

December 2015

Experimental Evaluation of Beneficial Use of Lake Michigan Dredged Materials in Flyash Based Geopolymer Concrete

Sara Dashti

University of Wisconsin-Milwaukee

Follow this and additional works at: <https://dc.uwm.edu/etd>



Part of the [Civil Engineering Commons](#)

Recommended Citation

Dashti, Sara, "Experimental Evaluation of Beneficial Use of Lake Michigan Dredged Materials in Flyash Based Geopolymer Concrete" (2015). *Theses and Dissertations*. 1046.
<https://dc.uwm.edu/etd/1046>

This Thesis is brought to you for free and open access by UWM Digital Commons. It has been accepted for inclusion in Theses and Dissertations by an authorized administrator of UWM Digital Commons. For more information, please contact open-access@uwm.edu.

EXPERIMENTAL EVALUATION OF BENEFICIAL USE OF LAKE MICHIGAN DREDGED
MATERIALS IN FLYASH BASED GEOPOLYMER CONCRETE

by

Sara Dashti

A Thesis Submitted in

Partial Fulfillment of the

Requirements for the Degree of

Master of Science

in Engineering

at

The University of Wisconsin-Milwaukee

December 2015

ABSTRACT

EXPERIMENTAL EVALUATION OF BENEFICIAL USE OF LAKE MICHIGAN DREDGED MATERIALS IN FLYASH BASED GEOPOLYMER CONCRETE

by

Sara Dashti

The University of Wisconsin-Milwaukee, 2015
Under the Supervision of Professor Habib Tabatabai

Dredging harbors and rivers are necessary to maintain the appropriate water depth for navigation. However the disposal facilities for storing dredged materials around the U.S. Great Lakes are at or near their capacities and finding beneficial uses for these materials is a major concern. On the other hand, carbon emission and global warming have become the greatest environmental issues during the last decade. Cement manufacturing is a major contributor to CO₂ release into the atmosphere. The objective of this study was to develop a low-cost, environment-friendly geopolymer concrete paste with dredged materials as a substantial mix ingredient. Geopolymer concrete does not use the portland cement binder. Dredged materials used in this study were obtained from the confined disposal facility at the Port of Milwaukee, Wisconsin. Different geopolymer paste mix designs were tested to obtain optimum compressive strength while maximizing the use of dredged materials. Paste mix ingredients included dredged materials, Class F fly ash, and a combination of sodium hydroxide and sodium silicate liquids (alkali liquids). The ratios of alkali liquids to fly ash and sodium silicate to sodium hydroxide used in the test mixes were selected chosen based on work by Rangan et al. (2005). The mixtures were placed in a 60°C oven for 24 hours followed by air curing at room temperature. Compressive strength test were performed on 2-in (51mm) cube specimens. Results indicate that compressive strength exceeding 20

MPa was achievable (at an age of 14 days) with dredged materials comprising up to 40% of the total mass of the geopolymer mixture. Therefore, beneficial use of substantial quantities of dredged materials is possible in geopolymer concrete applications. Previous research has shown that geopolymer concretes can also reduce leaching of contaminants that may exist in mix ingredients.

TABLE OF CONTENTS

1. INTRODUCTION.....	1
1.1 Problem statement.....	1
1.2 Research objectives and scope.....	2
1.3 Organization of thesis.....	3
2. LITERATURE REVIEW.....	4
2.1 Dredged Material.....	4
2.2 Beneficial uses.....	5
2.3 Dredged material management.....	8
2.3.1 Open water disposal.....	8
2.3.2 Confined Disposal Facilities.....	9
2.4 Geopolymer Concrete.....	9
2.4.1 Background.....	9
2.4.2 Mixture Proportions, Production and Curing of Geopolymer Concrete.....	11
2.4.3 Geopolymer Application	14
2.5 Fly Ash.....	15
2.5.1 Overview.....	15
2.5.2 Fly Ash Composition.....	16
2.5.3 Use of Fly Ash in Concrete Applications.....	17
3. TEST MATERIALS AND PROCEDURES.....	18
3.1 Dredged Materials.....	18
3.2 Fly Ash.....	22

3.3 Liquid Phase.....	24
3.4 Mix Design Procedure.....	25
3.5 Preparation of Test Specimens.....	26
3.6 Compressive Strength Test.....	28
 4. EXPERIMENTAL RESULTS AND DISCUSSIONS.....	 29
4.1 Overview	29
4.2 Unit Weight and Compressive Strength	29
 5. CONCLUSIONS.....	 35
5.1 Recommendation for Future Study	36
REFERENCES.....	37

LIST OF FIGURES

Figure 2-1 Great Lakes Management Dredging Char.....	5
Figure 3-1 Port of Milwaukee CDF Location.....	18
Figure 3-2 Dredged Material (North) SEM pictures.....	21
Figure 3-3 Milwaukee Harbor CDF Dredged Material Particle Size Distribution.....	22
Figure 3-4 Sodium Silicate (Water Glass) and Sodium Hydroxide Powder and Solution.....	26
Figure 3-5 Mixer, Fly Ash, Dredged Material.....	27
Figure 3-6 Fresh Geopolymer paste and cube molds.....	27
Figure 3-7 Thermo Scientific Oven Used for Oven Curing.....	28
Figure 3-8 ADR- Auto ELE Compression Machine.....	28
Figure 4-1 Geopolymer Mortar Specimens with Different Mix Design.....	29
Figure 4-2 Geopolymer Specimen under Compressive Strength Test.....	31
Figure 4-3 SEM Pictures of Mix I (800020-GPP).....	32
Figure 4-4 SEM Pictures of Mix II (602020-GPP).....	33
Figure 4-5 SEM Pictures of Mix III (503020-GPP).....	33
Figure 4-6 SEM Pictures of Mix IV (404020-GPP).....	33
Figure 4-7 Compressive Strength of Different Mixtures at age 14 and 28 days.....	34

Figure 4-8 Change in Compressive Strength of Geopolymer pastes with Age.....34

Figure 4-9 Effect of dredged material on geopolymer paste Compressive strength.....35

LIST OF TABLES

Table 2-1 Dredged Material Disposal Application.....	4
Table 2-2 Dredged Material Physical Suitability.....	7
Table 2-3 Application of Geopolymer Materials Based on Si:Al Atomic Ratio.....	14
Table 2-4 Fly Ash Classification per ASTM 618-12a.....	16
Table 3-1 Geotechnical Properties of the Dredged Material (North) from Milwaukee Harbor CDF.....	22
Table 3-2 Elemental Analysis on Milwaukee Harbor CDF Dredged Materials.....	22
Table 3-3 Chemical and Physical properties of Fly Ash Class F.....	23
Table 3-4 Elemental Analysis of Class F fly ash.....	23
Table 3-5 Test Mix parameters	25
Table 3-6 Test Mix Proportions.....	26
Table 4-1 Mean Unit Weight of geopolymer paste	30
Table 4-2 Mean Compressive Strength.....	31

ACKNOWLEDGEMENTS

I would like to thank Professor Tabatabai for his endless support throughout this research. This work would not have been possible without his insight, discernment, and contributions. His guidance and support throughout my graduate studies has been endless. I would also like to thank Prof. Konstantin Sobolev, for his tremendous help throughout my graduate studies including the writing of this thesis.

I am really thankful to Prof. Tabatabai, Professor Sobolev and Professor Ben Church for being part of my thesis defense jury.

I would also like to thank Dr. Marina Kozhukhova for the many hours that she has spent working with me especially at the early stages of the project, development of mixtures and providing helpful thoughts for this research. Additionally, this work could not have been performed without the contributions and great help of UWM graduate assistants Rani Pradoro, M. Reza Moini and Meysam Tabandeh Khorshid as well as my research colleague from the UW Madison, Mr. Yu Hua.

I would like also to give a special thanks to Brian Mullen who helped me with all the heavy works in taking samples from Milwaukee Harbor.

Finally, I would like to thank my brother, my parents and my love, for their love and their endless support throughout my studies and my life. I would definitely not be here without their love and support.

1. INTRODUCTION

This chapter briefly discusses the problems and opportunities related to dredged material (DM) management in the Great Lakes region and options for beneficial use of DM. A general overview and scope of the project and organization of this thesis are also summarized.

1.1. Problem Statement

Commercial and recreational movement of vessels in the Great Lakes relies on the maintenance of water depth in harbors, channels, and rivers. To maintain proper water depth, periodic dredging operations have been performed in the Great Lakes waters for many years. Water-borne access to commercial ports requires maintenance of certain water depth that would be impossible without periodic dredging.

According to the Great Lakes Dredging Team, (Clark et al. 2013) 2-3 million cubic yards of DM are removed from ports, harbors and channels maintained by the U.S Army Corps of Engineers. These materials may be contaminated to various degree from industrial waste disposals, agricultural runoff or other activities, and thus require confinement in specifically designed Confined Disposal Facilities (CDF). Since 1970, the Army Corps of Engineers has built 45 CDFs, but such facilities are rapidly reaching their capacity limits. More than half of CDFs are at 80% of their capacities (Clark et al. 2013). Issues such as construction costs and lack of site availability make building new CDFs increasingly difficult.

However, according to GLDT (Clark et al. 2013), over three decades of environmental improvement and industrial site cleanup have resulted in a significant decrease in the contamination level of dredged materials stored in CDFs. The dredged materials are cleaner and therefore more suitable for certain types of beneficial use.

While a long-term, economic and environment-friendly solution is greatly needed to reduce the amount of dredged material placed on CDFs, there also is significant interest in using dredged material to develop effective and low-cost construction materials.

In this thesis, the development of a geopolymer concrete paste (GPP) with a substantial component of dredged materials is studied. Various GPP mix designs are tested with respect to strength for use in construction applications.

1.2. Research Objective and Scope

The objective of this research is to assess feasibility of using substantial quantities of dredged materials in developing geopolymer paste formulations for concrete that are suitable for structural applications. Thus, a new approach for beneficial use of dredged materials in construction applications is proposed. This involves using dredged materials from the Milwaukee CDF as a substantial source material in the production of geopolymer matrix for concrete.

Five geopolymer paste mixes with varying proportions of dredged materials and Class F fly ash were tested to determine 14- and 28-day compressive strength of 2-in (51mm) cube specimens. Sand was not added to the mixture. The specimens were placed in a 60° C oven for 24 hours after mixing, and were then kept uncovered at room temperature until testing.

Geopolymer concrete has been the subject of numerous studies as a replacement for portland cement-based concrete. Production of portland cement releases significant quantities of CO₂ into the atmosphere contributory to climate change (Wallah and Rangan, 2006). Geopolymer concrete shows considerable potential for application in the concrete industry as a substitute binder for portland cement (Duxson et al., 2007). Geopolymer technology has the potential to considerably reduce CO₂ emission caused by cement manufacturing. The geopolymerization process also

helps to reduce leaching of contaminants that may exist within mix ingredients (Luna et al, 2007)

1.3 Organization of Thesis

Chapter 2: Literature Review- This chapter discusses information from literature regarding dredged materials and geopolymer-based concrete using fly ash.

Chapter 3: Materials and Procedures- This chapter provides information about materials that were used in this research as well as test methods and parameters, test equipment and procedures used in conducting the tests.

Chapter 4: Results and Discussion- This chapter presents the test results and discusses the important parameters.

Chapter 5: Summery and Conclusions- This chapter provide a summary of research findings and conclusions.

2. LITERATURE REVIEW

This chapter presents a brief overview of various aspects of dredged materials, issues involving confined disposal facilities, and cement beneficial uses. Then, a brief discussion of geopolymers, concrete, its applications, and research results are described.

2.1 Dredged Material

According to the US Army Corps of Engineers (Price, 2008), approximately 300 million cubic yards of sediments are dredged annually to maintain the navigation depth in channels, harbors and ports. Nearly 5 to 10 percent of sediments is contaminated and need to store and monitored in CDFs (Price, 2008). Table 2-1 shows the types of disposal and the corresponding percentages.

Table 2-1 Dredged Material Disposal Applications (USACE, 2008)

Disposal Type	Cubic yds	% of Total
Beach Nourishment	4,833,125	3.3
Confined	12,565,711	8.6
Underwater Confined	2,926,000	2.0
Mixed Types	5,186,694	3.5
Overboard & Open Water	50,050,381	34.2
Open & Upland	3,435,000	2.3
Beach & Upland	929,000	0.6
Upland	3,897,019	2.7
Wetland Nourishment	49,075,000	33.5
Undefined	13,385,700	9.2

However, over half of dredged materials are placed in CDFs (Figure 2-1), (Price, 2008). Since there is a decreasing acceptance of open water replacement, beneficial use must be increased to provide sustainable long-term management options for dredged materials (Price, 2008)

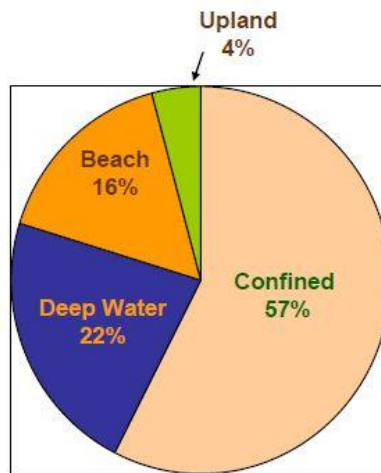


Figure 2-1 Great Lakes Dredging Management Chart (Price, 2008)

2.2 Beneficial Uses

According to the US Army Corps of Engineer (Price, 2008), there are two primary approaches for beneficial use of dredged materials. First, beneficial use is part of the dredging and placement process, which is related to regional sediment management. Second, beneficial use is part of the CDF operations and management process, which is intended to maintain the CDF's capacities.

Beneficial uses of dredged materials include the following applications (Price, 2008)

- Beach Nourishment
- Berm Creation
- Capping
- Land Creation
- Land Improvement

- Replacement Fill
- Shore Protection
- Aquaculture
- Crop Production
- Construction Materials
- Landscaping Products
- Top Soil
- Wildlife Habitat
- Fisheries Improvement
- Wetland Creation

Beach nourishment is the placement of sandy dredged material along the shore area for sand replacement and beach restoration (Clark et al. 2013). Capping involves placing clean, or nearly clean, dredged materials on top of other soil deposits or sediments that may be contaminated.

This method aims to shield the environment and public health from the contaminated soil layers. Additionally, the dredged materials are need for land improvement through construction of dikes, berms, and raising the elevation of low-lying land areas (Clark et al. 2013).

Table 2-2 identifies the physical suitability of different types of dredged materials in various applications (Price, 2008)

Table 2-2 Dredged Material Physical Suitability (Price, 2008)

	Dredged Material Sediment Types				
Beneficial Use Options	Rock	Gravel and Sand	Consolidated Clay	Silt/Soft Clay	Mixture
Engineered Uses					
Land Creation	×	×	×	×	×
Land Improvement	×	×	×	×	×
Bern Creation	×	×	×		×
Shore Protection	×	×	×		
Replacement fill	×	×			×
Beach nourishment		×			
Capping		×	×		×
Agricultural/Product uses					
Construction materials	×	×	×	×	×
Aquaculture			×	×	×
Topsoil				×	×
Environmental Enhancements					
Wildlife habitats	×	×	×	×	×
Fisheries improvement	×	×	×	×	×
Wetland restoration			×	×	×

A lack of clear regulatory guidance and uncertainty about dealing with contaminants has limited the beneficial use of dredged materials (Price, 2008). To address this, the US Army Corps of Engineers has developed a “Beneficial Use Testing Manual “(BUTM) to provide guidance for determining suitability of dredged material for beneficial uses (Price, 2008).

2.3 Dredged Material Management

Dredged materials removed from lakes, rivers, and navigation channels are handled in a variety of ways. In many cases, dredged material is clean enough for use as a sustainable resource and a product with value. In other cases, it has to be properly disposed or used in beneficial applications.

Three major approaches for managing dredged materials are: open water disposal, confined disposal facilities, and beneficial uses.

2.3.1 Open Water Disposal

Open lake placement is a common and less expensive practice to control the clean and uncontaminated dredged material (Clark et al. 2013). However, this approach is not universally accepted as the most desirable placement option in the Great Lakes region. According to Clark et al. (2013) 30 to 50 percent of dredged materials are transported for replacement in the open waters of the Great Lakes. This practice is currently allowed in Illinois, Indiana, Michigan, New York and Ohio (Clark et al. 2013). Other states such as Pennsylvania, Minnesota and Wisconsin restrict open-water placement and only accept limited exceptions for beneficial uses such as beach nourishment (Clark et al. 2013). However there is an increasing interest in utilizing clean dredged materials from harbors as a valuable and sustainable resource.

2.3.2 Confined Disposal

Contaminated sediments are not acceptable for open water placement and are usually transported for storage at designated confined disposal facilities. Some studies have focused on alternative treatments that could decrease the degree of contamination and produce a marketable product (Bowman, 2002). The ultimate goal in the confined disposal approach is to develop future facilities such that dredged materials from CDFs could be processed/ amended for beneficial uses.

2.4 GEOPOLYMER CONCRETE

2.4.1 Background

Geopolymer concrete (GPC) is concrete which does not utilize portland cement as its binder materials. Instead, it relies on alkali activation of solid materials that are rich in silicon and aluminum. GPC has been shown to be a promising possible alternative to portland cement concrete (Davidovits, 2005).

The term “geopolymer” was first proposed by Davidovits in 1978 (Wllah and Rangan, 2006). He stated that “an alkaline liquid could be used to react with the silicon (Si) and the aluminum (Al) in a source material of geological origin or in by-product materials such as fly ash and rice husk ash to produce binders”(Wallah and Rangan, 2006). Since the chemical reaction that takes place in this binder is a polymerization process, he introduced the term ‘geopolymer’ to represent such binders (Wallah and Rangan, 2006).

However, the basic principle of alkaline activation of blast furnace slags (called AAS), and other alumino-silicate materials has been known since the 1940s (Krivenko, 1999). AAS was developed and patented by a research team headed by Gluhovsky in 1956 (Gluhovsky, 1981). Their

material was obtained by mixing ground slag with a proper alkali activator (similar to the "geopolymer" concept). Therefore, the geopolymer concrete may not have been "discovered" (as a new fundamental material) by Davidovits in 1978, but he further advanced its development and application, and proposed a new name for this class of materials. However, Davidovits believes that there is a particular polymerization process in "Geopolymers" that is not present in AAS (Krivenko, 1999).

Geopolymers were originally developed as a fire resistant alternative to organic thermosetting polymers following a series of fires in Europe (Davidovits, 2005). They have been used as fire protection coating on carbon-fiber composites, thermal protection for wooden structure, heat-resistant adhesive and in many other applications (Davidovits, 2005).

The idea of producing construction materials by alkaline activation was first demonstrated by Purdon (1940). Davidovits and Orlinski (1988) and Palomo and Glasser (1992) published the first detailed studies on metakaolin geopolymers in the late 1990's. Subsequently, other researchers in Spain, New Zealand, Germany and Australia and conducted further studies on geopolymers (Lloyd and Rangan, 2010)

According to Rangan et al. (2006), geopolymer concrete can be produced by using a low-calcium fly ash (ASTM Class F) obtained from coal-burning power stations. They reported on successful use of low-calcium fly ash to produce geopolymer concrete when the silicon and aluminum oxides constituted about 80% of the source material by mass and Si/Al ratio was approximately 2.0.

Their experimental results showed that a combination of sodium silicate and sodium hydroxide solutions could be used as the alkali liquid in geopolymer mixtures. The sodium silicate solution used in their study had a SiO₂-to-Na₂O ratio by mass of approximately 2.0, and the SiO₂, Na₂O

and water contents were 29.4%, 14.7% and 55.9% by weight respectively (Rengan et al. 2006). Sodium hydroxide solids with 97-98% purity were dissolved in water and used in laboratory studies. The concentration of sodium hydroxide solutions used by Wallah and Rangan (2006) was 8 Molar and 14 Molar.

Van Jaarsveld et al. (1997 and 1999) discovered the potential use of waste or by- product materials such as fly ash, contaminated soil, mine tailings and building waste to immobilize toxic metals through the geopolymerization process. Palomo et al. (1999) reported on the results of a study on fly ash-based geopolymer. They used a combination of sodium and potassium hydroxide and sodium and potassium silicate as the liquid phase. They reported that the type of alkaline liquid has significant effect on mechanical strength and the combination of sodium silicate with sodium hydroxide would result in a higher compressive strength.

Gourley (2003) stated that the existence of calcium in fly ash in significant quantities could interrupt the polymerization process and change the microstructure. Therefore, it is recommended that low calcium fly ash (ASTM Class F) be used instead of high calcium fly ash (ASTM Class C) as a source material in the manufacture of geopolymer concretes.

2.4.2 Mixture Proportioning, Production and Curing of Geopolymer Concrete

According to Alvarez-Ayuso et al. (2007), geopolymer concrete has rapid compressive strength development, low permeability, good resistance to freeze-thaw cycles, and good resistance to acid attack. More importantly, geopolymer concrete has the potential to drastically reduce the mobility of most heavy ions contained within the geopolymeric structure (Alvarez-Ayuso et al. 2007).

The primary difference between portland cement concrete and geopolymer concrete is the choice of the binder (Rangan et al.2005). Rangan et al. (2005), developed geopolymer concrete mixtures using fly ash. The low calcium fly ash containing silicon and aluminum oxides reacts with the alkali liquids to form the geopolymer paste. The paste binds the coarse and fine aggregates, fine aggregates and other un-reacted materials together. They note that geopolymer concrete mixtures can be designed and mixed using tools available for portland cement concrete (Rangan et al. 2005).

Rangan et al. (2005) present the following mix proportioning parameters that they believe have significant effect on geopolymer concrete's strength and workability:

- “Higher concentration (in term of molar) of sodium hydroxide solution results in higher compressive strength of geopolymer concrete.
- The higher ratio of liquid phase (sodium silicate solution-to-sodium hydroxide solution), the higher compressive strength of geopolymer concrete.
- The slump value of the fresh geopolymer concrete increases when the water content of the mixture increases.
- As the H_2O -to- Na_2O molar ratio increases, the compressive strength of geopolymer concrete decreases”.

Rangan et al. (2005) discussed a single parameter called “water-to-geopolymer solids ratio” by mass. When calculating this parameter, the mass of water includes water in sodium silicate and sodium hydroxide solutions plus any extra water that may be added to the mixture. The mass of geopolymer solids is the sum of the mass of fly ash, sodium silicate and sodium hydroxide solids.

Hardjito and Rangan (2005) performed various tests to establish the effect of different water-to-geopolymer solids ratios, different liquid phase ratios, and different liquid to fly ash ratios on the compressive strength and workability of the geopolymer concrete. They placed the geopolymer concrete in 100×200 mm cylinders and heat-cured them for 24 hours in an oven with different temperatures between 60°C and 90°C for 24 hours. The compressive strength decreased as the water-to geopolymer solids ratio increased.

Xie and Xi (2001) studied the hardening mechanism of an alkaline activated class F fly ash. They found that a fraction of fly ash reacted with “water glass” and formed crystalline compounds of type $\text{Na}_2\text{O}-\text{Al}_2\text{O}_3-\text{SiO}_2$ after the paste was cured at 60 degree Celsius for 24 hours. They reported that the formation of crystalline sodium silicate in the matrix helps to achieve compressive strength.

Sathia et al. (2008) studied the durability of low-calcium fly ash geopolymer prepared with sodium silicate and sodium hydroxide activators. The concrete was made with fly ash contents of 350,450 and 550 Kg/m^3 , and activator solution to fly ash ratios of 0.4 and 0.5. The performance of these concretes in aggressive environments was studied using absorption and acid resistance tests. They reported that water absorption decreased with an increase in the strength of concrete and the fly ash content. All samples exhibited excellent resistance to acid attack (3% sulphuric acid) when compared to normal concrete.

Lee and Van Deventer (2004) reported the interface between natural siliceous aggregates and geopolymers. They mentioned that the higher soluble silicate activator will increase the compressive strength of geopolymer concrete.

2.4.3 Geopolymer Applications

According to Davidovits (1988), geopolymeric materials have many applications in automobile, aerospace, construction, and plastic industries. One of the most prominent fields of application for geopolymeric materials is in immobilizing toxic materials since they behave similar to zeolitic materials that have been known for their ability to control the toxic chemical wastes (Davidovits, 1988). Comrie et al. (1988) present an overview and related test results regarding the potential of geopolymer technology in toxic waste management. They reported some tests using a proprietary "GEOPOLYMITE 50" material, and suggest that geopolymeric materials could be used in controlling waste contaminants. According to Davidovits (1988), GEOPOLYMITE 50 is a registered trademark of Cordi-Geopolymere SA, a type of geopolymeric binder prepared by mixing various alumina-silicates precondensates with alkali hardeners".

Davidovits (1999) classified the types of geopolymer material applications based on their Si to Al ratio. Table 2-2 shows the different application classifications and their Si to Al ratios.

Table 2-3 Application of Geopolymer Materials Based on Si:Al Atomic Ratio (Davidovits,1999)

Si:Al ratio	Applications
1	Bricks Ceramics Fire Protection
2	Low CO ₂ cements and concretes Radioactive and toxic waste encapsulation
3	Fire protection fiber glass composite Foundry equipment Heat resistant composites, 200°C to 1000°C Tooling for aeronautics titanium process
>3	Sealants for industry, 200°C to 600°C Tooling for aeronautics DPF aluminum
20-35	Fire resistant and heat resistant fiber composites

Comrie et al. (1988) and Malone et al. (1985) have reported that geopolymer concretes have advantages with respect to resistance to chemical attack and freeze/thaw damage, and have very low shrinkage coefficient in comparison with portland cement concrete.

2.5 FLY ASH

2.5.1 Overview

The American Concrete Institute defines fly ash as “the finely divided residue that results from combustion of ground or powdered coal and that is transported by flue gases from the combustion zone to the particle removal system” (ACI Committee 232, 2004).

Chemical composition of fly ash is related to the different types and relative amounts of fire-resistant materials present in the coal. Fly ash particles are typically spherical, ranging in diameter from less than 1 μm to 150 μm (Malhotra, 2008).

Davis et al. (1937) were the first to publish reports regarding the use of fly ash in concrete.

Roughly twenty years later, Timms and Grieb, (1956) reported that considerable amount of portland cement in concrete could be replaced with fly ash without significantly change in long-term strength of concrete. Throughout the years, the impact of fly ash on the properties of fresh and hardened concrete has been studied extensively. Nowadays, fly ash is used in significant amounts (up to 50% cement replacement by weight) in high volume fly ash based concrete (HVFAC) matrixes (Joshi and Lohtia, 1997).

Chemical elements in fly ash include aluminum, silicon, calcium, magnesium, and iron (ASTM C618, 2013).

The American Society for Testing and Materials standard C125(ASTM C125, 2013) 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 presence of moisture, chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties”. Generally, the ability of fly ash to react with calcium hydroxide to form calcium silicate hydrates (which possess pozzolanic and hydraulic properties) made fly ash an interesting pozzolanic material in construction (Wisconsin Electric Power Company Coal Combustion Products Utilization Handbook, 2000).

2.5.2 Fly Ash Composition

According to ASTM C618 (2012), there are two types of fly ash: Class C, known as high calcium fly ash, is normally produced from lignite or sub-bituminous coals; and Class F, low calcium fly ash, is usually formed from bituminous coals. The silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) contents should not exceed 50% of the fly ash in Class C, while in Class F ash the summation of these three components should be greater than 70% (ACI committee 226 report, 2004).

Table 2-4 shows the ASTM 618-12a classification for fly ash.

Table 2-4 Fly Ash classification per ASTM 618-12a (Abram et al, 2008)

Class	Description	Requirements
F	Pozzolanic Properties	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 70\%$
C	Pozzolanic and cementitious properties	$\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3 > 50\%$

Class F fly ash is in the form of soft powder, and its color could vary from gray to black depending on the amount of unburned carbon and iron oxide contents. It is pozzolanic but typically not cementitious. Class C fly ash has a lighter gray/beige color, with both cementitious and pozzolanic characteristics. Fly ash material is considered suitable for use as a pozzolan for concrete

if more than 55% of its particles pass the No. 325 (45 μ m) sieve in wet-sieve condition. (ASTM C618, 2012)

2.5.3 USE OF FLY ASH IN CONCRETE APPLICATIONS

From the standpoint of practical applications, ASTM limits the fly ash usage in portland cement concrete mix to 20% or 25% replacement of cement. However because of the increase in demand for sustainable cement and concrete, significant steps have been taken with the development of high volume fly ash (HVFA) concretes (Mehta, 2001).

Mehta (2001) reported that “high volume fly ash concrete is the best, due to the simplicity of the technology, low initial cost, high durability and high environmental friendliness of the product. Super-plasticized high-volume fly ash concrete is expected to have a huge impact on the concrete industry”.

Davis (1954) reported that chemical reaction of fly ash with available lime and other alkali solutions produces additional cementitious compounds to help develop strength. Fly ash- lime binders help concrete continue to gain strength in the long term and reduce permeability (exposure to water and aggressive chemicals).

According to Hardjito and Rangan (2005), concerns regarding sustainable development in the construction industry have led to studies on the activation of fly ash with alkaline solutions. The combination of fly ash with alkaline solutions such as sodium hydroxide and sodium silicate produces a binding material similar to cement. Alkali-activated fly ash has facilitated the movement towards production of concrete without portland cement (Hardjito and Rangan, 2005).

3. TEST MATERIALS AND PROCEDURES

This chapter discusses the materials and procedures that were used in this research. More specifically, the properties and specifications of the materials, geopolymer paste mix proportions, curing time and temperatures, and experimental procedures are discussed.

3.1 Dredged materials

The dredged materials that were used in this research were collected from the CDF facility at the Port of Milwaukee, Wisconsin. Milwaukee CDF is an in-lake facility located at the south end of Milwaukee Harbor. Figure 3-1 shows the location of the Milwaukee Harbor CDF. Samples were collected from the ground surface using a shovel at depths ranging from 0.2 to 0.5 m. Three different samples, two from the east side of the CDF (Identified as East I and East II) and one from the north side of the Lake Michigan's CDF were collected for this research. The east side samples were reportedly dredged from the rivers that feed into the lake, and the north side materials dredged from the lake itself.



Figure 3-1 Port of Milwaukee CDF Location

The Milwaukee Harbor CDF (on Jones Island) is a 44 acre facility along the Lake Michigan shoreline (Bowman, 2003). This facility was constructed in 1975 for the US Army Corps of Engineers maintenance of the Federal Navigation Channels in Milwaukee. Each year almost 50,000 cubic yards of sediments are placed in this CDF, 90% of which are fine-grained silts and clays and may be contaminated to various degrees with PCBs, PAHs, and metals (Bowman, 2003).

The Wisconsin Department of Natural Resources (WDNR) governs regulations pertaining to testing and the beneficial reuse of Milwaukee and Green Bay dredge materials. Three most applicable sets of regulations in Wisconsin are (Logan, 2013):

- NR-347: Sediment Sampling and Analysis, Monitoring Protocol and Disposal Criteria for Dredging Projects
- NR 538: Beneficial Use of Industrial Byproducts
- NR 500: General Solid Waste Management Requirements.

Table 3-1 shows the basic geotechnical properties of Milwaukee Harbor dredged materials, conducted at the University of Wisconsin Madison (Hua, 2014). The samples used in this work were taken at the same time and location as the samples used in this thesis. In this table W_N is the in situ water content, G_s is the specific gravity, fines is percentage passing No.200 sieve, LL is liquid limit; PI is the plasticity index, γ_d is the maximum dry unit weight, W_{OPT} represents the optimum water content (ASTM D698), CBR stands for California bearing ratio (performed with optimum water content), c_u =undrained shear strength (performed with 100 Kpa confining pressure), and UCS is the unconfined compressive strength (Hua, 2014).

Table 3-1 Geotechnical properties of the Dredged Material (North sample) from Milwaukee Harbor CDF
(Hua, 2014)

Item	Properties
Specimen Name	RDM
USCS	MH
AASHTO	A-7-5
w_N	67.3
Organic Content (%)	9.8
G_s	2.59
Gravel (%)	0
Sand (%)	3.4
Fines (%)	96.6
LL	61.5
PI	19.3
γ_d (kN/m ³)	12.9
w_{OPT} (%)	30
CBR	1.5
c_u (kPa)	240
UCS (kPa)	27.7

Elemental analysis is needed to identify the potential of dredged material for use as binders in geopolymer concrete. According to Davidovits (2005), materials that are rich in silicon (Si) and aluminum (Al) could be used in geopolymer concrete. Table 3-2 shows the elemental analysis of tests results conducted on three different DM samples at the University of Wisconsin Madison. Unfortunately they did not report the amount of silicon in the dredged materials samples that were tested.

Table 3-2 Elemental Analysis on Milwaukee Harbor CDF Dredged Materials.

Elements	North	East I	East II
P%	0.09	0.08	0.12
K%	0.30	0.30	0.30
Ca%	9.35	8.07	7.79
Mg%	4.74	3.17	3.08
S%	0.18	0.25	0.26
Zn (ppm)	203.63	155.61	266.21
B (ppm)	30.63	23.46	25.40
Mn (ppm)	259.72	227.76	244.61
Fe (ppm)	12960.3	13780.2	13707.0
Cu (ppm)	60.33	38.10	53.20
Al (ppm)	9071.9	9507.0	11261.6
Na (ppm)	184.8	229.3	241.4
LOI	3.56	3.12	4.21

Scanning Electron Microscope (SEM) images of dredged material sample (North) was obtained.

The observed particle size distribution varied from very fine to sandy materials. Figure 3-2 shows the SEM picture of dredged materials from the North sample.

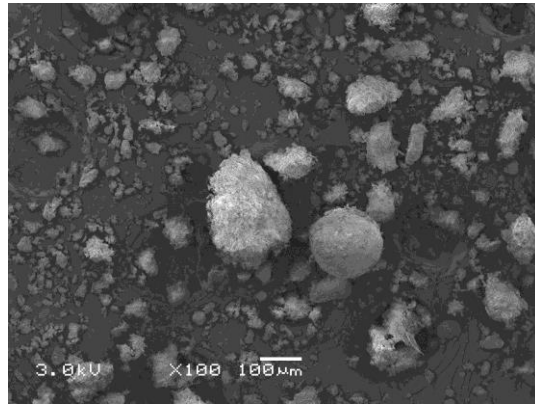


Figure 3-2 Dredged Material (North) SEM Image

Particle size distribution of dredged materials (figure 3-3) shows that almost 70% of dredged materials pass No.200 sieve (Hua, 2014).

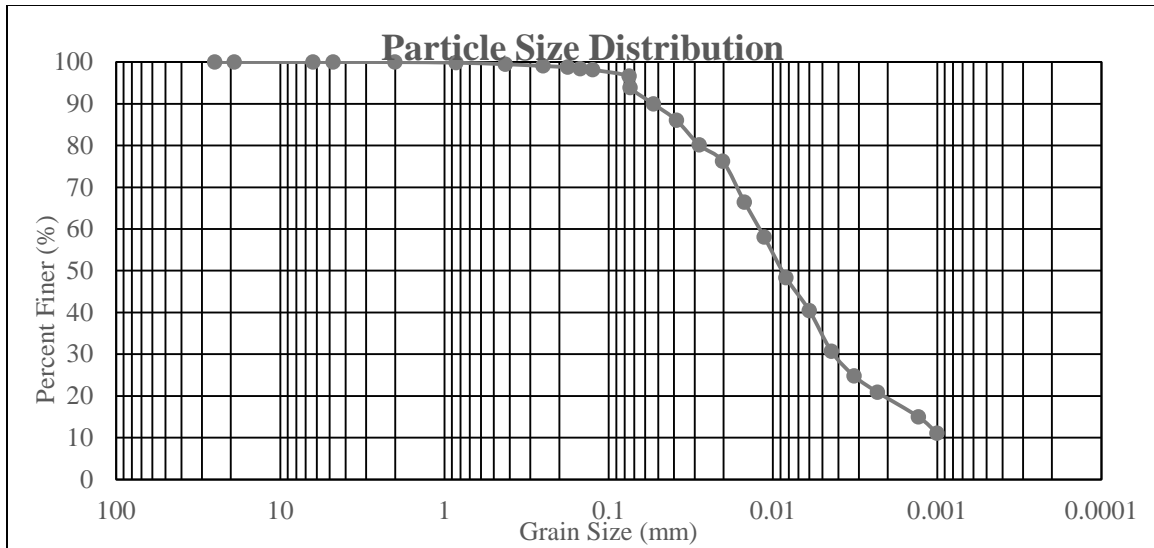


Table 3-3 Chemical and Physical Properties of Fly Ash Class F (Moini, 2015)

Chemical Parameter	Class F (AF)	ASTM C618 limits, Class F
SiO ₂ , %	46.9	-
Al ₂ O ₃ , %	22.9	-
Fe ₂ O ₃ , %	19.2	-
Total, SiO ₂ +Al ₂ O ₃ +Fe ₂ O ₃ , %	89.0	70 min 5.0 Max
SO ₃ , %	0.3	-
CaO, %	3.8	-
MgO, %	0.8	-
K ₂ O, %	1.7	-
Na ₂ O, %	0.6	-
Moisture Content, %	0.1	3.0 Max 6.0 Max
Loss on Ignition, %	2.3	Max
Physical Parameter	Class F (AF)	ASTM C618 limits, Class F
Specific Gravity	2.50	-
7 Days Strength Activity Index, %	77.5	75 min 105 Max
Water Requirement, %	102	Max

Table 3-4 Elemental Analysis of Class F fly ash

Elements	FA-F
P%	0.09
K%	0.18
Ca%	1.61
Mg%	0.14
S%	0.42
Zn (ppm)	41.42
B (ppm)	338.35
Mn (ppm)	50.92
Fe (ppm)	42926.9
Cu (ppm)	24.30
Al (ppm)	17344.3
Na (ppm)	689.7
LOI	0.7

3.3 LIQUID PHASE

A combination of sodium hydroxide solution and sodium silicate solution were used in this study to produce the geopolymer paste mixtures. The sodium silicate solution was purchased from a chemical supply company in 2-gallon pails. This product is commercially sold by Fisher Scientific under the label “Water Glass” ($\text{SiO}_2 = 24\%$, and water = 55% by mass). The sodium hydroxide solution was prepared in the UWM-Concrete laboratory. Sodium hydroxide powder (89% purity) from Fisher Scientific was dissolved in water to achieve the 8 M concentration.

Figure 3-4 shows Sodium silicate and sodium hydroxide products (left) and the laboratory equipment used to make solutions (right).

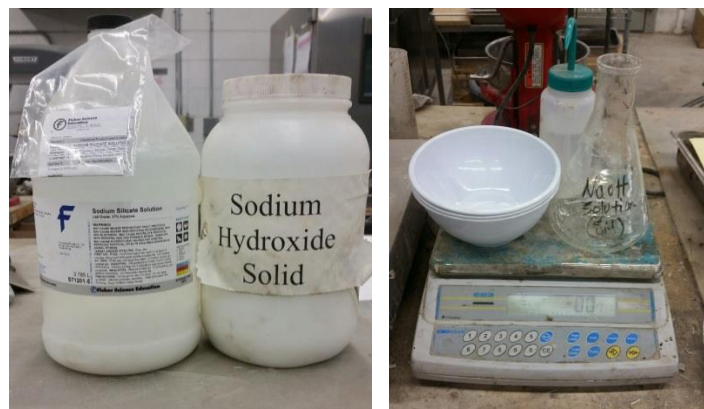


Figure 3- 4 Sodium Silicate (Water glass) and Sodium hydroxide powder and solution

Using the procedures discussed by Wallah and Rangan (2006), the solutions were prepared 24 hours before mixing of geopolymer paste. The sodium hydroxide solution with a concentration of 8 M was used in this research based on the work by Wallah and Rangan (2006).

The NaOH solution with a concentration of 8M consisted of 320 grams (8 times the molecular weight of NaOH as 40) of NaOH solids per liter of water.

3.4 MIX DESIGN PROCEDURES

In this study, the low-calcium Class F fly ash based geopolymer concrete proposed by Hardjito and Rangan (2005) was following closely. It was determined that the mixing procedure, the curing time, and the mixture proportions proposed by Hardjito and Rangan (2005) were appropriate, although some adjustments were made using the trial and error approach..

Initial tests were conducted to compare the effects of different water-to- solid ratios, liquid phase ratios and dredged material percentage ratios. After many trial and error mixtures, the proportions with potential for a high strength mix were chosen and used for the rest of the experiments. The details of the final test mixtures are given in table 3-5 and table 3-6. It should be noted that the test mixtures are different in dredged material and fly ash contents only, and the other parameters are kept constant. The final mix parameters were as follows:

- 1) Sodium silicate (SS) to sodium hydroxide (SH) solution ratio of 1.0
- 2) The water-to- geopolymer solid ratio of 0.25
- 3) Sodium hydroxide solution molarity of 8M.

Table 3-5 Test Mix Parameters

Mix Type		Fly Ash %	DM %	Liquid phase %	SS/SH ratio	Liquid/Solid ratio
Mix I	800020-GPP	80	0	20	1.0	0.25
Mix II	602020-GPP	60	20	20	1.0	0.25
Mix III	503020-GPP	50	30	20	1.0	0.25
Mix IV	404020-GPP	40	40	20	1.0	0.25

Table 3-6 Test Mix proportions

Materials	Weight (Kg/m ³)			
	Mix I	Mix II	Mix III	Mix IV
Fly ash (Class F)	1920	1440	1200	960
Dredged Material (North)	0	480	720	960
Sodium Hydroxide Solution (8M)	240	240	240	240
Sodium Silicate (Water Glass)	240	240	240	240
Water (If any added)	-	-	-	-

3.5 PREPARATION OF TEST SPECIMENS

A batch of geopolymer paste was made for each mix shown in table 3-8. A total of 78 cube samples were made and tested. Dredged materials were first air dried in room temperature by spreading them on a flat surface. They were then passed through sieve number 7 (size 2.83 mm (0.11 in)). The sodium hydroxide solution and sodium silicate solution were mixed with each other 24 hours before test.

Dry materials were mixed together first for 2 minutes, using a Hobart tabletop mixer (Figure 3-6). The liquids were then added to the mixture and mixing was continued for 4 more minutes. The paste mix was poured into 51mm (2 in) cube molds in 3 layers. After placement of each layer, 20-30 strokes of a rod were used to consolidate the mixture. Specimens were then covered and placed in a Thermo Scientific oven (Figure 3-7) set at 60°C oven for 24 hours. Subsequently, the samples were removed from molds and kept at room temperature until testing.

Figure 3-5 shows the equipment and materials used in the mixing. Five quarter Hobart counter-top mixer, a bucket of Class F Fly ash and dredged materials.

Figure 3-6 shows the fresh mixed geopolymer paste (left) and placement of geopolymer paste in 2in cubes (right) before moving the specimens into the oven.



Figure 3-5 Mixer (left), Fly ash and Dredged materials (right)



Figure 3-6 Fresh Geopolymer paste(left)and cube molds (right)



Figure 3-7 Thermo Scientific Oven used for oven curing

3.6 COMPRESSIVE STENGTH TEST

The ASTM C109, “Standard test method for compressive strength of hydraulic cement mortars, using 2in (50 mm) cube specimens” was followed for the compression testing of cubes. These specimens were tested using an ADR-Auto ELE compression machine (Figure 3-8) and loaded at a rate of 1.4kN/sec. The maximum load and maximum compressive stress were recorded. These tests were performed at ages of 14 and 28 days for each mix type.



Figure 3-8 ADR-Auto ELE Compression Machine

4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Overview

The test results are presented and discussed in this chapter. The test results include the unit weight and compressive strengths, the effect of age on the compressive strength, and the effect of dredged material content on strength of paste.

Test specimens were made using five different geopolymer paste mixtures (Mix I, Mix II, Mix II and Mix IV).The details of these mixtures and the test details are given in Chapter 3. Figure 4-1 shows the various test cubes.



Figure 4-1 Geopolymer Paste Specimens With Different Mix Design

4.2 UNIT WEIGHT AND COMPRESSIVE STRENGTH

Three cubes were tested for compressive strength at age of fourteen days and twenty eight days after casting for each of the geopolymer paste mixture. The unit weight of hardened specimens was determined at the same time using the measured weight and dimensions of the cubes. The unit weight and compressive results are shown in Tables 4-1 and 4-2, respectively. Mixture designation XXYYZZ-GPP indicates the percent of fly ash (XX), DM (YY), and liquid phase (ZZ),

respectively. For example, 800020-GPP refers to a geopolymer paste mixture containing 80% fly ash, 0% DM, and 20% liquid phase. Figure 4-2 shows test samples under compression loading and after failure.

Table 4-1 Mean Unit Weight of geopolymer pastes

Mixtures	Unit Weight (kg/m³)			
	14-Days	Standard Devia- tion	28-Days	Standard Deviation
800020-GPP	1982	2.5	1760	0.5
602020-GPP	2010	1.6	1840	0.43
503020-GPP	2032	0.5	1961	0.6
404020-GPP	2144	1.0	1984	0.5

Table 4-2 Mean Compressive Strength

Mixtures	Compressive Strength (MPa)			
	14-Days Old	Standard Deviation	28-Days Old	Standard Deviation
800020-GPP	35.7	0.5	38.9	1.4
602020-GPP	25.28	2.1	31.13	2.7
503020-GPP	25.9	3.1	28.6	1.7
404020-GPP	20.87	0.6	26.1	1.8



Figure 4-2 Dredged Material Sample (404020-GPP) inside the Compression test Machine

The test results show the effect of dredged material content on both the compressive strength and unit weight. As dredged material content is increased, the strength decreases. On the other hand, results show an increase in unit weight of samples when more dredged material is added to the

geopolymer concrete mixtures. However, even samples with the highest dredged material content (40 percent) had a compressive strength of over 3000 psi (20 MPa), which would make these mixtures suitable for use as structural concrete.

The SEM image obtained from different mixtures were obtained Figure 4-3, 4-4, 4-5 and 4-6 shows SEM images from Mix I through Mix IV, respectfully. These show particle distribution. The spherical fly ash particles are evident in the images. All SEM images show porosity in the various samples.

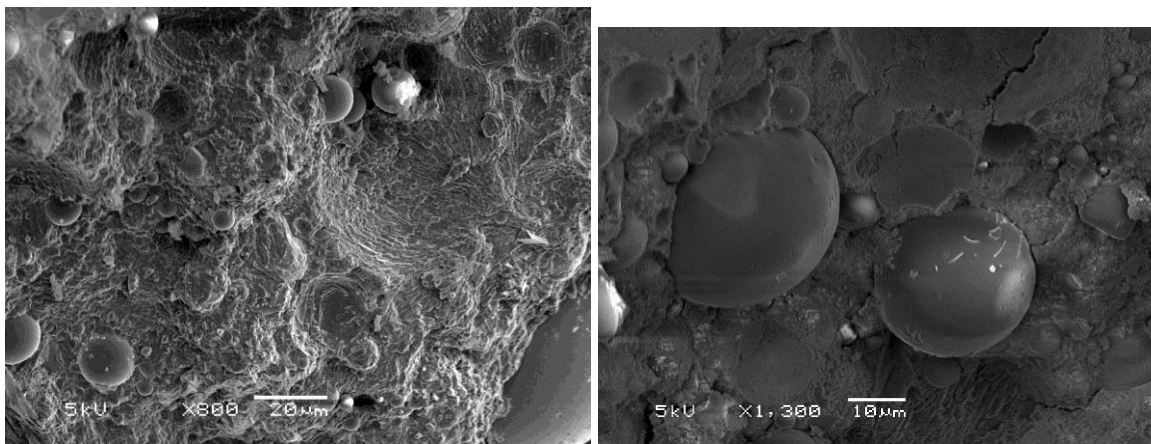


Figure 4-3 SEM image of Mix I (800020-GPC) at 1300X(right) and 800X (left) Magnification

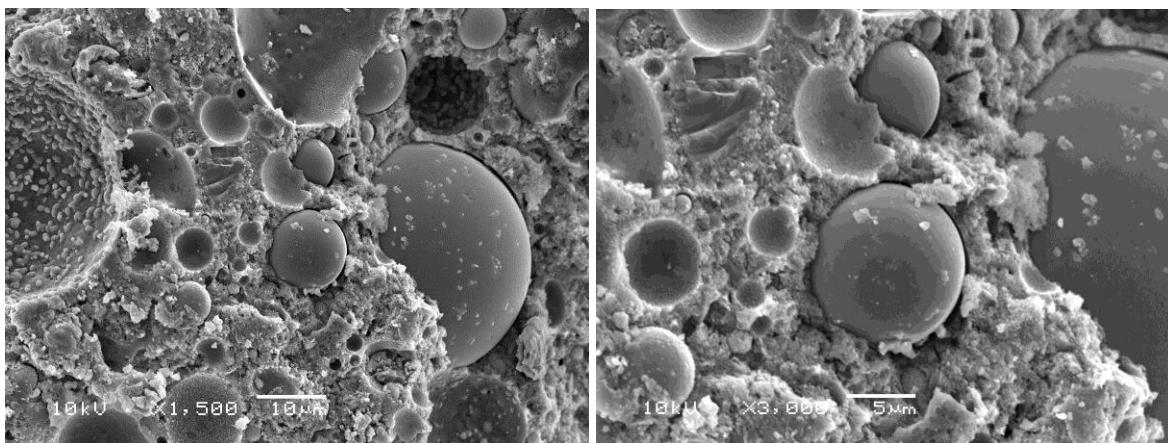


Figure 4-4 SEM Pictures of Mix II (602020-GPC) at 1500X and 3000X Magnification

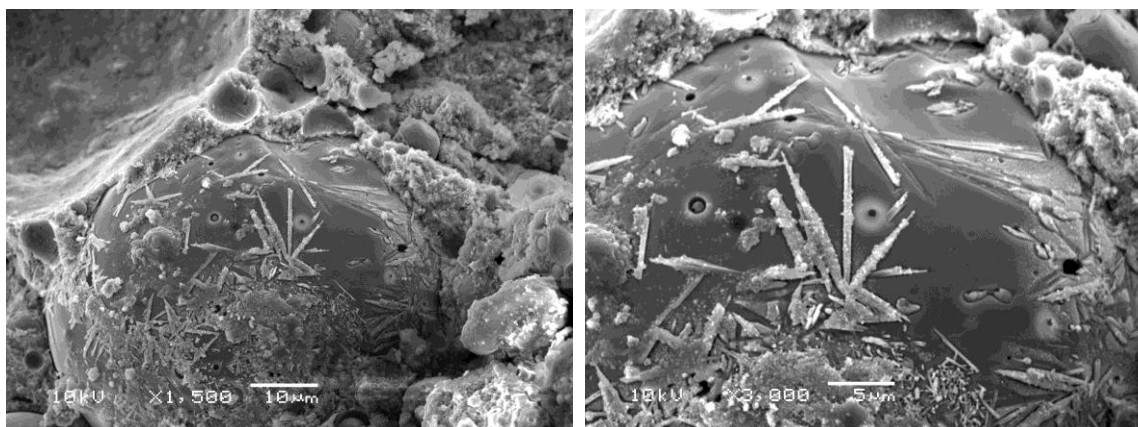


Figure 4-5 SEM Pictures of Mix III (503020-GPC) at 1500X and 3000X Magnification

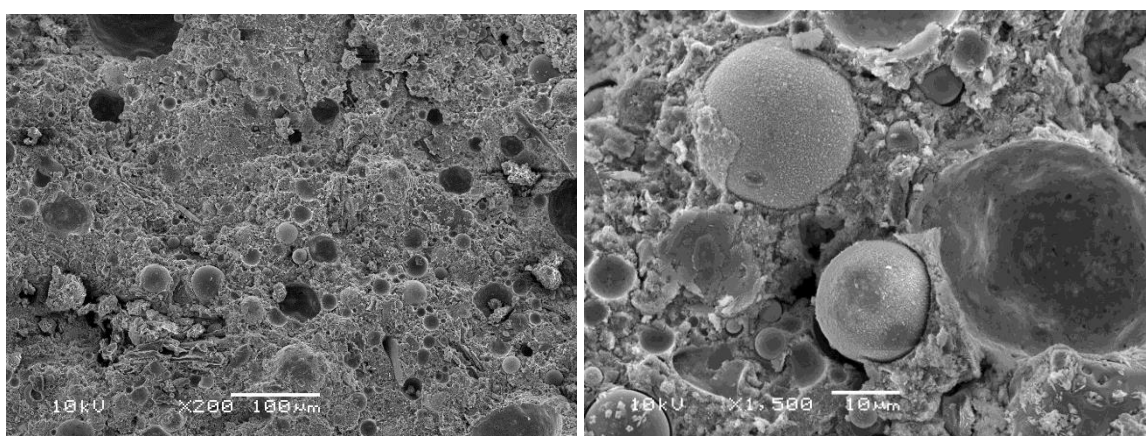


Figure 4-6 SEM Pictures of Mix IV (404020-GPC) at 200X and 1500X Magnification

Figure 4-7 compares the average compressive strength of different samples at 14 and 28 days.

The original geopolymer paste (zero DM) had the highest strength, the strength declined as DM content increased.

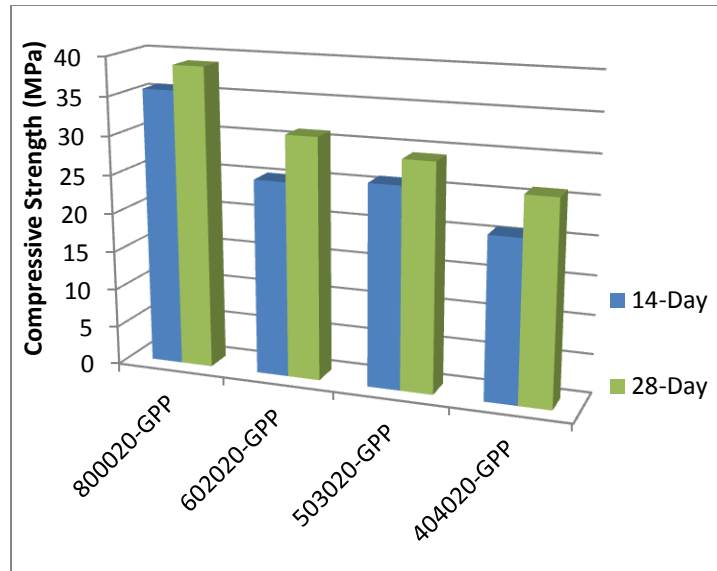


Figure 4-7 Compressive Strength of different mixtures at age of 14 and 28 days

Figure 4-8 presents a constant increase in specimen's compressive strength by ageing.

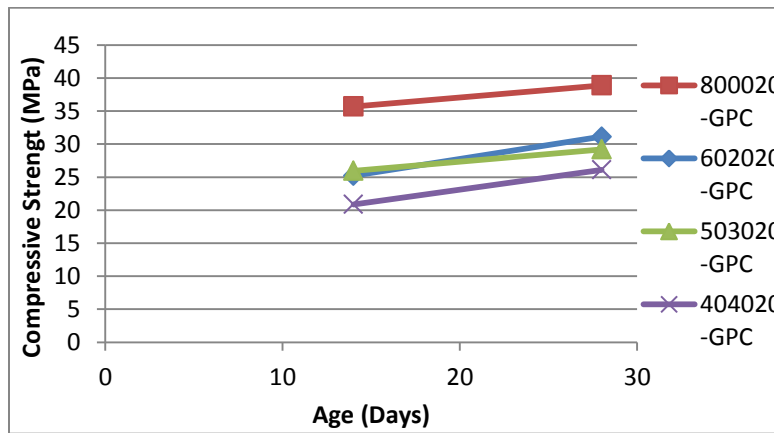


Figure 4-8 Change in Compressive Strength of Geopolymer paste with Age

Figure 4-9 plots the compressive strength of the geopolymer paste as a function of dredged material content at an age of 28 days. A linear trend line is fit to the data. It is shown that up to 40% dredged material use in the geopolymer paste is feasible. Such use can result in large-scale beneficial use of dredged materials.

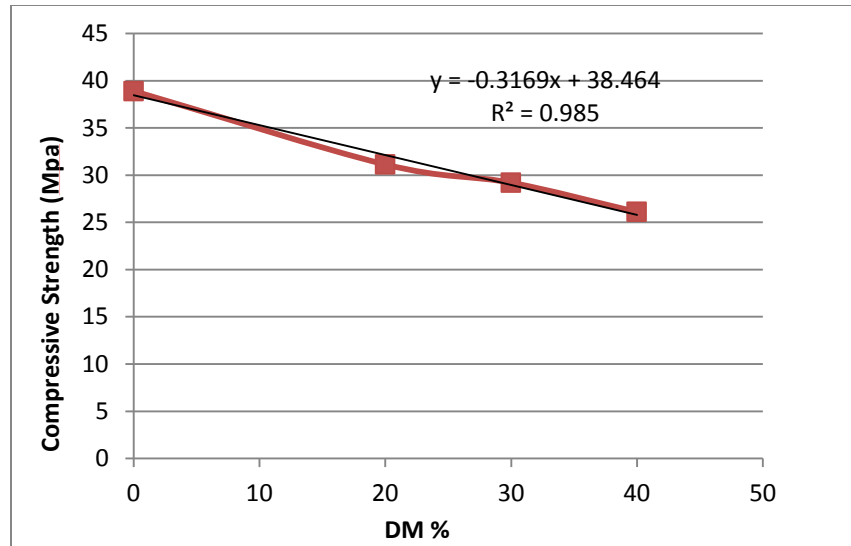


Figure 4-9 Effect of dredged material on geopolymer mortar Compressive strength

5 – CONCOLUSIONS

The primary goal of this research was to stablsh the feasibility of utilizing dredged materials as a significant component of geopolymer-based concretes, and to develop suitable mix proportions to achieve sufficient strength for structural use. Regarding mitigating the presence of heavy metals and other contaminants in dredged materials, the geopolymerization process is known to trap and isolate the contaminants inside the binders. Based on analysis of results the following conclusions can be made:

- The geopolymerization process was successful because sufficient strength of the paste was achieved when dredged materials were added up to 40% of total mass in a geopolymer paste mixture.
- Feasibility of using dredged material as a significant component in geopolymer- based concrete is established.

- Geopolymerization could be an important tool in immobilizing contaminants within dredged materials (based on previous research).
- Compressive strength was reduced linearly as DM content was increased.

5.1 RECOMMENDATIONS FOR FUTURE STUDY

The various aspects of this research can be further extended in a future study. Based on promising results of this research, mix designs for geopolymer concrete (including aggregates) can be developed and tested. Furthermore, by conducting leaching test on geopolymer concrete specimens, immobilization of heavy metals and other contaminants in dredged materials can be directly evaluated.

The development of different curing methods (such as moist or room temperature curing) can be considered to reduce the production costs. Furthermore, other tests such as creep, shrinkage, flexure, and sulfate resistance tests can be useful for full implementation of this beneficial use of dredged materials.

REFERENCES

1. ACI Committee 232, (2004), "Use of Fly Ash in Concrete", American Concrete Institute, Farmington Hills, Michigan
2. ASTM C109, "Standard test method for compressive strength of hydraulic cement mortars, using 2in (50 mm) cube specimens" ASTM International, West Conshohocken, PA.
3. Geopolymer chemistry and application, Davidovits,(2005)
4. Duxson, P. Fernández-Jiménez, A. Provis, J.L. Lukey, G.C. Palomo, A. van Deventer, J.S.J. Geopolymer Technology: The Current State of Art, (2007)
5. Beneficial Use Testing Manual *Guidance for Assessing Suitability of Dredged Material for Beneficial Use*, Richard A Price US Army Corps of Engineers (2008)
6. Rangan, B. V., Hardijito, D., Wallah, S. E., & Sumajouw, D. M. J. Fly ash-based geopolymer concrete: a construction material for sustainable development. Concrete in Australia, (2005a)
7. Van Jaarsveld, J, G. S., van Deventer, r, J. S. J., & Lorenzen, L. The Potential use of geopolymeric materials to immobilize toxic metals: Part I. Theory and applications. *Minerals Engineering*, (1997)
8. Van Jaarsveld, J, G. S., van Deventer, J.S.J., & Schwartzman, A. The potential use of geopolymeric materials to immobilise toxic metals: Part II. Material and leaching characteristics, *Minerals Engineering*, (1999)
9. Palomo, A., M.W.Grutzeck, & M.T.Blanco. Alkali-activated fly ashes a cement for the future. Cement And Concrete Research, (1999)
10. Gourley, J. T. Geopolymers; Opportunities for Environmentally Friendly Construction Materials. Paper presented at the Materials 2003 Conference: Adaptive Materials for a Modern Society, Sydney, (2003)
11. Hardjito, D., & Rangan, B. V. Development and Properties of Low-Calcium Fly Ash-Based Geopolymer Concrete. Research Report GC1, Perth, Australia: Faculty of Engineering, Curtin University of Technology, (2005)
12. Zhahni Xie, Hardening mechanisms of an alkaline-activated class F fly ash, Journal of Cement & Concrete Research, (2001)
13. Lee, W.K. W & Van Deventer, J.S.J, "The Interface between Natural siliceous aggregate and geopolymer" Journal of Cement and concrete research, (2004)
14. Davidovits, J. Geopolymer Chemistry and Properties. Paper presented at the Geopolymer '88, First European Conference on Soft Mineralurgy, Compiègne, France, (1988 b)

15. Comrie, D. C., Paterson, J. H., & Ritchey, D. J. Geopolymer Technologies in Toxic Waste Management. Paper presented at the Geopolymer '88, First European Conference on Soft Mineralurgy, Compiègne, France, (1988)
16. Davidovits, J. Chemistry of Geopolymeric Systems, Terminology. Paper presented at the Geopolymers '99 International Conference, Saint-Quentin, France, (1999, 30 June - 2 July 1999).
17. Malone, P. G., Charlie A. Randall, J., & Kirkpatrick, T. Potential Applications of Alkali-Activated Alumino-Silicate Binders in Military Operations. Washington, DC: Department of The Army, Assistant Secretary of the Army (R&D), (1985).
18. Malhotra, V.M., "Concrete in Marine Environment." Proceedings Third CANMET/ACI International Conference, St. Andrews-by-the-Sea, Canada, (1996)
19. Malhotra, V. M., & Mehta, P. K. High-Performance, High-Volume Fly Ash Concrete: Materials, Mixture Proportioning, Properties, Construction Practice, and Case Histories. Ottawa: Supplementary Cementing Materials for Sustainable Development Inc, (2002)
20. Joshi, R.C. and Lohtia, R.P., "Fly Ash in Concrete: Production, Properties and Uses." Overseas Publishers Association, Amsterdam, Netherlands, (1997).
21. Abrams, D., *A tribute to Proportioning Concrete Mixtures*. ACI Special Publication, 2008.
22. Claisse, P. and Ganjian, E. (2010), "Aut, Concrete Technology and Durability Research Center, Iran CSIC, Corrosion and Durability of Concrete Structures, Spain." Proceedings of Special Technical Sessions, Second International Conference on Sustainable Construction Materials and Technologies, Ancona, Italy, 28-30 June, (2010)
23. R Sathia, K Ganesh Babu, Manu Santhanam, "Durability study of low calcium fly ash Geopolymer concrete", 3rd ACF International conference, (2008)
24. Mehta, Kumar P., "Reducing the Environmental Impact of Concrete." Elsevier Science Publishers LTD, New York, NY, USA (2001).
25. ACI Committee 226, Use of Fly ash in concrete, (1988)
26. Ramme, Tharaniyil, Wisconsin Electric Power Company, Coal Combustion Products Utilization Handbook, (1999)
27. B V RANGAN, Engineering properties of geopolymer concrete, Curtin University of Technology, Australia (2006)
28. E. A´lvarez-Ayuso a,*, X. Querol a, F. Plana a, A. Alastuey a, N. Morenoa, M. Izquierdo a, O. Font a, T. Morenoa, S. Diez a, E. V´azquez b, M. Barra b, Environmental, physical and

structural characterization of geopolymer matrixes synthesized from coal (co-)combustion fly ashes, (2007)

29. Lloyd, N. A., and B. V. Rangan. "Geopolymer concrete with fly ash." *Second international conference on sustainable construction materials and technologies*. Vol. 3. 2010

30. Jones K W , Feng H, Stern E A, et al. Dredged materials decontaminated demonstration for the port of New York & New Jersey. *Journal of Hazardous Materials*,(2001)

31. David W. Bowman¹, Tommy E. Myers, Ph.D.², Richard A. Price³, and Scott Cieniawski⁴. Attempts to Develop Beneficial Uses for Milwaukee Harbor and Green Bay Harbor Dredged Material, 2002.

32. Clark, G. and Knight, D.L, "Beneficial Use of Dredged Materials in the Great Lakes.", published by Great Lakes Dredging Team, March 2013, qpp.

33. Abood, Karim A., and Felicia Orah Rein. "Barriers to the Beneficial Use of Dredged Material and Potential Solutions." *Bridges* 10.40680 (2003)

34. Hua Yu, Beneficial Use of Dredged Materials in Great Lakes Commercial Ports for Transportation Projects, (2014)

35. M. Reza Moini, The Optimization of Concrete Mixtures for Use in Highway Applications, (2015)

36. Wallah, S.E. and Rangan, B.V. (2006). Low-Calcium fly ash-based geopolymer concrete: Long-term properties. Curtin University of Technology.

37. Davidovits, Joseph. *Geopolymer chemistry and applications*. Geopolymer Institute, 2008

38. Gluhovsky V.D., Slag-alkali concretes produced from fine - grained slag, Visheha Shkola Kiev, 1981, 229 pp.

39. Krivenko P., Alkali cements and concretes: problem of durability. Kiev, Ukraine, 1999, pp. 3-43