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M.Sc. in Civil Engineering

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HASAN KALYONCU UNIVERSITY

GRADUATE SCHOOL OF

NATURAL & APPLIED SCIENCES

EFFECT OF AGGREGATE PROPERTIES ON THE MECHANICAL AND ABSORPTION CHARACTERISTICS OF GEOPOLYMER MORTAR

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Effect of Aggregate Properties on the Mechanical and Absorption Characteristics of Geopolymer Mortar

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Assist. Prof. Dr. Kasım MERMERDAŞ

By

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Soran MANGURI

ABSTRACT

EFFECT OF AGGREGATE PROPERTIES ON THE MECHANICAL AND ABSORPTION CHARACTERISTICS OF GEOPOLYMER MORTAR

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M.Sc. in Civil Engineering
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Various amounts of natural resources are consumed to manufacture ordinary Portland cement which causes considerable environmental problems for its production. A new technological process called geopolymerization provides an innovative solution in this issue. In addition to potentially reducing carbon emissions, geopolymers can be synthesized with many industrial waste products or natural pozzolans such as fly ash, ground granulated blast furnace slag, metakaolin, etc. In the present study, the experimental study was executed to establish the relation between aggregate features and some engineering properties of fly ash based geopolymer mortar. To achieve this goal, two types of sand and four grading of each type of aggregate were used. The geopolymer binder is mixture of alkaline liquids and fly ash. Compressive strength values were in the range of 47.83-40.25 MPa, 44.93-38.09 MPa, and 39.37-28.25 MPa, for crushed limestone, combined sand, and natural sand respectively. In addition, the absorption of geopolymer mortar, made of these mixes, was also studied, using water absorption test and water sorptivity test. The test results indicated that absorption of fly ash based geopolymer mortar was improved by using combined sand aggregate (50% crushed limestone and 50% natural sand) compared to the ones with single aggregate type.

Key Words: Geopolymer, Aggregate properties, Strength, Absorption

ÖZET

AGREGA ÖZELLİKLERİNİN JEOPOLİMER HARÇLARININ MEKANİK VE ABSORPSİYON ÖZELLİKLERİNE ETKİSİ

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Aralık 2016, 72 sayfa

Üretiminde önemli çevresel sorunlara neden olan Portland çimentosunun imalatı için çeşitli doğal kaynaklar tüketilmektedir. Jeopolimerizasyon adı verilen yeni bir teknolojik süreç bu konuda yenilikçi bir çözüm getirmektedir. Jeopolimerler karbon emisyonu potansiyelini düşürmenin yanı sıra, uçucu kül, öğütülmüş yüksek fırın cürufu, metakaolin, vb. gibi birçok endüstriyel atık ürünü veya doğal puzolan ile sentezlenebilir. Bu çalışmada, uçucu kül esaslı jeopolimer harcın agrega özellikleri ile bazı mühendislik özellikleri arasındaki ilişkiyi ortaya koymak amacıyla deneysel bir çalışma yürütülmüştür. Bu amaç doğrultusunda, agrega olarak iki tür kum ve dört farklı gradasyon kullanılmıştır. Jeopolimer bağlayıcı, alkalin sıvılar ve uçucu kül karışımından oluşmaktadır. Kırma kireç taşı, karışık kum ve doğal kum için sırasıyla basınç dayanımı değerleri 47.83-40.25 MPa, 44.93-38.09 MPa, ve, 39.37-28.25 MPa aralığındadır. Ayrıca, su emme ve kılcal su emme deneyleri ile jeopolimer harçların geçirimlilikleri değerlendirilmiştir. Elde edilen test sonuçlarına göre uçucu kül esaslı jeopolimer harcın su emme kapasitesinin karışık agregalı olanlarda (%50 kırma kireç taşı ve %50 doğal kum), tek tip agregalı olanlara kıyasla iyileştiği gözlenmiştir.

Anahtar Kelimeler: Jeopolimer, Agrega özellikleri, Dayanım, Absorpsiyon

To My Parents, I am grateful to God for having parents like you. Your unconditional love and support made my every achievement possible.

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LIST OF SYMBOLS/ABBREVIATIONS

Al	Aluminum
ASTM	American Standard for Testing and Materials
ACI	American concrete Institute
CaO	Calcium Oxide
$Ca(OH)_2$	Calcium Hydroxide
CL	Crushed Limestone
CO_2	Carbon Dioxide
CS	Combined Sand
FA	Fly Ash
f_c	Compressive strength
f_s	Splitting Tensile Strength
GPC	Geopolymer Concrete
GPM	Geopolymer Mortar
GGBS	Ground Granulated Blast Furnace Slag
KOH	Potassium Hydroxide
K_2SiO_3	Potassium Silicate
NaOH	Sodium Hydroxide
Na_2SiO_3	Sodium Silicate

NO_2	Nitrogen Dioxide
NS	Natural Sand
OPC	Ordinary Portland cement
PC	Portland Cement
Si	Silicon
SO_2	Sulfur Dioxide
W/C	Water to cement ratio

CHAPTER 1

INTRODUCTION

1.1 General

OPC-based concrete is mostly used in construction industry. Every year hundreds of millions of tons are used in the worldwide. The global use for concrete is only second to water, it accounts for 70% of all building and construction materials. The essential and main binder for producing concrete is ordinary Portland cement (OPC). Moreover, the production of (OPC) is increase at a rate about 3% per year, due to the raw materials are available all over the world, also because of its versatile and diverse behavior which gave architectural freedom and ease application (McCaffrey, 2002).

On the other hand, the paramount concern of the concrete industry is the use of Portland cement. It could be considered as one of the reason contributing to global warming. Harmful gasses like CO_2, NO_2, SO_2 and specks of dust are discharged into the atmosphere during the production of Portland cement because of the calcination of limestone and combustion of fossil fuel (Hardjito, 2005). Along with environmental issues, Portland cement production also requires a considerable amount of energy, following steel and aluminum (Hardjito, 2005). For this concern several efforts have been developed for reducing ordinary Portland cement in concrete by using supplementary cementitious material to address the global warming. These by product materials by itself does not has the binding properties. Development of high volume fly ash was a good achievement for reducing Portland cement successfully up to 60-65% (Malhotra, 2002; Malhotra and Mehta, 2002). Common supplementary cementitious materials used are fly ash, GGBS, rice husk ash, and metakaolin.

In recent years, geopolymer technology has been developed to decrease the use of Portland cement in concrete (Davidovits, 1994). As part of the sustainability movement in the concrete industry, the technology has led researchers to the discovery of a green concrete as a substitute for traditional concrete. This binder in the resulting caused by low-cost and greener compare to PC. In geopolymers production half amount energy required to produce the activator compared to the PC production. Geopolymer concrete has a potential to reduce CO_2 emission by 80% (Daniel et al., 2006). In addition, by product material such as fly ash has cheaper than Portland cement about 10-30 percent according to (Rangan, 2008).

Mechanical properties of geopolymer are better than cement paste. Therefore, not only helps to generate less CO_2 than PC, but also one of the best behavior of geopolymer is converting waste material such as fly ash, slag and other materials to useful material for making friendly-economic concrete.

Generally, concrete volume contains around 80% of aggregate, which could greatly influence the characteristic of concrete, freshness as well as its hardness. Plus, this will have an influence upon the concrete cost (Hudson, 1999). Aggregates grading, shape, and texture greatly affect workability, finishability, bleeding, pumpability, and segregation of fresh concrete. However, when hardened characteristics are taken into account, strength, stiffness, shrinkage, creep, density, permeability, and durability are also highly affected by aggregate features. It was also mentioned that the poor mixture proportioning and grading variation will cause construction and durability problems (Lafrenz, 1997).

If the voids between aggregates are decreased, the amount of paste need to fill these voids will be decreased, keeping desired workability and target strength. Therefore, best mixture proportion will create good concrete-quality with a lowest amount of cement. The lesser cement paste at a constant water to cement ratio provide the concrete more durable (Shilstone, 1994).

1.2 Objective of the Research

This study was carried out to investigate the possibility of utilizing fly ash to replace Portland cement in different construction applications. Moreover, this thesis will cover the following objectives:

1. To make a new green binder to replace cement mortar, with a low- cost, better mechanical strength and improving absorption properties.
2. Effect of grading and type of aggregate on mechanical strength and absorption properties of geopolymer mortar.

Class F fly ash was used as 100% replacement of Portland cement to develop geopolymer mortar. In addition, the technology and the equipment currently used to produce cement mortar or concrete were used throughout the experiments. The concrete properties studied mainly included compressive strength, splitting tensile strength, water absorption, and water sorptivity along with early features of fresh mortar property like flow table test.

1.3 Research Layout

Chapter one: includes the introduction of the geopolymer material disadvantage of OPC, some aggregate properties, and objective of the research.

Chapter two: previous studies based on the scope of the study have been reviewed and maintained, reviews the utilization of fly ash in geopolymer. It presents the mechanism of geopolymerization, application of geopolymer material, properties of the fly ash based geopolymer materials and the factor affecting geopolymer properties, as well as discussed about aggregate, and characterization. It was also dialed with the effect of different type and grading of aggregate on cement concrete and mortar. Besides, the effect of type and grading of aggregate on properties of fly ash based geopolymer.

Chapter three: materials and experimental design, gives the details of the materials and equipment used in the study. It also explains the procedure for the research and the experiments in detail.

Chapter four: experiment analysis, result and discussion, presents test results. Also, it analyzes the results of the experiments.

In chapter five: the conclusion built on the results or these comparative investigations were provided in this section.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The development of geopolymer by Davidovits is the major advantage in concrete technology which provided a cleaner and environmentally friendly alternate to the traditional cement binders in some engineering applications. Using fly ash as a source materials for the production of geopolymer achieve a good economical and environmental benefits and very good physical and mechanical properties which is in some cases better than Portland cement. This chapter will include available literature related to geopolymer concrete and mortar. It will also present the current and possible usage of geopolymer in different construction applications and the factors affecting its performance.

2.2 Geopolymer and Environment

One of the major sources of CO_2 emission is ordinary Portland cement. As a result of a reduction in the use of Portland cement will have a notable impact on CO_2 emission. Each ton of Portland cement generates approximately 0.51 tons of chemical CO_2 and 0.40 tons of CO_2 from fuel combustion (Wallah and Rangan, 2006). It has been estimated that the energy required to produce the activators for geopolymers is less than half the energy required to produce Portland cement, and the chemical CO_2 produced by geopolymers is less than 20% the amount produced by portland cement (Davidovits et al., 1999). So, a conservative estimate shows that each ton of geopolymer will produce 0.3 tons of CO_2 emissions, 67% less than the amount produced by Portland cement. This finding for material emissions alone is comparable to a case study investigating the carbon emissions from geopolymer concrete compare to ordinary portland cement concrete in the Australian market. The case study factored in transportation emissions as well as the material emissions and found that production and placement of geopolymer concrete emits 44-64% less CO_2

than ordinary Portland cement concretes (Nazari et al., 2013). The total CO_2 emissions in the U. S. As well as the emissions due to Portland cement production in the U.S. are illustrated in Figure 2.1 (Fillenwarth, 2013). Similarly, total CO_2 emissions worldwide and the emissions due to Portland cement production worldwide are illustrated in Figure 2.2 (Fillenwarth, 2013).

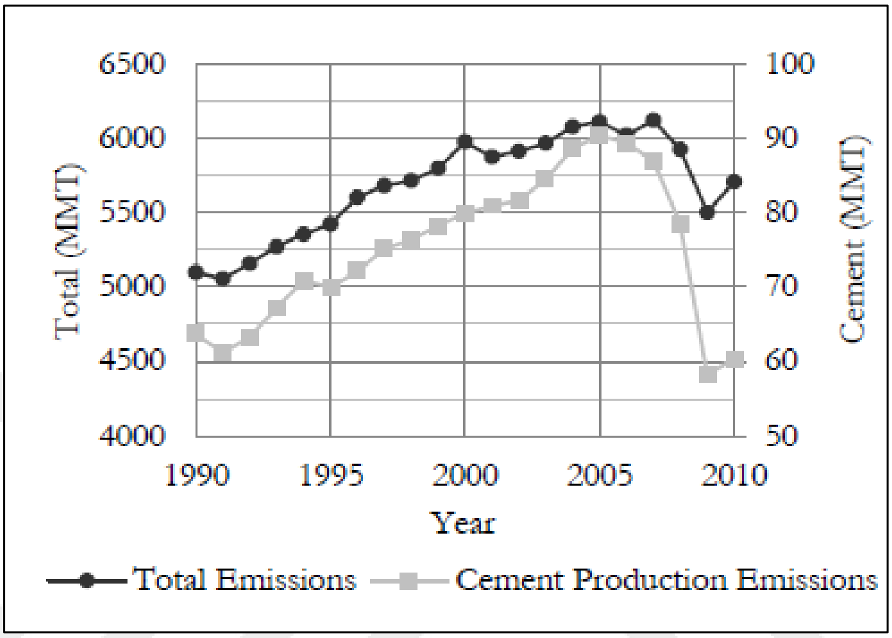

Figure 2.1 U. S. CO_2 emissions (Fillenwarth, 2013)

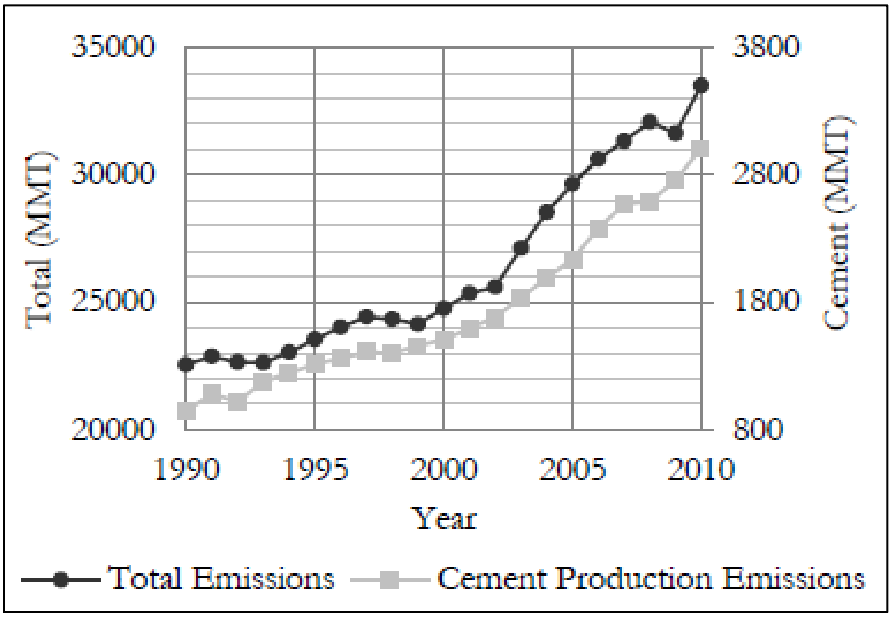

Figure 2.2 Worldwide CO_2 emissions (Fillenwarth, 2013)

These figures indicate that the CO_2 emissions due to Portland cement production in the U.S. has stayed around 1% of the total from 1990 to the present, but the CO_2 emissions due to Portland cement production worldwide has steadily increased from 4% of the total in 1990 to 9% of the total in 2010. From this and knowing geopolymers will produce at least 67% less CO_2 emissions than portland cement, it can be concluded that a complete replacement of portland cement with geopolymer cement will yield at least a 6% reduction in global CO_2 emissions.

2.3 Geopolymer

Geopolymer is listed as classified a member of inorganic polymers, the "geopolymer" term was first coined by French scientist Joseph Davidovits (1978) in reference to alumino-silicate polymers with an amorphous microstructure, and formed in alkaline environment. It was also conducted that geopolymer binder could be formed by the aluminum (Al) and silicon (Si) in a source material of byproduct materials such as rice husk ash, fly ash and slag react with alkaline activators (alkaline hydroxide and alkaline silicate).

Rangan (2008) conducted a research on geopolymers as member of the family of inorganic polymers. The chemical composition of the geopolymers is similar to natural zeolitic materials. It was described that the geopolymerization process is a substantially fast chemical reaction under alkaline activators resulted in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds (Davidovits, 1994b, 1999), as follows:

$$Mn\ [-(SiO_2)\ z–AlO_2]\ n.\ wH_2O$$

Where: M is the alkaline element or cation such as sodium, potassium, or calcium;
The icon – indicates the presence of a bond,
n represents the degree of polycondensation or polymerization;
z equal to 1, 2, 3, or higher, up to 32

Davidovits (1988a; 1991; 1994; 1999) mentioned that polysialate consist of three types, the name and structures of these polysialates can be seen in Figure 2.3.

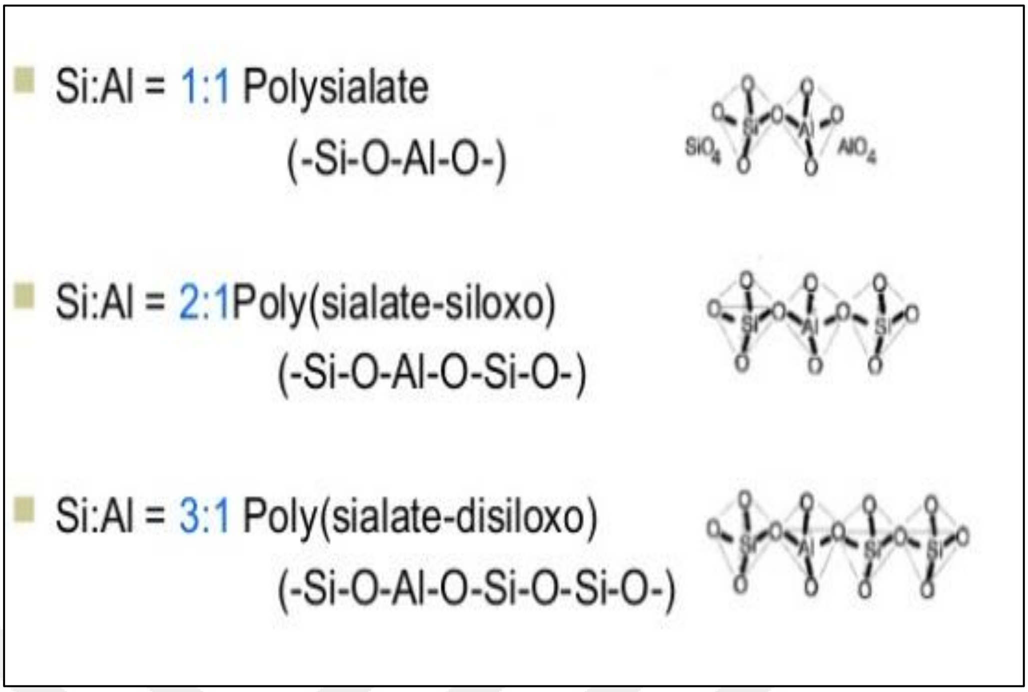

Figure 2.3 The chemical structure of polysialates type (Davidovits, 1988a; 1991; 1994; 1999)

In addition, Palomo et al. (1999) stated that geopolymerization process requires the chemical reaction of alumino-silicate oxides (Si_2O_5, Al_2O_2) with alkali polysilicates leading to polymeric Si – O – Al bonds.

The schematic formation of geopolymer material as defined by Van Jaarsveld et al. (1997); Davidovits (1999); and Wallah and Rangan (2006) are presented as equations (1) and (2) in Figure 2.4. These chemical equations demonstrate that any materials which are rich in silicon (Si) and aluminum (Al) can be processed into geopolymer material.

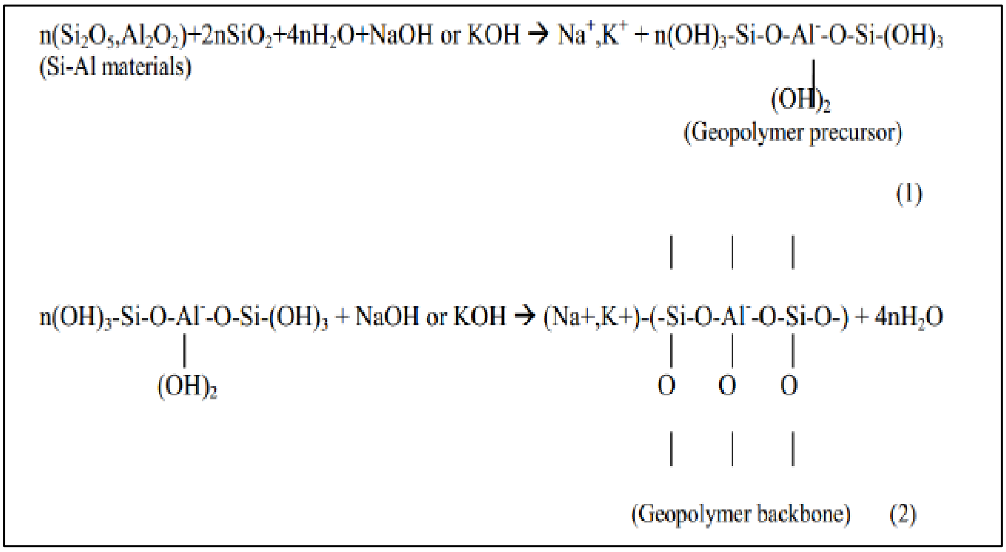

Figure 2.4 Mechanisms of geopolymerization, (Van Jaarsveld et al., 1997; Davidovits , 1999; Wallah and Rangan, 2006)

Rangan (2008) provided a substantial explanation of the second part of the previous equation, and it is reported that water is released by the chemical reaction which is occurs during the geopolymeric formation. This water leads to the formation of discontinuous nano-pores in the matrix which provides benefits to the performance of geopolymers. This water has no role in the chemical reaction except providing workability to the mix.

Nonetheless, the most popular conceptual model proposed for setting and hardening of geopolymer materials comprises the following stages (Davidovits, 1999; Xu and Van Deventer, 2000):

1. Dissolution of Si and Al atoms from the source material through the action of hydroxide ions.
2. Transportation or orientation or condensation of precursor ions into monomers.
3- Setting or polycondensation/polymerization of monomers into polymeric structures.

Palomo et al. (1999) sited that these three steps can be intersect with each other and happens in the same time ,which make it hard to separate and test each of them individually.

Yao et al. (2009) benefited from isothermal calorimetric method for alkali-metakaolin mix. However, in the study of He (2012) geopolymerization involves a number of processes including dissolution, reorientation, and solidification as shown in Figure 2.5.

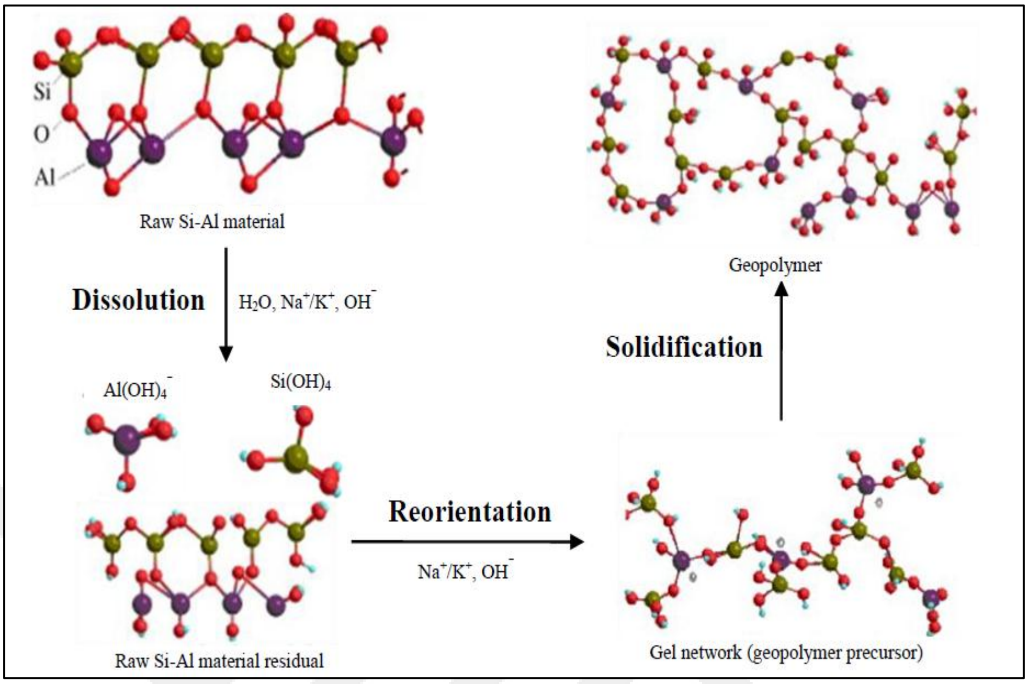

Figure (2.5) Typical reaction mechanism of geopolymerization (Yao et al., 2009; He, 2012)

Nicholson et al. (2005) asserted that geopolymer concrete is an inorganic polymer formed by reaction of aluminosilicate source and an alkali activator at room temperature. The little energy process cause a fast-setting material exhibiting exceptional strength and hardness. A comparison of the reactions in Figure 2.6 shows that traditional cement is composed of portlandite $Ca(OH)_2$ and calcium silicate hydrate (C-S-H) phases whereas, geopolymer cement is based on an aluminosilicate framework. It was also mentioned that aluminosilicate materials has very high resistant to chemical attack, like by acids, compare to calcium-rich Portland cement. In the polymerization process, there is no calcination step (heating to 1450 ºC) which is mitigating the release of CO_2 as shown in Figure 2.6. Therefore, from this, it can be concluded that geopolymer have more advantage than Portland cement concrete.

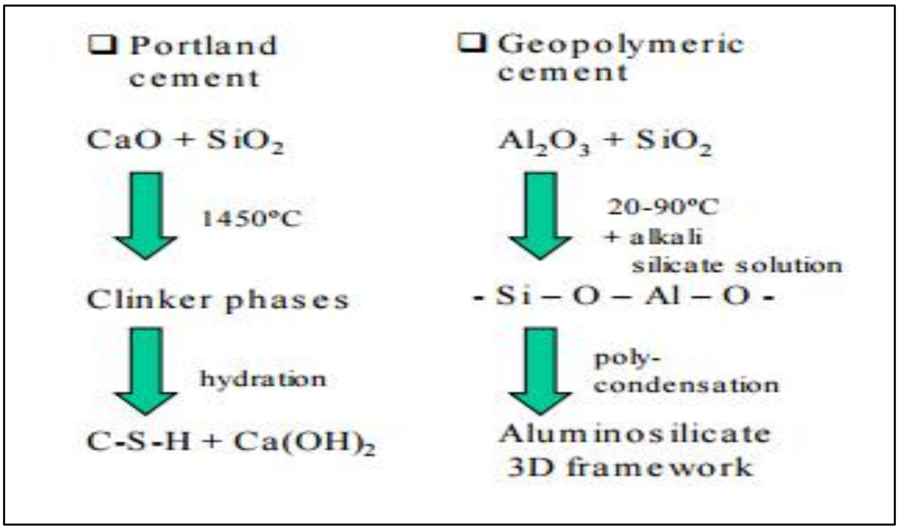

Figure 2.6 Comparison of the reactions of Portland cement and geopolymeric cement (Nicholson et al., 2005)

2.4 Constituents of Geopolymer

Geopolymer has two key components, namely the source materials and the alkaline liquids.

2.4.1 Source Materials

Davidovits (1988b) demonstrated source material of geopolymers binder should contain the high amount of two main minerals which are: aluminum (Al) and silicon (Si). Also, the source material of geopolymers has two types natural and by product, natural minerals like; clay, kaolinite, micas and etc. As well as by-product mineral sources for instance rice husk ash, granulated furnace slag and, especially fly ash. The pick of the source materials for producing geopolymers rely on several factors such as accessibility, cost, application type and specific needs of the end users.

In the range of the source materials previously noted, many of them have been investigated in the making of geopolymer concrete. However, the most popular among them in the technology of geopolymers are clay materials kaolinite and metakaolin, and industrial wastes (furnace slag, fly ash).

Xu and Van Deventer (2002) concluded that utilizing a combination non-calcined material (e.g. kaolinite or kaoline clay and albite) and calcined (e.g. fly ash) resulted in good improvement in reduction in reaction time and compressive strength.

Deb et al. (2014) concluded that using 20% of GGBS with 80 % fly ash would obtain high compressive strength (51MPa) up to 180 days also decrease workability, when cured in ambient curing at 20^{o}C.

An investigation was done by Davidovits (1999), he concluded that calcined materials like fly ash, granulated blast furnace slag, and fly ash will produce high compressive strength than those made from non-calcined materials such as metakaolin clays.

However, using fly ash to produce geopolymer is cheaper than using metakaolin due to the use of the calcination in producing metakaolin.

Swanepoel and Strydom (2002) studied fly ash as a basic component of a geopolymeric binder material, it was showed that fly ash has the potential to be used as raw material in the manufacturing of geopolymer.

Interesting research carried out by Fernandez-Jimenez and Palomo (2003) intended to find out the potential reactivity of fly ashes as alkaline cement. The test results showed that the different fly ashes used for the investigations were not only suitable to be alkali cement, but also their potential reactivity came from the following key factors such as the particle size distribution, the content of reactive silica, and the vitreous phase content. In addition, they stated that in order to produce a material with optimal binding properties by alkali liquid activation, the main characteristics of the low-calcium fly ash should be a percentage of unburned material less than 5%, a content of Fe_2O_3 equal to 10% or less, a low CaO content, a reactive silica content 40 to 50%, and 80-90% of particles should have average size smaller than 45 μm.

Van Jaarsveld et al. (2003) conducted an investigation about the characteristics of a source material in fly ash, they summarized that the size of particle, alkali content, morphology, calcium content, and origin of fly ash has great effect on the properties of geopolymer. Also, it was demonstrated that the calcium content has great role in development of strength and final compressive strength, which higher the content of calcium in fly ash led to faster development of strength and at the early age has higher compressive strength.

Gourley (2003) wrote that the utilization of by-products, such as slag and especially fly ash as raw material in the production of geopolymer concrete has been considered as the most promising materials due to the abundance and availability of fly ash worldwide. It has been shown that fly ash is more useful than slag because its finer particles make it possess high reactivity. Also, as in the case of high volume fly ash concrete, low calcium fly ash is recommended rather than high calcium fly ash. This preference for the Class F is because of the existence of high quantity of calcium in the Class C which can interfere with the polymerization process, and modify the microstructure.

2.4.2 Alkaline Activators

Generally, the common alkaline activator used for producing geopolymer is a combination of sodium silicate with sodium hydroxide NaOH and potassium silicate with potassium hydroxide KOH (Xu and Van Deventer, 2000; Davidovits , 1999; Xu and Van Deventer, 2002; Swanepoel and Strydom, 2002; Yao et al., 2009; Temuujin et al., 2010). In addition, single alkaline activators were used by (Palomo et al. 1999; Görhan and Kürklü, 2014).

Palomo et al. (1999) demonstrated that the type of alkaline activator used for activating fly ash significantly affect the reaction development. Furthermore, they stated that high rate reaction occur when alkaline liquid activator solution contains silicate soluble, each, potassium or sodium silicate, in comparison to using only single alkaline hydroxides.

Xu and Van Deventer (2000) asserted that the reaction between the source material and alkaline liquid improved by adding solution to the NaOH solution. Also, after a conduct of the geopolymerization of sixteen natural Al-Si minerals, they established that commonly using the NaOH solution resulted in higher degree of dissolution of the raw material compare to KOH solution.

2.5 Application of Geopolymer

The use of geopolymer technology is primarily to contribute to the reduction of the environmental impact of ordinary Portland cement. However, geopolymer have various other areas of applications from civil engineering field to automobile and aerospace industries as shown in Table 2.1 (Edouard, 2011).

Table 2.1 Fields application of geopolymer (Edouard, 2011)

Area	Applications
Civil engineering	Low CO 2, fast setting cement, precast concrete products and ready mixed concrete
Building materials	Bricks, blocks, pavers, self glazed tiles, acoustic panels, pipes
Archeology	Archeological monuments by geopolymerization, Repairing & restoration
Composite material	Tooling for aeronautics Functional composite for structural ceramic application
Fire resistant material	Fire and heat resistant fiber composite material Carbon fiber composite
Refractory application	Refractory moulds for metal casting, Use of geopolymer as adhesive refractory, Refractory castables
Utilization of waste	Use of fly ash, blast furnace slag and tailings for geopolymer products
Immobilization of toxic material	Encapsulation of domestic, hazardous, radioactive and contaminated materials in a very impervious, high strength material
Others	Paints, Coatings, Adhesive

In accordance to Davidovits (1999), the type of application of geopolymeric material depends on the Si:Al ratio, as it can be seen in Table 2.2. It appeared from this table that a low Si:Al ratio is suitable for many applications in the civil engineering as shown in Table 2.2.

Table 2.2 Application of geopolymer based on Si:Al (Davidovits, 1999)

Si/Al	Application
1	Bricks, ceramics, fire protection
2	Low CO_2 cements, concrete, radioactive, and toxic waste encapsulation
3	Heat resistance composites , foundry equipments, fibre glass composites
<3	Sealants for industry
20<Si/Al<35	Fire resistance and heat resistance fibre composites

An experimental study was done by Balaguru et al. (1997) on the strength behavior of reinforced concrete beams with carbon fiber fabrics and geopolymer. Their research aimed to demonstrate the ability of geopolymer to be used as substitute to organic polymers for fastening the carbon fabrics to concrete. It was observed that geopolymer provides excellent adhesion both to surface of concrete and in the inter-laminar planes of fabrics.

Comrie et al. (1988) conducted a study to evaluate the applications of geopolymer technology to waste stabilization. This investigation targeted the physical properties of solidified waste and sand mortar mixes, on the basis of compressive strength testing. The results showed that this inorganic binder has the potential to efficiently immobilize hazardous wastes by reducing metal leachability. In addition, it was found that geopolymer technology is extremely effective not only in the case of heavy metals, but also for a wide variety of elements, ions, and compounds (Provis and Van Deventer, 2009).

2.6 Fly Ash

Fly ash is a by-product from the coal combustion, e.g. in the power plants, or in the production of iron. It has various chemical compositions based on the source coals. The main oxide components are SiO_2, Al_2O_3, CaO, Fe_2O_3, and SO_3 (Khale and Chaudhary, 2007).

Besides, fly ash is a by-product collected in the de-dusting of gases derived from the combustion of pulverized coal used in power plants. Fly ash is composed of fine particles, and its chemical composition is related to the different types and relative amounts of incombustible materials present in the coal. Generally, the particle of fly ash is spherical, diameter ranged from less than 1 μm to no more than 150 μm (Nawy, 2008). Generally, its constitutive elements are: aluminum, silicon, calcium, magnesium, and iron. Thus are depending on the combustion process and the type of fuel (Edouard, 2011).

Generally, the constitutive elements of fly ash are aluminum, silicon, calcium, magnesium, and iron, although its composition changes with the source of coal. According to ASTM C618, there are two types of fly ash – Class F, usually formed from bituminous coals, and identified as low calcium fly ash - Class C, normally made from lignite or sub-bituminous coals, and known as high calcium fly ash .In order for a fly ash material to be classified as Class C, the silica (SiO_2), the alumina (Al_2O_3), and the iron oxide (Fe_2O_3) constituents should not exceed by much 50% of the composition, while, Class F the summation of this three components can be greater than 70% (ACI committee 226 report).

According to Fernández-Jiménez and Paolomo (2003), the percentage of unburned material in low-calcium fly ash should be less than 5%, reactive silica content SiO_2 should be range between 40- 50%, Fe_2O_3 content should be less than 10%, 80-90% particles of low-calcium fly ash should be smaller than 45 μm, and has low CaO content (less than 10%).

It can be noticed that Class F fly ashes possess pozzolanic properties. Soft to the touch, (class F) is in the form of powder from gray to black in color depending on the unburned fuel and iron oxide contents, Whereas class C fly ash have the form of a fine gray powder, with physical properties and/or pozzolanic characteristics. They mainly contain reactive lime, reactive silica, and alumina. The amount of lime (CaO) in this type of ash is high. Therefore they are likely to consolidate without the use of binder.

Van Jaarsveld et al. (2003) mentioned that the high-calcium fly ash resulted in higher compressive strength in the primary age due to forming the calcium-silicate-hydrate gel and other calcium mixtures.

2.7 Aggregate

In general, the coarse and fine aggregates occupies 60% to 75% of the volume of concrete and ranged (70% to 85% by mass), which greatly affect the mixture proportions, fresh and hardened properties of concrete, as well as economy. Normally, fine aggregates composed of crushed limestone or natural sand and the particle size are mostly smaller than 5 mm. On the other hand, coarse aggregates consist of gravels or crushed limestone with particle size mostly larger than 5 mm, and commonly ranged from 9.5 mm to 37.5 mm. Natural sand and gravel are ordinarily dug or dredged from a lake, river, seabed or pit, while crushed limestone can be produced by crushing boulders, cobbles, quarry rock, or large size of gravel. Crushed limestone is mostly angular, elongated particles and rough-textured. Furthermore, natural sand aggregate particles are rounded and smooth (Kosmatka et al., 2011).

Generally, natural river sand will be utilized as a fine aggregate in both concrete and mortar. It is considered as the most favorite material to be used as a fine aggregate material. Natural river sand is made of rocks by natural weathering over a long period of time equal to million years. Also, river sands are considered as a high- class material used for construction purposes.

The call for sand has increased since the development of building construction industry. This led to real environmental problems especially in the last few days, fore that it has been thinking for finding a potential source as an alternative for river sand. Therefore, so many researchers have used a manufactured sand as a replacement of natural river sand (Praveen and Krishna, 2015; Fathi, 2014). Offshore sand, quarry dust, crushed limestone, quartzite and other manufactured sand have been identified as good alternative for river sand.

As stated by Folliard and Kreger (2003) there are a great influence made by the fine aggregate considering its shape and texture on the workability of fresh concrete as well the strength and durability at hardened stage. Also, it’s mentioned that texture and shape of fine aggregate are considered to be more effective than the coarse aggregate's effectiveness.

The study done by Shilstone (1999) showed that rounded or cubical particles required water and less paste for workability, because those particles have low surface area compared to elongated and flat particles. Moreover, flaky and elongated particles have a negative impact on workability, causing very harsh mixtures.

The void content is affected by angularity. In fact, because the angular particles have a higher void content than the rounded particles, it will need more water than the rounded one. Research done by Kaplan (1959) demonstrated that mechanical strength of concrete rely on the angularity. Angular particles lead to increase in strength.

According to Hudson (1999), natural river sands commonly need less water than crushed sands for a specified workability and this is because of natural river sand are rounded and smoother than manufactured sands. Nonetheless, the angular and rough particle can make a workable concrete, if their particle size are rounded and well graded aggregates.

The grade of fine aggregate and coarse aggregate should be uniform. If the fine aggregate is too fine, the need for water will be increased. But, if fine aggregate is too coarse, it will lead to some harmful affective like bleeding, harshness, and segregation (Galloway, 1994).

A study was carried out by Cramer (1995) indicated that by using well-graded mixtures, the increase of concrete strength can be obtained.

Folliard and Kreger (2003) said that permeability is one of the most significant factors which affect the durability of concrete. It is clearly correlated to void content of aggregate, in other words, the lower void content cause decrease in permeability. By reducing the permeability, it is possible to have the high amount of aggregate content. Therefore, producing a mixture with a well uniformly graded aggregate will make more durable concrete.

2.7.1 Effect of Aggregate on Cement Mortar and Concrete

Jadhav and Kulkarni (2013) conducted the effect of using manufactured sand as partial replacement of natural river sand on the cement mortar's compressive strength. The proportion 1:6, 1:3 and 1:2 with w/c ratio as 0.55 and 0.5 were conducted. By comparing the results of the present study with a reference mix of 100% natural river sand, the higher compressive strength of cement mortar was observed with using 50% of manufactured sand as a replacement of natural river sand compared to reference mix. The manufactured sand has the ability to come up with another option to natural sand which in turn will aid to conserve both environmental and low-cost price. The rarity of natural sand at a low price has pushed to look for other materials. Manufactured sand can be classified as a preferable option at sensible price. It has been proven that when manufactured sand used in cement mortar, lead to a better result from the cohesiveness and strangeness side this is because of the good gradation which is lacked in natural sand.

Wakchaure et al. (2012) studied the influence of type of fine aggregate on the mechanical strength of concrete. In their research, natural sand and artificial sand were used as a fine aggregates. Mechanical strength such us compressive strength, indirect tensile strength, and flexural strength were evaluated, based on the results, compressive strength and flexural strength improved by replacing total natural fine aggregate by artificial sand. It was also demonstrated that splitting tensile strength with natural fine aggregate obtained better results than with artificial sand.

The effect of grading of sand on the mechanical strength of cement grout was done by Lim et al. (2013). To address the mechanical strength properties of cement grouts, three different grading of sand used for preparing all mixtures, namely 100% passing through 1.18 mm sieve (P1.18 mm), 0.90 mm sieve (P0.90 mm), and 0.60 mm sieve (P0.60 mm), respectively. By measuring the flow of mortar, results shown that the samples with the finer grading of sand had lower flow, in comparison to the coarser grade of sand due to the finer grade of sand samples need a high w/c ratio to obtain a suitable workability. When the lower w/c ratio (0.61 to 0.63) adopted, the coarser grade of sand samples obtained higher compressive strength at 7 and 28 days than the finer sand grading specimens. Nonetheless, when high w/c ratio (0.65–0.67) was adopted, the finer sand grading specimens obtained high long term compressive, splitting tensile and flexural strength compare to the coarser sand grading.

The effect of grading of sand on the mortar's characteristics and soil–cement block masonry was studied by Reddy and Gupta (2008). Three type of grading sand were used, workability, compressive strength, and drying shrinkage were measured for cement mortar. They demonstrated that finer sand needs 25 to 30% more water for a given consistency. In addition, they concluded that coarser sand gives higher compressive strength than finer sand.

2.7.2 Effect of Aggregate on Geopolymer

Sreenivasulu et al. (2016) mainly focused on finding the mechanical properties of geopolymer concrete (GPC) mixes with different fine aggregate blending. Sand and granite slurry (GS) are blended in different proportions (100:0, 80:20, 60:40 and 40:60). Two sizes of coarse aggregates 20 mm and 10 mm are blended in 60:40 proportions by percentage of the weight of the total coarse aggregate. Fly ash (class F) and (GGBS) were used at 50:50 ratios as geopolymer binders. Compressive strength, flexural strength and split tensile strength were studied after 7, 28 and 90 days of curing at ambient room temperature. From the results, it was revealed that the mechanical properties increased till fine aggregate blending of 60:40 and decreasing trend has been observed at 40:60 fine aggregate blending. It was also stated that optimum fine aggregate blending is 60:40.

Olivia and Nikraz (2011) reported on the compressive strength and water penetrability of geopolymer concrete. The study included the compressive strength development, water permeability and water absorption of geopolymer concrete, the variation of geopolymer concrete mixtures, the ratio of aggregate to binder, water to binder ratio, grading of aggregate and the ratio of alkaline to fly ash were studied. Strength was evaluated by compressive strength, whereas to address water penetrability, water permeability and water absorption were measured. According to The test results, the compressive strength of geopolymer concrete was improved by decreasing the ratio of aggregate to binder and water/binder ratio. In addition, water absorption of geopolymer concrete was enhanced by using a well-graded aggregate, increase the fly ash content, and reducing the ratio of water to binder ratio.

Moreover, the permeability coefficient of geopolymer concrete was not changed significantly with different parameters.

Mane and Jadhav (2012) studied the effect of elevated temperatures on geopolymer concrete and mortar for different types of fine and coarse aggregates. Besides, the experimental results are compared with the ordinary Portland cement concrete of grade M20. The geopolymer was produced with fly ash, sodium hydroxide solution, and sodium silicate solution. Granite and basalt aggregates were used as coarse aggregates for concrete specimens, whereas fine aggregates were used for mortar specimens are crushed sand and river sand. The test resulted showed that the geopolymer concrete has an excellent strength performance compare to OPC concrete, in both elevated temperature and ambient curing. Using coarse granite aggregate for producing geopolymer shows better strength than using basalt aggregates. Whereas crushed sand gives high strength compare to river sand in case of mortar. It was also observed that fly ash geopolymer concrete has a superb compressive strength (68% more for basalt aggregates and 67% more for granite aggregates) than the OPC concrete, and it is appropriate for structural applications. Similarly, geopolymer mortar gives excellent compressive strength (89% more for crushed sand and 81% more for natural river sand) than the OPC mortar.

Temuujin et al. (2010) studied preparation and characterization of fly ash geopolymer mortars. Geopolymer mortars with different amount of sand aggregate (0- 50) % were made, and their mechanical and physical properties investigated. The ratio of geopolymer binder to weight of sand aggregate was changed from 9 to 1. Compressive strength of the fly ash based geopolymer paste was 60 MPa. It was also observed that the addition of sand aggregate up to 50% by weight reduce the level of geopolymerization, while it did not considerably affect the compressive strength. Strong bonding was revealed between geopolymer binder and sand aggregate. Besides, the amount of geopolymerization within the binder system decreased by increasing sand contents without increasing alkaline activator.

Nuaklog et al. (2016) conducted a research on the effect of concrete’s recycled aggregate on strength and durability of geopolymer concrete. GPC specimens were synthesized with (high calcium fly ash, sodium based activator, crushed limestone and recycled concrete aggregate as a coarse aggregate, and natural sand was utilized as a fine aggregate). Based on the test results, it was presented that concrete's recycled aggregate can be utilized as a coarse aggregate for producing geopolymer concretes, 30.6 and 38.4 MPa compressive strength was obtained at 7-day, which were little fewer than those geopolymer concretes with crushed limestone. In addition, it was stated that the density of geopolymer concrete ranged between (2350 and 2390 kg/m^3), which were nearly the same as ordinary concrete (2400 kg/m^3). It was also concluded that using recycled concrete aggregate lead to decrease density of geopolymer concrete by 6% to 10% ranged between (2160-2210 kg/m^3). Eventually, it was claimed that using recycle concrete aggregate caused high sorptivity and water absorption.

Joseph and Mathew (2012) studied the behavior of fly ash geopolymer concrete by effect of aggregate content. They concluded that increasing aggregate content lead to increase the split tensile strength of GPC. In their study, total amount of aggregate content in the range of 60% to 75% (with constant fine aggregate to total aggregate ratio of 0.35) was used. It was found that the flexural and split tensile strength increased by 30.6 % and 45.5 %, respectively.

2.8 Superplasticizer

Superplasticizer is considered as a high range water reducer. Possibly a flowing concrete with high slump ranged between 175-225 mm will be produced when superplasticizer is used, which can be utilized in a heavy structure reinforcement, where suitable consolidation cannot be obtained by vibration. It was mentioned that by using the superplasticizer, with w/c ratio of 0.3 to 0.4, high-strength concrete can be achieved. It can also improve the flow of slump (Najmabadi, 2012).

Pacheco et al. (2011) stated that the workability of metakaolin based geopolymer mortar decreases with the increase of sodium hydroxide concentration, it was also observed that by increasing the amount of calcium hydroxide and superplasticizer, the workability of mortar will be increased. The test results showed that the mortar flow can be improved from less than 50% to upon 90%, by using 3% of superplasticizer, with 10% of calcium hydroxide content, while remaining a high compressive and flexural strength.

Interesting research was reported by Nurrudin et al. (2011) on the influence of NaOH and superplasticizer on the strength and workability of self-compacted geopolymer concrete SCGC. It was concluded that strength and workability increased by adding superplasticizer with 6% by weight of fly ash.

2.9 Properties of Geopolymer

In the development of geopolymer materials so many researches have been performed in order to determine the physical and chemical properties of geopolymers, as well as their long-term durability. It should be reminded that the physical properties take into account the behavior of materials subjected to the effect of temperature, electric or magnetic field, or light, whereas the chemical properties characterize the behavior of materials subjected to an environment more or less aggressive. Other properties are the mechanical that reflect the performance of materials deformed by force systems. Obviously, the most properties of geopolymer will be reviewed. Especially, those that will be addressed in this thesis and brief review of other properties will be discussed.

2.9.1 Workability

Workability is one of the fresh properties of concrete that effect strength and durability, and it has effect on easy handling and compaction of concrete. Many factors affect the workability of geopolymer mortar such as water, superplasticizer, admixtures, and proportion of material by mass.

Sathia et al. (2008) stated that the workability of geopolymer will be improved by using water, as well as caused the porosity in concrete as a result of the evaporation of water during curing process at elevated temperature.

Chindaprasirt et al. (2007) concluded that flow of mortar will reduce by increasing the concentration of sodium hydroxide and sodium silicate. It was also stated that the flow of mortar in geopolymer was in the range of 110 mm ± 5 mm to 135 mm ± 5%.

Bhavsar et al. (2014) concluded that using accelerator admixture like silica fume decrease workability of geopolymer concrete.

2.9.2 Setting Time

Having knowledge of the time available to cast a geopolymer into forms is critical for successful planning and execution of a project. A standard method for measuring the available time to work with cement pastes exists (ASTM C191) and has been shown to work well for determining available working time of geopolymer pastes. Since the setting of the paste in geopolymers occurs when the rate of network growth in the geopolymer begins to exceed the rate of dissolution, the set time can also be used as a relative measure of the reaction rate.

It is well established that calcium present in the mix will result in a faster set time. A small addition of calcium into the mix will result in a large reduction in set time with further additions resulting in smaller reductions. The main reason for this is the Ca2+ ions are able to act as charge balancers in addition to the Na+ and K+ ions present in the system. A higher quantity of available charge balancers will result in faster formation of aluminosilicate networks (Fillenwarth, 2013).

A second possible explanation for the reduced set time is that calcium silicate glasses are more reactive in water compared to glasses with higher silicate concentrations (Dombrowski et al., 2007). So, as the calcium content in the base material is increased, the calcium silicate glass phases present will dissolve faster than the phases with higher silicate concentrations making the species needed for network formation available sooner. The presence of compounds other than Al_2O_3 and SiO_2 in the source material may also delay the setting (Hardjito et al., 2004).

The study done by Hardjito et al. (2008) came to conclude that the start setting time and final setting time were in the range 129 minutes and 270 minutes. It was also observed by increasing the temperature of curing, caused increase the rate of geopolymerization and it will result less setting time is required.

2.9.3 Mechanical Properties

Davidovits et al. (1988) stated that mechanical properties of geopolymer binder hardened quickly at room temperature, while the compressive strength increases up to 20 MPa after only 4 hours at 20^{o}C, and around 70-100 MPa after 28 days.

Comrie et al. (1988) following physical tests conducted on unconfined cubes made from mortar mixes of sand and geopolymer. In their research, the 40 MPa of compressive strengths was obtained over a period of 28 days of curing. Furthermore, during the first two days of curing, they were able to attain strengths of 30 MPa, which represents 75% of the final strength. Therefore, when comparing concrete mortars manufactured from ordinary Portland cement with geopolymer mortars it appeared that strengths were acquired more quickly with the latter.

According to Palomo et al. (1999), temperature is a reaction accelerator in geopolymeric binders. Geopolymer materials are likely to gain in mechanical strengths when the temperature increases. Generally, the type of activator and the temperature are important factors affecting the mechanical strengths of geopolymer materials as well as the longer the time of curing.

Joseph and Mathew (2012) demonstrated that the development in strength of geopolymer concrete at early age can be obtained by choosing the appropriate curing temperature and the curing period. They also concluded that 96.4 % of 28th day compressive strength can be achieved in 7 days' time with 24 hrs of curing at 100°C.

Hardjito and Rangan (2005) reported that splitting tensile strength of geopolymer concrete is very close to OPC concrete, it was stated that splitting tensile strength is only a fraction of the compressive strength. Also, they mentioned that the splitting tensile strength of fly ash geopolymer concrete was greater than the values recommends by Australian standards (2001).

Mishra et al. (2008) pointed out that compressive strength and split tensile strength increases with the increase of alkaline activators, curing time, and period of curing. But, at 48 to 72 hours, increase rate of strength not significant.

2.9.4 Density of Geopolymer

The density of OPC concrete mainly relies on the unit mass of aggregates utilized in the mixture. Moreover, the aggregate content, the amount of entrained air, the cement content, and water have effect on density of concrete. Density is a key to figure out how one material is compacted compared to another one, because of the different mix designs (Najmabadi, 2012).

Also, the density of geopolymer concrete depend on a unit mass of aggregate, it was found that density of low calcium fly ash based geopolymer concrete was ranged from 2330 - 2430 kg/m^3 (Hardjito and Rangan, 2005).

An investigation on the strength and density of fly ash geopolymer mortar was done by Wazien et al. (2016). In their study, it was reported that density of geopolymer mortar was in the range of 2.0 to 2.23 g/cm^3, and the density of geopolymer paste was below 2.0 g/cm^3 observed, it was also concluded that the aggregate content has effect on the density of geopolymer mortar, by decreasing level of aggregate the density of geopolymer mortar was decreased.

Kotwal et al. (2015) carried out an investigation on the characterization and early age of physical properties of class C fly ash geopolymer mortar cured at ambient temperature. It was concluded that the fresh density ranged between 2.084 to 2.254 kg/m^3, while the hardened density ranged from (2.041 - 2.220) kg/m^3, it was observed that density does not vary with the age of mortar, However high content of aggregate resulted denser geopolymer mortar.

Olivia and Nikraz (2011) wrote that density of fly ash geopolymer concrete close to normal concrete. In their study, hardened density between (2248 – 2315) kg/m^3 were obtained, which was close to ordinary concrete (2200 to 2600 kg/m^3).

2.9.5 Thermal Properties of Geopolymer

A 28-storey building caught fire and at least 42 people were killed and 90 more people were critically injured on November 15th 2010 in Shanghai, China, which aroused a great concern on the fire performance of structures. Another tragedy in this century is the twin towers in New York destroyed in 9/11 attacks, 2001. The steel building collapsed quickly within two hours in fire. Moreover, most organic matrix cannot bear the temperature more than 200^oC and will issue poison gas when on heat/fire. Therefore, there is an urgent necessity to enhance the fire/heat resistant performance of structures. Geopolymer concrete, coating, and matrix may resolve these problems. The geopolymers discovered recently are reported to possess excellent fire resistant performance due to their ceramic like characteristics and they are prepared using alkali activation and alumino-silicate raw materials.

Geopolymer binder are superior in term of the heat and fire resistance of compared to Portland cement, geopolymer materials have shown a better behavior (Davidovits, 1988 & 1994). Basically, OPC materials when exposed to temperature up to 300°C underwent rapid deterioration in their compressive strength (explode above this temperature), while geopolymeric binders remained stable at 600°C. Geopolymer cements also demonstrated extremely low shrinkage in comparison to Portland cement (Wallah and Rangan, 2006).

One application geopolymer based concretes are well suited for that Portland cement based concretes are not is in high temperature applications. Portland cement based concretes lose their entire load bearing capabilities between 300°C and 400°C. Geopolymer based concrete however doesn't start losing strength until 600°C, and gradually decreases from that point until it loses most load bearing capabilities around 1100°C (Davidovits, 2005). This particular property also makes geopolymers well suited for high temperature composite applications as well as fire insulation applications.

2.9.6 Absorption Properties of Geopolymer

Absorption properties in much circumstance are very important especially for durability criteria. Geopolymer material is superior to Portland cement with respect to water sorptivity and water absorption. Luhar and Khandelwal (2015) studied water absorption and water sorptivity of geopolymer concrete and results compared with control concrete. The results showed that the sorptivity curve is less linear as compared to that of control concrete. That means the rate of absorption of geopolymer is less. Test results of water absorption showed that the porosity of geopolymer concrete is less as fly ash is finer than OPC which resulted in less water absorption than control concrete.

Olivia et al. (2008) conducted an investigation on strength and water penetrability of fly ash geopolymer concrete, In their research, sodium based activator and fly ash were used for synthesize of geopolymer, the compressive strength test was measured to address the strength, water penetrability properties was measured by water permeability and water absorption. 100x200 mm cylinders were used for casting seven mixes, specimens were cured at 60°C for 24 hours in a chamber steam curing.

Results indicated low water sorptivity, and water absorption. It was also observed that water sorptivity and water absorption of class F fly ash geopolymer concrete are lower compared to corresponding OPC concrete mixes. Moreover, it was found that using low ratio of water to binder, and well graded aggregate have significant impact to obtain low permeability of geopolymer concrete.

Mishra et al. (2008) executed an investigation on effect of alkaline activator concentration and curing time on the strength and water absorption of fly ash based GPC. Three concentration 8M, 12M, and 16M were used for preparing nine mixes, with a curing time as 24, 48, and 72hrs. Compressive, splitting tensile strength and water absorption were measured on each of the nine mixes. Test results showed that both splitting tensile strength and compressive strength increased, by increasing the concentration of NaOH. Also, strength was increased by increasing curing time. Moreover, after 48 hours of curing, the increase in compressive strength was not significant. With curing at 60°C, the 46MPa compressive strength was obtained. The results of water absorption test indicated that by increasing the NaOH concentration and curing time, water absorption will be reduced.

Soren (2013) concluded that fly ash geopolymer mortar has very low sorptivity with high water absorption. It was found that water absorption was in the range (6.61 to 12.617%) with different parameters, in case of sorptivity, it was evaluated that sorptivity was in the range (0.000427 to 0.0007 $mm/min^{0.5}$) with different parameters, after curing at 80^{o}C for 72 hours. It was demonstrated that both water absorption and sorptivity decreased by increasing the ratio of SiO_2 to Na_2O in the range (0.8 to 1.8). It was also observed by increasing the ratio of sand to fly ash in the range (1/1 to 2/1) resulted in decrease water absorption and sorptivity.

2.9.7 Chemical Properties of Geopolymer

Besides their mechanical and physical properties, geopolymer materials have shown excellent chemical properties. Geopolymer pastes and mortars have been proven to perform adequately when exposed to sulfates, acidic media, seawater attack, and akali-silica reaction (Edouard, 2011).

Comrie et al. (1988) stated that the ability of geopolymer to resist the chemical attack can be credited to the fact that, unlike Portland cement, lime does not have an important role in the lattice structure of geopolymers.

One of the common causes in OPC concrete deterioration is the alkali-aggregate reaction, which is a chemical reaction between alkalis from the Portland cement and certain types of aggregates. Usually, this chemical reaction may be either an alkali-silica reaction or an alkali-carbonate reaction. Under specific circumstances, the result of this reaction can be damaging expansion and cracking in the concrete structure. Therefore, the absence of factors such as reactive aggregate, alkalis in the cement, calcium-rich phases can prevent the chemical process to take place.

Davidovits (1994) used the standard Accelerated Mortar Bar Test to demonstrate the alkali-aggregate resistance of geopolymeric cements compared to OPC, while using much higher alkali content for the geopolymer pastes. It was revealed that geopolymer samples to be healthy, whereas the Portland cement specimens did generate alkali-aggregate reaction.

Another appealing property of geopolymer binder depicted by past researches is its resistance to acid attack. Almost all of them asserted that alkali-activated binders performed way better than OPC when subjected to chemical aggression by acid, because of the high calcium content of OPC (Wallah and Rangan, 2006).

Also, Davidovits et al. (1999) stated only 7% mass loss in metakaolin based geopolymer, after the specimens were submerged for four weeks in 5% solution of sulfuric acid (Provis and van Deventer, 2009).

Fernandez-Jimenez et al. (2007) conducted research on the behavior of alkali-activated fly ash and OPC specimens totally immersed in HCl solution. The test results demonstrated that the specimens manufactured with the alkali-activated fly ash revealed to be healthy after 90 days of exposition to acid solutions, whereas the OPC samples were deteriorated after only 56 days of immersion.

Similarly, Bakharev (2005); Fernandez-Jimenez et al. (2007) and many other authors concluded that fly ash geopolymer mortar and paste have a reasonable performance when exposed to sulfates and seawater.

2.10 Factor Affecting Properties of Geopolymer

There are many different opinions as to which main parameters that affect the properties of geopolymer concrete. This segment presents the review of the research studies done worldwide about the factors affecting geopolymer concrete properties.

Palomo et al. (1999) stated that the curing temperature was an acceleration reaction of fly ash based geopolymers, its' substantially influence the development of the mechanical strength, with alkaline activator and the time of curing. It was also found that higher temperature curing and longer curing time were resulted in higher compressive strength.

Jiang et al. (1992) explained the reason for the need of the heat treatment is that the activation of the fly ash is an endothermic reaction so that the heat curing is very important for the geopolymerization of the fly ash based geopolymer cement.

Hardjito (2005) concluded that by increasing the concentration of (NaOH) solution in term of molar, the compressive strength of geopolymer concrete was also increased. On the other hand, Compressive strength improved by increasing the ratio of Na_2SiO_3 to NaOH by mass of geopolymer concrete. Increasing the temperature of curing from (30 to 90), the compressive strength of geopolymer concrete as well increased. Longer time of curing from 4 to 96 hours resulted in higher compressive strength of geopolymer concrete. Nonetheless, after 48 hours of curing, the increase in compressive strength was not significant. Also, they demonstrated that the addition of high-range of superplasticizer up to about 4% by mass of fly ash, the workability of fresh geopolymer improved with a little influence on the strength of geopolymer concrete at hardening stage.

Panias et al. (2007) concluded that water content is important parameter in the production of fly ash based geopolymer concrete for the mechanical strengths development. Water plays important role during dissolution. Also, water and superplasticizer have great effect on workability of geopolymer, but superplasticizer has adverse effect on compressive strength of geopolymer.

In addition, source material possesses effect on geopolymer properties. Xu and Van Deventer (2003) concluded that using different type of source material will be resulted in improving the compressive strength.

Temuujin et al. (2009) conducted that adding calcium compounds $Ca(OH)_2$ and CaO improves the mechanical strength of the fly ash geopolymers cured at room temperature (ambient curing). Adding $Ca(OH)_2$ is accounted to be a more beneficial than the addition of CaO.

De Silva (2007) conducted an experimental study on the role of Al_2O_3 and SiO_2 on the metakaolin based geopolymer, he stated that setting time will increase by increasing the ratio of SiO_2/Al_2O_3. Moreover, the ratio of SiO_2/Al_2O_3 was found out to be responsible for higher strength gain especially at later age.

According to study that was done by Xu and Van Deventer (2000) on the geopolymerization of sixteen natural Si-Al minerals, it was observed that several factors such as the percentage of, K_2O, CaO, the ratio of Si-to-Al in the source material, the extent of dissolution of Si, the molar Si-to-Al ratio in solution and the type of alkaline activator considerably impacted the compressive strength of geopolymers.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Introduction

This chapter provides the methods and details of the experimental process employed for producing fly ash based geopolymer mortar. The properties and specifications of the materials, the mixture proportions, the manufacturing and curing of the test specimens are described. It is also includes the experimental techniques, where the specimen types, the test program, and the test parameters are explained. It is to be noted that geopolymer paste is used as 100% substitution to Portland cement. ASTM standard tests performed to analyze the material properties.

3.2 Materials

The materials utilized for producing geopolymer mortar are fly ash as a source material, the combination of sodium silicate and sodium hydroxide as alkaline liquid activator, superplasticizer in liquid form for improving workability and two types of aggregate which are natural sand and crushed limestone were used as well as the combined sand which includes (50% of the natural river sand and 50% of crushed limestone).

3.2.1 Fly Ash

In the present study low calcium fly ash (ASTM Class F) from local sources was utilized as a base and a source material. Table 3.1 shows chemical and physical compositions of fly ash.

Table 3.1 Physical and chemical properties of fly ash

Physical and chemical analysis (%)	FA
CaO	2.2
SiO_2	57.2
Al_2O_3	24.4
Fe_2O_3	7.1
MgO	2.4
SO_3	0.3
K_2O	3.4
Na_2O	0.4
Loss on ignition	1.5
Specific gravity	2.25
Specific surface area (m^2/kg)	379

3.2.2 Alkaline Activator

Sodium based activator (a combination of sodium silicate and sodium hydroxide solution) was chosen as the alkaline activator for activating fly ash. Sodium activator was picked because they were cheaper than potassium activators. The sodium hydroxide in flakes or pellets in form (3mm) was used, with a specific gravity of 2.15, as well as 97% purity. Alkaline activator was purchased from local supplier (Delta kimya), Adana, Turkey.

In order to prepare sodium hydroxide (NaOH) solution, the flakes or the pellets of solid sodium hydroxide was dissolved in water. The mass of NaOH solids in a solution varied depending on the concentration of the solution expressed in terms of molar, M. For instance, NaOH solution with a concentration of 12M consisted 12x40 = 480 grams of NaOH solids per liter of the solution, where 40 is the molecular weight of NaOH. The mass of NaOH was evaluated as 361 gram per 1 kg of NaOH solution of 12M concentration.

Note that the mass of NaOH solids was only a fraction of the mass of NaOH solution, and water is the major compound.

Sodium silicate was also purchased from a Delta kimya, Adana, Turkey. The chemical composition of the Na_2SiO_3 solution was water 55.9%, Na_2O=14.7%, and SiO_2=29.4% by mass. Besides, the specific gravity=1.48, and viscosity = 400 cp at 20°C.

Figure 3.1 Preparing alkaline activator

3.2.3 Aggregate

Two types of aggregates were used as a fine aggregate locally in western part of Turkey's Southeastern Anatolian Region, Gaziantep for producing fly ash based geopolymer mortar.

3.2.3.1 Crushed Fine Limestone

Local crushed limestone consist (0 to 4) mm, four different grades of these aggregates were used. (0-4, 2-4, 1-2 and 0-1) mm were used separately for producing fly ash-based geopolymer mortar. Specific gravity of each grade was (2.53, 2.56, 2.51 and 2.48) respectively. With fineness modulus was 2.83. Figure 3.3 illustrated different grading of crushed limestone.

The physical and mechanical properties of local limestone have been reported in a previous study (Marangoz, 2005). The results are summarized in Table 3.2.

Table 3.2 Physical and mechanical properties of Gaziantep limestone (Marangoz, 2005)

Bulk density	1.42 g/cm^3 – 2.62 g/cm^3
water absorption	1.24 % – 26.89 %
Brazilian tensile Strength	0.99 MPa – 15.06 MPa
Direct shear strength	1.36 MPa – 6.20 MPa
friction angle	40^o- 57^o
Cohesion	15 MPa – 2.1 MPa
Residual friction angle	38^o - 54^o
Uniaxial compressive strength	3.75 MPa – 49.8 MPa
Young's modulus	1.76 GPa – 14.62 GPa
Ultrasonic velocity	1950 m/s – 5910 m/s

3.2.3.2 Natural Sand

Local natural fine sand comprising (0 to 4) mm, four different grades of these fine aggregates were used. (0-4, 2-4, 1-2, and 0-1) mm were used separately for producing fly ash-based geopolymer mortar, specific gravity of each grade was (2.64, 2.68, 2.62, and 2.58) respectively. With fineness modulus was 3.48, Figure 3.4 illustrated different grades of sand

3.2.3.3 Combined Sand

Combined sand includes (50% of crushed limestone and 50% of natural sand). Similarly, four grades of aggregate (0-4, 2-4, 1-2, and 0-1) mm were also used.

Table 3.3 shows particle size distribution of each type of aggregates.

Figure 3.2 shows grading curve for each type of aggregate.

Table 3.3 Particle size distribution of aggregates

Sieve Size mm	Passing %		
	Crushed Limestone	Natural Sand	Combined Sand
4	100	100	100
2	72.4	65.6	69
1	57	46	51.5
0.5	45.4	28.2	36.8
0.25	33.6	8.7	21.1
0.125	22.3	2.8	12.6
pan	0	0	0

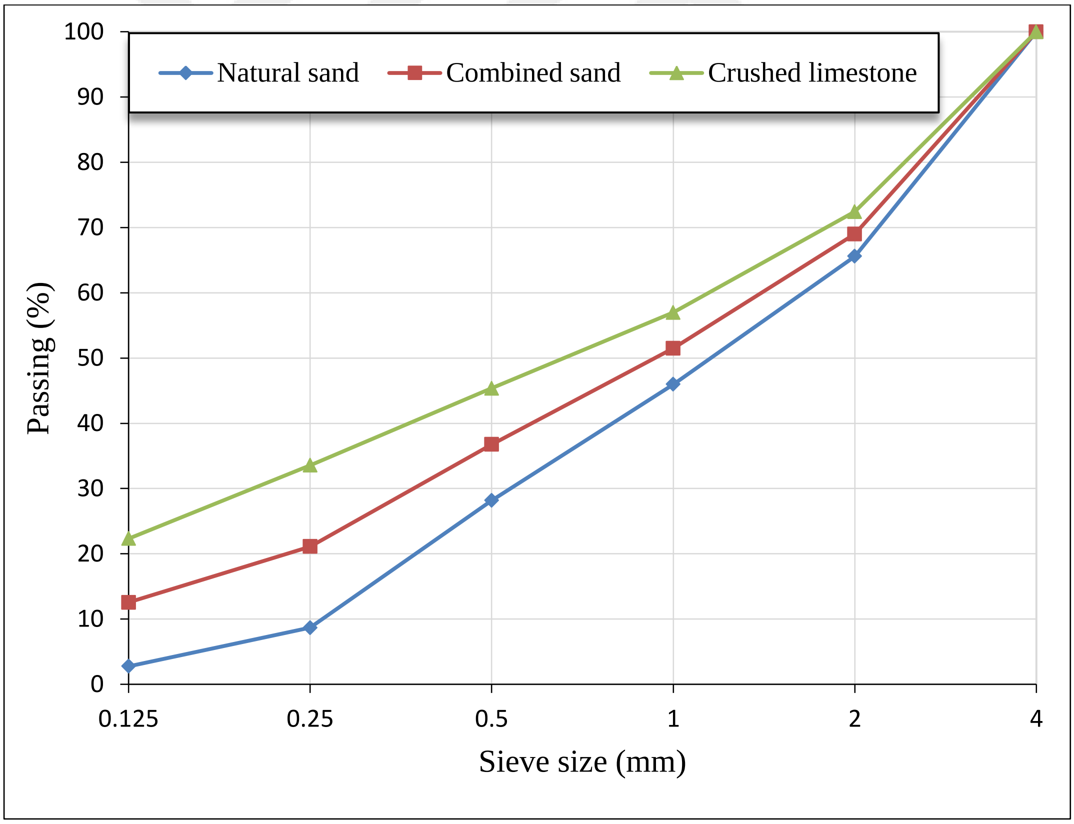

Figure 3.2 Grading curves for aggregates

3.2.4 Superplasticizer

Workability of fly ash based- geopolymer mortar was adjusted by adding (Glenium 51), and specific gravity was 1.07 as a superplasticizer in a liquid form by 6% of fly ash weight in all mixtures.

Table 3.4 Properties of superplasticizer

Properties	Superplasticizer
Name	Glenium 51
Color tone	Dark brown
State	Liquid
Specific gravity (kg/1)	1.07
Chemical description	Polycarboxilate ether

3.3 Manufacture Geopolymer Mortar

Sodium based activator was prepared by mixing sodium hydroxide and sodium silicate one day in advance to ensure it to cool down in a room at temperature (25°C)**.** Fly ash and the aggregates were first mixed together in the 2.5-litre capacity laboratory mortar mixer for about 3 minutes to ensure homogeneity of the mixture. Then, mortar mixer stopped. The liquid components that contain sodium hydroxide solution, sodium silicate, and superplasticizer were added to the dry materials and the mixing continued for further about 5 minutes to produce the fresh fly ash based geopolymer mortar as shown in Figure 3.5.

Then, the fresh geopolymer mortar was poured into 50x50x50 mm cube molds directly after mixing in to two layers, as described in the ASTM C109 standard. Moreover, for the compaction of the specimens the rod was employed, and each layer of geopolymer mortar was tamped 25 times with a rod. To remove air voids, all the cast specimens were vibrated on a vibrating table for 2 minutes.

Figure 3.3 Preparing geopolymer mortar constituents

Figure 3.4 Geopolymer mortars constituent

Figure 3.5 Adding alkaline activator to the dry components

Figure 3.6 Casting geopolymer mortars

3.4 Curing

After casting, for minimizing water evaporation, the test specimens were wrapped with vacuum bagging film at high temperature. In this study dry heat curing was used, the specimens were cured in oven dry for (90°C), for the period 24 hours.

After the curing period, the test specimens were left in the molds. Some specimens immediately after demolding cubic specimens were tested and the other specimens were left to air- dry (ambient curing) in the laboratory room at (25°C) until the day of the test.

Figure 3.7 Curing cubic specimens by oven dry

3.5 Mixture Proportion

Following Table 3.5, 3.6, and 3.7 respectively, summarized the detail of three mixtures proportions based on types of aggregate that were tried during the experimental research for producing geopolymer mortar. Main feature are:

1- In all mixtures low calcium fly ash was used (ASTM-Class F)

2-NaOH molarity was kept constant at 12 M.

3- Water just used for dissolution NaOH pellets.

4- Na_2SiO_3 /NaOH=2.5 in all mixtures.

5- Fly ash to Alkaline activator kept at (2/1) by weight.

6- Superplasticizer was kept constant at 6% in all mixtures

7- Curing temperature kept at (90°C).

8- Curing period was 24 hrs.

9- Oven dry curing was used.

Table 3.5 Mix proportions of geopolymers produced by crushed limestone aggregate

Materials	Weight (kg/m^3)			
	Mixture 1 (0-4) mm	Mixture 2 (2-4) mm	Mixture 3 (1-2) mm	Mixture 4 (0-1) mm
Fly ash	799.92	799.92	799.92	799.92
Crushed Limestone	796.61	806.06	790.31	780.87
Sodium Hydroxide Solution	114.24	114.24	114.24	114.24
Sodium silicate Solution	285.6	285.6	285.6	285.6
Superplasticizer	47.99	47.99	47.99	47.99

Table 3.6 Mix proportions of geopolymers produced by natural river sand

Materials	Weight (kg/m^3)			
	Mixture 5 (0-4) mm	Mixture 6 (2-4) mm	Mixture 7 (1-2) mm	Mixture 8 (0-1) mm
Fly ash	799.92	799.92	799.92	799.92
Natural Sand	831.24	843.84	824.95	812.35
Sodium Hydroxide solution	114.24	114.24	114.24	114.24
Sodium silicate solution	285.6	285.6	285.6	285.6
Superplasticizer	47.99	47.99	47.99	47.99

Table 3.7 Mix proportions of geopolymers produced by combined aggregate

Materials	Weight (kg/m^3)			
	Mixture 9 (0-4) mm	Mixture 10 (2-4) mm	Mixture 11 (1-2) mm	Mixture 12 (0-1) mm
Fly ash	799.92	799.92	799.92	799.92
Crushed Limestone	406.96	412.47	403.81	398.3
Natural Sand	406.96	412.47	403.81	398.3
Sodium Hydroxide solution	114.24	114.24	114.24	114.24
Sodium silicate solution	285.6	285.6	285.6	285.6
Superplasticizer	47.99	47.99	47.99	47.99

3.6 Experimental Tests for Geopolymer Mortar

3.6.1 Flow Table

In accordance to ASTM C1437, the workability of fresh geopolymer mortar determined by using flow table test shown in the Figure 3.8, the cone dimensions are bottom diameter 100 mmm, top diameter 70 mm and height diameter 60 mm. The cone is placed on a center of flow table instrument, and then mold cone filled with fresh mortar in to two layers each layer tamped 20 times with a tamper, tamping pressure should be sufficient to compact the mortar uniformly. After the top surface of mold wiped and leveled the mold instantly lifted vertically, then the flow table is dropped 25 times in 15 sec. The percentage of flow table mortar can be measured by computing four symmetrically measured diameters in two axes. Then, the flow table percentage can be founded by (long diameter minus short diameter divided by short and multiply by 100). Workability of geopolymer mortar can be classified as high, moderate, and stiff.

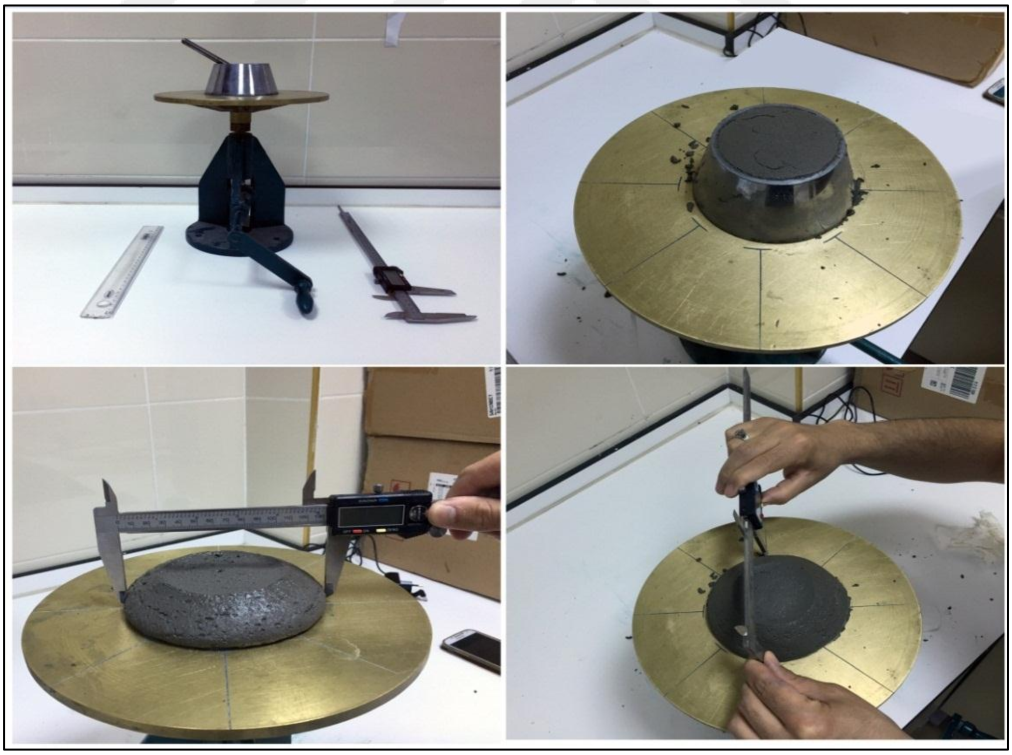

Figure 3.8 Flow table test of geopolymer mortar

3.6.2 Unit Weight

The unit weight of the concrete was measured following ASTM Cl38. The cubic mold for the unit weight test was utilized to measure the unit weight of mortar. The volume of the cubic mold was known. It was filled with freshly mixed mortar and leveled with the plainer. The weight of the empty mold and the mold filled with mortar was measured separately. The unit weight was calculated using the following equation:

$$\text{Unit weight} = \frac{Mf-Me}{V}$$

Where M_f = weight of the container full with mortar

M_e = w eight of the empty mold

V = volume of the mold

3.6.3 Compressive Strength

In the study of strength of materials, the compressive strength is the capacity of a material or structure to withstand loads tending to reduce. According to ASTM C109 for cement mortar cubes were followed. Each mix was cast into several cube molds, by filling the mold halfway and vibrating for 30 seconds, filling the mold the rest of the way and vibrating again for 30 seconds, then leveling off the top. The molds were then covered in plastic and covered again in vacuum wrapping to keep a humid environment during curing. Molds were placed in the oven at 90°C for 24 hours after mixing. A load 3000 kN capacity digital compressive testing machine as shown in Figure 3.9 with a loading rate 0.5 kN/sec was used. Three identical specimens were tested, then, the results of compressive strength were reported in a table and graphs after 24 hours of curing at 90°C, and the compressive strength at 7, 28, and 56 days age of room temperature (ambient curing) at 25°C were also presented. For each parameter investigation, three identical samples were tested in accordance with ASTM C-109 and the mean values of compressive strength are reported in relevant tables and graphs. The compressive strength of the samples was evaluated by using the following equation:

$$f_c = \frac{P}{A}$$

Where f_c is compressive strength in (MPa), P is ultimate load during the test in (N), and A = loading area in square millimeter (mm^2).

Figure 3.9 Compressive strength test

3.6.4 Splitting Tensile Strength

Hardening fly ash geopolymer mortar specimens after 24 hours curing at 90^oC, splitting tensile strength was performed on 3000 kN capacity digital machine in accordance to ASTM C37 with a loading rate 0.1 kN/sec. For every mixture three identical specimen cubic 50x50x50 mm were tested, the result value are given and was reported in various figures and graphs.

Splitting tensile strength of the specimen was calculated using the expression below

$$f_s = \frac{2P}{\pi a^2}$$

Where f_s is splitting tensile strength (MPa), P is splitting load (N), a is dimension of cubic specimen (mm)

3.6.5 Water Absorption

The main factor for evaluating the durability of concrete and mortar is permeability. The durability in mortar largely depends on ease entering and moving the liquid components through the specimen matrix. Water absorption can be described by it's the amount of water can be absorbed by materials under a specific condition. Also, it is the volume of pore space in specimen matrix that liquid components can penetrate in. Generally, water absorption test is carry out by drying a specimen to a constant mass, immersing the specimen in to the water up to fully saturation, and computing the specimen mass increases as the dry mass percentage.

Figure 3.10 Water absorption test by total immersion

In the present research, at 7 day's age water absorption of specimens have been determined. For each mix three identical specimens were dried for 24 hours at 100°C until constant mass, and then the mortar specimens were immersed in water for 24 hours to become a fully saturate, after that, the specimens wiped cleanly, and immediately, the increase in mass evaluated in a saturated-surface-dry (SSD) condition.

Water absorption can by find by this method:

Water absorption = $\frac{W2-W1}{W1}$ x100 where:

W1 is weight of specimen in grams at drying condition.

W2 is weight of specimen in grams at saturate surface condition.

3.6.6 Water Sorptivity

Sorptivity can be considered as one of the easier test for evaluating permeability of mortar/concrete. Water can penetrate into the concrete or mortar specimens by capillary suction. In addition, it can measure the rate of absorption fluid that was entering the mortar/concrete by capillary suction. Sorptivity will be determined by measuring the capillary water sorption by sorption depends on both the capillary pressure and effective porosity. Capillary pressure connected to the size of pores according to Young-Laplace equation, as well as effective porosity relate to the pore space in the gel pores and capillary according to Neville (2000). The sorptivity test evaluates the amount of capillary rise absorbed by mortar or concrete specimens. At 7 days age, for each mix, three identical specimens were dried in oven at 100°C for 24 hours, then the specimen take out in oven and their side coated with silicone sealing in order to ensure that water can ingress only in bottom of specimen, then the mortar specimens were immersed in water as shown in Figure 3.11. It should be observed that water level not more than 3-5 mm above the base of specimen. The increase in the mass gain weighted at different time intervals of the prism at 1, 4, 9, 16, 25, 36, 49, and 64. The absorbed water volume was determined by dividing the mass gained by the nominal surface area of the sample and by the water density. Then, the square root of time versus these values was plotted and the sorptivity index of mortar was calculated by the slope of the line of the best fit.

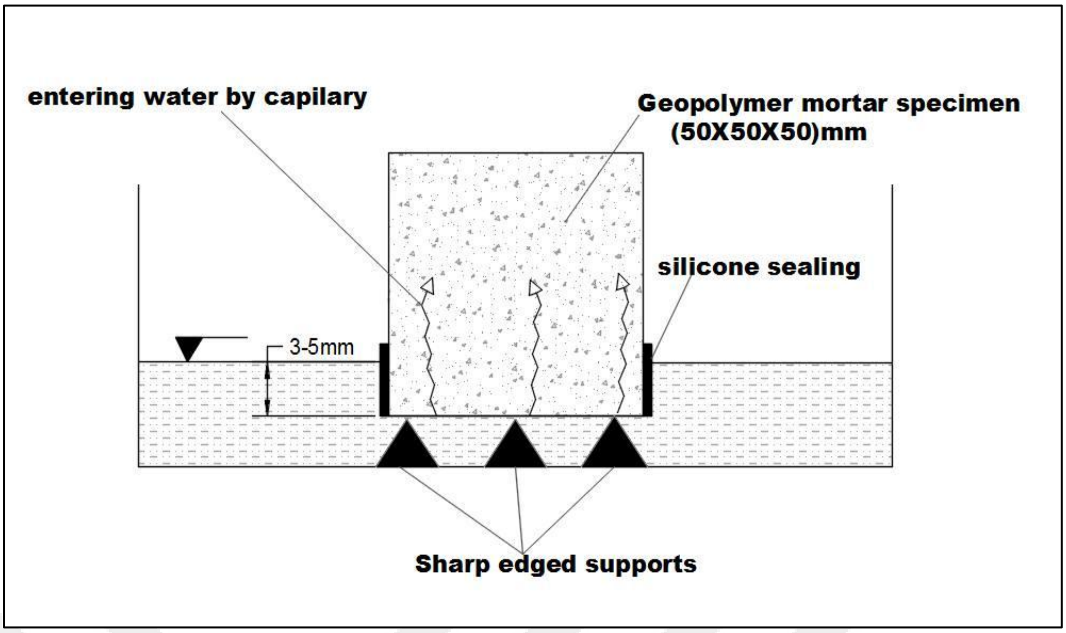

Figure 3.11 Sorptivity test for geopolymer mortar

Sorptivity can be determining by:

I= S $\sqrt{t}$

Sorptivity = I/$\sqrt{t}$

I = $\frac{(W2-W1)}{A*Dw}$

W2 is the weight of specimen after capillary suction at the end of each time interval.

W1 is oven dry weight of specimen in grams.

A is a surface area of the specimen through which water penetrated.

t is a time in minute, at which the mass is determined.

S: Sorptivity in $mm^3/mm^2/min^{0.5}$.

Dw is the density of water in g/mm^3.

Then by plotting I against $\sqrt{t}$, the sorptivity can be determined by slope index of a line of best fit.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Flow

Workability is a combination of several proportion including plasticity, consistency and cohesion. Plasticity and cohesions are difficult to measure in situ. However, consistency is frequency used as the measured of the workability. Aggregate grading and material property largely affect the workability of geopolymer mortar, in the present study several test have been carried out for finding the effect of type of aggregate and grading of aggregate of each type on the workability of geopolymer mortar, test results presented in Table 4.1 and Figure 4.1.

Table 4.1 Effect of type and grading of aggregates on flow

Mix ID	Type of Aggregate	Grading of Aggregate mm	Flow Table %
GPM 1	CL	0-4	32
GPM 2	CL	2-4	89.5
GPM 3	CL	1-2	87.5
GPM 4	CL	0-1	25
GPM 5	NS	0-4	102
GPM 6	NS	2-4	137
GPM 7	NS	1-2	127.5
GPM 8	NS	0-1	91.5
GPM 9	CS	0-4	78.5
GPM 10	CS	2-4	118
GPM 11	CS	1-2	105
GPM 12	CS	0-1	45.5

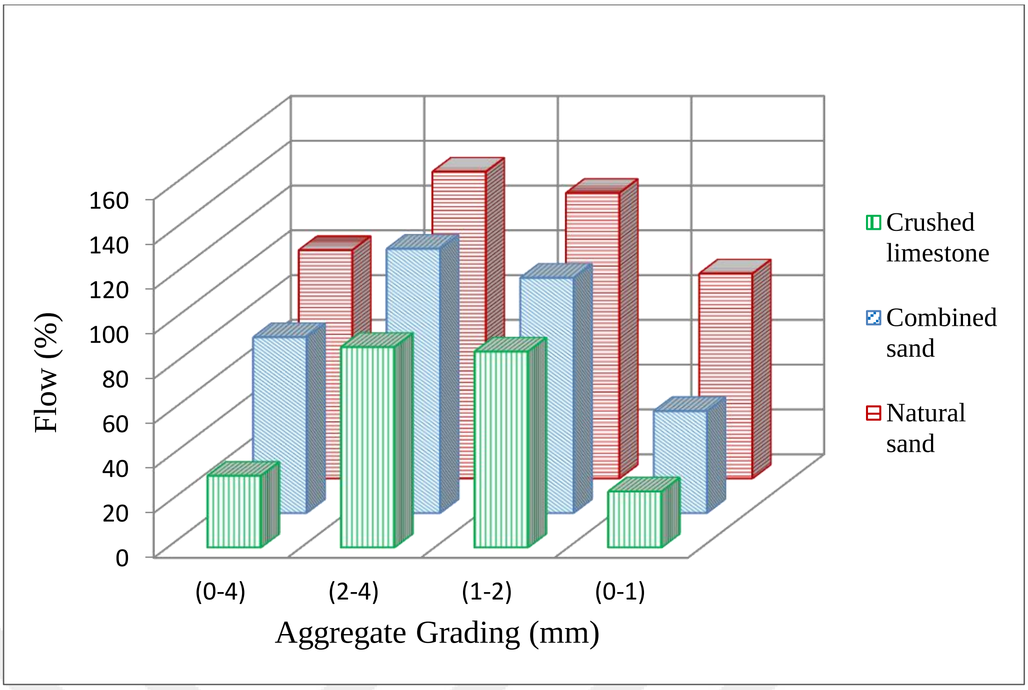

Figure 4.1 Effect of type and grading of aggregate on flow of geopolymer mortar

It was observed that all mixtures were cohesive and stiff due to having high content of alkaline activator (mixing sodium hydroxide and sodium silicate). Figure 4.1 shows that the type of aggregate has great effect on workability of geopolymer mortar, it was found that geopolymer mortar with natural sand has higher workability in comparison to other types of aggregate due to natural sand's rounded particle shape and consequently lower specific surface area. Nonetheless, grading of aggregate affected the flow of fly ash based geopolymer mortar as well. Higher flow of geopolymer mortar was obtained when larger particle size distribution (2-4) mm without depending on type of aggregate were used. Also, it was found that geopolymer mortar with finer sand (0-1) mm has a low mortar flow, it needs more alkaline activator to achieve a good flow compared to other grades because of finer sand has high surface area compared to coarse sand.

4.2 Unit Weight

Fresh unit weight of fly ash geopolymer mortar carried out directly after casting the geopolymer mortar, and hardened unit weight executed during the tests. The test results were presented in Table 4.2, Figure 4.2 and Figure 4.3.

Table 4.2 Effect of type and grading of aggregate on density

MIX ID	Type of Aggregate	Grading of Aggregate (mm)	Unit Weight (kg/m^3)	
			Fresh	Hardened
GPM 1	CL	0-4	2145.55	2054.00
GPM 2	CL	2-4	2158.88	2067.20
GPM 3	CL	1-2	2140.67	2048.00
GPM 4	CL	0-1	2124.67	2030.90
GPM 5	NS	0-4	2205.00	2112.30
GPM 6	NS	2-4	2216.00	2129.33
GPM 7	NS	1-2	2193.20	2103.24
GPM 8	NS	0-1	2178.00	2085.60
GPM 9	CS	0-4	2174.00	2089.86
GPM 10	CS	2-4	2191.33	2098.40
GPM 11	CS	1-2	2172.00	2081.07
GPM 12	CS	0-1	2161.67	2072.73

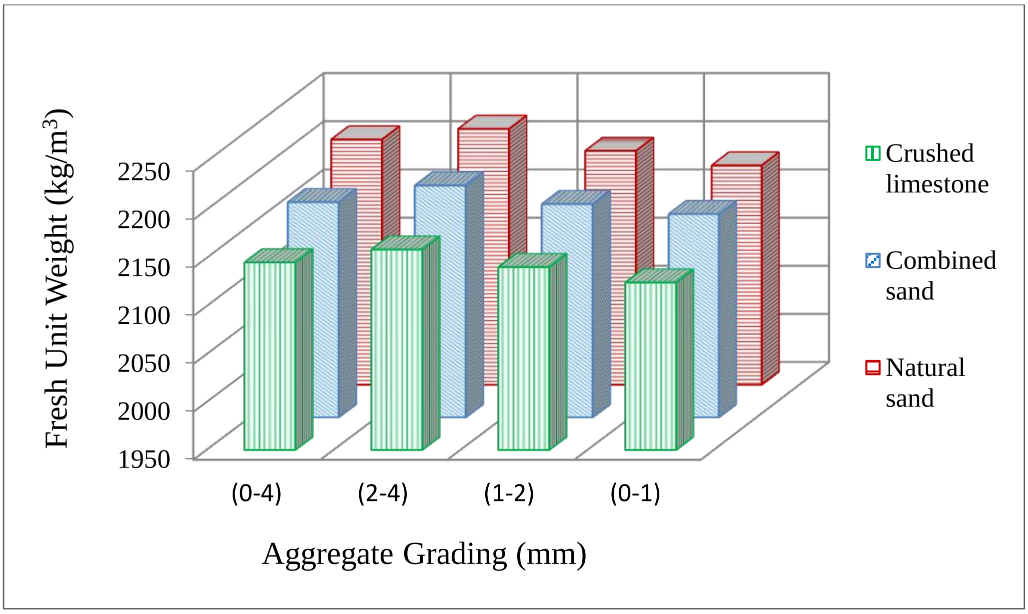

Figure 4.2 Effect of type and grading of aggregate on fresh unit weight

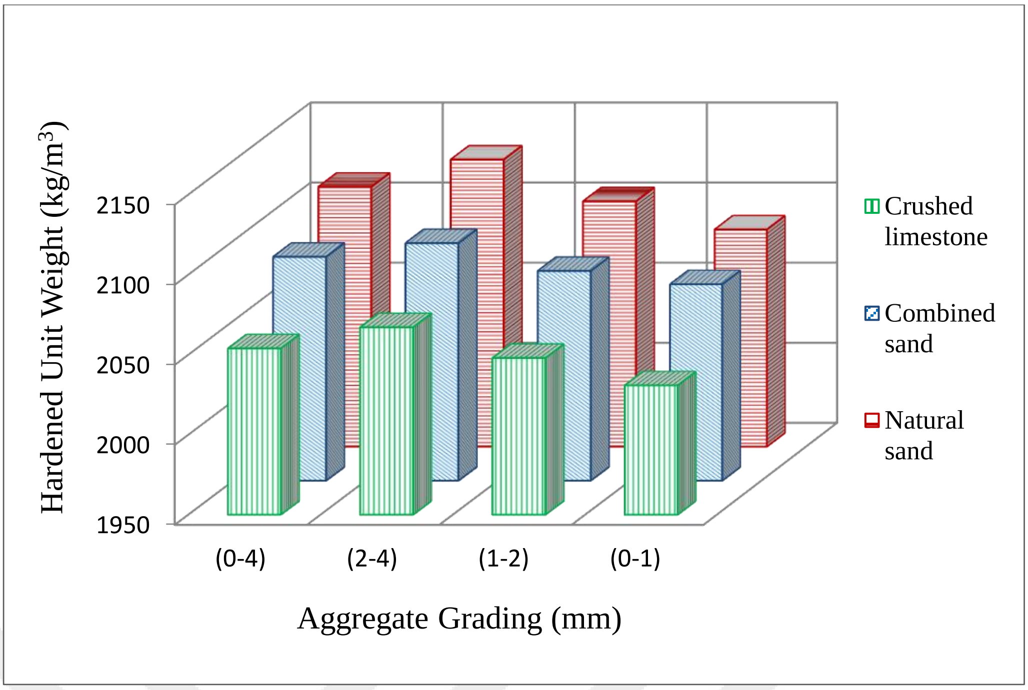

Figure 4.3 Effect of type and grading of aggregate on hardened unit weight

Table 4.2 and Figure 4.2 shown that fresh unit weight is varying because, the unit weight of geopolymer concrete and mortar are depend on the unit mass of aggregate (Hardjito, 2005). In the present study, the fresh unit weight (density) is ranged between 2216.00 and 2124.67 kg/m^3. Geopolymer mortar with natural sand has higher fresh unit weight because the density (specific gravity) of natural sand is greater than the other two aggregates. Nonetheless, aggregate grading has an effect on the unit weight of geopolymer mortar. In all type of aggregates, geopolymer mortar with the coarser sand (2-4) mm has a higher fresh unit weight compared to other grades because the specific gravity of sand (2-4) mm is greater than the other grades.

Table 4.2 and Figure 4.3 indicated that the type and grading of aggregate significantly affected hardened unit weight, ranged between 2129.33 to 2030.90 kg/m^3. Geopolymer mortar with coarser natural sand grade (2-4) has a high hardened unit weight (density), due to specific gravity of the natural sand and grade (2-4) are higher than other sands. However, geopolymer mortar with limestone and grade (0-1) has a low density due to lower specific gravity compared to the other sands.

4.3 Compressive Strength

4.3.1 Effect of Type and Grading of Aggregate on Compressive Strength

Compressive strength is considered as one of the most important properties of hardened concrete. It is generally the main property value used to investigate the quality of concrete according to ASTM C109. That is why it is important to evaluate whether changes in the mixture composition will affect the early and late compressive strength of concrete. Compressive strength results of GPM for cubic molds 50x50x50 at age 1day given in Table 4.3 and Figure 4.4.

Table 4.3 Effect of type and grading of aggregate on compressive strength at 1 day

Mix ID	Type of Aggregate	Grading of Aggregate (mm)	Compressive Strength (MPa)
GPM 1	CL	0-4	46.52
GPM 2	CL	2-4	47.83
GPM 3	CL	1-2	44.20
GPM 4	CL	0-1	40.25
GPM 5	NS	0-4	35.51
GPM 6	NS	2-4	39.37
GPM 7	NS	1-2	34.73
GPM 8	NS	0-1	28.25
GPM 9	CS	0-4	42.10
GPM 10	CS	2-4	44.93
GPM 11	CS	1-2	41.18
GPM 12	CS	0-1	38.09

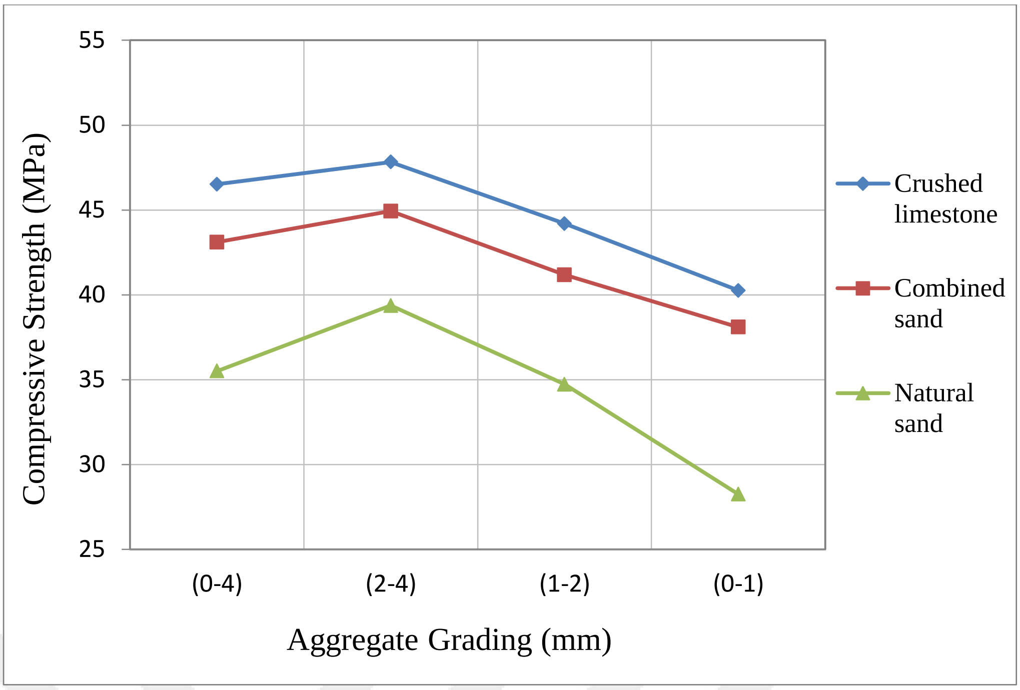

Figure 4.4 Effect of type and grading of aggregate on compressive strength at 1 day

The most important characteristic of fly ash geopolymer mortar is compressive strength (Kotwal, 2015). The results shown in Table 4.3 and Figure 4.4, compressive strength of geopolymer mortar after 1 day was in the range (47.83 to 28.25). It was observed that using crushed limestone for producing fly ash based geopolymer mortar resulted in a higher compressive strength after 1day compared to other aggregates. The reason of higher compressive strength is due to crushed limestone include much more angular which provides a higher surface-to-volume ratio leading to better bond characteristics and strong interlock between particles. However, it requires more binder to produce a workable mixture. Furthermore, in the present study results indicated that fine aggregate with a coarser grade (2-4) mm has a higher compressive strength (47.83) after 1day. Natural river sand shows lower compressive strength due to its rounded and smooth surface particles of river sand. The rounded shape of river sand causes less bonding strength with the matrix.

4.3.2 Effect of Age on Compressive Strength

Age is considered to be important to figure out the mechanical properties of fly ash geopolymer mortar over time. The chemical reaction of the high temperature-cured geopolymer concrete is considerably fast polymerization process (Davidovits, 1999; 1994). The compressive strength of geopolymer does not change with age of concrete. This observation is unlike to OPC concrete behavior, which the hydration process continues gain strength with time (Hardjito and Rangan, 2005). In the present study, several tests have been carried out to find the effect of age on the compressive strength of geopolymer mortar with different type of aggregate and with different age, the test results summarized in Table 4.4 and Figure 4.5, Figure 4.6 and Figure 4.7.

Table 4.4 Compressive strength of geopolymer mortar with different age

Mix ID	Type of Aggregate	Grading of Aggregate mm	Compressive Strength (MPa)			
			1 day	7 days	28 days	56 days
GPM 1	CL	0-4	46.52	46.80	46.85	47.10
GPM 2	CL	2-4	47.83	48.20	48.3	48.9
GPM 3	CL	1-2	44.20	44.60	44.72	44.88
GPM 4	CL	0-1	40.25	41.00	41.4	41.9
GPM 5	NS	0-4	35.51	36.48	36.9	37.15
GPM 6	NS	2-4	39.37	40.15	40.42	41.2
GPM 7	NS	1-2	34.73	35.43	35.7	36.15
GPM 8	NS	0-1	28.25	30.52	31	31.32
GPM 9	CS	0-4	43.10	43.50	43.60	43.9
GPM 10	CS	2-4	44.93	45.16	45.45	45.68
GPM 11	CS	1-2	41.18	42.18	42.5	42.9
GPM 12	CS	0-1	38.09	38.76	39.4	39.72

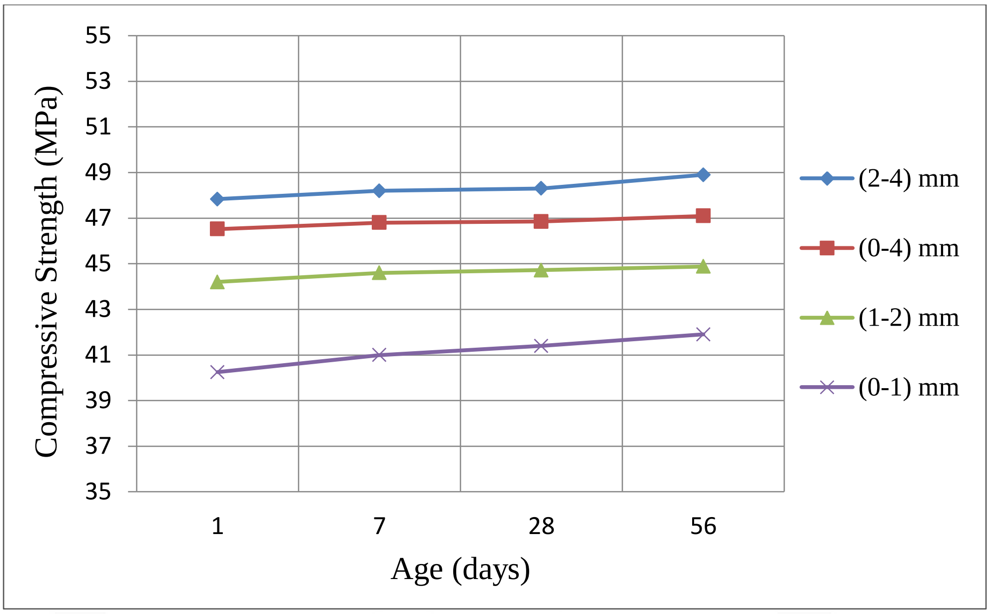

Figure 4.5 Effect of age on compressive strength of GPM with crushed limestone

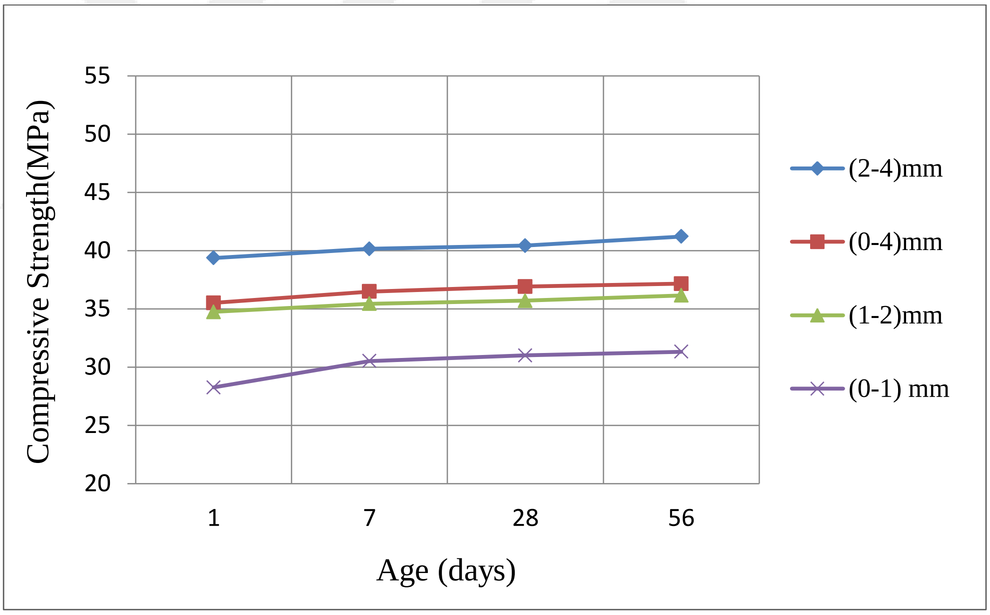

Figure 4.6 Effect of age on compressive strength of GPM with natural sand

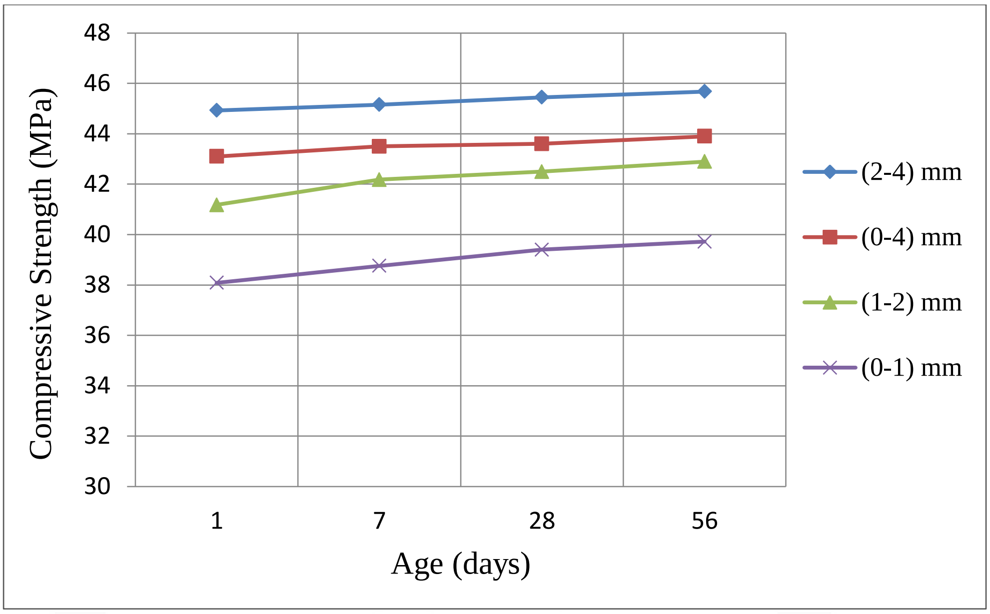

Figure 4.7 Effect of age on compressive strength of GPM with combined sand

Figure 4.5, 4.6, and 4.7, indicate that compressive strength of all types of fine aggregates and all grades slightly increase till 7 days (Kotwal, 2015). then the gain of strength in 7days to 56 days is very little, therefore, the test results confirms a good agreement of previous researches that compressive strength does not vary with age (Hardjito; Hardjito and Rangan , (2005)

4.4 Relationship between Compressive Strength and Hardened Density

The correlation of hardened density and compressive strength based on type and grading of aggregate illustrated in Figure (4.8)

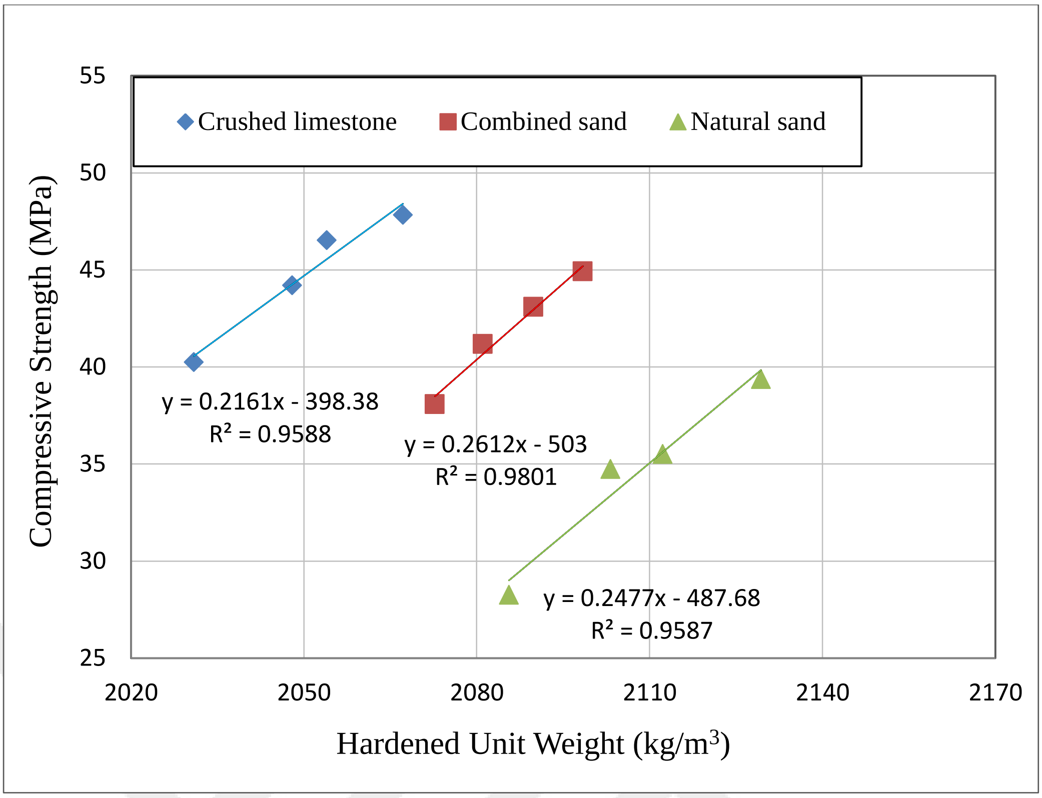

Figure 4.8 Correlation of compressive strength and hardened density

Figure 4.8 confirms that in all type of aggregate, denser material caused high compressive strength of fly ash geopolymer mortar (Kotwal, 2015). But, in case of changing the type of aggregate, the denser material does not cause higher strength because the compressive strength of fly ash geopolymer mortar depending on the bond between binder and aggregates, surface area, surface texture and angularity. Natural sand is a denser material but the bond between binder and aggregate not strong, this cause low compressive strength, differently, the density of crushed limestone is low compare to natural sand but because the bond between binder and aggregate are strong as well as high surface area and angular particles resulted in high compressive strength.

4.5 Splitting Tensile Strength

The concrete and mortar is very weak in tension due to its hard brittle nature and is not expected to resist the direct tension. The cracks of concrete improve when subjected to tensile forces. Therefore, it is needed to find out the split tensile strength of concrete for determining the load at which the members of concrete may crack. Results of split tensile strength summarized in Table 4.5 and Figure 4.9.

Table 4.5 Effect of type and grading of aggregate on splitting tensile strength

Mix ID	Type of Aggregates	Grading of Aggregate mm	Split Tensile Strength MPa
GPM 1	CL	0-4	6.83
GPM 2	CL	2-4	6.91
GPM 3	CL	1-2	6.78
GPM 4	CL	0-1	6.67
GPM 5	NS	0-4	6.49
GPM 6	NS	2-4	6.60
GPM 7	NS	1-2	6.45
GPM 8	NS	0-1	6.31
GPM 9	CS	0-4	6.64
GPM10	CS	2-4	6.70
GPM 11	CS	1-2	6.61
GPM 12	CS	0-1	6.51

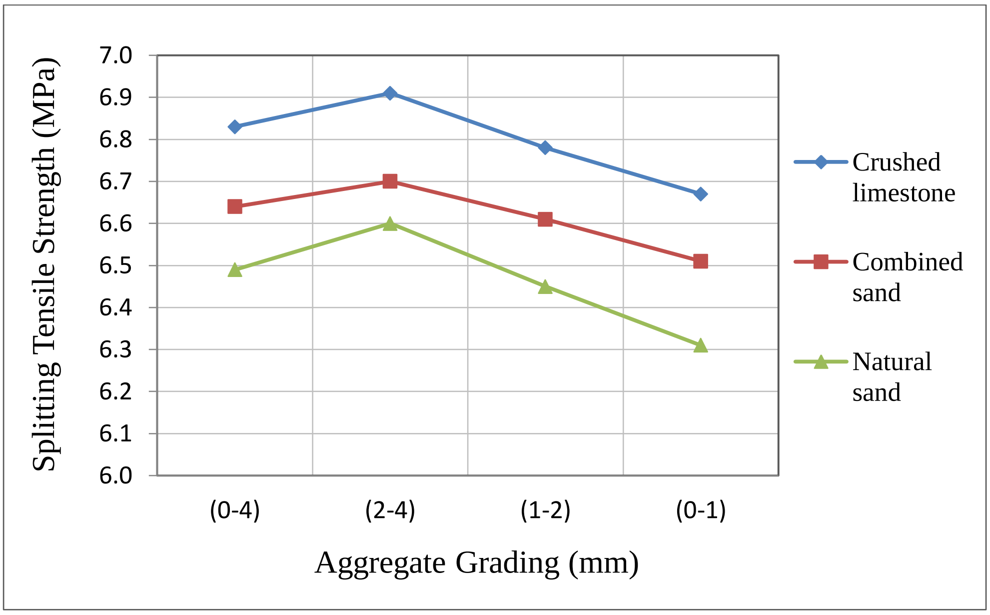

Figure 4.9 Splitting tensile strength of geopolymer mortar versus aggregate properties

Table 4.5 and Figure 4.9 show that splitting tensile strength varies when, type and grading of aggregate changes. The results shown that splitting tensile strength is higher in geopolymer mortar with crushed limestone sand followed by combined sand and natural river sand, better splitting tensile strength in crushed limestone, due to the particles of crushed limestone are angular caused a better bond between particles.

Semilarly, Kataria and Shah (2015) studied using manufactured sand as a replacement for natural sand in fine aggregate for producing concrete, they demonstrated that concrete made with manufactured sand showed higher splitting tensile strength compared to natural sand. Also, Figure 4.8 shows that coarse sand grade (2-4) mm gives higher splitting tensile strength of fly ash geopolymer mortar in all type of aggregates.

4.6 Relationship between Compressive Strength and Splitting Tensile Strength

There was a direct relationship between compressive strength and splitting tensile strength. However, more investigation is required to plot and introduce a correlation with high accuracy which was not in the scope of this research.

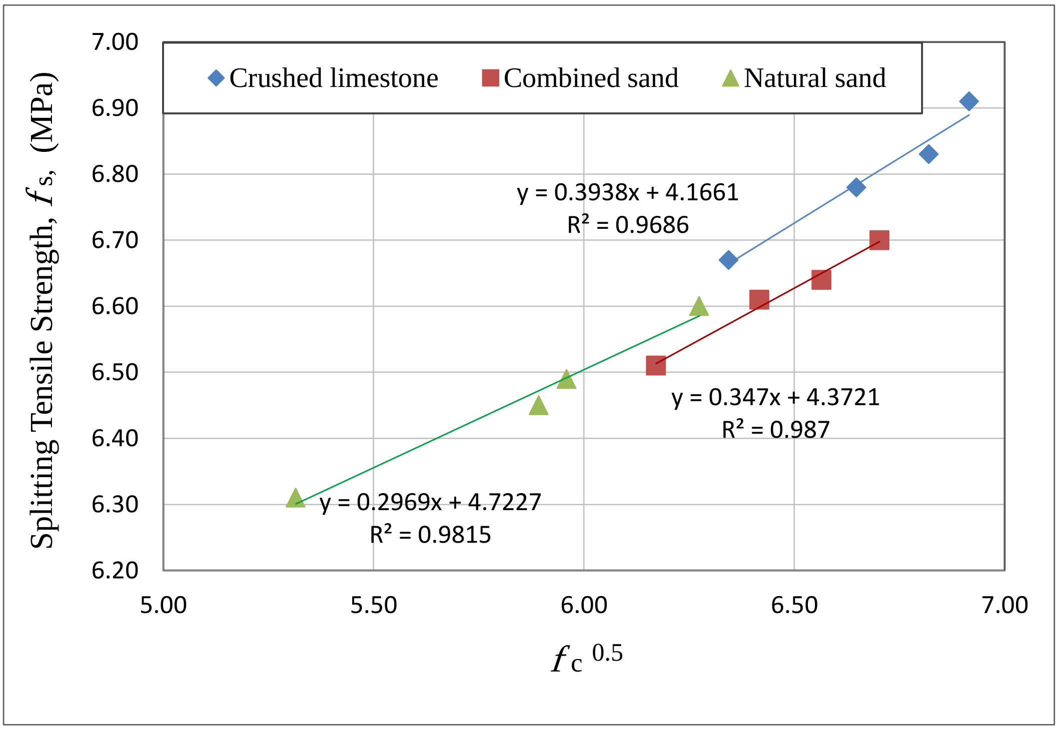

Figure 4.10 Correlation of compressive strength and splitting tensile strength

Based on the test results that shown in Figure 4.10, with the increase of compressive strength geopolymer mortar in all type of aggregate and each grade of aggregate that were used, the splitting tensile strength also increased gradually.

4.7 Water Absorption

Water absorption is amount of water can be absorbed by material. The results of water absorption test are presented in Table 4.6 and Figure 4.11.

Table 4.6 Effect of type and grading of aggregate on water absorption

Mix ID	Type of Aggregate	Grading of Aggregate mm	Dry Unit Weight kg/m^3	Saturated Unit Weight kg/m^3	Absorption %
GPM 1	CL	0-4	1907.40	2075.5	8.81
GPM 2	CL	2-4	1932.43	2103.67	8.86
GPM 3	CL	1-2	1922.33	2097.00	9.09
GPM 4	CL	0-1	1901.12	2083.50	9.59
GPM 5	NS	0-4	1959.60	2149.33	9.68
GPM 6	NS	2-4	1999.13	2194.33	9.76
GPM 7	NS	1-2	1978.20	2175.93	10.05
GPM 8	NS	0-1	1927.86	2136.10	10.80
GPM 9	CS	0-4	1945.40	2102.00	8.05
GPM 10	CS	2-4	1980.67	2141.43	8.12
GPM 11	CS	1-2	1939.73	2106.00	8.57
GPM 12	CS	0-1	1925.00	2099.00	9.04

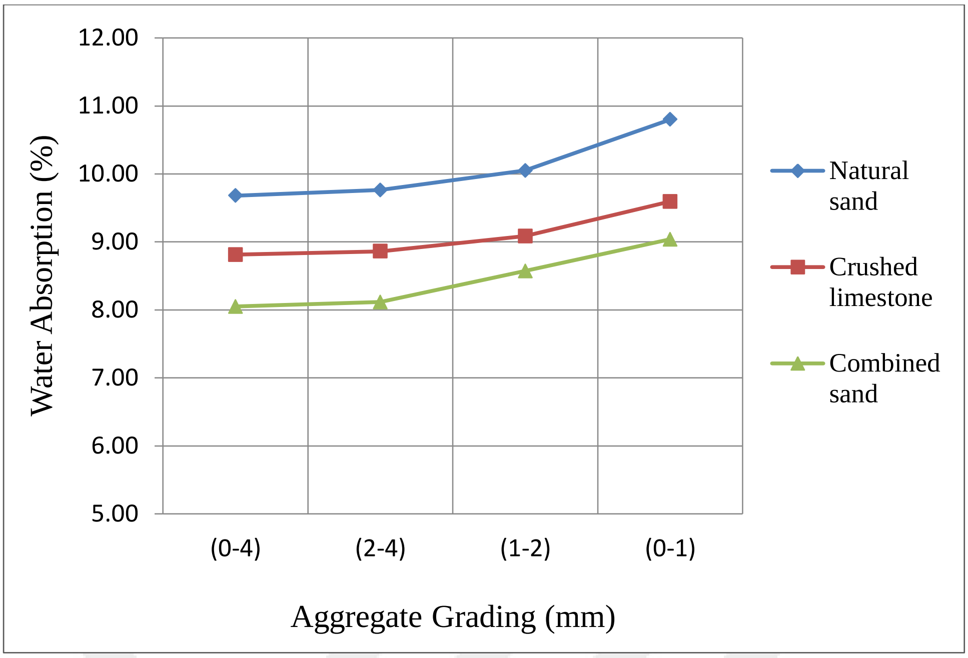

Figure 4.11 Effects of grading and type of fine aggregate on water absorption

Table 4.6 and Figure 4.11 show that water absorption of geopolymer mortar was in the range 8.05 to 10.80%. Better results was found in geopolymer mortar with combined aggregate (crushed limestone 50% and natural sand 50%) has lower values in comparison to others, ranged between (8.05 to 9.04%). The possible reason for this decrease may be due to the water absorption depending on the porosity of the mortar. When crushed limestone mixed with natural sand, which contain high amount of finer particles lead to reduce the spaces between particles and the pores become less and pore sizes decreases. Moreover, the workability of combined aggregate mortars are better as a result of the fact that alkaline activator disperse among particles.

It was also observed that grading of aggregate effect the water absorption of geopolymer mortar, grade (0-4) mm of aggregates shows less water absorption of fly ash based geopolymer mortar compared to other aggregates, due to grade (0-4) mm is uniformly graded, it has a lower void content than single-sized aggregate due to proper particle packing.

Irrespective to type and grading of aggregate, the results of water absorption was shows a good agreement with a research by Soren (2013), he concluded that water absorption was in the range 6.61 to 12.617% with different parameters.

4.8 Water Sorptivity

The sorptivity of a mortar is a measure of the rate of water absorbed by mortar over a time period of determined time. Specifically, it is the gradient of the straight line fitted to the plot of water absorbed by the mortar unit against the square root of time. A major objective in the development of the sorptivity test was to better account for the critical period in mortar bond development, namely the first few minutes when the free water in the mortar can migrate to the pores carrying the early hydration products (Goodwin and West, 1982). This process cannot continue for the 24 hours allowed for in the total absorption test, nor can it be represented by a 1 minute time period of the IRA test (RedaTaha et al., 2001). Results of sorptivity tests are summarized in Table 4.7. The plot of sorptivity versus grading and type of aggregate is shown in Figure 4.12.

Table 4.7 Effect of type and grading of aggregate on water sorptivity

Mix ID	Type of Aggregates	Grading of Aggregate mm	Sorptivity (mm/min$^{0.5}$)
GPM 1	CL	0-4	0.0240
GPM 2	CL	2-4	0.0244
GPM 3	CL	1-2	0.0246
GPM 4	CL	0-1	0.0251
GPM 5	NS	0-4	0.0253
GPM 6	NS	2-4	0.0256
GPM 7	NS	1-2	0.0258
GPM 8	NS	0-1	0.0262
GPM 9	CS	0-4	0.0222
GPM10	CS	2-4	0.0224
GPM 11	CS	1-2	0.0227
GPM 12	CS	0-1	0.0233

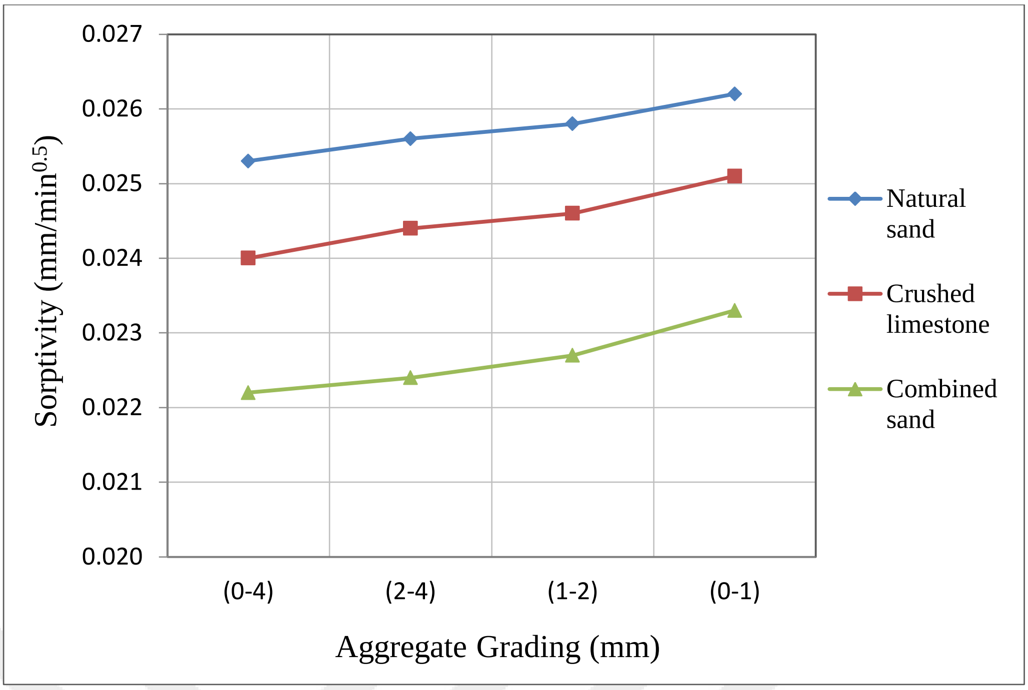

Figure 4.12 Effect of type and grading of aggregate on sorptivity

Figure 4.12 shows that fly ash based geopolymer mortar has very low water sorptivity for all type of mortars without depending on the type and grading of aggregate. The values are ranged between' (0.0222 to 0.0262) mm/min$^{0.5}$. Geopolymer mortar with combined sand shows better result (0.0222 to 0.0233) mm/min$^{0.5}$, compared to others. Better results may be attributed to their denser structure which was obtained from filling of the pores by various size particles. Furthermore, the aggregate grading (0-4) mm had better results in all types of sand, this may be due to grade (0-4) mm has all sizes of particles and more fines fill the pores.

Irrespective the type and grading of aggregate, the sorptivity results were low compared to cement mortar and concrete.

Similarly, Soren (2013) concluded that that fly ash geopolymer mortar has very little water sorptivity ranged between (0.000427 to 0.0007) mm/min$^{0.5}$, with different parameters.

CHAPTER 5

CONCLUSION

The primary focus of this thesis is to evaluate the strength and absorption of fly ash based geopolymer mortar experimentally. By utilizing three types of aggregate including natural river sand, crushed limestone, and combined sand (50% natural river sand and 50% crushed limestone) different mixtures of geopolymer mortars were produced. Four grades (0-4, 2-4, 1-2, and 0-1) mm for each type of aggregate were also used.

By analyzing and comparing the behavior and properties of each types of aggregate, it was observed that:

1. Type of aggregate shows great effect on flow table test results of geopolymer mortar. Using crushed limestone resulted in low mortar flow while combined sand shows better flow. On the other hand, geopolymer mortar including natural sand shows better flowability compared to ones with other aggregates. The effect of grading was also verified experimentally. Differences in grading resulted in differences in flow, coarse grading of sand caused higher flow as a result of lower specific surface area.

2. The highest compressive strength of geopolymer mortar (47.83 MPa) was obtained in crushed limestone and grade (2-4) mm after 1day of curing, and the lowest compressive strength (28.25 MPa) was observed in natural river sand and grading of (0-1) mm.

3. The effects of age on the compressive strength of the geopolymer mortar are different from those of the OPC. It was found that the geopolymer mortar, actually possesses high early compressive strength, and in all type of sand aggregate does not vary with age.

4. According to the results, the splitting tensile strength is only a fraction of compressive strength in all types and all grades of each aggregate. It was observed that splitting tensile strength gradually increased with the increase of compressive strength.

5. Based on the results, the combined sand which includes (50% river sand and 50% crushed limestone) shows less water absorption than other aggregates, it was also stated that grade (0-4) mm has low water absorption compared to other grades in each type of aggregate.

6. Water sorptivity in geopolymer mortar for all type of sand aggregate is very low compare to OPC Concrete and mortar, combined sand shows very low sorptivity, Also, the grading 0-4 mm shows less sorptivity than the other grades in all type of aggregate.

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