ADVANCEMENTS IN SUSTAINABLE CONCRETE PRACTICES AND THEIR

POTENTIAL IMPACT ON DESIGN AND CONSTRUCTION

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ABSTRACT

Concrete is one of the most widely used construction materials in the world, and Portland Cement is the most commonly used cement in the industry. The manufacturing of materials is dependent on research and industry specification standards. This report focuses on current innovations in concrete developments, with a specific emphasis on Aluminosilicate or 'geopolymer' cements and their possible implications on the evolution of a sustainable architecture in the United States.

Aluminosilicate cements are currently being researched worldwide and have been implemented in various countries as a replacement for portland cement. It is one of many sustainable cement solutions, but unlike others, provides enhanced characteristics while remaining in the same price range as ordinary portland cement mixtures. This technology uses no limestone or water, thus eliminating the need for high amounts of energy use in the production of its initial ingredients.

Introducing new construction materials is challenging, especially to a well-established concrete industry such as that of the United States. Precast concrete offers an ideal medium for new concrete materials and their introduction into common practice due to the ability for tight controls. As more sustainable and durable materials are becoming available, construction processes can change and have the ability to affect the future evolution of architectural design. This report articulates these advancements and the importance of architectural involvement within the United States construction industry.

CHAPTER 1

INTRODUCTION

Concrete is the most commonly used construction material in the world, and it has been a part of architecture and our civilization for thousands of years. Cement, the binder used with many types of aggregates to create what we understand as concrete, has evolved to meet our needs through the centuries. As an essential material to construction, the qualities and presence of concrete affect our daily lives, and the development of more advanced and sustainable manufacturing of cement has the opportunity to affect both our built and natural environments. Our society has recently discovered the need for more sustainable methods of living and construction, bringing more attention to the many ways, both negative and positive, concrete effects our civilization and ecosystem [24]. In addition to these important facts, it is understood that modern architectural design would not be possible without the use of concrete. The material affects the urban environment in which it is both manufactured and placed, while its material properties affect the possibilities of architectural form allowing for change in design typologies, and the evolution of construction methods. With the development of new materials, comes the possibility of new forms and a greater balance between the environment and our architecture.

1.1 Importance of Sustainable Advancements in Concrete to Architecture

Sustainability has been a design focus in recent architecture for decades, and although this has been a central element in much of the design completed throughout the world, only recently has it become a greater focus here in the United States. The durability of building materials, and the effect their manufacture has on our environment contributes greatly to the overall sustainable nature of a finished work. Concrete, as the most commonly used building material, thus has an amazingly large impact on sustainable architectural possibilities.

Current, modern concrete production is one of the top leading producers of carbon dioxide in the atmosphere today. The cement industry is responsible for 8% of global CO_2 emissions, due to the process of turning limestone into lime [100] the key component to ordinary portland cement (OPC) which allows it to be a hydraulic binder, a key property that has allowed concrete to be the widely used construction material it is. In a report by The World Wide Fund for Nature partnering with Lafarge and consultants from Ecofys, a leading consultancy in renewable energy, energy & carbon efficiency, it is stated that "Currently the production of one ton of cement commonly results in the release of 0.65 to 0.95 tonnes of CO_2 depending on the efficiency of the process, the fuels used, and the specific type of cement product. Considering the scale of the worldwide cement production, even a slight decrease in the average global emissions per ton has a large CO_2 reduction potential." [100] Materials science and civil engineering based research around the world is working towards new methods of refining current concrete manufacture.

As with all innovations there is the possibility to provoke change; a subject not so widely accepted in most construction industry but especially that within the United States for various, complex, and often political reasons. For instance, if concrete was developed to be more durable against sulfate attack, we would not have as many issues with repair work on our road systems, especially concrete bridges and overpasses. There is then the possibility that these municipal funds could be allocated elsewhere. This of course would also mean that those responsible for such repair work would have a drastically reduced work load, and some may lose their work all together. This type of concrete is actually one of the newer developments of the industry, Ultra High Performance Concretes. They are more expensive, but exhibit a strength 6 to 8 times stronger than ordinary concretes and are also stronger and more durable than regular high strength concretes.

If there was a possibility that the primary structure of a building could last for hundreds of years and the building envelope and interior partitions changed as desired, how would that affect architectural design? If perhaps concrete panels were used, how could they be reused, if dismantling them had no effect on their capacity to be erected on a new building? How long would it take to build a building made of precast elements that took three days to reach their full strength? These issues in concrete affect the design world, and the construction industry as a whole. But it is we, the architects, who need to recognize these new materials, because it is us who in the end speaks with the client, who understands the program, and who designs the end product of the structure. In an industry where engineers do most of the research behind such materials, how do architects address this evolution? How should they become more involved in the process of materials research and design? I believe it is imperative that in order, not only for architectural design to keep pace with new technology, but for new technology to be pushed into existence, architects in the field need to be more involved in the research process within their country, in this case, the United States.

The implementation of new materials is a very lengthy process, especially in a country such as the United States where regulations, legislation, and politics play a large role in our society as a whole. There is already a large amount of interest in the topic of innovative materials in cement and concrete here within the sustainable engineering industries. In one such thesis *Discovering Institutional Drivers and Barriers to Sustainable Concrete Construction*, it is claimed that the conservative and technocratic culture of the concrete industry has had lasting impacts on the industry with respect to innovation and potentially more sustainable concrete construction. [4] A key factor which has held back the development of more durable concrete in the United States is that "Industry standards and project specifications have institutionalized concrete optimized for high early strength and rapid construction rather than durability." [4] The Two organizations that are most responsible for concrete specifications, construction code, and other industry standards in the United States are the American Concrete Institute (ACI) and the American Society for Testing and Materials (ASTM). Although architects are welcome to join the technical committees in both of these organizations, as an architecture student I have recently joined the ACI 236 material science of concrete as an associate member, few become involved. The simple facts that these meetings can be quite bureaucratic, inundated with what an architect might consider 'dry engineers', and most importantly require additional time and effort in the already completely time consuming architectural industry, are enough to start explaining the lack of architectural involvement. While other nations have a more intertwined architectural and engineering construction industry, ours here in the U.S remains very divided, at the detriment of our design and materials development. Materials research in this country is mostly done by chemical and civil engineers. Although this is ideal it is not complete; those completing the research are often not designers involved in the built world. There are two sides to the construction industry, and at a cultural level for architecture, it is imperative that we become more involved in the entire process in a practical manner.

Architects who design with sustainable methods not only must be familiar with space configuration, building systems, and environment quality but with materials that reduce the energy footprint of the building itself. This is common knowledge, visible through design and basic standards such as LEED. "As Designers we have a responsibility to specify buildings that have low CO_2 emissions, both in their construction and in their long-term energy performance." [8] It is not enough that raw building materials produce less CO_2 but that in their implementation and subsequent lifetime less CO_2 is emitted. For instance, a local material which emits significantly less CO_2 in its manufacture and is durable against all environmental conditions is ideal, rather than the current which requires more repairs and thus energy to be expended in its maintenance.

There is a clear market and interest in the propagation of sustainable design. "Conventional Construction and operations of buildings are resource-intensive processes that create a significant amount of waste and contribute to global climate change. The environmental impact of a building is significant, and has implications for the local community and the world beyond our borders."[92] The facilities services and standards of the University of Chicago, for example, demand the use of efficient and advanced building and design methods. As a global leader in higher education they help to contribute to planning and design trends on their historically and architecturally significant main campus. Institutions across the nation are taking a greater interest in advancing the use of sustainable construction and renovations.

There is a need for increased research to improve the basic construction methods of the United States. For instance, “The current model of house design is approximately 50 years old and has not adjusted to the change in demands associated with evolving resource demands and other world changes.” [19] It is recognized that most commonly used construction methods in the U.S. are in need of more sustainable improvements, and that the fundamental aspects to construction are the materials and configurations of the systems used. The U.S. is behind much of the modern world in housing design, while modern housing in Europe is significantly more energy efficient and consists of much concrete construction [43]. Precast Concrete is one of many options that can be used to improve the housing industry today, and using an innovative concrete in precast manufacture could be the next step of putting it at the forefront of sustainable construction methods [52, 58]. Dukane precast, as another example, is a major manufacturer which has been marketing precast housing design and utilizing the most up to date concrete mixtures to maximize durability and lower carbon footprint. Precast offers a wide variety of design capabilities, it is a method that can be utilized to propagate the use of innovative mixes and offer a wide variety of design flexibility with efficient construction.

Figure 1. Precast Building Examples [29, 76]

1.2 Aluminosilicate or 'Geopolymer' Cement for use in Precast Concrete Manufacture

Geopolymer, or Aluminosilicate cement[1], is a new type of cement. Geopolymers "are new ceramic-like, inorganic composite building materials produced at low temperatures with dramatically lower emissions compared to concrete. Add in that they are fully recyclable, as well as fire, blast, and acid-resistant, and it's obvious why they have the potential to transform the building products industry." [87] This is possible because Geopolymer is a type of cement which has a different molecular structure than Portland cement, and has the possibility to replace it completely in both structural and aesthetic concrete applications. It is an innovation in the concrete industry currently in use in Australia and being researched throughout the world. Geopolymer, or alumiosilicate cement, is considered a sustainable innovation to the concrete industry not only because it makes more durable concrete which is affordable, but because it is made up of waste by-products such as fly ash, or slag and no water. It is not hydraulic cement. It can also be made using kaolin clay, which takes far less energy to be processed than the lime currently used in the creation of portland cement. The liquid base is most commonly made up of what is commonly known as lye (sodium hydroxide) and liquid glass (sodium silicate). Because these products are caustic alkaline liquids, labor skilled with handling chemicals as well as concrete construction is needed. [53] Protective clothes are generally required while working with basic geopolymer cements, although some have been developed privately to be poured exactly as OPC (ordinary portland cement) (Note:

[1] See Chapter 3 for further explanation of Aluminosilicate cement

Protective wear is also a common practice with ordinary portland cement, due to its similar ph level) One very important thing about geopolymer cement is that there is no single way to mix it, its composition and raw materials can vary in composition throughout the world. This fact makes it one of the more sustainable solutions, using local materials in the same way as portland cement, but it forces extreme amounts of initial chemical research and changes to standard requirements usually referenced when testing or classifying portland cement based concretes. [41] Current code is changing to allow for the inclusion of pozolan cements and alternative mixes in the United States and throughout the world. [3] Common practice for this issue is for companies to prove and set up their own testing methods and to then submit them to the respective regulatory bodies and specifiers for acceptance. [41]

At this point in aluminosilicate cement development, it is necessary to use it in precast applications to fully exploit its potential. Geopolymer based concrete can set at both elevated and ambient temperatures. [88] The mixes set at ambient temperatures have strength comparable to portland cement and usually contain a certain amount of water to enhance the workability of the mix. It is important to note that the water is not needed for the chemical reaction, and evaporates while setting occurs. There is a greater range of attainable characteristics for the material when used in a precast environment, as the strength can change based on the temperature used to cure it, something that cannot be easily controlled for poured in place applications. According to the geopolymer laboratory at L.A Tech, geopolymer can have a compressive strength of 6,000 – 16,000 psi depending on the fly ash used (modern high strength concrete usually has a strength higher than 6,000 psi), a flexural strength of approximately twice that of ordinary portland cement, be ten times less permeable than OPC, have full strength gain within 1 to 3 days with a setting time of 30 to 120 minutes, and reduce the CO_2 emissions by 90%. [53] Geopolymer or aluminosilicate based concrete precast construction could provide a low CO_2 emitting, high strength, and fast setting system.

Although geopolymers are not widely accepted throughout the concrete construction industry in the U.S, they are recognized by academic, industry, and government sources. Universities in Louisiana, Illinois, North Carolina and Florida are researching different properties and the structural uses for geopolymer concretes, most agreeing on their potential for precast applications. A tech brief on geopolymer concrete from the U.S Department of Transportation recognizes its potential to improve the road systems:

> In the short term, there is potential for geopolymer applications for bridges, such as precast structural elements and decks as well as structural retrofits using geopolymer-fiber composites. Geopolymer technology is most advanced in precast applications due to the relative ease in handling sensitive materials (e.g., high-alkali activating solutions) and the need for a controlled high-temperature curing environment required for many current geopolymer systems…the durability attributes of geopolymers make them attractive for use in high-cost, severe-environment applications such as bridges. [91]

A recent online article from the ecologist claims: "With the growth of a low carbon building industry, geopolymer technology may be coming to a pavement near you. For five years, Australian company, Zeobond, has been developing E-Crete ready-mix concrete that, claims CEO Peter Duxson, emits up to 60 per cent less CO_2 than conventional concrete in its manufacture." [59] Sustainable solutions for the concrete industry are evolving, geopolymer precast applications may soon be a reality for the construction industry of the United States. What other such construction material advancements will become available in the years to come? How will we has designers take advantage of them?

CHAPTER 2

HISTORY OF CONCRETE

Human civilizations have used concrete throughout known history. The need for durable, affordable, and adaptable construction materials has driven the evolution of this material through the centuries. There is record of it having existed for the past 7000 years. [64] Like all construction materials, the methods of manufacturing cement and consequently concrete have depended on the raw materials and technology available to the location at that time. In theory, concrete has been thought of as liquid stone. Those who develop it always have the goal of making it more and more like the actual stone it attempts to imitate. From a mixture of naturally found elements to the advanced chemical compounds we use today, durability and aesthetic have always been central concerns.

In addition to concrete evolving with civilization it has in turn been used to support the evolution of our civilizations throughout the world. It is the primary building material for current high rises in tropical areas, and used in fire protection for modern construction to only name a couple. We have chemically manipulated it, poured it for infrastructure, precast it for building blocks, sprayed it to reinforce and fireproof steel structure, smoothed it for highways, and pumped it 100's of feet high to form some of our tallest and most advanced architecture. Our methods develop it and it develops into a place to breed our methods. Our current need as a society is to develop more sustainable methods so that we can continue to live in and use our concrete and other such materials.

2.1 Ancient Developments

Concrete is a building technology unlike any other in that it has appeared and disappeared throughout history; its presence has always coincided with a rise in the spread of major civilizations. In ancient times the secret of concrete was a science carried out by master builders and the elite, who were deeply involved in their religious culture and often associated with royalty. Unlike technologies such as metallurgy which could be carried on through history by a few individuals, for consistent use in small projects such as weapons and other tools, concrete is associated with large building projects central to their cultures. Concrete is not an art that is easily passed on, and it was not preserved in western culture. [64] It was not often viewed as practical in times such as the dark ages when stone was readily available and designs never called for anything that stone was not capable of accomplishing. At a time when questioning your superiors was reason to fear for your life, and the few who had access to documents with explanations of concrete believed it to be a pagan practice of no importance, the material past though history unknown by master builders.

With our current understanding of history and ability to question almost anything, a new theory has been developed suggesting that the pyramids where made of cement. This would date concrete back 7000 years. Cement production started in the upper reaches of the Nile River thousands of years before the Christian era, and this theory strongly suggests that the pyramids were actually made of cement and that the secret of how to mix it was kept by the high priests, both highly organized and highly secretive. [64] This process was discovered by "an obscure French chemist" (Dr. Joseph Davidovits - founder of the Geopolymer Institute) Professor Davidovits originally studied and discovered the similarity between the inorganic polymers he was studying and the 'limestone' of the pyramids while having a portion of it analyzed at a lab. He was searching for a concrete polymer that could help improve the fire resistance of infrastructure and construction materials.

> In June, 1974, I realized that what we were producing were materials that were very close to natural cements, such as rocks based on feldspars, the feld spathoids. One day, as a joke, I asked my scientific partners at the Musee D'Histoire Naturelle de Paris what would happen if we buried in the ground a piece of the product that we were synthesizing in the laboratory at the time, and an archaeologist were to discover it in 3,000 years time…Their answer was surprising: the archeologist would analyze this object disinterred from the garden of a ruin in Saint-Quentin, and the analysis would reveal that the nearest natural outcrop of the stone was in Egypt in the Aswan Region! [64]

Figure 2. Experiment with Professor Davidovits [40]

Egypt has held a significant interest for the fields of design and science sense major discoveries in the early twentieth century. This interest in Egypt was started with the discovery of Tutankhaman's tomb, by Lord Carnavon in 1922. The study of Egyptian aesthetics influenced the artistic style and design of the 20th century. "The spate of paperweights and wallpaper, lamps and furniture and other gewgaws led the Bauhaus artists into a holography of derived images that not even an Egyptian high priest would recognize." [64] It is argued that this superficial interest in Egyptian culture and art caused a widespread misunderstanding of the engineering and intellectual significance of the culture as a whole, which in turn led to the long accepted misunderstanding of their technology and aptitude with construction. The general accepted understanding of how the pyramids were built was that the Egyptians hauled extremely heavy and large stones into place using dirt ramps and the power of many slaves. Although this theory does not go on to explain how a couple of the blocks which were larger than the majority, weighing prox. 70 tons each, got into place, not to mention "how they were cut to precision with only copper tools, and how they could be raised and put in place with the accuracy that the pyramid constructors required." [64] [2]

The theory goes on to explain that, from Egypt, the art of concrete was leaked to Asia Minor through travel and trade. Cementitious materials were used in the high art of mosaic construction. In the Chaldea (a tribe and portion of east Mesopotamia and at one point the whole of Babylon), columns were covered with small cones of fired clay in patterns that eventually evolved into the imbedding of flat tiles depicting scenes of war and victory. The best preserved samples of this ancient use of mosaic can be found in Pompeii "where the newly rediscovered lime mortar concrete was in evident use in the building construction as well as surface decoration" [64] Some of the knowledge of cement construction lasted for thousands of years before the rise of the Roman empire, but why cement construction disappears and reappears out of history is still a mystery. One can only imagine if Egyptian concrete techniques had survived how western civilization would have developed. What were once indigenous tribes might have had

[2] Please refer to Table 3 in Chapter 3 for detailed explanations of the theory on the Egyptian pyramids.

more stable housing; a structure which could provide the safety a tribe needs in order to allow their culture to flourish.

The Nabateans were the ones to rediscover the technology of concrete that holds water; they developed and burnt limestone for the production of pozzolan concrete hundreds of years before a similar process was rediscovered by the Roman engineers. [64] They used this technology to line hidden cisterns throughout the desert region, allowing them to travel and thrive as a society. Again, Concrete technology is always coordinated with the rise of civilization, like such of the Nabateans who eventually evolved into the roman influenced civilization that created the ancient city of Petra an architectural marvel completely hewn out of rock.

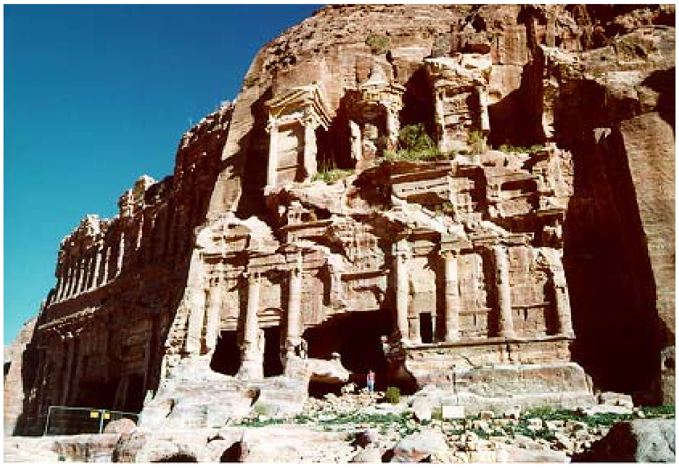

Figure 3. Ancient City of Petra [42]

> Large areas surrounding the cisterns were dug out of the desert and then covered with a thin layer of concrete. This waterproof layer was sloped down into a cistern. The entire catchment was then covered with the desert sand, which left a mark above ground yet provided a slow but continual replenishment of the water levels in the cisterns. The light rains and dews that gathered onto the sand above the catchment would seep down to the waterproof layer and be guided by the slope of the concrete into the cistern. By keeping the water underground and interdicting it from

> disappearing in the depths of the desert sands, the Nabateans were able to water their camels on the long trek from Jordan to the Mediterranean carrying the spices of Arabia to Europe. [64]

Non-structural uses of concrete kept the technology alive until Roman times where it was discovered and used widely through the architecture and aqueducts their civilization is known for. Such famous works as the coliseum and aqueducts found throughout Europe are often commonly thought of as the first concrete structures in the world. Roman mathematics and engineering is made evident through their architecture, much of which in turn is made possible through the use of their concrete. If these structures had not remained throughout the dark ages, what would have been the renaissance style? How would the art of Vitruvius been reborn if all that remained was his obscure texts with no living examples of the architecture itself? Our understanding of concrete is based on the Roman uses of the material since the reintroduction of its use in the Renaissance. The word itself is from the Latin word concretus which means mixed together or compounded. [54] One of the most inspiring works of roman architecture is the Pantheon which was designed and constructed by the consul Marcus Vipsanius Agrippa in 27B.C. It is the largest dome built in antiquity and was not surpassed for a millennium and a half until Brunelleschi constructed the dome of the Cathedral of Florence, completed in 1436. [64]

Figure 4. Pantheon Dome (by Painting Giovanni Paolo Panini) and El Duomo, Florence

It was constructed in sections of unreinforced Roman concrete which, much like the modern developments of aluminosilicate cements, had a much higher tensile strength than that of current portland cement based concretes. This tensile strength was due to the inclusion of volcanic ash as well as the way it was applied in the molds. It was layered in small amounts and each one was tamped down to remove excess water helping to avoid air pockets or voids which would have seriously compromised the structure.

Past the time of the Roman Empire and through the dark ages the secrets of concrete were kept safe through written documentation preserved in monasteries. Vitruvius' *De Architectura* was eventually discovered and translated by Fra Giovanni Giocondo in 1511, a thousand years after the Roman Empire had declined and one hundred years after it was found in a secluded monastery in Switzerland. He was a member of the Frères du Pont, a group of engineer friars who had come together under the aegis of the papal authority in the twelfth century to preserve and advance the art of bridge building. [64] He was also an engineer and architect before such sciences had a name, and in addition to being a scholar of Latin texts he was greatly interested in the bare remnants of the Roman Empire which spread across the face of Europe. Unlike translators before him, he recognized the value of this text and edited it for the future use of architects and engineers of the period. In addition, Giocondo was a very well-known architect of his time, respected by Louis XII, and the first European to use waterproof cement in bridge construction. But like all new innovations it took a long time to become a widely used method, and even Giocando did not experiment with it until asked to build a bridge in Paris, perhaps for potential fear of risking his reputation in Rome. Although the bridge itself was repaired over the centuries, it was noted that the original concrete footings did not need replacement. The technology was then left unused for another century.

Figure 5. Pont du Notredame, Constructed with Concrete Footings [82]

Joseph Moxon was the next to have any significant influence on the development of concrete. Through the sixteenth, and seventieth centuries there are scattered references to cementitious materials being used, but nothing of significance until the treatise *The Doctrine of Handy-Works* by Joseph Moxon in 1685. This was a self-published work, one of many of his books dealing with the sciences of the time. Having originally become famous for a book of maps he printed while mostly involved in printing puritan religious works, he became a well-known and respected man of his time. In this doctrine he states the art of concrete in English, using the same method as was mentioned by Vitruvius and Giocando. *Di architectura* had been lost to the engineering world in the mass of classical Latin books.

> 'Lime mixt with sand is much used in buildings,' and Vitruvius says, 'that you may put three parts of Sand that is digged and one part of Lime to make Mortar.' But Vitruvius his Proportion of Sand seems to much, altho' he should mean the Lime before it is slacked; for one bushel of Lime before it is slacked will be five Pecks after 'tis slacked. Here at London, where for the most part our Lime is made of Chalk, we put about thirty six Bushels of Pit-Sand, to Twenty five Bushels of Quick-Lime, …and if it lye in a heap two or three years before 'tis used, it will be stronger and better, and the reasons for so many insufficient buildings, is the using of the Mortar, as soon as tis made…There is other Mortar used in making Water-courses, Cisterns, fish-ponds, etc.. which is very hard and durable, as may be seen ot Rome… [64]

Even through this was revealed through what would have been a popular common language book at the time, the science was again ignored for another hundred years until the industrial revolution.

Although concrete has had a patchy appearance through history it has been available for thousands of years, and always contributes to advancements in construction. In the industrial revolution what is now known as portland cement was invented; this along with the demand for such technology brought concrete to the forefront of construction technology.

2.2 Introduction of Portland Cement

The influences of the Enlightenment, rationalist philosophers, and the industrial revolution pushed cement into being developed for widespread use in the ninetieth century. Due to the scientific methods being developed, cement was now starting to be analyzed from a chemical perspective, rather than the previous, somewhat mysterious recipe of raw materials. A market for the material was already in place with the rise in construction and increased interest in financial opportunity. “Real change came as the laws of patent rights developed. With patents a man’s work could be protected and income from his experiments could be stretched into the future. Suddenly the ‘kitchen dabblers’ became respected inventors with legal protection for their inventions.” [64] At this time when men were finding that they could elevate their social and financial standing by the use of intellect there was a wide spread interest in the study of using free water and limestone to create liquid stone. In 1779 the first concrete related patent was awarded to Bry Higgins for a type of hydraulic cement used to waterproof walls. This was stucco which is still used in the same fashion today. Like many before and after him he was set up for success by being a well off and well educated man, able to pay for the one hundred pound sterling fee required for application of the patent. Being a chemist and physician he published a treatise entitled “Experiments and Observations Made with the View of Improving the Art of Composing and applying Calcereous Cements and preparing quicklime.” In the work he explained the he was motivated to reproduce and improve the Roman cement which has lasted for so many centuries; he eventually settled on a formula of ‘well slaked lime, sparingly used, combined with fine and coarse sand, bone ash and water.’ [64] Slacked lime is hydrated lime also known as Calcium

Hydroxide; it is made by heating a lime product such as sea shells or chalk till it decomposes into quicklime (the chalk or shells decompose into calcium oxide which is quicklime, and carbon dioxide at high temperatures which are possible to be reached using an ordinary gas stove) and then adding water until it is done reacting, which is a process where it will bubble and hiss and then stabilize. [46] Bone ash is primarily composed of calcium phosphate and is the powdery ash left from the burning or calcination of bones. Slacked lime was used and is still considered a good mortar and putty. The publication of Bry Higgins paper had such a widespread distribution that a reference to it was found in the notes of George Washington dated 1784. [64] The search for an easily reproducible and durable concrete continued for decades following.

Much like current innovations in concrete, or any building material for that matter, many solutions were presented but only the well marketed and financially backed stood any chance of succeeding. John Smeaton patented his mixture in 1779, this cement product was closer to Roman Cement than that of Higgins. This was closely followed by a mix by James Parker in 1794 but it was just a year after Smeaton announced his product and was thus overlooked in the marketplace. Antoine-Joseph Loriot was another who discovered a concrete mixture, but although he had the ear of the French king he lacked the historical accuracy and marketing mind to make his product a success, claiming that he had discovered a lost art of the Greeks. Louis Vicat produced a type of artificial cement which he marketed with the name “white gold” in 1817. Although his testing methods lived on, his invention soon lost popularity with the introduction of the Portland Cements of England in the 1820’s. [64]

Portland cement was invented in a kitchen by a mason who fully understood the construction market. He is responsible for the success of what we now still call portland cement. "In 1824, Joseph Aspdin, a British stone mason, obtained a patent for a cement he produced in his kitchen. The inventor heated a mixture of finely ground limestone and clay in his kitchen stove and ground the mixture into a powder to create a hydraulic cement…He names the product portland cement because it resembled a stone quarried on the Isle of Portland off the British Coast." [68] Portland cement was a better type of cement because rather than simply reducing lime at moderate temperature, like natural cements before, portland cement required the heating of a combination of chalk, lime, and clay at a higher temperature, till completely ridding the mixture of CO_2 which was a weakening agent. It is important to note that it is not only the vast amounts of fuel used to heat limestone that contribute to the current polluting effects of manufacturing ordinary portland cement, but the actual chemical process required to decompose limestone into a useful cement product, a characteristic which defines OPC.

Aspdin's mistrust of the patent process caused him to be very secretive with his mix. Portland had been long recognized for the superior building materials quarried there. The combination of this secret mix and the use of the word 'portland' assured for the success of his product. Those who worked in building construction knew portland rock to be of exceptional quality and this aspect was carried with the name when choosing a cement. It was even imported from England for decades to America, despite the process being commonly known through manufacturing in New York and Pennsylvania, because of the belief that it must be better. Construction has been a conservative industry, slow to change, for centuries. New materials must cling to properties of the familiar, thus causing small steps towards advancement to be small. Eventually there was a high demand for local portland type cement because of the interest in canal and infrastructure construction in America; which caused for the interest in local development of the material in the U.S. [64]

Before portland cement was created, concrete was made with natural cements which had no added compounds or minerals. They were cheap to sell and fast to make, although sometimes they would also set in minutes and thus had to be mixed on site. This would require not only good timing and preparation, but space for on-site production. Portland cement created a more reliable concrete product. Natural cements eventually disappeared from the industry as the demand for portland cement rose. The modern concrete industry was being created through the involvement of many small business owners and contractors. Manufacturing processes evolved to the rotating kilns developed by Thomas Edison which saved on fuel and labor coasts, elements which endangered the industry with the previous use of vertical kilns. [64]

With the growing popularity of concrete and rise of portland cement, precasting techniques were also revisited. Precasting concrete has been in use throughout the history of the material, as it has stood out as an alternative to the more labor taxing poured in place method of construction. The earliest forms of precast concrete were used in Roman times. Through the centuries people considered concrete liquid rock, and thus used it to create well shaped masonry blocks. In the early twentieth century this process saved space and labor on the site from being used to produce concrete mix. "…from the moment concrete began to be noticed above ground in respectable architectural, or even mundane building forms, efforts were made to devise proprietary 'systems' of formwork suitable for less skilled labour, and to improve the quality of the concrete surfaces…" [60] Natural cement used before the development of portland cement required a highly skilled, and therefore more expensive, work force, and the development of ready-mixed concrete, concrete made and delivered to the construction site, was not to be seen till the 1950's. [20] The first patented precast system was created by W. H. Lascelles in 1875. [60] Precast did not experience any lasting changes until that time, as it continued to be used for masonry parts up till the late ninetieth century.

Due to the name portland cement there was a relatively large market for imitation or 'artificial', stone blocks in the mid ninetieth century. At this point precast was used for structure in the form of blocks and also in aesthetic applications, such as imitation stone veneers, also included in Lascelles patent. From this point on, precast concrete was only really seen intermittently until its general acceptance in architectural practice after the Second World War, "following the lead of Le Corbusier" [60] The evolution of new forms of architecture has always brought attention to innovations in construction and materials use.

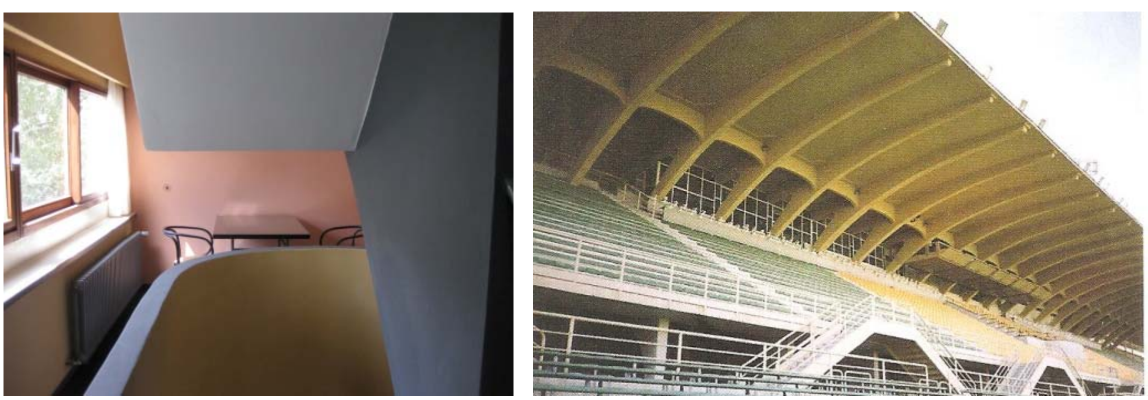

Figure 6. Concrete as Used in Early Modern Architecture, Corbusier 1927 and Nervi 1930 [14]

A call for standardization of material formulations and setting times rose as the industry and construction progressed. Organizations were eventually formed in the pursuit of standards and the sharing of relevant knowledge. Formerly known as the American Society for Testing and Materials, ASTM International was founded in 1898 with an interest in the steel industry. New comities were formed in 1902, one of which was for cement, lime and clay products, which became the leader in standardizing and testing methods for the concrete industry. [5] The American Concrete Institute was founded in 1904 with the goal of advancing concrete knowledge and standardization through research and communications between those in the construction and concrete manufacturing industries. The Portland Cement Association was founded in 1916 to aid in the development, engineering, and research of portland cement use and manufacture. The newest leading institute with the goals of certification and education within the industry is the Precast/Prestressed Concrete Institute which was founded in 1954 by "the engineers and firms that pioneered prestressed concrete technology in the United States." [67] These Standards, initially put in place with the current methods centering on the use of portland cement caused the industry itself to become dependent on its use. From then on there was so much study done to advance the technology [1] and mix ratios with portland cement that other cements never reached mainstream use and popularity. The nature of the building industry has been conservative throughout history, and not without reason, considering the enormous risks involved with changing them. Only as need arises are methods changed, progress for the sake of progress alone has never been a motto of the concrete or construction industries because of the risks of failure, financial loss, and potential danger to people building and afterwards using the structure. At the same time, it is this conservative manner and occasional narrow mindedness that has held back the potential for creativity and long term solutions to weaknesses such as deterioration caused by water and spalling or sulfate attack. “Using industry standards to commodify cement beginning in 1904, the cement and concrete industry surrendered control of their product to the market and the concrete industry as a whole developed a technocratic and conservative culture.” [4] Although the industry and its standards recognize the need for innovation in durable / sustainable concrete it will take a lot of time before new methods such as aluminosilicate cements are widely accepted.

Concrete has evolved from a high art to an inventor’s dabbling to mass commercialization and then concluded on the current standards centered on portland cement based concrete. Although it has had some downfalls, without it we would not have the ease of concrete production and construction that we have had for this past century. This material has inarguably changed the possible aesthetic and structural capabilities for architectural design. One of the largest weaknesses, in my opinion, of modern concrete is that it is not expected to maintain its full integrity past fifty years. This, of course has been accepted due to the ever evolving nature of our urban and cityscapes. Concrete has gone from being a slow building process that lasted for thousands of years to being a mass commercialized and relatively fast construction process that lasts under a century [20]. It takes such a long period time to research methods which bring any such widely used construction material into popularity. Only now are people starting to seriously change mixtures to improve concrete as a whole, in a way that is being accepted by the industry at an international scale.

2.3 Modern Portland Cement Processing and the Development of Addmixtures

Modern concrete has allowed for the evolution of architecture in the twentieth century both at professional and amateur levels. It has a place in the worlds vast array of construction projects, from a homeowner repairing brick work, to the city repairing infrastructure; the creation of the dome like leaves of the Sydney opera house, and the tallest buildings in the world all involve a primary use of concrete. The unique ability for concrete to be molded into building components has allowed for its ubiquitous use in our world today. Innovations in the twentieth century have focused on improving this plastic durability. If regular concrete was as durable as the limestone masonry of past architectural construction we would truly have liquid rock. The goal has been to work towards accomplishing this strength while maintaining an affordable and reliable construction material.

Much of the architecture from the ninetieth and early twentieth centuries, which is still standing in its near original character with little or no repair to the façade, is made of limestone and other masonry. The ‘brown stones’ of Chicago, the famous architecture of the Renaissance, and cathedrals of the middle ages have stood the test of time where modern concrete has not; only ancient concrete has any resemblance to such durability. Many factors cause this: the change of the molecular structure which comes with modern invention and mass manufacture, the presence of steel reinforcement and evolution in structural geometries to name a few. Despite changing cityscapes and building design, it is this ancient durability that is still being sought today through modern, sustainable, economic, and efficient concrete construction methods.

> After all, cement and concrete have been around since at least Roman times, it's just that their concrete would have taken a year or more to harden, with scaffolding in place. While such lime-based cements, made from heating limestone gently, are still available, they have their constraints. What the world needs is cement that has the qualities of modern Portland cement – ability to harden quickly under water, strong, long-lasting, durable – without the carbon emissions. 'We live in a world where one of the main concerns is the level of carbon dioxide in the atmosphere,' says Dr Martin Schneider, director of the European Cement Research Academy which held its first conference on new, low carbon, cements in May last year. [60]

The sciences have evolved this last century and we have taken this same time to analyze and improve portland cement manufacture. It will likely take a similar process, although possibly less time due to the advancements made in the study of materials, for any other type of cement to ever fully replace its use.

Portland cement is a calcium silicate cement made from a combination of calcium, silicon, aluminum, and iron ore which are minded from a quarry near the plant. These ingredients are crushed at the quarries in two different processes till the pieces are less than an inch in size. They are then brought to the plant where they are proportioned to make a cement with a specific chemical composition. [68] After being proportioned the pieces are ground to a fine powder which is eventually put through a kiln at 1400 to 1600 °C to form clinker. This clinker is the cement in lump form, the product of the chemical reaction which binds the raw materials. It is then processed again and ground into a very fine powder which is then used as cement in a concrete mixture. This process has not changed much sense its invention in the early nineteenth century, only the precision of the process has changed with the efficiency of machinery, and constant quality control of the end product. "This processing requires 60 to 80 separate and continuous operations, the use of a great deal of heavy machinery and equipment, and the consumption of large amounts of fuel and electrical energy." [2]

Both dry and wet methods are used to create the cement. In the first the materials are ground to a powder and fed to the kiln in a dry state, while in the second they are ground while wet and fed to the kiln in a slurry state. [68] Before 1950 there were disadvantages and advantages to both, although the processes were very similar. The wet process was most efficient for grinding the raw material, and because the material was held together by the water it exited the kiln in a granular crumble, making it ideal for later processing. This process took extra time and energy to evaporate the water in the mixture before it became hot enough to transform into cement, causing a rise in CO_2 emissions and expenses for fuel. In the dry process, it was hard to keep the raw material in the kiln because the fast-flowing combustion gasses would push it back out. Dry kilns were often sprayed inside with water in order to "damp down" the dry mix. There was actually very little difference between these two methods. The wet process was more commonly used until more recently, sense the development of more efficient machinery concerning the flow of powdered raw material and more directly controlled passage system leading to the kiln and its specific incline. There are situations where the wet process is still used today, which are made financially efficient by the use of waste as fuel. Companies will pay the cement plant to dispose of their byproducts which are high in energy content and safely disposed of in such a kiln. These practices are not being practiced by those concerned with sustainable means, due to the fact that they produce more CO_2 emissions over time. Based on the ratio of the different materials in this process there are eight different types of portland cement with various characteristics such as moderate sulfate resistance and high early strength.[3]

[3] Please see Chapter 6 for further detail

Through the second half of the twentieth century engineers have dabbled with improvements and additions to concrete mixes in an attempt to improve the material. There have been two different sides to these efforts. One has been an attempt to make the manufacturing process more efficient, and less pollutant, while maintaining the same basic properties of the end product, such as strength, sulfate resistance, or color etc… The other is more focused on increasing the strength and durability of concrete with the addition of other pozolanic materials, admixtures, fibers, or rebar arrangements. “Early-twentieth-century concrete was a pedestrian material that attracted plodding and pedestrian researchers. Laboratories all over the world were busily altering the amounts of cement versus aggregate in order to increase the strength, the ductility, and over characteristics of a material that had been developed some thousands of years earlier and had sustained precious little change since then.” [64] In addition to these main stream evolutions “Work outside the great research centers by individual, often autodidact, inventors is often lost for want of the economic power to bring it to the marketplace.” [63] One of such researchers was H.H. Bache, a trained civil engineer, who after realizing his lack of interest in all traditional engineering positions, took a job at the Concrete Research Laboratory in Karlstrup, Denmark and eventually invented CRC (compact reinforced composite). He realized that the strength of concrete is in an inverse ratio to the size of aggregate and cement particles. This is true because of the chemical and physical nature of concrete. With the addition of the water portland cement crystallizes and the bond between the crystals and the aggregate is what give it its strength. With more surface area, there are more bonds, and thus an increase in strength. There is a balance where the aggregate is the smallest possible with the most surface area, and yet large enough to not get lost in the matrix. This coupled with the same principle towards steel reinforcements, having bundles of cable rather than solid rods, greatly increases the strength of the material. A CRC beam is more like a steel beam, in strength and ductility, than is any ordinary concrete beam. Because its density is lower than that of steel it has a higher strength to weight ratio making it ideal for long spans, and cantilevered structures.

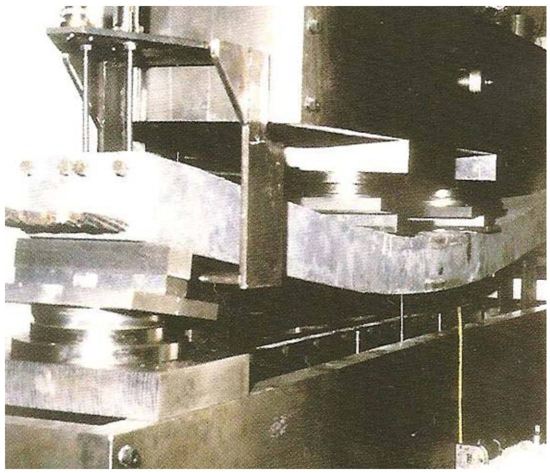

Figure 7. Test demonstrating tensile strength – CRC [64]

Fiber reinforcement in concrete was introduced in the 1970s and works off the same principles of shared surface area between the reinforcement and cement. Chemistry, the detailed reality behind how concrete sets and pours, has been and remains the chief means of manipulating and developing the material. It is within the microstructure that material properties are manifested. This level of analysis has led to the current advancements in concrete leading to the development of ultra high strength concrete, privately patented mixes, and CRC type concretes such as Ductal by Lafarge.

Table 1. New Concrete Types Currently in Use [11]

Type	Description
Ductal	An Ultra High Performance Concrete with up to 30,000 psi compressive and 7,000 psi flexural. For precast only, not spray or cast in place applications.
Translucent	96% concrete 4% optical fibre, 7500 psi compressive strength. Only available as prefabricated building blocks
Pervious	Almost no sand, paste coated aggregate with a compressive strength of 500 – 3000psi. Primary application is pavements.
Ecosmart	High-Volume Fly-Ash Concrete, with up to 80% SCM, good with mass applications when low permeability is required. Has a slower strength development.
Syndecrete	Recycled content, precast concrete surfacing material.
Transbuoyant	High Tensile Strength Concrete. Made of portland cement, sand and required admixture high tensile and compressive strength (exact numbers not found)
Eco-Cement	Carbon – Dioxide Absorbing Cement, High magnesium-oxide cement same basic properties as OPC
Rastra	Wall panels made of recycled foam plastics in a cement matrix. Which serve as thermal and acoustic insulating wall forms for residential and commercial structures.
Carbon Cure	Precast concrete block system used to sequester carbon dioxide during the cement production process.

Silica fume, fly ash, and slag have been used to improve the strength of concrete mixes sense the 1980s. In 1985 silica fume was introduced as a pozzolanic additive. The ‘highest strength’ concrete was used in building Union Plaza in Seattle, Washington. In addition to adding different found materials or byproducts such as slag or fly ash, chemically created admixtures have had a great impact on the concrete industry these past 60 years. Chemical admixtures currently make our high-strength concretes possible. "No single group of materials has contributed to expanding the capabilities of hydraulic cement concrete more than chemical admixtures." [12] There are admixtures for high-range water reducing, retarding, and hydration stabilization.

Table 2. Common Admixtures and Their Purposes [71]

Type	**Use**
Water -reducing	Reduce the required water content by 5 to 10%. Allowing for the possibility of a higher strength concrete without increasing the amount of cement.
Retarding	Slow the setting rate, used to counteract the accelerating effect of hot weather on concrete setting
Accelerating	Increase the rate of early strength development, which reduces the time needed for proper curing and protection.
Superplacticizers	Reduce water content by 12 – 30 percent. It helps produce a highly fluid but workable concrete which can be placed with little or no vibration or compaction.
Corrosion-inhibiting	A specialty admixture used to slow corrosion in reinforcing steel in concrete.
Viscosity Modifying	Used to increase the viscosity, used to increase stability for various projects such as underwater applications

> Ultra high performance concretes are used increasingly for a range of structural applications, and standards in a number of countries are being revised to accommodate these improved materials. Often they are more brittle than conventional precast concretes, which can lead to problems in failure more as well as under service conditions. [7]

Other than altering or adding chemicals to portland cement based concretes to increase strength, durability, or workability, the more recently accepted concept of removing portland cement from the mix altogether is under investigation. Inventing and testing the new material is just one of the major stepping stones to being able to bring innovations to the concretes which will be used in our buildings.

The first testing system for concrete was used to control the water-to-cement ratio, a method still ingrained in both EU and US standards. "…and one which does not necessarily have any meaning for alkali-activated or other alternative cements, because they do not always simply involve adding water to a solid precursor."[31] These methods are being developed alongside that of the materials. Due to the concern of the environment, fuel costs and increasing demand on concrete as a material in our modern world, researchers have been working on several different alternatives, one of which is aluminosilicate or geopolymer based concrete.

CHAPTER 3

HISTORY OF ALUMINOSILICATE CEMENT

3.1 Original Invention and Use, as 'Geopolymer'

Aluminosilicate cement is also known as geopolymer cement, so named by its primary inventor, Dr. Joseph Davidovits. He gave it this name, because it resembles rock and has a polymer-like structure, although it is neither a rock nor a true polymer, like such that is found in nature. There are thus those who, in the scientific community of cement materials science, dislike the name Geopolymer and refer to it only as aluminosilicate cement. Aluminosilicate cement is essentially an inorganic polymer. Polymers have only been recently recognized in the world of chemistry this past century. Like many substances, some polymers are found in nature and some are manmade; they make up many common materials we see every day, most in the form of plastics. They are substances formed of giant molecules, or macromolecules, covalently bonded[4] in a composition of repeating structural units. [18] This unique structure gives them the durability or malleability they are known for. Polymers were first discovered in the early twentieth century, but the concept of large molecules which bonded together to form other larger ones and thus the true structural unit for the substance, or as was more technically termed 'the presence of physical forces of aggregation in colloidal [glue-like] systems', was not supported by the chemists of the day. No molecule was thought to be above a molecular mass of 5000 g/mol. Polymers have a molecular mass far above that even in the millions of g/mol. Hermann Staudinger, a German organic chemist decided it was worth looking into, and thus after many protests from his fellow colleagues he

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[4] Please see Chapter 6 for more detailed information on the chemistry of cement.

slowly started to prove they existed. The term polymer is derived from the fact that they are made of many bonded molecules. Substances such as rubber, starch, and cellulose are naturally occurring polymers. Organic polymers can often be more complex than those which are inorganic. [18] Through the past century the development of various polymers has allowed for the evolution of our technologies, especially in regard to electronics and various forms of construction with the invention of silicones, resins, and subsequently advanced adhesives and more commonly available, durable materials.

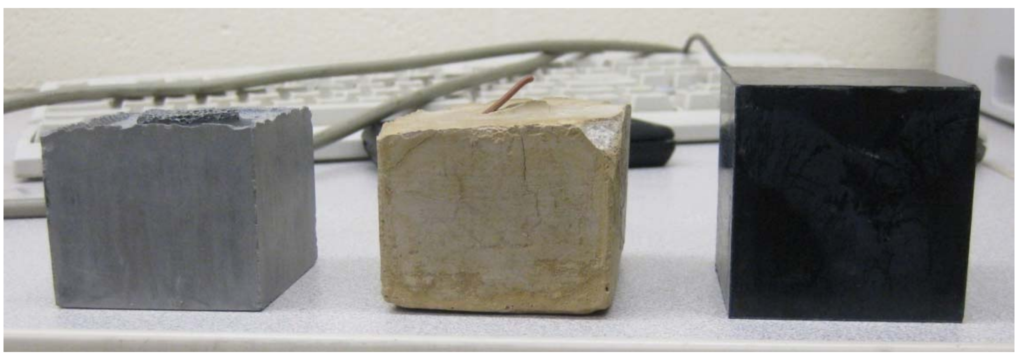

Figure 8. Geopolymer Cement Samples, UIUC [49]

Geopolymer cement is a unique polymer in that it mimics the appearance and properties of stone. It was originally discovered by Prof. Dr. Joseph Davidovits in the search for nonflammable and noncombustible plastic materials to be used in fireproofing. “In the aftermath of various catastrophic fires in France between 1970-73, which involved common organic plastic, research on nonflammable and noncombustible plastic materials became my objective.” [21] While studying inorganic polymers “he was struck by the fact that simple hydrothermal conditions govern the synthesis of some organic plastics and also heat-resistant mineral feldspathoids and zeolites.” [21] The creation of geopolymers was inspired by his realization that some organic plastics and heat resistant minerals were governed by similar conditions for synthesis. Felspathoids and zeolites are commonly used industrial minerals. Zeolites have a three dimensional crystal framework which is stable through hydration and dehydration (water does not degrade its molecular structure) and have the ability to absorb gasses, amongst other properties. [35] Felspathoids, or feldspars, make up an estimated 60% of exposed rocks on the earth crust. They are aluminum silicate minerals with varying proportions of calcium, potassium, and /or sodium. Certain types of feldspars have a composition similar to granite. [35] The discovery of a material which artificially produces a fireproof stone to mimic the qualities of such widely useful and durable minerals was what led to the many applications of geopolymers.

The first product which utilized geopolymer technology was a fire-resistant wood chipboard composite panel. The material was first tested in 1972 with the ceramicist team J.P. Latapie, where it was discovered that water-resistant ceramic tiles could be produced at temperatures lower than 450°C (842°F), i.e without firing. One mixture of Kaolinite (dehydroxilated to from metakaolin) reacted with caustic soda [lye] at 150°C. Although this reaction was previously researched starting in 1935 its industrial use was not recognized till this study took place [99].

Geopolymers were then put to use in several ceramic applications. For instance, a geopolymer was developed for use in ceramic fuses. It did not have sufficient water absorption, thus in this case the project was abandoned**.** [21] The material, in its many forms, lends itself to high temperature, quick setting, chemical resistant applications, making it a more durable solution for replacement of portland cement in construction.

Figure 9. Timeline of 'Geopolymer' Materials [21]

In 1979 the term 'geopolymer' was coined for types based on silico-aluminates. Geopolymer is essentially man-made rock[5] and it was eventually discovered that this rock was much like the rock of the pyramids.

[5] Please see Chapter 6 for further details on man-made rock geosynthesis.

A whole new theory was developed concerning the construction of the pyramids as a result of the study of geopolymers[6]. This theory has been tested within the Geopolymer Institute as well as in academic settings such as a class at the Massachusetts Institute of Technology. [15]

Table 3. Argument for Pyramid Theory [64]

Argument for Pyramid Theory – Dr. Joseph Davidovits
For the most part the chemistry and geology of the bedrock in Giza does not match the stones of the pyramids.
The Pyramid Blocks contain no strata, a key feature of all natural limestone, which shows that the rocks were altered from their original state.
Geochemical analysis has shown that the stone of the pyramids matches that of at least twenty different Egyptian quarries. The stone was not quarried from local bedrock.
Standardization of the stones by mold is much more probable and logical If they were indeed carved by hand they would not have gone to the lengths of using standard sizes.
Copper tools were the only available at the time, bronze did not come to that area for another 1000 years, and they cut limestone inefficiently and slowly.
The longest blocks always have the same length, this would be impossible by cutting natural rock due to the strata.
If these were indeed carved by hand, there should be a large body of evidence of cracked blocks. Even with modern tools this margin of error would be impossible to avoid.
It was noticed that the pyramid blocks are 20% lighter than the local bedrock limestone. Cast blocks are always lighter than natural stone due to the presence of trapped air bubbles.

[6] Please see Chapter 2, The History of Concrete, for further details.

The first paper on low CO_2 cement by Joseph Davidovits, titled “Carbon-Dioxide Greenhouse-Warming: What Future for Portland Cement.” was presented at the Emerging Technologies Symposium on Cements and Concretes in the Global Environment which was organized by the Portland Cement Association, Chicago, IL. March 1993. The recognition of alternative cements by the PCA shows the potential for this sector of the construction industry to change. The recognition of geopolymer cement as a potential building material has led to the study and conclusion that it has the capacity to replace currently used portland cement [22]. Although it may remain a boutique concrete in light of the sustainable developments in the already established concrete industry, it is now recognized worldwide as an available replacement for portland cement if developed for the specific region. There are two main reasons for this, firstly because it answers the need to drastically reduce the carbon dioxide output of construction, and secondly it has the potential to produce a more durable concrete while remaining affordable. “Geopolymer materials represent an innovative technology that is generating considerable interest in the construction industry, particularly in light of the ongoing emphasis on sustainability.”[91]

3.2 Current Use in Construction

Geopolymer cement is currently in use for several poured in place and precast applications internationally. There are a few known companies which currently manufacture aluminosilicate or geopolymer based concrete.

Table 4. Companies Manufacturing Aluminosilicate Cement (Page 1 of 2) [39]

Company and Location	**Name of Aluminosilicate based concrete manufactured**
Wagners – Brisbane, Queensland, Australia	Earth Friendly Concrete
Universal Enterprise – Cuttack, Orrissa, India	Fly ash based geopolymer brick
Jajil Enterprises – Birsa Nagar, Jamshedpur, India	Pavement Blocks using steel slag and flay ash
Zeobond pty Ltd – Simerton, Victoria, Australia	E-crete, producing both precast and poured in place aluminocilicate based concrete
Schlumberger – France and U.S.A	EverCrete – Co_2 resistant cement
Banhan Uk Ltd – Northern Ireland	BanhaCem, BanhaCrete, BanhaBlock All using geopolymer cements, the block incorporates polystyrene for use in passivhaus applications.
Novacem	Carbon Negative Cement – new process using magnesium silicates, essentially an aluminosilicate based cement, although it does not appear to use any industrial by-products

Large obstacles which must be overcome, in order to more frequently implement this material, not does it need acceptance by concrete manufacturers, but the localized research and standards development necessary to produce and use it needs interest and funding. “It takes years of development and trials with your actual materials to gain an understanding of the chemistry and its effect on the geopolymer concrete of the raw source binder powders that are being used.” [41] Tom Glasby is a project manager for Wagner, a concrete manufacturer which produces a geopolymer concrete they name EFC, or Eco friendly concrete. Geopolymer or Aluminosilicate based concrete can be placed as a poured in place or precast element, depending on the mix and water content. Water content here is used to enhance the workability of the mix, and is not part of the chemical bonding process.

Figure 10. 'Geopolymer' Cement Pavement and Precast Panels by Zeobond [102]

Looking back through the history of portland cement[7], A pattern can be seen between the creation and acceptance of new construction materials. Builders are slow to change their methods, and innovations can become successful by masking their newness with a commonly desired name or property. The current marketing of geopolymer involves it having names such as, eco-cement and earth friendly concrete or EFC, focusing on its ability to replace portland cement with a much lower CO^2 output. Due to the nature of marketing, it is likely that aluminosilicate cement is going to be accepted as a sustainable replacement to portland cement before it is accepted and developed as any kind of structural advancement. It is not perceived as a material capable of structural advancement because it is in the first stage of marketable development, where such things

[7] See Chapter 2

as the deliverability to the site, rather than its possible use in a CRC, currently define its limits.

3.3 Current Research on Aluminosilicate Based Concrete

The key interests of research for geopolymer concrete deal with its setting and maleable chemical makeup. Geopolymer can be made using many different types of materials, the primary ones under most consideration being: slag, fly ash, or metakaolin; the two first ingredients have a wide range of chemical composition and are amoungst the recognized pozzolanic materials for use in ordinary concrete [16]. These mineral admixtures are similar in chemistry to the primary ingredients of cements produced many centuries ago. In this way geopolymers are a marriage of the new and old technologies. ASTM C 618 defines a pozzolan as “A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value but which will, in finely divided form and in the procesnce of moisture, chemically react with calcium hudroxide at ordinary temperatures to form compounds possessing cementitious properties.” There are natural and by-product pozzolans respectively: volcanic ashes, diatomaceous earth, clacined clay, metakaolin clay, rice hull ash, and fly ash, slag, and silica fume. When incorporated in portland cement based concrete they rely on the chemical reaction of the hydration process, where in geopolymer they are the principle component to a completely different chemical reaction producing a similar product. Fly ash is in great abundance as a waste by product around the world, due to all of the energy produced by burning coal, expecially in developing nations [16]. There are several types of fly ash. Class C and Class F are the types used for cement applications due to their pozzolanic properties, which are the result of the type of coal that has been burned. The Research being conducted at the University of Illinois at Urbana Champagn is concentrating on the setting behaviors of geopolymer made with fly ash. Because fly ash is a waste by product, its classification has never been a very detailed science and within class C and F there are still variations in the chemistry that effect the properties of geopolymer cement. There are numerous areas of characterisitics within the behaviour, possible addmixtures, and resulting mechanical properties of geopolymer cement, all with the hope of making the material more commercially viable.

Figure 11. Locations for ‘Geopolymer’ Research [27]

Although geopolymers were first invented in France, Australia is where they are most used. The University of Melbourne has played a large role in the research towards geopolymer concrete use with the establishment of the Geopolymer and Minerals Processing Group within the Department of Chemical and Bimolecular Engineering. In addition there are other research centers outside the realm of academics, such as the

Cooperative Research Centers' Geopolymer Program which is an Australian government initiative [17]. A key aspect to why Australia has become the leading producer of geopolymer cement is their government's involvement and agenda towards innovation and a more sustainable environment. In the United States, within the Environmental Protection Agency, the Department for Transportation and the like, sustainability is an underlying issue which has only recently become a topic of more urgent concern within all branches of research. It is more common for the EPA to produce research on what the problems are, and why before researching any type of solution. When a solution is produced it fits in place with what is currently in practice; therefore completely new ideas are not always nurtured or promoted. While in Australia, for instance, there is a newly formed Department of Innovation, Industry, Science, Research and Tertiary Education [6] which concentrates on just that, the promotion of innovations within industry practice and small business etc. There is of course an economic and business dynamic to this situation which will not be discussed at this time. There was a previously existing Center for Sustainable Resource Processing, closed in 2010 to be continued by Curtain University of Technology, which had a Geopolymer Research Program. It had a goal of investigating the microstructure, and producing samples for possible large scale manufacture in addition to gathering a collective of willing stakeholders to develop geopolymer applications. [6] Other leading institutions in geopolymer research are located throughout Europe such as GEOASH the project sponsored by the EU for 'understanding and mastering coal fired ashes geopolymerization process in order to turn potential into profit'.

In addition to academic or government based research there are also professional organizations concentrating on sustainable concrete or geopolymer manufacturing. The Geopolymer Institute in Saint-Quentin, France was founded by Joseph Davidovits who originally coined and discovered the material in the 1970s. The annual Geopolymer Camp is an international conference for the research and manufacture of geopolymer applications. This conference brings together the many researches from both private and public sectors of the industry. On a less specific note, The International Concrete Sustainability Conference sponsored by the National Ready Mix Concrete Association is another major hub for shared information, both academic and professional; it helps close the gap between the two types of research and has been held for the past ten years. Geopolymers are recognized by those concentrating on sustainable concrete innovations [80], and can be a subject of conversation at such events.

Aluminosilicate concrete is gaining ground in the industry and has had an increased amount of interest from all research sectors worldwide over the past decade and in most recent years [38]. There is a possibility that this form of concrete manufacture and design could change the processes as we know it in the years to come, by changing construction timelines, and eventually the basic properties of concrete as we know them. It is a material I feel the architecture industry, both professional and academic, should explore.

CHAPTER 4

SUSTAINABILITY

Sustainability has become an increasingly relevant topic since the rise of the industrial revolution in the mid ninetieth century. Beginning with a select few scientists and philosophers, the need to maintain a balance with our natural environment is now recognized by all major industries and is no longer a subject which can be ignored. As humanity has evolved into a society that depends greatly on our technology, our technology has greatly taxed our natural environment; this trend is now beginning to be reversed.

4.1 Relevant Issues in the U.S. Construction Industry

Sustainability is often seen in two ways, or from two directions. Firstly, if a material or structure is more durable, less of it needs to be produced because it needs to be repaired less frequently causing for a reduction in energy spent. Contrarily, if the material in question takes a significantly reduced amount of energy to produce, uses renewable resources, or what would otherwise be considered waste material, there is less energy put into its production. The best solutions address both of these issues. Regarding Concrete, the most popular current methods of reducing emissions are to either recycle the concrete for use as an aggregate and /or to reduce the amount of portland cement used in a mix with the addition of other mineral admixtures such as fly ash, kaolin clays, or slag. There is also recognition for the need to use high strength concrete more frequently, but at this time that is often cost prohibitive. These are both slow processes towards a sustainable industry. Recycling is not a common practice in the United States, 2-10% of the 455 million cubic yards of concrete produced in the U.S is returned to the plants for recycling. [63]

The cement industry is a building block of United States construction. [69] The extensive use of this material has accounted for the overwhelming impact it has on our environment. Cement production accounts for 95% of all CO2 emissions of concrete. Cement currently contributes roughly to 8% of worldwide anthropogenic CO_2 emissions or 6% of total green house gas emissions in our atmosphere today. [100] The production of one ton of cement commonly results in the release of 0.65 to 0.95 tons of CO_2 depending on the methods and efficiency of the plant. Even though there have been significant advances in the efficiency and sustainable practices of concrete manufacture, there is still an expectation for these emissions to increase by 260% between the years 1990 – 2050. [94] Around 55% of the CO_2 emissions in the production of cement clinker originate from the conversion of limestone into lime, and 40% of the energy used is contributed to the combustion processes necessary for this reaction. [100] Thus, 95% of the Carbon footprint of concrete is the binder, cement. [59] It is well known that concrete manufacture is a large contributor to the degradation of our environment and climate change, for these statistics can be found in many different sources through many leading associations internationally.

The systems for concrete production are not going to be improved through programs such as carbon offsets, carbon taxation or point systems such as the Leadership Energy and Environment Design (LEED) system, or the Building Research Establishment Environmental Assessment Method (BREEAM). They will be changed through industry acceptance and the evolution of research standards.

The LEED system is accepted in the United States as the leader in sustainable building rating systems, and was launched in 2000 by the United States Green Building Counsel (USGBC). BREEAM is the leading sustainable building rating system in the United Kingdom, and was first launched in 1990. These motivations help the construction industry adopt better practices, they do not directly create solutions for our built environment, but aid in recognizing existing ones. [66] It is a commonly recognized problem that there are some issues in the LEED system which cause conflict when designing more efficient concrete mixtures. For instance, there are points rewarded for a use of 30% of a Recovered Mineral Component (RMC), but that does not take into consideration the use of more than one type of RMC. RMCs are mineral waste by-products, such as slag and fly ash, added in differing proportions in order to manipulate many different properties of a mix. With this limitation, if you have 30% fly ash in a mix you get points, but if you have 10% slag and 25% fly ash, more than 30% you get no points. The point system does not currently follow the reality of some detailed situations, and thus does not always help promote sustainability. [61]

Industry standards greatly affect the limits of sustainable innovations in the United States. Due to our democratic and capitalist system, this is a slowly changing process. For instance, there has recently been a change in the acceptance and use of portland limestone cement in the United States. [57] There was a proposal within C-1 of the ASTM for the allowance of up to 5% limestone to be ground into portland cement clinker. Portland limestone cement is a mixture of limestone and portland cement with 5-15% limestone, and has been an accepted mix in Europe sense the 1960s. [67] This is a controversial subject within the committee which writes standards for cement production.

"The proponents claim a significant savings of energy during production without degradation in quality and even cite improvements in some cement and concrete characteristics. The opponents charge that limestone acts merely as an adulterant, that strengths are reduced, and that the proposal should be abandoned on ethical grounds." [57] This type of situation has become more and more common within leading industry communities.

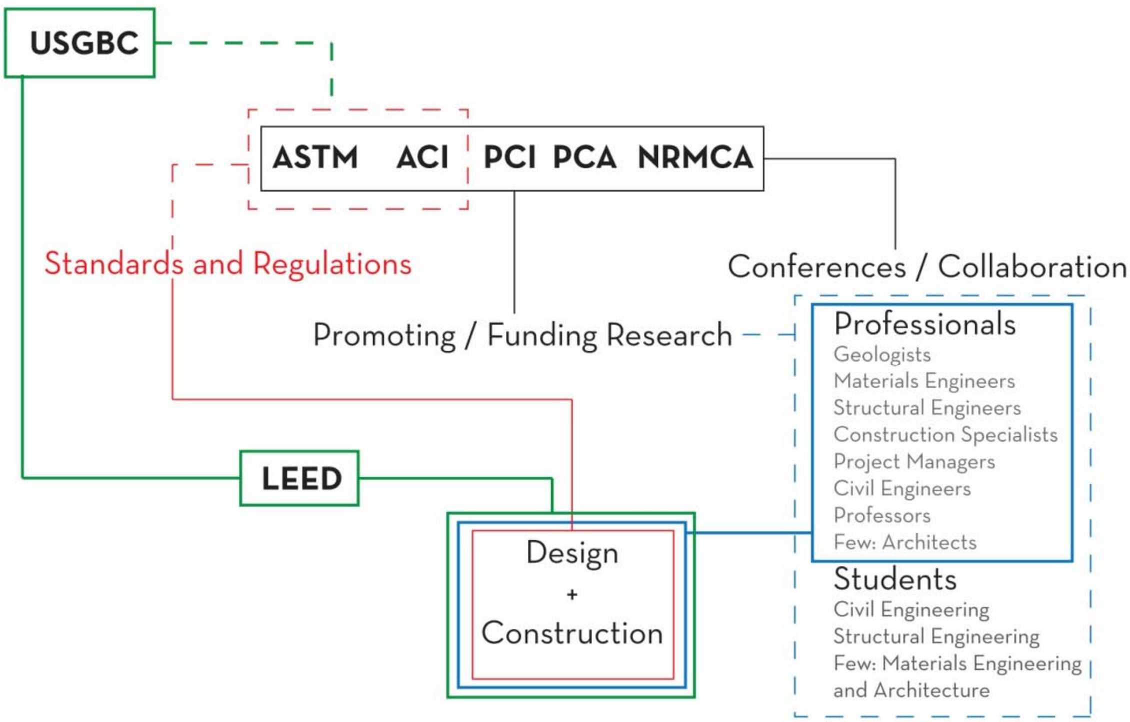

Figure 12. Organizations Creating Standards in the Construction Industry

4.2 Current Construction Practices in the Concrete Industry

The concrete industry of the United States has made the cement manufacturing process as efficient as possible, and has also reduced the amount of portland cement used in mixtures. These may seem like straight forward and basic concepts, but they require very detailed and complex solutions.

Concrete sustainability has been a topic of concern sense the 1970s; the calculations of its true effects on our environment are complex. All stages of a materials life must be considered when calculating the environmental effects of its production. Each component of a material has a manufacturing, and transportation energy which when all added up, equal the embodied energy of a material. There is also associated waste of all of these components which needs to be factored into its environmental aspect. [84] The materials of concrete are traditionally non-renewable, consume large amounts of energy in the manufacturing process, and at the end of a buildings use are rarely recycled and thus contribute to a large amount of construction waste. Issues concerning water, formwork, or transportation are not considered in this report, although they are all issues when considering the sustainable nature of concrete. One way to estimate life-cycle greenhouse gas emission factors for concrete is the Environmental Protection Agency's (EPA) Waste Reduction Model (WARM) [34]. WARM focuses on the waste generation of each step in concrete production. All green-house gas emissions are calculated per short ton of concrete. These are calculated based off energy used during the acquisition and manufacturing processes, transportation, and emissions resulting from manufacturing processes. Through this detailed calculation benefits, such as using recycled aggregate, can be considered and data can be obtained to support sustainable practices from both an economic and emissions perspective.

The promotion of sustainable manufacturing in concrete addresses different issues from all steps of the life cycle of the material. This promotion is achieved through an array of different industry associations which specialize in information on concrete, through the publication of research reports and the organizing of conferences for professional and academic collaboration. Leading associations are the Portland Cement Association (PCA), the National Ready Mixed Concrete Association (NRMCA), the Precast and Pre-stressed Concrete Institute (PCI), and the American Concrete Institute (ACI). There are, of course, other institutes and organizations which add to the knowledge base or accepted standards for the concrete industry, but the previous are associations concentrating on concrete alone. They all offer views on sustainable concrete practices, and publish educational material or sponsor programs to promote the spread of this knowledge. In many ways they act as a go between for the academic and professional sectors.

The PCI offers a Sustainable Plant Program recently launched in December 2011. The PCI is the leader in precast concrete production in the U.S and is working to promote more sustainable practices [77]. Those of the PCI concentrate more on the efficiency and energy use of the production facilities for precast concrete when addressing sustainability issues. [74] The material focuses on energy usage, concentrating on our need as a country to reduce our use per capita; significant space is dedicated to the description of why we need to be more sustainable as an industry and maintains precast as the most sustainable concrete option.

> As precast producers (and Suppliers) we have a clear understanding of the sustainable attributes of our products and services. With the maturity and evolution of programs like the USGBC, LEED rating system, we understand the competitive need to understand green building systems. However, with the progression of environmental awareness (and in some policy) driving sustainable improvements precast producers must know look at plant operations. [74]

Making a precast plant more sustainable deals with the amounts of water and energy used, as well as how the waste is processed and what is recycled. The key 'hot spots' listed in the working draft of the Sustainable Plants Manual are: "1. Reducing and optimizing the use of cement in precast products, 2. Reduce and optimize the use of steel products and, 3. Implementing programs to reduce energy demand in precast operations, 4. Reduce land-filled waste, and 5. Conserve and reduce the amount of water consumed in precast operations." [74] Clearly, environmental concerns are a priority here.

Not only is sustainability promoted for environmental reasons but for economic efficiency as well. The more efficient an operation the more cost effective it is, this fact is a major driving force in sustainable issues within most industries, and must be fully understood if sustainable practices are to become common place. Companies are rarely going to change the way they operate, a process that often causes for an investment of funds, if the change does not have a clear economic gain for the future.

The PCA often addresses efficiency in portland cement manufacture without directly mentioning sustainability as a goal, although they are leading funders of sustainable research initiatives [72]. The Joint Sustainability Initiative is one of such, dedicated to the education of all members and the public. According to them: "Compared to 1972, it takes 37% less energy to produce a ton of cement, enough to power 2.3 million homes a year." There is not much more that can be done to decrease traditional limestone based portland cement's CO_2 emissions, because it is the actual chemical process which lets off so much CO_2 and requires so much heat and thus energy consumption.

Without consideration of modern advancements in sustainable practices, concrete is still considered a sustainable product for two main reasons: firstly because 11% of concrete is portland cement, making the overall product not as demanding as its essential binder, and secondly because it is viewed as a very durable and affordable material for construction. In addition, in comparison with other leading methods of construction, there is a greater number of plants which produce cement containing a minimal volume of calcium from limestone [67].

Raw material use is the central concern to more sustainable means of concrete production. Basically four elements are necessary for cement production, calcium, silicon, aluminum, and iron [68]. Portland cement can be made with a wide variety of materials. Although limestone is the most commonly used as a raw material, sea shells, shale, blast-furnace slag, or fly ash can also be added and are becoming more and more common. In addition to the materials used, air quality is also a large concern for cement manufacturing, and has been addressed through more advanced filtration systems in manufacturing plants [68].

Practices for concrete mixtures include the use of certain admixtures, aggregates and supplementary cementitious materials (SCMs). For instance, high range water reducer has allowed for mixes to reduce the amount of water needed while maintaining the workability of the concrete. Fly ash and slag, both industrial waste byproducts can help to replace clinker in portland cement mixes; they often aid in making the concrete more durable. This is due to the way they work with the existing concrete matrix, they aid in making it tighter, filling in the micro spaces which otherwise make ordinary concrete more porous [55]. The control of the size of particles in a concrete matrix is a leading cause in the current innovations of today's modern concretes. Class C and F fly ashes are used as cementitious materials. The difference between the two is in their chemical composition. Class C is higher in lime content than class F, this effect can cause an earlier strength gain in the concrete and help manipulate setting times. There are many different types of additions for concrete mixtures which manipulate the product to more specific needs. [94]

Due to the wide acceptance and established nature of portland cement technology in concrete manufacture, the continuing research towards more efficient and environmentally safe practices continues to revolve around OPC rather than seeking alternative cements all together. This can be seen through the policies and topics of many different organizations currently involved in cement and concrete research.

The National Ready Mix Concrete Association (NRMCA) is a leader in promoting sustainable concrete practices and research. Much like the PCA the NRMCA is another resource for those in the concrete industry, but rather than concentrating on portland cement alone, it concentrates on the ready mixed concrete industry as a whole. It was created twenty years before the PCI. Its view on sustainability is in line with that of the PCA and PCI. Amongst others, a large contribution of the NRMCA is its annual sponsoring of the International Concrete Sustainability Conference, which was started ten years ago. This meeting is one of the most influential for the spread of sustainable industry practices.

Figure 13. International Concrete Sustainability Conference Program [61]

The acceptance that a more refined understanding of cement and concrete technology will bring more efficient methods and a more sustainable end product has promoted innovative research in the past couple of decades. With the advent of nanotechnology and the physical sciences associated at that scale, researchers are able to study cement in more detail [10]. With this in mind, one recent attempt to solve the sustainability issue of portland cement is the Concrete Sustainability Hub (CSH) at the Massachusetts Institute of Technology. The Hub is sponsored in equal parts by the

Portland Cement Association and the Ready Mix Concrete (RMC) Research and Education Foundation. The RMC Research and Education Foundation was created in order to pool the resources of the different sectors of concrete industry into funding more research and product development. The CSH was founded in 2009 in order to analyze cement from the bottom up. There is a group of 30 graduate and undergraduate students, 10 professors, in two schools and five departments that work on this research every day. [90] They operate as a collaboration between the engineering, architecture, and management schools, creating a unique environment for innovation.

Table 5. Concrete Sustainability Hub Research Topics [56]

Research Projects at the Concrete Sustainability Hub
Concrete Materials Science Platform - The Genesis of Concrete at the Concrete Sustainability Hub: our goal
Concrete Building Technology Platform - The Edge of Concrete: A Life-Cycle Investigation of Concrete and Concrete Structures

The study of the creation and the destruction of concrete adds valuable information to the understanding of its manufacture and implementation. An interesting aspect of concrete research is the investigative analysis of failed concrete structures. Completing the circle, the analysis of structures after their initial design and often years of use, brings certain issues to the attention of those completing initial designs and chemical analysis. Petrographic analysis determines failure at the microscopic level. [73] If these situations can be avoided, there can be fewer repairs, and thus less wasted product and energy. Problems within a mix include the analysis of how the cement adhered to the aggregate, and/or how the acidity of a possible component of the mix degraded the rebar. On occasion it is seen that the wrong type of cement mixture was used for the application, or the fly ash ratio has caused inherit problems in the concrete. If the particles of a concrete mixture do not adhere well, if the ratios are not correct, the concrete can crumble and the structure will fail. An example of this was the cement composition of a decorative earn atop a civic building in Milwaukee, after many years it started to crumble and fall from the roof line potentially causing serious injury to those below. After analysis the decades, near century old, concrete mixture was found to contain a larger than recommended portion of sand. [73] Durability, sustainability, chemistry, and everything involved in life cycle analysis has real world practical applications and effects. Notice the difference between the example on the left of ordinary portland cement and the right of the ultra high performance concrete, Ductal below.

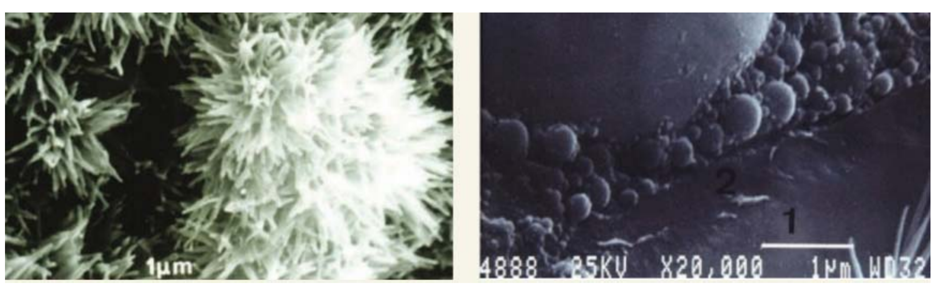

Figure 14. Petrographic Analysis Examples [51]

There are also great concerns amongst engineers in the industry regarding the degradation of skilled labor used in United States construction. Projects would be more efficient if their placement followed their design with greater exactness, the end product is what really matters here. No matter what kind of engineering calculations and chemical mixtures are added, if, the project is not constructed properly it is all for nothing. For instance, if the rebar is placed too close to the surface of a poured in place slab it can fail in a significantly shorter amount of time. If the surface quality is worn away over time (due to traffic or sulfate attack as example), the steel becomes more susceptible to corrosion by moisture, which gets trapped, and through freeze and thaw degrades the whole microstructure of the slab. There are many side discussions amongst engineers which make such advancements a concern. For instance, I have heard mention that using high performance concrete also calls for the reinforcement values to go up. I relaised that this only is an issue when designing high performance structures, and thus is not a concern in regular applications. Most issues regarding sustainable innovations are multi sided with differing levels of support within the industry [66].

A motivation for sustainable research in the U.S is the recent evolution in concern for the environment and the development of public interest in more sustainable methods and designs. For instance, it is commonly understood that trying to reduce the carbon footprint of concrete is good for industry public relations [32]. This is the same reasoning behind the many new ‘earth friendly’, or ‘eco’ products seen throughout many industries, from cleaning products to T-shirts. The construction industry is equally affected by this sentiment, and it has driven the industry to create and develop new competitive sustainable products.

Within the scheme of sustainable development, the United States is seen as being behind in the design and implementation of durable and environmentally sound methods of construction [43]. During a presentation on ‘Achieving Differential Durability and

Extended Service Life with Blended Cements' by Lafarge it is noted that the United States is greatly lacking in the use of blended cements. [66] It is important that concrete increases in durability first, not necessarily versatility of form. With a new material, durability and strength new forms can be efficiently made. Others say it is important that we invest in our infrastructure; we need to build to last. Essentially, more high performance cement needs to be used in conventional applications. Industry and leading researchers recognize the necessity for a change in manufacturing, performance based standards and the involvement of architects in order to change the role and quality of modern concrete.

During a conversation with Colin Lobo, Senior Vice President of Engineering for the NRMCA he stated that: "Usually performance based specifications have a negative effect on sustainable development." There is a link between performance based initiatives and sustainable development, one must allow for the other in order to move forward. Within the NRMCA there are three focuses: to improve the product by making it more sustainable, findings ways to optimize our materials by improving the production process while including uses of more sustainable methods, and to improve the benefits of concrete with respect to long service life and durability. Improving this product is strained by the specifications set for it, and the process for setting specifications is based on industry initiatives. For instance, to be competitive with the steel and asphalt industries the concrete industry needs to increase its recycled content.

One instance of regulation having a negative effect on concrete use and production is the required water cement ratio, which may not be needed but is specified. [66] If a certain amount of water is required in concrete then there has to be a certain amount of cement. If this fact could be changed, there would not be as much need for portland cement. Prescription specs lend another dimension to the problem, because they limit the types of materials and quantities you must use. Sometimes these call for things that cannot be found locally for the site, causing embodied energy for the requirement of certain materials. Performance properties measured by tests and acceptance criteria also need to evolve [66]. The industry of concrete is currently in the process of recognizing the need for change, and implementing it slowly with the goals of developing a more sustainable and durable construction material.

It is also quite difficult to compare one type of cement to another in terms of sustainable properties, due to the complex nature of its complete life cycle. One of the major differences, often overlooked in high performance cement manufacture, is that many materials come from further away. The question always remains, is this difference in emissions or energy use worth it for a particular application? There are cases when this is true and when, it is not. Pavements are worth making as durable as possible because there are no plans to change them in the foreseeable future, while an ordinary structure does not call for more durable concrete, and if moved is more often than not sent to a landfill. Although it would call for a change in architectural typologies, if its components were reusable there may be more interest in using high strength concrete.

Many intricate components are considered when implementing sustainable manufacturing innovations for concrete. Our understanding of the chemistry of the substances what we are trying to use, and how efficient we can use them control our capacity for sustainable development. Thus, evolution of such a material is a complex process dealing not only with vast amounts of testing and research, but the spread of this information, acceptance by the industry, and various methods of adoption into common practice often through architectural design.

Geopolymers are being considered as a replacement for portland cement in the United States. Its current ideal application would be for pavements and our severely degraded infrastructure. “Inorganic polymer concretes, or ‘geopolymers,’ have emerged as a novel engineering materials with the potential to form a substantial element of an environmentally sustainable construction and building products industry.” [30] This material shows great potential to drastically improve chemical resistance and thus improve the durability of concrete while severely reducing the CO2 emissions of the concrete industry. Geopolymer is listed specifically as an emerging cementitious system in the “Sustainable Concrete Pavements Manual” recently published in January 2012 by the Iowa State University Institute for Transportation. “Future work on cementitious materials will likely include finding alternative sources of raw materials that will not involve the decomposition of carbonate but rather use calcium-rich industrial byproducts, or possibly shifting away from the use of calcium-based cements entirely and perhaps using magnesium-silicate raw materials.” [94] Public interest drives research, which drives real concepts, material technologies, developments, and their final applications. Detailed research is ongoing to find and investigate multiple solutions to the negative effects the concrete industry has on our environment [25]; these changes could potentially help evolve the way architecture works with concrete.

CHAPTER 5

IMPLICATIONS FOR ARCHITECTURE

As history reveals, architecture is a constant evolving reaction to humanities needs and wants, constructed within the limitations of the available technology of the time. The advancements made in materials are central technological advancements which affect architecture. Immediate spatial qualities of architectural designs have actually not changed as much over time, in my opinion - due to the lack of great change in human dimensions and general activity, but material changes the way we use these spaces, and the effect they have on our senses. Durability of structures and spaces with natural light are interconnected qualities which have been a hallmark of architectural evolution. As the material strength of structures becomes greater structural components become thinner, and thus allow for more natural light, ventilation and a chance to constantly experience our immediate environment. Durability is a practical concept that essentially means we do not have spend additional energy or resources to maintain the initial properties of what we built. If a concrete bridge is poured, it would be ideal that it did not need patching 15 years from then. When a structure faces the test of time it does not only prove to be a practical and good investment, but becomes engrained in people's lives and memory of that place. Would the Coliseum be as famous if it had crumbled away in 100 years, would the aqueducts have so inspired Giocondo to admire Roman architecture?

Concrete is the only known structural building material which is completely malleable, customizable, and affordable. It is common knowledge that it permits a freedom of design that is unavailable with all other building materials. While concrete has not always played a pivotal role in our architectural design, it has become indispensible in the architecture of the past century and will undoubtedly continue to be so in years to come.

5.1 Influence of Concrete on the Evolution of Design

Concrete has allowed for an evolution of architectural design both structurally and aesthetically, which has in turn affected the daily lives of those who experience it [36]. Concrete allowed for the accessibility of a wider range of architectural design. Large buildings could be completed in less time and for less money. By being a malleable material, concrete has the ability to replace more expensive and time consuming work. Commodities such as sculpture were made available to a wider range of people. One of the first uses for concrete was to reproduce what would otherwise be too expensive to make with traditional craftsmanship [20]. It was generally used to replace rock and other familiar designs in construction, it eventually evolved into its current use in shaping modern architecture and for composite structures with steel.

Figure 15. Recognizing Concrete for Use in Architecture 1876 and 2010 [98, 8]

The form of beam, column, and slab has not much changed from the beginning of the twentieth century except to get more slender. This typology has been tweaked through the decades and occasionally radically changed, but only in particular cases where cost efficiency was often not the primary goal of the design.

The plasticity, strength, local availability, affordable manufacture, and fire resistance of concrete has led to the designs of current architecture and the proliferation of similar design types around the world. Concrete has not only played a major role in the development of our current designs, but also has become a highly used building material for specifically sustainable designs. For instance, precast fabrication is only possible with this material, and is considered a more efficient mode of construction. Other qualities, such as its thermal capacity to store heat, have been exploited in designs such as tromb walls.

Figure 16. Sustainable Design with Concrete - Tromb Wall [28]

A possible and feasible way for sustainable architecture to improve its impact would be for the widely depended upon and applied material of concrete to reduce its impact on the environment and increase its durability.

5.2 Future Possibilities

The evolution of architectural design is illustrated through the changes in architectural theory. Theory and ideals generally take advantage of the technologies available and makes evident the ideals of style important at that time. This process is important to the evolution of structure. It is not enough that a new material be available, it must be recognized for its potential for practical use, so that design can be tailored to it's full capacity. It can only make an impact on design through the recognition that it is unique. In order for new types of concrete to be utilized, designers must recognize their existence as more than a replacement for something else. Although, at the same time, one cannot market any new thing without there being a strong interest or demand from those paying for it. In that way architects and structural engineers are responsible for marketing and using new technologies, for recognizing the need and then reacting accordingly. This is obviously a complex process, due to the varying client opinions, budgets, timelines, and other aspects of the building design and construction industry. Though, in small ways architectural design must still address technological advancements, despite the complex situation, for them to succeed.

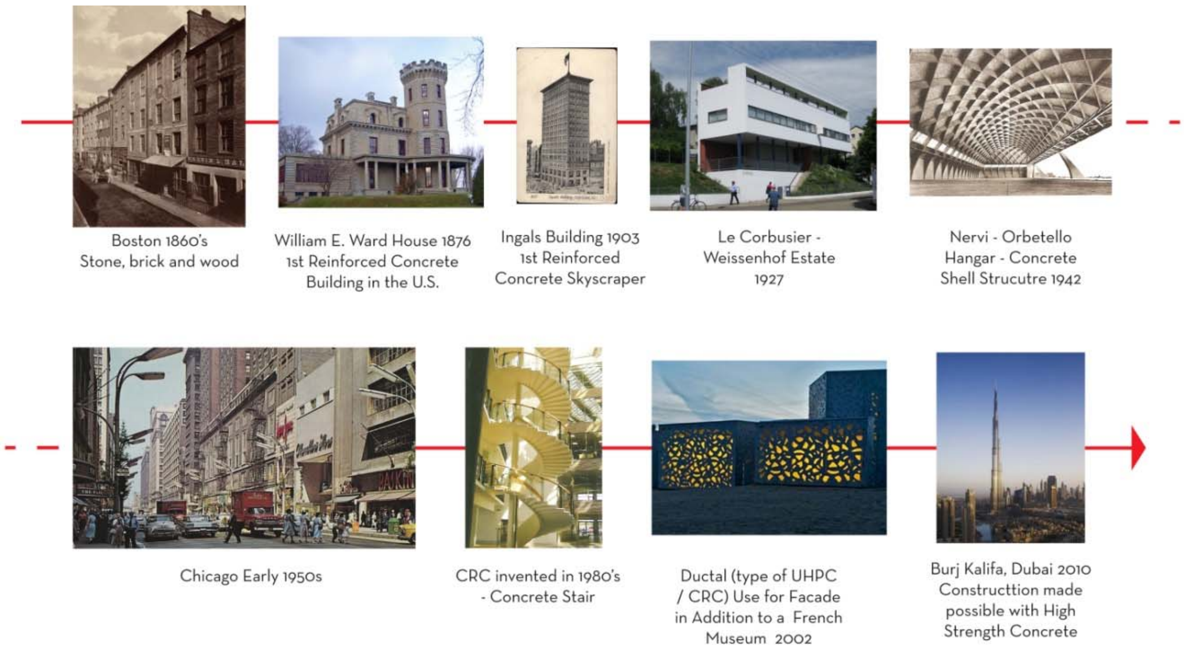

Figure 17. Evolution of Concrete Use in Construction [62, 98, 13, 89, 14, 50, 81]

Public opinion plays an important role in architectural evolution because the built environment is in many ways the outward expression of a societies understanding and expectations. In this way, media does affect the possibilities of architectural design. Sustainability is currently a large concern and thus has been used in the marketing of many different products, from soaps, to clothing. Environmentally friendly practices in all manufacturing processes and material uses have become law through different legislation and regulations. They are the constant subject of research and revision. Sustainable design has thus permeated the interest of our society.

Environmental concerns in architecture do not only involve the form of the structure but the materials it is made from, for the sake of durability and reduction of the energy it consumes. It is important that sustainable designs last, that they essentially sustain themselves for many decades. Geopolymer based concrete is an example that offers a new way to create a familiar material, its different properties of tensile and compressive strength as well as a much increased resistance to acid and sulfate attack present interesting design opportunities. There are many new types of concrete which present different opportunities for design, but a primary advantage of aluminosilicate is that it is designed to be affordable.

The report tilted 'Sustainable Structures of Tall Buildings' by Mahjoub Elnimeiri and Prairan Gupta states "Good structural engineering revolves around achieving efficiency and minimization of material. However, thinking will have to be broadened to accommodate the pressing needs of the environment. Structure can no longer stay on the sidelines and will have to be an active partner in the building-design process." [33]

With the rise in materials technology, a basic understanding of structural engineering alone may not be sufficient for the practice and study of architecture. With the wide variety of materials available it is important that we understand not only structural form but what limitations or lack of limitations exist for the material that can make it. Architects can benefit from understanding construction materials chemistry, by recognizing the possibilities therein and the direction and need for further development. I believe, Architects have the unique ability to give a practical and artistic direction to construction materials research.

When structural engineers, civil engineers, contractors, and manufactures collaborate on a project it is ideal that they are well versed in the latest technology and that each understand the basic concepts being applied by the other. Architects have an important role in this collaboration. The Concrete Sustainability Hub of the Massachusetts Institute of Technology is an example of a program that recognizes the need for architectural involvement in the engineering sector of the construction industry. Through the collaboration of engineers and architects, new materials and their sustainable applications, have a better chance of existing sooner than later. During the opening presentation at the Concrete Sustainability Hub Industry Day of 2011 architect Hubert Muray spoke to emphasize the continued development of the collaboration between concrete engineering and architecture. In this lecture he states that there are three dots to connect: concrete, carbon emissions and architecture. In order to reach our aspirations of a more sustainable environment, architectural practice needs to take advantage of developing materials and technologies for all designs. [90]

CHAPTER 6

ALUMINOSILICATE CEMENT FOR PRECAST MANUFACTURE

6.1 Essential Differences Between Aluminosilicate and Portland Cement

Geopolymer cement has a different molecular structure than portland cement, allowing it to have different properties while maintaining very similar user constraints and an appearance similar to portland cement based concrete.

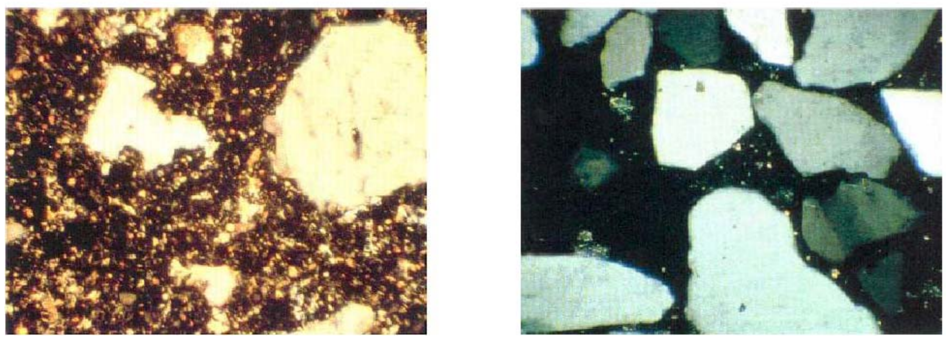

Figure 18. Portland Cement V.S Aluminosilicate Cement at the Micro Scale [26]

There are eight different types of portland cement [71] and nine different types of geopolymers [39]. The eight types of portland cement, various chemical admixtures, and proportions of alternative pozzolans give modern concrete the specific properties for different applications. Within the Geopolymer types, only those which are comprised of aluminosilicates are useful to completely replace portland cement in concrete construction [23]. Aluminosilicates are minerals composed of or containing aluminum, silicon, and oxygen such as k-feldspar, muscovite, biotite, calcium aluminate, sodium aluminate, philipsite, class C and F fly ash, kaolinate, and slag [35].

> Naturally occurring alumino-silicates, such as kaolinate, are transformed at low-temperature, in an astonishingly short time, into tridimentional texto-aluminosilicates… The process yields nanocompoites that are actually man-made rocks. This geosythesis is manifest in nature itself in great abundance. At least 55% of the volume of the Earth's crust is composed of siloxo-sialates and sialates, with pure silica or quarts at only 12% [99]

The microstructure of these materials directly affects the mechanical properties of the concrete made with them. It is the ongoing study and manipulation of these elements in a material's structure which lead to the creation of more efficient, sustainable and/or durable concretes [47, 86]. Simply put, the tighter the structure at the nano and micro level the more durable the concrete. This is affected by the size and chemical properties of all particles involved and the ratio of water or other liquid agents in the initial mixture. There are near endless variations of these mixes all affected by the chemical reaction with the different particles of different types of supplementary cementitious materials, aggregates, and the resulting portland cement from various types of manufacture. This explains the many types of concrete available today and research being carried out in the private, academic, and public sectors.

Portland cement has a molecular structure which is completely different from aluminosilicate cements. I have been told that in simple terms, portland cement is essentially stronger in one direction than the other (at the molecular level), forming a structure of 'sheets'. Because these sheets have looser bonds between them the material is not as resistant in the direction perpendicular to them, which allows for molecules of other materials to affect it, such as water with the effect of spalling. [83] It must be noted that this is a very simple way of viewing an extremely complex and varied molecular configuration. Geopolymers are analogous with organic polymers derived from oil, which have strong bonds in all directions, forming a tighter three dimensional framework and a more resilient resulting material. They "are transformed, undergo polycondensation, and set rapidly at low temperatures, within a few minutes. But they are, in addition, Geo-polymers, i.e. inorganic, hard, stable at temperature up to 1250°C and non-inflammable." [23] Both materials are porous, but at different levels and different ways.

Geopolymer cement is made up of an alumniosilicate mineral, sodium silicate, and sodium hydroxide. Unlike portland cement which relies on the hydration of calcium silicate, geopolymers require no water to set. Water can be added to the mix of geopolymer to add workability, but it evaporates and is not used as part of the chemical reaction. Because it is made with liquid glass, and lye, two widely available industrial products, it has a high alkalinity (sometimes with a ph up to 14) it can be difficult to handle without protective clothing. Because alkalinity is also a property in portland cement while it is poured, this is not a rare concept for those working in concrete construction. Portland cement mixes can reach a ph of just under 14. [44]

As with any developing material meant to replace one which is already established in common practice, its abilities must at least meet those of the material it is replacing. There was concern that aluminosilicate cements would be highly susceptible to the destructive nature of alkali-silica reaction sometimes found in portland cement based concretes. There has been concern in the past that alkalis are the cause of deleterious alkali-aggregate-reaction. Alkali-silica reaction (ASR) and Alkali-carbonate reaction (ACR) are alkali-aggregate reactions. "In ASR, aggregates containing certain forms of silica will react with alkali hydroxide in concrete to form a gel that swells as it adsorbs water from the surrounding cement paste or the environment. These gels can swell and induce enough expansive pressure to damage concrete" [70] ACR causes a similar reaction, but is less common because it effects dolomitic rock aggregate specifically, which is rarely used to begin with. [70] But it has been found that the addition of alkaline natural pozzolans substantially reduce this reaction in high-alkali cements. [23] Geopolymer cement has alkali contents as high as 9.2% and it has been found that it does not generate any dangerous alkali-aggregate reaction. Various studies have proved that geopolymer can use the same rebar and aggregate as portland cement based concrete. It is thus able to be a commercially competitive material, being a possible direct replacement of portland cements in concrete. In addition, the primary ingredients: Metakaolin, fly ash and slag, are commonly available products already in use within the concrete industry.

6.2 Manufacture of Aluminosilicate Cement

The manufacture of geopolymer concrete takes much less processing than portland cement. Due to high interest in the sustainable benefits, fly ash will most likely be one of the most often used aluminosilicates [95]. It is available and currently in use in precast plants as an available admixture. [9] Metakaolin is another possible mineral ingredient which is easily mined in the United States, and only needs to be ground in to a fine powder, with no heating, to be used in a geopolymer mix. Sodium Silicate, liquid glass, is a common industrial chemical used for many applications such as metal and car repair, agriculture, and water treatment. Sodium Hydroxide, or lye, is another common industrial product with various applications, one if which is as an ingredient in cleansing agents. Those manufacturing geopolymer concrete have found that it is not significantly more expensive to manufacture than portland cement concrete. [96]

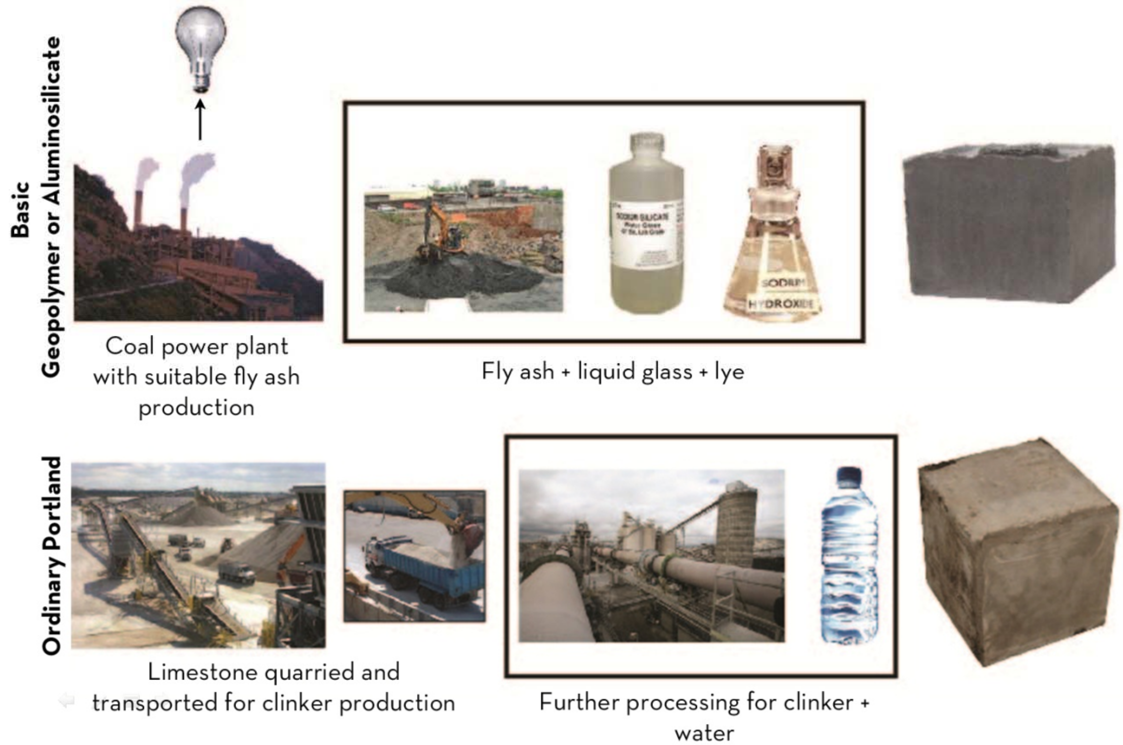

Figure 19. Manufacturing Differences Between 'Geopolymer' and Portland Cement [53,49]

One of the major investments that need to be made for the manufacture of geopolymer to be possible is the intense research needed to classify and thus fully take advantage of the local products available. It takes years of research and chemical analysis of local materials to form a product base for geopolymer cement in any region. After this is accomplished it can be used in any way that Portland cement is used. Fly ash is not a uniform material due to the simple fact that the coal which is burnt to make it does not have a uniform chemical composition. The properties of fly ash which affect concrete manufacture where never important in the burning of coal for energy, and thus remain unknown by coal plants. Recognizing the complex nature of fly ash is one of the leading hurdles to making geopolymer cement available for wide spread use.

Researchers at the University of Illinois at Urbana Champagne are working to better classify what chemical properties allow for the ideal setting behavior of geopolymer cement. Working primarily with class C fly ash, which has higher calcium content, they are currently studying the reactions during the curing of geopolymer type cement. It has been found that there are usually two byproducts when using this type of flyash, Calcium Silicate Hydrate (CSH) and the Alumnia Silicate, but the amounts of these byproducts differ from sample to sample, although they all use the same raw materials. They are tracking down exactly what controls this reaction. CSH is usually what is found in ordinary portland cement mixtures and is connected to the amount of water present in the mixture. This study, in addition to many others looking at different aspects of fly ash properties on geopolymer reactions in cement formation [97] are amassing the information necessary to give aluminosilicate based concrete basic standards and a place in the market. The standardizing of geopolymer or aluminosilicate cements is a long and complex process [49, 83].

Another concern within the industry concerning coal or fly ash is its possible radioactive properties. An article on coal plants in the magazine *Scientific American* states:

> Among the surprising conclusions[of studies over the past decade]: the waste produced by coal plants is actually more radioactive than that generated by their nuclear counterparts. In fact, the fly ash emitted by a power plant—a by-product from burning coal for electricity—carries into the surrounding environment 100 times more radiation than a nuclear power plant producing the same amount of energy [45].

It was found that those living near coal plants are exposed to the same if not a higher level of radiation than those living near nuclear power plants. Fly ash has a higher radiation level than coal because it is the condensed byproduct of burning coal. This information has been noted by many within the cement industry, and the general consensus is that the amount of radiation found in fly ash is negligible when used in cement and concrete production. It is either nonexistent or when trace amounts are present they are generally neutralized by the production and curing of the concrete itself. Geopolymerization of fly ash reacts differently with fly ash, which presents yet another aspect of fly ash which needs investigation for the standardization of aluminosilicate or geopolymer cements.

The concrete industry uses the majority of fly ash produced, and continues to search for ways to use it entirely. In 2009 a proposed national policy on the use of fly ash was made to "enable cement manufacturers source fly ash at reasonable cost and produce more eco-friendly pozzolana cement." [78] 30% of the fly ash produced is recycled, out of this the cement industry was consuming 28-30 million tons in 2009, above 70% of the recycled ash used. There is still a large portion of fly ash made into slury and disposed of in ponds, about 85 million tones. [78] Consequently, there is a great interest in using as much fly ash waste as possible within the cement industry.

> Usage of fly ash means increased capacity/production resulting in saving of huge capital expenditure required for such capacity additions. Savings in utilisation of natural resources like limestone, ultimately increasing running life of mines. Availability of sustainable/ compatible product at a lower cost to the consumers. Optimal utilisation of clinker resulting in less carbon emissions, reduced pollution levels and CDM benefits. [78]

Geopolymer cement manufacture presents an opportunity use the fly ash currently being generated by our coal plants in large capacities. "Geopolymerization could convert a wide range of aluminosilicate materials into building materials with excellent physical and chemical properties as well as long-term durability." [101] Within a study on the effects of source materials on geopolymer reaction it was found that fly ash required less binding energy making it a more reactive base for geopolymer cements than others available such as kaolinite (metakaolin) or Albite. Fly ash geopolymers also have the capacity to create geopolymer cements with higher compressive strengths [101]. The increased reactivity and resulting properties of aluminosilicate cements created with fly ash allow for a fast setting concrete that maintains a sound structural and chemical integrity. The further study and manipulation of this mix can result in a dramatically increased use of our current fly ash waste byproducts, keeping them from landfills and natural water sources.

A defining property of aluminosilicate cement based concrete is that its setting time is much shorter than portland cement based concrete [95]. It can reach full strength in under three days, and can set fully anywhere between a few minutes to ten hours [88]. Most manufacturers of geopolymer cement have developed mixes which are possible for ready mix use, although they are held within the companies under the patents developed during those first couple years of research. Traditional geopolymer cement has a high strength and fast setting time, making it an ideal candidate for precast manufacturing.

6.3 Aluminosilicate Cement used for Precast Concrete

Precast methods allow for the highest level of control in concrete construction. It is an ideal setting for newly developing materials, and sensitive mixes [48]. The current machinery and set up used in most precast manufacturing facilities is ideal for geopolymer based concretes as well, only an exchange in raw materials and a method for handling the liquid component needs to be organized. In addition, it is also possible to kiln dry precast pieces, which often aids in forming higher strength geopolymer concretes [88, 53]. There are many properties and aspects of geopolymer cements yet to be explored, but it is commonly understood by those who work with them that precast manufacture [41, 3] is the medium for it to start being produced in the United States market.

CHAPTER 7

CONCLUSION

Architecture has evolved with the advent of new material possibilities, manufacturing technologies, and sustainable interests. Over the centuries since the beginning of the industrial revolution [79] concrete has become the most widely used construction material in the world, affecting humanities urban landscape and propagating a change in architectural typologies. As design takes advantage of engineering innovations, architectural developments can be explored in a real and practical way. Aluminosilicate cement is an evolution with real potential to affect concrete construction practices if even in a small way, through use as a specialized or 'boutique' concrete. With all new materials and innovations, so dependent on standards which affect the structure of our cities and thus the potential safety of our population, changes are often slow. Perhaps new cement production such as aluminosilicates will have greater impact in the future, as its standards and development continue.

The concrete industry has many collaborating aspects, through academic and professional research in new construction methods, analysis of past construction methods, standardizing, rating, and building technique development. Despite concrete playing such a large role in architecture, and offering a material which has been heavily exploited through innovative designs, architects greatly remain as onlookers of its industry practices. As research continues to search for a new sustainable method of concrete construction, it is agreed that it is important that possible future design initiatives are taken into consideration.

Concrete manufacture is currently one of the leading pollutants of our global society. Geopolymer or aluminosilicate cement based concrete offers a potential solution by replacing portland cement completely, while offering an affordable increase in performance and durability as well as a reduction of CO_2 emissions by 80% for concrete production [85]. There is still much to be learned about this type of cement regarding local manufacture, exact chemical makeup, and how these affect mechanical behavior and design applications for standardization [37]. Precast concrete production offers an ideal controlled environment for geopolymer to be introduced into widespread use in the United States, as it has been employed in other countries. The creation and manipulation of this material will present potential opportunities for sustainable design and construction. As testing methods and standards for construction are developed, through the wide spread public and private research interest, it will likely present a change in the concrete manufacture of the United States.

APPENDIX A

ARCHITECTURAL AND ENGINEERING

TOPICS FOR FUTURE STUDY

1. Study the timeline of material transportation and production. How would Geopolymer based concrete effect the cost of materials, cost of labor, and time needed for construction of a basic project? What would be the potential environmental impacts of this situation, considering the construction site as well as carbon dioxide emissions of all materials involved? Perhaps take an already existing project and compare them.
2. Design a project with geopolymer, would this material's durability and economic feasibility make it ideal for the environmental design challenges found in a tropical zone such as India?
3. Map and study the different types of Fly ash and their production with regard to their use in geopolymer concrete
4. Analyze the production and invention process of aluminosilicate cement more closely and study the beginnings of admixtures for Alumino Silicate cement or geopolymer.
5. Study the possible use of geopolymer for pervious concrete design.
6. Study the structural limitations of geopolymer, concentrating on applications which utilize its tensile strength.
7. Study the environmental effects of using sodium hydroxide and sodium silicate for such mass production.
8. Compare final properties with of aluminosilicate with that of other fly ash concretes currently being developed for use with hydraulic cements.
9. Taking a more theoretical stance, analyze the conception of and relationship between scientific terms, the words used to market them, and the way this is

adapted or relates to the architecture and construction profession. Ex: in this case geopolymer is a marketing term for the more technically correct aluminosilicate cement, which is then sometimes marketed under 'green' or earth friendly names, then possibly awarded points under the LEED system with implemented in construction. How exactly is this motivation and marketing affecting the development of innovations for sustainable or durable building technologies?

10. Study of current Ultra High Strength Concretes VS. Alumino Silicate cement or 'Geopolymers' see if there is a future for using geopolymer as a compact reinforced composite (crc) and if it would have similar mechanical performance with different materials. Would it be less expensive? This is something that needs to be seen after the method of creating a stable geopolymer chemistry is achieved. As the production of such existing concretes have taken decades of research and development.

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