses compared to traditional fiber placement methods, to justify the excess in optic fibers used with the time saved in preparation.

4.2 Prototype Production

The LTA is to be composed of cement, water, optic fibers, and plastic aggregates. A pilot batch of LTA was cured to evaluate the feasibility of production. The pilot batch had the following composition:

6 ABS pipe molds of 1 inch thickness and 1 inch diameter were prepared atop a rigid foam base to make 3 samples of optic fiber embedded Aircretes, and 3 samples of regular Aircretes. The optic fiber embedded Aircrete were made by pouring Aircrete sludge into the ABS mold which encompassed optic fibers embedded into a foam base (Figure 1). the optic fibers are embedded into the foam by hand, one by one. The optic fibers were taller than the mold, such that the fibers can be shaved from the top and the bottom of the cured concrete, and polished, to provide a pristine finish. Upon curing, it was apparent that this batch of Aircrete was extremely light, but equally as brittle. Also, the concrete had lost some of its volume from its sludge form due to the usage of Dawn dish soap, which is known to collapse marginally throughout the curing stage (AircreteHarry, 2018). After curing for 3 days, the Aircrete was so fragile that it crumbled in hand without any significant pressure applied.

Furthermore, the optic fiber embedded Aircrete batch had cracked throughout its volume (Figure 1). Visually, it was clear that the cracking happened because the sludge stuck itself to the ABS mold and the optic fibers through water adhesion, but as the bubbles receded, the adhesion forces pulled on the concrete highly unevenly. This problem was not present in the regular Aircrete because there were no optic fibers to cause the uneven adhesion.

Figure 1: Cracked fiber embedded Aircrete from first trial

This problem was solved with three potential solutions; adding head pressure to the fiber embedded Aircrete by pouring the concrete sludge much higher than the height of the fibers, making the mixture denser thus heavier to minimize fragility, and to add plastic aggregates to make the adhesion force of the water more even throughout the mixture. The plastic aggregate is proposed instead of sand or pebbles because we hypothesize that with a sludge as light as Aircrete, plastic will mix better. Also, given that the optic fibers are also plastic, plastic aggregates will have similar adhesion characteristics to water. Furthermore, the plastic aggregates are proposed also to entertain a way to reuse non-recyclable plastics into concretes. However, for this project, the plastics are sourced from Dollarama in the form of plastic jewelry beads. The beads are frozen, then ground finely to ensure the Aircrete mixture is as fluid as possible, which aids when pouring into the fiber embedded mold.

The second batch made through the aforementioned corrections had the composition as presented in Table 9. Since the concrete is poured higher than the length of the optic fibers, this sample has to be sliced to reveal the fiber cross sections (Figure 2). The batch cured without problems and created LTA cylinders. When sliced, the optic fibers were revealed, and light transmission was confirmed. Although this production method proved successful to produce LTA, we understand that it is only sensible for small scaled prototype production specifically for our purposes, and industrial production will not follow this method because the individual fiber embedding inside the foam board is simply impractical.

Figure 2: Light transmitting Aircrete disk cured in final batch

As for the transparent mortar, a small 1" diameter and 1" thick epoxy resin sample embedded in plastic beads was prepared to observe its clarity and evaluate its effectiveness as a transparent medium between to LTA. Visually, the sample was very cloudy. In order to determine if the problem was with the plastics used or with the concept of embedding plastics inside epoxy resin, various types of plastics beads were used to produce more epoxy resin samples. As discussed later in design analysis, some plastics performed drastically better than others proving that given the right choice in plastic or glass fragments, mortar of significant clarity can be produced.

Figure 3: Cured Aircrete samples and transparent mortar samples

4.3 Amorphous Fiber Placement Method

For LTA using optic fiber embedding, fiber orientation is quintessential for light transmission. The ends of one continuous piece of optic fiber must be exposed at opposing side (incident side and transmission side) for the photons to be carried through. Presented is the Amorphous Cross Section method, whose procedure is as follows:

•Create an oversized batch of concrete sludge, size enough to be able to produce multiple blocks

•Insert long winding and dense batch of optic fiber end to end with respect to the incident and transmitting side such that the optic fibers will be largely parallel with path of light (Appendix 7)

•Cure for 28 days

•Cut the cured concrete down multiple pieces of desired block size

This method depends on the randomness of fiber placement being able to produce enough fiber density at the concrete block faces (Appendix 6), and the length of the long windings being long enough to connect the incident and transmission faces. The drawback of this method is the dependence on the randomness of the fiber placement, which has a possibility of not producing enough fiber density. The effectiveness of this method must be determined through experimentation and compared with a sample of LTA where the fibers are systematically oriented.

5. Design Analysis

5.1 Compressive Strength Test

To characterize the strength of LTA, compressive tests were conducted. Flexural test was not conducted due to time limitations. This was justified by the fact that in typical wall applications, compressive strength is the concrete property of quintessence (Nemati, 2015). This is further made evident by Aircrete building guides such as the "H+H Celcon Aircrete Building Guide", indicating the suitable concrete strengths for applications in terms of the minimum allowable compressive strengths (H+H United Kingdom, 2018).

Equation 1:

$$\sigma = F/A$$

$$A = area$$

$$F = force\ applied\ by\ Instron$$

$$\sigma = Stress$$

Compressive strength test was conducted on 3 different variants of concrete samples; Aircrete, optic fiber embedded Aircrete, and concrete. Each variant was tested with 3 samples except the concrete sample, which had to be tested with 2 samples due to one sample being damaged during handling. The Aircretes were tested in an Instron which has a maximum compressive strength of 9kN. This was not enough strength to test the concrete sample, which was then tested in an AMETEK Universal Testing Machine.

All the samples were prepared using the same initial concrete mixture. Dawn dish soap foam was further added to the concrete mixture to produce the Aircrete. They were shaped into small cylindrical pucks of 1" thickness and 2" diameter under the consultation of Yvan Gariepy, senior research engineer at McGill in charge of the Instron Machine at Macdonald Campus.

Concrete Type	*Sample #*	*Compressive strength (MPa)*	*Average compressive strength (MPa)*	*Adjusted average compressive strength (MPa)*
Aircrete	1	3.14	2.92	3.19
	2	3.24		
	3	2.37		
Fiber embedded Aircrete	1	2.69	2.37	2.65
	2	2.60		
	3	1.83		
Concrete	1	23.8	22.17	22.17
	2	20.4		

Table 11: Compressive strength of concrete samples tested

Compressive strength test is sensitive to the shape of the sample tested. The cylinders must be perfectly flat for a sensible result. Unfortunately, not all the concrete samples were prepared to the same quality. Hence, sample 3 of Aircrete and fiber embedded Aircrete produced a highly anomalous result clearly inconsistent with the other two results. Therefore, two different averages were taken for compressive strength, where one of the averages were taken for the two sensible samples and ignoring the anomaly. Due to the lack of a third sample, it was impossible to determine if either of the result for the concrete sample was anomalous, thus, the average was taken.

Figure 4: Light transmitting Aircrete disk cured in final batch

Figure 5: Crushed Aircrete sample under the Instron universal testing machine

Aircrete only has 14.4% of the compressive strength of the concrete. fiber embedded Aircrete has 83% the compressive strength of Aircrete, and 11.95% of the compressive strength of concrete. 3 MPa compressive strength is above the acceptable range of Aircrete used for wall construction of up to 2.7m high according to H+H Celcon Guide (H+H United Kingdom, 2018). Hence, the compressive strength achieved by the Aircrete is sensible. However, the inferiority of the fiber embedded Aircrete was counter to initial hypothesis and revealed a fault in the experiment conducted. Due to the convention of fiber reinforced concrete, the hypothesis was that the optic fiber embedded samples will be stronger than Aircrete. Unfortunately, the samples used for the compression test had fibers oriented parallel to the direction of the compression, while in building application, the fibers will run perpendicular to the direction of compression. Vertically oriented, the fibers do not contribute to any compressive reinforcement of the concrete, whereas horizontally, they would reinforce against tensile stresses, and add ductility to the material (Government of Hong Kong, 2012). In fact, the fibers in a vertical orientation simply introduces multiple points of stress concentration such as holes and notches, which facilitates the cracking, as seen by lower compressive strengths (Budynas, Nisbett, 2015). Oriented properly, even if it is in the form of an amorphous spool, the fibers are likely not to hinder the compressive strength of the Aircrete. However, it is up to further experimentation to evaluate if the fibers can increase the compressive strength of the concrete beyond its non-fiber embedded compressive strength.

The samples were 8 days old during the compressive strength testing. Concrete fully cures after 28 days, thus, at 8 days old, the concrete samples did not represent the full strength of the concretes. Data from the paper “Predicting 28 Days Compressive Strength of Concrete from 7 Days Test Result” by Kabir et al., shows that concrete cures to just under 70% of its strength after 7 days of curing. Assuming 8 days is equivalent to a week, this implied that the Aircrete will have a full compressive strength of 4.55 MPa. This compressive strength can be further improved by reinforcements from materials such as steel fibers (Garbis, 2013).

Compressive strength test of epoxy sample was conducted as well using a sample of ½” thickness and 1” diameter. However, the sample’s compressive strength had exceeded the total applicable force of the UTM at 60,000 lb. this translates to a compressive strength of 76,000 psi, whereas epoxy typically has a compressive strength of 10,000 psi (MARYLAND STANDARD METHOD OF TESTS, 2012). The experiment was not successful because the deformation of the epoxy sample had reached plastic deformation long before the 60,000lb, however, the elasticity of the material never allowed the sample to reach a fracture point and to be registered by the UTM. This is likely caused by the very short curing time of 4 days for the resin sample. However, given that epoxy has a significantly higher compressive strength than concrete, the failure to obtain a specific compressive strength for the sample should not hinder the structural integrity a wall made from LTA with epoxy mortar.

Object	Fiber Density (% Area)	Thickness (mm)	Lux	Light Transmittance (%)
Air	-	12.7	68000	-
	-	25.4	51000	-
	-	38.1	53300	-
C1	1.125	12.7	365	0.54
C2	2.250	12.7	810	1.19
C3	4.500	12.7	2150	3.16
C4	4.500	12.7	1950	2.87
Epoxy Resin	-	12.7	52800	77.65
C3 + C3	-	25.4	50	0.074
C3 + Air + C3	-	38.1	31	0.044
C3 + Resin + C3	-	38.1	25	0.037
Test tube	-	145	15500	-
Test tube bead 1	-	145	9	0.06
Test tube bead 2	-	145	4	0.03
Resin test tube	-	145	8800	56.77
Resin test tube phosphorus	-	145	3	0.02
Resin test tube bead 1	-	145	880	5.68
Resin test tube bead phosphorus	-	145	2	0.01
Resin test tube bead 2	-	145	466	3.01
Resin test tube bead phosphorus	-	145	2	0.01

Table 12: Light transmissivity chart for the samples tested. C refers to the optic fiber embedded plaster. C1 has 50 fiber, C2 has 100, C3 and C4 has 200.

5.2 Light Transmission Test

Light transmissivity of LTA differentiates it from standard Aircrete and fiber embedded Aircrete. Light transmission of LTA is driven by optic fibers. The light transmissivity of an ideal optic fiber is 100%, implying that the transmissivity of optic fiber is solely dependent upon the light incident amount. Incident can be increased by adding more fiber in a given cross sectional area, and by polishing the fiber cross sectional surfaces to minimize incident and transmission losses. These characteristics are largely independent of the fact that the fibers will be embedded within concrete. therefore, the quintessential element of LTA's light transmittance is to determine the optimal optic fiber density. Optic fiber is denoted in % area of optic fibers within total concrete cross sectional area. The density should not only provide a sensible amount of transmittance, but it should not hamper the mechanical characteristics of the concrete. Furthermore, the amount of optic fibers used should not be so excessive that the resulting optic fiber density is such that the fiber embedding process becomes hectic.

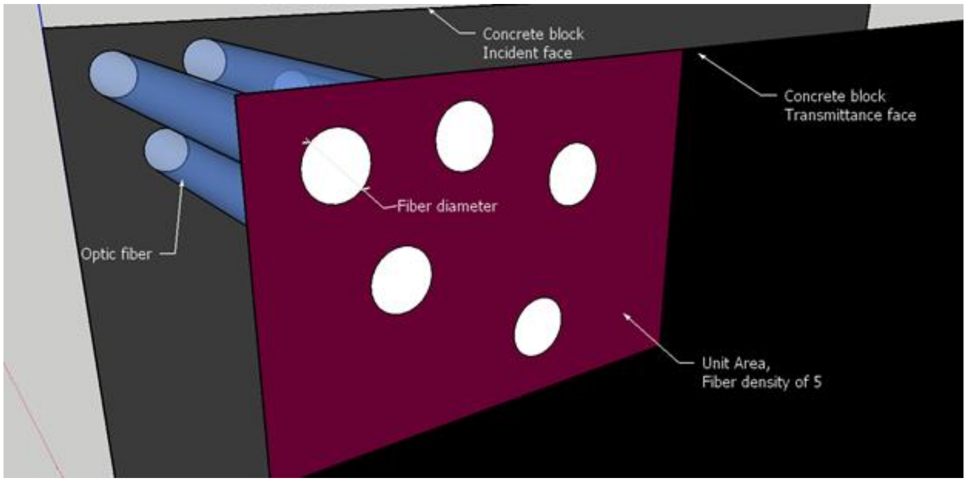

Figure 6: Optic fiber placement inside concrete block

The LTA composite wall design also necessitates that the LTA blocks be stackable with the use of a transparent epoxy mortar. The transmittance of clear epoxy resin is compared to epoxy embedded with translucent plastics. Furthermore, luminescent powder was added to clear resin to observe the effect of luminescence on overall light transmittance. Though luminescent, the powder itself is opaque, decreasing the clarity of the resin. This luminescent resin sample is then also embedded with plastic beads to compare the effect of plastics in clear resin with plastics in resin with luminescent powder impurity. Luminescence absorbs EM waves into the UV range, thus, the potential of luminescent powders enhancing the light transmission is tested, despite the powder reducing the resin's clarity.

The following 4 tests were conducted to assess the transmittance properties:

5.2.1 Optimal Fiber Density Test.

Optimal optic fiber density was determined by conducting light transmittivity tests on samples of varying optic fiber density. The test was conducted inside a transmissometer, designed with the influence of ASTM D1494-17 and the consultation of Dr. Lefsrud.

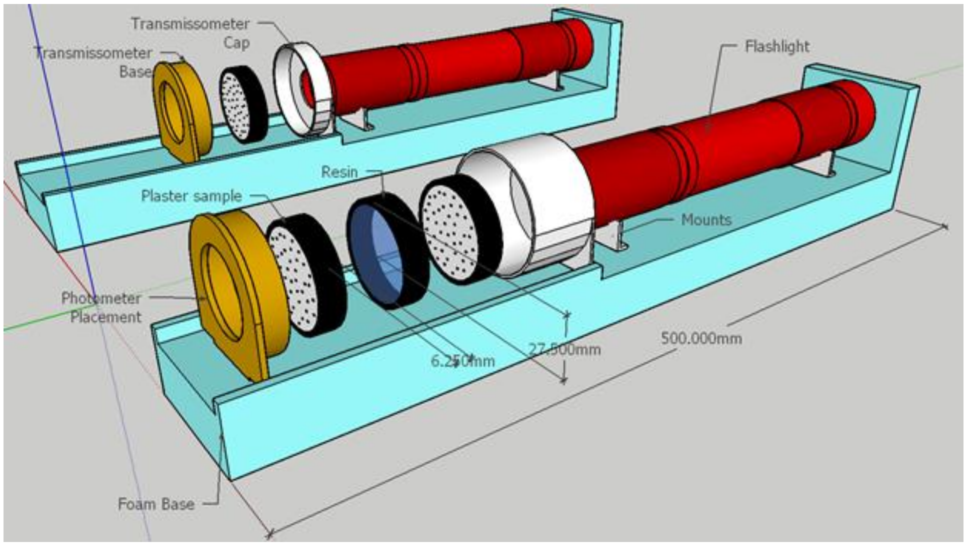

Figure 7: 3D render of transmissometer

A transmissometer was used to measure light transmittance through a light source and a photometer, sandwiching the sample inside a light proof container. The transmissometer was designed to use Snap-On hybrid flashlight, and a Dr. Meter LX1010B photometer. The apparatus was designed in SketchUp and 3D printed out of PLA. The transmissometer can to house up to 3 stacks of ½" thick 2" diameter discs of the samples to be tested. The stackability within the transmissometer is important to test the light transmittance of LTA samples stacked together.

Firstly, the transmissometer was used to test the light transmissivity of a ½" thick and 2" wide epoxy disc, which is 77.65%. ½" is representative of mortar thickness between two CMUs (ACME BRICK, 2009). Then, three variants of ½" thick 2" diameter optic fiber embedded plaster discs were prepared in ABS pipe molds, with optic fiber densities of 1.125% (C1), 2.25% (C2), and 4.5% (C3, C4) area. Two samples were made for the 4.5% sample because they are also used for the composite wall test, with epoxy in between. Plaster is used as a substitute for concrete, because plaster is easier to shape and faster to cure, and under the assumption that the light transmissivity of optic fibers is dependent solely on the optic fiber density, and not the material it is embedded inside.

5.2.2 Transmittance Formula

It was observed that in doubling the optic fiber density, the transmittance increased by a little more than double. Unfortunately, only 3 fiber densities were used to conduct the experiment, therefore it is difficult to declare the true linearity of the relation. However, for this sample size, the linearity is 93%, hence for the scope of this project, the relationship will be considered linear.

As it was difficult to produce the 4.5% density sample for the small samples, the rest of the testing and prototyping was conducted with the 4.5% samples and no samples of any higher densities were produced. Though it is out of scope for this project, the linear relation allows for the scaling of fiber density based on desired light transmittance as necessary. Hence, 6% transmittance is achievable.

5.2.3. Composite Wall Transmissivity Test.

This test represents the light transmissivity of a two-block thick LTA wall. The C3 and C4 disks were stacked together to represent the stacking of two LTA blocks. The light transmissivity of the stacked disks was determined for disks spaced with epoxy mortar, disks spaced with a hollow spacer, and disks stacked back to back without spacing. The light transmittances were 0.037%, 0.044%, and 0.074%, respectively.

The results were counter to the hypothesis that LTAs stacked back to back will barely transmit light compared to blocks spaced with epoxy and air. On the contrary, they transmitted light the brightest, however, the transmittance of light was quite uneven across the surface area. The disks spaced with air and epoxy had significantly lower transmittance, but the light was evenly distributed across the surface of the disk. The hypothesis was wrong because the initial assumption was that the distribution of fibers would be such that the fibers will rarely line up between two plaster disks. In fact, the fiber density was high enough that quite a lot of fibers lined up with each other, though often imperfectly, transmitting a lot of the incident light. For building application, it is impractical to not have any spacing between blocks. However, this test demonstrates that the ideal transparent mortar is as transparent and as thin as possible to minimize light loss.

5.2.4 Clear Resin, Plastic Embedded Resin Transmissivity Test.

Clear epoxy and polyurethane resin are very costly. Therefore, tests were done to determine the light transmissivity potential of clear plastic embedded resin. The addition of plastics cuts costs and proposes a method to recycle clear plastics and glass.

This test was conducted inside a test tube. Similar standards to ASTM D1494-17 were followed, but with heavy modification to suit the shape of the test tube. A long and perfectly cylindrical glass apparatus is ideal because the cylinder's length can represent a good mortar thickness, while the volume of sample needed to fill the cylinder is minimal, reducing costs. But due to cost limitations, test tubes were a good compromise to represent that shape, and the length of the test tube at 145mm represented the thickness of epoxy resin mortar. The thickness is important because the plastic beads inside the resin are oriented randomly, and it was hypothesized that a thicker sample will have less anomalous variation in light transmission from plastic orientation. The perimeter of the test tubes was sealed with tape to ensure minimal light loss.

Two kinds of plastic beads, B1 and B2, were used for this experiment. On their own inside the test tube, they had a light transmission of 0.06% and 0.03% respectively. Embedded in epoxy at weight ratio of 36:140 or 26% bead to epoxy, their light transmittance improved to 5.68% and 3.01% respectively, whereas the resin on its own had 56.77%

transmittance. Using B1 as a sample, the light transmittance of epoxy decreased 10x over the distance of 145mm, however, the transmittance increased 94.67x from the beads alone. Hence, it is plausible to use plastic inside the mortar and have decent light transmission, however, the refraction index of the plastic must be very close to the resin.

5.2.5 Luminescent Resin and Plastic Embedded Luminescent Resin Transmissivity Test

A 44% luminescent powder to resin density mix was prepared for this test. On its own, it had a light transmittance of 0.02%. embedded with B1 and B2 at the same density as test III, they both had the light transmittance of 0.01%. The luminescent powder density is likely too high for the resin to transmit any meaning amount of light, however, even at this high relative concentration, when the sample was exposed to a 800 Lux light for 1 hour, it did not register any readings according to the photometer measurement. Furthermore, samples with clear resin and resin with beads had around the same transmittance when doped with luminescent powder. The hypothesis was that in the presence of luminescent powder, plastic embedded will have similar transmittance to clear resin, due to luminescent powders being a significant part of the light emittance. Though numerically this was true, the low light transmittance of 0.02% and 0.01% suggests that the luminescent powder concentration was too high for any meaningful analysis. Therefore, luminescent powder in the epoxy resin was useless in increasing its transmittance property.

Figure 8: Epoy resin samples in test tube. From left to right – epoxy, epoxy + B1, B1, epoxy + B2, B2

5.3. Heat Transfer Test

To assess the thermal insulation capacity of the sample, a one-dimensional steady state cylindrical heat transfer test was conducted (Payam et al., 2018). An evaluation was made to assess the necessity in including fiber optics within a sample cured for thermal insulation testing, for the prospect of saving cost and time. Incidentally, acrylic optic fibers as they are used for this experiment have similar thermal conductivity to light weight concrete; 0.2 and 0.11-0.19 W/m*k respectively. For precaution however, %Error in thermal resistivity was calculated for samples with and without embedded optic fibers at a cross sectional optic fiber density of 4.5%, assuming an Aircrete thermal conductivity of 0.11.

Equation 2: Thermal Resistivity

$$R_1 = R_{Concrete} = L/(k_1 * A_1)$$

$$R_2 = R_{Fiber} = L/(k_2 * A_2)$$

$$A_2 = 0.045 * A_1$$

$$R_{Total} = R_{Concrete\ with\ fiber} = (1/R_1 + 1/R_2)^{-1}$$

$$\%Error = 100*(1 - (R_{Concrete})/R_{Total})$$

With the assumption that heat transfer through a concrete block can be simplified as a one-dimensional heat transfer, thermal resistivity was calculated for a 15cm thick concrete wall of unit area. The equations demonstrated that the %Error in thermal resistance value of concrete samples with and without optic fibers is 7.35%. Given that the Aircrete cured for the project will be denser than typical Aircrete in order to be structural, the thermal conductivity assumption of 0.11 is very conservative. Realistically, with a higher concrete thermal conductivity of at least 0.18, the %Error is less than 4.76%; a value which represents that a concrete block sample in the presence of specified optic fiber composition has 95.23% the thermal resistivity. Suggesting that the 4.76% error is insignificant with respect to the time and cost in embedding the fibers into the test sample, the thermal test sample was made without optic fiber embedding.

5.3.1 Thermal Resistivity Test

Upon the advisement of Yvon Gariepy, laboratory director at Macdonald Campus of McGill University, a one-dimensional cylindrical steady state heat transfer analysis was designed to obtain the thermal conductivity of the Aircrete sample. A cylinder of 5cm diameter and 10 cm height was cured to conduct a test of one-dimensional steady state heat transfer through a cylinder with heat generation at the core. A vertical hole of about 6cm was bored in the middle of the cylinder to house a resistive heating wire and a thermocouple. The thermocouple and resistive wire were wrapped tightly and evenly in aluminum foil to ensure an even heat generation and to minimize thermal contact resistance to concrete. The cylinder wall was insulated with flexible foam to minimize convective heat loss. A secondary hole of the same depth is drilled at a set distance R_o from the core to house another thermocouple, and together with the thermocouple at the center, would provide the steady state temperature differential. The assumptions governing the test is that the system has negligible heat loss to the environment, the heat generated from the wire is solely emitted radially, and that the voltage and current as read by the resistive heating apparatus correctly represents the power $\dot{Q}$ (W) input into the concrete.

A steady state one-dimensional heat transfer differential equation was set up for a cylinder with heat generated at the center. It was solved for an equation to get T_{max}, which was rearranged to solve for thermal conductivity k. To and Ts were obtained via thermocouple readings.

Equation 3: Differential equation of heat transfer

$$(1/r)*(d/dr)*(r*dT/dr) = -\dot{q}/k$$

$$dT = (dr/r)*[((-\dot{q}*r^2)/(2*k)) + C_1)]$$

$$T = ((-\dot{q}*r^2)/(4*k)) + C_1*r + C_2$$

Boundary conditions:

$$dT/dr|_{r=0} = 0$$

$$T(0) = T_0$$

$$T(Ro) = T_s$$

Solution to the differential equation - Steady state 1D heat transfer equation for cylinder with core heat generation

$$T(r) = T_s + ((\dot{q}*r^2)/(4*k))*(1 - (r/R_0)^2)$$

$$T_{max} = T(0) = T_s + ((\dot{q}*r^2)/(4*k))$$

$$k = (\dot{q}*R_0^2)/(4*(T_0 - T_s))$$

Resistive heating was used to generate heat flux at the cylinder core. Current I (A) and voltage V (V) were recorded from the voltage input, which were used to calculate the total power $\dot{Q}$ (W) applied to the wire. The power divided by the volume of the concrete sample being heated provided the heat flux, $\dot{q}$ (W/m^3).

Equation 4: Power calculation

$$\dot{Q} = I*V$$

$$\dot{q} = \dot{Q}/V_s$$

As the resistive heating element was inserted to the depth of 6cm, and control volume limited to the outer radius of Ro = 1.3cm, and with the assumption that all the heat was emitted radially, the control volume of the concrete sample, Vs, was 3.6945*10-5m^3. The voltage and current read was 5V and 2.4A, which gave a power of $\dot{Q}$ of 10.5W. Consequently, $\dot{q}$ was 284.2 kW/m^3. The thermocouple readings showed a T_0 of 62.2 and T_s of 28.9, providing a dT of 33.3°C, and thermal conductivity k was 0.36 W/mK. R value as rated on industrial insulations are in the units of h*ft^2°F/BTU. For a standard 1 inch thickness of the concrete sample, the R value was 0.42.

Equation 5: R value

$$R_{Value} = L/k$$

Although the thermal conductivity test was likely inferior in accuracy when compared to laboratories equipped and seasoned in conducting thermal conductivity testing, the R value found at 0.42 is likely an acceptable thermal resistivity value for the Aircrete sample. This can be argued because the thermal conductivity value, upon which the R value is dependent, seems to be highly consistent with thermal conductivity that is to be expected from a concrete with a density of just above 1000 kg/m3 as reported by Hasan et al., 2012. The Aircrete sample has a density of 949 kg/m3, which is, though a bit lower, around the representative range of densities to have the sort of thermal conductivity.

The R value of 0.42 is more than double the insulation capacity of a concrete masonry unit which can range from 0.11 – 0.2. This means that to achieve the same amount of thermal insulation, Aircrete wall can be at least half the thickness and even up to 1/4th. This R value is equivalent to ½" gypsum boards, but unfortunately it is only 8.4% as effective as an insulation as an extruded polystyrene foam which has an R value of 5. However, in current production, structural Aircretes can have thermal conductivities as low as 0.11 W/m*k, which translates to an R value of 1.375, which is equivalent to the thermal resistivity of 1" thick plywood, or a 12" thick concrete masonry unit wall (Forterra, 2019). Therefore, in refining the production method, material composition, and the thermal conduction test of Aircrete, it is plausible to improve its R value about 3.3 times than achieved from this project. This margin of improvement is highly critical. It suggests that the wall thickness, when made from improved Aircrete, can be 3.3 times thinner than the Aircrete made for this project, which is already more than twice as insulating as concrete masonry units. It implies a drastic saving in material cost and weight.

The R value of 0.42 per inch translates to a block resistivity of 1.6 as the block is 4 inches thick. The goal was to achieve R5 on the block, so by refining the deign such as the thermal conductivity is 0.11 W/m*k, it is achievable.

5.4 Amorphous Fiber Placement Method Experimental Trial

The performance of the amorphous fiber placement method was evaluated by comparing the optic fiber density with the highest possible optic fiber density. For this test, a 4” high 4” diameter concrete cylinder was prepared. The ideal optic fiber density of this concrete was arbitrarily set to be 300 fibers. Assuming the same number of optic fibers exposed on the incident and transmittance side of the concrete, the minimum length of optic fiber necessary was calculated by the height of the concrete cylinder multiplied by the number of optic fibers exposed on the face. This provided a value of 30m of optic fiber.

Figure 9: Amorphous fiber bundle

The weight of 30m of optic fiber was determined to be 13.5g and made into a spool, which was then embedded into the concrete sludge. The cured concrete was then cured, and the top and bottom 1inch was removed to expose the optic fibers, creating a concrete cylinder of 2” height. The number of exposed optic fibers were recorded to be 52. The 2” thick sample was further sliced into half to make two of 1” thick samples, whose optic fiber exposure points was recorded to be 78. Comparing the highest number of optic fibers exposed from the amorphous samples, it is apparent that only a maximum of 27% of the intended optic fiber exposure amount was actually achieved. The test was repeated on another 4” high concrete sample with another spool, and the results were very similar, which suggests the presence of a repeatable optic fiber density achievable through the amorphous spool method.

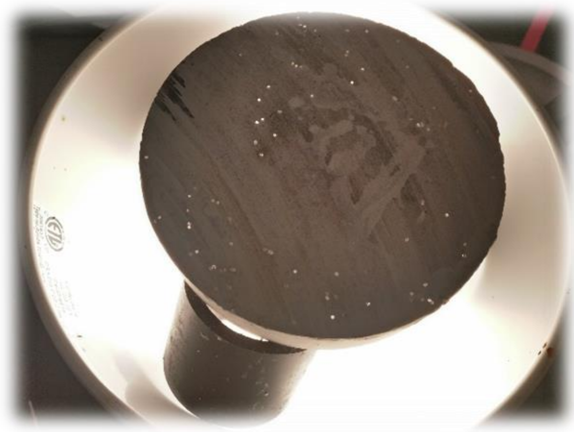

Figure 10: Cross section of concrete embedded with amorphous fiber bundle

6. Socio-economic and Environmental Considerations

6.1. Environmental Considerations

Durability. Concrete is considered a highly durable material with a long service life. Able to withstand climatic pressures and time, concrete is a durable and sustainable material. Light transmitting concrete should be durable as well.

Cement Emissions. Cement production causes a significant amount of greenhouse gas CO2. Though cement is a key ingredient in concrete, it is possible to use alternative forms of cement such as fly-ash or use a reduced portion of cement to factor in environmental benefits.

Life Cycle Recycling. Crushed concrete aggregates can be reused in future applications. However, with the increasing complexity of composite concrete, it becomes too difficult to separate the materials and impossible to recycle the material.

Energy Consumption Reduction. Lighting transmitting concrete with insulation properties can reduce energy consumption regarding indoor lighting and HVAC requirements.

6.1.1. Life-cycle Assessment (LCA)

Using a life cycle assessment approach when designing, building and maintaining concrete buildings and infrastructure helps assess the environmental impact of a product at all stages. Relevant stages in general concrete production include raw material extraction, materials processing, concrete manufacturing, distribution and transportation, on-site construction, operational service life period, maintenance and repair, demolition followed by end of life which can consists of disposal, repurposing, re-using or recycling (Park, 2004). To determine sustainability indicators, certain environmental data can be quantified such as the land use, greenhouse gas emissions, renewable and non-renewable energy consumption, hazardous waste generation, pollutants released into the air, water or land, and water consumption. Other data that may be more difficult to model in a life cycle assessment approach include the potential for concrete to contribute to specific environmental issues such as climate change, eutrophication, acidification, smog and toxic residue. Previous studies have shown that raw materials extraction, especially cement production, and transportation operations are the biggest contributors to concrete's negative environmental impact (Sjunnesson, 2005). The environment impact of raw materials extraction can be minimized by reducing or substituting cement content or by offsetting negative impacts with positive ones such as energy savings by minimizing lighting or heating costs such as in light transmitting concrete with insulative and light transmitting properties.

Currently, due to its novel nature, there no published research on life cycle assessment (LCA) studies of light transmitting concrete according the literature review preformed. However, many life cycle assessment studies have been conducted on various concrete products. Overall, the main environmental impact from concrete is the greenhouse gas (GHG) emissions, a known accelerator of climate change, from cement production. Additionally, the energy consumption, specifically non-renewable energy such as fossil fuels, is significant in the transportation of finished products and raw materials to concrete manufacturing sites. In a cradle to grave assessment of light transmitting concrete, the end of life stage is problematic due to a lack of specific recycling technology and specialized facilities (Martinez et al., 2014). On the other hand, standard concrete, made from fine and coarse stone aggregate, cement and water does have waste management procedures and can be reused or recycled instead of disposed in a landfill shortly after demolition. For example, standard concrete can be crushed back into coarse aggregates. However, standard concrete is often reinforced using steel rebar to increase his tensile strength and though challenging, these components have been separated for recycling purposes in the construction industry. Due to concrete's long service life and the light transmitting concrete being a relatively recent technology, most light transmitting concrete products have not reached their product lifespan. As such, there are no developed waste or recycling management procedures in place. Consequently, it is postulated the separation of glass or plastic fibers from the light transmitting concrete blocks may prove to be too challenging and they may simply be landfilled. Subsequently, Aircrete is an uncommon practice due to the restrictive nature of some building codes and its specific life cycle assessment (LCA) hasn't been determined in depth either. However, it should be similar in environmental impact to regular concrete despite not utilizing coarse aggregates such as stone. Fine aggregates such as sand are sometimes used in Aircrete production, but it is possible for the foam to replace the aggregates entirely. In that case, cement content may be higher and therefore there would be more GHG emissions produced during its manufacturing. Additionally, a key component of light transmitting concrete is the embedded optic fiber which can be made of plastic or sand. Plastic is generally preferred to lower cost and no shatter risk due to additional material flexibility. Besides light transmitting concrete, fiber optics are also used in telecommunications and LCA have been conducted to assess their environmental impact and reliability evaluation compared to copper wiring (Unger and Gough, 2007; Limin and Yunna, 2013). However, these studies are not representative of the current designed application and context and it may be more appropriate to consider the manufacturing of plastic optic fiber in general for the life cycle inventory. Due to it being made of plastic, it is postulated optic fibers may be recycled if melted in large quantities and remolded, but spare optic fibers may not be economically viable to recycle if not properly separated and not found in significant quantities. Furthermore, plastic recycling is not infinitely renewable as there is a loss in quality after each recycling process as lower grade plastic is produced. This lower grade plastic may not be suitable to use as optic fiber as it may lose its properties related to transmission attributed to total internal reflection. Instead, the recycle plastic may be used as a component of everyday plastic objects such as benches or containers. Unfortunately, it is more likely that it will be impossible to recover significant amounts of fiber optics in light transmitting concrete for recycling purposes due to separation of materials being too difficult or too economically costly to justify the recycling process.

6.2. Social Considerations

Aesthetic Value. While standard concrete is known to be a grey and dull looking material, light transmitting concrete will promote aesthetic value. It can be used for artistic and decorative purposes.

Human Well-Being. Optimizing natural lighting in a building using light transmitting concrete will promote human well-being. The insulation provided by the concrete wall will assist in producing comfortable indoor conditions.

Toxicity of Materials. It is imperative that building materials be non-toxic especially when they are in close contact and interaction with human as is the case with walls. Any toxic particulates leeching must be limited.

Technology Transferability. Technology transferability is interesting to consider in engineering design as it can identify limitations that prevent a design from being adopted. Standard concrete has proven to have technology transferability as it is used worldwide by countries with varying socio-economic, cultural and political climates.

6.2.1. Occupational Health and Safety Risk Mitigation

Risk Factor	Risk Rank	Risk Contributors	Mitigation Procedure
Exposure to Cement Dust Irritation or Chemical Burn	2	-Contact with eyes, nose, throat, skin -Lack of safety clothes and gloves	-Use soap and water to wash cement dust to avoid skin damage -Wear proper safety clothes and equipment
Exposure to Wet Concrete Irritation or Chemical Burns	2	-Contact with eyes, nose, throat, skin -Lack of safety clothes and gloves	-Wear gloves, long sleeves and full-length pants, waterproof boots, eye protection -Wash contaminated skin area with cold water as soon as possible
Machine Guarding	2	-Unguarded machinery can lead to worker injury	-Follow proper instructions for machines especially turning them off
Poor Ergonomics Sprains and Strains	3	-Improper lifting -Awkward postures -Repetitive motions	-Take regular breaks -Honor personal physical limits

Table 13: Risk Factor Matrix for Concrete Manufacturing Worker Safety

6.3. Economic Considerations

The manufacturing process for the 20 blocks follows the manufacturing process for the prototypes. The cost of 20 masonry blocks assume a total concrete block volume of 45 liters. The density of LTA at 949 kg/m3 is less than half of concrete, hence the amount of cement and water needed are also halved. The electricity needs are solely present in the operation of the foamer and the blade cutters, but the total time of operation does not amount to more than one hour, and therefore is not considered in the cost. The water amount is also negligible in terms of the price.

The costs are separated into fixed and variable costs. The fixed cost is comprised of the foamer, mold, mixing buckets, circular saw, and the saw blade, and they in total amount of $636.95. the variable cost, comprised of the concrete ingredients and electricity, amount to $398.25. The tabulated costs do not include any plastic aggregates because plastic will not be bought but recovered from waste. hence, just for one batch of 20 masonry block production, the manufacturing cost is $1035.20, or $51.76 per block. With cinder blocks ranging from $2 to $5, LTA blocks are 10-25 times more expensive to manufacture than the market price of the cinder blocks (BOEHMERS, 2017).

However, mass produced, the fixed cost will eventually become ignorable. For example, after the production of 10,000 units, the fixed cost becomes 10 cents per block. Thus, after a significantly high volume of production, LTAs will cost $19.91 per block, which is still 10 times the cost of a cinder block. Here, the main cost is most notably the optic fibers, which cost $18.27 per LTA block. A cheaper optic fiber source can reduce the cost drastically. Furthermore, the pricing above does not include manual labor, of which is needed in order to embed the optic fibers inside the foam mold, as done for the prototype manufacturing. However, mechanized fiber placement within a mold will improve the labor cost. Another method to reduce labor cost is to employ the amorphous fiber orientation method. However, this method is only around 27% as efficient as a perfectly placed fiber mold manufacturing method, implying that the cost of the optic fiber will be double.

This costing also does not include epoxy mortars. The amount of mortar used in construction is variable upon the shape and size of the blocks used, and their placement. The epoxy used for this project cost 31.04 CAD for 236mL. For instance, assuming a half inch thick mortar throughout an LTA block wall that is two blocks wide and 5 blocks high, the mortar volume necessary is 2.4L. a cement mortar at this price point costs in excess of $1, while epoxy will cost $310.40. Understandably, the cost of epoxy will be lower with appropriate distribution pricing, however, it is still a gap of 300x. This cost can be drastically reduced with the plentiful mixing of plastic beads within the epoxy resin. Though it was seen that the coating of epoxy resin can improve the light transmissivity of certain plastic beads by 95x, the minimum allowable amount of epoxy for a given number of plastic beads for meaningful light transmission is still up to further experimentation. Furthermore, certain plastics and glass fragments are more closely suited for resin than others due to their index of refraction, which will influence the amount of epoxy necessary in the mix. All in all, epoxy mortars are financially highly impractical, but there are definitive methods to cut the cost.

6.3.1. Costs Breakdown

Expense for 20 Masonry Blocks

Product	Quantity	Unit price ($)	Total price ($)	Online link
Optic fibers	2	158.87/2.7km	317.74	https://amzn.to/2YXCx6i
Cement	1	12.20/40kg	12.20	https://bit.ly/2UrApFl
Dish soap	4	4.09/638mL	16.36	https://bit.ly/2OZeyiw
Water	<50L			
Electricity		0.08/kWh	-	https://bit.ly/2D9qjy9
Foamer	1	24.99	24.99	https://amzn.to/2YSI1PE
Foam mold	8	7.49		https://bit.ly/2D6QF3T
Buckets	3	3.50	10.50	https://bit.ly/2If1fdt
Circular saw	1	361.06	361.06	https://amzn.to/2GbU03m
Masonry blade	1	97.40	97.40	https://amzn.to/2IlxITX
Total			560.17	
Total (+tax)			**644.20**	

Table 14: Economic Analysis for Production of 20 Light Transmitting Aircrete (LTA) Masonry Blocks

7. Discussions

7.1 Possible Applications

With strong insulation and structural capacity, the design will able to bear loads while providing indoor building inhabitants with comfortable temperature conditions. Particularly, the design is aimed towards indoor applications to increase natural or artificial lighting for greater human wellbeing in buildings or rooms with little windows. Though the design will not replace windows or lighting fixtures entirely, it will be aimed as a supplementary ambient lighting to rooms and buildings. Particularly, some office rooms or classrooms do not receive an adequate amount of lighting and certain tiles and walls could be retrofitted with the product to increase incoming lighting as well as remaining a load bearing structure capable of providing an appropriate amount of insulation for inhabitants. In addition to being used indoors and outdoors for decorative building elements such as walls, partition walls, pavements and floors, light transmitting Aircrete (LTA) is versatile in use for structural applications as well. Some examples include light installations, signs, furniture such as benches, desks and countertops. Due to its insulating properties, it can be used as a building material and supplemental light transmitter for underground structures such as metro stations (Market Research Engine, 2018). It is particularly useful in colder climates where insulation is important as it can thermally insulate without fully blocking out available natural sunlight. Light transmitting Aircrete (LTA) is also useful in road or pedestrian safety as LTA pavements or speed bumps could be lit from below at night and lighting could dynamically adapt to required signal and traffic fluctuations. Besides indoor visually appealing applications for company branding or lit stairwells for safety and style, it could also be integrated into walls for additional outdoor lighting transmission in case of emergency power failure such as in fire escapes. By replacing the fine aggregate in LTA with crushed recycled plastic or glass, the sustainability merits of LTA are increased. In fact, since it incorporates both the properties of concrete and glass or plastic, it can be tailored towards architectural applications where glass, plastic and concrete are presently used. Not only does it admit light, thermally insulate, it also retains privacy by having opacity and is structural integral. LTA offers many advantages over traditional concrete formulations including less energy consumption related to lighting and heating, the possibility of illuminating pavements and applying an aesthetic finishing surface, low required maintenance due to its durability and a high degree of workability and stackability thanks to its light weight design.

7.2 Recommendations

The refinement of LTA and the transparent mortar is crucial in entertaining the production possibility. The LTA does not have sufficient thermal resistivity to be considered a replacement for foam insulation, and the light transmissivity is quite poor when the blocks are stacked together. The thermal resistivity can be improved through the refinement in the ingredient ratios; foam in particular. Furthermore, the thermal conductivity of the sample should be measured by laboratories specializing in thermal conductivity testing. Given that structural Aircretes of 0.11 W/mK are available in the market, the scope for improvement is quite apparent. However, the potential to improve the light transmissivity of Aircrete is slightly more difficult. If the means of light transmission remains to be through optic fibers, the only way to improve the transmissivity is through the increase in optic fiber density. This is very costly but possible. The highest optic fiber density tested for this project is 4.5% producing a 3% transmittance. The doubling of the optic fiber density should increase the light transmittance to 6%, which was our initial goal, but that would imply that 9% of the surface area of the LTA block will be occupied by optic fibers. This is a significant amount of optic fibers and is not affordable for widespread application. Another potential way to increase the light transmittance is to entertain ways for the concrete itself to absorb and reemit light, following the principle of phospholuminescence. The effectiveness of this, however, is up to rigorous experimentation.

The amorphous fiber orientation method can also be improved. The fiber bundles produced for the test was random, however, the scale of the test conducted meant that the bundle was of a certain size with the fibers curling in certain manners. On a larger sample, the fibers would not be curled up to the same degree. In addition, the fiber bundle was extruded from a spool which encouraged a lot of loop formations which, despite our best efforts, pushed against the side of the cylindrical mold, resulting in the concrete sample to have a fiber concentration around the perimeter. These parameters need to be characterized, and tests must be conducted to see if there is a better way to bundle the fibers and achieve a high enough degree of fiber placement, such as 70% or more.

In addition, given more availability in time, a full-scale prototype production is ideal. Also, light transmittance can be quantified, for concrete with possible aesthetic applications, a qualitative analysis is also important. The goal of 6% transmittance was not based on any regulation, so it is possible that 3% transmittance is significant enough for potential customers to desire its purchase or production.

8. Conclusion

Though the light transmissivity of the LTA blocks do not satisfy the goal of 6% light transmittance when stacked, it still transmits a visible amount of light which can be used for aesthetic purposes. Moreover, the light is likely enough to register changes in lighting outside, such as humans walking by, which is if nothing else, cool. The compressive strength and insulation values indicate that the production of LTA will be viable for real world application as an insulating concrete. Perhaps LTA can be solely used as 1 block thick walls, which can deliver the 6% light transmittance. Either way, the cost is enormous, and production will be slow as the amorphous placement method is not very efficient. All in all, the project was successful in creating a fiber embedded Aircrete whose potential in the real world is currently nebulous, but it is quintessential a novel material born out of this project.

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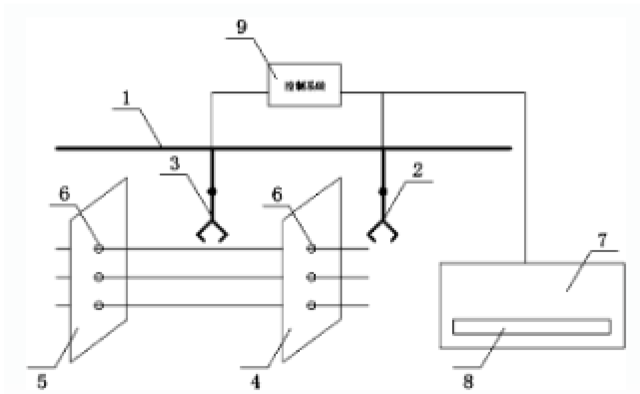
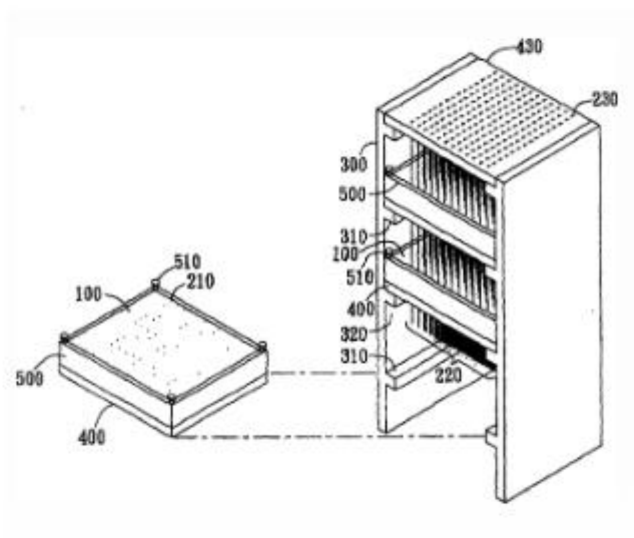
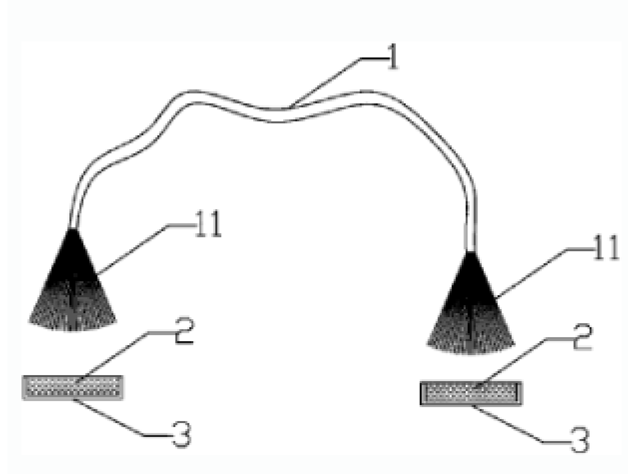
Appendix



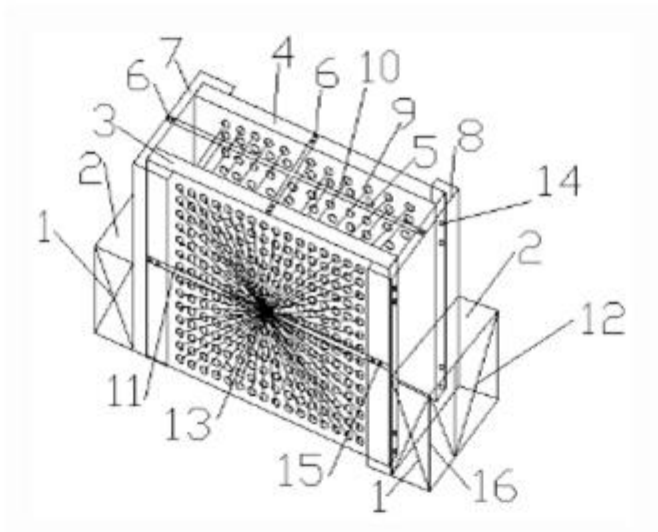
Appendix 1: Patent No. CN207044385 – Robotic arm assembly for threading optic fiber through two opposing faces of the concrete mold of a light transmitting concrete



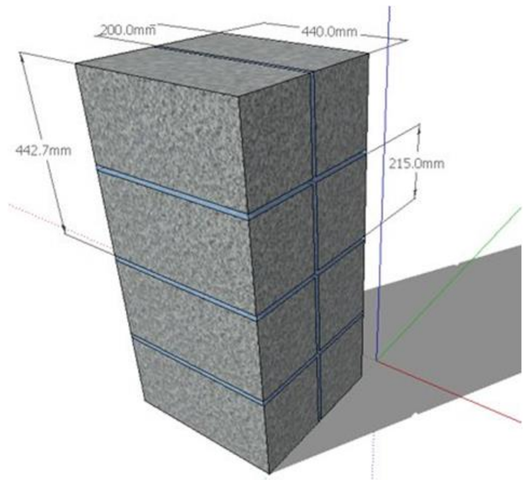
Appendix 2: Patent No. CN101234510 - A



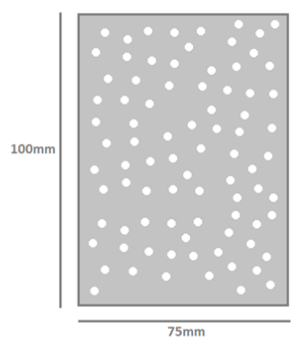
Appendix 3: Patent No. CN102758496



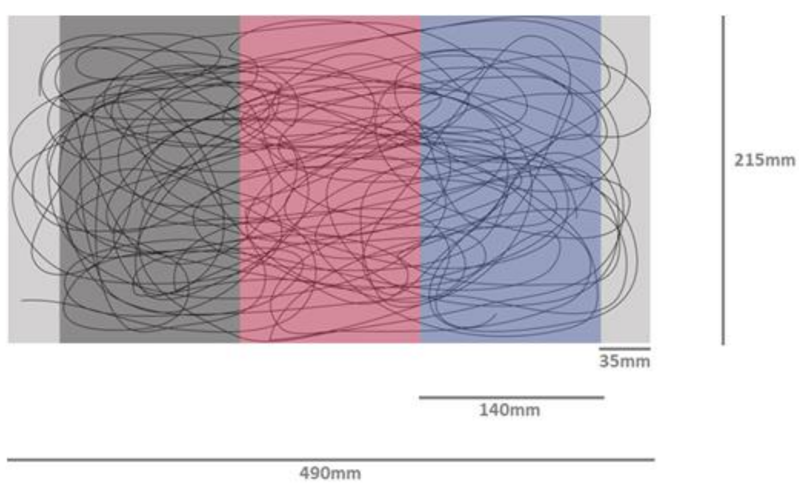
Appendix 4: Patent No. CN105818252



Appendix 5: Four-story 2 layered concrete wall, incident and transmission faces on the green axis (we will create only one-story sample)

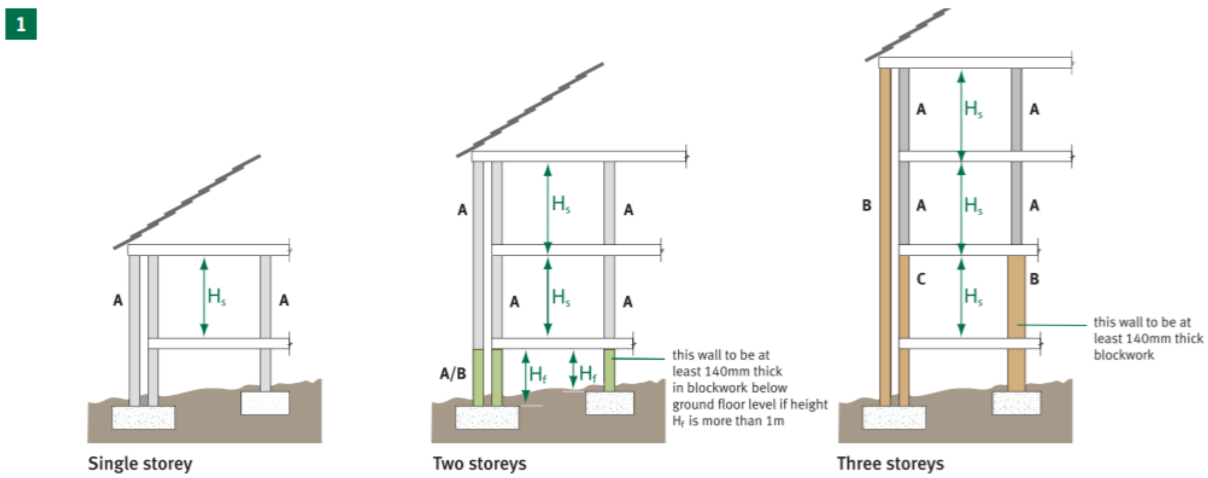


Appendix 6: Fiber density is represented by the number of fibers present in a given surface area



Appendix 7: Left side view (red axis view of Appendix 5) of amorphous fiber orientation; grey, red, and blue represent 3 distinct blocks which will be produced from the entire mix

Declared Compressive Strength Values of H+H Aircrete				
	Solar Grade	Standard Grade	High Strength Grade	Super Strength Grade
BS EN 771-4	2.9N/mm^2	3.6N/mm^2	7.3N/mm^2	8.7N/mm^2



Key: Min strength

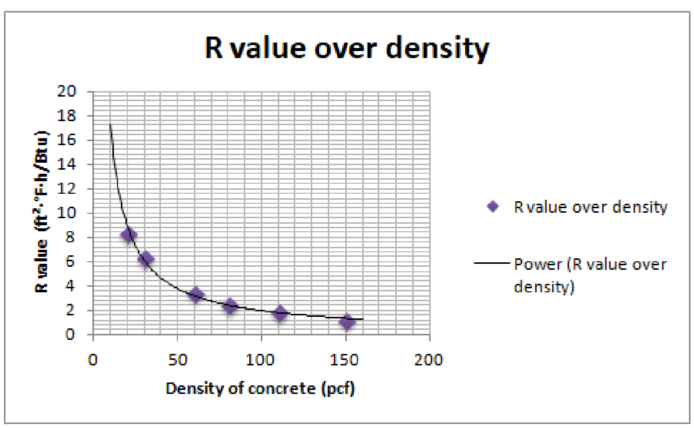
- A — 2.9N/mm^2 where H_s is 2.7m max
- A/B — H_f less than or equal to 1m – 2.9N/mm^2; H_f greater than 1m – 7.3N/mm^2
- B & C — 7.3N/mm^2

Notes

1. If H_s is not more than 2.7m, the compressive strength of blocks used in the wall should be as indicated by the key.
2. If H_s is more than 2.7m, the compressive strength of blocks used in the wall should be at least Condition B, or as indicated by the key whichever is greater.
3. If the external wall is solid construction, the blocks should have a compressive strength of at least that shown for the internal leaf of a cavity wall in the same position.
4. Timber roof construction, 12m max span.
5. Timber or concrete floor, 6m max span.
6. Wall lengths 12m max.

This diagram is taken from Figure 12 and Table 5 of BS 8103-2

Appendix 8: H+H UK Aircrete Building Guide Compressive Strength Specifications



Appendix 9: R value and concrete density graph, data retrieve from ASHRAE, 1993