SUSTAINABLE MATERIALS:

FOR ZERO WASTE DESIGN

Discovering alternative materials for the future of zero waste architecture

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Spring 2015

DCP4290 Capstone

CHAPTER 1: INTRODUCTION

Zero Waste

Zero Waste is the philosophy that encourages the redesign of resource life cycles so that all products are reused and no trash is sent to landfills or incinerators. The definition most commonly used was created by the Zero Waste International Alliance:

> "Zero Waste is a goal that is ethical, economical, efficient, and visionary, to guide people in changing their lifestyles and practices to emulate sustainable natural cycles, where all discarded materials are designed to become resources for others to use. Zero Waste means designing and managing products and processes to systematically avoid and eliminate the volume and toxicity of waste and materials, conserve and recover all resources, and not burn or bury them."[1]

This includes more than eliminating waste through reusing and recycling, it focuses on changing the structure of production and distribution processes to help remove waste altogether, similar to the cyclical movement of nature. It encompasses all aspects of sustainability and has the opportunity to change the way future buildings are designed, built and used.

The concept of Zero Waste is not a new thing. The term zero waste was first used publicly in the name of a company, Zero Waste Systems Inc., a company in Oakland, California, founded by PhD chemist Paul Palmer in the 1970s. This company specialized in resourcing used chemicals from the rapidly growing electronics industry, and selling it

[1] "ZW Definition." Zero Waste International Alliance. N.p., 2009. Web.

back to various scientists and companies. Being the only company that did this, they gained a lot of international recognition. Soon after, Palmer formed the Zero Waste Institute, which introduced the idea to stop the production of waste rather than try to reuse waste. The Zero Waste movement reached its highest publicity in the late 1990s to early 2000s. Many zero waste initiative websites, such as Zero Waste Institute Alliance, Eco-Cycle, and GrassRoots Recycling Network documented communities around the world that created public policies to promote zero-waste practices and gave workshops and conferences about zero-waste activities. Today the movement continues to grow in all types of the built environment.

Zero waste encompasses all parts of sustainability, but the built environment is a significant factor in the production of waste. Buildings generate waste before a building has even started construction, beginning as early as using paper for preliminary drawings. In order to better understand where waste is coming from, waste production needs to be analyzed from every point in the building cycle: design, construction, operation, and demolition. The concept of zero waste aims to eliminate rather than manage waste. Thus, achieving a Zero Waste design starts with approaching the reasoning behind why waste is created, and working from there to eliminate this concept all together. "Doing more with less played a valuable role in slowing ecological destruction in the late 20th century but it is not up to the challenges presented by the kind of growth and global change expected in the 21st".[2] Improving on yesterday's recycling approach, zero waste can push sustainability in

[2] McDonough, William, and Michael Braungart. "Toward a Sustaining Architecture for the 21st Century: The Promise of Cradle-to-Cradle Design." McDonough Innovation. N.p., 2003. Web.

the right direction. Working to solve this issue can lead to monumental discoveries for material usage in the future of sustainable architecture.

The Cradle-to-Cradle Concept

The Cradle-to-Cradle concept was created to do just that. C2C was developed by Architect William McDonough and Chemist Michael Braungart as a new perspective on how to approach waste, recycling, and today's industry. C2C models human industry on nature's processes, viewing materials as nutrients circulating in healthy, safe metabolisms. The term was originally coined by Walter R. Stahel in the 1970s and is now a registered trademark of McDonough Brangaurt Design Consultants (MBDC). In 2012, they turned over the certification to an independent, non-profit organization called the cradle-to-Cradle Projects Innovation Institute.

In the Cradle-to-Cradle model, all materials used in industrial or commercial processes fall into two different categories of nutrients: technical and biological. Technical nutrients is defined as non-toxic, non-harmful synthetic materials that have no negative effects on the natural environment. These can be used continuously in cycles as the same product without losing their quality, and would not have to be down-cycled and eventually thrown away. Biological nutrients is defined as organic materials that can be disposed of in any natural environment and decompose into the soil without effecting the natural environment. After studying what exactly got the world to this point, it was concluded that some negligent decisions and choices were made during the industrial revolution that generated many of the current problems we have today concerning toxic and mad-made waste. McDonough and Braungart sought to create something to challenge these issues in a way that recycling and efficiency do not. In 2002 they wrote a book called Cradle-to-Cradle: Remaking Way We Make Things that details the concept and specific ways to achieve the model.

The C2C system is a possible solution for the zero waste future. It is a regenerative design process that uses a biomimetic approach to the design of products and systems. McDonough and Brangaurt describe it in this way:

> “Cradle-to-cradle design is animated by ecological intelligence. In the natural world – a grand, evolving system based on hundreds of millions of years of research and development – the processes of each organism contribute to the health of the whole. One organism’s waste is food for another, and nutrients and energy flow perpetually in closed-loop cycles of growth, decay and rebirth. Waste equals food. Understanding natural systems allows architects and designers to recognize that all materials can be seen as nutrients that flow in natural or designed metabolisms”.[3]

The C2C concept describes yesterday’s resolutions of efficiency and conservation as a helpful yet misguided ideas of a solution. Using less natural gas and sending less building material to landfills simply limiting the negative impacts, not a long term answer to this global problem. We must adopt a strategy that will solve rather than merely alleviate the problems associated with buildings and construction, something that leaves only a positive human ecological footprint and more positive effects, rather than just less negative effects.

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[3] "Toward a Sustaining Architecture for the 21st Century”

The Cradle-to-Cradle concept references the most basic, biological system that has nourished the earth and kept it thriving for millions of years. Today's industry is viewed as singular things that can be changed and manipulated separately from one another. But in nature, nothing is singular. "The tree is not an isolated entity cut off from the systems around it: it is inextricably and productively engaged with the. This is a key difference between the growth of industrial systems as they now stand and the growth of nature".[4]

The Future

In this research, several questions were asked in order to better understand and analyze zero waste systems. The first question is what materials can be further researched and discovered as possible alternatives to conventional building materials that will work towards a sustainable, zero-waste future and be able to fit into the cycles in the Cradle-to-Cradle system? This information will assist in exploring the answers to the second research question. After researching two potential sustainable alternatives to building materials and how they work, based on a set of criteria, will help to give a better understanding of what direction to take in future sustainable design. Based on these findings, general recommendations for future use in zero waste design will be given for these millennial materials. Sustainable materials in architecture will be further discussed in the next chapter.

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[4] McDonough, William, and Michael Braungart. Cradle to Cradle: Remaking the Way We Make Things. New York: North Point, 2002. Print.

CHAPTER 2: MATERIALS IN ARCHITECTURE

Several aspects of a building define its ability to be considered environmentally-friendly and efficient. "The idea of local sustainability is not limited to materials, but it begins with them".[5] That being said, materiality, the pieces used to make up the physical building, is one of the most important parts of sustainable design. The materials used in a building have a substantial impact on whether the building is considered sustainable. This research began with defining Cradle-to-Cradle design and the criteria of the concept. What conditions must a material meet in order to be considered sustainable enough to work within the C2C system?

Material Life Cycles

In order to state a material as a sustainable material, all aspects of that material's life cycle must be taken into account. "During the last 30 years an increased understanding of materials and their characteristics has brought to light other less obvious impacts associated with materials, which affect people and environments well beyond the building envelope".[6] Addressing the entire life-cycle of the material is necessary and every step in its lifespan must be considered. There are five general stages in a material's lifecycle: material resourcing, manufacturing process, energy use and transportation, material us, and material disposal. A material's life span starts with material resourcing. This addresses

[5] Cradle to Cradle: Remaking the Way We Make Things.
[6] Sassi, Paola. "Materials." Strategies for Sustainable Architecture. London: Taylor & Francis, 2006. 144-97. Print.

where the resources are coming from and how much it is. It also includes the extraction and harvesting processes in order to obtain the resource, if necessary. The next step is the manufacturing process of the material. This means creating a usable material from a raw resource. While using other resources to combine and make the material, this step almost always requires some sort of energy and/or fossil fuel usage as well.

After the manufacturing of a resource, there is the transportation of the material. As stated in the previous step, there is energy use in the extraction and manufacturing of the resource, but this does not include the energy used to transport the material once manufacturing is complete. Transportation produces carbon dioxide into the atmosphere and contributes to pollution. Material use is the most common stage people are aware of when looking at the materials sustainable qualities, and refers to the use of the material and maintenance of it while in use. The final stage of a materials lifespan, also commonly considered in the sustainability of a material is the material disposal. What happens with the material when you are done with it? Where does it go? Many issues have risen from disposal of manmade materials in landfills, including harvesting toxic chemicals that leach into the ground. Recycling has alleviated the growing landfills but only helps a small percentage of the disposal of building materials.

In today's society, there are several commonly-known considerations for make a material 'sustainable. Paolo Sassi recommends several considerations to take when choosing building materials in her book, *Strategies for Sustainable Architecture*: design for longevity, use waste a resource, avoid resource depletion, minimizing manufacturing impacts, energy use in materials, and waste minimization. Designing for longevity means using current materials more efficiently. This lessens the waste being produced from those materials reducing the impact. There are three ways you can use existing materials: by using the existing building as a whole, reusing building components, and using recycled materials. Designing buildings so that components can be removed and replaced is not only beneficial in terms of sustainability, it also makes general maintenance and facilitation less costly. The second consideration is using waste as a resource. In order to reuse materials instead of using virgin materials there needs to be a balance between the reused and recycled materials available in construction. There needs to be a high demand for recycled and reclaimed material in order for there to be a sufficient movement in designing for the reuse of materials. There are issues however with using reclaimed materials like costs, availability, and compliance with performance standards, which are all things that need to be addressed.

The third strategy is avoiding resource depletion. "Sustainability is very much about considering the future and thinking long term".[7] There are some non-renewable materials that are considered plentiful, but the alternative to that is using renewable materials. But issues with exploitation in harvesting and/or extracting renewable resources can cause problems and disturb the environment, and must be taken into consideration. Minimizing manufacturing impacts is also suggested as a strategy for sustainable architecture. It always important to look at the manufacturing processes involved in their produces. In many cases, the cost, energy, and resourcing of materials that are 'natural' could possibly be very environmentally harmful. Energy use in production is a commonly known

[7] "Materials." Strategies for Sustainable Architecture. Pg. 166

consideration for sustainable material choice. “The manufacture of a building requires energy, materials, and often, water”.[8] The entire embodied energy of a material must be accounted for, meaning the energy taken to harvest or mine the resource, transport it, process and manufacture it, and finally install the material. And the last consideration discussed is waste minimization. Waste minimization means more recycling of materials and less new material needed to be produced. This is always advocated and encouraged as a building practice, as all parts of a building’s life, beginning with the building design all the way until the building demolition offers opportunities to minimize waste production.

All of these proposals for material efficacy are common ground for today’s understanding of sustainable materials and what must be considered when choosing an environmentally friendly and efficient building material. But these strategies can only go so far as being the most promising sustainable answer for green building. A push farther into developing truly sustainable and reusable materials that meets every criteria is needed to be considered functional in a zero waste cycle.

Materiality in Cradle-to-Cradle Design

The Cradle-to-Cradle concept has a different approach to building materials that can possibly solve the issue of whether a material is one hundred percent reusable. The difference between regular material efficiency in sustainable building and the concept of C2C design is in the material cycles. This concept is based upon the idea that waste equals

[8] “Materials." Strategies for Sustainable Architecture. Pg. 182

food. Rather than seeing materials as a waste management problem, as in the cradle-to-grave system, C2C design is based on the closed-loop nutrient cycles of nature. In the natural world the processes of each organism contribute to the health of the whole. Understanding natural systems allows designers to recognize that all materials can be seen as nutrients that flow in natural or designed metabolisms. Materials designed as biological nutrients provide nourishments for nature after use. Technical nutrients circulates through industrial systems in closed-loop cycles of production, recovery, and remanufacture. "Buildings constructed with these nutritious materials, and designed to respond to local energy flows and cultural settings, encourage patterns of human settlement that are restorative and regenerative".[9] Specific care needs to be taken to prevent contamination of these nutrients and avoid the mixing of the two.

By modeling human regenerative cycles, C2C design seeks systems that generate wholly positive effects, rather than just less negative effects. "Where eco-efficient designs aim to dematerialize—minimizing the negative effects of toxic materials and polluting fuels—cradle-to-cradle design seeks the rematerialization of safe, productive materials in systems powered by the sun".[10]

> "Rematerialization can be understood as both a process and a metaphor. In the industrial world, it refers to chemical recycling that adds value to materials, allowing them to be used again and again in high-quality products. As a metaphor growing from this process, it

[9] McDonough, William, and Michael Braungart. Cradle-to Cradle Design. "Toward a Sustaining Architecture for the 21st Century: The Promise of Cradle-to-Cradle Design." McDonough Innovation. N.p., 2003. Web.
[10] Waste Equals Food. "Toward a Sustaining Architecture for the 21st Century"

suggests a design strategy aimed at maximizing the positive effects of materials and energy and participating in the earth's abundant material flows".[11]

The answer to effective rematerialization is identifying material chemistry and tracing material flows. Valuable construction materials can be rematerialized into useful construction materials, rather than recycled into hybrids of lesser value, inevitably ending up in a landfill. Rematerialization can be achieved in a large scale through a nutrient management system called Intelligent Materials Pooling. "This system, designed to effectively manage flows of polymers, rare minerals and high-tech materials for industry and architecture, as well as local, low-tech flows of natural resources, calls for cooperative networks geared to optimizing materials' value".[12] This type of upcycling sets the Cradle-to-Cradle concept apart from today's current sustainable practices and has the opportunity to change the future of sustainable material and design.

'Sustainable' Building Material

What needs to change in present sustainable materials to be able to work within the biological or technical nutrient cycles of the Cradle-to-Cradle concept? In this research, two common building materials were chosen for individual assessment: concrete and insulation. These materials are used in almost every building structure and are under constant evaluation for efficiency and sustainability. The information critical to understanding these materials are material characteristics, positive and negative qualities

[11] Waste Equals Food. "Toward a Sustaining Architecture for the 21st Century"
[12] Intelligent Materials Pooling. "Toward a Sustaining Architecture for the 21st Century"

of the material, and possible sustainable alternatives that can fit into the C2C cycle. Based on these findings, an evaluation of the sustainable alternatives will be done, and specific recommendations will be made which material will work best based on the category of interest. In the following two chapters, these materials will be analyzed and discussed as materials in the Cradle-to-Cradle system and for the future of zero design.

CHAPTER 3: CONCRETE

Concrete is everywhere. "The basic components are water, sand, gravel, and cement. Sand and gravel are mined, usually quite close to their point of use. Cement is made from limestone primarily, heated and combined with other elements, then crushed into a powder".[13] In today's world, concrete can be found in almost every structure and is twice as commonly found in buildings than any other material. While there are positives and negatives to this material, there has always been discussion on whether concrete is considered a sustainable building material. First, let's examine the sustainable and unstainable qualities of concrete. Then using a set criteria, we will analyze two possible sustainable alternatives to concrete that can potentially work in the Cradle-to-Cradle cycle. After looking at the sustainable characteristics, cost, material sourcing, potential reuse, and climate application, we can compile this information and compare these two alternatives to conventional concrete and define a set of recommendations for using these materials for design application in the future.

[13] "What Is a Sustainable Material?" Concrete Joint Sustainability Initiative. N.p., n.d. Web.

Is Concrete Sustainable?

The Portland Cement Association and the Environmental Council of Concrete Organizations state that concrete is naturally sustainable material in every aspect of its application, from production to demolition. There are several positive qualities to the use of concrete in construction. "Its superior properties on strength, durability, thermal mass and affordability make it the material of choice for most purposes".[14] So believe the resource efficiency in the supplies need to make concrete play a significant role as to why it is considered sustainable. The principle material for the cement in concrete is limestone, which is an abundant resource. As well as limestone, concrete can also be made with fly ash, slag cement, and silica fume, which are all waste byproducts from power plants, steel mills, and other manufacturing facilities.

> "As a nearly inert material, concrete is an ideal medium for recycling waste or industrial byproducts. Many materials that would end up in landfills can be used instead to make concrete. Blast furnace slag, recycled polystyrene, and fly ash are among materials that can be included in the recipe for concrete and further enhance its appeal. Waste products such as scrap tires and kiln dust are used to fuel the manufacture of cement. Even old concrete itself can be reborn as aggregate for new concrete mixtures."[15]

After extracting material from quarries, these areas can be easily reclaimed for recreational, residential, or commercial use, or preferably restored to their natural state. Concrete is also durable and long-lasting material choice, which increases the lifespan of

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[14] "Sustainability with Concrete." Cement Sustainability Initiative. World Business Council for Sustainable Development (WBCSD), n.d. Web.

[15] "Environmental Properties of Concrete: Green Building." Maryland Ready Mix Concrete Association. N.p., n.d. Web.

concrete structures that also will not rust, rot, or burn. The thermal mass of concrete allows it to absorb and retain heat, aiding in energy efficiency when used for the walls, foundations, or floors. This allows the decrease use in air conditioning or heating, and in some climates the possibility to eliminate them altogether.

Reflectivity, ability to absorb rainwater, and minimal waste are also factors of concrete's sustainable qualities. Light-colored concrete minimizes urban heat island effect by absorbing less heat and reflecting more solar radiation, which can reduce the need for a larger air conditioning unit as well. Concrete has been known to cause blockage in natural water flow on the ground, causing water imbalance in the natural ecosystem. This leads to problems like erosion, flash floods, water table depletion, and pollution. “Pervious concrete is a special type of structural concrete with a sponge-like network of voids that water passes through readily. When used for driveways, sidewalks, parking lots, and other pavements, pervious concrete can help to retain stormwater runoff and replenish local water supplies”.[16] Concrete displays several sustainable qualities in its production, use, and demolition, but there are numerous negative problems concrete generates for the natural world that cannot be ignored.

While concrete can be considered more efficient or environmentally friendly than other building materials, there are still several issues pertaining to the overall lifecycle of concrete and its ability to be sustainable. The resources used to make concrete will not always be as abundant as they are now. Water shortages are a huge environmental issue today. “Sand and gravel are non-renewable resources and are quarried or dredged,

[16] Balogh, Anne. "What Makes Concrete a Sustainable Building Material?" The Concrete Network. The Concrete Network, n.d. Web.

involving a significant impact on the local environment… Crushed stone requires an additional input of energy in the crushing process".[17] And while transportation comprises much of the environmental impact of concrete, the carbon dioxide emitted in the production of cement constitutes the major CO_2 emissions from concrete.

Although it does decrease energy use in some climates through thermal mass, it does not aid in comfort control in hotter climates where heating a space is not needed. In addition to that, there is a big issue surrounding concrete about the harmful chemicals that can leak into building sites and landfills. And of course, a very common unsustainable quality concrete is known for, the waste it produces. "Concrete forms about half of all waste from construction and demolition".[18] And though recycling concrete does decrease waste, some of that concrete is down-cycled until it ultimately ends up in a landfill. "When green building depends on the recycling of materials it accepts a low level reuse strategy. The concrete, plaster and other heavy materials are not conserved as completed forms but are viewed as basic materials to be broken, smashed up and if possible, reused for minor and wasteful applications, such as broken aggregate for roads. Their high functions (as fully formed building components) are ignored".[19] There are both good and bad qualities to concrete, but for concrete to be seen as a sustainable material able to work in the Cradle-to-Cradle process, there cannot be wasted energy or materials in its life-cycle.

[17] "Elements." A Green Vitruvius: Principles and Practice of Sustainable Architectural Design. London: James & James, 1999. 95-126. Print.
[18] "Elements." A Green Vitruvius.
[19] "Buildings, Architecture, and Concrete." The Zero Waste Institute. N.p., n.d. Web.

Geopolymer Concrete

A possible substitution for concrete are geopolymer cement concrete. "Made from local earth and high-quality plastic, geopolymers are far more stable than concrete and require far less embodied energy to produce".[20] McDonough and Brangaurt state that, when designed for disassembly, building materials made of geopolymers can be used again in new buildings, or simply returned to technical cycles and used in other high-quality products. Concrete is a general term to describe a mix of aggregates held together by a binder, the cement. The binder used in conventional concrete is called Portland cement, but the binder in a geopolymer concrete mix is a geopolymer cement. Let us look further into the possibilities of geopolymer concrete.

Geopolymer concrete results from the reaction of a source material that is rich in silica and alumina with alkaline liquid. "There are two main constituents of geopolymers, namely the source materials and the alkaline liquids. The source materials for geopolymers based on alumina-silicate should be rich in silicon (Si) and aluminium (Al)".[21] These could be natural minerals such as kaolinite or clay or by-product materials such as fly ash, silica fume, slag, rice-husk ash, red mud, depending on availability, cost, type of application, and demand.

The main difference between geopolymer concrete and Portland cement concrete is the binder. "The silicon and aluminium oxides in the low-calcium fly ash reacts with the alkaline liquid to form the geopolymer paste that binds the loose coarse aggregates, fine

[20] Waste Equals Food. "Toward a Sustaining Architecture for the 21st Century"
[21] Lloyd, N A, and B V Rangan. "Geopolymer Concrete with Fly Ash."

aggregates, and other un-reacted materials together to form the geopolymer concrete".[22] The same influence of aggregate is used in geopolymer concrete and regular Portland cement concrete, such as grading, angularity and strength, meaning this aspect of geopolymer concrete mixtures can be designed using the tools currently existing for Portland cement concrete. Geopolymer concrete can also be manufactured using the conventional methods utilized in the manufacture of Portland cement concrete (PCC). It can be cast and compacted by the same processes used for PCC and measured by the conventional slump test. The elastic properties and structural behavior of hardened geopolymer concrete are similar to that of Portland cement concrete.

Now that we are more familiar with geopolymer concrete, we will be specifically evaluating fly ash geopolymer concrete. Looking more in depth at this material we will analyze the sustainable characteristics, cost, and material sourcing. We will also be addressing aspects like manufacturing process, material strength, waterproof and fireproof ability, disposal and reuse, and over overall efficiency of geopolymer concrete. From there, a set of recommendations for the material's use based on the criteria can be more accurately discussed.

Sustainable Characteristics

Firstly, let's discuss the sustainable characterizes of fly ash geopolymer cements. "Geopolymer cements don't need to be fired in production nor do they give off CO2 during curing. Though they do need to be heated at low temperatures to cure, the energy required to produce GCC is considerably less than that required for PCC mixes, resulting in an up to

[22] Lloyd, N A, and B V Rangan. "Geopolymer Concrete with Fly Ash."

90% reduction in carbon emissions".[23] Coal-burning power stations generate huge volumes of fly ash; most of the fly ash is not effectively used. In the case of fly-ash geopolymer concrete, GCC can use all discarded fly ash so that it does not end up in landfills. An important ingredient in the conventional concrete is the Portland cement. Instead of Portland cement, fly-ash geopolymer concrete utilizes the fly ash from coal-burning power stations to make the binder necessary to manufacture concrete.

Environmental Impacts

There are, however, some sustainable limitations to geopolymer concrete. Until today, the GPC technology is still at the developmental stage due to several limitations over its acceptance. There is no availability of widely accepted specifications and guidelines for the production and use of GCC, which leaves skepticism for builders to use it in their projects. The production of GPC also requires great care, which would me something workers would need to willfully put in, compared to conventional concrete production.

Cost

Heat-cured low-calcium fly ash-based geopolymer concrete offers several economic benefits over Portland cement concrete. "The price of one ton of fly ash is only a small fraction of the price of one ton of Portland cement. Therefore, after allowing for the price of alkaline liquids needed to the make the geopolymer concrete, the price of fly ash-based geopolymer concrete is estimated to be about 10 to 30 percent cheaper than that of

[23] "Geopolymer Cement Concrete." Urban Eden College of Arts + Architecture / The William States Lee College of Engineering. UNC Charlotte, n.d. Web.

Portland cement concrete".[24] In addition, one ton low-calcium fly ash can be utilized to manufacture approximately three cubic meters of high quality fly ash-based geopolymer concrete, earning approximately one carbon-credit and qualifies for monetary benefits through carbon-credit trade.

There can also be many economic benefits because of its short curing time, little drying shrinkage, low creep, and resistance to acid and sulfate attack in future construction applications. However there are some cost issues still unsolved. "Until the Cement Industry takes full control of the retailing of all raw materials, including the activator, concrete supply costs will often be an issue."[25] In theory costs should be less than the conventional Portland Cement Concrete if the binder is purchased by concrete manufacturers at the price paid by cement companies. This would require fly ash generators and ash storage holders to become the providers of this resource at a cost-effective price.

Material Sourcing

Fly ash are the particulates that rise with flue gases when coal is combusted. Previously in the US, when coal was burned, fly ash was purely allowed to enter the atmosphere causing substantial toxic pollution. Through environmental regulation, technologies were implemented in the past decades to catch a considerable amount of this ash. Since close to 50% of our electrical production comes from coal, there is a lot of captured fly ash on hand, which is mostly put into landfills where it can leach into the water supply. Since the 1930's fly ash has been used as an additive in concrete mixes,

[24] Lloyd, N A, and B V Rangan. "Geopolymer Concrete with Fly Ash." Thesis. Curtin University of Technology, Perth, Western Australia, Australia, 2010. Web.
[25] Gourley, J. T. "Geopolymers in Australia."

replacing a portion of the Portland cement binder. Geopolymer cement concretes present a major new direction in fly ash recycling. Not only do GCC mixes use much more fly ash per unit volume than PCC, they have a completely different chemical make-up which results in a drastic reduction in CO2 emissions.

However, there are also issues with material resourcing that must be solved for the future of geopolymer concrete. Further development of strengths and other keys properties of geopolymer concrete as a viable sustainable substitute are directly dependent on the purity of the resource materials. Maintaining consistency in the source materials such as fly ash and purity of alkaline materials obtained from different manufacturers make the design of this concrete mix proportions difficult for its production. Until power stations acknowledge the value in flyash as a co-product rather than a waste, or the cement industry decided as a whole to change to aluminosilicate cement production, consistent supply and distribution and consistent raw material quality will not be consistent enough for geopolymer technology to become part of mainstream construction.

Manufacturing Process

Unlike the manufacturing process for producing traditional Portland cement, where a limestone blend is calcined and ground to release approximately one ton of CO2 emissions for every ton of Portland cement produced, there are no specific calcium carbonate calcining steps in the production of alumina-silicate binders. "…The limestone is replaced by alumina to produce an alumino-silicate "clinker" rather than a calcium silicate clinker. In fact if waste materials such as fly ash or slag are used as the binder then the reduction in CO2 from cement production can be as high as 84% and even greater if waste alkaline solutions are used".[26]

Using materials such as fly ash and slag that are easily available and accessible wastes significantly increase the sustainable quality of geopolymer cement.

> "In Australia, relatively similar quantities of OPC and flyash are produced (10's of millions of tonnes per annum). Currently about 10 to 15% of these ash wastes are used in concrete as SCM. The remainder is stored in coal-fired power station ash dams or used in simple fill applications. Instead of classifying to take out the finer fractions for cement substitution or for use as a geopolymer cement, Run-Of-Station ash can simply be dry milled to produce a continuous supply for geopolymer cement. The reserves stored in these dams can also be recovered, dried and milled to produce a geopolymer cement binder". [27]

The opportunity to use a current waste material as a resource for production is a positive attribute to Geopolymer concrete that is unique to this material.

Strength and Efficiency

Geopolymer cement concrete has been tested in various environmental applications and used in several cutting-edge buildings already. Geopolymer concrete in general can be used in various environments as can concrete. It can be very suitable for the construction of underwater structures where early strength and rapid setting is required. "The elastic properties of hardened geopolymer concrete and the behavior and strength of reinforced geopolymer concrete structural members are similar to those observed in the case of

[26] Gourley, J. T. "Geopolymers in Australia." Journal of the Australian Ceramics Society 50 (2014): 102-10. Web.
[27] Gourley, J. T. "Geopolymers in Australia."

Portland cement concrete".[28] The bond characteristics of reinforcing bar in geopolymer concrete have been equivalent or superior to Portland cement concrete. Similar to this, the shear and bond strength of reinforced fly ash-based geopolymer concrete beams can be calculated using the design requirements in current building codes and standards, meaning that design provisions in the current Standards and Codes can be used to design fly ash-based geopolymer concrete structural members.

The mechanical characteristics of geopolymer concrete are very positive because of its enhanced durability and fire resistance perspective, and can be used in precast structural members and slabs. Fly ash based geopolymer concrete can sustain when exposed to exposed to considerably high temperature. While OPC concrete degrades and degenerates at high temperature, fly ash geopolymer concrete can sustain its desired compressive strength even at 400 degree Celsius. The strength of GCC drops slightly when the temperature raises up 400 Celsius, but remains almost constant and the temperature increases. The geopolymerization process continues even at high temperature and it is the strength of the binder that prevents the concrete from disintegration.

Disposal/Reuse

One of the most important aspects of a materials sustainable qualities, is its ability to be appropriated deconstructed and recycled. In order for a material to work on the Cradle-to-Cradle process, it needs to be able to be reused again or deconstructed so that its

[28] Lloyd, N A, and B V Rangan. "Geopolymer Concrete with Fly Ash."

original resources can return to the cycle. Geopolymer Concrete can be recycled in whole pieces or crushed and used as aggregate in new concrete, just as conventional concrete can.

Hycrete

Hycrete admixtures is another possible sustainable alternative to conventional concrete. While this is not an entirely new product, but an admixture to regular concrete, that makes concrete virtually waterproof.

> "Hycrete admixtures for concrete shut down capillary transport of water and chlorides through concrete and protect steel rebar from corrosion. By shutting down capillary absorption of water and dissolved salts in concrete, effectively transforming concrete from a hard, porous sponge to a waterproof building material, Hycrete admixtures enhance structural durability and extend a building's useful life."[29]

With the addition of Hycrete admixtures, the need for traditional exterior-applied waterproofing solutions are eliminated, reducing material and labor used, pollutants emitted, and non-recyclables consumed. Regular concrete absorbs water and anything dissolved in it, but regular concrete becomes hydrophobic when adding Hycrete. It keeps water out, reduces moisture vapor transfer, and forms protective barriers around rebar, resulting in highly effective concrete corrosion inhibition.

[29] "Hycrete Admixtures." Cradle to Cradle Products Innovation Institute. N.p., 2014. Web.

Sustainable Characteristics

There are several sustainable qualities to Hycrete admixtures. This product has been certified under the MBDC Cradle to Cradle conventions. As stated above, the integral waterproofing eliminates exterior membranes or coatings. These membranes are usually applied using high VOC primers and adhesives, or made of petroleum-based substances. These adhesive coatings are permanently bonded to concrete and impede recycling after concrete use, meaning the concrete and membranes go straight to landfills. "Hycrete admixtures are environmentally benign and when mixed in concrete, do not detract from concrete's existing sustainable characteristics."[30] Thousands of pounds of non-renewable materials may be eliminated, works are not exposed to harmful chemicals, and labor requirements are decreased.

Environmental Impacts/Cost

There are still, however, some environmental drawbacks to Hycrete. As with regular concrete, the ability to recycle this concrete has not gotten any easier. Concrete can be recycled by being crushed and reused as aggregate for new concrete, but often times it is more economically efficient to demolish the building as a whole. In order for conventional concrete or Hycrete admixture concrete to be recycled, it must be efficiently deconstructed and removed separately, because once it is demolished the concrete cannot be recycled.

Hycrete admixtures provide leak-free structure and enhanced durability that is very affordable. "Depending upon the type of membrane being displaced, savings may be

[30] "Overview - Hycrete FAQs." Hycrete: Delivering Concete Solutions. N.p., 2015. Web.

between 20-60%."[31] Hycrete admixture is generally lower cost than traditional waterproofing membranes for concrete, making it an economical solution. In addition to initial costs, in the long run the durability of concrete with Hycrete admixture solution leads to reduced water penetration and corrosion, meaning longer lifespan of the concrete. And because there is no membrane coating to reapply, a substantial amount of repair and maintenance costs are reduced.

Material Resourcing

Concrete is made of largely sustainable materials: sand, rock, and water. However, the generic membranes used to waterproof concrete make recycling concrete inherently impossible. Several chemicals such as chloride that exist in waterporoofing solutions inhibit the recycling of the concrete, and can contaminate water and soil after being thrown away. Hycrete's admixtures are certifed through the Cradle to Cradle gold classificaton, meaning they are safe for human and ecological systems at all phases of their lifecycles. Hycrete's green concrete admixtures have essentially no VOCs and are created with recycled water content and renewable energy sources.[32]

Manufacturing Process

Hycrete admixture solutions facilitates membrane free production and removes an entire step in construction. "Hycrete admixtures react with metals in the water, concrete, and steel reinforcement. From the reaction, a precipitate is formed where one end of the

[31] "“Do More With Less” The Underlying Philosophy of Sustainability." Sustainable Waterproofing & Corrosion Protection Solutions for Concrete (n.d.): n. pag. Hycrete, Inc., 2012. Web.
[32] "Hycrete Sustainability." Hycrete: Creating Concrete Solutions. N.p., 2015. Web.

molecule has a long hydrocarbon chain. Like oil repels water, this precipitate fills the capillaries of the concrete, repelling water and shutting down capillary absorption."[33] The manufacture of this admixture is from recyclable resources and is environmentally friendly.

Strength and Efficiency

When water gets into concrete structures, not only does it cause leaks but it also may allow corrosion and weaken the structure. Hycrete admixtures protect the concrete in several ways: a reduction in permeability, offers a protective layer around reinforcing steel, and provides overall superior corrosion prevention. But while it provides exceptional corrosion and absorbency impediment, it is at the cost of slightly lower strength of concrete. There is a somewhat lower compressive strengths as a result of the 'hydrophobizing' of the aggregate, resulting in a 10-20% decrease in compressive strength.[34] However, this can be compensated in some cases by working with the concrete and water ratios in the mix.

Disposal/Reuse

Hycrete admixtures are batched in at the ready mix plant, eliminating packaging and scrap membrane materials on the jobsite. Also, because of its integral nature, it is easily recycled as part of the concrete after demolition.[35] Also, as stated earlier, the ability to recycle the concrete with Hycrete admixtures is much simpler that conventional concrete

[33] "Overview - Hycrete FAQs." Hycrete: Delivering Concete Solutions. N.p., 2015. Web.
[34] "Overview - Hycrete FAQs." Hycrete: Delivering Concete Solutions. N.p., 2015. Web.
[35] "“Do More With Less” The Underlying Philosophy of Sustainability."

with waterproofing membranes coated on it. Hycrete also extends the life of your building. Not only does Hycrete technology decrease water absorption in the concrete, it also protects the steel reinforcement. Hycrete admixtures chemically bond to the reinforcement surface to form a protective layer that drastically reduces corrosion by water and dissolved salts, extending the life ability of the concrete and building structure.

CHAPTER 4: INSULATION

Insulation is a complex material. In the simplest terms, it is designed to inhibit heat or sound from circulate from one area to another, such as your home or certain rooms in a building. "Insulation can work in a number of different ways, but it most commonly incorporates materials that consist of millions of tiny pockets of air. Still air is an extremely good insulator, and trapped pockets of air are what give most types of insulation their high thermal resistance".[36] There is no line that separates sustainable and un-sustainable insulation, as all insulations have some qualities from both sides, even the most 'green' types of insulation. Let's first consider conventional insulations and some 'sustainable' alternatives to understand what the main issues are. Then using a set criteria, we will analyze two possible sustainable alternatives to insulation that can potentially work in the Cradle-to-Cradle cycle. After looking characteristics such as the sustainable characteristics, cost, material sourcing, potential reuse, and climate application, we can compile this

[36] "What Is Insulation?" BUILD. N.p., n.d. Web.

information and compare these two alternatives to conventional insulation and define a set of recommendations for using these materials for design application in the future.

Conventional and 'Sustainable' Insulation

There are dozens of types of insulation that have been developed over the years, based on the different needs of buildings, climates, and other environmental aspects. Some are better than others, but for the most part, insulation is known to be fairly unsustainable.

> "Conventional insulation materials are made from petrochemicals and include: fibreglass, mineral wool, polystyrene, polyurethane foam, and multi-foils. These materials are widely used because not only are they inexpensive to buy and install, but there is an assumption from the building industry that their performance ability is higher than the natural alternatives. On the downside, almost all conventional insulation materials contain a wide range of chemical fire retardants, adhesives and other additives, and the embodied energy in the manufacturing process is very high".[37]

One of the most common one most people think of when someone says insulation is fiberglass. Fiberglass insulation come in batts and blankets and is common for residential insulation. There are many drawback towards fiberglass, though. It is difficult to work with, as tiny sharp particles from the fiberglass break off into the air and can lodge in your skin, eyes and lungs, causing small abrasions which lead to irritation. There also have been many health hazards connected to fiberglass insulation such as black mold. Cellulose insulation,

[37] Gray, Jennifer. "Insulation Materials." Sustainable Build. N.p., 4 Jan. 2015. Web.

pieces of newspaper shredded up and sprayed into a space, is another common type of insulation. While it is cheap, effective, and easy to install, it is also highly flammable, not water proof, and easily becomes moldy. Rigid Polystyrene is supposed to be a sustainable alternative cut-to-fit Styrofoam insulation. It has the best R-value, is relatively affordable, and takes a does not wear easily. But there have been many issues with CFC's and other hazardous chemical components in production of panels, making it very unsafe and not so sustainable. Some insulations have been created as 'sustainable' alternatives that have positive qualities, but still have subsequent environmental issues. An example of this is recycled denim insulation. It was thought to be very sustainable, but there have been problems with the chemicals involved in the dyeing and washing of the jeans beforehand that make the denim unsustainable.

HOIZ Eco Insulation

A possible sustainable substitution that has been Cradle-to-Cradle certified is a product called Baufritz-HOIZ-Eco Insulation. "'HOIZ', by Baufritz, is a unique eco-insulation material, made from wood chips, a breakthrough in natural insulation".[38] The company Baufritz has developed their own patented insulation material that they have been perfecting for over fifteen years. Made from wood shavings, this insulation is treated with only natural whey and soda to make them fire, fungus and pesticide resistant. When developing this innovative product, it was important to this of the complete production

[38] Bowman, Linda. "Baufritz - HOIZ - Eco Insulation." Sustainability Consciousness Class (2014): n. pag. Tongji University, 2014. Web.

cycles from the beginning, in order to not generate any waste or compromise the environment. An ideal product was created and manufactured without containing any hazardous or poisonous ingredients. And when this insulation has served its purposed and is no longer needed, it can be re-introduced into the natural biological cycle safely.[39]

Now that we are more familiar with Baufritz-HOIZ-Eco insulation, we will now evaluate this material more in depth. We will analyze the sustainable characteristics, cost, material sourcing, and environmental impacts. We will also be addressing aspects like manufacturing process, thermal and sound performance, waterproof and fireproof ability, mold and decay resistance, reuse/disposal, and overall efficiency of HOIZ eco insulation. From there, we will compare this information with conventional insulation and another sustainable alternative.

Sustainable Characteristics

HOIZ Eco insulation has several sustainable attributes. The insulation is made up of wood shavings treated with two natural additives, whey and soda, to render them fire retardant and fungus proof. Wood is a 100% natural and renewable material. This simple but very efficient material guarantees a healthy and chemical-free interior climate. Wood shavings can regulate humidity levels naturally, absorbing moisture from the air and releasing it again if required, no other natural insulation material can do this.

[39] "Ecology." Baufritz. N.p., 2015. Web. <http://www.baufritz.com/en/why-baufritz/ecology/>.

Cost

Wood shavings are a very ecological and inexpensive insulating material. They are obtained by planing processes in the production of wood houses, so there are no extra logistics are necessary to produce them. While sometimes natural insulation materials as a whole can be more expensive than traduaiotnal insulation, the results are worth they cost. The environmental and health benefits of natural insulation materials far outweigh their costs, and growing consumer demand combined with government regulation, and rising energy and fuel prices will inevitably push prices down. Even at a slightly higher price, natural insulation is an energy-efficient, healthy, and sustainable choice in the long run.

Material Sourcing/Manufacturing Process

Huge quantities of wood shavings are produced in the woodworking industries and in planing mills, which until now is mostly used for fuel. Wood shavings are naturally produced in the plant while planing boards for exterior siding using automatic molding machines. These dry shavings are separated from all fine and coarse particles, and have the ability to be recycled into insulation material.[40]

The dry shavings are treated in a continuous flow process by spraying a solution of soda and whey on it, components that are both considered to be non-hazardous additives. After the treatment the shavings are dried again down to a moisture content of about 12%.The addition of soda moves the pH-value of the shavings into the alkaline range and thus preserves them against fungi, while whey improves the endurance to fire. The wood

[40] Rehm, Oliver. "Sustainability – the Baufritz Way." Urban Environment (n.d.): n. pag. Pan European Networks, 2014. Web.

shaving mixture is stored in a silo and is then transported to the filling machine for the structural elements. The overall energy consumption for the processing of the shavings is 50 kilowatt hours per ever cubic meter produced, which is very little in comparison to other insulating materials. Further developments of the processing will reduce the energy consumption in the future.[41]

Thermal Performance/ Water, Fire, Mold, and Decay Resistance

The thermal insulation of HOIZ insulation is very effective against summer heat. "With a thermal conductivity of λ = 0.045W/m K (0.040 W/m K) wood shavings can compete with other insulating materials."[42] This insulation is classified in fire resistance classification B2: normal flammable. Wood shavings have a wholly different moisture behavior than traditional insulating materials. They are hygroscopic, and when even slightly compressed, wood shavings tend to create capillary water transport. In a studied conducted to test the moisture content in walls with HOIZ eco insulation, the average value of the moisture content remains close to the same level in every wall.

> "Over the year there are less moisture variations in the wood shavings. The insulating material in the roof elements showed little variations. With an average moisture content of ~10% the wood shavings stay extraordinarily dry… Despite the average value of 20% moisture over 30 months, fungal attack was not apparent. Moisture levels on the other walls did not exceed the critical point of 20%."[43]

[41] Porschitz, Hans R., and Bernhard Schwarz.
[42] Porschitz, Hans R., and Bernhard Schwarz.
[43] Porschitz, Hans R., and Bernhard Schwarz.

The construction of elements have to provide a reliable weather protection for insulation layer. The HOIZ insulation proved to be able to withstand weather impact, meaning it can be considered efficient for a building insulating material.

The most endangered sections for loose insulating material is the possibility of settling. Studies have been done to test the density and settling over time of wood shaving insulation. "The results showed a roughly homogeneous density in all sections. ~60% of the borings did not show a settling at all. The maximum observed gap was 15 mm."[44] Most of the material settled during transport of the elements, but evidence of further settling occurring while the house was being studied could not be found.

Disposal/Reuse

One of the most optimistic qualities of HOIZ Eco insulation is that it is completely recyclable. It is completely biodegradable and therefore environmentally friendly while still providing efficient insulation while in use. After a homeowner is done with their insulation or before a building is demolished. This insulation could be taken out an be used as compost in their own garden, as all ingredients can be re-introduced into the natural biological cycle safely. Since it is composed only by organic materials, compressed with air, at the end of its life then it can be disposal in an ecological way.

[44] Porschitz, Hans R., and Bernhard Schwarz.

Aerogel

Aerogels are the world's lightest solid materials made by the removal of liquid from gels. Such materials may contain up to 99 percent air and combine unique properties like high porousness and excellent thermal, acoustic and electrical insulation.[45] Researchers have conventionally focused on making inorganic aerogels from silica, clay and metal oxide, and these materials have found use in clothing, building insulation and aviation. Aerogel is a lightweight silica solid derived from gel in which the liquid component of the gel has been replaced with gas. When the liquid is removed, the result is an extremely low density solid with several remarkable properties, most notably its effectiveness as a thermal insulator. It is an advanced material which holds 15 entries in the Guinness Book of Records for properties such as lowest density solid and best insulator.[46] It is a silica-based substance, consisting of a loose dendritic network of the atom silicon.

Sustainable Characteristics

The unconventional properties of aerogels open the way to several opportunities for their application in buildings. One of the most important examples of aerogel uses to date is the application of silica aerogels as super insulation. Their main benefits include excellent insulating properties provide energy and cost savings due to reduced loss of heated or conditioned indoor air, healthier indoor environment due to removal of airborne contaminants, heat- and sound-retarding properties due to the non-combustibility and acoustic properties of the aerogel. Above all they are user-friendly, recyclable and reusable.

[45] Sustainable Organic Aerogels for Insulation (n.d.): n. pag. Wisconsin Alumni Research Foundation. Web.
[46] "Thermablok® Aerogel Insulation." *Thermablok*. N.p., 2011. Web.

Aerogel insulation can be used for highly insulated homes that are sealed from the outside, and can be applied to studs to prevent thermal bridging. Silica aerogel materials are in development and will hopefully displace mineral wool as a superior insulation in the future, resulting in greater efficiency that translates into reduced emissions from insulation. Unlike polyurethane and polystyrene insulations, no chlorofluorocarbon (CFC) blowing agents are required to manufacture aerogel insulation.[47]

Environmental Impacts and Cost

Inorganic aerogels often struggle with inherent brittleness, which limits their usefulness when tough, low-density materials are required. Also, the supercritical drying process used to make aerogels requires the use of organic solvents, which also is challenging to scale up. Similarly, the currently main constrains that avoid widespread use of super insulating aerogel materials are the high cost associated with its production. Unfortunately the material is still fairly expensive and out of the price range for the average homeowner.

Material Resourcing/Manufacturing Process

Aerogels can be prepared by using Alumina, Chromium, Tin oxide and Carbon, as well as cellulose, xylan, lignin, their mixtures and from spruce wood.[48] After gelification, the gel is left undisturbed in the solvent for 48 hours to complete the reaction. Once reaction will complete the alcogel product will form. The alcogel is then submitted to supercritical

[47] Acharya, Anjali, Deepa Joshi, and Vasudha A. Gokhale. AEROGEL – A Promising Building Material for Sustainable Buildings 9 (2013): n. pag. B.N. College of Architecture,Pune,India. Web.
[48] Acharya, Anjali, Deepa Joshi, and Vasudha A. Gokhale.

drying. After mixing, a diffusion of colloidal particles is generated, which form a three-dimensional network. The particle size depends on the catalyst and varies between nanometer and micrometer scale. After the gelation process the enclosed pore liquid has to be carefully removed to preserve the nanostructure of the aerogel. This entire process is known more commonly as the 'Critical Point Drying' technique.[49]

Thermal Performance/ Water, Fire, Mold, and Decay Resistance

The chief positive quality of aerogel insulation is it excellent thermal insulation properties. Because of the superior efficiency in aerogel, the overall thickness of insulating material can be decreased. It provides an enhancement of thermal resistance of the insulation layer in the building envelope. This decreases the demand of energy and improves the energy efficiency of the building.[50] The silica solids, which are poor conductors, consist of very small, intertwined clusters that comprise a very small amount of the volume of the aerogel, and therefore means that conduction through the solid is low. The remaining volume of the material is comprised of air in extremely small nanopores, where the air has little room to move, preventing both convection and gas-phase conduction.[51]

In addition to its thermal qualities, due to aerogel insulation's low thermal conductivity and acoustic property for noise abatement, aerogels can be used as adsorption

[49] Acharya, Anjali, Deepa Joshi, and Vasudha A. Gokhale. AEROGEL – A Promising Building Material for Sustainable Buildings 9 (2013): n. pag. B.N. College of Architecture,Pune,India. Web.

[50] "AEROGELS - Superinsulating Building Materials." Energy Efficient Sustainable Construction (n.d.): n. pag. TECNALIA. Web.

[51] "About Aerogel." *Aspen Aerogel*. N.p., n.d. Web.

and facilitators in indoor air purification inside the building. It is also non-combustible and and can be used as a fire retardant.

Disposal/Reuse

Since Aerogel insulation is still in the developmental stages of production, there are questionable qualities to it and its life after use in a building. Many aerogel insulations being developed and produced today are recyclable.[52] And since aerogel is mostly made up of air, there is already a significant initial decrease in the amount of material that's needs to be recycled or reused.

[52] Acharya, Anjali, Deepa Joshi, and Vasudha A. Gokhale.

	Portland Cement Concrete	Hycrete Admixture Concrete	Geopolymer Concrete
Performance/ Economic Criteria			
Cost	• Concrete is generally very inexpensive due to the abundance of resources that make up the product. • It is also low cost because of the efficiency to produce concrete.	• Hycrete waterproofing solutions are generally lower cost than membrane solutions. • In the long run, durability leads to reduced water penetration and corrosion. • No reapplication needed. lowering maintenance costs.	• One ton of fly ash is small fraction of price of one ton of Portland cement. • After allowing for price of alkaline liquids, price of fly ash GCC estimated to be 10-30% cheaper. • Cement Industry needs full control of retail of all raw materials needed.
Strength/ Overall Efficiency	• Concrete is an incredibly strong building material and the lifespan of conventional Portland Cement Concrete in a structure is fairly long. • Issues with moisture and decomposition can become problematic without proper water protection.	• Slightly lower compressive strengths as a result of the "hydrophobizing" of aggregate. • Can be compensated where needed by traditional means. • More waterproof than conventional concrete.	• GCC is fire resistant and suitable for underwater construction. • Elastic properties, durability, and strength of reinforced geopolymer concrete structural members are similar to PCC. • GPC can sustain desired compressive strength at 400 C.
Waste Criteria			
Material Resourcing	• Basic components are water, sand, gravel, and cement. • Sand and gravel are mined, usually quite close to their point of use. • Cement made from limestone, heated and combined with other elements, then crushed into powder.	• Safe for human and ecological systems at all phases of their lifecycles. • Virtually no VOCs and produced with recycled water content and renewable energy sources. • 80% composed of pre-consumer recycled materials.	• Close to 50% of electrical production is from coal, so there is a lot of captured fly ash on hand, put into landfills. • Maintaining consistency in fly ash and purity of alkaline materials obtained from different manufacturers makes production difficult.
Environmental Impacts	• Large contributor to global CO_2 emissions. • Does not aid in thermal comfort in hotter climates where heating is not needed. • Leaks harmful chemicals into building sites and landfills. • Most concrete is down-cycled until ends up in a landfill.	• Still deals with the recycling issues of regular concrete • Must efficiency deconstruct to be reused	• GPC technology is still at the developmental stage • No widely accepted set of guidelines for production and use of GCC. • Production of GPC requires great care, compared to conventional concrete production.
Manufacturing Process	• Cement is made from limestone, heated/ combined with other elements, crushed into powder. • Limestone blend is calcined and ground to release approximately one ton of CO_2 emissions for every ton of Portland cement produced.	• Hycrete admixtures react with water, concrete, and steel reinforcement. • Precipitate formed - molecule has hydrocarbon chain. • Precipitate fills the capillaries of the concrete, repelling water and shutting down capillary absorption.	• No calcium carbonate calcining steps in the production of alumina-silicate binders. • Fly ash can simply be dry milled to produce a continuous supply for geopolymer cement.
Disposal/Reuse	• Concrete can be recycled by being crushed into aggregate for new concrete. • Concrete can also be used whole pieces for new projects if it's deconstructed properly.	• Can be easily crushed as conventional concrete can. • Remain an integral part of the concrete matrix for the life of the structure.	• Can be recycled by being crushed into aggregate for new concrete. • Can also be used whole pieces for new projects if it's deconstructed properly.

	Fiberglass Insulation	HOIZ Eco Insulation	Aerogel Insulation
Performance/ Economic Criteria			
R-Value	• 3.14 per inch	• ~3.5 per inch	• ~3 - 10per inch
Cost	• Very inexpensive, $.50 to $1.00 per square foot	• Wood shavings arevery ecological and inexpensive. • Obtained by planing processes so no special logistics are necessary.	• High cost associated with its production. • Material is still fairly expensive and out of the price range for the commercial use. • $1.00 per cubic cm
Thermal and Sound Performance	• Fiberglass provides low levels of conductivity without the need for thermal breaks. • Has similar sound absorbing performance as mineral wool.	• Thermal insulation is made of natural materials • HOIZ is very effective against summer heat.	• Enhancement of thermal resistance in the building envelope. • Improvement of energy efficiency. • Heat- and sound-retarding properties due to non-combustibility and acoustic properties.
Water, Fire, Mold, and Decay Resistance	• Neither absorbs nor holds water. • Naturally noncombustible and remains so for the product's life.	• Fire resistance classification B2 (normal flammable). • Moisture contents of the wood shavings are ≤ 20%, No danger of fungi or damage by moisture.	• It's breathable and fireproof, and it absorbs both oil and water.
Waste Criteria			
Material Resourcing	• Silica sand, limestone, and soda ash. • Also include calcined alumina, borax, feldspar, nepheline syenite, magnesite, and kaolin clay.	• Huge quantities of wood shavings are produced in planning mills and woodworking industries.	• Can be made with Alumina, Chromium, Tin oxide and Carbon. • Silica based aerogel is easier and reliable. • A silica gel can be prepared through a number of chemical processes.
Environmental Impacts	• Tiny sharp particles break off into the air and can lodge in your skin, eyes and lungs. • Many health hazards connected to fiberglass insulation such as black mold.	• Issues of energy use and small amount of CO2 emissions in production.	• Supercritical drying process requires the use of organic solvents, which also is challenging to scale up.
Manufacturing Process	• Pultrusion - uses large furnaces to gradually melt materials. • Extrusion – into bushings of fiberglass. • Coated with a chemical solution.	• Treated in a flow process by spraying a solution of soda and whey on it. • Shavings are dried again down to a moisture content of about 12%.	• Aerogels, materials with extreme porosity and very low bulk density, can be made using the so called 'Critical Point Drying'- technique.
Disposal/Reuse	• Can be used again, but eventually becomes waste.	• Completely biodegradable	• Many types of aerogel insulation is recyclable. • Mostly made up of air

	Portland Cement Concrete	Hycrete Admixtures Concrete	Geopolymer Concrete	
Performance/ Economic Criteria				
Cost	3	2	1	**PCC**
Strength/ Efficiency	2	1	3	**GCC**
Waste Criteria				
Material Resourcing	1	2	3	**GCC**
Environmental Impacts	1	2	3	**GCC**
Manufacturing Process	1	2	3	**GCC**
Disposal/Reuse	1	2	3	**GCC**
	9	**11**	**16**	

	Fiberglass Insulation	HOIZ Eco Insulation	Aerogel Insulation	
Performance/ Economic Criteria				
R-Value	3.14 per inch	3.5 per inch	10per inch	
Cost	3	2	1	**Fiberglass**
Thermal and Sound performance	2	1	3	**Aerogel**
Water/Fire/ Mold/Decay Resistance	2	1	3	**Aerogel**
Waste Criteria				
Material Resourcing	2	3	1	**HOIZ**
Environmental Impacts	1	3	2	**HOIZ**
Disposal/ Reuse	1	3	2	**HOIZ**
	12	**16**	**14**	

Chapter 5: Conclusion

After compiling the data in each table based on the criteria of each building material, I compared the two sustainable alternative materials to one another and to the conventional option for each category. Then, using a basic scoring mechanism, I rated the three possible materials from one to three, one being the worst choice and three being the best possible choice, for on each criteria. It is important to note that when making these decisions for each criteria, there was not one material that was well-suited for every criteria. While one material was better rated in strength and overall efficiency, another would be rated higher in material sourcing. The decision to use one material over another is based on the prioritization of certain criteria over another based on what is important for that specific buildings.

For example, if a cost efficiency is a large concern in a building's construction, using the conventional type of concrete and insulation would be a better choice than the sustainable alternatives. If strength in material and lifespan of the structure was important in the building, using Geopolymer concrete over conventional concrete would be a better choice. Similarly, if the overall life of the building is the most important in the construction, using HOIZ Eco insulation would be the best choice of insulation because it is 100% biodegradable. But if energy efficiency in the building lifespan is an important aspect of the design, Aerogel insulation is a better choice in the long term. There are trade-offs for every material studied and each have positive sustainable qualities, but also have room to be further developed to resolve the possible unstainable or inefficient traits they have.

After consideration, it was decided to split the list of criteria in the evaluation into separate lists: performance and economic criteria and waste criteria. This is because, while performance and economic criteria are important in deciding whether or not you use the material in a building, they do not directly correlate with the waste cycles of the materials. It is also important to note that a material might be efficient and economic but not sustainable. But there are overlaps in these two categories of evaluation, and the outcome of one category can affect the other in many ways. It is possible that having enhanced performance or efficiency means less material, meaning less waste to find use for over time. A big part of a material working in a life cycle process, such as the Cradle-to-Cradle model, is that is proficient in performance, economic, and waste criteria. In order for a material to be sustainable, it must encompass all three points of the Triple Bottom Line: social, environmental, and financial, that make up the Three Pillars of Sustainability. While environmentally friendly qualities of a material may seem like it is the most important point in whether a material is considered sustainable, the other two points are vital and must be considered in the overall development and future of green materials.

Criteria	Suitable Material
Performance/Economic Criteria	
Cost	OPC or Hycrete
Strength/Overall Efficiency	OPC or Geopolymer Concrete
Waste Criteria	
Material Resourcing	Geopolymer Concrete
Environmental Impacts	Geopolymer Concrete
Manufacturing Process	Geopolymer Concrete
Disposal/Reuse	Geopolymer Concrete

Criteria	Suitable Material
Performance/Economic Criteria	
Cost	Fiberglass
Thermal and Sound performance	Aerogel
Water/Fire/ Mold/Decay Resistance	Aerogel
Waste Criteria	
Material Resourcing	HOIZ
Environmental Impacts	HOIZ
Disposal/ Reuse	HOIZ

Why These Materials?

Two sustainable alternatives were chosen for each conventional building material. Concrete and Insulation were chosen because they are both materials that are used in almost every building today and are under the constant evaluation for efficiency. The sustainable alternatives were chosen in variety based on use, initial sustainable qualities shown, and present reviews of the material. I tried to find a variety of materials that had very different makeups and qualities to them, so that each material presented very different advantages and disadvantage in evaluation. This is so that there are several possible future research questions produced from these initial questions and evaluation. Some materials, such as Geopolymer concrete has been used and studied a good deal more than other materials such as Aerogel. In the case of concrete, Hycrete, this was one company's type of waterproofing admixture to concrete that has been proven to be a sustainable alternative, while Geopolymer concrete is a general class of concrete that has sustainable qualities as well, but produced by several manufacturers. Similarly, HOIZ Eco

Insulation is one brand of wood shaving insulation that has been tested and deemed sustainable and able to work in the Cradle-to-Cradle cycle, while Aerogel is a new class of insulation that has been discovered to have excellent insulating properties characteristics, and is being produced as a sustainable building material by several different companies.

Introducing Sustainable Building Materials into the Construction World

In order for these (or any) material to be further developed and implemented as sustainable alternatives, they must be introduced as options in the built environment. But how do products become established into the construction world? In the case of several sustainable materials, it is usually a discovery or development made by one person or company, and then marketed and manufactured by that particular company alone for that material. Internal testing and evaluation happens so that these products meet standard guidelines for safety in application, but the general material use and manufacturing process is only known to that company. In some cases this is not an issue, however most of the time this leads to one company producing a highly priced material that is not widely used in conventional building.

The construction world is primarily driven by economics and the ability to reproduce manufacturing processes of a material. It can seem rather hard for another company to produce a similar sustainable product without knowing the details of the first product. If a sustainable material could be produced by several different manufacturers, the cost of the resources needed to make it, and subsequently the material, would be eventually lowered to a price that compares to the conventional alternative. The possibility of shared information through a main organization or an equivalent would bring only positive results to the future of sustainable material development in architecture.

Sustainability and the Built Environment

Sustainability can be defined as creating economic and social development while protecting the natural world and not causing environmental issued for future generations. It is important to be able to relate this research and evaluation directly back to the development and prosperity sustainability in the built environment. The Cradle-to-Cradle concept is a process to eliminate waste and create imminently sustainable materials and processes for the future, aiding the goal of a zero waste future. Sustainable materials are the future nutrients of this model and are the building points for further progression of sustainable design in the Cradle-to-Cradle concept.

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