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ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

EFFECTS OF PUMICE AS A PARTIAL REPLACEMENT ON THE PERFORMANCE OF PERVIOUS CEMENT CONCRETE

By

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A Thesis

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The undersigned have examined the thesis entitled '**Effects of Pumice as a Partial Replacement on the Performance of Pervious Cement Concrete'** presented by **Abel Wube** , a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

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ABSTRACT

Pervious cement concrete pavement is an innovative pavement system, which have the ability to drain water and absorb traffic noise generated by tyre-pavement interaction. Its use in parking lots, walkways and low traffic zone pavements has been promising in the past. The main feature that differentiates pervious cement concrete from any other mixes is, its large interconnected pores measuring up to 35% of the total volume of concrete. Despite the effectiveness of these large interconnected pores to drain water and absorb noise, their negative effect on strength is significant. Therefore strength and permeability are of special properties that need to be balanced.

Whether conventional dense graded concrete or pervious concrete, the structure of the aggregate to cement matrix remains the same i.e. aggregate, hardened cement paste (hcp) and interfacial transition zone (ITZ) are the main components. ITZ is the weakest in the solid system of pervious concrete and is a region where crack initiation and propagation occur with less energy. Therefore, a mechanism to increase the strength of ITZ i.e. which can be taken as the whole concrete system shall be devised.

Little research has been conducted that characterizes the performance of grounded pumice (GP) on pervious concrete. In this research, the performance of GP as OPC replacement is investigated. The characterizations are done using compressive, splitting tensile strength, permeability, hardened density and porosity tests. The experiment is designed by preparing control mix containing 100% OPC and the experimental mix that contains 5%, 10%, 15%, 20%, 25% and 30% GP. Tests are conducted at the ages of 3,7,28 and 56 days.

Based on the experimental investigations, GP has resulted an increase in compressive and splitting tensile strength up to 11% and 26%, respectively. It is also found that, GP can partially replace OPC up to 15%. The optimum replacement level both for strength and permeability is found to be 5%. The ideal porosity that reconciles hydraulic conductivity and strength is found to be 17%. The high water demand by addition of GP has also been mitigated by proposing consistency driven water demand for pervious concrete mixes containing GP.

Key words: Consistency Driven Water Demand, Grounded Pumice, hcp, Hydraulic Conductivity, ITZ, Pavement, Pervious Concrete, Pozzolanic Materials

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A page dedicated to:

Eng. Ephrem G/Egeziabher

(Great academician and practitioner)

ACRONYMS AND NOTATIONS

A	Cross sectional area
ACI	American Concrete Institute
Al_2O_3	Aluminum Oxide
ASTM	American Society of Testing Materials
b	Solid volume of coarse aggregate in a unit volume of concrete
b/b_o	Dry-rodded volume of coarse aggregate in a unit volume of concrete
b_o	Solid volume of coarse aggregate in a unit volume of coarse aggregate
C	Cement Content
CA	Coarse Aggregate
$Ca(OH)_2$	Calcium Hydroxide or Portlandite
C-A-H	Calcium Aluminate Hydrate
CaO	Calcium Oxide
CO_2	Carbon di-oxide
C-S-H	Calcium Silicate Hydrate
Cukα	Copper radiation source
d	Inter-planer spacing
D	Diameter
E_{ITZ}	Modulus of Interfacial Transition Zone
E_{MTX}	Modulus of Cement Matrix
FA	Fine Aggregate
F_{crit}	Critical Force
Fe_2O_3	Iron Oxide
ft	Feet
gm	Gram
GP	Grounded pumice
GPP	Grounded pumice powder
H_2O	Water
hcp	Hardened Cement Paste
hkl	Lattice parameters

h_1	Depth of water column measured from the top of the stand pipe before opening of the valve
h_2	Depth of water column measured from the top of the stand pipe after an elapsed time ‘t’
ITZ	Interfacial Transition Zone
Kg	Kilogram
K	Hydraulic conductivity
K_2O	Potassium Oxide
L	Length
LAA	Los-Angeles Abrasion and attrition test
LEED	Leadership in Energy & Environmental Design
LoI	Loss on Ignition
m	Meter
m^3	Square meter
m^3	Cubic meter
Mm	Thousands of a meter
MgO	Magnesium Oxide
MnO	Manganese Oxide
MPa	Mega Pascal
MTD	Maximum theoretical density
n	Order of reflection
Na_2O	Sodium Oxide
OPC	Ordinary Portland Cement
P_2O_5	Phosphorous Oxide
PAI	Pozzolanic Activity Index
PC	Pervious Concrete
PCC	Pervious Cement Concrete
PCCP	Pervious Cement Concrete Pavement
PDF	Powder Diffraction File
PONCKS	Partial or No Known Crystal Structure
PPC	Portland Pozzolanic Cement

PSD	Particle size distribution
PVC	Poly-Vinyl-Chloride
Q	Discharge collected
Ra	Roughness of aggregate
R_a	Corrected hydrometer reading
r_{Agg}	Radius of Aggregate
SAI	Strength Activity Index
SCC	Self-compacting Concrete
SCM	Supplementary/ Sustainable Cementitious Materials
SiO_2	Silicon di-oxide
SSD	Saturated Surface dry condition
TiO_2	Titanium Oxide
t	Elapsed time between the opening and closure of the valve
UTM	Universal Testing Machine
V_a	Volume of aggregate
V_c	Volume of cement
V_{FA}	Volume of fine aggregate
V_p	Volume of paste
V_S	Volume of solids
V_w	Volume of water
W/C	Water to cement ratio
w/b	Water to binder ratio
W_{FA}	Weight of Fine aggregate
W_w	Weight of water
XRD	X-ray Powder diffraction
℃	Degree Celsius
θ	Angle of Incidence
λ	Wave length
μm	Millionth of a meter
Δh	Head loss

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CHAPTER ONE

1. INTRODUCTION

1.1 Background of the study

In recent years, the use of pervious cement concrete pavement has been increasing around the globe. The high water percolation rate makes it environmentally friendly and able to decrease flooding on urban streets. This unique property of draining water makes it different from the conventional dense graded cement concrete pavement. This property is imparted because of the high void content. The void content is in the range of 15-35% of the total volume (Boniceli, et.al , 2016).

Researches made on pervious cement concrete pavement uses 5 up to 10 % of fine aggregate from the total coarse aggregate mass (Rangelov, et.al, 2017). This is because of the need to not affect the permeability of the pervious cement concrete mix. Such great care restricts the use of fine aggregates to enhance the mechanical stregth of the porous cement concrete mixes. Previous research are made with natural river sand as a fine aggregate or other supplementary cementitious materials (SCM). Some researchers extend the proportion to 50%, although the effect of reduction in permeability is obvious.

Hypothetically, concrete mix (whether it is the conventional one or pervious mix) can be modeled as a whole mass containing hardened cement paste (hcp), aggregate particles (the coarse and the fine one) and the interfacial transition zone. As conventional concrete behaves, pervious concrete also is weak in the interfacial transition zone (ITZ). The zone is composed of the calcium hydroxide $Ca(OH)_2$ and ettringite needles. It is due to this structures that the weakness emanates in low to middle strength concretes.

There are different methods of increasing the mechanical properties of ITZ, for example, the influence of surface roughness in conjunction with SCM and latex has been investigated by Qudoos, et.al , (2018). The resulting mixes were subjected to tests of micro-hardness and compressive strength. What has been found is that, the micro-hardness and the compressive strength of the specimens made by the rough aggregates in the plain mix (with no SCM) has increased the compressive strength and the micro-hardness of the mixes. The reason being, the enhanced mechanical strength of the aggregate and cement interface, ITZ.

The use of pozzolanic materials is also implemented on conventional and other types of mixes. Many researches have shown that, the use of pozzolanic materials will enhance the properties of concrete up to a limited percent of replacement. Those properties are the fresh and hardened properties. For example, the use of pozzolanic materials has proven to decrease the workability of fresh mix. This is because of, as in grounded pumice, for example, is the porous and rough surfaces of the particles those demanding high amount of water than their OPC counterparts (Karatas, et.al 2017).

The hardened properties including the compressive, the modulus of rupture and durability are also affected sometimes positively and sometimes negatively. Compressive strength, for example, has been observed to increase or remains equal compared to the control mixes in conventional dense concrete. This increase in strength has been observed mostly after long term curing. But in other special types of concrete, such as SCC and light weight concrete containing pozzolans as light weight aggregates, a slight decrease in strength was observed (Hossain & Anwar, 2004). Durability, resistance to sulfate attack and retention of weight is also positively affected for all concrete types. Therefore use of pozzolanic materials makes them one of the choices for enhancing different properties of concrete.

Pozzolanic materials, such as grounded pumice, GP, mainly contains siliceous compounds ,66 % as in the SiO_2 content of the GP used in this research. This compounds will enable these pozzolanic materials to form additional C-S-H and C-A-H structures, those increasing the long term strength. Their use in conventional and other special types of concrete has been extensively studied. But limited research is available for their use in pervious cement concrete mixes. The researcher of this thesis argument is that, since the overall structure remains the same for all concrte mixes i.e. all concrete mixes whether conventional, SCC and light weight concrete contains three distinct structures, the aggregate, the hcp and the ITZ, we can use grounded pumice for pervious concrete mixes to enhance properties.

The methodology emloyed is that, first the materials used in the mix design are characterized with their physical properties such as gradation, absorption, density and chemical compostion.

Then mix was designed to contain control mix with 100% OPC and experimental mix containing 5%,10%,15%,20%,25% and 30% GP. The tests conducted are compressive, splitting and hydraulic conductivity. The hydraulic conductivity of the pervious mix is measured using laboratory made falling head permeability apparatus.

The application of GP in replacing the OPC was done by grounding the pumice to fine level by using LAA machine and sieving using 75 μm sieve and using the passing material to replace OPC. Then strength activity index of the mix was checked and was comapred to applicable standards. The tests were conducted after curing periods of 3, 7, 28 and 56 days.

Microstructural analysis, using XRD, on the grounded pumice, hardened cement paste from control mixture and hardened cement paste from expermental mixture was conducted. Because of the absence of all inclusive data base (PDF), detailed quantificaton of chemical composition was not done. But the angle of diffraction and major chemical components are analyzed. The result is presented in Annex G.

The main findings of the research are the application of grounding mechanism of pumice stone to fine level of upto 3,533 cm^2/gm, the establishment of optimum replacement level of GP for tensile, compressive and hydraulic conductivity requirements, the use of cement consistency driven water demand for concrete mixing and the investigation of different relationships among properties.

1.2 Statement of the problem

In the design of mixes for pervious cement concrete there exists a tradeoff between strength and permeability properties (Alireza J. , et.al , 2015). When the fine aggregate content increases in pervious cement concrete mixes, it has been shown that, the permeability of the mix decreases significantly (Mohammed, et.al, 2016). ACI (2010) states the challenge in pervious concrete mixture as, achieving a balance between an acceptable percolation rate and an acceptable compressive strength.

It has also been observed that the addition of fines has increased the strength and durability of mixes. For example, addition of fine aggregate less than 2.4mm can increase the strength and durability of pervious cement concrete mixes (Mohammed, et.al, 2016).

The addition of fine aggregates has also been shown to decrease the hydraulic conductivity of pervious mixes. Therefore the use of fine aggregates in pervious mixes has been restricted. ACI, for example, has only fine aggregate replacement level of up to 20% in its mix design table.

Concrete on its hardened state can be modeled as a system comprising three components 1) the hcp 2) aggregates in general and 3) the ITZ. From those components the weakest one that needs improvement is believed to be the ITZ (Illston & Domone, 2002). Several methods have been implemented to enhance the properties of this zone. Use of rough aggregates, addition of geo-polymers and fibers, admixtures and use of SCM especially mineral admixtures are some of them. Their effectiveness depends on several parameters. Economy and strength being prominent factors, recently an environmental aspect has also been considered including CO_2 emissions.

Pervious concrete is no exception. Having little or no fines its strength is low compared to the conventional concrete. Therefore, this has to be mitigated. In this research, the replacement of pozzolanic material, specifically GP, will be investigated to resolve the problem. Two hypotheses will emerge at this stage:

1) Addition of Grounded pumice will either have comparable effect or reduced effect i.e. affects the properties of the mix negatively or,
2) Addition of Grounded Pumice will enhance the properties of pervious mixes i.e. affects the properties of the mix positively.

Additionally, this research will try to address the problem of alternative pavement system in the city, Addis Ababa, for low traffic zones. The major pavement systems that are used are asphalt concrete pavement and conventional dense graded cement concrete pavement. Those are used for all traffic classes. This will lead to intense amount of runoff on cities. Therefore, though not the direct aim, the research will try to point out the application of pervious cement concrete pavement (PCCP) in mitigating the existing problem.

Using only OPC as a binding material has also disadvantages. One of them is environmental. The consumption of energy during cement production subsequently the emission of CO_2 has increased the greenhouse gasses. Studies have shown that, for every tons of concrete produced a ton of CO_2 will be emitted (Mathew, 2017).

Therefore, alternative/ the one that replaces binding material/cement should be incorporated in our mix designs. Pervious concrete, being environmentally friendly from the start, it will be more eco-friendly if mineral admixtures such as ground pumice replace the OPC.

The research questions are:-

1) What is the general effect of grounded pumice powder in pervious cement concrete when used as partial replacement of Ordinary Portland Cement?
2) What is the optimum range of replacing grounded pumice to be used in pervious cement concrete to enhance strength?
3) What is the effect of partially replacing OPC with grounded pumice in terms of permeability?
4) How much of a storm will be drained per unit area of pervious cement concrete pavement? or what is the contribution of PCCP in storm water reduction?

1.3 Research objectives

1.3.1 General Objectives

The main goal of this research is to characterize the performance and behavior of pervious cement concrete by the application of grounded pumice as partial replacement of OPC. Introducing pervious cement concrete pavement for mitigation of storm water flooding in streets of the city, Addis Ababa, is also considered in circuitous manner.

1.3.2 Specific Objectives

The specific objectives of the thesis that the research is sought to answer are:-

1. to investigate the effects of grounded pumice powder in physical properties of pervious cement concrete,
2. to examine the effect of grounded pumice in compressive and splitting tensile strength of pervious cement concrete. i.e. to develop the optimum range of replacement of grounded pumice powder in pervious cement concrete.
3. to measure the hydraulic conductivity of pervious cement concrete containing grounded pumice.

4. to propose an alternative pavement material in storm water management and/or drainage problem.

1.4 Scope and limitations

The research covers the assessment of the performance of pervious concrete mix. The main interest of the study is to investigate the application of grounded pumice powder in pervious cement concrete mixes. The performance of the pervious mix made from grounded pumice powder is quantified using tests such as compressive strength test, splitting tensile strength test and permeability tests.

In this research, the mitigation of weakness of the interfacial transition zone is believed to be enhanced by the reinforcement of additional strength imparted due to rough faces of the ground pumice powder particles and additional strength due to pozzolanic activity i.e. C-S-H and C-A-H formation.

The limitation of this study emanates from the laboratory equipment, instrument and duration of the study. For example, fatigue performance and durability tests are rarely available and has not been assessed.

Additionally the limited number of researches made on pervious cement concrete, such as its characterization, made the study to be restricted to assessing the effect of grounded pumice powder in compressive, tensile and permeability characters of the mix.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Concrete

In a simple and precise word, concrete is an artificial stone. In its simplest form, concrete is a mixture of cement, water and aggregates in which the cement and water have combined to bind the aggregate particles together to form a monolithic whole.

Concrete properties that are important are the fresh properties and the hardened concrete properties. According to Illston & Domone (2002), those properties are complicated due to the following factors:

- the addition of materials for property modifications,
- the need to transport concrete from material of production to the area of pouring,
- the extended period of chemical reaction, as strength development, for example, the 50-60% of the ultimate strength develops within 7 days and 80-85% within 28 days,
- durability of concrete and reinforcement, if any.

Accordingly, the behavior of concrete depends on the individual ingredients and the components that they eventually create in the reaction process. In the following sections a brief investigation into the component of concrete is presented.

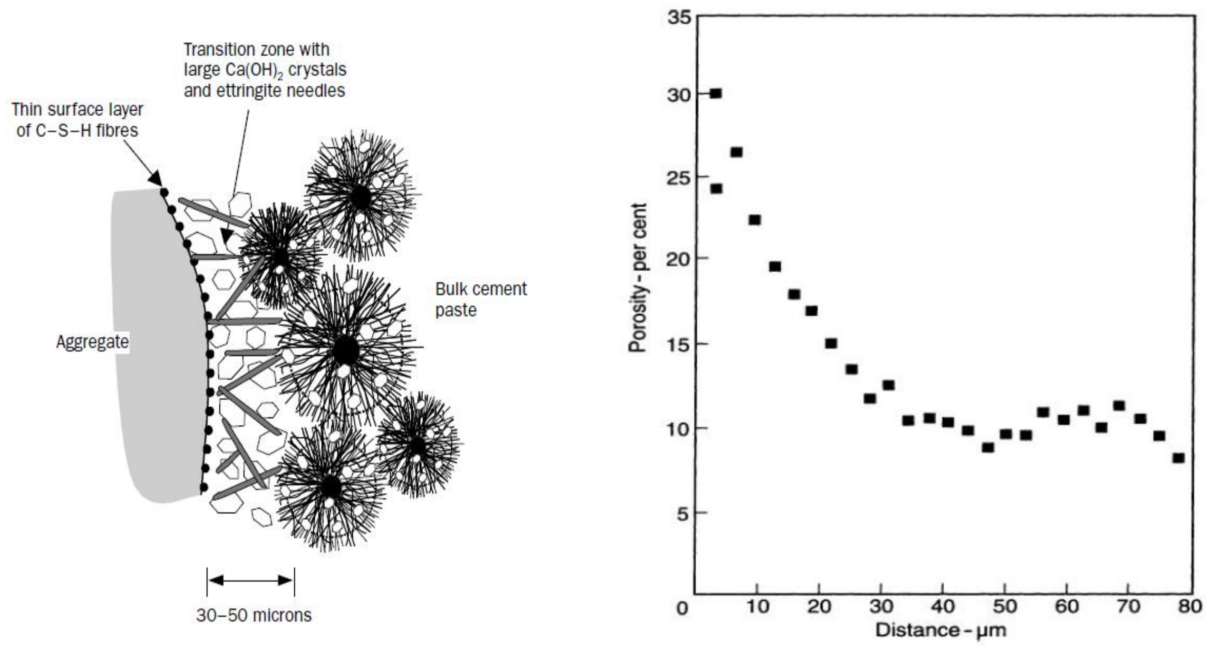
2.2 Interfacial transition zone (ITZ)

Hypothetically, concrete mix (whether it is the conventional one or pervious mix) can be modeled as a whole mass containing hcp (hardened cement paste), aggregate particles (the coarse and the fine one) and the interfacial transition zone. The area of interest in concrete technology has been shifted towards ITZ since it is the weakest one that needs improvement.

ITZ is 30-50 microns zone where cracks initiate. Why? The answer lies on the main feature of the zone. The two man features as indicated on Illston & Domone (2002) are:-

1) It is a very thin surface layer of calcium silicate hydrate on the aggregate, also containing some small calcium hydroxide (calcite) crystals;
2) Most of the zone consists mainly of larger calcite crystals and fine needles of calcium sulfo-aluminate.

In Figure 2-1 (a) the interfacial zone is shown represented as composed of the calcium hydroxide ($Ca(OH)_2$) and ettringite needles. It is due to this structures that the weakness emanates. Due to the stated reasons, the zone has more pores than the hcp (Neville, 2011). The pores are created due to the so called the ‘wall effect’ of the aggregates rather than being a hub for C-S-H formation. This property is indicated on Figure 2-1 (b).



(a) (b)

Figure 2-1: Interfacial Transition Zone (a) and Porosity on ITZ (b) (**(Neville, 2011)**)

2.2.1 Strength enhancement methods of the ITZ

As discussed above, the strength of concrete means the strength of ITZ. Several studies have been conducted in order to enhance the property of this zone. For example, Malikova & Klusak (2018), have conducted a study in order to model the cracking behavior of the ITZ, hence and/, concrete by means of finite element method.

What has been found from their studies is that, in order the maximum critical load to be resisted, the ITZ layer shall be thin, compliant and the aggregate sizes shall be of larger sizes. Figure 2-2 shows that the larger the size of the aggregates and the smaller the thickness of the ITZ the more the load can be resisted.

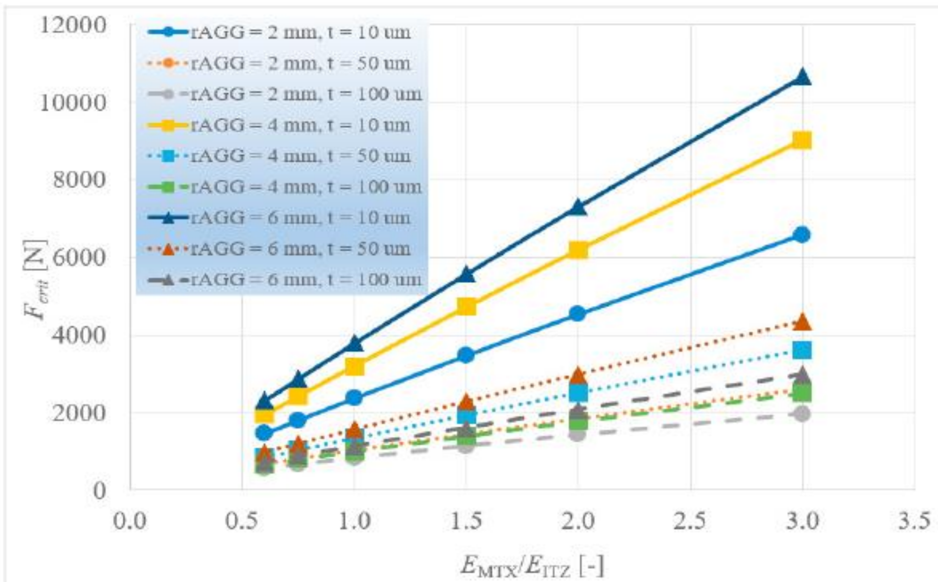


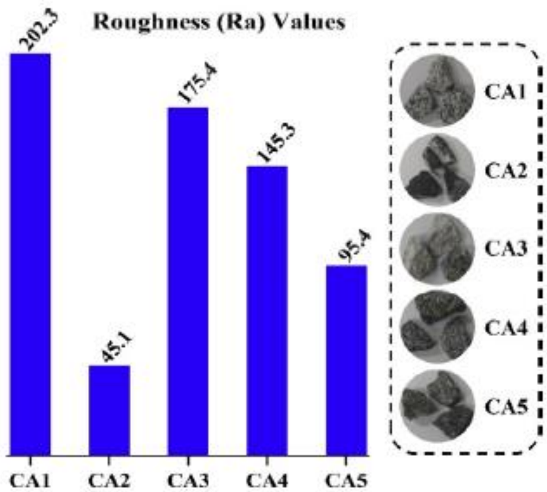
Figure 2-2: Fracture resistance of concrete (F_{crit} is the maximum load, rAGG is the radius of the aggregate, E_{MTX} and E_{ITZ} are the modulus of the cement matrix and the ITZ, respectively.)

(Malikova & Klusak, 2018)

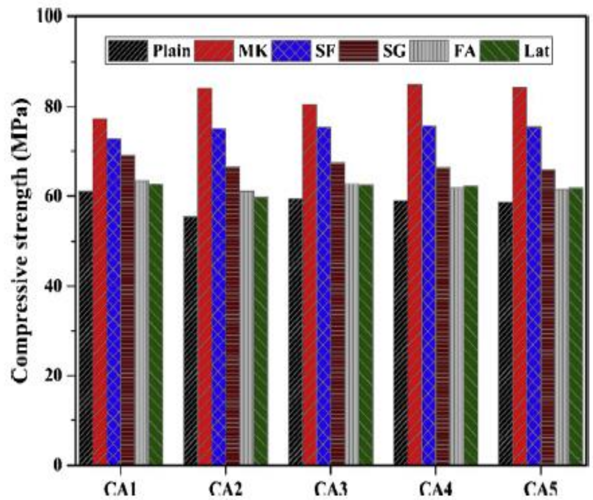
The mechanical interlocking between the aggregate and the cement paste also plays an important role in enhancing the ITZ strength. The influence of surface roughness in conjunction with SCM and latex has been investigated by Qudoos, et.al, (2018). Five different aggregates with different roughness values, Ra, have been used to prepare mixes with the same cement, water and aggregate contents but with different SCM including plain, metakaolin, fly-ash, silica-flume, slag and latex. Figure 2-3 (a) depicts the roughness values of the aggregates.

The resulting mixes were subjected to tests to micro-hardness and compressive strength tests. What has been found is, the micro-hardness and the compressive strength of the specimens made by the rough aggregates in the plain mix (with no SCM) has increased the compressive strength and the micro-hardness of the mixes (Figure 2-3 (b)). The reason being, the enhanced mechanical strength of the aggregate and cement interface, ITZ.

Additionally, the research has also revealed that, the use of the SCM has significantly increased the micro-hardness and the compressive strength; in fact the effect is more pronounced than the plane mix alone.



(a)



(b)

Figure 2-3: Roughness values, Ra, of the aggregates (a) Compressive strength results (b) (Qudoos, et.al, 2018).

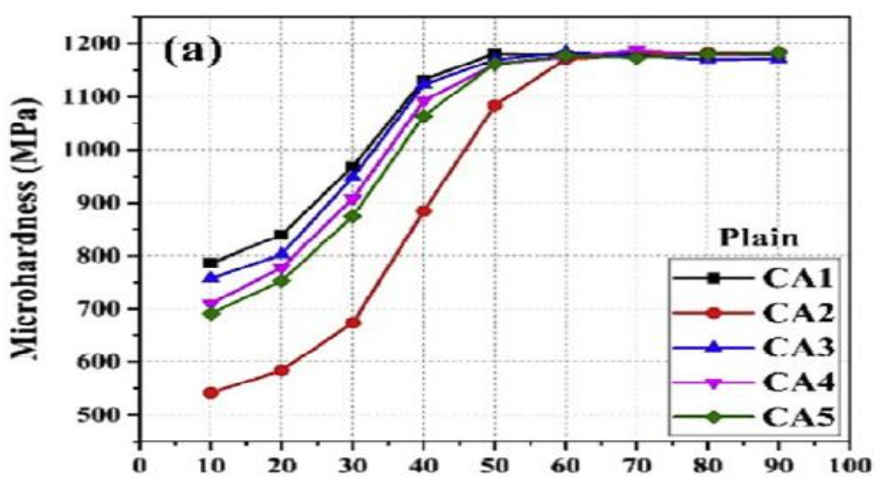


Figure 2-4: Microhardness values (the horizontal axis is the distance from the aggregate surface, μm) (Qudoos, et.al, 2018).

As can be seen from Figure 2-4, the micro-hardness will increase as we move away from the aggregate surface. This is an indication of the fact that if treatment shall be applied it is this zone that shall be strengthened.

Apart from the above ways to increase the strength of the ITZ, which is translated to the increase in the strength of concrete, adding natural pozzolanic materials is believed to increase the strength and durability of concrete. Karatas, et.al (2017) have investigated the mechanical properties and durability of self-compacting mortars produced from grounded pumice powder (GPP) as mineral additives and reported a 14.4 % increase in compressive strength. The reason, as per the discussion of the authors is, GGP has pozzoloanic activity attributed to the presence of SiO_2 and Al_2O_3, those forming additional calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) by reacting with calcium hydroxide during cement hydration to form a denser matrix that provides high strength and better durability.

In conventional concrete the influence of grounded pumice (GP) has also been investigated. Özcan & Mehmet , (2018) have studied the influence of GP addition on compressive strength and air content of air entrained and non-air entrained concrete. They reported that all GP containing non-air entrained concretes developed higher compressive strength than the control concrete at 90 and 180 days. What has been observed is that the influence of GP is significant at later curing days i.e. long term strength.

Not only is the compressive strength of GP has been investigated recently. Mboya, et.al (2019) have studied the effects of GP on Moduli of rupture and found out that at 20% replacement level over 7 and 28 days showed dramatic increase in the moduli of rupture (Figure 2-5).

The reason as explained by the authors is due to high amount of C-S-H and C-A-H in the microstructure resulting from good progression of pozzolanic reactions favored by low amount of Fe_2O_3. They also indicated that at 20% replacement level the microstructure can absorb more stress than the other levels.

Industrial wastes such as coal bottom ash, CBA, have also been used to increase the different properties of concrete. Ali, et.al (2019) have investigated the performance of concrete containing CBA exposed to sea water and found out that at early ages specimens containing CBA (designated as M2 and M3) performed well in terms of compressive strength as compared to the control mix (M1) in normal water as well as sea water (Figure 2. 6).

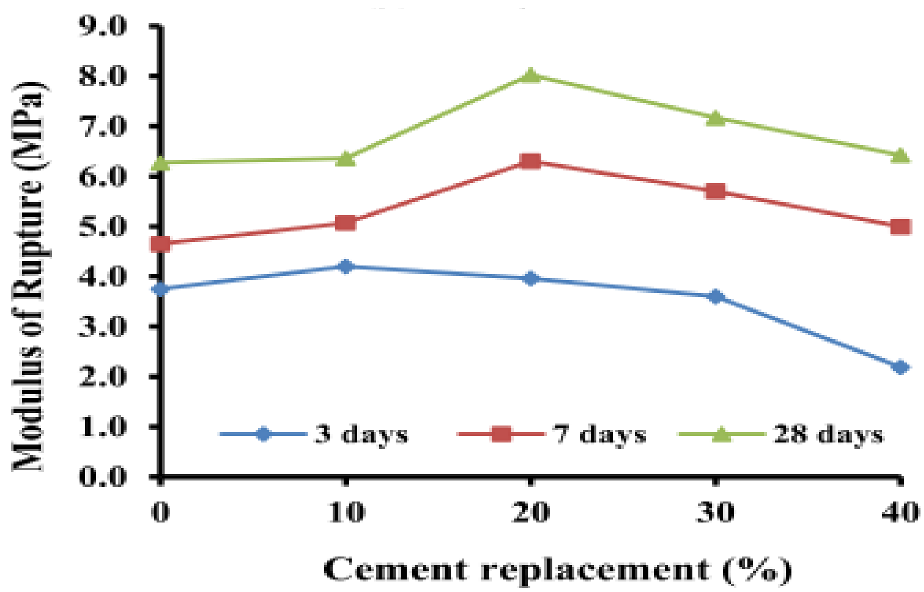


Figure 2-5: Influence of Pumice on Rupture Behavior of Concrete (Mboya, et.al , 2019)

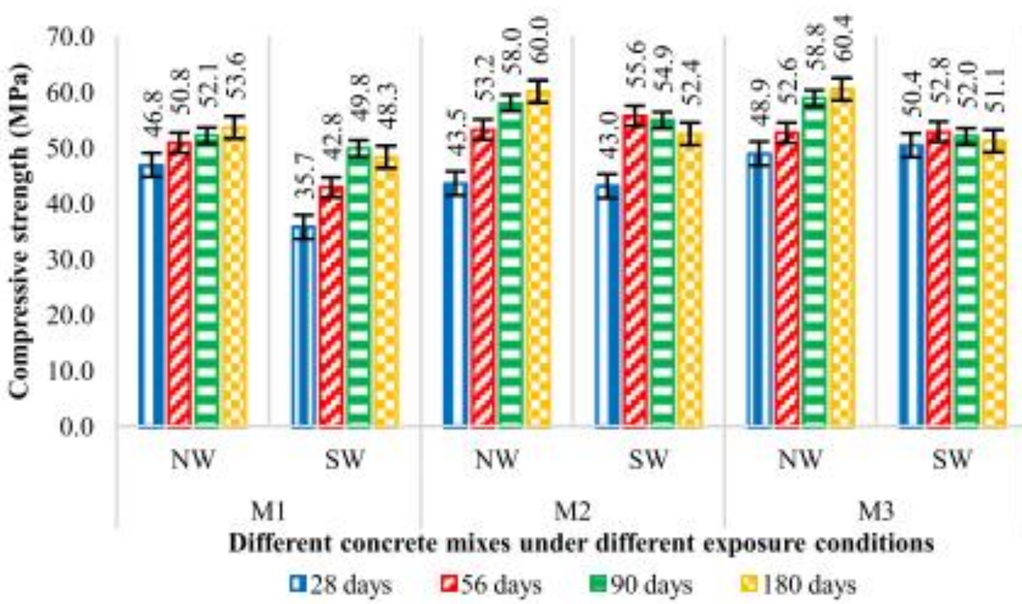


Figure 2-6: Compressive strength of specimens in normal and sea water (Ali, et.al, 2019)

2.3 Pervious Cement Concrete Pavement

Pervious cement concrete, sometimes referred to as no-fines, gap-graded, permeable, or enhanced porosity concrete, is an innovative approach to controlling, managing, and treating storm water runoff (Pervious Concrete, 2012). The term Pervious Concrete will be used throughout this paper.

Pervious concrete is an open graded structure with interconnected voids through which rain and storm water is permitted to percolate into the aquifer. It consists of cement, coarse aggregate, some percentage of fine aggregate and water. It can be used for lower traffic roads, shoulders, sidewalks and parking lots. This will add points to a project with a sustainable material managing storm water, reducing ground water pollution (Maguesvari & Narasimha, 2013).

Of the main applications is the creation of environmentally friendly pavement (Tennis, et.al, 2004). Due to urbanization, flooding is becoming a prolem. For example, in China 262 flooded cities had a maximum waterlogged depth >50 mm, and waterlogging lasted >12 h in 57 cities (Xiaogeng, et.al, 2018). To mitigate this problem the concept of spongey cities has been developed (Figure 2-7).

A "Sponge city" refers to a city where its urban underground water system operates like a sponge to absorb, store, leak and purify rainwater, and release it for reuse when necessary.

Figure 2-7: Application of Pervious Concrete on Smart Cities (Xiaogeng, et.al, 2018)

The advantages and disadvantages of pervious concrete pavement are summarized in (Pervious Concrete, 2012) as follows (Table 2-1):-

Table 2-1: Advantages and Disadvantages of Porous Concrete

Benefits/Advantages	Limitations/disadvantages
• Effective management of storm water runoff, which may reduce the need for curbs and the number and sizes of storm sewers.	Limited use in heavy vehicle traffic areas.
• Reduced contamination in waterways.	Specialized construction practices.
• Recharging of groundwater supplies.	Extended curing time.
• More efficient land use by eliminating need for retention ponds and swales.	Sensitivity to water content and control in fresh concrete.
• Reduced heat island effect (due to evaporative cooling effect of water and convective airflow).	Lack of standardized test methods
• Elimination of surface ponding of water and hydroplaning potential.	Special attention and care in design of some soil types such as expansive soils and frost-susceptible ones
• Reduced noise emissions caused by tire–pavement interaction.	Special attention possibly required with high groundwater.
• Earned LEED credits.	

2.3.1 Pavement Structure

In pervious cement concrete pavement system, a 150–300 mm pervious concrete (PC) layer with a high air void content is placed on a highly voided stone bed as the base layer, to allow for a rapid infiltration of runoff through the pavement system rather than allowing it to pond or run on the surface (Figure 2-8 and Figure 2-9). PC's prominent characteristic is the high content of hardened air void, typically ranging between 15 and 25 percent of the total volume (Rangelov, et.al , 2017).

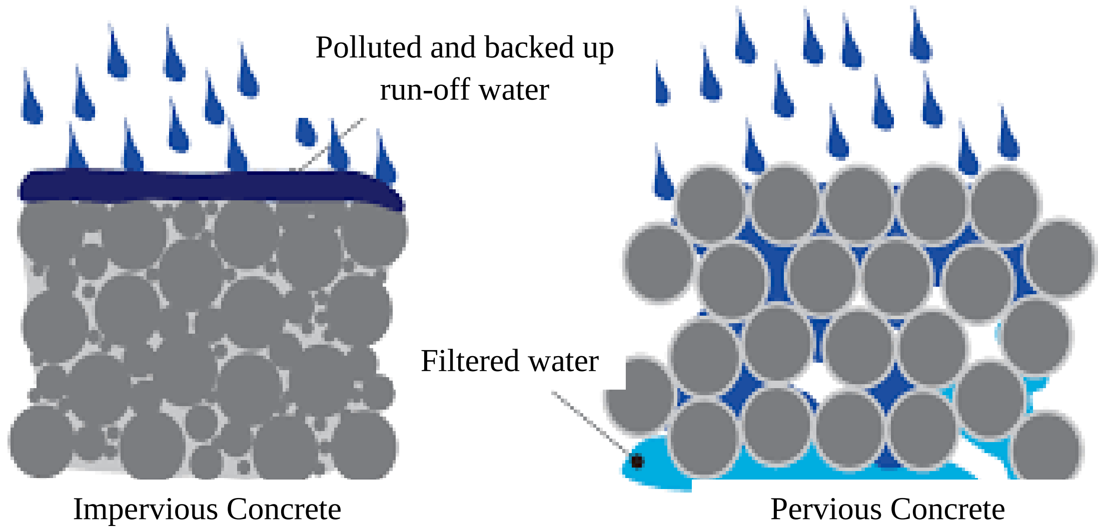


Figure 2-8: Advantages of pervious concrete over impervious concrete (Zhong et al. , 2015)

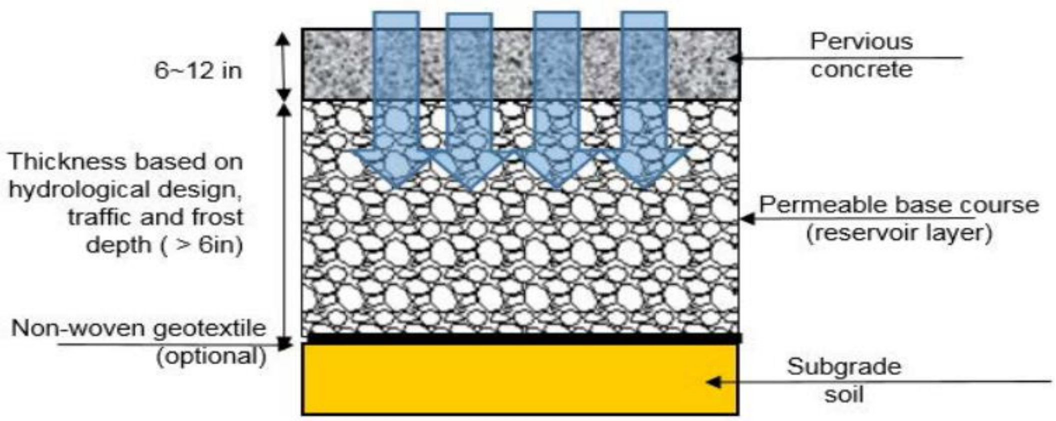


Figure 2-9: Typical cross section of a pervious concrete pavement (Nassiri, et.al, 2017)

Porosity is an essential property of PC, impacting its hydraulic, mechanical and durability characteristics, and is highly dependent on the mixture design parameters and the method of compaction (ACI, 2010).

PC mixture design is based on limiting the coarse aggregate grade to single-sized or grade 9.5–19 mm, and either completely removing or using a minimal amount of fine aggregate for added strength.

The end result is a matrix of coarse aggregate that are bridged by the paste as opposed to the conventional Portland cement concrete (PCC), where the aggregate is fully embedded in the paste (Rangelov, et.al , 2017) .

The main use of pervious pavement is storm water management (Pervious Pavement Design Guide, 2013). The other major uses are for sidewalks, reduced icing and therefore pedestrian slipping, and for parking lots/bike trails and light traffic streets, reduced hydroplaning and wet weather accidents (Nassiri, et.al, 2017).

2.3.2 Supplementary cementitious materials in pervious concrete mixes

The SCMs, interchangeably called the mineral admixtures, are siliceous and aluminous materials which by themselves possess little or no cementitious value but will in finely divided form and in the presence of moisture chemically react with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties (ASTM, 1998).

According to ASTM C-618 there are three classes of SCMs. Those are class N, F and C. Pumice is categorized under Class N. The chemical requirements for each class are tabulated on Table 2-2.

Table 2-2: Chemical requirements of SCMs

	Mineral Admixture Class		
	N	F	C
Silicon dioxide (SiO_2) plus aluminum oxide (Al_2O_3) Plus iron oxide (Fe_2O_3), min, %	70.0	70.0	50.0
Sulfur trioxide (SO_3), max, %	4.0	5.0	5.0
Moisture content, max , %	3.0	3.0	3.0
Loss on ignition, max , %	10.0	6.0 [A]	6.0

[A] The use of class F pozzolan containing up to 12.0 % loss on ignition maybe approved by the user if either acceptable performance records or laboratory test results are made available.

2.3.3 Porosity

Of the many applications of pervious concrete discussed above, its ability to drain water is the prominent one. Therefore pervious cement concrete shall have greater permeability than the surrounding soil. It should not easily clog (Maurizio & Calogero , 2018).

The permeability of the pervious mix is largely affected by the porosity of the mix. The higher the interconnected porosity the higher will be the permeability. The porosity of the pervious mix is obtained using the following relation (Ibrahim, et.al , 2014).

$$P = \frac{\left(\frac{w_1 - w_2}{p_w}\right)}{v_1} * 100\ \% \qquad (1)$$

Where:

P = the total porosity of the pervious concrete (%),

W_1 = the pervious concrete sample weight air-dried for 24 h (kg),

W_2 = the pervious concrete sample submerged underwater weight (kg),

V_1 = the pervious concrete sample volume (mm^3), and

p_w = density of water (kg/mm^3)

2.3.4 Compaction

Compaction of pervious concrete determines the percentage of voids, density and strength. There are different suggestions made to compact pervious concrete mixes by considering strength and porosity. Ammar & K. (2016) has used vibrator to compact pervious mixes. But according to Meininger (1988), ASTM C-31 rodding compaction by 25 strokes on each three layer has the highest compressive strength test result.

2.4 Geology of Pumice Stone

The geological definition of pumice stone according to Doanld (1992), is a volcanic rock composed of bubbles or vesicles in glass matrix formed by the effervescence of gases and rapid cooling of molten material during an eruption. There are different terms associated with volcanic materials such as pyroclastic and tephra. Those terms are used to describe the type of deposits either fragmented or unconsolidated.

Geologically, pumice stone is categorized as extrusive i.e formed by the rapid cooling of magma at the surface of the earth (Asrat, 2006) .This makes pumice deposits prone to weathering effects and most of the pumice deposits are geologically young. Figure 2-10 depicts the formation of pyroclasts including pumice at the surface of the earth.

The formation and preservation of pumice requires a balance between internal gas pressure, viscosity and temperature of an erupting magma. If higher viscosity, impermeable country rocks, or a blocked vent prevent rapid escape of gases from magma as it nears the surface, an explosive eruption may occur shattering the bubble walls and generating a volcanic ash of fine glass shards rather than vesicular pumice (Wenk, et.al, 2004).

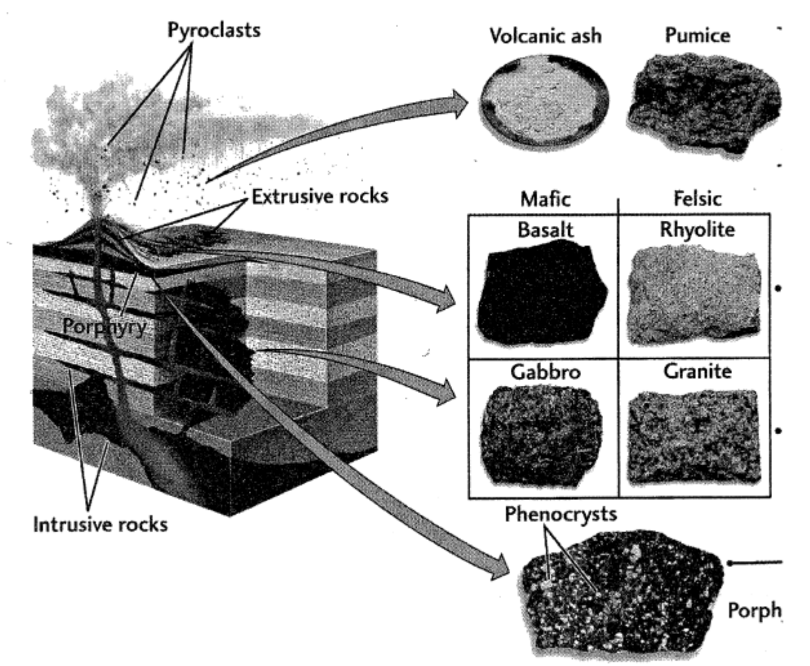


Figure 2-10: Volcanic formation of Pumice (Asrat, 2006)

In Ethiopia the location of pumice deposits is concentrated in central and eastern parts of the country. The location of map of pumice is annexed in Annex F. Taye (2007) describes the pumice deposits around Adama as, where the pumice stone is came for this thesis, the deposit covers areally extensive area and in some hydrothermally active areas it forms gentler slope even faraway from the caldera with the exposed thickness of about 4.5 m. Figure 2-11 shows the pumice deposits at Melka Ida where the pumice obtained from.

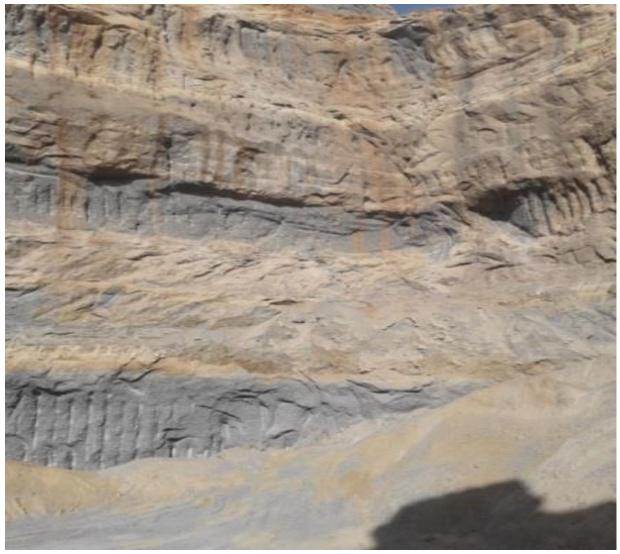


Figure 2-11: Pumice deposits at Melka Ida

2.5 Mix design

2.5.1 Trial and error methods

Basically, the mix design of pervious concrete is made with different approaches. Most of the available methods use a trial batch method to reach a specified property of the end product. For example, Mohammed, et.al (2016) recommends to use a trial batches to arrive a specified properties i.e. strength and permeability. The method, however is, very tedious and is not replicable.

2.5.2 Optimization Techniques

The other approach in designing mixes is using optimization techniques. The optimization technique focuses on the finding of the minimum number of trials to achieve the desired properties. One of the methods is application of the Taguchi method for minimization of trials. Alireza J. et.al, (2015) uses this method to decrease the variability of mix properties. It has been found that, the application of this method has reduced the number of trials from 21 trial batches to 9.

Another method based on optimization technique is use of “Excess paste theory” (Figure 2-12). In this method mixes are designed using the principle that aggregates are coated using the cement paste to ensure better performance. Strength suitable for most uses is found using this method (Dang , et.al , 2014).

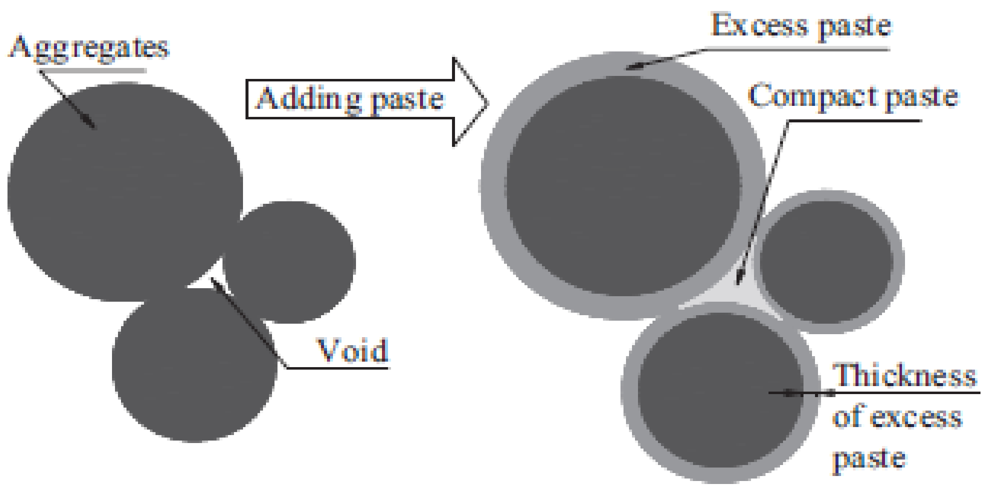


Figure 2-12: Principle of excess paste theory (Dang , et.al , 2014)

2.5.3 The ACI method

The other popular method and the one that considers the use of fine aggregates unlike the previous methods, is the b/b_o method. Accordingly, the dry rodded volume of coarse aggregate b/b_o, can be used as a design relationship.

Where:-

b/b_o = dry-rodded volume of coarse aggregate in a unit volume of concrete

b = solid volume of coarse aggregate in a unit volume of concrete

b_o = solid volume of coarse aggregate in a unit volume of coarse aggregate

Since it is one of the objectives of this research to examine the performance of pervious mix containing fine aggregate, this method is used in the design of mixes. In this method, the dry-rodded volume of coarse aggregate in a unit volume of concrete determines the amount of coarse aggregate used, subsequently the rest of the mixture ingredients.

According to ACI (2010), the following eight steps are used in order to design a pervious cement concrete mix using b/b_o method.

1. Determine the aggregate weight
2. Adjust to SSD Weight
3. Determine the paste volume
4. Determine cementitious content
5. Determine water content
6. Determine solid volume
7. Check void content
8. Iterative trial batching

The effective b/b_o values given are shown in Table 2-3.

Table 2-3: Effective b/b_o values

Percent fine aggregate	b/b_o	
	ASTM C33/C33M Size No.8	ASTM C33/C33M Size No.67
0	0.99	0.99
10	0.93	0.93
20	0.85	0.86

The paste volume is determined using the relationship given in Figure 2-13.

The rest of the mix constituents are found using the following relationships:

Paste volume, V_p = Cement volume + Water Volume

$$V_p = c/\ (3.15*1000\ kg/m^3) + w/1000\ kg/m^3 \qquad (2)$$

Form the general principle that w = (w/b)*c and substituting into the above relationship:

$$V_p = c/(3.15*1000\ kg/m^3) + ((w/b)*c)/1000kg/m^3 \qquad (3)$$

Then solving for cement content,

$$c = [V_p/(0.315 + w/b)] * 1000kg/m^3 \qquad (4)$$

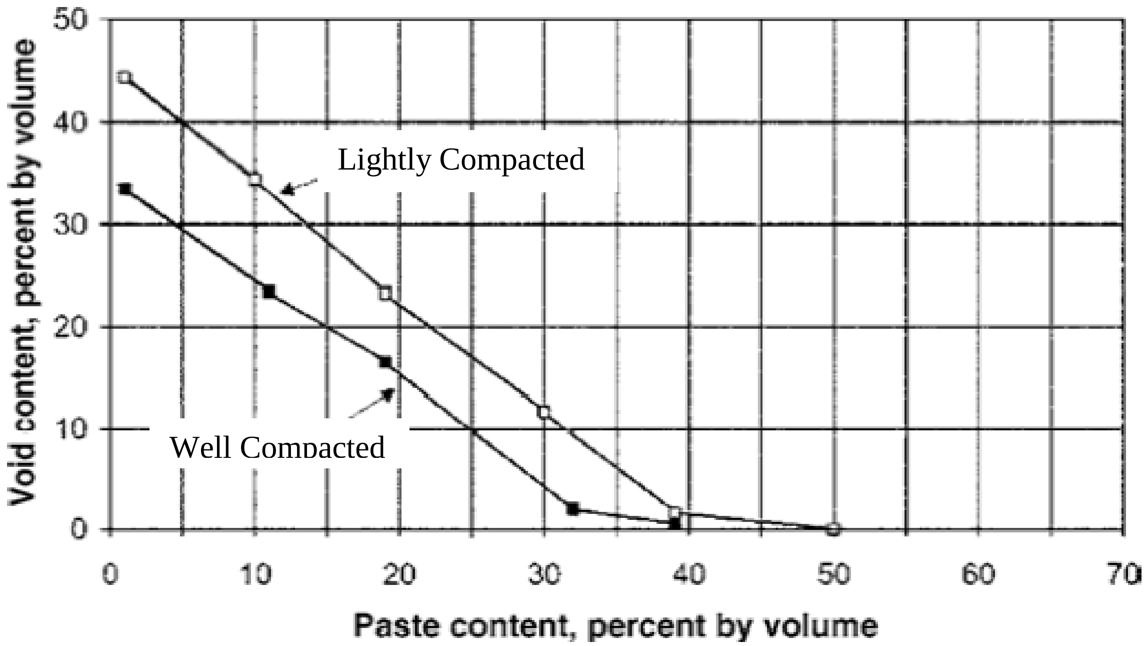


Figure 2-13: Relationship between void content and paste volume (ACI, 2010)

Where:

C = the cement content in kg

w = the water content in kg

w/b = water to binder

V_p = volume of paste, m^3

Therefore, after the paste volume and the cement content determined, the mass of water will be determined. When fine aggregate is used the paste volume should be reduced by 2% for each 10% fine aggregate of the total aggregate for well compacted pervious concrete and by 1% for each 10% fine aggregate of the total aggregate for lightly compacted pervious concrete (ACI, 2010).

2.6 Laboratory tests

2.6.1 Performance Tests

2.6.1.1 Permeability test

The permeability of pervious concrete, because of its high porosity, is in the range of 2–6 mm/s. Contrary to regular concrete, pervious concrete prevents water from pooling on horizontal surfaces and, if properly designed, positively affects the surrounding soil and ground water quality (Ivanka , et.al , 2018).

In order to measure the permeability of concrete pavement two prominent methods are available: the Constant head permeability and Falling head permeability tests. Sandoval et al., (2017) by use of laboratory analysis found out that, the use of constant head permeability is more representative than Falling head permeability test. But ACI (2010) recommends the falling head test based on previous researches made (Figure 2-14).

The coefficient of water permeability will be calculated following Darcy's law as shown in the following equation (Zaetang, et.al , 2013):

$$K= (Q*L)/ (H*A*t) \tag{5}$$

Where:-

K = the water permeability coefficient (cm/s),
Q = the quantity of water collected (cm^3) over time t (s),
L = the length of specimen (cm),
H = the water head (cm), and
A = the cross sectional area of the specimen (cm^2).

2.6.1.2 Compressive and split tensile strength tests

The compressive strength of porous concrete is measured with the same method and equipment as that of conventional dense concrete (Figure 2-15). The strength of hardened pervious cement concrete is created by the bonding between the cementations paste and aggregate.

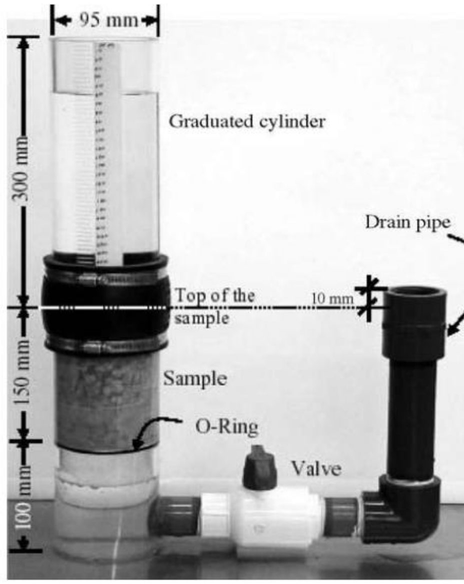


Figure 2-14: Schematic of variable head permeability test in (ACI, 2010)

There are many factors affecting the strength of porous concrete including the cementations content, water to binder ratio, compaction level and aggregate gradation and quality. For the optimization of any porous concrete mix design, a balance between the strength and permeability is the key factor (Mohammed , et.al , 2016).

(a) (b)

Figure 2-15: Schematic of Compressive strength test (a), Screen displaying compressive strngth parameters (b) (Photograph courtesy of Abel W.)

In many literatures the strength of porous concrete is stated as low compared to the conventional concrete. For example, under normal conditions the compressive strength obtained can range from of 5 to 30 MPa.

The tensile strength of porous concrete pavement is performed using indirect method of testing called splitting tensile strength test in laboratory (Figure 2-16). The splitting tensile strength of porous concrete is performed using 100 mm * 300 mm sized concrete cylindrical specimens (Maguesvari & Narasimha, 2013). The splitting tensile strength of the specimen is computed using the following equation:-

$$T = \frac{(2*P)}{\Pi*L*D} \tag{6}$$

Where:-

T = The splitting tensile strength (MPa)

P = Applied load (KN)

L = Length (m)

D = Diameter (m)

(a) (b)

Figure 2-16: Schematic of splitting tensile strength test (a) Parameter Indicator of the UTM (Photograph courtesy of Abel W.)

2.7 X-ray Powder Diffraction (XRD)

XRD is a powerful tool in identifying the various chemical compositions in a given sample. The principle of XRD is based on the very fact that, accelerated electrons with sufficiently high energy displace electrons from within the inner electrons shells (e.g. K shells) of an atom. This high energy, released from irradiating elements, contains/emits the so called X-rays (Klein & Philpotts, 2017).

According to Bragg's law (Tedesco & Brunelli, 2017), as depicted on equation 7, there are two requirements that shall be fulfilled as stated below.

1) The lattice planes (hkl) must be in a reflection orientation between the incident and diffracted X-ray waves,
2) Diffraction occurs at a specific angle that is determined by the d-spacing of the lattice planes.

$$2d\sin\theta = n\lambda \tag{7}$$

Where:-

d = inter-planar spacing

θ = angle of incidence/Bragg's angle

n = order of reflection

λ = wave length of the X-ray source

According to Scrivener et.al, (2016) there are two analysis methods for XRD when cement and cementitious materials is considered, the qualitative and quantitative analysis methods. The quantitative analysis method is in turn divided into the external and internal standard methods (R. Snellings, et.al , 2014). In the qualitative analysis method, the diffraction pattern of the unknown sample is compared to a database of previously known diffraction patterns. Whereas in the quantitative analysis methods, such as in the Rietveld, the method minimizes the error between the measured and the calculated parameters using the least square approach (Scrivener, et.al, 2004).

The recent and most inclusive method that considers the presence of SCM, which are believed to contain non crystalline component is the Partial Or No Known Crystal Structure (PONKCS) method. The method depends on a calibrated XRD profile of each individual phase, which is also possible for amorphous phases. Using this method the precision for SCM's was found to be 2-3 wt% (R. Snellings, et.al , 2014).

2.8 Summary of Literature Review

The hardened structure of pervious cement concrete is the same as that of the hardened structure of conventional dense graded cement concrete. ITZ, hcp and aggregate are the main components. From these zones ITZ is weak in strength and is a region where crack initiation and propagation occurs with less energy. The main reason that is given as in many literatures is the presence of unreacted portlandite or calcite compounds leading to a 30 - 50 micron porous zone in combination with the wall effect created by the aggregate surface.

Based on the literature review made, it has been clearly seen that different methods can be implemented to somewhat enhance the performance of the ITZ, hence concrete. Pozzolanic materials such as grounded pumice have large amount of major oxides which enables them to react with the unreacted portlandite to form additional C-S-H and C-A-H in the microstructure of hardened concrete thus increasing the strength of the ITZ hence, concrete.

Therefore selection depends on availability, economy and environmental advantages. Environmental aspect plays a vital role. The use of SCM has the benefit of reduction in CO_2 emissions as their production in concrete consumes less energy than the conventional unblended ordinary Portland cement. It has been reported that, for every ton of cement produced a ton of CO_2 is released into the atmosphere.

Accordingly, it is the researcher of this thesis belief that investigation of the properties of pervious cement concrete made from ground pumice is necessary and will probably make the properties of pervious concrete enhanced. The selection of pumice is based on the fact that it is available and its application in conventional and other high performing mixes has produced comparable or even best performance in the past when used as a replacement to OPC.

Different macro-characterization methods are also available. Strength test methods such as compressive strength and splitting tensile strength can characterize the mechanical properties of pervious concrete and the physical properties of pervious concrete can be characterized by hardened density and porosity tests. Hydraulic conductivity test, typically of falling head permeability apparatus can measure the permeability of pervious concrete. It is also learnt that the apparatus can be made in laboratory. The micro-characterization of hydration products of pervious concrete can be studied using XRD. By conducting XRD, the main chemical products of pervious cement concrete can also be studied.

Mix design of pervious cement concrete can be done using several methods such as ACI. Trial mix design to reach a specified mix property is needed. Considerations in compactions and curing shall be given of special emphasis.

CHAPTER THREE

3. EXPERIMENTAL DESIGN AND METHODOLOGY

3.1 Procedure

The thesis is conducted in a set of defined tasks with predefined steps, but not too rigid that they cannot be easily adjusted further. The major milestones of the thesis are detailed as literature review, experimental task and data analysis and interpretation of results.

The two ends of the procedure are more of desk works while the experimental task involves laboratory work where samples collected from local quarry sources are subjected for quality tests and their conformance with the minimum standard specifications is checked. After doing so, mix is designed according to ACI method of mix design. Those specimens are subjected to compressive, permeability, hardened density and porosity; and splitting tensile strength tests.

Concerning the preparation of grounded pumice as cement replacement, first the pumice is oven dried. After all the moisture has been dried, it is subjected in LAA machine and is reduced to powder. After doing so the powder is sieved with 75µm sieve. The material passing the specified sieve is used as a partial replacement of OPC.

Subsequently the use of pumice as SCM is examined by conducting both chemical and physical analysis to meet the ASTM requirements. The physical requirement includes checking the strength activity index to conform the pozzolanic behavior of pumice. The schematic showing the proposed procedure is shown in Figure 3-1.

3.2 Data Sources and Analysis

3.2.1 Sources of data

3.2.1.1 Primary and Secondary

Most of the research was done using primary data generated form laboratory test as stated on the methodology. Secondary data necessary for locating the sources of grounded pumice has also been used.

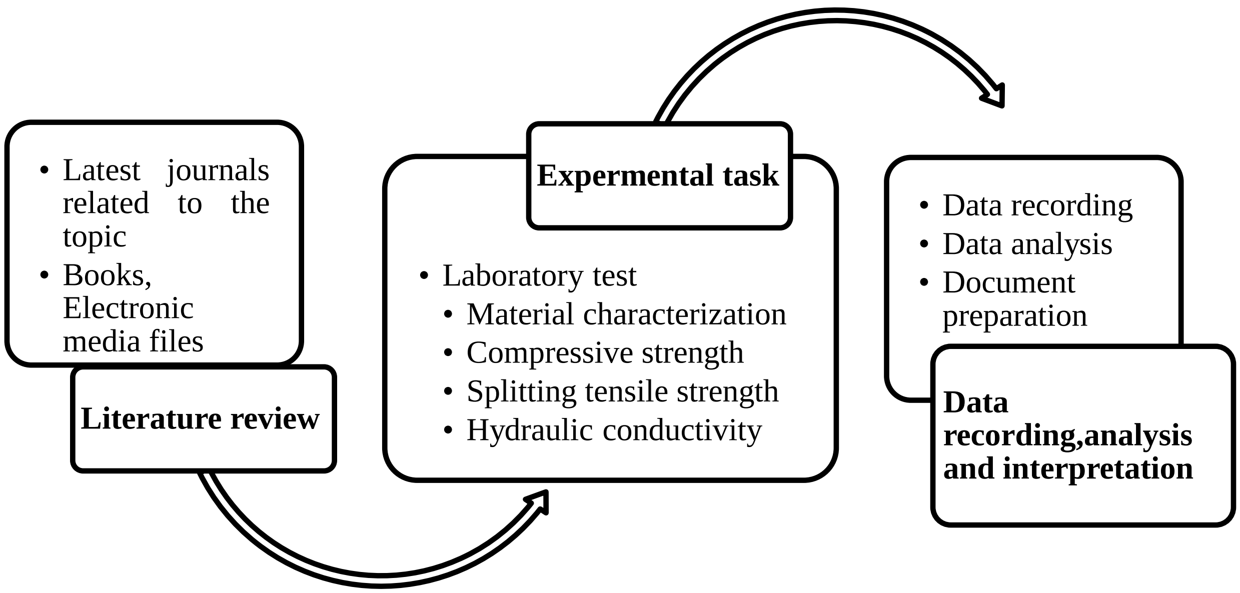


Figure 3-1: Procedure of the thesis

3.2.1.2 Data types and logging

Most of the data are discrete in nature. For example, strength test results are measured as a discrete variables. In the primary data, the physical properties of aggregates, ground pumice and cement is recorded before conducting laboratory tests. Mixes are then prepared and is designated by their percentage of GP used. Then their properties are recorded at the time of tests.

3.2.1.3 Analysis

The recorded data is analyzed using table and graphs. Additionally, relationships between variables are generated indicating the performance of GP in pervious concrete.

The effect of ingredient variation is established, for example, amount of grounded pumice used. The effect of varying GP content is also established. The following correlations are analyzed:-

- Amount of GP content versus fresh and hardened properties,
- Optimum amount of GP replacement with respect to strength and permeability,
- Compressive strength attained versus density and porosity,
- Amount of runoff reduced versus strength attained.

Those characteristics are plotted by using statistical software such as Excel.

3.3 Experimental design

Two sets of experimental group are considered, the control and the experimental groups. A brief explanation is given in the following sections.

3.3.1 Control Groups

The control group consists of specimens that are made and casted with natural river sand content of 10% by mass from the coarse aggregate. This is designated as 10%_FA_0% GP. There is no grounded pumice replacement in this group of samples.

Samples are prepared for compressive strength, splitting tensile strength, hydraulic conductivity, hardened density and porosity testes. The specimens for compressive and splitting tensile strength tests are prepared for the ages of 3, 7, 28 and 56 days.

The total number of samples for compressive and splitting tensile strength tests is 12 cube specimens and 12 cylindrical specimens respectively. For hydraulic conductivity and hardened density and porosity tests the number of samples prepared is 6.

3.3.2 Experimental Group

The experimental groups are specimens containing different proportion of grounded pumice. The proposed percentages are 5%, 10%, 15%, 20%, 25% and 30%. Accordingly, based on the amount of GP replacement the samples are designated as:-

- 10%_FA_5% GP [Mix with 10% FA and with 5% grounded pumice replaced]
- 10%_FA_10% GP [Mix with 10% FA and with 10% grounded pumice replaced]
- 10%_FA_15% GP [Mix with 10% FA and with 15% grounded pumice replaced]
- 10%_FA_20% GP [Mix with 10% FA and with 20% grounded pumice replaced]
- 10%_FA_25% GP [Mix with 10% FA and with 25% grounded pumice replaced]
- 10%_FA_30% GP [Mix with 10% FA and with 30% grounded pumice replaced]

Likewise a total of 144 compressive and splitting strength samples were prepared. For hydraulic conductivity and hardened density and porosity tests 42 specimens were prepared.

3.4 Methodology

3.4.1 Material Characterization

3.4.1.1 Coarse aggregates (02 aggregates)

a) Source

The source of the coarse aggregate used in this research is from Bole Bulbulla quarry located in Addis Ababa. The gradation analysis of the aggregate indicates that the nominal maximum aggregate size is 19 mm. The aggregate is a crushed basaltic rock. A total of 3 m^3 of the aggregate is used in this research.

b) Gradation Analysis

The sieve analysis of the 02 aggregates indicates that the aggregates used are coarser than the 4.75 mm sieve. This gradation of the aggregate is suitable in the use of the pervious cement concrete in a sense that, the required percentage of voids can be achieved since the voids in the aggregate alone is enough to achieve the desired porosity of the porous concrete mix.

The suggestion given in ACI, (2010) to use the gradation envelope for conventional dense graded concrete is not used as this requirement is for producing a dense aggregate to cement matrix. Therefore implementation of this dense matrix will not provide enough voids that will make the pervious cement concrete capable of draining. Figure 3-2 shows the particle size distribution curve of the coarse aggregate used.

c) Bulk density and voids in the aggregates

The bulk density of coarse aggregate used, as measured using rodding, was found to be 1,505 kg/m^3, which is typical for a use in most of concrete mixes. The total voids in the aggregates using the same method were found to be 41 %. Both are used in the mix design as parameters.

d) Specific Gravity and absorption

The average bulk specific gravity, bulk specific gravity in SSD basis and the apparent specific gravity of the aggregate used in this research was found to be 2.46, 2.52 and 2.63 respectively. The bulk specific gravity is used in the mix design.

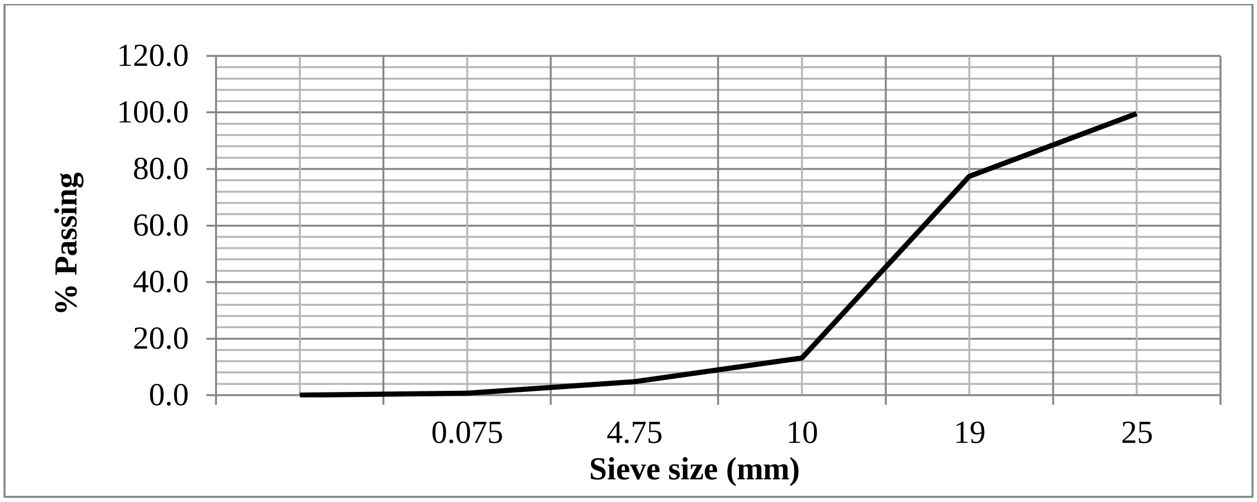


Figure 3-2: Particle size distribution of the coarse aggregate

The absorption was measured to be 2.18 %. Based on the absorption obtained the water demand obtained from the mix design was adjusted accordingly.

e) Soundness and LAA

For samples subjected to cycles of sodium sulfate solution, the soundness was measure to be 3%. Hence it can be said that, the material can be classified as a sound material. By the particle size distribution analysis it was found that the aggregate falls into class A in the LAA test class. Accordingly the LAA value was found to be 20%, indicating the material is abrasion resistant.

3.4.1.2 Natural River Sand (Fine Aggregates)

a) Source

The source of the fine aggregate is located in Addis Ababa, namely, Latessa quarry. The sand used is natural river sand. The total amount of sand used purchased is 1m^3.

b) Gradation

Based on the sieve analysis conducted the sand has been observed to contain a small amount of materials coarser than 4.75 mm. Since one of the aim of this research is to find a balance between the strength and permeability of pervious concrete mixes, the materials coarser than 4.75 mm sieve has been discarded. Figure 3-3 shows the gradation analysis of the natural river sand used.

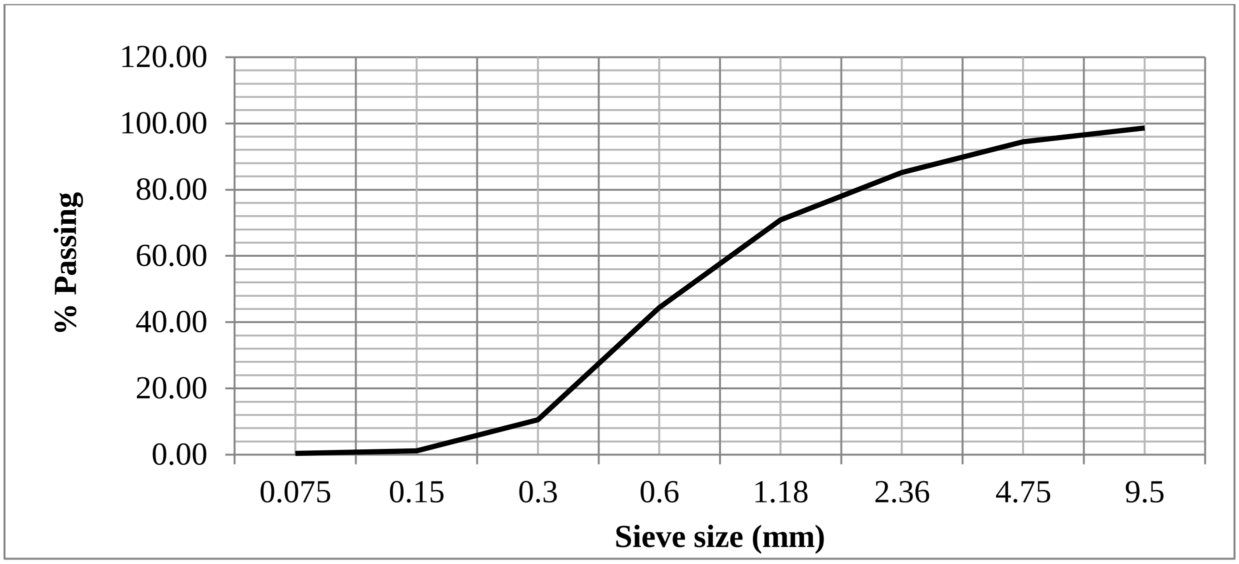


Figure 3-3: Particle size distribution of fine aggregate

Circuitously, clay content of the fine aggregate was calculated and is found to be 1.4 %. Additionally the fineness modulus was found to be 2.95.

c) Dry and Loose Unit Weight

The dry and loose unit weights of the fine aggregate were found to be 1.52 gm/cm^3 and 1.38 gm/cm^3. It is obvious that this value will have effect on the overall density of the pervious mix when the fine aggregate replaces the coarse aggregate.

d) Specific Gravity and Absorption

The bulk specific gravity, bulk specific gravity in SSD basis and the apparent specific gravity of the aggregate used in this research was found to be 2.36, 2.47 and 2.65 respectively. The absorption of the fine aggregate was found to be higher i.e. 4.7%. Accordingly this has been used to adjust the amount of water demand in the mix design of the pervious mixes.

3.4.1.3 Pumice stone

a) Source

Originally the pumice stone was sourced from a place called Wonji Melka Ida, a town in vicinity of Adama, 107 Km away from the capital Addis Ababa. The pumice was naturally found in a fractured aggregate form. A total of 300 kg was purchased for this research.

b) Gradation

Since the purpose of the pumice stone is to replace the ordinary Portland cement in its finely grounded form, the particle size distribution of the pumice stone aggregates is not of a concern. Therefore no particle size analysis was done for pumice stone.

c) Chemical composition analysis (Silicate analysis)

Since the chemical composition of volcanic pumice shall be known, silicate analysis was conducted in order to estimate the oxide composition. SiO_2, Al_2O_3 and Fe_2O_3 are the prominent oxides present in pozzolanic materials.

Therefore their presence and amount is used to classify pozzolanic materials. The volcanic pumice used in this research has 85.07 % of the prominent oxides which makes the volcanic pumice class N pozzolanic supplementary cementitious material as per ASTM C 618. Table 3-1 shows the chemical compositions of the volcanic pumice used.

Table 3-1: Silicate analysis of volcanic pumice

Chemical Oxide	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
Percentage (%)	66.76	11.97	6.34	2.72	0.92	2.92	3.42	0.2	0.05	0.14	1.13	4.81
Sum (%)		85.07										

d) Density

Volcanic pumice is light weight by its nature. As described on the literature review part of this research, the unit weight of the material is small which makes the density much less than its OPC counterpart. Uncrushed pumice stone, even, floats on water. Figure 3-4 shows this behavior of pumice stone.

In this research, the density of grounded pumice has been determined using pycnometer method. For determining the volume, kerosene is used as it has a known density i.e. 0.8 gm/ml. Since the density of kerosene, the volume of pycnometer and the mass of pumice are known, using simple arithmetic, the volume occupied by the grounded pumice can be found.

Figure 3-4: Volcanic pumice aggregates floating on laboratory water bath (Photograph courtesy of Abel W.)

In this research the density of pumice was found to be 2.05 gm/ml, which is averaged from two trials.

e) Fineness of grounded pumice by Air Permeability apparatus

Fineness of a given material plays an important role in the acceleration of chemical reaction. The more fine a material, the higher will be its surface area to volume ratio. This in turn means the more it will react compared to a less finer material. Since one of the objectives of this research is to observe the behavior of grounded pumice as a cement replacement, the fineness of pumice plays an important role.

There are different methods to determine the fineness level of grounded materials. One can use ASTM C-430-96 Fineness of Hydraulic cement by the 45 μm (No. 325) Sieve or Air Permeability methods. There are different versions of the Air Permeability methods the most well-known is the Blain apparatus as shown in Figure 3-5.

The principle in the Blain method is that, controlled air will pass through the sample and the time required by a standard liquid to pass through two known points is recorded and this is compared to a standard time.

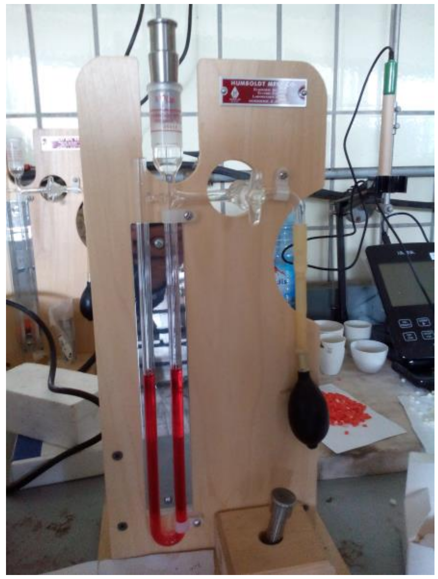


Figure 3-5: Blain air permeability apparatus (Photograph courtesy of Abel W.)

Different fineness levels can be achieved by changing the number of revolution of the LAA machine. For example, in this research, for a revolution of 1,000 the fineness level achieved was 2,728 cm^2/gm and for a revolution of 1,500 the fineness level achieved was 3,533 cm^2/gm, which is comparable to the OPC.

f) Hydrometer analysis

In order to investigate the particle size distribution of grounded pumice, the hydrometer analysis test was conducted on 75 µm passing material. The result of the test has shown that, for example, 30.9 % of the grounded pumice contains 9 µm or less particle diameter (Figure 3-6). This indicates that, the fineness level of the grounded pumice used is very high as this is further interpreted as promising for good chemical reaction and the effective grounding mechanism applied.

3.4.1.4 Cement

a) Source and/ type

The cement purchased for this research is OPC with a market brand of DANGOTE. OPC is used because, since the objective of the research is to replace the cement with pozzolanic material, the effect of replacing the grounded pumice will be best seen on OPC type of cement other than PPC.

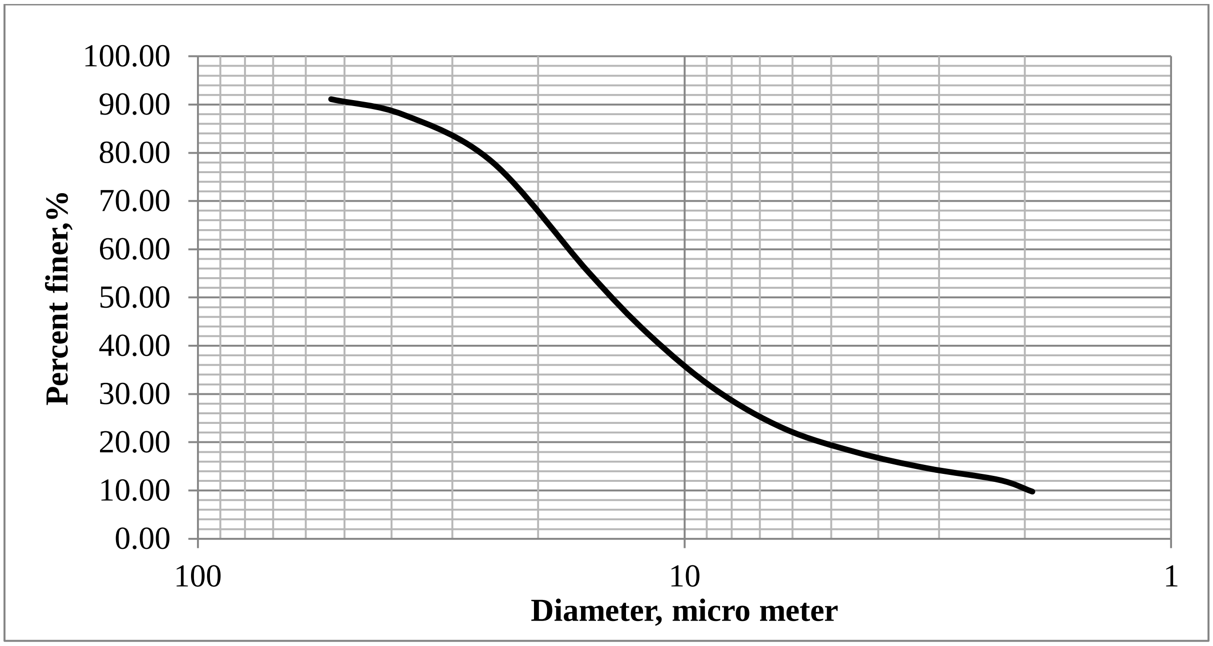
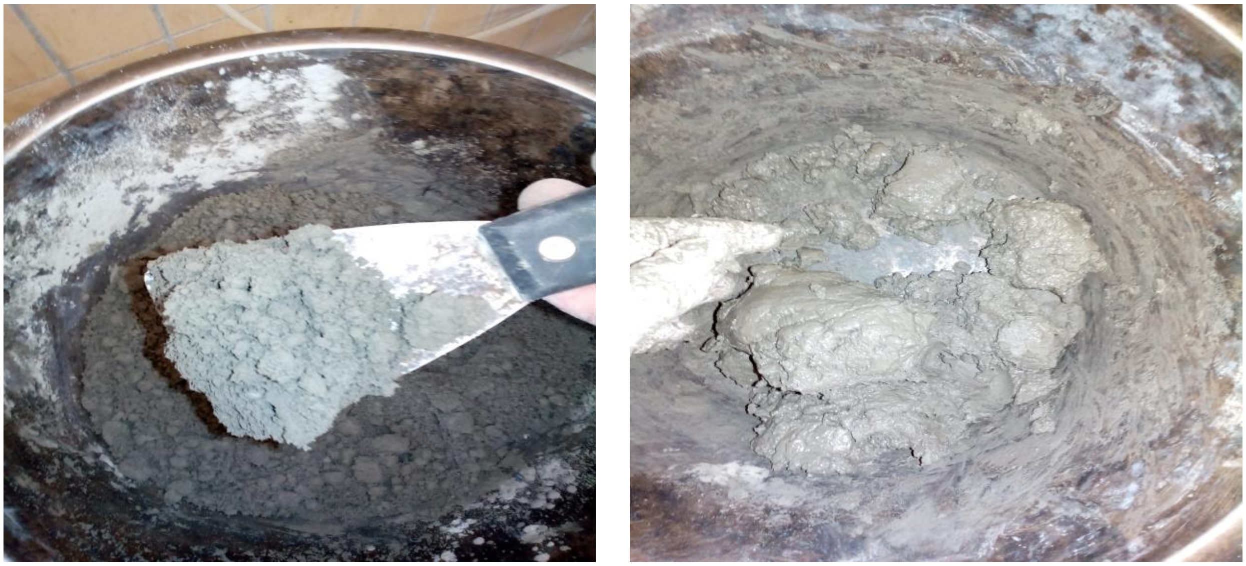


Figure 3-6: PSD of grounded pumice

b) Standard consistency of cement

Since the consistency test of cement is used to estimate the minimum amount of water required to complete hydration, the test was conducted for sample consisting only OPC and sample prepared with a replacement of different percentage of grounded pumice. The w/b content of the sample containing only cement to reach a standard consistency of 10 mm was found to be 0.27 and for sample containing grounded pumice, say for example, 30 % replaced grounded pumice, the w/b to reach a standard consistency of 10 mm is found to be 0.32.

An interesting fact of the test results is that, the addition of grounded pumice in the mix, say 30 %, will increase the water demand by 19%. The reason according to Karatas, et.al (2017) is the rough and porous faces of the grounded pumice powder as examined using scanning micrographs. At w/b of 0.27 the blended mix will not be even molded to Vicat apparatus since it crumbles when mixed, but this water content was the threshold for the virgin cement sample to reach its consistency. Figure 3-7 shows the blended mix with a w/b content of 0.27 and 0.32. As the figure depicts, it is clear that, grounded pumice demands an additional amount of water to reach its consistency. Hence this change in demand shall be considered in the pervious concrete mix design (Please refer section 4.1 for further explanation).



(a) Blended Mix with w/b of 0.27 (b) Blended Mix with w/b of 0.32

Figure 3-7: Blended mix at different w/b

3.4.2 Preparation of Grounded Pumice

In order to prepare the pumice stone for blending, it shall be grounded to a fine level. The fineness level depends on the method and effort of grounding method used.

In this research, LAA (Los-Angeles Abrasion and Attrition) machine is used to ground the pumice. Normally, LAA is not intended for grounding purposes. Based on the literature review conducted it has been found that, LAA machine can be used for grounding light weight construction materials. The steel balls weighing 390 gm will create the effect of ball milling as they come in contact between themselves and the walls of the machine. In this research the number of balls used was 12 for each cycles of revolution. Therefore LAA machine is used to ground the whole amount of pumice stone used in the research. Figure 3-8 depicts the LAA machine and the spherical balls used for grounding the pumice.

In order to make sure that a fineness level comparable to or greater than OPC is obtained, a trial procedure was conducted to reach a satisfactory level of fineness. After each trial, with a specified revolution, the fineness of the grounded pumice was measured using Air Permeability method, specifically by using Blain apparatus.

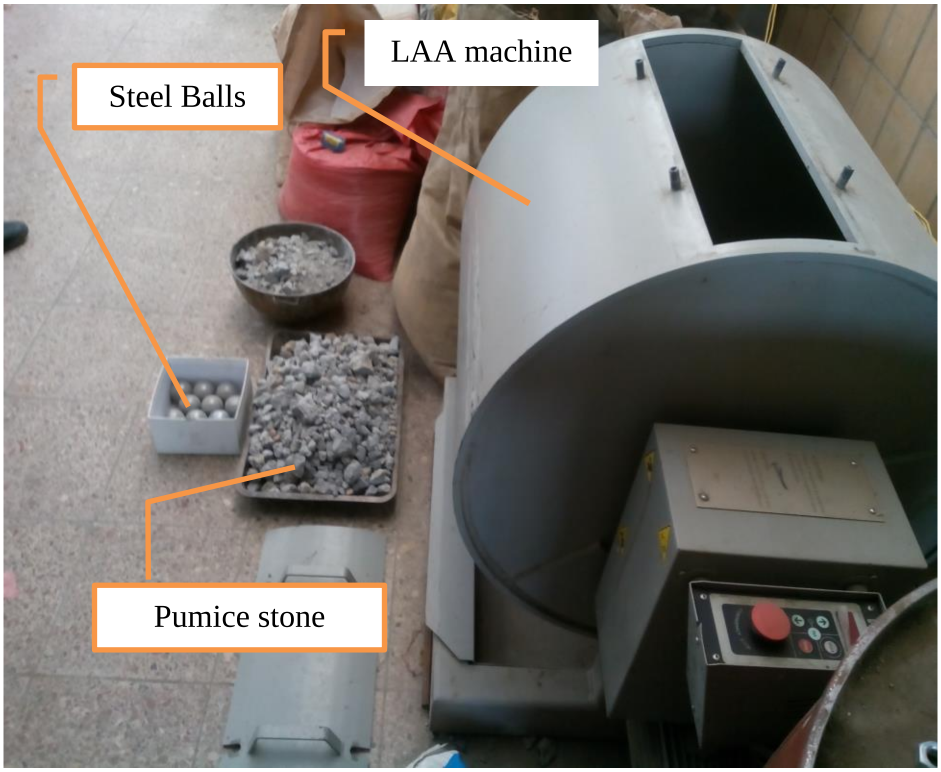


Figure 3-8: LAA machine and steel balls

On the first trial procedure, the LAA machine was set to 1000 revolutions and a fineness of 2,728 cm^2/gm was obtained. This value is compared to the fineness of OPC which is in the order of 3,000 cm^2/gm. Basically, the resulting fineness i.e. 2,728 cm^2/gm is comparable to the fineness level to that of OPC at a physical observation level. The significant level is in the logarithmic scale i.e. in the order of 10,000 or more.

The second trial procedure was done by setting the revolution to 1,500 and a fineness level of 3,533 cm^2/gm was obtained. Consequently, since the result is satisfactory, bulk production of the grounded pumice has continued.

First, pumice stone is oven dried for about 24 hrs with a temperature of 110 ^oC. This will make the pumice stone surface dried and ideal for grounding. Additionally, it has been observed through laboratory work that, wet pumice will not be grounded effectively to the desired level compared to the oven dried one. Such material is also very harsh to work with as it sticks together in the walls of the LAA machine and was unable to pass the 75 micron sieve at the time of sieving.

After oven drying the pumice stone will be air dried for about 1 hr. until the pumice is cooled as shown in Figure 3-9. Since the purpose of the procedure is to ground the pumice stone to fine level, as much as possible, measuring the material weight of pumice stone i.e. before pouring to the LAA machine and after collecting the grounded material was not of much a concern as in the standard procedure of LAA test to measure the abrasion resistance of aggregates. But what has been observed is that, grounding 5-6 kg of pumice stone at once has given better result compared to a bulk amount of material.

Figure 3-9: Air dried Pumice stone ready for grounding

The possible reason being when too much amount of pumice stone is poured on the machine, the tendency of the steel balls colliding with the pumice stone and with the wall of the machine or the chance of finding pumice stone between the steel balls will be much reduced and the only grounding mechanism of the pumice stone will be the contact between the pumice stone particles, which is not effective.

Subsequently, the LAA machine was set and locked at a revolution of 1,500 for about 45 minutes. The resulting material is collected using pan and stored for further sieving as shown in Figure 3-10 (a). In order to obtain the finely grounded pumice for replacement of OPC, the resulting material from LAA machine was sieved using 75 micron sieve as shown in Figure 3-10 (b).

After all, the resulting grounded pumice, as depicted in Figure 3-10 (c), was stored in a dry place until further specimen preparation. By this procedure the required amount for replacing OPC i.e. 65 kg has been prepared.

(a) (b)

(c)

Figure 3-10: (a) Grounded (b) Pumice Sieving (c) Grounded Pumice Powder

3.4.3 Preparation of Aggregates

a) Fine Aggregates

The fine aggregate for use in the mix design has been sieved using 4.75 mm sieve to discard coarser materials. Figure 3-11 shows the natural sand used where the materials coarser than the 4.75 sieve are discarded and the passing material is stocked to be checked for saturated surface dry condition. The main reason for discarding the material coarser than the 4.75 sieve is in order not to reduce the porosity of the resulting mix.

Figure 3-11: Preparation of sand for specimen preparation

b) Coarse aggregate

Coarse aggregate gradation was also adjusted in order not to affect the porosity of the mix. The materials passing the 4.75 mm sieve were discarded. The resulting coarse aggregate coarser than the 4.75 mm sieve is taken as the coarse aggregate for mix design. Due to the lack of specification limits on the gradation of aggregates for pervious cement concrete mixes, the sieve size No. 67 is taken.

3.4.4 Hydraulic Conductivity Apparatus Description

The apparatus used to measure the hudraulic conductivity of the pervious concrete has been developed in laboratory workshop. The constructed apparatus is of the falling head permeameter type.

The apparatus consists of a 110 mm PVC stand pipe for measuring the head of the standing water column, O-clamps for thightning the specimen and the stand pipe, “T” PVC with a 50 mm reducer, a ball valve for controlling the flow of water and drain pipe for draining water. The specimen is held between the two clamps wraped with plastic sheet and rubber for halting side drainage (Figure 3-12).

Since the dimension of the specimen is 100 mm * 200 mm and the diameter of the stand pipe is 110 mm, the gap in between will obviously create a leakage point. Therefore inorder to prevent the resulting leakage, silcon is used as a sealant in combination with rope.

The side drainage of the specimen is prevented using a plastic sheet to wrap the entire surface. The leakage between the pipe and pipe connection and/ pipe and valve conection is also prevented by silicon as a sealant.

The working principle of the apparatus is that, a known depth of water column, h_1, will be maintained with the ball valve closed and the ball valve will be opened to measure another depth ,h_2, after an elapsed time of 't' and the difference between this depths of water column is recoreded as head loss, Δh. Then using the basic Darcy's law (equation 5) the hydraulic conductivity of the specimen will be calculated.

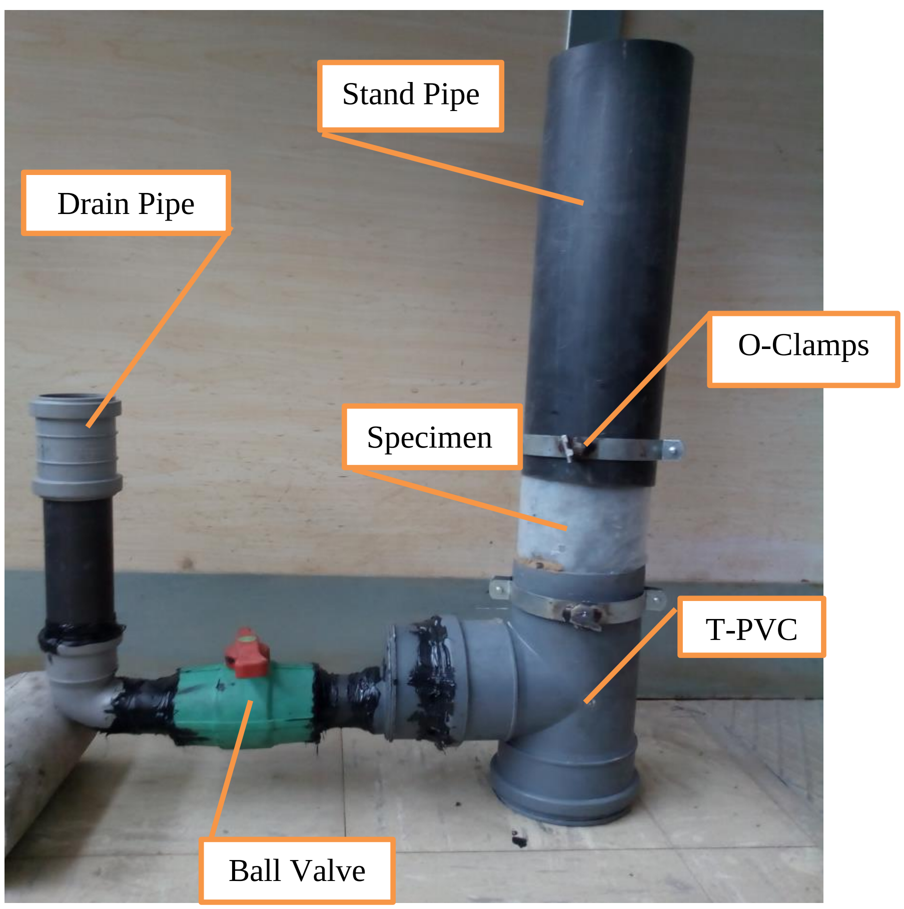


Figure 3-12: Componenets of the Permeability apparatus

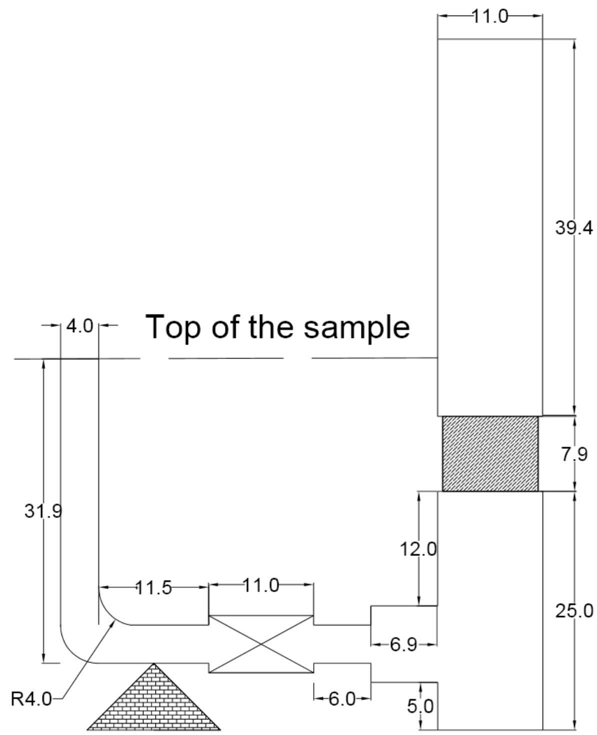


Figure 3-13: Dimensions of the apparatus (cm)

3.4.5 Mix design

3.4.5.1 Pervious Concrete mix design

'ACI 522R-10 Report on Pervious Concrete' has been used as a design guideline to design the whole concrete mix. The design inputs such as unit weight of coarse and fine aggregate, absorption of coarse and fine aggregate, density and specific gravity of the ingredients has first been determined in the laboratory as described on the methodology section of the thesis.

Consequently, using the procedure described in the literature review, the mix design of the mixes i.e. base (0% FA & 0% GP) and mix with 10 % fine aggregate with different levels of grounded pumice replacement (10% FA and XX% GP) has been used to estimate the amount of ingredients used at the same w/b. The desired porosity of the mix was set to be 15%.

This value is in the range of 15-30% porosity which is considered the ideal porosity for good permeability.

It should be bear in mind that in designing mixes for pervious concrete, a so called “base mix” (mix that only contains coarse aggregate, OPC and water) shall first be designed prior to the replacement of OPC by supplementary cementitious material and coarse aggregate by fine aggregate. Therefore a base mix has been designed accordingly. Table 3-2 depicts the mix design properties of the base mix.

Table 3-2: Mix design parameters for the base mix

Mix design Parameter	Value
$V_p(m^3)$ (Paste Volume)	0.23
C (kg/m^3) (Cement Content)	344.96
W_w (kg/m^3) (Water Content)	120.74
W_{FA} ,Fine Aggregate Weight, kg	0.00
$V_a(m^3)$ (Volume of aggregates)	0.6
$V_c(m^3)$ (Volume of Cement)	0.11
$V_w(m^3)$ (Volume of Water)	0.12
V_{FA}, Volume of Fine Aggregate, (m^3)	0
$V_s(m^3) = V_a + V_c + V_w$ (Volume of Solids)	0.83
Percent Voids (%)[A]	16.57

[A] This void is the predicted void and is always greater than the anticipated void after mix design. The reason being the compaction mechanism employed.

Subsequently the control mix has been designed by replacing the coarse aggregate with 10% fine aggregate and OPC with pumice at different replacement level. The control mix contains coarse aggregate, fine aggregate, OPC and water. No grounded pumice was used. For a desired porosity of 15% and w/b of 0.35 the control mix has a paste content of 0.22 m^3. The total volume of solids including the aggregates, water and cementitious material was estimated to be 0.85 m^3. The cement content of the control mix was estimated to be 338 kg/m^3. The aggregate content per m^3 of pervious concrete mix on SSD basis is 1,430 kg.

Table 3-3 depicts the summary of the mix design for the control mix. Appendix D has the detailed mix design procedure for all types of mixes.

Table 3-3: Summary of the mix design for the control mix

Mix design Parameter	Value
$V_p(m^3)$ (Paste Volume)	0.22
C (kg/m^3) (Cement Content)	338.06
W_w (kg/m^3) (Water Content)	118.32
W_{FA} ,Fine Aggregate Weight, kg	149.21
$V_a(m^3)$ (Volume of aggregates)	0.57
$V_c(m^3)$ (Volume of Cement)	0.11
$V_w(m^3)$ (Volume of Water)	0.12
V_{FA}, Volume of Fine Aggregate, (m^3)	0.06
$Vs = V_a + V_C + V_W + V_{FA}$ (m^3)	0.85
Percent Voids (%)	14.65

As tabulated on Table 3-3 the paste volume has decreased by 4.35% compared to the base mix. This is to account the addition of 10% of sand as the sand will occupy and/ displaces the cement paste. The w/b content has been maintained the same to the base mix. Additionally the amount of coarse aggregate on SSD basis has decreased from 1,522 kg to 1,430.08 kg compared to the base mix.

This happens because the parameter b/bo, that accounts the percentage of coarse aggregate on the total volume of concrete, has decreased from 0.99 to 0.93 to account the 10% sand used to replace the coarse aggregate. The cement content has also decreased form 344.96 kg/m^3 to 338.06 kg/m^3 to account the replacement of coarse aggregate by 10 % of sand. The percentage of voids has also decreased, at least theoretically, to account the presence of fine aggregates.

Therefore, the total amount of concrete needed for each test has been determined using the mix design results. The type of tests that have been conducted and the concrete demand has been tabulated in Table 3-4.

Table 3-4: Type of tests and their concrete demand

Sr. No.	Type test	Specimen dimensions [A]	Volume (m^3)	Expected Test repetitions	Total volume (m^3)
1	Compressive strength	0.15*0.15*0.15	0.00338	108	0.365
2	Split tensile strength	0.15 * 0.3	0.00530	108	0.572
3	Density and void content cylinders	0.1*0.2	0.00157	36	0.057
4	Density and void content cylinders (Fresh)	-	0.00685	9	0.062
				Sum of concrete	1.055
				With 5 % wastage	1.108

[A] all dimensions are in meter

A total of 261 specimens are prepared for all types of tests. The tests for compressive and split tensile strength are conducted for 3, 7, 28 and 56 days whereas the test for permeability test is done at 28 days. The mix design material demand has been tabulated on Annex D.

3.4.5.2 Mortar mix design

In order to calculate the SAI of the grounded pumice mortar mix design was necessary. Therefore the mortar mix was designed using ASTM C 109 recommendation. The mix design ingredients and their content are depicted on Table 3-5.

3.4.6 Trial mix design

The mix design used for trial is the base mix i.e. containing only coarse aggregate, OPC and water. The target void content in the mix was taken to be 18%. The cement and water content of the trial mix was 335 kg/m^3 and 100.01 kg/m^3 respectively. Table 3-6 shows the ingredient contents of the mix.

Table 3-5: Mortar Mix design and demand

Sr. No.	Type of test	Type of Mix	Specimen Dimension (m)	Volume (m^3)	No. of Samples	Mortar Demand(m^3)
1	SAI	Control	.05*0.05*0.05	0.000125	6	0.00075
2	SAI	GP Replaced (10%)	0.05*0.05*0.05	0.000125	6	0.00075
3	SAI	GP Replaced (20%)	0.05*0.05*0.05	0.000125	6	0.00075
4	SAI	GP Replaced (30%)	0.05*0.05*0.06	0.000125	6	0.00075
Sr. No.	Type of Mix	Unit	Sand	Cement	Pumice	Water
1	Control	Kg	1.38	0.50	0.00	0.24
2	GP Replaced (10%)	Kg	1.38	0.50	0.05	0.24
3	GP Replaced (20%)	Kg	1.38	0.50	0.10	0.24
4	GP Replaced (30%)	Kg	1.38	0.50	0.15	0.24
		Sum	5.500	2.000	0.300	0.968
		Sum (10% Wastage)	6.050	2.200	0.330	1.065

Three compressive strength cube samples with dimensions of 0.15 m * 0.15 m * 0.15 m and three split tensile strength samples with dimensions of 0.15 m * 0.3 m were casted. For permeability and void content tests, one cylindrical specimen with a dimension of 0.1 m * 0.2 m was casted. In order to estimate the fresh density and void content of the mix a 0.0068 m^3 of measure is used.

3.4.6.1 Mixing, compaction and curing procedure

A pan type mixer with 0.5 m^3 capacity was used. First 5% of the cement and aggregate from the trial batch was mixed with 50 % of the total water for about one minute. Then by adding the remaining ingredients the mix was mixed for three minutes. After resting for three minutes the mix was again mixed for two minutes until a uniform mix was obtained.

The specimen is then poured into molds where each mold is painted with oil so that the specimen will be de-molded by retaining its shape.

Table 3-6: Ingredient contents of the trial mix

Mix design for Trial mix						
Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
	Unit	kg	kg	Kg	kg	kg
1	Per Unit Volume of Pervious Concrete (kg/m^3)	1,522.34	0.00	0.00	335.70	100.71
2	Compressive Strength	15.41	0.00	0.00	3.40	1.02
3	Split Tensile Strength	24.20	0.00	0.00	5.34	1.60
4	Density and Void Content	10.43	0.00	0.00	2.30	0.69
5	Permeability	8.07	0.00	0.00	1.78	0.53
6	Sum	58.11	0.00	0.00	12.81	3.84
7	Absorption of CA (%) = 2.18					
8	Adjusted for Absorption	58.11	0.00	0.00	12.81	3.93
9	Sum with 10% wastage	63.92	-	-	14.09	4.32

CA = Coarse aggregate FA = Fine aggregate GP = Grounded Pumice C = Cement W = Water

For compressive, split tensile and permeability specimens the concrete is casted in three layers in which each layer is compacted for 25 strokes and for fresh density and voids test the specimen is poured with two layers in which each layer has been compacted with a standard proctor hammer for 20 drops.

The specimens for compressive, split tensile and permeability are also vibrated for 5 seconds using plate vibrator. Figure 3-14 shows the casted specimens (A), de-molded specimens (B) and compacted fresh density specimens (C).

After the samples are casted the specimens will stay in the molds for 24 hours and will be de-molded and then are cured in the water bath for seven days. Figure 3-15 shows specimens being cured in water till testing day.



Casted specimens (A) De-molded specimens (B) Fresh density specimen (C)

Figure 3-14: Casted specimens (A), De-molded Specimens (B) and Fresh density (C)

Figure 3-15: Specimens inside a curing bath

3.4.6.2 Trial Test results

a) Fresh density and void contents

For fresh density and void content specimen the mass and volume of the measure has first been measured. Then the mass of the measure with the specimen is measured. The net concrete mass, M_c was found to be 12.78 kg. The MTD, maximum theoretical density, of the mix was found by adding the contents of OPC, coarse aggregate (SSD basis) and water i.e 335.71 kg/m^3, 1,522.34 kg/m^3 and 100.71 kg/m^3, respectively, and was found to be 1,960.75 kg/m^3.Then using the equations described in the literature review the fresh density, D, and the voids are found to be 1,838.90 kg/m^3 and 6%, respectively.

b) Compressive strength test results

The compressive strength of the trial mix was estimated from cubic specimens by applying compressive force at a loading rate of 0.14 to 0.34 MPa/sec until the specimen fails. The average maximum load carried by the specimen as indicated by the testing machine was 165.37 KN. Therefore the average seven day maximum compressive strength of the specimen as calculated was found to be 7.3 MPa.

c) Splitting tensile strength test results

The splitting tensile strength of the trial pervious concrete mix are estimated from cylindrical specimens by applying diametral compressive force along the length of cylindrical concrete with the loading rate of 689- 1380 kPa/min. The average maximum applied load as indicated on the machine was found to be 54.4 kN .The seven day average splitting tensile strength calculated using equation 6 was found to be 0.77 MPa.

d) Hardened Density and Porosity

The specimens used to estimate the hardened density and porosity of the samples are 10*20 cm cylindrical samples. The hardened density and porosity of the samples were estimated by measuring the air dry weight, the weight of the specimen measured inside water and the volume of the specimen. Accordingly, the hardened density and porosity of the sample was found to be 1,856.89 kg/m^3 and 25 % respectively.

e) Hydraulic conductivity and/ permeability

The permeability of the specimens was measured using a variable head permeability apparatus constructed in the laboratory. The hydraulic conductivity of the samples was found to be 0.018 m/s.

3.4.6.3 Lessons learnt from trial test

In the trial tests conducted the following points have been learnt for conducting the performance tests:-

1) Fresh density and porosity test does not typically represent the actual fresh properties of the pervious concrete,
2) Compaction method shall be changed to heavy compaction as described in the literature review,
3) Cement content and/ paste volume shall be increased:
    a) to increase the compressive and splitting tensile strength
    b) to reduce the voids in the previous concrete
4) Strict loading rate control in splitting tensile strength shall be maintained to get a fairly representative values ,
5) The hardened density and porosity of the samples were found to be consistent to the theoretical values obtained in the mix design.
6) Improved/ tight leakage control in the hydraulic conductivity apparatus shall be maintained to obtain fairly consistent results,
7) While conducting the splitting tensile strength test uniform diametral load distribution is crucial and so to achieve this, specimen preparation is necessary. Therefore, for the control experimental test specimens a thin line of gypsum is painted to fill the voids and create a uniform load distribution platform. Figure 3-16 (a) depicts the specimen lined with gypsum and (b) failed specimen under uniform loading.

(a)

(b)

Figure 3-16: Gypsum lined specimens (a) Failed specimen under load (b)

CHAPTER FOUR

4. RESULTS AND DISCUSSION

4.1 Consistency driven water demand

Most of the mix design methods for concrete are based on the typical behavior of Portland cement. But the recent global show of appetite for the application of supplementary/sustainable cementitious materials, SCM, in concrete production, has posed a threat for obsolesces of such mix design methods (argument of the researcher).

The behavior of SCM, typically grounded pumice, when used as partial replacement to cement varies uniquely (Nihat, et.al , 2015). It has been reported that, the behavior of SCM, for example as in grounded pumice, its addition has resulted an increase in water content to achieve standard consistency (Karatas, et.al , 2017).

In this research, the fact that the addition of grounded pumice in the concrete mix demands more water than its OPC counterpart, has been taken into account and/ considered by using standard consistency test results. Thus the mix design for the control mix was adjusted based on the consistency driven water demand requirement for each levels of replacement.

Figure 4-1 shows the increase in water demand to reach a standard consistency by grounded pumice. The control cement paste has reached its standard consistency by a w/c of 0.27 and the 30% grounded pumice replaced paste (water + cement + grounded pumice mix) has reached its standard consistency with a w/b of 0.32. Thus the increase in water demand is 19% at 30% replacement level. This value is very significant as it plays a vital role in the hydration process later and on the physical property of the mix, such as workability, earlier.

Therefore by taking into account the previously stated fact, the mix design of the pervious cement concrete was adjusted according to the water demand of each replacement levels which is in turn caused by the addition of a highly water demanding and/ thirsty cementitious material called, grounded pumice. Short and precisely, it is not logical to compare two different materials with different characteristics. Table 4-1 provides the mix water content for pervious concrete.

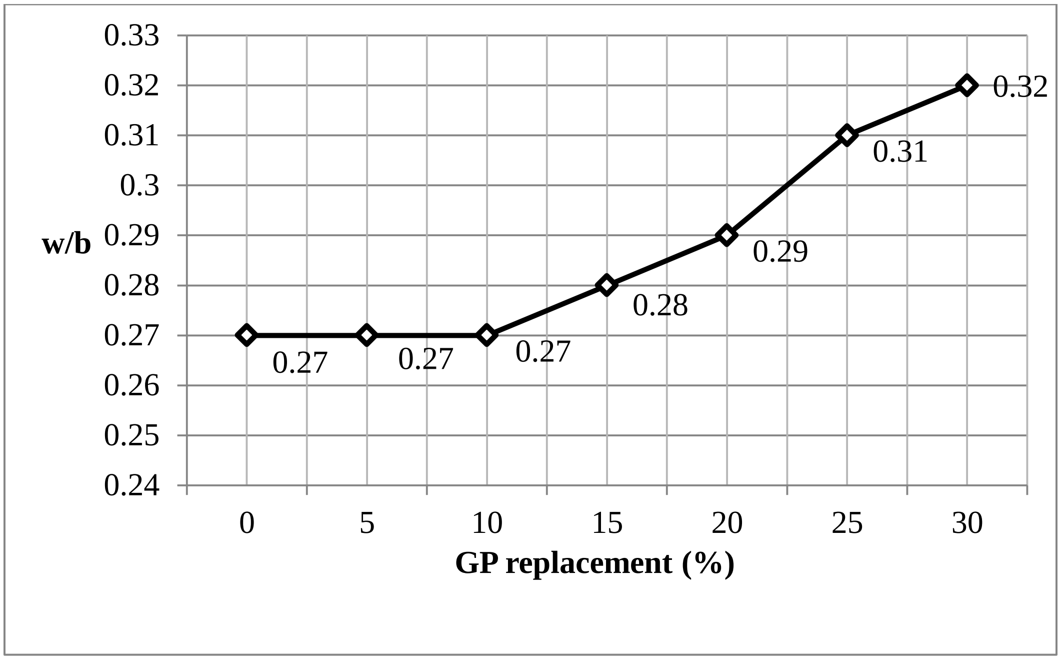


Figure 4-1: Water demand as per the consistency test result

Table 4-1: Water Content for Mix Design

Mix ID	Water Content (kg/m^3)	Remark
10% FA_0_GP	118.32	Control
10% FA_5_GP	118.32	The same w/b
10% FA_10_GP	118.32	The same w/b
10% FA_15_GP	123.05	4% increment
10% FA_20_GP	126.60	7% increment
10% FA_25_GP	136.07	15% increment
10% FA_30_GP	140.80	19% increment

4.2 Pozzolanic/ Strength Activity Index

The measure of reactivity of supplementary cemenitious material with cement is known to be measured by PAI/SAI. As per (ASTM, 1998) either the 7th or the 28th day specification limit can be used as compliance to the specification.

Accordingly, the SAI of the 7th day for control, 10% GP replaced mix, 20% GP replaced mix and 30% GP replaced mix is 100%, 67%, 64% and 54 % respectively. The ASTM requirement is 34% and subsequently the 7th day requirement is full field.

But if we look at the 28th day SAI values i.e 100%, 74%, 70% and 59% for control, 10% GP replaced mix, 20% GP replaced mix and 30% GP replaced mix, respectively, the requirement as specified on the ASTM, which is 75%, is not met (Figure 4-2). The possible reason being, with the progression of time, the hydration process in concrete mixes decreases and this will also affect the reaction of the pozzolanic material. Also as in (Alex , et.al , 2017) grounded pumice has not met the requirement until 28th day.

One interesting fact that can be seen from the results is that, if we compare the reactivity (i.e. rate of strength development) of the mixes by comparing the 7th and 28th day compressive strength of the mortar cubes, as depicted on Figure 4-3, the reaction progression of the control, 10% GP replaced mix, 20% GP replaced mix and 30% GP replaced mix are 51.2%, 68.3 %, 65.8% and 54.9 % respectively. Hence the mix containing 10% grounded pumice shows the highest reaction progression than any other mixes. This will be further explained as the 10% grounded pumice replaced mix in the concrete shows higher compressive and splitting tensile strength values than its control counterpart (Please refer section 4.3 and 4.4).

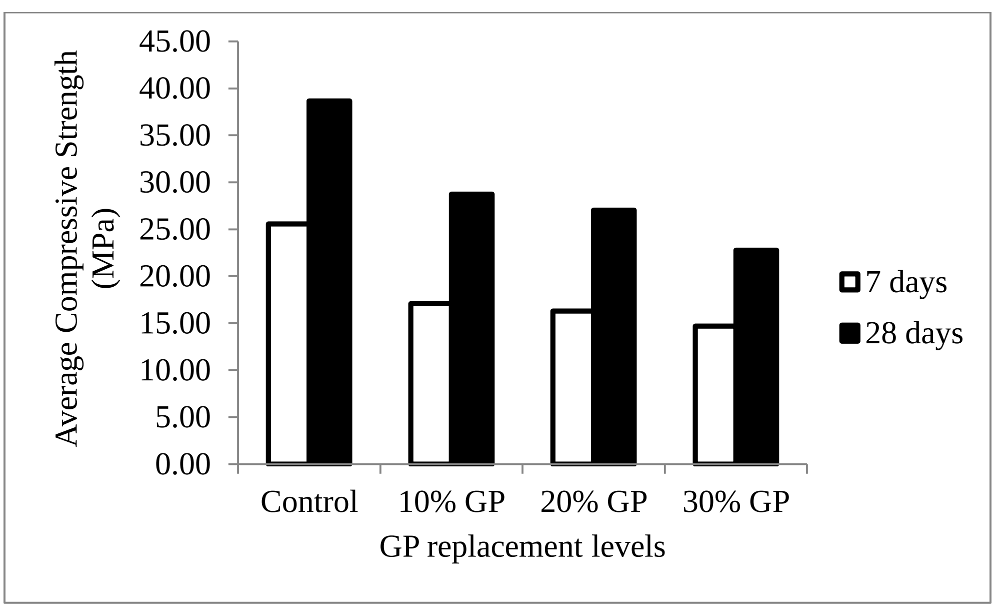


Figure 4-2: SAI at different replacement levels

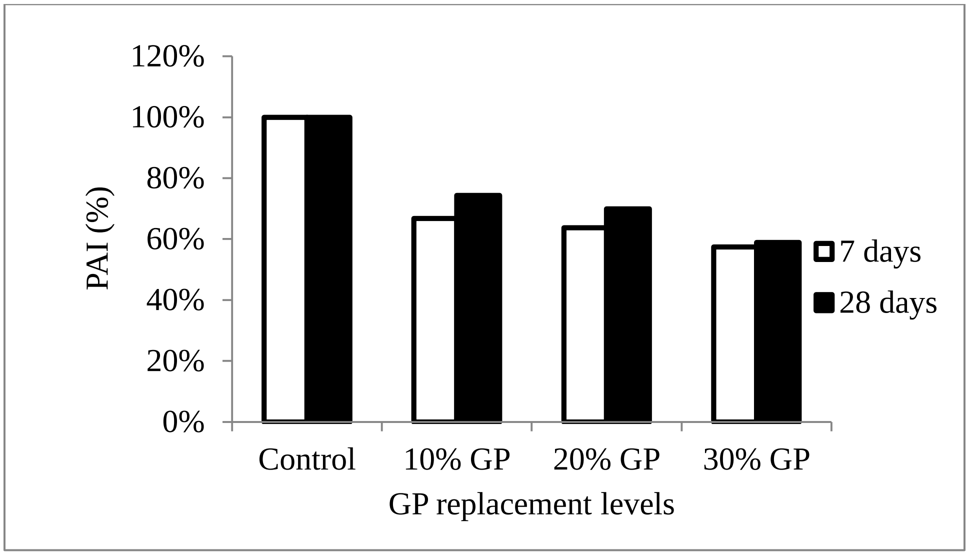


Figure 4-3: PAI of mortar cubes

4.3 Compressive strength

The compressive strength of cubic specimens at different days of curing has been checked for different replacement levels of grounded pumice. The specimens have been cured for 3, 7, 28 and 56 days. Figure 4-3 shows the compressive strength of the specimens at different days of curing.

As can be seen on Figure 4-3 the average compressive strength of the control mix i.e. 10% FA 0% GP at 28^{th} day, for example, is 15.85 MPa. In the specified date, the compressive strength of the 10% FA_5% GP, 10% FA_10% GP, 10% FA_15% GP are 17.60 MPa, 16.54 MPa and 16.53 MPa respectively.

Hence the replacement of grounded pumice at 5%, 10% and 15% has increased the average compressive strength by 11%, 4%, and 4 % respectively. Such an increase of compressive strength on the conventional concrete by the addition of grounded pumice was observed up to 15% replacement level (Özcan & Koç, 2018).

There can be many factors that can be listed for the increase of the strength obtained by the addition of grounded pumice. The usual and most common rhetoric for the increase in strength is, the presence of SiO_2 and Al_2O_3 which favors the formation of additional C-S-H and C-A-H by reacting with portlandite forming a denser matrix (Hieronimi, et.al, 2019).

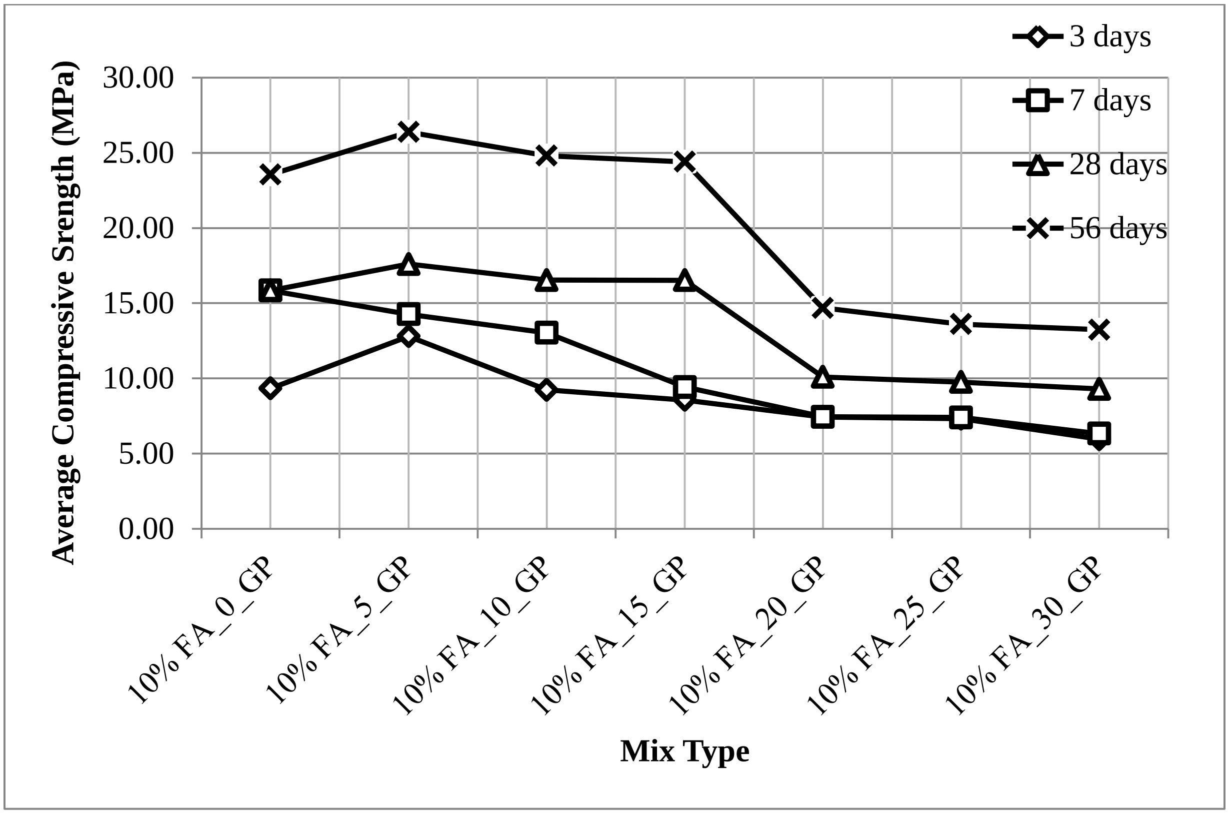


Figure 4-4: Average Compressive Strength of Cubic Specimens

Therefore, grounded pumice can replace ordinary Portland cement at replacement levels of 5%, 10% and 15 % without compromising strength and with a slight effect on permeability. The best replacement level for higher amount of compressive strength is at 5% and other replacement levels such as 10% and 15% are also possible. The optimum level of replacement of pumice in the past agrees with the findings of this research for pervious concrete, say for example, in high strength self-compacting mortars the optimum replacement level was found to be 15% (Samimi, et.al , (2017)).

4.4 Splitting tensile strength

The splitting tensile strength of cylindrical specimens at different days of curing has been checked for different replacement levels of grounded pumice.

The specimens have been cured for 3, 7, 28 and 56 days. Figure 4-5 shows the splitting tensile strength of the specimens at different days of curing.

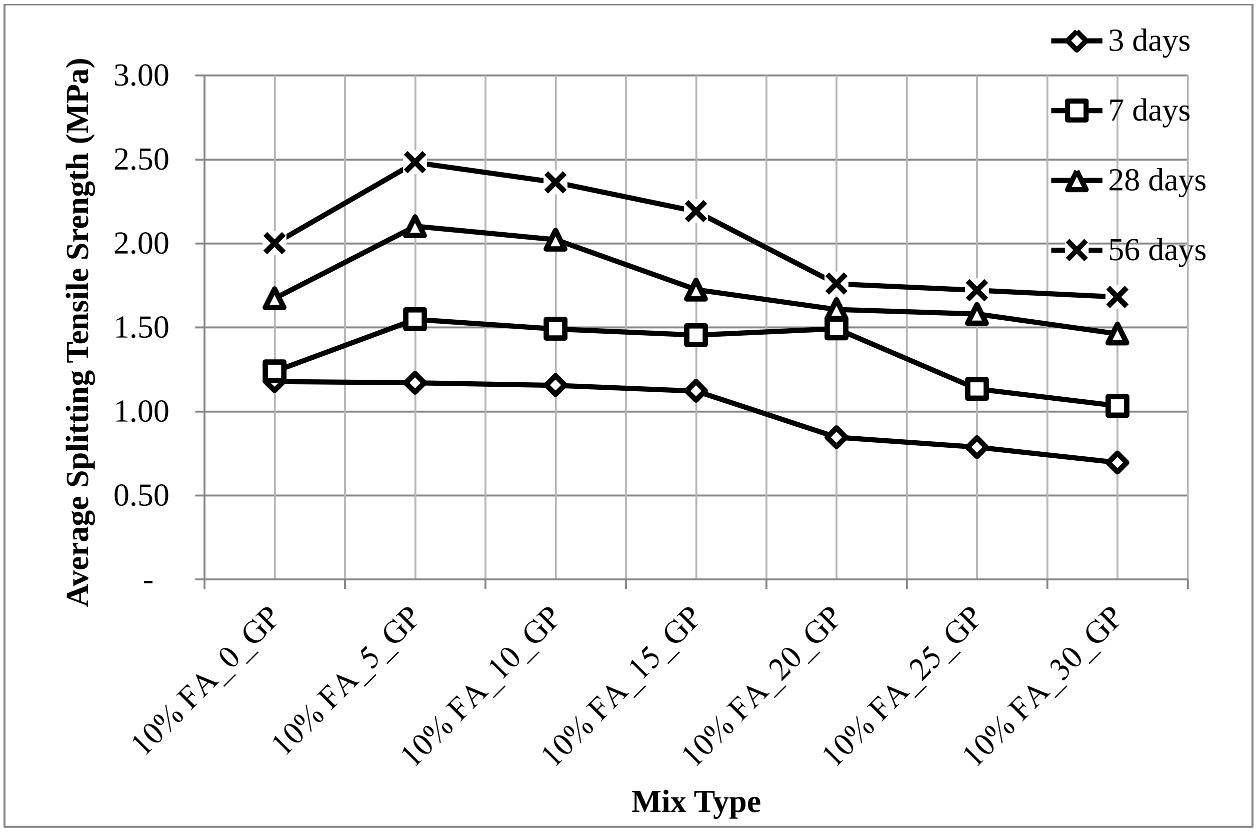


Figure 4-5: Splitting Tensile strength of cylindrical specimens

It can be seen on Figure 4-5 that, the average splitting tensile strength of the specimens at say, for example, 28 days for the control mix i.e. 10%_FA_0%_GP is 1.67 MPa. The average splitting tensile strength of the experimental mixes i.e 10%_FA_5% GP, 10%_FA_10 % GP and 10%_FA_15% GP were found to be 2.10 MPa, 2.02 MPa and 1.73 MPa respectively. The enhancement in tensile strength compared to the control mix is 26%, 21% and 3%.

There can be different reasons for the increase in tensile strength by replacement of cement by grounded pumice. Hieronimi, et.al, 2019 has founded that, the increase in strength is due to high amount of C-S-H and C-A-H in the microstructure resulting from good progression of pozzolanic reactions favored by low amount of Fe_2O_3. Accordingly, the 5% replacement level has been found to be the best replacement level and other replacement levels such as 10% and 15 % also have positive role.

4.5 Hydraulic conductivity (permeability)

The hydraulic conductivity of the control pervious mix is measured to be 0.017 m/s. This was found to be the highest of all the mixes. The mix which exhibits the least conductivity is the 10%_FA_30% GP which is 0.001 m/s.

The hydraulic conductivity of the pervious cement concrete mix decreases substantially and the possible reason being, the decrease in the interconnected porosity leading to the presence of larger paste volume due to the addition of extra amount of water as per the consistency driven water demand proposed. In a research paper that examines the effect of paste thickness on the performance of pervious concrete, it has been found that, thicker cement coating will lead to a lower percolation rate by reducing the porosity (Anthony, et.al, 2015).

As shown on Figure 4-5 a sharp decrease in the conductivity of the pervious cement concrete mix was observed for 10%_FA_15%_GP. This is due to the addition of a higher amount of water and/ increase in paste volume than the control mix leading to the sharp decline in the permeability of the mix.

4.6 Hardened Density

The hardened density of pervious mix at different grounded pumice replacement level was investigated.

The control mix is the denser mix compared to the other mixes. Hardened density gently decreases as the replacement level of grounded pumice increases as depicted on Figure 4-7. This can be related to the lower density inherited by pumice. Therefore this lower density was reflected on the pervious concrete mix.

It has also been observed in self-compacting mortars that, the density of mix decreases as the content of grounded pumice powder increases because of the rough and porous structure of grounded pumice (Karatas, et.al , 2017).

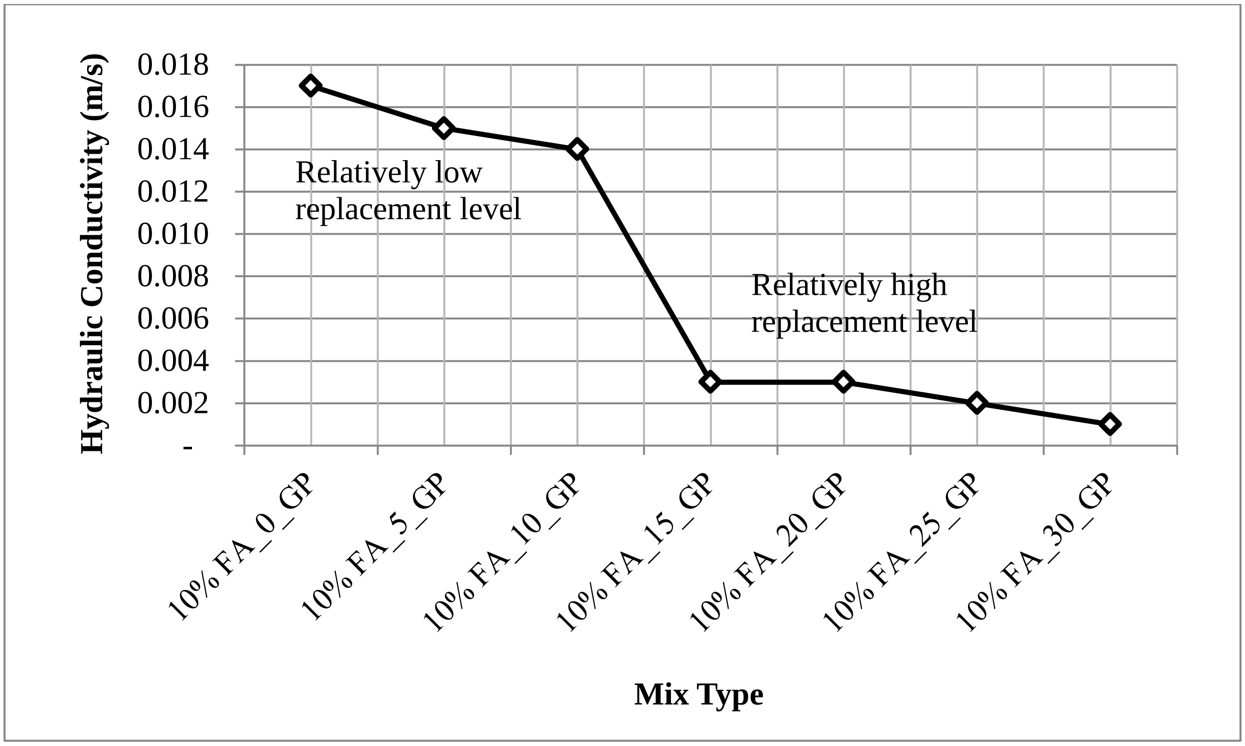


Figure 4-6: Hydraulic conductivity

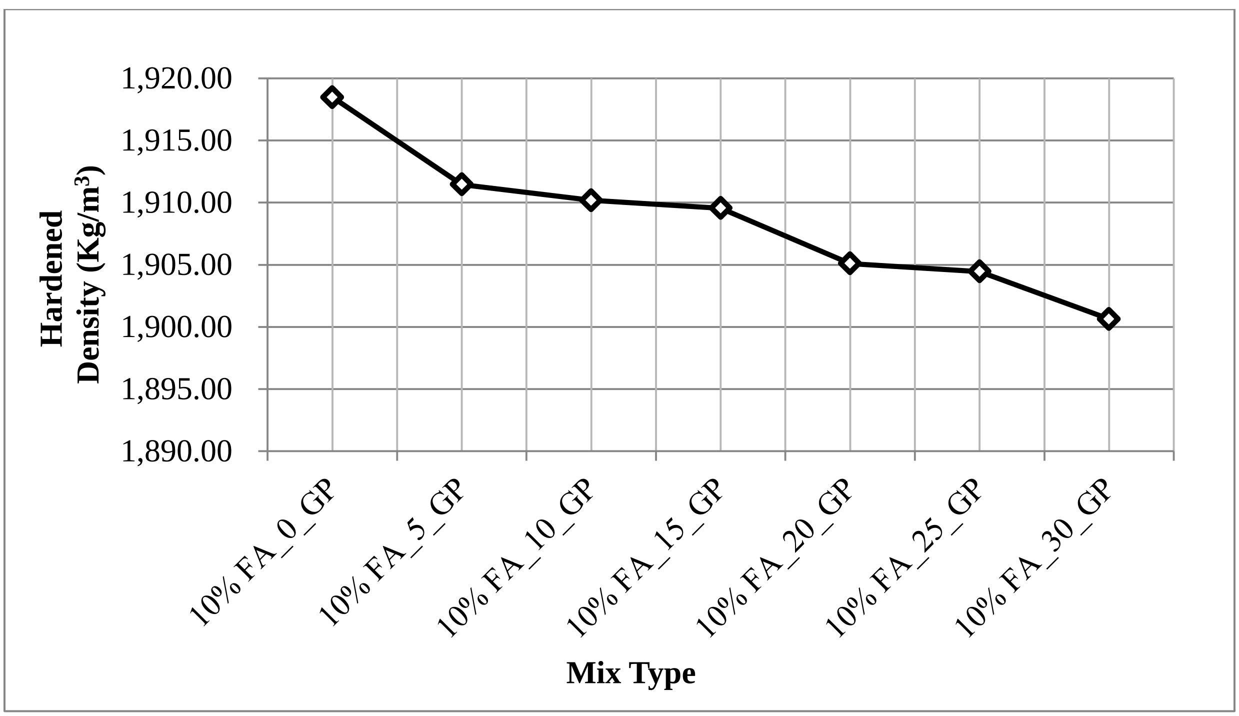


Figure 4-7: Hardened density

4.7 Compressive Strength, Splitting tensile Strength and Porosity

Unlike the usual case, where the compressive strength increases as the interconnected porosity decreases; for example as in a paper (C. Liyan, et.al, 2011), the trend as shown on Figure 4-8 follows the opposite scenario. The main reason is, the addition of extra amount of water leading to the increase in paste volume which in turn decreases the porosity and the compressive strength.

When the water content increases, the void which was previously filled with air will gradually be substituted by cement paste leading to the substantial decrease in the porosity. For compressive strength also, the addition of more water means the formation of weak structure.

Additionally, the addition of grounded pumice beyond the optimal level has also shown to decrease the compressive strength. This has been depicted in the case where the compressive strength has decreased when the replacement level of pumice increases from 5% to 10% albeit the w/b remains the same.

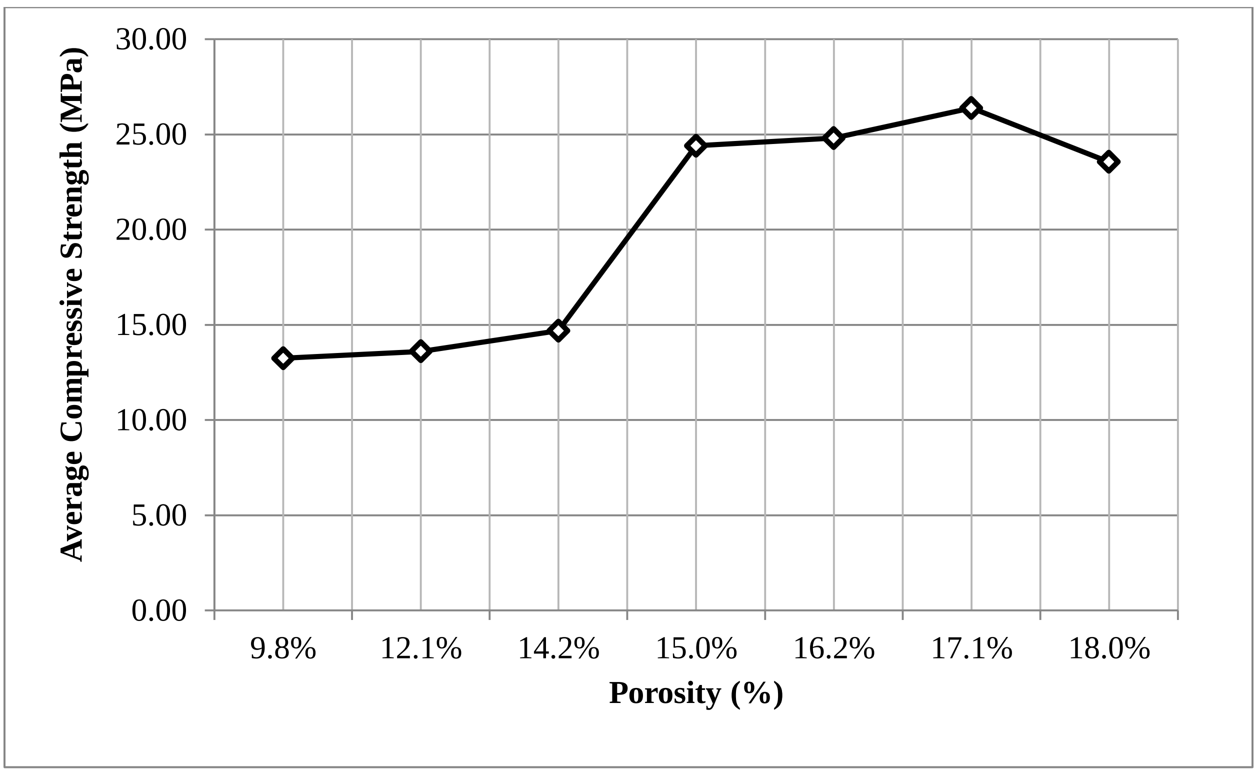


Figure 4-8: Average compressive strength Vs Porosiy

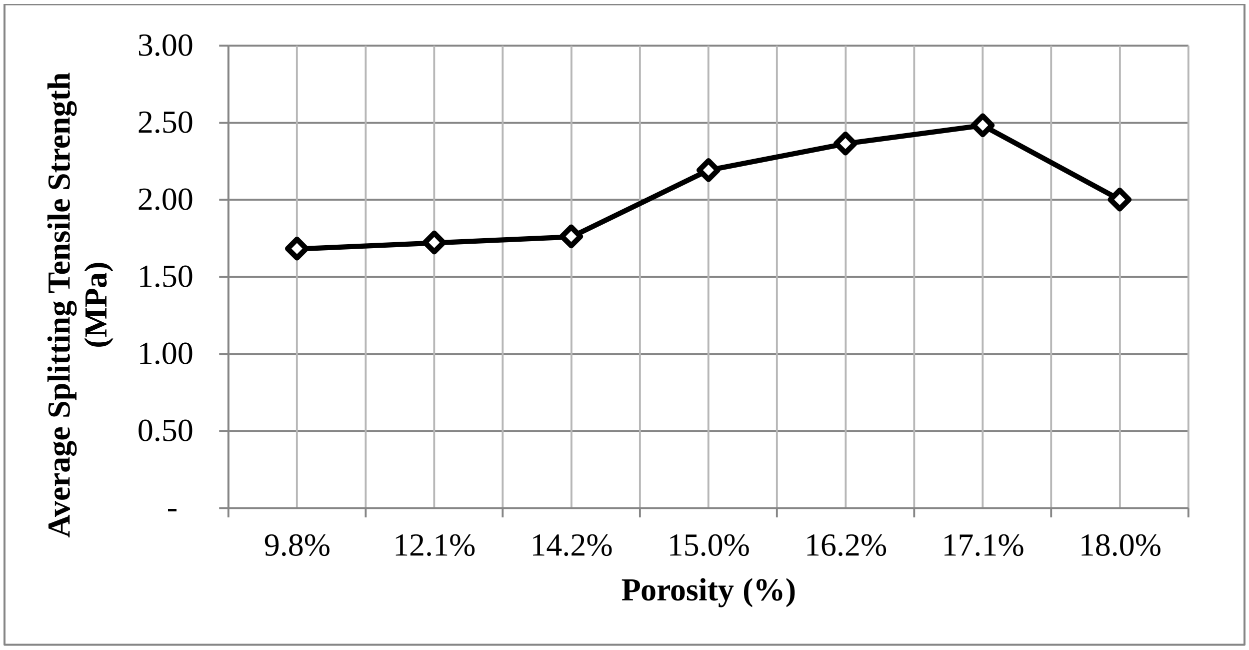


Figure 4-9: Average splitting tensile strength and Porosity

Similar trend has also been observed for splitting tensile strength. The same reason might be put forward as in the case of the compressive strength i.e. the addition of water has clogged voids i.e. more paste, by increasing the paste volume which in turn results the formation of weak hydration structures/products. Figure 4-9 depicts the relation between porosity and splitting tensile strength.

4.8 Hydraulic Conductivity and Porosity

The relation between conductivity and porosity of the mixes is directly related. This is indicated in Figure 4-10 as the porosity decreases so does the conductivity of the mixes. This general trend is also observed by Ibrahim, et.al, (2014) in which the measured porosity is the total porosity.

The main reason for the decrease in permeability is the filling of the porosity by cement paste and probably the decline of the interconnectedness of the pores. The sharp increase in permeability, provided that the increase in porosity is insignificant remains a puzzle for the researcher. But the hypothetical reason might be the increase in interconnected porosity.

(Note that, total porosity is different from interconnected porosity and interconnected porosity is the one that is capable of draining)

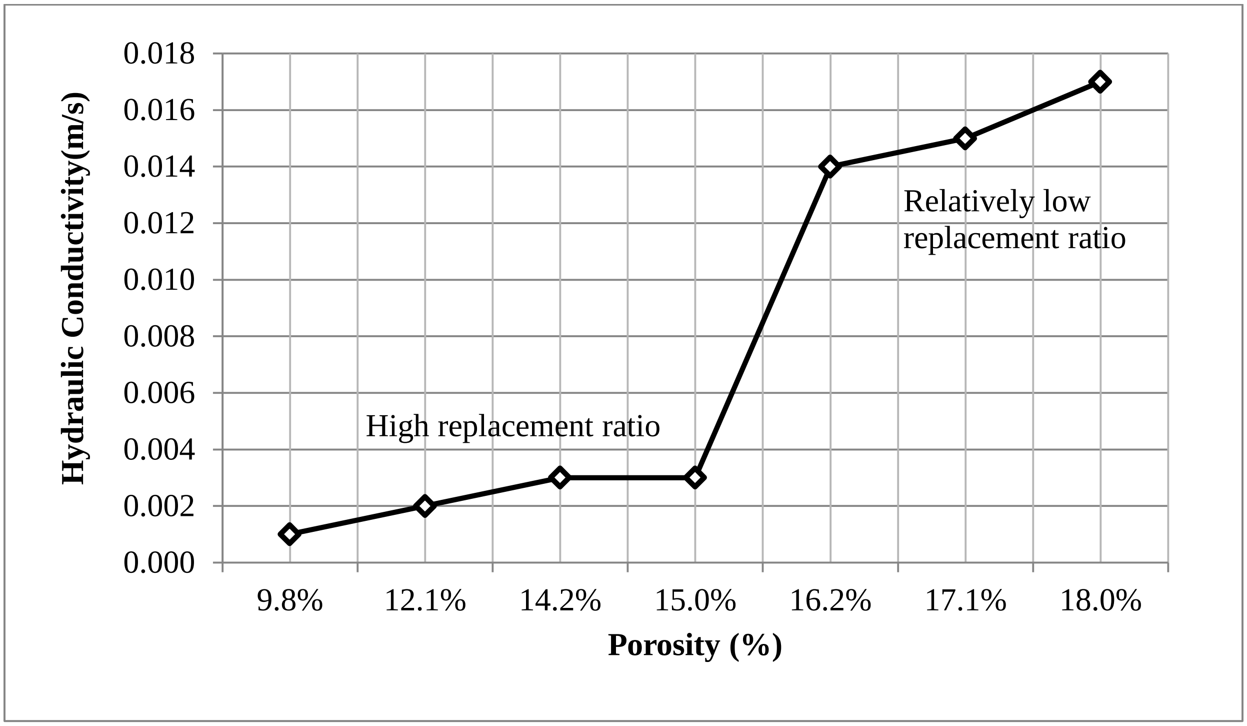


Figure 4-10: Relation of porosity and hydraulic conductivity

4.9 Hardened density, Compressive strength and splitting tensile strength

The relation between hardened density and average compressive strength of the pervious mix follows a general increment trend i.e as the hardened density of the mix increases so does the compressive strength of the pervious mix. This is attributed to the formation denser aggregate cement matrix leading to higher compressive strength.

Regarding the relation between the hardened density of the pervious mix and the corresponding splitting tensile strength, the splitting tensile strength increases as the hardened density increases. The formation of relatively denser cement to aggregate matrix is believed to be responsible for the increase in strength up to 15% replacement level.

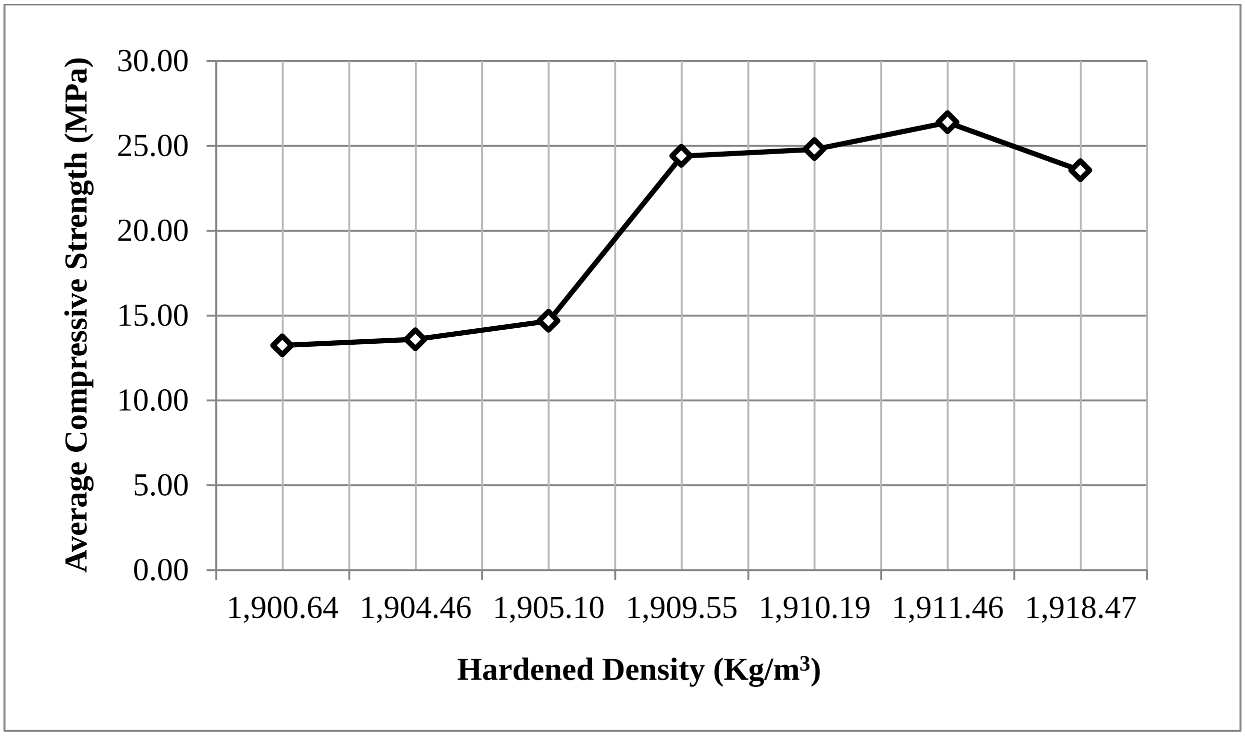


Figure 4-11: Average compressive strength and Hardened density

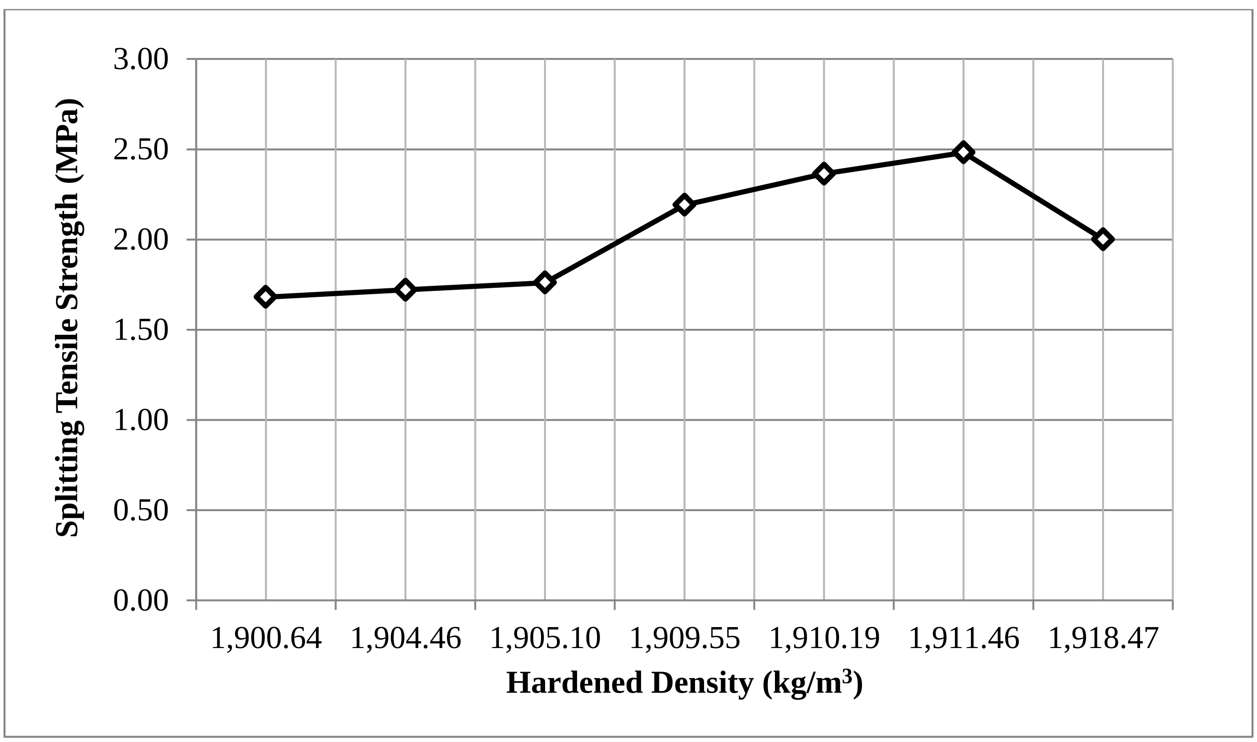


Figure 4-12: Average splitting tensile strength and Hardened density

CHAPTER FIVE

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this research, an effort has been made to characterize the performance of grounded pumice on pervious cement concrete. The characterization was made using compressive, splitting tensile strength and hydraulic conductivity tests. Other tests on the hardened specimens have also been conducted.

This research has been able to reach a set of defined characterizations of pervious concrete containing grounded pumice as partial cement replacement. The following conclusions and/ findings can be drawn:-

1) Grounded pumice can partially replace OPC with the added benefit of increasing the strength and with little impact on the permeability of the pervious mix. The reduction in cement production i.e. cost wise and the mitigation of environmental impacts by OPC bulk production are also the other uses that can be considered.
2) Grounding Pumice stone by LAA can produce the desired fineness level.
3) The water demand of the grounded pumice has also been assessed. What has been learnt is that, it is very crucial to adjust the mix design ingredient estimation (i.e. mix design formulated in consideration of OPC as a cementitious material) by the amount suitable for obtaining desirable mix property. The desirable mix property is to mean a mix with an acceptable fresh and hardened properties i.e. workability and strength.
   What has been observed by the standard consistency test is that, cement paste containing grounded pumice at 30% replacement, needs 19% additional amount of water to reach standard consistency. Therefore a consistency driven water demand is proposed to mix pervious concrete containing grounded pumice as a cementitious material.
4) The reactivity of grounded pumice with OPC has also been assessed. The reactivity of grounded pumice at the 7th day meets the specification requirement. Most importantly, the reaction progression of grounded pumice was much higher than its OPC counterpart.
5) The performance of pervious concrete containing grounded pumice at different replacement levels has also been assessed.

With a control group and experimental groups compared, the replacement of grounded pumice has resulted in higher compressive strength. The highest compressive strength obtained was with the 5% replacement level with 11% increase in strength compared to the control mix. Other replacement levels up to 15% will also increase the compressive strength of pervious mixes. Therefore grounded pumice can replace OPC up to 15%, without affecting the permeability of the mix and with little impact on the physical properties such as density.

6) The effect of replacing OPC with grounded pumice as a pozzolanic material has also been assessed and its performance with respect to splitting tensile strength has been measured. What has been learnt is that, addition of grounded pumice will enhance the splitting tensile strength of pervious mix. The highest increase in strength was obtained at a replacement level of 5%. The increase in strength was found to be 26% and replacement levels up to 15% were observed to increase the splitting tensile strength of pervious mix as compared to the control mix.
7) The hydraulic conductivity of pervious mix containing different levels of grounded pumice was measured using falling head permeability equipment constructed in laboratory. The permeability of the mix decreases as the grounded pumice replacement level increases. This is attributed to the additional water added because of the presence of grounded pumice. The ideal replacement level that will reconcile permeability and strength (both in compressive and splitting tensile) is the range of 5-10 % replacement level.
8) Hardened density was observed to decrease as the grounded pumice replacement increases. Therefore the replacement of grounded pumice decreases the density of the pervious mix. But the reduction is not significant as it is countered by the addition of water.

5.2 Recommendations and future research

It is known that, innovation on construction materials has been growing since the beginning of the endeavor of mankind to shape nature for his consumption. In doing so, consideration on value for money and environmental impacts has been targets.

The road construction sector is no exception. The introduction of adding SCM's on concrete has enabled the industry to combat environmental challenges apart from producing economical building material.

Pervious concrete, with its vital uses, is believed to be one of the innovations made on the pavement sector. The reduction of runoff on urban streets, damping capability of noise generated by traffic and reduction of cement consumption are of its main benefits carried by pervious concrete.

Addis Ababa is a city grappling with problems related to runoff and alternate pavement material. Almost all of the entire pavement constructed in the past and currently is by impermeable pavement. Not only is the pavement impermeable, but it is also not environmentally friendly.

Therefore the following points can be suggested as recommendation and future research work:

a) Recommendations

- Pervious cement concrete pavement can be used in urban cities such as Addis Ababa for preventing heavy runoff and will enable to reduce noise,
- In pervious cement concrete pavement, grounded pumice can partially replace OPC with the added benefit of increase in strength,
- In pervious cement concrete, grounded pumice can be used to partially replace OPC up to 15% without affecting much the permeability of the pervious mix,
- It is both economical and environmentally friendly to incorporate grounded pumice in pervious concrete production, but detailed economic and environmental impact analysis shall be conducted,
- In order to mitigate the high water consumption of pervious cement concrete containing grounded pumice, mix design shall be adjusted by the consistency driven water demand.

b) Future research work

- The performance of grounded pumice shall also be studied in detail in conjunction with fatigue resistance and modulus of resilience.
- The performance of grounded pumice in conventional concrete shall also be investigated. This is because; it is the researcher's belief that, since the cement

paste is dense in conventional concrete, there can be favorable condition for the grounded pumice for better reaction.

- The performance of pervious concrete containing grounded pumice with constant water to cementitious ratio shall be investigated. This can be done by implementing high-range water reducers/ superplasticiezers.
- Additional microstructural analysis such as Scanning Micrographs shall be investigated to further learn the behavior of grounded pumice.
- Structural response of pervious concrete shall also be investigated in detail to use this innovative pavement material for heavy traffic.

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APPENDIX

Annex A: Tests on Fine Aggregate

A.1 Dry Rodded Unit Weight of Fine Aggregate

Description	Test 1	Test 2	Test 3
[A] Mass of Mold (g)	3,671	3,671	3,671
[B] Mass of Mold and Sample (g)	11,289	11,350	11,348
[C] = [B] - [A] Mass of sample (g)	7,618	7,679	7,677
[D] Volume of Mold (cm^3)	5,037	5,037	5,037
Loose Unit Weight of Sand [C/D]	1.51	1.52	1.52
Average Unit Weight of Sand		1.52	
Remark			

A.2 Loose Unit Weight of Natural Sand

Description	Test 1	Test 2	Test 3
[A] Mass of Mold (g)	3,671	3,671	3,671
[B] Mass of Mold and Sample (g)	10,605	10,642	10,652
[C] = [B] - [A] Mass of sample (g)	6,934	6,971	6,981
[D] Volume of Mold (cm^3)	5,037	5,037	5,037
Loose Unit Weight of Sand [C/D]	1.38	1.38	1.39
Average Unit Weight of Sand		1.38	
Remark			

A.3 Specific Gravity and Absorption of Fine Aggregates

Description	Test 1	Test 2	Average
Pycnometer No.	1	2	
Temperature of Water (^{o}C)	24	24	
[A] Mass of Oven Dry Sample in Air (g)	477	478	
[B] Mass of Saturated Surface Dry (SSD) in air (g)	500	500	
[C] Mass of Flask + Water (g)	1689.5	1689.5	
[D] Mass of Flask + Water + Sample (g)	1987	1987.5	
Absorption (%) = ((B - A) / A) *100	4.8	4.6	4.7
Apparent Specific Gravity = ((A/(A-(D-C)))*K	2.65	2.65	2.65
Bulk Specific Gravity (Oven Dry) = ((A/(B-(D-C)))*K	2.35	2.36	2.36
Bulk Specific Gravity (SSD basis) = ((B/(B-(D-C)))*K	2.47	2.47	2.47
Correction Factor K @ 24 ^{o}C = 0.9991			
Specific Gravity Reported to 0.01 Water Absorption Reported to 0.1			

A.4 Sand Sieve Analysis

Weight (g) Before Wash		833.5		
Weight (g) After Wash		821.5		
Sieve size (mm)	Weight Retained (g)	% Retained	Cumulative retained (%)	Cumulative passing (%)
9.5	11.5	1.40	1.40	98.60
4.75	34	4.14	5.54	94.46
2.36	76	9.25	14.79	85.21
1.18	118	14.36	29.15	70.85
0.6	217.5	26.48	55.63	44.37
0.3	278	33.84	89.47	10.53
0.15	77	9.37	98.84	1.16
0.075	6	0.73	99.57	0.43
Pan	3.5	0.43	100.00	0.00
Total	821.5			
Wash Loss (g)	12			
	Fineness Modulus =	∑(Cumulative % retained)/100		2.95
	Clay Content =	(Wash Loss/Before Wash)*100		1.4%

Annex B: Tests on Coarse Aggregate

B.1 Bulk density and Voids in Aggregate (Rodding)

Calibration of Measure			
	Trial 1		
Mass of Measure , kg	4.64		
Mass of Measure + Water , kg	11.475		
Mass of Water, kg	6.835		
Density of Water, kg/m^3	998		
Volume , m^3, = Mass/Density	0.0068		
Bulk density and Voids in Aggregate			
	Trial 1	Trial 2	Trial 3
Mass of measure + Material, kg	14.86	14.98	15
Mass of Material, kg	10.22	10.34	10.36
Bulk density, kg/m^3	1,492.25	1,509.78	1,512.70
Bulk Specific Gravity (dry basis)	2.56	2.56	2.56
Voids, %	41.54	40.86	40.74

B.2 Specific Gravity and Absorption of Coarse Aggregate

	Trial 1 (02 Aggregate)	Trial 2 (01 Aggregate)
[B] Mass SSD, kg	3.98	1.985
[C] Mass SSD in Water, kg	2.424	1.187
[A] Mass of Oven Dry Sample, kg	3.895	1.925
Bulk sp gr = [A]/([B]-[C])	2.50	2.41
Bulk sp gr (SSD) = [B]/([B]-[C])	2.56	2.49
Apparent sp gr = [A]/([A]-[C])	2.65	2.61
Absorption, %	2.18	3.12

B.3 Gradation Analysis of Coarse Aggregate

Sieve size (mm)	Weight Retained (g)	% Retained	Cumulative retained (%)	Cumulative passing (%)
25	24	0.5	0.5	99.5
19	1169	22.1	22.6	77.4
10	3400	64.3	86.8	13.2
4.75	441	8.3	95.2	4.8
0.075	219	4.1	99.3	0.7
Pan	36	0.7	100.0	0.0
Total	5,289			

B.4 Soundness and LAA of Coarse Aggregate

Type of Test Conducted	Standard Test Method	Test Result
Soundness by Sodium Sulphate	AASHTO T104	3.00
Los Angeles Abrasion(LAA)	AASHTO T-96	20,Grade A

Annex C: Test on Grounded Pumice

C.1 Density of Grounded Pumice

	Trial 1	Trial 2	Average
[A] Mass of Pycnometer, gm	25.7291	25.7442	25.73665
[B] Mass of Pycnometer + Pumice, gm	46.602	48.1721	47.38705
[C] Mass of Pycnometer + Pumice + Kerosene, gm	78.4256	79.4375	78.93155
[D] Density of Kerosene, gm/ml	0.8	0.8	0.8
[E] Volume of Pycnometer, ml	50	50	50
[F] Mass of Kerosene = [C]-[B] , gm	31.8236	31.2654	31.5445
[G] Volume of Kerosene = [F]/[D] , ml	39.7795	39.08175	39.430625
[H] Volume occupied by Pumice =[E]-[G]	10.2205	10.91825	10.569375
[I] Mass of Pumice = [B]-[A] , gm	20.8729	22.4279	21.6504
[J] Density of Pumice = [I]/[H] , gm/ml	2.0423	2.0542	2.0482

C.2 Fineness of Grounded Pumice by Air Permeability Method (Blain Apparatus)

Grounding at 1,000 revolutions			
	Trial 1	Trial 2	Average
Density of Pumice (gm/cm^3), ρ	2.05	2.05	2.05
Volume of Sample (cm^3),V	1.852	1.852	1.852
Desired porosity, ϵ	0.5	0.5	0.5
Weight of sample (gm) ,W = V* ρ (1- ϵ)	1.898	1.898	1.898
T_s (s), Measured time interval of standard sample	37.8	37.8	37.8
S_s (cm^2/gm), Specific Surface of standard sample	3,774	3,774	3,774
T (s), Measured time interval of sample	19.78	19.73	19.76
S (cm^2/gm) , Specific surface of the sample = (S_s * Sqrt (T))/Sqrt (T_s)	2,730.04	2,726.59	2,728.32

Grounding at 1,500 revolutions			
	Trial 1	Trial 2	Average
Density of Pumice (gm/cm^3), ρ	2.05	2.05	2.05
Volume of Sample (cm^3),V	1.852	1.852	1.852
Desired porosity, ϵ	0.5	0.5	0.5
Weight of sample (gm) ,W = V* ρ (1- ϵ)	1.898	1.898	1.898
T_s (s), Measured time interval of standard sample	37.8	37.8	37.8
S_s (cm^2/gm), Specific Surface of standard sample	3,774	3,774	3,774
T (s), Measured time interval of sample	31.74	34.54	33.14
S (cm^2/gm) , Specific surface of the sample = (S_s * Sqrt (T))/Sqrt (T_s)	3,458.27	3,607.59	3,533.72

C.3 Hydrometer Analysis of Grounded Pumice

Hydrometer type :- ASTM 151H

Type of dispersing agent:- Sodium hexametaphosphate

Type of dispersing equipment:- Mechanical stirrer

Soil Sample type:- Grounded Pumice

Soil sample:- Pass 75 micron

Specific Gravity, G_s = 2.05

Total Weight of Sample = 60 g

T (min)	Temp (°C)	R_a, Control Jar	R_a, Pumice Jar	Density of water, g/cm^3	Dynamic Viscosity of Water, poise	Effective Depth, L(cm)	Percentage finer, %	Diameter, mm
0	17	1.003	1.03	0.9988	0.0108	8.4	0	0
1	17	1.003	1.03	0.99862	0.0105	8.4	91.11	0.0532
2	17	1.003	1.029	0.99844	0.0103	8.6	87.86	0.0377
5	17	1.0025	1.0255	0.99823	0.01005	9.55	78.10	0.0248
15	17.5	1.003	1.019	0.998425	0.010275	11.3	55.32	0.0158
30	18	1.0025	1.0145	0.99862	0.0105	12.45	42.30	0.0118
60	18.5	1.0025	1.011	0.99853	0.0104	13.4	30.91	0.0086
120	19	1.0025	1.0085	0.99844	0.0103	14.05	22.78	0.0062
240	20	1.002	1.0065	0.01005	0.01005	14.55	17.90	0.0044
480	19	1.0025	1.006	0.99844	0.0103	14.7	14.64	0.0032
960	17.5	1.0	1.0055	0.998425	0.010275	14.85	12.20	0.0023
1440	16	1.003	1.005	0.99897	0.01111	15	9.76	0.0019

C.4 Silicate analysis results

	GEOLOGICAL SURVEY OF ETHIOPIA	Doc.Number: GLD/F5.10.2	Version No: 1
	GEOCHEMICAL LABORATORY DIRECTORATE		Page 1 of 1
Document Title:	Complete Silicate Analysis Report	Effective date:	May, 2017

Issue Date: -17/04/2019

Customer Name:- Abel Wube

Request No:- GLD/TR/167/19

Report No:- GLD/TR/185/19

Sample type:- Pumice stone

Sample Preparation: - 200 Mesh

Date Submitted: - 19/03/2019

Number of Sample:- One(1)

Analytical Result: In percent (%) Element to be determined Major Oxides & Minor Oxides

Analytical Method: $LiBO_2$ FUSION, HF attack, GRAVIMETERIC, COLORIMETRIC and AAS

Collector's code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
P-Ca-01	66.76	11.97	6.34	2.72	0.92	2.92	3.42	0.20	0.05	0.14	1.13	4.81

-

Note: - This result represent only for the sample submitted to the laboratory.

Analysts	Checked By	Approved By	Quality Control
Yirgalem Abriham Tihitna Beletkachew Tizita Zemene Yohanis Getachew Elsa Fisseha Bethelhem Tefera	Dessie Abebe	Gosa Haile	Negash Worku

Annex D: Mix Design

D.1 Mix design for Base mix

Mix Design for Base Mix		
Sr. No.	Specific properties of the aggregate	Value
1	Coarse aggregate size	Size No. 67 (20 mm)
2	Coarse aggregate density (kg/m^3)	1,504.91
3	Absorption (%)	2.18
4	Specific Gravity of Coarse aggregate	2.52
5	Target Void Content,%	15
6	Compaction Index,%	5
7	W/CM	0.35
Step 1	Select the b/bo value from ACI 522 R-10 Table 6.1 Effective b/bo values	
		0.99
Step 2	Determine the aggregate weight, Wa (kg)	
		1489.86
Step 3	Adjust to SSD weight, W_{ssd} , (kg)	
		1522.34
Step 4	Determine the paste volume, V_p (m^3)	
		0.229
Step 5	Determine Cement content, C (kg/m^3)	
		344.96
Step 6	Determine Water content, W (kg/m^3)	
		120.74
Step 7	Determine solid volume, V_s (m^3)	
	V_a	0.60
	V_c,	0.11
	V_w ,	0.12
	V_s ,	0.83
Step- 8	Determine percent voids (%)	
		16.57
Step 9	Check estimated porosity from ACI 522 R-10 Figure 6.1 Minimum Percolation Rates (mm/min)	
		178.00

Step 10	Summary of Material requirements per m^3 of porous concrete	
	$V_p(m^3)$ (Paste Volume)	0.23
	C (kg/m^3) (Cement Content)	344.96
	W_w (kg/m^3) (Water Content)	120.74
	W_{FA}, Fine Aggregate Weight, Kg	0.00
	$V_a(m^3)$ (Volume of aggregates)	0.60
	$V_c(m^3)$ (Volume of Cement)	0.11
	$V_w(m^3)$ (Volume of Water)	0.12
	V_{FA}, Volume of Fine Aggregate, (m^3)	0
	$V_s(m^3) = V_a + V_c + V_w$ (Volume of Solids)	0.83
	Percent Voids (%)	16.57

D.2 Mix design for Control

Mix Design for Control Mix		
Sr. No.	Specific properties of the aggregate	Value
1	Coarse aggregate size	Size No. 67 (20 mm)
2	Coarse aggregate density (kg/m^3)	1,504.91
3	Absorption (%)	2.18
4	Specific Gravity of Coarse aggregate	2.52
5	Specific Gravity of Fine Aggregate	2.47
6	Dry rodded Unit weight of Fine Aggregate (kg/m^3)	1,520.35
7	Target Void Content,%	15
8	Compaction Index,%	5
9	w/b	0.35
Step 1	Select the b/bo value from ACI 522 R-10 Table 6.1 Effective b/bo values	0.93
Step 2	Determine the aggregate weight, W_a (kg)	1399.57
Step 3	Adjust to SSD weight, W_{ssd} , (kg)	1430.08
Step 4	Determine Fine Aggregate Volume, m^3	0.06
Step 5	Determine the Fine Aggregate Content, kg	149.21
Step 6	Determine the paste volume, V_p (m^3)	0.225
Step 7	Determine Cement content, C (kg/m^3)	338.06
Step 8	Determine Water content, W (kg/m^3) 118.32	
Step 9	Determine solid volume, V_s (m^3)	
	V_a,	0.57
	V_c,	0.11
	V_w ,	0.12
	V_{FA},	0.06
	V_s	0.85

Step 10	Determine percent voids (%)	
		14.65
Step 11	Check estimated porosity from ACI 522 R-10 Figure 6.1 Minimum Percolation Rates (mm/min)	
		350.00
Step 12	Summary of Material requirements per m^3 of porous concrete	
	$V_p(m^3)$ (Paste Volume)	0.22
	C (kg/m^3) (Cement Content)	338.06
	W_w (kg/m^3) (Water Content)	118.32
	W_{FA} ,Fine Aggregate Weight, kg	149.21
	$V_a(m^3)$ (Volume of aggregates)	0.57
	$V_c(m^3)$ (Volume of Cement)	0.11
	$V_w(m^3)$ (Volume of Water)	0.12
	V_{FA}, Volume of Fine Aggregate, (m^3)	0.06
	$V_s = V_a + V_C + V_W + V_{FA}$ (m^3)	0.85
	Percent Voids (%)	14.65

D.4 Material requirements for all mixes

10%_FA_0% GP						
Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	0.00	338.06	118.32
3	Compressive Strength	57.92	6.04	0.00	13.69	4.79
4	Split Tensile Strength	90.93	9.49	0.00	21.50	7.52
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.00	1.59	0.56
	Sum	155.59	16.23	0.00	36.78	12.87

10% _FA_10% GP						
Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	33.81	304.25	118.32
3	Compressive Strength	57.92	6.04	1.37	12.32	4.79
4	Split Tensile Strength	90.93	9.49	2.15	19.35	7.52
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.16	1.43	0.56
	Sum	155.59	16.23	3.68	33.10	12.87

10%_FA_20% GP						
Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	67.61	270.45	126.60
3	Compressive Strength	57.92	6.04	2.74	10.95	5.13
4	Split Tensile Strength	90.93	9.49	4.30	17.20	8.05
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.32	1.27	0.60
	Sum	155.59	16.23	7.36	29.42	13.77

10%_FA_30% GP						
Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	101.42	236.64	140.80
3	Compressive Strength	57.92	6.04	4.11	9.58	5.70
4	Split Tensile Strength	90.93	9.49	6.45	15.05	8.95
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.48	1.11	0.66
	Sum	155.59	16.23	11.03	25.75	15.32

10% _FA_5% GP						
Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	16.90	321.16	118.32
3	Compressive Strength	57.92	6.04	0.68	13.01	4.79
4	Split Tensile Strength	90.93	9.94	1.07	20.42	7.52
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.08	1.51	0.56
	Sum	155.59	16.23	1.84	34.94	12.87

10% mix_15% GP

Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	Kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	50.71	287.35	123.05
3	Compressive Strength	57.92	6.04	2.05	11.64	4.98
4	Split Tensile Strength	90.93	9.49	3.22	18.27	7.82
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.24	1.35	0.58
	Sum	155.59	16.23	5.52	31.26	13.39

10%_FA_25% GP

Sr. No.	Type of test	Materials				
		CA	FA	GP	C	W
1	Unit	kg	Kg	kg	kg	Kg
2	Per Unit Volume of Concrete	1,430.08	149.21	84.51	253.54	136.07
3	Compressive Strength	57.92	6.04	3.42	10.27	5.51
4	Split Tensile Strength	90.93	9.49	5.37	16.12	8.65
5	Density and Void Content	0.00	0.00	0.00	0.00	0.00
6	Permeability	6.74	0.70	0.40	1.19	0.64
	Sum	155.59	16.23	9.19	27.58	14.80

CA = Coarse aggregate FA = Fine aggregate GP = Grounded Pumice C = Cement W = Water

Annex E: Strength and Permeability Test Results

E.1 Hardened Density and Porosity

Mix_ID	Hardened Density (kg/m^3)	Porosity (%)
10% FA_0_GP	1,918.47	18.0%
10% FA_5_GP	1,911.46	17.1%
10% FA_10_GP	1,910.19	16.2%
10% FA_15_GP	1,909.55	15.0%
10% FA_20_GP	1,905.10	14.2%
10% FA_25_GP	1,904.46	12.1%
10% FA_30_GP	1,900.64	9.8%

E.2 Splitting Tensile Strength

Mix_ID	Average Splitting Tensile Strength (MPa)			
	3 days	7 days	28 days	56 days
10% FA_0_GP	1.18	1.24	1.67	2.00
10% FA_5_GP	1.17	1.55	2.10	2.48
10% FA_10_GP	1.16	1.49	2.02	2.36
10% FA_15_GP	1.12	1.45	1.73	2.19
10% FA_20_GP	0.85	1.49	1.61	1.76
10% FA_25_GP	0.79	1.13	1.58	1.72
10% FA_30_GP	0.70	1.03	1.46	1.68

E.3 Compressive Strength

Mix_ID	Average Compressive Strength (MPa)			
	3 days	7 days	28 days	56 days
10% FA_0_GP	9.33	15.84	15.85	23.55
10% FA_5_GP	12.81	14.27	17.60	26.39
10% FA_10_GP	9.24	13.03	16.54	24.80
10% FA_15_GP	8.56	9.42	16.53	24.40
10% FA_20_GP	7.43	7.45	10.09	14.69
10% FA_25_GP	7.32	7.40	9.76	13.61
10% FA_30_GP	5.95	6.33	9.29	13.24

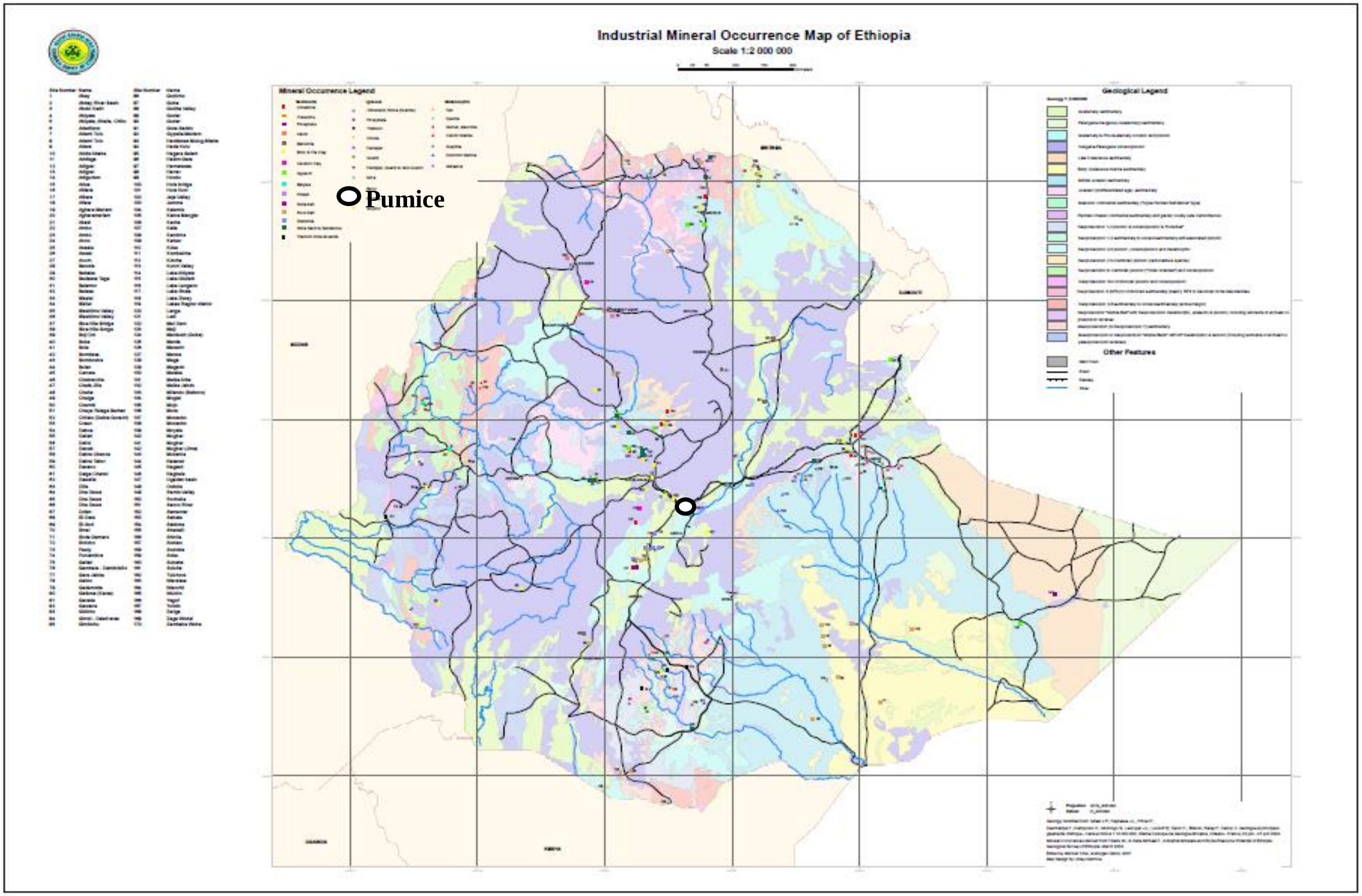
E.4 Pozzolanic Activity Index

Mix_ID	Average Compressive Strength (MPa)		PAI	
	7 days	28 days	PAI_7	PAI_28
Control	25.58	38.67	100%	100%
10% GP	17.07	28.73	67%	74%
20% GP	16.30	27.03	64%	70%
30% GP	14.69	22.76	57%	59%

E.5 Hydraulic Conductivity

Mix_ID	Hydraulic Conductivity (m/s)
10% FA_0_GP	0.017
10% FA_5_GP	0.015
10% FA_10_GP	0.014
10% FA_15_GP	0.003
10% FA_20_GP	0.003
10% FA_25_GP	0.002
10% FA_30_GP	0.001

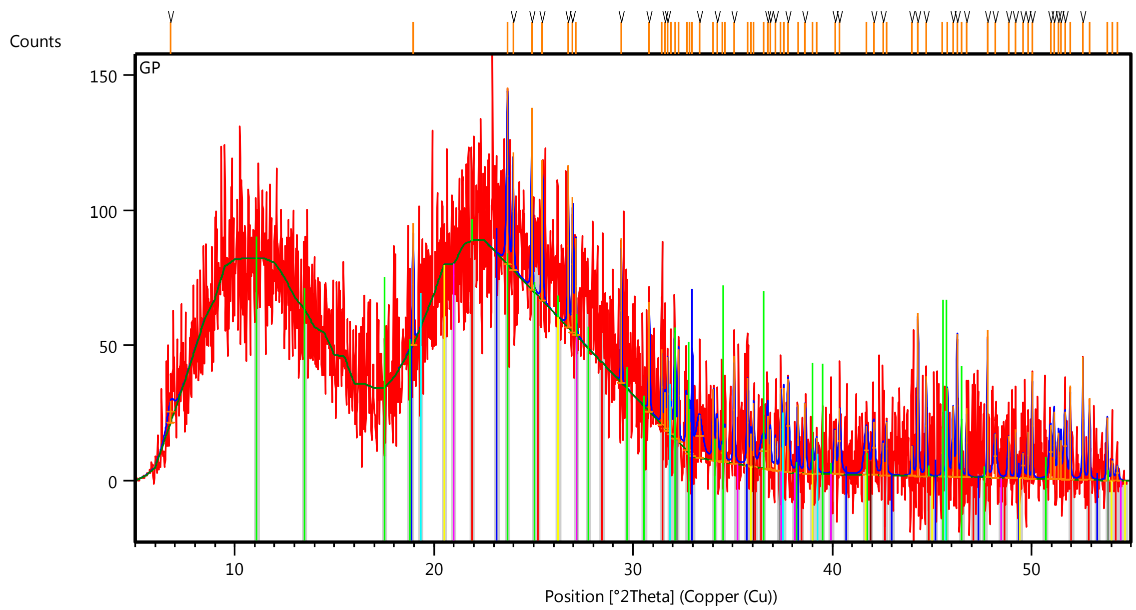
Annex F: Location Map of Pumice in Ethiopia (Geological Survey of Ethiopia, March 2003)



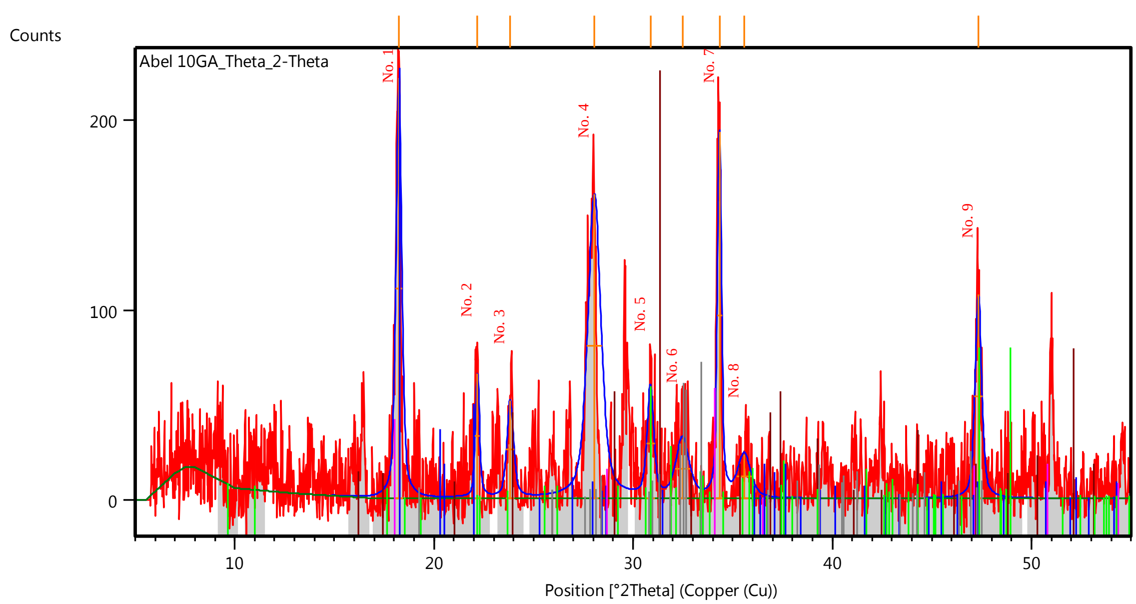
Annex G: XRD results

F.1 XRD pattern

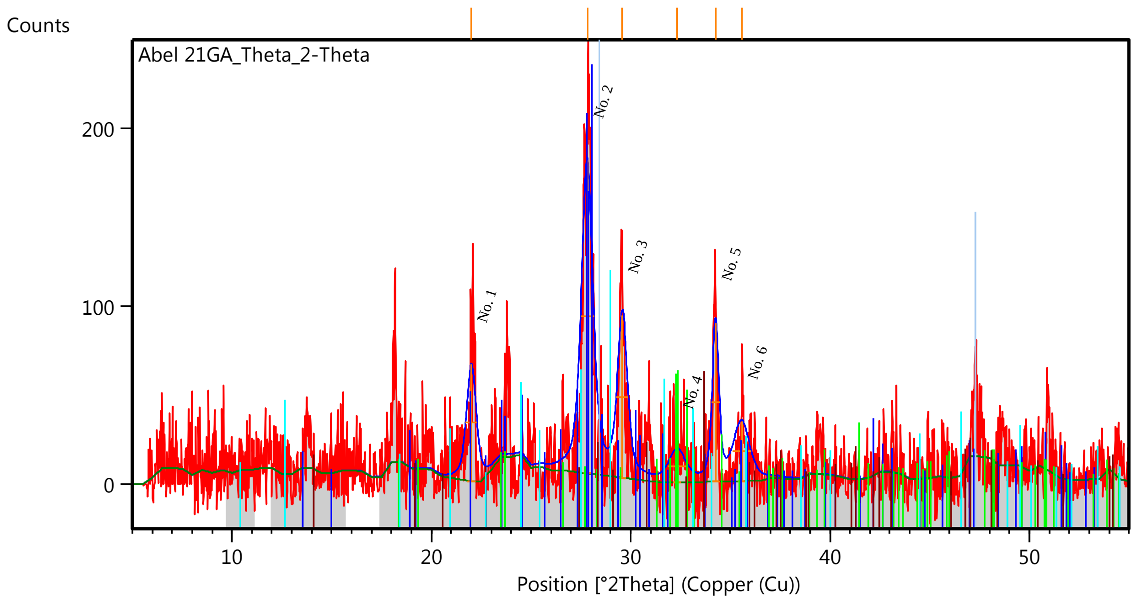
F.1.1 Grounded Pumice



F.1.2 Hydrated paste from the control (10%_FA_0%_GP)



F.1.3 Hydrated paste from 10%_FA_5%_GP



F.2 Peak List

F.2.1 Grounded Pumice

No.	Ref. Code	Compound Name	Chemical Formula
1	00-039-0238	Iron Oxide	Fe_2O_3
2	00-046-1215	Aluminum Oxide	Al_2O_3
3	00-004-0777	Calcium Oxide	CaO
4	00-006-0615	Iron Oxide	FeO
5	00-050-0741	Aluminum Oxide	Al_2O_3
6	00-026-0031	Aluminum Oxide	Al_2O_3
7	00-047-1144	Silicon Oxide	SiO_2
8	00-011-0695	Silicon Oxide	SiO_2

F.1.2 Hydrated paste from the control (10%_FA_0%_GP)

No.	Ref. Code	Compound Name	Chemical Formula
1	00-007-0324	Aluminum Hydroxide	$Al(OH)_3$
2	00-047-1301	Silicon Oxide	SiO_2
3	00-020-0199	Calcium Aluminum Silicate	$Ca_2 Al_2 SiO_7$
4	00-044-1481	Calcium Hydroxide	$Ca(OH)_2$
5	00-039-1425	Silicon Oxide	SiO_2
6	00-044-1400	Calcium Aluminum Silicate Hydroxide	$Ca_2 Al_3(SiO_4)(Si_2O_7)O(OH)$
7	00-033-0303	Calcium Silicate	$Ca_2 Si O_4$

F.1.3 Hydrated paste from 10%_FA_5%_GP

No.	Ref. Code	Compound Name	Chemical Formula
1	00-041-1486	Calcium Aluminum Silicate	$CaAl_2 Si_2O_8$
2	00-033-0302	Calcium Silicate	Ca_2SiO_4
3	00-030-0024	Aluminum Iron Oxide	$AlFeO_3$
4	00-023-0125	Calcium Silicate Hydrate	$Ca_6 Si_6O_{17}(OH)_2$