Experimental Investigation on the Property of Pervious Concrete with Replacement of Coarse Aggregate by Waste Clay Brick

Debele Beri Guda

A Thesis Submitted to the Department of Civil Engineering

School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Construction Engineering and Management

Office of Graduate Studies

Adama Science and Technology University

May, 2024

Adama, Ethiopia

Experimental Investigation on the Property of Pervious Concrete with Replacement of Coarse Aggregate by Waste Clay Brick

Debele Beri Guda

Advisor: Bahiru Bewket (PhD)

A Thesis Submitted to the Department of Civil Engineering
School of Civil Engineering and Architecture

Presented in Partial Fulfillment of the Requirement for the Degree of Master's in Construction Engineering and Management

Office of Graduate Studies

Adama Science and Technology University

May, 2024

Adama, Ethiopia

DECLARATION

I hereby declare that this Master Thesis entitled "**Experimental Investigation on the Property of Pervious Concrete with Replacement of Coarse Aggregate by Waste Clay Brick**" is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Debele Beri Guda	____________________	____________________
Name of student	Signature	Date

RECOMMENDATION

I, the major advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled "**Experimental Investigation on the Property of Pervious Concrete with Replacement of Coarse Aggregate by Waste Clay Brick**" prepared under my guidance by **Debele Beri Guda**. submitted in partial fulfillment of the requirements for the degree of Mater's of Science in Construction Engineering and Management. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

Bahiru Bewket (PhD)	____________________	____________________
Major Advisor	Signature	Date

APPROVAL SHEET

I, the advisors of the thesis entitled "**Experimental Investigation on the Property of Pervious Concrete with Replacement of Coarse Aggregate by Waste Clay Brick**" and developed by **Debele Beri Guda**, hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Bahiru Bewket (PhD)	____________________	____________________
Major Advisor	Signature	Date

We, the undersigned, members of the Board of Examiners of the thesis by **Debele Beri Guda** have read and evaluated the thesis entitled "**Experimental Investigation on the Property of Pervious Concrete with Replacement of Coarse Aggregate by Waste Clay Brick**" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in Construction Engineering and Management.

Fikreyesus Demeke (PhD)	______________	________________
Chairperson	Signature	Date
____________________	______________	________________
Internal Examiner	Signature	Date
____________________	______________	________________
External Examiner	Signature	Date

Final approval and acceptance of the thesis proposal is contingent upon submission of its final copy to the Office of Postgraduate Studies (OPGS) through the Department Graduate Council (DGC) and School Graduate Committee (SGC).

____________________	____________________	________________
Department Head	Signature	Date
____________________	____________________	________________
School Dean	Signature	Date
____________________	____________________	________________
Postgraduate Dean	Signature	Date

ACKNOWLEDGMENT

First of all, I would like to give thanks and praise to God for who He is. Next, I want to express my gratitude for my advisor Dr. Bahiru Bewket. He has consistently dedicated his time to advise me in my thesis work and bring it to completion. I also want to give thanks to my family, for helping me throughout the journey.

TABLE OF CONTENTS

LIST OF TABLES

TABLE PAGE

LIST OF FIGURES

FIGURE PAGE

LIST OF ACRONYMS

t	Ton
D	Decision matrix
P_i	Ranking
W_j	Weight of attribute
f_c	Compressive strength
f_r	Flexural strength
W	Maximum load
k	Water permeability coefficients

LIST OF ABBREVIATIONS

A/C	Aggregate to Cement
ACV	Aggregate crushing value
AIV	Aggregate impact value
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
BC	Before Christ
BS	British Standards
CCB	Crushed Clay Brick
IS	Indian Standards
mm	millimeter
MPa	Mega Pascal
NA	Natural aggregate
NRMCA	National Ready Mix Concrete Association
OPC	Ordinary Portland Cement
PC	Pervious Concrete
PGC	Pervious Geopolymer Concrete
RA	Recycled Aggregates
SEM	Scanning Electron Microscope
SSD	Saturated Surface Dry
U.S	United States
W/C	water to Cement
ITZ	Interfacial Transition Zone
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
MCDM	Multi Criteria Decision Making
WCBA	Waste Clay Brick

ABSTRACT

In recent years, due to high urbanization in the main cities of Ethiopia and the growing demand for infrastructure, the production of coarse aggregate has been increasing. The impact of increased production of coarse aggregate is seen in the increasing depletion of natural aggregates (NA). To meet this inordinate depletion the construction industry needs to have alternative sources from waste of clay brick factory, waste clay brick aggregate (WCBA) has earned great attention due to creates huge land acquisition problems and environmental pollution. The different types of aggregate gradations, water to cement ratio (W/C), and aggregate to cement ratio (A/C) play an important role in the mixture designing of pervious concrete (PC) mixtures. The main purpose of this research is to study the properties (compressive strength, void ratio, and permeability) of PC using WCBA as coarse aggregate. The scanning electron microscope (SEM) tests will be conducted to obtain the micro-morphological of the interfacial transition zone (ITZ) and adjacent cement paste). This paper used the multi criteria decision making techniques (MCDM) for ranking PC mix. Test results showed that higher compressive strength is obtained in PC with NA compared to PC with WCB. The obtained results showed that the binary blended aggregate size (G-4 50% of 10 mm, 50% of 12.5 mm) provides the best strength compared to the single-size aggregate. The optimum porosity, W/C, and A/C for PC with WCBA is 28.68%, 0.3 and 5, respectively, in the studied ranges. In summary, the results confirmed that the NA could be replaced with WCBA has better permeability, and porosity; however, the strength of PC with WCBA is lower than that of the NA concrete.

Key words: - Pervious concrete, Waste clay brick, Aggregate size, Compressive strength, Porosity, Permeability.

CHAPTER ONE

1. INTRODUCTION

1.1 Background of the Study

The term “pervious concrete” typically describes a near zero-slump, open-graded material consisting of Portland cement, coarse aggregate, little or no fine aggregate, admixtures, and water. The void content can range from 15 to 35%, with typical compressive strengths of 2.8 to 28MPa (ACI 522R-10, 2010). The volume of aggregates in porous concrete approximately ranges from 50% to 65%. This porosity makes porous concrete very beneficial from an environmental factor of view (Ibrahim, Mahmoud, Yamin, & Patibandla, 2014).

The purpose of pervious concrete design is to increase its permeability without much compromising on its compressive strength. The type and size of coarse aggregate, water-binder ratio, and aggregate-binder ratio thus require careful consideration. The compressive strength of pervious concrete depends on the water-cement ratio, and on the aggregate-cement ratio.

The growing need for natural aggregates in the construction industry is causing a scarcity of materials, and leading to an environmental imbalance (Tam, Soomro, & Evangelista, 2018). As the countries do not have their own source of natural aggregates and depend on other countries, the import cost of natural aggregates is much higher in such areas (Zachariah, Sarkar, & Pal, 2021). As the world is becoming environmentally more conscious, any project these days not only first-rate considers the economy of the project, but additionally also checks the environmental impact that the project would have on the livelihood of the human being. Being a nonrenewable resource, natural aggregates require an alternative to counteract their overuse and shortages (Yunchao et al., 2021).

Clay brick is one of the oldest and most popular construction materials because of its durability, aesthetics, and ease to handle. The other benefits of utilizing wastes in concrete construction include the conservation of natural aggregate resources especially when an abundant amount of discarded aggregate is available (Abed, Nemes, & Tayeh, 2020), and the reduction of land used for solid waste disposal and finding better destinations for these wastes (Leite & Santana, 2019), The main sources of such solid wastes are concrete and bricks (B. V. Kumar, Ananthan, & Balaji, 2017).

In China, about 20 billion m^3 of waste clay bricks have been produced over the past 50 years (Zhao, Gao, Chen, Liu, & Chen, 2018). The recent annual production of bricks is more than 1.3 billion units, which are expected to increase (Zhang, 2013). Furthermore, rejected bricks (i.e. broken) can be considered as wastes from the industry that are caused by surplus production, leading to environmental hazards (Sadek, 2012). It is critical to find out the possibility of recycling crushed clay brick (CCB) as a construction material (Wongsa, Sata, Nuaklong, & Chindaprasirt, 2018).

One way of using waste materials in sustainable way is utilizing the materials in construction materials such as concrete. Different research studies have focused on replacing natural materials in concrete with waste products. In doing so, the environmental impact caused by using natural resources will be reduced significantly (Sandanayake, Bouras, Haigh, & Vrcelj, 2020).

1.2 Statement of the Problem

Basically, there are different types of naturally available aggregates i.e. Quartzite gravel, crushed limestone, river gravel, crushed granite, etc. have been used in the past in making pervious concrete and are properly documented (Kevern, Schaefer, Wang, & Suleiman, 2008; Malhotra, 1976). These natural virgin aggregates although readily available in urban settings; however, are not mined in urban areas and must be shipped. As a result, aggregate needs to be carried to the construction sites from the remote quarries which are costly on the basis of transportation, handling, also inconvenience. The scarcity of natural aggregates leads the researcher to find alternative sources.

Due to high urbanization in the main cities of Ethiopia and the growing demand for infrastructure, the production of coarse aggregate has been increasing for the last three decades. The impact of increased production of coarse aggregate is seen in the destabilization of the landscape and pollution of water and atmosphere as coarse aggregates are produced by quarrying, and crushing large masses of natural parent rocks (Assefa & Gebregziabher, 2020). The properties of stone aggregate concrete with those of brick aggregate concrete by replacing an equal amount of stone with brick (Mansur, Wee, & Lee, 1999). The above-mentioned studies was for normal-strength concrete; however, attempts have also been made to produce high-strength concrete using brick chips as coarse aggregate (Mansur et al., 1999). Brick aggregate concrete also performs well or even better than natural aggregate concrete under high temperature (Khalaf & DeVenny, 2004).

As studied by (Hossain, Salam, & Kader, 2012), the strength of brick aggregate pervious concrete is less than that of stone aggregate concrete for the same aggregate size. However, the permeability of brick aggregate pervious concrete is higher than stone aggregate pervious concrete. All these studies show the use of crushed clay brick as an alternative source of coarse aggregate in pervious concrete. Also, the study shows a single size of aggregate was used in making pervious concrete to eliminate aggregate size as a variable. Therefore, appropriate mix design based on aggregate sizes, W/C ratio and A/C ratio is needed to develop a pervious concrete with good strength and permeability. This research was critically focused on the extensive use of waste clay bricks obtained from Burayu Brick Factory found in Sheger City to replace the natural aggregate as it is the dominant constituent material in pervious concrete production.

1.3 Objective of the Study

1.3.1 General Objective

The general objective of this research is an experimental investigation on the property of pervious concrete with replacement of coarse aggregate by waste clay brick.

1.3.2 Specific Objectives

The research will have the following specific objectives:

- Characterization of the physical and mechanical properties of waste clay brick to use as coarse aggregate.
- To investigate mechanical and permeability properties of pervious concrete with replacement of coarse aggregate by waste clay brick.
- To study the morphological properties of pervious concrete by using scanning electron microscope (SEM).
- To prioritize pervious concrete mix using multi-criteria decision making (MCDM) techniques.

1.4 Significance of Research

The study is believed to contribute a new knowledge area on the using waste clay bricks from brick factories around Addis Ababa on the property of pervious concrete as coarse aggregate. Based on the limited available literature, it can be ascertained that aggregate gradation type, water-to-cement ratio (W/C), and aggregate-to-cement ratio (A/C) play an important role that greatly influences the compressive strength, porosity, and permeability characteristics of pervious concrete (PC) mixes.

However, most of the available literature was based on the utilization of single-sized aggregates only. Therefore, this study mainly focuses to explore the effect of various aggregate gradation types, W/C ratios, and A/C ratios for the production of pervious concrete mixes whilst maintaining a balance between the porosity, permeability, and compressive strength characteristics and its effect on the various aforementioned properties of the PC mixes. It is believed that the findings from this study will help to bring a better understanding of different types of possible gradation, W/C ratios, and A/C ratios usage and would certainly help in the rational design of a PC mixture in the future.

1.5 Scope of Research

The research is covered only the effect of different aggregate gradation types, W/C ratios, and A/C ratios on the properties of pervious concrete with the replacement of coarse aggregate by waste clay brick. There are different available clay brick factories found in and around Addis Ababa. From the different brick factories Burayu Brick Factory with a higher production capacity was selected. The research is mainly covered to evaluating the properties of pervious concrete such as compressive strength, porosity, and permeability.

1.6 Limitations of the Study.

The main limitations faced when conducting this study. Standard practice for mixing, curing, and batching of pervious concrete is needed. In the lack of a standard, various procedures were found in the literature for PC production. The mixture design for PC in this study falls in accepted range values of the existing limited standard. Experimental optimization of concrete mixtures was generally depended on the availability of large experimental datasets. An optimal mixture design of PC satisfies user’s demands on material’s mechanical and permeability properties, as well as the requirements for economy, sustainability, and cost. In this study a multi criteria decision making (MCDM) models can be applied to establish such relationships between mixture design variables and desired properties, i.e., mechanical, and water permeability properties indices. Therefore, due to lack of large data, and criteria this study only limited to rank the PC mixes by using MCDM. Further research is required to develop a collective mixture design method to optimize the mixes based on these accepted ranges of values.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

Burnt clay bricks are made after subjecting clay mixture through molding, sun drying and burning processes. The properties of burnt clay bricks depend upon the nature of material and manufacturing process (Kazmi, Abbas, Saleem, Munir, & Khitab, 2016). Clay bricks have always been one of the widely used construction materials in the construction industry. The use of dried clay bricks was recorded as far back as 8000 BC, while fired clay bricks were used as early as 4500 BC (Arshad & Pawade, 2014). Clay bricks are produced in large amount throughout the world and the demand for them is expected to continuously rise. Nowadays, advanced production technology is employed in producing these clay bricks. Nevertheless, significant proportion of bricks get distorted, damaged, broken, under or over burned (Arshad & Pawade, 2014).

In earlier times of construction, these waste clay bricks were used as concrete aggregate in crushed form (De Pauw, Taerwe, & DESMYTER, 2000). Crushed clay brick is the form of this material that has an aggregate size between 0.075 mm up to 50 mm and ground brick is another form powdered to cement fineness (Bektas, 2007). The densities of these aggregates were in the range of 1500-2000 kg/m^3, which is a difficult range to explicitly categorize these kinds of aggregates. For instance, (De Pauw et al., 2000) classified them between the lightweight aggregate and normal weight aggregate. However, looking at some other characteristics such as porosity and water absorption, the aggregates would be classified as lightweight aggregate (De Pauw et al., 2000).

According to statistics, the global demand for concrete aggregates was 45 x 10^9t in 2017, and this number will increase to 66 x 10^9t by the end of 2025 (de Brito & Agrela, 2018). As a result, concrete with aggregate is widely used to construct mega structures, notably tall and large structures (Meng et al., 2021). The issue arises when a restrained delivery of natural coarse aggregate stone varies based on the region's geology. If natural resources, particularly coarse aggregate stone to be mixed with concrete, are in short supply, these might stymie the project's progress (Makul et al., 2021). For that reason, crushed clay brick is chosen for this study in order to produce lightweight, porous concrete. Lightweight concrete is concrete which densities vary from the range 300 to 1850 kg/m^3 (Arhin, Madhi, & Khan, 2014).

2.2 Properties of Pervious Concrete

Usually, PC consists of Portland cement (supplementary cementitious materials sometimes are used), aggregates, and water. The difference from conventional concrete is that PC contains no fine aggregates and a lesser amount of cement paste is used to fill the voids between the aggregate particles. As a result, open cells (pores) are formed and the induced high porosity of PC leads to good internal drainage and infiltration. The common properties of normal PC are shown in table 2.1 according to the American Concrete Institute (ACI 522R-10, 2010).

Table 2.1 Properties of common pervious concrete (ACI 522R-10, 2010)

Properties	Compressive strength (MPa)	Drainage rate (mm/s)	Porosity
Value range	2.8 - 28	1.4-12.2	15 - 35%

Obviously, the requirement for the compressive strength of PC is relatively low as compared to conventional concrete. This provides an opportunity to reuse waste materials in the production of PC. The main properties of concrete which are density, porosity, strength, and permeability are discussed subsequently.

2.2.1 Density of Pervious Concrete

Normal weight concrete used for conventional structure works has a density between 2200 and 2400 kg/m^3. The density of concrete is mainly affected by the density of the aggregate, the amount of entrapped or entrained air, and the water and cement contents, which in turn are influenced by the maximum size of aggregate used. For instance, when the amount of cement paste content is decreased or when the aggregate volume is increased, the concrete‘s density will increase (Kosmatka, Panarese, & Kerkhoff, 2002).

Concrete other than the normal weight concrete with varying density can be produced by using aggregates of different unit weight. For instance, ultra-lightweight concrete is one type of concrete with a bulk density that ranges between 800 and 1100 kg/m^3, which can only be used for nonstructural members such as partition walls. This type of concrete is produced with aggregates which have a unit weight of less than 500 kg/m^3. Lightweight concrete is another type of concrete that can be produced by using aggregates which have unit weights between 500 and 1120 kg/m^3. The concrete made of lightweight aggregate has a bulk density between 1200 and 1800 kg/m^3 which can either be used for a structural or nonstructural member, depending on the type of aggregate used. If the unit weight of aggregate used is greater than 2100 kg/m^3, the aggregate is categorized as heavy-weight aggregate. The concrete produced with such aggregates will have a bulk density between 3200 and 4000 kg/m^3. This kind of concrete is used for dangerous radiation shields in hospitals and nuclear plants (Z. Li, 2011). In this study, lightweight aggregate is being used to produce pervious concrete. As a result, pervious concrete contains a multitude of voids and reduces the density. Higher the porosity, lesser will be the density of the hardened PC specimens and it usually lies between 1600 kg/m^3 to 2000 kg/m^3 (ASTM C, 2012).

2.2.2 Porosity of Pervious Concrete

The sample porosity is defined by the volume of voids divided by the total volume of the sample. A water displacement method can be used to determine the total porosity of pervious concrete (Montes et al., 2005). Porosity should be in the range of 15–25% (Tennis et al., 2004). The porosity of a concrete mix is determined by the water-to cement ratio, the type and size of aggregate particles as well as the compaction effort (ACI Committee 522, 2010). Porous concretes with high porosity reduce porous concrete's mechanical properties. On the other hand, this high porosity allows water to permeate through the voids (Yu, Sun, Wang, & Hu, 2019).

2.2.3 Compressive Strength of Pervious Concrete

Pervious concretes have relatively lower compressive strengths as compared to conventional concretes. This is mainly attributed to the presence of macro-sized pores and large pore volumes and to the absence of fine aggregates (Cackler et al., 2006). Pervious concrete’s compressive strength can range from 2.8 to 28 MPa (ACI Committee 522, 2010). On other hand pervious concrete’s compressive strength can range from 3.45 to 27.58 MPa, whereas conventional concrete’s compressive strength typically varies from 20.68 to 48.26 MPa (Hamdy, 2016). The low strength of conventional pervious concrete not only limits its application in heavy traffic pavement but also affect the stability and durability of the structures. Therefore, it is important to investigate the main factors affecting the compressive strength of pervious concrete and find ways to improve its applicability.

The compressive strength of pervious concrete is strongly influenced by the mixture proportion and compaction effort during placement. Experimental investigation on pervious concrete for paving were conducted by (Meininger, 1988), and conclusions were drawn regarding the percentage of air voids required for adequate permeability, the optimum water–

cement ratio range, and the amounts of compaction and curing required. A study by (Mulligan, 2005) shows a relationship between pervious concrete compressive strength and unit weight. The conclusions were drawn based on another series of laboratory tests where one size of coarse aggregate was used and compaction effort and the aggregate-cement ratio were varied.

The total cement content of a pervious concrete mixture is important for the development of compressive strength and void structure. An excessive paste content may result in a filled void structure and, consequently, decrease porosity. A small cementitious content can result in reduced paste coating of the aggregate and decrease compressive strength. The optimum cement content is strongly dependent on aggregate size and gradation. For the aggregate size chosen, binder drainage tests are recommended to be carried out to ascertain the optimum cementitious content (Nelson and Phillips, 1994). Although porosity is the most important factor in compressive and flexural strength, aggregate size, shape, and gradation can impact pervious concrete strength (Crouch et al., 2007). Another factor that can have a significant impact on the strength of pervious concretes is the thickness of the paste layer surrounding the aggregate. This is related to the aggregate size, cementitious material content, and the w/cm.

2.2.4 Flexural Strength of Pervious Concrete

As pervious concretes are mostly used as paved sections, the flexural response also becomes important. The variations of flexural strength (f_r) are somewhat similar to that of compressive strength (f_{cs}) due to the poor strength of RBA. The path of flexural load transfer mostly propagates through the aggregates, and hence the weaker RBAs can't take more loads. The typical lower limit of f_r was suggested as 1 MPa (Chen et al., 2019). According to (Deb et al., 2022) the important thing that can be noticed here is that the value of f_r is higher for smaller aggregates compared to larger aggregates, which is primarily happening due to the presence of smaller pore sizes. The gap between two large aggregates is much higher than the gap between two small aggregates, and hence the crack propagation in the mixes with larger aggregates becomes much easier.

2.2.5 Permeability of Pervious Concrete

One of the most important features of PC is its ability to percolate water through the matrix. The percolation rate of pervious concrete is directly related to the porosity and the pore sizes. Tests have shown (Meininger, 1988) that a minimum porosity of approximately 15% is required to achieve significant percolation. For a porosity of 20 to 25%, the coefficient of permeability is reported be approximately 0.01 m/s (Brite/Euram Report, 1994). Another study (Nissoux et al., 1993) reports a permeability of (36 L/m2/s).

According to (ACI 522R, 2010), permeability of porous concrete ranges from (1.4-12.2) mm/s. A study by (Meininger, 1988) shows the relationship between the void content and permeability coefficient of a PC mixture. Because the percolation rate increases as air void content increases and, consequently, compressive strength decreases, the challenge in pervious concrete mixture proportioning is achieving a balance between an acceptable percolation rate and an acceptable compressive strength. The permeability of pervious concrete can be measured by a simple falling-head permeameter (Neithalath et al., 2003). According to (Cui et al., 2017) the permeability was measured using a fabricated falling head permeameter.

2.3 Components of Pervious Concrete

2.3.1 Cement

Cement is a fine grey powder and the most versatile and widely used construction material which when reacted with water hardens to form a rigid chemical mineral structure which holds the aggregates together acting like glue and gives the concrete its strengths (Steven et al., 2003). These types of cements are generally known as hydraulic cements which are of a great interest in making concrete. Hydraulic cements are mainly made up of silicates and aluminates of lime, and can be classified broadly as natural cements, Portland cements, and high-alumina cements (Adam M Neville, 1995). Portland cement is produced by grinding clinker which consists primarily of hydraulic calcium silicates. Clinker also contains some calcium aluminates and calcium aluminum ferrites and one or more forms of calcium sulfate (gypsum) are ground together with the clinker to make the final product (Steven et al., 2003).

2.3.2 Water

The main considerations on the quality of mixing water are related to the performance of concrete in fresh and hardened state (Kucche, Jamkar, & Sadgir, 2015). The quality of mixing water in concrete is significant since it can alter setting time and strength of concrete. Almost all natural waters, fresh waters, and municipally treated waters are suitable for use as concrete mixing water if they have no discernible odor or flavor (Hassan, Abdul-Kareem, & Shihab, 2014). The presence of impurities in water may interfere with the setting of the cement, strength and durability of concrete (Kucche et al., 2015).

2.3.3 Aggregates

Aggregates can be defined as granular materials that can be crushed stone, gravel or sand that can be used with cement to form concrete or mortar (ASTM C125 − 13a, 2013). During pervious concrete's production, it consumes a lot of natural resources, which mainly includes water, crushed stone, etc. Out of all materials used for pervious concrete production, aggregates have the largest volume that accounts for 50% to 65% of pervious concrete's volume, which is obtained through extraction (Chandrappa and Biligiri, 2016).

Aggregates are inert materials which can increase the volume and alter the properties of pervious concrete. In fact, aggregates occupy a large volume in a pervious concrete mixture. Hence, they can affect the fresh properties, hardened properties, mix design, and environmental impact. However, the major function of aggregates is to provide an economic volume-filling material. In addition, they may enhance various mixture properties and reduce volume changes, compared to cement paste alone. Hence, a common practice is to use as much aggregates as possible, without violating mix designing standards, in order to decrease the cost and enhance the volume stability of concrete.

2.3.3.1 Classification of Aggregates

Concrete aggregates can be classified mainly based on their origin and physical characteristics such as particle size and bulk density. In terms of their origin, rocks are classified into three main groups namely igneous, sedimentary and metamorphic (Alexander & Mindess, 2005). Based on their physical characteristics such as particle size, aggregates are mainly classified as coarse aggregates which usually have particle size of greater than 4.75 mm and fine aggregates with a particle size equal or less than 4.75 mm. Regarding density, aggregates are classified as lightweight, normal weight and heavy weight with a bulk density range of less than 1120 kg/m^3, 1500–1700 kg/m^3 and greater than 2000 kg/m^3 respectively (Alexander & Mindess, 2005).

Lightweight aggregates can be obtained from natural resources or they can be synthetic, industrial by products and waste materials. Volcanic materials are the main natural resources for lightweight aggregates. Manmade aggregates on the other hand are produced by different processes in factories. These obtained lightweight aggregates can have a unit weight ranging from 50 kg/m^3 up to 1000 kg/m^3. They are used in a wide range for the production of concrete and mortars. The property of concrete produced is associated to the properties of the aggregates used for the production. Again the properties of aggregates depend upon the type of material and the process used for producing them (Chandra & Berntsson, 2002).

2.3.3.2 Physical Properties of Aggregates

The origin of an aggregate has a huge factor on the properties of aggregates such as the mineral composition, hardness, and pore structure. The properties of these aggregates used in concrete production have effect on the quality and property of the fresh and hardened concrete produced (Adam M Neville, 1995). The aggregates not only produce concrete economical by occupying more volume, but also impart volume stability and increase durability. The properties, such as size, gradation, shape and surface texture, have marked influence on workability and strength of concrete.

The purpose of the measurement of aggregate shape was felt long back. The earlier attempts to measure numerically the shape of aggregate were based on observation and measurement of dimensions of individual particles. Based on measurement of dimensions of individual particles the ratios of intermediate to larger dimension and smaller to intermediate dimension were used for the classification of shape as oblate, prolate, triaxial and equiaxial. This concept was further modified and shape was classified into five classes as angular, sub-angular, sub-rounded, rounded and well rounded (Pettijohn, 1957). Flakiness and elongation indices, as suggested by various codes, are often used for the assessment of shape of aggregate particles (IS: 2386 Part-I, 1963).

Aggregates having more angularity and rough surface texture contain more voids than the rounded aggregates with smooth surface texture and hence requires more water to produce workable concrete (Murdock, 1960). Secondly, the mechanical bond between the aggregate surface and cement paste, by virtue of interlocking, influences the strength of concrete (Kaplan, 1959). Grading is the particle size distribution of aggregates that determines the paste requirement for a workable concrete since the quantity of voids among aggregate particles requires the same amount of cement paste to covers the concrete mixture. Sieve analysis is required to obtain a grading curve for an aggregate (Z. Li, 2011).

If there are grading variations from batch to batch, the uniformity of the concrete produced will be greatly affected. Using very fine sands often leads to uneconomical mix and using very coarse aggregates can produce unworkable mixes. Generally, using aggregates that do not contain excess grading sizes or have aggregates that do not have a huge deficiency of any size gives a smooth grading curve that in turn produces suitable concrete mixtures

(Kosmatka et al., 2002). The bulk density or unit weight of an aggregate is the ratio of the mass required to fill a given container to that of the specified unit volume of the container. The volume includes both that is occupied by aggregates and the voids between aggregate particles (Kosmatka et al., 2002).

The bulk density evidently depends on how densely the aggregates are packed. This, in turn, is affected by the size distribution and shape of the aggregate particles for a material of given specific gravity. If the size distributions of the aggregate particles are of only one size, then the aggregates can only be packed to some degree. To increase the degree in which the aggregates are packed or to increase the bulk density of the aggregates, smaller particles can be added in the voids that are formed by the same large aggregate particles. If a coarse aggregate with a given specific gravity has a higher bulk density, then that means there are fewer voids to be filled with cement and fine aggregate (Adam M Neville, 1995).

Porosity of aggregates refers to the proportion of the volume of internal pores to the total volume of the solid matter (Alexander & Mindess, 2005). The porosity, permeability, and absorption of aggregate have an impact on the bond between it and the cement paste, as well as the freezing and thawing resistance of concrete, chemical stability, abrasion resistance, and specific gravity. Aggregate pores come in a variety of sizes, but even the tiniest ones are larger than the gel pores in cement paste. Some aggregate pores are entirely within the solid, while others open onto the particle's surface, allowing water to pass through, with the amount and rate of penetration varying on the pores' size, continuity, and total volume (Adam M. Neville & Brooks, 2010).

Absorption can easily be measured by making an aggregate in an oven-dry condition and then by letting it absorb water by immersion to achieve a saturated-surface-dry condition. Then the absorption of the aggregate is expressed in percentage as the ratio of the increase in mass of the oven dried aggregate as a result of water immersion and being saturated, to the mass of the oven-dried sample (Alexander & Mindess, 2005). The absorption of water by lightweight aggregates is substantial in producing concrete due to the high porosity and absorption capacity of the aggregates. It is therefore appropriate to prevent such absorption during the process of concrete production. It is reasonable to soak aggregates with high absorption capacity before mixing (Chandra & Berntsson, 2002).

There are four different moisture conditions in which aggregates usually attain. The first one is an oven dry condition where the aggregate loses the evaporable water within when it is exposed to a temperature between 100 and 1100℃. The second condition is an air-dry condition where the aggregates are dry and balanced to the surrounding air and some internal moisture is taken by the aggregates. The third condition is a saturated surface dry (SSD) condition, where the aggregates contain water to the point of full saturation but there is no excess moisture on the surface. The fourth condition is a wet condition in which the aggregates are fully saturated and contain excess moisture on the surface. The moisture condition of the aggregates will have an effect on the density of aggregate hence density should be measured at some specified moisture state. From the four moisture conditions, the most useful state is the saturated surface dry condition. Because at this state, the aggregate will neither give off extra water to the mix and reduce the strength nor take up from the mixing water and affect workability (Alexander & Mindess, 2005).

The test for strength of aggregates is not done often as it does not have much effect on the strength of normal weight conventional concrete. More than the strength of aggregates, the strength of the paste and the paste-aggregate bond has much effect on the strength of concrete produced. Nevertheless, the strength of aggregates becomes important in lightweight and high-strength concrete (Kosmatka et al., 2002).

2.4 Clay Brick

Bricks are more commonly used in the construction of buildings than any other material, with the exception of wood. Brick and terracotta architecture are dominant within its field and various industries have been developed and invested in the manufacturing of different types of bricks of all shapes and colors. With the advancement of modern machinery, earth moving equipment, powerful electric motors and modern tunnel kilns, making bricks has become far more productive and efficient than ever before (Tadesse, 2013). Bricks can be made from a variety of materials the most common being clay, but also calcium silicate and concrete are raw materials for brick production. With clay bricks being the most popular, they are now manufactured using three processes: soft mud, dry press and extruded processing (BS 3921, 1985).

2.4.1 Clay Brick Production Process

Basically, bricks are produced by mixing grounded clay with water, and forming the clay into the desired shape, then drying and firing. Even though individual manufacturing plants adapt their production method to fit their particular raw materials and operation, then basic principles of manufacturing are fairly uniform. The basic phases of brick manufacturing are;

mining of raw materials, preparing raw materials, mixing and forming the brick, drying, firing and cooling.

The manufacture of fired clay bricks can be divided into four stages (Límon and Alvarez de Buergo, 1997) according to basic principles followed for thousands of years: selection and preparation of the clays; mixing and molding; drying of the fresh material; and firing of the clay units. The first step is extraction and preparation of the raw clay. As soon as the raw material is extracted, it is accumulated and moved to an open-air deposit, where it is left to putrefy for several days or weeks. At this period, the raw material should be rummaged to decrease soluble salts to a minimum, leading to a more homogeneous material. The choice of the raw material was very important to improve the performance and durability of the bricks (Vitruvius and Morgan, 1960). However, the selection of the raw material depended mainly on its availability in the construction site or nearby (Alvarez de Buergo and Limon, 1994).

Secondly, the raw material is further crushed and mixed with water, in an operation designated by tempering (Weaver, 1997). The amount of water used depends on the type of element being produced and, usually, the finest the final piece, the greater the amount of water needed. The final resultant mixing must be characterized by sufficient plasticity to simplify the molding.

For being readily molded or formed by hand, raw clays might also be "too plastic." This property derives to increase shrinkage during the drying stage, resulting in warping, twisting, or cracking. At this stage, the plasticity of the clay must be reduced by adding sand. Early brick makers often used a mix of about 30% of sand and 70% of plastic clay (Weaver, 1997; Vekey, 1998). Generally, the molds were bottomless wood molds placed down over the ground or over tables, which, usually, were covered with a thin film of sand to reduce the brick remaining attached to the bottom base during the drying process. The excess was trimmed with the aid of a rope.

Thirdly, the clay elements still crude is removed from the mold and are dried in a protected space, which is generally a shelter made of scraps of wood and with straw thatch roofs, known as hovels, where it acquires its final shape. Although inexpensive, this primitive method required a lot of open free space and was severely conditioned by climacteric conditions. Generally, the drying of clay bricks lasts for a week or more, depending on the specific climacteric conditions. In hot temperature regions, drying is faster, but bricks should be protected from direct sunlight since they can undergo warping and cracking (Alvarez de Buergo and Limon, 1994).

In colder regions, drying takes more time due to the low temperatures and moisture. Additionally, too fast drying hardens the surface faster than the core, which remains crude for a longer time. During this phase, the size reduction, or shrinkage, of the clay bricks occurs due to the elimination of the mixing water. If a too fast drying occurs or too much water is used, cracks will appear in the brick. Lastly, wet bricks from molding machines can contain 7 up to 30 percent moisture, depending upon the forming method. Before the firing process begins, most of this water is evaporated in dryer chambers at temperatures from 38ºC to 204ºC. The extent of drying time, which varies with different clays, usually is between 24 to 48 hours.

During the firing process, the dried clay bricks are heated to a high temperature. The temperature of firing should normally be more than 930°C and the extent of firing depends on both time and temperature. The inter-particulate bond, strengths, pore structure, and color of the clay bricks are all developed during the firing process. The amount of time spent firing should be sufficient to achieve the degree of those qualities specified by the product's specifications (Tadesse, 2013). After the firing temperature has peaked and is maintained for the prescribed time, the cooling process begins. This is an important stage in brick manufacturing because the rate of cooling has a direct effect on color.

2.4.3 Chemical Composition of Clay Bricks

The major constituents of clay used for brick making are silica and alumina mixed in such quantity, that the clay turns out to be more plastic when water is added to it. It also contains a slight amount of lime, iron, manganese, sulfur, etc. (S.K. Duggal, 2005). silicon oxide (SiO_2), aluminum oxide (Al_2O_3), iron oxide (Fe_2O_3) or ferrous oxide (Fe_3O_4), potassium oxide (K_2O), titanium dioxide (TiO_2), sodium oxide (Na_2O), calcium oxide (CaO), and magnesium oxide (MgO) are metal oxides usually found in the clay bricks however, Manganese, magnesium, and calcium are found to be in lower amounts (Fernandes, 2019).

The color of the bricks differs highly based on the chemical composition of the clay and the operating conditions during firing. Due to different factors such as the nature of the clay minerals, the number of impurities (organic matter, lime, sand, etc.), and the concentration of iron oxides and hydroxides, the colors range from light beige to dark violet. Commonly, clays with a small concentration of iron compounds end up with yellowish bricks; however, clays with a high concentration of iron compound give red and violet bricks. The presence of limestone might bring about orange-tone bricks. In presence of a raised amount of organic matter, bricks become dark in color. Other colors can also be acquired based on the proportion of the corresponding metallic oxide: red brick (5%-10% of Fe_2O_3), yellow brick (3%-10% of TiO_2), brownish brick (0.5%-4% of MnO_2) etc., (Fernandes, 2019).

Table 2.2 Standard chemical composition of a good clay soil

No.	Ingredients/oxides	Proportions	Remark
1	Silica (SiO_2)	50-60%	
2	Alumina (Al_2O_3)	20-30%	
3	Lime (CaO)	< 10%	
4	Magnesia (MgO)	< 1%	The sum of these ingredients is less than 20%
5	Ferric oxide (Fe_2O_3)	< 7%	
6	Alkalis (NaOH, KOH...)	< 10%	
7	Carbon dioxide (CO_2)		Very small percentage
8	Sulphur trioxide (SO_3)		
9	Water (H_2O)		

The Functions of Various oxides of clay (S.K. Duggal, 2000).

Silica (SiO_2): it gives the brick the ability to hold its shape and durability, avoid shrinkage and warping. A surplus amount of silica makes the brick brittle and weak on burning. Although the presence of silica is necessary to reduce shrinkage in firing and to increase the refractoriness of low alumina clays, a huge amount of uncombined silica and sand is unwanted. Alumina (Al_2O_3): Absorbs water and renders the clay plastic. If alumina exists more than the required amount, it produces cracks on drying. Clays having passing high alumina content are probably to be refractory. Lime (CaO): usually occupy 10 percent of the clay. The effect of lime in clay brick are listed as follows: Decreases the shrinkage on drying, it makes the silica to be melted on firing and therefore helps to bind it, when it is found in the form of the carbonate it reduces the point of fusion, and an excess amount of lime results in the melting of brick and consequently causes the loses of shape. Magnesia (MgO): once in a while surpassing 1% affect the color and makes the brick yellow in burning; it makes the clay mellow at a slower rate. The following characteristics are given by iron oxide (Fe_2O_3): gives red color on burning when an abundance of oxygen is accessible and dark brown or even black color when there is no sufficient amount of oxygen. However, an overabundance of ferric oxide makes the brick dark blue, increase impermeability and sturdiness. In general, it lowers the fusion point of the clay, particularly if present as ferrous oxide, and gives strength and hardness.

2.4.4 Physical Properties of Clay Brick

2.4.4.1 Porosity

Firing of clay bricks produces a series of mineralogical, textural and physical changes that depend on many factors that influence porosity. Porosity can be defined as the ratio between the volume of void spaces (pores and cracks) and the total volume of the specimen. Porosity is an important variable concerning clay bricks due to its impact on properties such as chemical reactivity, mechanical strength, durability and the overall quality of the clay brick.

Commonly, clay bricks exhibit high porosity values, ranging between 15% and more than 40% (Esbert et al., 1997; Livingston, 1993; Maierhofer et al., 1998). The dimension and distribution of the pores is influenced by the quality of the raw clay, the presence of additives or impurities, the amount of water and the firing temperature. According to (Mamillan, 1979; Cultrone et al., 2004) observed that if the firing temperature increases, the proportion of large pores (3–15 μm) increases and the connectivity between pores is reduced, whereas the quantity of small pores diminishes. This has a major influence on the durability of the bricks as it has been shown that large pores are less impact by soluble salts and freeze/thaw cycles. Furthermore, several studies by (Cultrone et al. 2004; Elert et al., 2003) noted that the formation of small pores, with a diameter less than 1 μm, is promoted by carbonates in the raw clay (low quality material) and by a firing temperature between 800 and 1000°C. Such pore sizes negatively affect the quality of the clay bricks, as their capacity to absorb and retain water increases.

2.4.4.2 Water Absorption

Pores constitute a large part of the clay brick’s volume, and when the clay bricks are exposed to rainfall or rising damp, water penetrates into the pores. Water absorption then determines the capacity of the water to be stored and to circulate within the clay brick, favoring deterioration and reduction of mechanical strength. In countries where temperatures fall below 0°C, the water inside the pores can freeze leading to surface delamination’s, disintegration or cracking. Moreover, in the presence of soluble salts, water tends to react with them and to cause efflorescence. Though this is mostly an aesthetic deterioration of the surface of the clay brick, the volume increase caused by the crystallization of the salts can cause severe damage.

The values found in the literature are significantly scattered, with a large quantity of bricks with higher-than-average water absorption rates. The way water enters the brick also affects the brick's durability, as it allows water to enter and stay within the brick's mass. The two major parameters that must be determined are water absorption and the suction rate. The first gives an estimation of the proportion of water that can enter the brick, with typical values around 10%-25% of the brick's mass (Lopez-Arce et al., 2003).

Another relevant parameter is the velocity of water absorption, measured by suction rate. The water is sucked by the pores as a result of capillary tension along the walls of the pores. According to (López-Arce et al., 2003) recommended that tension is stronger in small pores than in large ones. Generally, bricks exhibit water absorption values range between 0.5 and 3.5 kg m^{-2} min^{-1}, which were further confirmed by (Fernandes, 2006), who reported values in the range 0.7–2.5 kg m^{-2} min^{-1}.

2.4.4.3 Saturation Coefficient

Saturation coefficient is a ratio that is used to show the relationship of two kinds of water absorption. The first one is the absorption that is determined by immersing the brick in cold water for a period of 24 hours. The second is determined by submerging the brick in boiling water for 5 hours. The ratio between the values of the two tests gives a rough indication of the vacant space in the brick to hold the expansive pressure of freezing of water. Therefore, if a brick has lower value of saturation coefficient, then there is more space for the freezing pressure to be relieved. Thus the probability for the brick to be damaged is less likely (Tadesse, 2013).

2.4.4.4 Compressive Strength

Compressive strength is strongly influenced by the characteristics of the raw material and by the production process. It is known that the raw clay of old bricks was often of low quality and the manufacturing process was relatively primitive and inefficient. Other characteristics of existing old bricks can provide an indication about compressive strength, such as mineral composition, texture, crack pattern and porosity level, by revealing the conditions of drying and firing. On the other hand, the evaluation of the mechanical strength of bricks belonging to old buildings is often difficult due to the high variability in production and additional variability caused by deterioration from the weather or chemical agents such as soluble salts, freeze–thawing cycles or load–unload cycles. Moreover, clay bricks in a given structural element or building can belong to different construction periods or productions.

Finally, the experimental test set-up conditions (dimensions and moisture content of the sample, boundary conditions, temperature, etc.) can also influence the results. According to

(Pauri et al., 1994), the original properties of old clay bricks would only be obtained through the manufacture of bricks using traditional methodologies and raw materials recovered from indications in archives, which is impossible. The range of values found in the literature is quite wide (about 1.5–32 MPa), meaning that in situ testing or destructive testing of samples must be carried out when the compressive strength of the brick is required.

Compressive strength of bricks is the resistance to compression load. It is the main property of clay bricks that affects the strength of the masonry built and is an essential input for structural brick work design. Compressive strength can be measured in the laboratory by applying a compression load that is perpendicular to the largest face of the brick Compressive strength of bricks is the resistance to compression load. It is the main property of clay bricks that affects the strength of the masonry built and is an essential input for structural brick work design. Compressive strength can be measured in the laboratory by applying a compression load that is perpendicular to the largest face of the brick (Tadesse, 2013). The compressive strength of a given brick shall not be less than the specified minimum strength for the respective class of brick. Common bricks have a minimum compressive strength of 3.5 MPa. For a given class of brick, the result of any single brick should not fall below the specified respective average compressive strength by a value greater than 20% (Getachew, 2017).

The compressive strength is the main property of clay bricks that enables the evaluation of material’s ability to carry the compressive loads present in the structure. The value of the compressive strength is strongly influenced by the characteristics of the raw material as well as by the production process. The raw clay of old materials was often of low quality, and the manufacturing process was relatively primitive and inefficient, although some civilizations managed to obtain very good clay bricks. Additionally, the characteristics of existing clay bricks can indicate important information about the compressive strength, such as the mineral composition, texture, and porosity level, by revealing the conditions of drying and firing. Therefore, the quality of the raw material, acceptable firing time and temperature, are fundamental aspects to obtain resistance and, hence, durable bricks.

2.4.5 Effect of Firing Temperature on Clay Bricks

The firing temperature of clay bricks range between 800 and 1100^{o}C depending on the nature of the clay raw material and the quality requirement of the fired brick. The quality and physical properties of fired bricks may vary within the same batch due to the variation of the temperature in the kiln. In order to get fired bricks with uniform and good quality, the firing temperature in the kiln should be as uniform as possible (S. Kumar & Maithel, 2016).

Over and under burnt clay bricks are the results of poor management of kiln temperature. When the firing temperature in the kiln is above the temperature range of 800-1100℃ for an extended period of time, the clay will be over burnt and it will have a dark color that negatively affects the quality of the brick. On the other hand, under burnt clay bricks are fired below the temperature range of 800-1100℃ which causes the brick not to develop the adequate strength and as a result the brick is easily broken (Tadesse, 2013).

Firing temperature is a crucial factor that affects the physical properties of clay bricks such as compressive strength, water absorption and density. Compressive strength of brick greatly improves when firing temperature increases because of the decrease in porosity. Similarly, water absorption of clay brick linearly decreases when firing temperature increases. The water absorption has an effect on the density of the brick as well. At high firing temperature the amount of water the brick absorbs will be less and therefore the pore sizes will be smaller. This will make the brick to have more density (Karaman, Gunal, & Ersahin, 2006).

2.4.6 Sources of Recycled Clay Brick

Recycled clay bricks can be obtained from two major sources. One is from construction, and demolition waste, and the second is from clay brick manufacturing factories. Construction and demolition wastes are the surplus material from construction activities such as demolition and new construction. In developed countries, construction and demolition wastes are generated in hundreds of millions of tons annually. Even though it is difficult to get such reliable data in developing countries, the construction, and demolition waste amount could be expected to be high due to the substantial infrastructural development in these countries. Recyclable-fired clay bricks make up a considerable amount of construction and demolition wastes in the European Union and the US (Bektas, 2007).

Since the discovery of the first fired bricks back in the years between 5000-4500 BC in the Mesopotamia region, fired bricks are still being manufactured and used in construction. Even though the manufacturing process has developed over the years, substantial amounts of products are rejected due to failure to conform to the standards. For instance, the improper firing of clay bricks may produce under-burnt, over burnt or distorted bricks that do not meet the standard requirements (Bektas, 2007). Research on recycled aggregates from waste bricks starts in 1990s (Zheng et al., 2018). As a massive quantity of solid waste clay bricks is generated in many countries, the RA made from waste clay bricks attracts particular attention. Clay brick has become the main component of construction waste due to the demolition of old buildings, especially in China. The landfill has always been the main treatment method for waste, but this treatment method will bring other problems, such as soil pollution, water pollution, and space occupation (Zhao et al., 2018).

2.4.7 Crushed Clay Brick as Concrete Aggregate

Brick manufacturing industry produces large amount of rejected fired clay bricks due to being off-standard (i.e., broken, distorted, under burned, or over burned). The off-standard bricks are usually dumped into sites around the brick factories causing environmental problems (Padmini, Ramamurthy, & Mathews, 2001). Thus, the recycling of crushed bricks as alternative aggregates has a particular interest as it can considerably reduce the problem of waste storage and on the other hand can help in the preservation of natural aggregates (Debieb & Kenai, 2008).

A number of studies were conducted to evaluate the potential of using crushed bricks as aggregates. According to (Zakaria & Cabrera, 1996) reported that concrete containing coarse crushed bricks had a relatively lower strength at early ages than normal aggregate concrete. This is due to the higher water absorption of crushed brick aggregates compared to natural aggregates. Another study by (Poon & Chan, 2006) investigated the possibility of using crushed clay brick as aggregates in sub-base materials. According to (Akhtaruzzaman & Hasnat, 1983) studied the use of crushed clay brick aggregate as a 100% replacement of coarse natural aggregate in concrete. The physical and mechanical properties of solid cement brick manufactured with crushed clay brick as a recycled aggregate have been reported by (Sadek, 2012). A study by (Ge, Gao, Sun, & Zheng, 2012) shows that the effect of clay brick powder on concrete mechanical properties.

According to (Debieb & Kenai, 2008) found that the compressive strength decreased by 35, 30 and 40%, respectively, when coarse, fine or both fine and coarse aggregates were fully substituted by crushed bricks. Water absorption, percolation rate and shrinkage of clay brick aggregate concrete were significantly higher than those of the natural aggregate concrete. They reported that the use of crushed clay bricks aggregates should be limited to low performance concrete like pavement blocks. From previous researches, the main advantages of using crushed clay brick aggregates as alternative aggregates are reducing concrete density, reducing natural aggregate consumption, and being considered environmentally friendly approach. Contradictorily, such problems may contribute serious barriers to both recycling activities and applications. Therefore, these obstacles can be summarized as: High porosity leads to high absorption rate and variation in quality, Specifications are insufficient in place, Uncertainties on regular supply and the lack of unfamiliar in use of these materials are considered the common barriers.

Most of the researches focused on the recycling of crushed clay bricks as either coarse or fine aggregate individually in pervious concrete, although it has a significant influence on the strength, porosity, and permeability of PC. Thus, its recycling of this material is still limited especially in developing countries. However, the shortcomings of using crushed bricks can be avoided by the production of non-structural concrete products such as cement brick. This paper investigates the potential of using clay bricks as alternative aggregates in the production of PC and to conserve the natural aggregates to be used in the important industries such as concrete industry. Compressive strength, unit weight, porosity, and water permeability of PC containing clay brick aggregates were investigated and compared with the limits of the national and international standards.

2.4.8 Effect of Aggregate Gradation, W/C and A/C on Properties of PC

The foregoing studies on PCs have incorporated several governing factors such as size, shape, and type of aggregate, mix proportions, void content, water–cement ratio, aggregate–binder ratio, compaction type, and many others. Different literature has suggested different mix design and mix proportions for optimum design of pervious concrete. The most common principle used for mix design is to provide enough cement paste for coating the aggregate considering the required porosity level. The porosity of pervious concrete mainly depends upon the volume of voids, the total amount of cement pastes and the paste thickness around the aggregates.

The aggregate gradation of PC also affects the permeability coefficient, and strength to a great extent. Both these parameters are inversely related to each other. Larger size aggregates result in larger voids, leading to greater permeability and lowered strength (Cui et al., 2017). The major aspect that creates a difference between normal Concrete and pervious Concrete is the size, gradation and quantity of aggregates. The main requirement of pervious concrete is to have substantial voids in order to permeate water through its pores and for having a sufficient vacuum pore, American Concrete Association has used large size aggregates ranging from 19 to 9.5mm (ACI 522, 2010). Nevertheless, some investigators have used smaller aggregates of sizes 9.5–2.36 mm in order to increase the strength of concrete (Kevern et al., 2009a; Deo et al., 2010; Huang et al., 2010; Nguyen et al., 2014). But, the use of very fine aggregate is strictly prohibited as the fine aggregates occupy the void areas, thereby reduces the infiltration rate.

However, according to (Crouch et al., 2007), smaller aggregate will result in higher compressive strength than the larger size aggregates with a similar porosity distribution and the study suggested to use uniformly graded aggregate for beneficial field installation. Another research carried out at the Iowa State University indicates that single size aggregates provide higher permeability rate, but with a low pavement strength (Kevern et al., 2010). According to (Marolf et al., 2004) studied the effect of aggregate size and gradation on the acoustic absorption for pervious concrete. They reported that pervious concrete mixtures with single sized aggregates provide substantial improvement to sound absorption as compared with conventional concrete (Marolf et al., 2004).

Researches on the effect of aggregate size on compressive strength and permeability of PC have been carried out in recent years. Generally, pervious concrete applied single size aggregates to constitute its skeleton (Zhong, Leng, & Poon, 2018). The pores characteristics and cementitious paste thickness were influenced significantly by the aggregate size (Torres, Hu, & Ramos, 2015). Moreover, the pores characteristics and cementitious paste thickness have an impact on the compressive strength and permeability of pervious concrete (Zhong & Wille, 2016). According to (Liu et al., 2018) studied the effect of porosity and aggregate size on water permeability and mechanical properties by laboratory tests, recommend that the aggregate size is the major factor of the porosity distribution.

Water-cement ratio is one of the key parameters which not only controls the workability of the mix but also affects the interlocking of aggregates with the cement paste as well as manages the pore volume. As the w/c ratio reduces, the reduced amount of water leads to a harsh mix which reduces the proper bondage between the aggregates by offering higher resistance to compaction, and thereby, leading to the higher porosity and lower compressive strength. Consequently, as w/c ratio goes on increasing, the presence of more amount of water lubricates the pervious concrete mixtures offering better compaction of the mix, which results in lower porosity value. But at a high w/c ratio, the available amount of water exceeds the required limit, making an over workable mix, which again results in high porosity and permeability due to the presence of thinner cement paste. Therefore, a limiting range of water-cement ratio needs to be selected in order to maintain the workability and the strength of the mix.

The binding material that is generally used for pervious concrete is Ordinary Portland Cement (OPC) confirming the properties prescribed in ASTM C150 (2017). OPC provides sufficient paste thickness for coating and binding the aggregates together that increases the strength and durability criterion. The cement paste thickness is further dependent upon the size of aggregates; smaller aggregates offer lesser paste thickness due to their larger surface area whereas, larger sized aggregates show higher paste thickness. The cement paste thickness also has a great impact on pore properties of the structure for attributing the required porosity level. The size of pore structures and cement paste thicknesses can be identified by using the scanning electron microscope, CT scanning or X-ray tomography (Kayhanian et al. 2012; Torres et al. 2015).

Lastly aggregate-cement ratio (A/C) is also having the similar effect as W/C on the properties of permeable mix, the high A/C ratio possesses weak contact between particles and thereby offers low strength, whereas low A/C ratio causes strong contact between particles, thick paste layer around aggregates, however, these can also occupy the hydraulic channels and void spaces, leading to the reduction of hydraulic conductivity (Tong, 2011). The aggregate to cement ratio is generally kept between 4:1 and 6:1 (ACI 522R, 2010). As pervious concrete is supposed to have zero slumps, many researchers have used water reducing admixtures to maintain the workability without increasing the amount of water. The use of various types of admixtures is also suggested in the report (ACI 522R, 2010).

2.5 Literature Summary and Gap Identification

According to (Debieb & Kenai, 2008) studied that aimed to investigate the compressive strength, flexural, and modulus of elasticity properties of concrete produced by using single size of crushed bricks as coarse aggregate. The results of the research indicated the reductions of the compressive strength, flexural and modulus of elasticity properties of concrete. Therefore, the present study recommends appropriate mix design based on aggregate gradation, and types may produce a concrete with good strength and permeability.

Another study by (Hossain et al., 2012) investigated the compressive strength, and permeability properties of pervious concrete produced by using brick aggregate. The results showed that less strength and higher permeability of brick aggregate of pervious concrete than stone aggregate pervious concrete. Mixture of different size of brick aggregate may produce higher strength concrete therefore; use of aggregate gradation is recommended for future study. Yet another study by (Sata, Wongsa, & Chindaprasirt, 2013) conducted a test on compressive strength, splitting tensile strength, total void ratio, and water permeability coefficient of the PGCs produced by using of recycled aggregates crushed structural concrete member (RC), and crushed clay brick (RB). The results of the research indicated that both RC and RB can be used as recycled coarse aggregates for making PGC with acceptable properties. In this study single size of aggregate was used in making PGC to eliminate aggregate gradation as a variable. According to the conclusion of a research study the size of aggregate or the aggregate gradation has the maximum effect on the porosity and permeability of the mix.

Most studies investigated the effect of a single size of aggregate in making pervious concrete. Investigations on the effect of the mixture of different sizes of brick aggregate as a variable remain limited. Also, the water to cement ratio (W/C), and aggregate to cement ratio (A/C) play an important role in the mixture designing of PC mixtures. Bricks have various raw materials, origins, and properties. The effect of the mixture of different types of aggregate gradation, W/C and A/C ratios as a variable in producing pervious concrete is yet not known. Therefore, based on this gap, this research aims to study the possibility and the effect of the mixture of different types of aggregate gradation using sourced from Burayu Brick Factory found in sheger city as a variable to produce pervious concrete.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Introduction

The aim of this research is to study the effect of using waste clay bricks obtained from Burayu Brick factories located in Sheger City as coarse aggregate in pervious concrete production. The research is conducted through laboratory experimental works by replacing the natural coarse aggregate of a reference concrete mix with waste clay bricks by using different types of aggregate gradation, W/C ratio and A/C ratio as a parameter.

The experimental study includes material characterization, mix design proportioning, concrete specimens' preparation and conducting laboratory tests on the hardened concrete. On the hardened concrete; density, compressive strength, porosity, and water permeability tests were conducted. All the laboratory works of the experimental study were conducted in ASTU department of Civil Engineering in construction material, highway material engineering, and applied biology laboratory. But the chemical composition analysis test of the waste clay bricks, which was conducted in the geochemical laboratory of Geological Survey of Ethiopia.

3.2 Materials

The binding material that is generally used for pervious concrete is Ordinary Portland Cement (OPC) confirming the properties prescribed in ASTM C150 (ASTM C150, 2017). The cement used for the research is Ordinary Portland Cement supplied by Habesh Cement Factory. For PC mixing and curing of specimens, drinkable tap water supplied in ASTU campus was used. Six different gradations viz. G1, G2, G3, G4, G5, and G6 were considered in the present laboratory investigation: three single-sized of natural aggregates having nominal maximum size 10 mm (denoted as G-1), 12.5 mm (denoted as G-2), 20 mm (denoted as G-3), and three gradations with equal proportions of two single-sized aggregates such as 50% 10 mm - 50% 12.5 mm (denoted as G-4), 50% 10 mm - 50% 20 mm (denoted as G-5), and 50% 12.5 mm - 50% 20 mm (denoted as G-6).

The commercially available natural aggregates were used as coarse aggregate on the other hand waste clay bricks was collected from Burayu brick manufacturing factories found in Sheger City used as the coarse aggregate in the present investigation is shows in Figure 3.1. The test methods used to characterize particle shape, mechanical and physical properties of the considered aggregates and their relevant testing standards are being presented in Table 3.1. The sieve analysis for the coarse aggregate was conducted with the grading requirement of the IS:383 (IS:383, 2016). The particle size distribution of considered aggregates is shown in Figure 3.2.

Figure 3.1 Waste clay bricks and natural coarse aggregates.

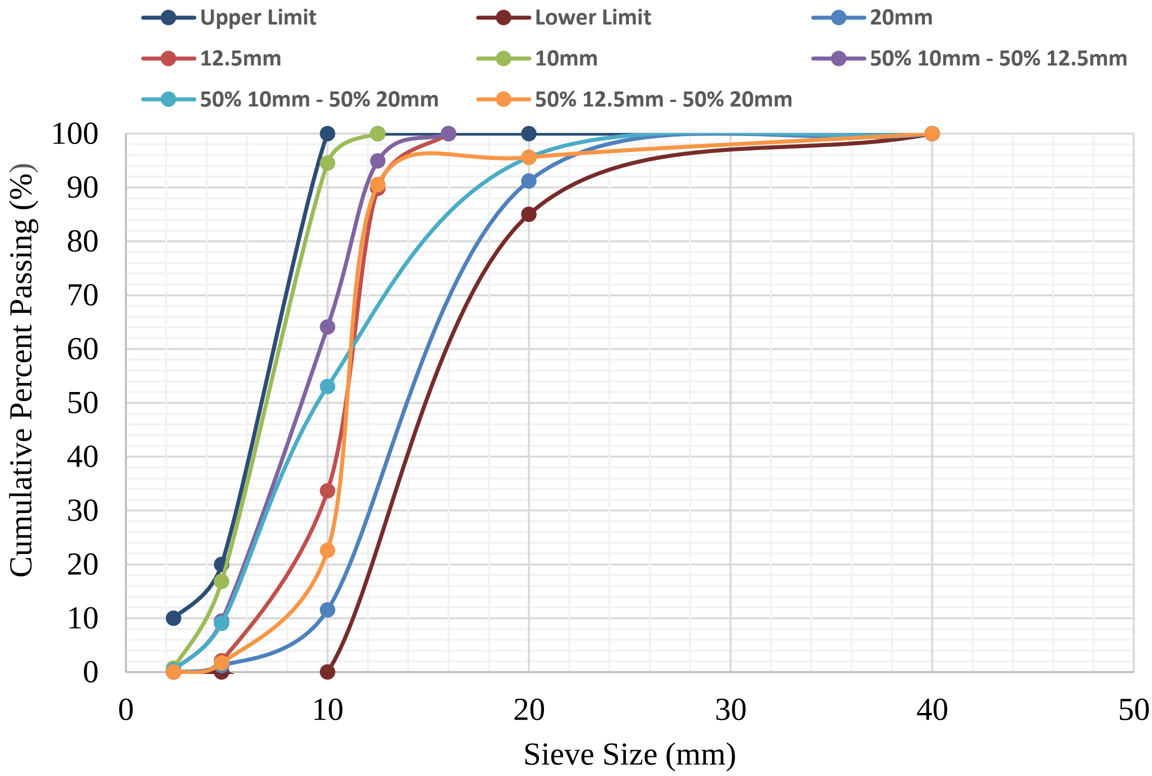

Figure 3.2 Particle size distribution curve for various sizes of coarse aggregates.

Table 3.1 Test methods used to characterize the aggregates.

Property Under Evaluation	Standard Guidelines
Unit Weight (kg/m3)	IS:2386-Part- III, 1963
Specific Gravity	IS:2386-Part- III, 1963
Absorption (%)	IS:2386-Part- III, 1963
Voids (%)	IS:2386-Part- III, 1963
Los Angeles Abrasion Value (%)	IS:2386-Part- IV, 1963
Aggregate Crushing Value (%)	IS:2386-Part- IV, 1963
Aggregate Impact Value (%)	IS:2386-Part- IV, 1963
Flakiness Index (%)	IS:2386-Part- I, 1963
Elongation Index (%)	IS:2386-Part- I, 1963

Strength of aggregates plays a dominant role on the overall strength of pervious concrete; thus, it was necessary to determine strength characteristics of aggregates as a whole. Los Angeles abrasion test was carried out on both types of aggregate to find out its resistance against abrasion and impact loading following the procedure stated in IS:2386-Part- IV standard (IS:2386-Part- IV, 1963). Aggregate crushing test is used to measure the resistance of an aggregate to crushing load. The crushing value obtained from this test can be used as an indicator of aggregates strength for aggregates that have unknown performance. It can also be used to check aggregates ‘strength when a lower strength is anticipated. The ability of an aggregate to resist crushing is determined through the aggregate crushing value (ACV) test according to the IS:2386-Part- IV standard (IS:2386-Part- IV, 1963).

The aggregate impact test (AIV) is used to determine the impact value of bulk aggregate and toughness. The value obtained from this test is related to the crushing value and it is an alternative test that can easily be done on the field. The aggregate impact test was also done for the basaltic coarse aggregate and the WCB aggregates. It was done according to the IS:2386-Part- IV, Methods for determination of aggregate impact value (AIV) test (IS:2386-Part- IV, 1963). Similar to the ACV test procedure, the WCB aggregate was used in a surface dry condition which passed the 12.5 mm sieve and retained on the 9.5 mm sieve. Since pervious concrete does not contain any fine aggregates, strength of concrete comes from bonding of cement paste coated on aggregates and also from interlocking friction of aggregate themselves. Thus, it was deemed necessary to determine the shape test which is a measure of absence of roundness of aggregate (IS:2386-Part- I, 1963).

The waste clay bricks used in this experimental study was collected from Burayu brick manufacturing factories found around Addis Ababa. The brick factories are selected based on production capacity and location. There are six available brick factories found in and around Addis Ababa (Tadesse, 2013). Among the six factories, four of them are located around Addis Ababa and the rest two are located in Addis Ababa. The waste clay brick was sampled from the factory's waste stockpiles randomly from the top, middle, and bottom of the stockpile so as to collect a representative sample. Waste lay bricks that were visually discolored to black color due to over burning were not used for the experimental study so as to study their effect separately. The brick factories from which the waste clay brick was obtained is shown in Table 3.2 along with the owner, location and annual production capacity of the factories. Clay brick waste pile in Burayu brick factory is shown in Figure 3.3.

Table 3.2 General information about Burayu brick factory

Name of factory	Owner	Location	Annual Clay Brick production (pcs/yr)
Burayu Brick Factory	Brick Products processing S.C	At Sheger City Burayu town	6,350,000

Figure 3.3 Clay Brick waste pile in Burayu brick factory

Chemical composition analysis was done for the waste clay bricks collected from the Burayu brick factory to evaluate the chemical composition of the clay bricks and to test the existence of reactive elements such as chlorides and sulfates in the Geochemical laboratory of the Geological Survey of Ethiopia. To examine the possible differences that exist between the normal and the waste clay brick, chemical composition analysis was also conducted on a waste clay brick sourced from Burayu brick factory.

The same procedure was used to prepare all the types of WCB coarse aggregates used for this experimental study. Enough amount of waste clay bricks to produce all the concrete mixes for the study was collected from brick factories. The clay bricks were in the size as shown in above Figure 3.3 when obtained from the factories ‘waste stock piles. The waste clay bricks were then slightly reduced in to smaller sizes as shown in Figure 3.4 manually using a steel hammer.

Figure 3.4 Size of manually crushed waste clay brick.

The reduced sizes of the waste clay bricks were of different sieve sizes; therefore, it was sieved and separated in to sieve sizes similar to the gradation of the crushed natural coarse aggregate as shown in Figure 3.5.

Figure 3.5 Crushed waste clay bricks aggregates of different sieve sizes.

3.2.1 Mix Design

The mix proportioning was done following the procedures of National Ready Mix Concrete Association (NRMCA) design of PC mixes (NRMCA, 2010). The detailed mix design calculation is presented in Annex A. Choice of W/C ratio is crucial as it is directly correlated to strength and workability of PC mix (Debnath & Sarkar, 2020). Higher W/C ratios generate excess cement paste, which may choke pores, and thus disturb interconnectivity of pores (Xie et al., 2018; Debnath and Sarkar, 2020). A study by (L. G. Li, Feng, Zhu, Chu, & Kwan, 2021) emphasized the impact of W/C ratio and cement paste on pore connectivity. The literature demonstrate that typical range of W/C ratio lies between 0.27 and 0.44 (Tennis, Leming, & Akers, 2004).

The pervious concrete mixes were found to have sufficient workability, as assessed by hand-ball rolling test (Aoki, Sri Ravindrarajah, & Khabbaz, 2008). The consistency of the PC mixture obtained in this research is illustrated in Figure 3.6. Make trial batches with calculated mix proportions, and adjust the value of W/C to find the best mixing W/C. The best mixing W/C is described as when a ball formed by a handful of pervious concrete will not crumble or lose its void structure as the paste flows into the spaces between the aggregates, which is 0.3 and 0.35 in this study.

Figure 3.6 The consistency of the PC mixture.

Another indispensable parameter in PC mix design is A/C ratio, which influences strength and pore characteristics (Debnath and Sarkar, 2020). Aggregate constitutes to 50–65% and 60–75% by volume in common concrete and PC, respectively (Chandrappa, Biligiri, &

Materials, 2016a). According to literature, A/C ratios in PC studies have been traditionally varied in the range of 2.0–10.0 (Deo, Neithalath, & Materials, 2011) (Deo and Neithalath, 2011, Maguesvari ange of 2.0–10.0 (Deo and Neithalath, 2011, Maguesvari ange of 2.0–10.0 (Deo and Neithalath, 2011, (Maguesvari, Narasimha, & Sciences, 2013) Chandrappa and Biligiri, 2016, Mohammed et al., 2016, Zhong et al., 2018).

In PC mixes, increase in A/C ratio improves porosity but reduced strength (Debnath and Sarkar, 2020). To prepare PC mixes, this study deployed two different A/C ratios; 4 and 5. According to the mix design, the quantities of the constituent materials for G-3 gradation trial mix concrete per m^3 for a W/C ratio of 0.27, 0.3, 0.35, and 0.4 at A/C of 4 are presented in Table 3.3.

Table 3.3 Mix proportions for trial PC mixes.

Gradation Name	Aggregate Size (mm)	Mix Types (M-X-Y) *	Coarse aggregate (kg/m3)		Cement (kg/m3)		Water (kg/m3)	
			WCBA	NA	WCBA	NA	WCBA	NA
G-3	20	TR1-0.27-4	1257	1567	314	392	85	106
		TR2-0.3-4	1257	1567	314	392	94	118
		TR3-0.35-4	1257	1567	314	392	110	137
		TR4-0.4-4	1257	1567	314	392	126	157

* X-water/cement ratio, and Y-aggregate/cement ratio

Four trial mixes for both types of aggregate were prepared based on the result of the mix design and by adjusting the W/C ratio until the required compressive strength was attained. The results obtained for the trial mixes are presented in Table 3.4.

Table 3.4 compressive strength for trial mixes.

Gradation Name	Aggregate Size (mm)	Mix Types (M-X-Y) *	Average 7th day compressive strength (Mpa)	
			WCBA	NA
G-3	20	TR1-0.27-4	1.42	2.54
		TR2-0.3-4	3.81	6.08
		TR3-0.35-4	4.04	6.58
		TR4-0.4-4	2.24	3.12

The water/cement ratio for the final G-3 PC mix that satisfied the compressive strength requirement was found to be 0.3, and 0.35 at A/C ratio of 4.0 and the quantities of the constituent material used per one cubic meter of concrete for the G-3 control mix is shown in Table 3.5.

Table 3.5 Mix proportions for G3 PC mixes.

Gradation Name	Aggregate Size (mm)	Mix Types (M-X-Y) *	Coarse aggregate		Cement (kg/m3)		Water (kg/m3)	
			WCBA	NA	WCBA	NA	WCBA	NA
G-3	20	TR2-0.3-4	1257	1567	314	392	94	118
		TR3-0.35-4	1257	1567	314	392	110	137

The mix proportions considered in the present investigation is tabulated in Table 3.6, considering the absolute volume mix design and fixing 20% void content.

Table 3.6 Pervious concrete Mix proportions for Different Size of Aggregate

Gradation Name	Aggregate Size (mm)	Mix Types (M-X-Y) *	Coarse aggregate (kg/m^3)		Cement (kg/m^3)		Water (kg/m^3)	
			NA	WCB	NA	WCB	NA	WCB
G-1	10	M-0.3-4	1618	1270	404	317	121	95
		M-0.3-5	1618	1270	324	254	97	76
		M-0.35-4	1618	1270	404	317	142	111
		M-0.35-5	1618	1270	324	254	113	89
G-2	12.5	M-0.3-4	1590	1244	398	311	119	93
		M-0.3-5	1590	1244	318	249	95	75
		M-0.35-4	1590	1244	398	311	139	109
		M-0.35-5	1590	1244	318	249	111	87
G-3	20	M-0.3-4	1567	1257	392	314	118	94
		M-0.3-5	1567	1257	313	251	94	75
		M-0.35-4	1567	1257	392	314	137	110
		M-0.35-5	1567	1257	313	251	110	88
G-4	50% (10) + 50% (12.5)	M-0.3-4	1632	1316	408	329	122	99
		M-0.3-5	1632	1316	326	263	98	79
		M-0.35-4	1632	1316	408	329	143	115
		M-0.35-5	1632	1316	326	263	114	92
G-5	50% (10) + 50% (20)	M-0.3-4	1625	1289	406	322	122	97
		M-0.3-5	1625	1289	325	258	97	77
		M-0.35-4	1625	1289	406	322	142	113
		M-0.35-5	1625	1289	325	258	114	90
G-6	50% (12.5) + 50% (20)	M-0.3-4	1600	1294	400	323	120	97
		M-0.3-5	1600	1294	320	259	96	78
		M-0.35-4	1600	1294	400	323	140	113
		M-0.35-5	1600	1294	320	259	112	91

* M- WCBA, and NA mix; X-water/cement ratio; Y-aggregate/cement ratio.

3.3 Methods

The methodology adopted in this study is presented in Figure 3.7 indicates that this research was a laboratory-analytical study that was carried out in two stages. Laboratory stage: this first stage involved the production of concrete samples according to the different PC designs based on expert opinion. This phase aimed to validate the different characteristics of the PC designs to determine whether or not they achieved the standards claimed by the experts. The study was carried out by conducting laboratory tests on hardened property of PC. The waste clay brick was crushed and sieved in to the same particle size as that of the natural coarse aggregate. The natural and waste clay bricks aggregates were saturated in water for more than 24 hours and removed from water an hour before the concrete mixing. The aggregates were batched in the saturated surface dry (SSD) condition. No chemical admixture was used in the pervious concrete mixes.

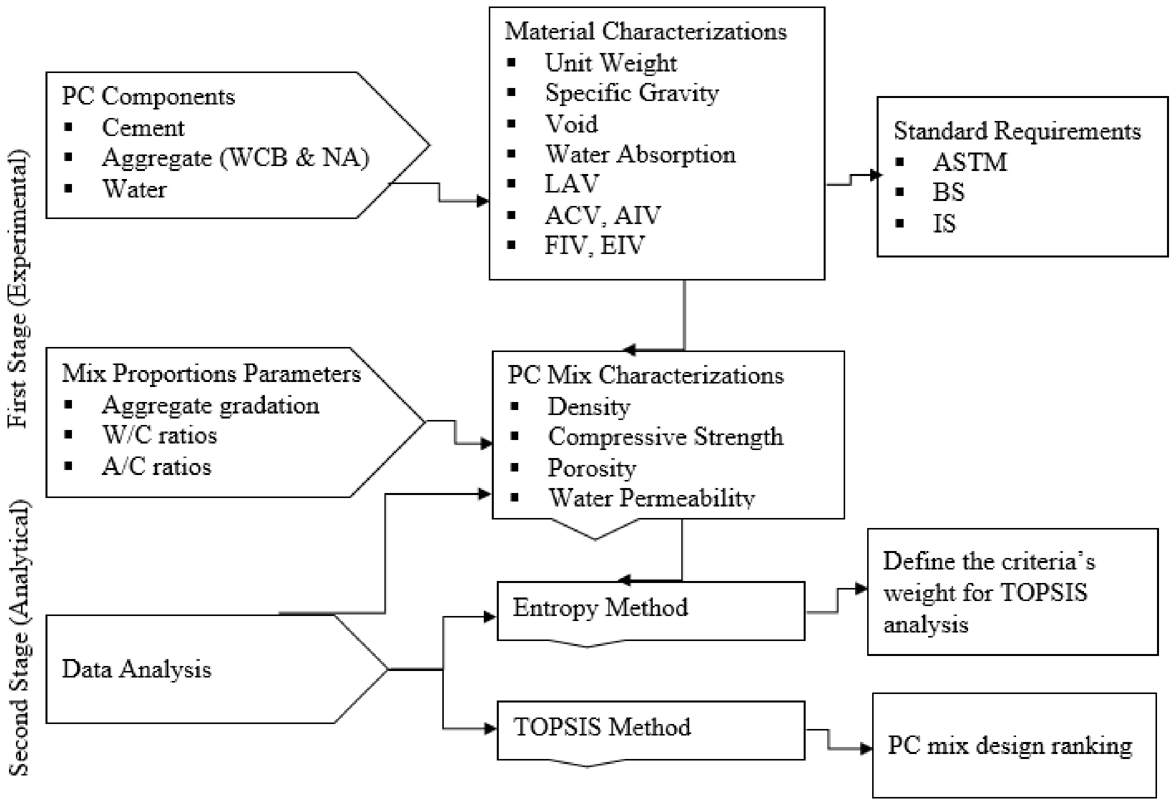

Figure 3.7 Methodology involved in PC study.

To test the 7th and 28th day compressive strength and the hardened density of the concrete produced with WCB aggregate, waste clay bricks were used from brick factories selected. Then the porosity and water permeability tests were conducted. Also, Scanning electron microscopy (SEM) was performed under ASTM C1723-16 standards (C-16, 2016). The

Analytical stage: the second stage (analytical) aimed to prioritize PC mix design. This stage is carried out in two steps. The first step is to calculate the weight of the criteria by using Entropy Method. The second step is ranking the PC mix design by using TOPSIS Method.

3.3.1 Laboratory Specimen Preparation

Specimens were prepared with the aim to investigated compressive strength, porosity, and permeability. Mixing of concrete was performed following the ASTM C192 standard using a concrete mixing machine. To improve bond between aggregate and cement paste, aggregate was first mixed with dry cement for one minute and then half of water was added and mixed for another one minute. Next remaining cement and water were added and mixed for five more minutes before casting as shows in Figure 3.8.

Figure 3.8 Casted pervious concrete molds.

The Wet concrete was placed inside mould in three layers with each layer compacted with help of a standard proctor hammer of 2.5 kg for 20 numbers of blows. All compacted specimens were then covered with plastic bags to prevent water evaporation and demolded after 24 hours. The demolded specimens were placed inside water tank in room temperature and cured until the testing age according to the ASTM C192 standard.

3.3.2 Density of PC Concrete

The hardened densities of the PCs were determined using the methods described in ASTM C1754 specified for hardened pervious concrete (ASTM C1754, 2012). The specimens were placed in the oven at a temperature of 105°C until the weight was constant. Then the dry weight (W_{dry}) was measured and the specimen volume (V) was calculated. The reported results were the average values of two PC specimens. The density of PCs can be calculated following the equation 3.1:

$$D = \frac{W_{dry}}{V} \quad (3.1)$$

Where: D the density of specimen (g/cm^3), W_{dry} the oven dry mass of specimen (g), and V the volume of specimen (cm^3).

3.3.3 Porosity of PC Concrete

The porosity (void content) of the PCs was also evaluated in accordance with ASTM C1754 (ASTM C1754, 2012). First, the specimens were completely immerged in water for 30 minutes, and then the mass of specimens in water was measured and the value was named as M_1. Afterward, the specimens were dried in the oven at 105°C for 24 hr., and the dried mass of specimens in air were measured and named as M_2. For each batch of PC, two specimens were used for porosity determination and the average values were reported. The porosity (P_v) can be calculated as follows the equation 3.2:

$$P_v = \left(1 - \frac{M_2 - M_1}{p_w . V}\right) x100\% \quad (3.2)$$

Where: P_v represents the volumetric porosity of specimen (%), M_2 represents the dry mass of specimen (g), M_1 represents the submerged mass of specimen (g), V represents the volume of specimen (cm^3), and p_w represents the apparent density of water (g/cm3).

3.3.4 Compressive Strength of PC Concrete

The compressive strength tests according to the ASTM C39 were carried out to investigate the mechanical behavior of the PC (ASTM C39, 2018). It was determined by using a compression machine with a maximum loading capacity of 3000 kN. The PC were loaded at rate of 0.6 MPa/s with 200×100 mm^2 surface upward until failure. The maximum load (W)

was measured, and the compressive strength (f_c) was calculated using the following equation 3.3.

The average compressive strength of three specimens was reported.

$$f_c = \frac{W}{A} \quad (3.3)$$

Where: f_c represents compressive strength (MPa), W represents maximum load (N), and A represents compression area (cm^2).

Figure 3.9 PC specimen in compression test machine

3.3.5 Water Permeability Test

After porosity the test, the specimen will be placed in the water permeability test set-up prepared by (Cui et al., 2017). The above work of literature indicates the permeability was measured using a fabricated falling head permeameter. The graduated tube was made up of poly vinyl chloride (PVC) pipe with graduations marked using a scale to a least count of 0.5cm and an inner diameter of nearly 10 cm. In this research, the permeability of PC was tested from initial head h1 (30 cm). The final head h2 was maintained at 5 cm above the specimen surfaces to ensure the saturated condition. During the test, the time taken (t) for the flow of water from h1 to h2 through the specimen was recorded using a stopwatch. After the test, the permeability coefficient was determined by applying the Darcy's law. The water permeability coefficients (k) were the averages values of two specimens by using the following equation 3.4.

$$K = (L \times a) / (t \times A) \ln (h1/h2) \quad (3.4)$$

where, K coefficient permeability (cm/s), a cross-section area of specimen in (cm^{2}), A cross section area of the tube (cm^2), L length of the specimen (cm), and t time taken for the water to flow from h1 to h2 (seconds).

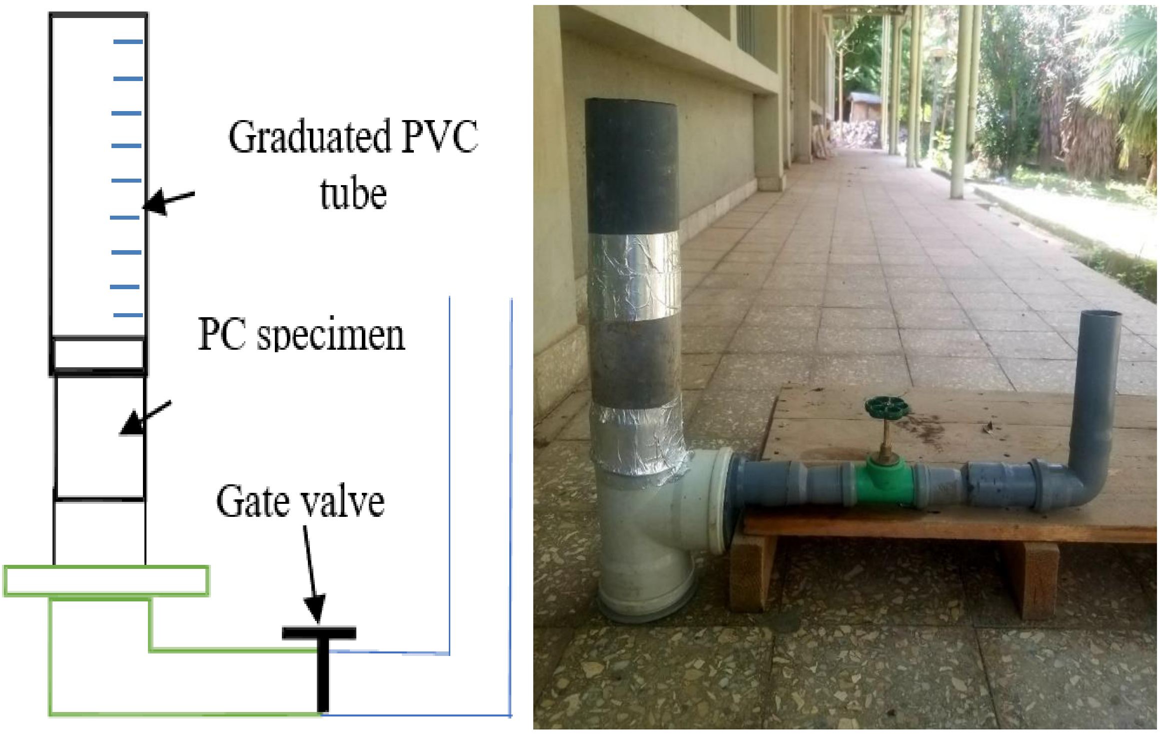

Figure 3.10 Permeability Test Set Up

3.3.6 Morphological Properties of Pervious Concrete

Scanning electron microscopy (SEM) was performed under ASTM C1723-16 standards (C-16, 2016). The samples were examined at magnifications of 100x, and 200x. SEM analyses were performed to examine the interfacial zone between the cement paste and both types of aggregates, crushed gravel and waste clay brick aggregate. The microscopic images at the ITZ were obtained from SEM, which shows the material morphology and provides evidence of cement hydration products.

3.3.7 Entropy and TOPSIS analysis to prioritize the mix design of PC

The TOPSIS method, first developed by (Hwang, Yoon, Hwang, Yoon, & survey, 1981), is one of the common Multi-Criteria Decision Making (MCDM) methods to determine a solution from a finite set of points. TOPSIS is a linear weighting method and is the abbreviation for Technique for Order Preference by Similarity to Ideal Solution. TOPSIS can be used with both fuzzy and numbers. The method is based on defining both positive and negative ideal solutions and subsequently ranking their feasibility according to the longest distance from the negative ideal solution and the shortest distance from the positive ideal solution. TOPSIS also presents an index called closeness to the positive-ideal solution and furthest from the negative-ideal solution, in which the alternative with the highest similarity to the positive-ideal solution should be selected (Onat, Gumus, Kucukvar, Tatari, & Consumption, 2016).

One of the main advantages of the TOPSIS approach is that it delivers influence results for the ranking of alternatives that have absolute data for each indicator (Onat et al., 2016). According to (Dos Santos, Godoy, & Campos, 2019) recommended that the integration of TOPSIS with other MCDM method may solve problems more efficiently and flexibly. On the other hand, Shannon's Entropy is suggested that to determine the weight of the criteria since it is an effective method that makes decision-making more reliable and accurate with no significant modeling difficulties (Song, Zhu, Peng, Gonzalez, & Engineering, 2017).

According to (X. Li et al., 2011), evaluation of the weights of indexes through subjective weight methods such as the survey method, Delphi method, Analytic Hierarchy Method (AHP), etc., could derived to deviations of indexes' weights due to subjective factors. On the contrary, objective define weight approach such as entropy could effectively exclude human-made disturbances because they are conducted according to the inherent information of indictors and define the weight of indictors, which make results consistent with facts (Jozi, Shafiee, MoradiMajd, Saffarian, & assessment, 2012).

These methods focus on creating a weight for each criterion, scoring the normalization for each criterion, and estimating the geometric distance between each alternative and the ideal alternative. The study adopted an integrated and more realistic MCDM methodology, two-phase Entropy and TOPSIS method, to select the priority pervious concrete mix for high performance. For this purpose, the weights that are defined from Entropy Method calculations are used in TOPSIS calculations.

The selection steps determine the weights (importance) of the mix factors and the prioritization of the mix. Determine weights of attributes by using Entropy Method. This method consisted of six attributes: density of PC (C1), …... that related to the mix design results. The values of these attributes were determined for the different PC mix designs introduced in stage one. These attribute values can be set in a decision matrix (matrix D) as follows:

$$D: \begin{array}{cccccc} & C_1 & C_2 & & C_n \\ A_1 & x_{11} & x_{12} & \ldots\ldots & x_{1n} \\ . & . & . & & . \\ . & . & . & & . \\ A_1 & x_{11} & x_{12} & \ldots\ldots & x_{1n} \end{array} \qquad (3.5)$$

A decision matrix features rows and columns including alternatives and attributes, respectively. In decision matrix D (equation (1) C_j and A_i represent the j^{th} attribute and i^{ih} alternative, respectively, and x_{ij} represents the value of the j^{th} attribute for the i^{ih} alternative. Also, m is the number of alternatives (the PC mix designs in this study) and n is the number of attributes. The aim is to obtain the weights of the attributes based on matrix D. The entropy method was used for this purpose. From this method, the higher the scatter for an attribute's values, the more important that attribute is. The entropy method consists of the following five steps using Equations (3.6 – 3.9) (Wang et al., 2017):

Step 1. Form the decision matrix (here, matrix D).

Step 2. Normalize the data given in the matrix. If p_{ij} is the normalized value of x_{ij}, it can be obtained as

$$P_{ij} = \frac{x}{\Sigma_{i=1}^{m} x_{ij}} \quad ; j = 1, ..., n \qquad (3.6)$$

Step 3. Calculate the entropy of attribute *j* (E_j) as

$$E_j = -\mathrm{k}\, \Sigma_{i=1}^{m} p_{ij}.\ln(p_{ij}) \quad ; j = 1, ..., n \qquad (3.7)$$

where k = 1/ln (m), m is the number of alternatives. E_j will be between 0 and 1.

Step 4. Calculate the value of d_j as

$$d_j = 1 - E_j \quad ; j = 1, ..., n \qquad (3.8)$$

Step 5. Calculate the weight of attribute j as

$$W_j = \frac{d_j}{\Sigma_{j=1}^{n} d_j} \quad ; j = 1, ..., n \qquad (3.9)$$

In TOPSIS method all equations were formulated and linked using cells in an Excel sheet that represented all properties, assuming that the property was considered in determining an alternative. Referencing the value fixed to the j^{th} criterion of the i^{th} alternative, where x_{ij} is the decision matrix, the equivalent weight of the property is expressed as w1, w2, ..., wn, and the TOPSIS method analysis is expressed in five steps using Equation (3.10 – 3.14) (Hwang et al., 1981).

Step 1. Normalize the decision matrix. This can be calculated by

$$\bar{X}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^2}} \qquad (3.10)$$

$r_{ij} = x_{ij}$__$m_k = 1 \text{ x } 2k_j$, $i = 1, . . ., m; j = 1, . . ., n$, where: r_{ij} denotes the normalized value of the j^{th} criterion for the i^{th} alternative A_i.

Step 2. Calculate the weighted normalized decision matrix. V_{ij} can be calculated as

$$V_{ij} = \bar{X}_{ij} \text{ x } W_j \qquad (3.11)$$

$V_{ij} = w_j r_{ij}$, $i = 1, . . ., m; j = 1, . . ., n$ (2), where: w_j is the weight of the j^{th} criterion or attribute.

Step 3. Determine the ideal positive and negative solutions S_i^+ which can be calculated by

$$S_i^+ = [\sum_{j=1}^{m} (v_{ij} - v_j^+)^2]^{0.5} \qquad (3.12)$$

Where: V_{ij} weighted and normalized decision matrix (V_{ij}), S^+ the Euclidean distance from the ideal best, $V^+ = \text{MIN } [A_iC_i :A_nC_i]$, $V^- = \text{MAX } [A_iC_i :A_nC_i]$

Step 4. Calculate the Euclidean distance from the ideal worst condition. S_i^- can be described as

$$S_i^- = [\sum_{j=1}^{m} (v_{ij} - v_j^-)^2]^{0.5} \qquad (3.13)$$

Where: V_{ij} weighted and normalized decision matrix (V_{ij}), S_i^- the Euclidean distance from the ideal worst,

step 5. Calculate the performance score and ranking P_i This can be calculated by

$$P_i = \frac{S_i^-}{S_i^+ + S_i^-} \qquad (3.14)$$

CHAPTER FOUR

4. RESULTS AND DISCUSSIONS

In this section, the results of the laboratory tests are discussed. The results presented include the characterization of the natural coarse aggregates and waste clay brick coarse aggregates. For the hardened property of PC; density, compressive strength, porosity, and water permeability tests results were discussed. Also Scanning electron microscopy (SEM) test was performed. Finaly analyzed the PC mix design by using MCDM method.

The test results are presented graphically in category of density, compressive strength, void ratio, permeability and age of concrete. The sizes of aggregates, water-cement ratio, and aggregate-cement ratio were varied for PC mixes using waste clay brick and natural crushed aggregate. The natural crushed aggregate concrete was used as for comparison purposes.

4.1 The Characterization of Natural and Waste Clay Brick Aggregates

Table 4.1 and 4.2 shows the results obtained in the characterization of the natural coarse aggregates and waste clay brick coarse aggregates respectively, namely, in the dry roodded unit weight, loose unit weight, bulk Specific gravity, bulk specific gravity (SSD), water absorption and volume of voids. The grading curves of aggregates were already presented in Figure 3.1. In this study the unit weight of brick aggregate was much lower than that of stone aggregate.

Table 4.1 Physical properties of natural coarse aggregates

Properties	Natural Coarse Aggregate Sizes (mm)					
	20	12.5	10	20+12.5	20+10	12.5+10
Dry roodded unit weight (kg/m^3)	1576	1598	1620	1602	1626	1632
Loose unit weight (kg/m^3)	1523	1542	1567	1554	1572	1621
Bulk Specific gravity	2.73	2.71	2.69	2.68	2.66	2.65
Bulk specific gravity (SSD)	2.77	2.74	2.73	2.72	2.7	2.7
Absorption (%)	1.18	1.22	1.56	1.56	1.6	1.67
Voids (%)	42.4	41.08	39.77	40.12	38.78	38.47

As aggregate size becomes smaller, the unit weight becomes smaller. The void ratio of waste clay brick aggregate was much higher than that of natural aggregates.

IS:2386, Part-III standard procedure was used to measure the bulk specific gravity and absorption of aggregates.

Table 4.2 Physical properties of waste clay brick coarse aggregates

Properties	Waste Clay Brick Coarse Aggregate Sizes (mm)					
	20	12.5	10	20+12.5	20+10	12.5+10
Dry roodded unit weight (kg/m3)	1060	1076	1098	1092	1114	1136
Loose unit weight (kg/m3)	1003	1011	1024	1020	1032	1045
Bulk Specific gravity	1.99	1.97	1.96	1.98	1.96	1.95
Bulk specific gravity (SSD)	2.4	2.32	2.31	2.39	2.31	2.3
Absorption (%)	20.82	17.77	17.76	20.64	17.79	17.91
Voids (%)	45.92	45.31	44.01	44.96	43.09	41.85

The specific gravity of waste clay brick aggregate was found much lower than the specific gravity of natural aggregates. The absorption capacity of waste clay brick aggregate was found to be 20.82% as compared to 1.67% of natural aggregates. The porosity of brick aggregate plays a major role in producing its high absorption properties. Due inclusion of this porosity in brick aggregate comes during its making process. Clay was dried in the shape of brick before it was burnt in a kiln. However, some of the water entrapped inside the brick, and when burnt, the water evaporated leaving the brick porous.

The shape and strength characteristics of WCBA and NA are summarized in Table 4.3. It was found that abrasion value for waste clay brick aggregate was 47.9% and for natural aggregate it was 27.9%. The ACV of waste clay brick aggregate was found to be 36.43% and that of natural aggregate was 13.64%.

Table 4.3 The shape and strength characteristics of WCBA and NA.

Parameters	Crushed NA Coarse Aggregate	Waste Clay Brick Coarse Aggregate
Los Angeles Abrasion Value (%)	27.9	47.9
Aggregate Crushing Value (%)	13.64	36.43
Aggregate Impact Value (%)	6.33	33.07
Flakiness Index Value (%)	14.59	27.47
Elongation Index Value (%)	15.02	38.19

The AIV of waste clay brick aggregate was found to be 33.07% and that of natural aggregate was 6.33%. Basic idea is that if a single size spherical aggregate is compacted in its dense form, then total volume of solid will be 67 percent and volume of voids will be 33 percent of total volume (BS 812). However, if aggregates are angular or irregular then total volume of solid will be decrease, consequently an increase in volume of voids. Measured flakiness index (FIV), and elongation index (EIV) for waste clay brick aggregate were found to be 27.47, 38.19 and those for natural aggregate were 14.59, and 15.02. Waste clay brick was manually crushed to produce aggregate resulting sharp edge of particles as can be seen from Figure 3.4 which may have also resulted for its high flakiness index and elongation index value.

The chemical composition test results for normal clay brick are summarized in Table 4.4. The silica (SiO_2) content of the brick from Burayu factory is a little above this range. The alumina (Al_2O_3) content is within the 20–30% range.

Table 4.4 Chemical composition test result for normal clay brick

Element Names	Burayu Brick Factory Oxide Contents (%)	Acceptable Range
SiO_2	64.5	50-60 %
Al_2O_3	21.22	20-30 %
Fe_2O_3	8.13	<7 %
CaO	<0.01	<10 %
MgO	<0.01	<1 %
Na_2O	<0.01	Very small percentage
K_2O	<0.01	
MnO	0.14	
P_2O_5	0.2	
TiO_2	0.34	
H_2O	0.43	
LoI	2.29	-
SO_3	0.44	-
Cl^{-1}	<0.01	-

The ferric oxide (Fe_2O_3) is slightly above 7% but for a good clay brick, the ferric oxide (Fe_2O_3) content is usually recommended less than 7%. The lime (CaO) is below 0.01% and as given in Table 2.2 the lime content for a good clay brick is up to 10%. The lime content of bricks is very small and insignificant. This shows the brick type lack lime (CaO) and as a result the brick could be susceptible to shrinkage upon drying. As for the loss on ignition (LoI) which refers to the mass loss of a combustion residue whenever it is heated in an air or oxygen atmosphere to high temperatures ASTM D7348-13 (ASTM D7348-13, 2013), the brick has a LoI value less than 5% as specified in ASTM C330-99 (ASTM C330-99, 1999).

Additional to the complete silicate analysis test, the existence of chloride (Cl^-) and Sulphur trioxide (SO_3) were tested because aggregates that contain such compounds known to react chemically with Portland cement producing volume instability and interfere with the normal hydration of cement can be harmful to concrete (Kosmatka et al., 2002). BS 3797:1996 recommends the Sulphur trioxide (SO_3) content to not be more than 1.0% (BS 3797, 1996). The brick has Sulphur trioxide (SO_3) content less than 1.0%. The chloride content is also negligible in this brick types. To examine the possible differences that exist between the normal and the waste clay brick, chemical composition analysis was also conducted on a waste clay brick sourced from Burayu brick factory. The result for the analysis is as presented in Table 4.5.

Table 4.5 Chemical composition test result for waste clay brick

Element Names	Waste Clay Brick Oxide Contents (%)
SiO_2	62.16
Al_2O_3	26.42
Fe_2O_3	7.14
CaO	0.24
MgO	0.2
Na_2O	1.01
K_2O	1.12
MnO	0.09
P_2O_5	0.19
TiO_2	0.41
H_2O	0.38
LoI	0.03

According to the result presented in Table 4.5, the oxide contents of the waste clay brick is within similar ranges with that of the normal clay bricks presented in Table 4.4. However, the loss on ignition which is a measure of total volatiles in a material, has a much lower value.

4.2 Effect of Mix Variables

4.2.1 Effect of aggregate gradation on porosity and density

The density and porosity were measured as per standard code ASTM C1754-12 (ASTM C1754-12). It was observed that the aggregate gradation had a prominent effect on the porosity of PC mixes. Fig. 4.1 shows the effect of gradations on the measured porosity of the pervious concrete using natural aggregates and waste clay brick aggregates. From the figure it is clear that for waste clay brick aggregate void ratio is higher than natural aggregates for same sieve opening. This extra void for waste clay brick is due to its porosity.

When entrapped water evaporated during burning of clay bricks it leaves the place empty and this void place on the surface of the aggregate was filled with cement paste, therefore intra-aggregate voids become more in waste clay brick aggregate pervious concrete. G-3 PC mixes with NA showed the highest porosity of about 26.92%, 26.48%, 24.89%, and 24.25% at w/c-a/c ratios 0.3-5, 0.35-5, 0.3-4, and 0.35-4 respectively and this may be attributed to the inclusion of larger single sized graded aggregates 20 mm which may have induced more interconnected macro pores within the hardened PC specimen. But when blended two single sized graded aggregates were used, the porosity reduces considerably to about 23.52%, 23.10%, 21.25%, and 20.81% with respect to G-4 mixes, at w/c-a/c ratios 0.3-5, 0.35-5, 0.3-4, and 0.35-4 respectively.

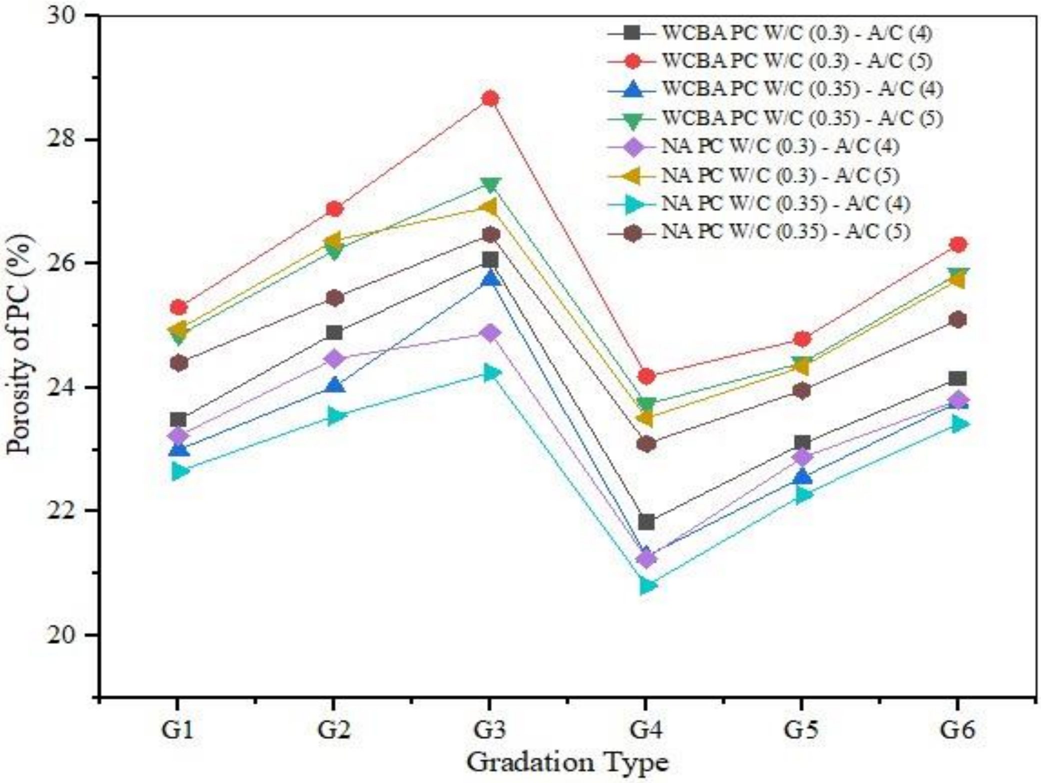

Figure 4.1 Effect of different aggregate gradation on porosity of PC.

For instances, at all w/c ratios and a/c ratios, the porosity value of G-1 to G6 PC mixes of both types of aggregate was noted to lie in the range of 20.81 to 28.68% and which is agreement with the literature reported porosity values. The recommended porosity for PC mixes is usually in the range of 15 to 3% (ACI 522R, 2010). This indicates the suitability of waste clay bricks aggregate for production of PC mixtures although strength improvement could be expected.

However, these reported barriers could be eradicated by the utilization of binary blended graded aggregates G-4, G-5, and G-6 mixes with WCBA since a desirable porosity value of about 21.29 to 28.68% as well as a satisfactory compressive strength was also observed. As far as the density of hardened PC specimens are concerned, an inverse trend to that of the porosity was observed and the same is being shown in Fig. 4.2. Higher the porosity, lesser will be the density of the hardened PC specimens and it usually lies between 1600 kg/m^3 to 2000 kg/m^3. In the present study, the density of all the considered mixes was noted to be in the range 1054 to 1496 kg/m^3. Despite the density values lying within the permissible range, only the G3 mixes exhibited satisfactory porosity values indicating that the utilization of binary blended graded aggregates would provide a balanced dense and porous PC mixture.

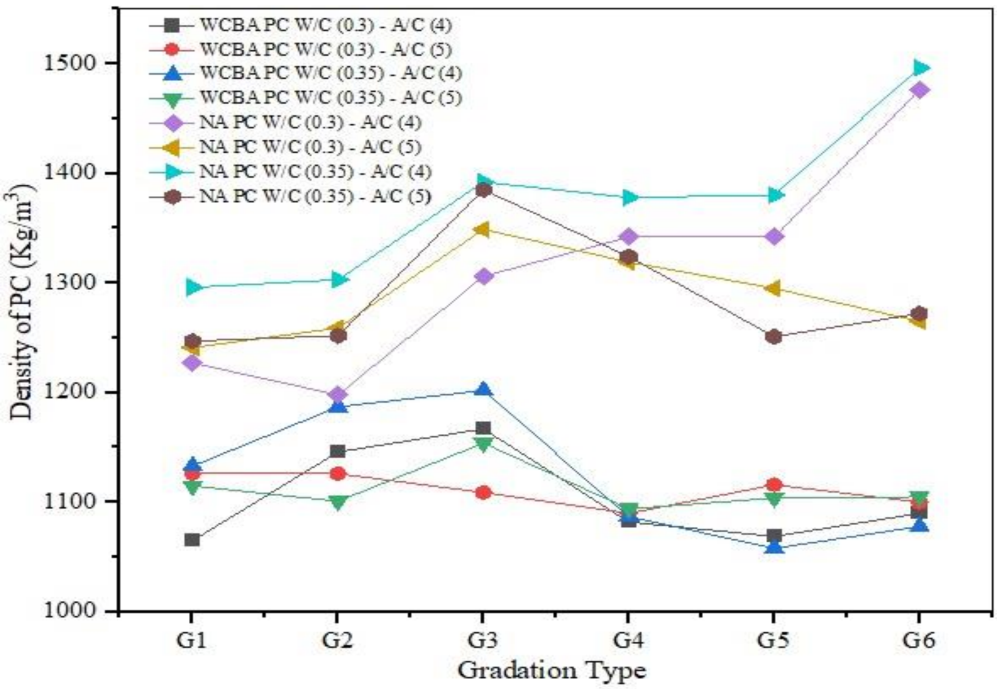

Figure 4.2 Effect of different aggregate gradation on density of PC.

4.2.2 Effect of W/C and A/C Ratio on Porosity and Density

The role of w/c and a/c ratio on the porosity and density of hardened PC specimens can be seen in Figs. 4.3 and 4.4. As the w/c ratio increases, the role of mortar becomes prominent since the cement mortar would have countered the effect of aggregate interlocking owing to filling of the gaps between the aggregates (Sahdeo, Ransinchung, Rahul, Debbarma, & Materials, 2020). Similar effect was also noted in the present study wherein a reduction in the porosity and increase in the density was observed with increase in the w/c ratio which is agreement with the literature (Sahdeo et al., 2020). For G1 mixes with WCBA, as the w/c ratio increases from 0.30 to 0.35, the porosity reduces from 23.48% to 23.01%, whereas, the density increases from 1065 kg/m^3 to 1133 kg/m^3.

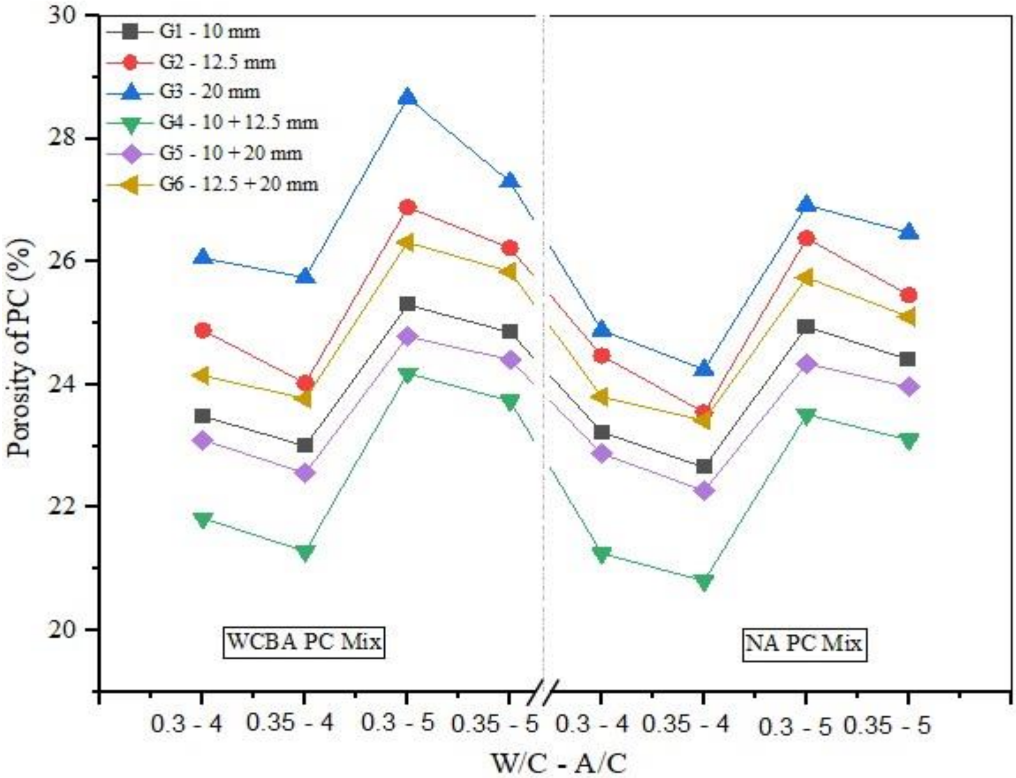

Figure 4.3 Effect of W/C, and A/C ratios on porosity of PC.

This reduction in the porosity as the w/c ratio increases may be attributed to the larger size of aggregates used in the G-3 mixes owing to which a higher cement paste volume is required to coat the aggregates which in turn decrease the workability. Similar trend on the effect of w/c ratio on porosity and density was also observed in the G-5 mixes but in the latter case, the presence of natural fines resulted in the densification of the paste volume, and subsequently, leading to higher density and low porosity. Contrarily, G-2, G-3, and G-4 mixes exhibited inverse trend to that of G-1 and G-5 mixes wherein the porosity was noted to decrease when the w/c was increased from 0.30 to 0.35. But as the w/c ratio increases beyond 0.35, the porosity starts to increase. Similar effect was also noted in the density values, however, in an inverse trend.

Also, at a low w/c ratio of 0.30 the hydration process is relatively slower which results in a lesser colloids and crystal formation, and subsequently, increasing the concentration of pore volume and decreasing the hardened density of the pervious concrete. As the w/c ratio tends to increase to 0.35 in this case, the density gradually increases to an optimum level whilst the pore volume starts to rather decrease. But when the w/c ratio increases further to 0.38, that is when the w/c becomes too high, the fluidity of the paste increases, and as a result, a substantial amount of the paste volume settles down to the bottom of the specimens leaving a relatively lesser amount of paste at the upper portion of the specimens. As a result, lower porosity and higher density were noted at higher w/c ratios. In the present study, it was observed that the G-3 mix, that is the mixes containing binary blended single-sized exhibited the most favorable aggregate gradation which showed desirable density and porosity lying within the acceptable limits.

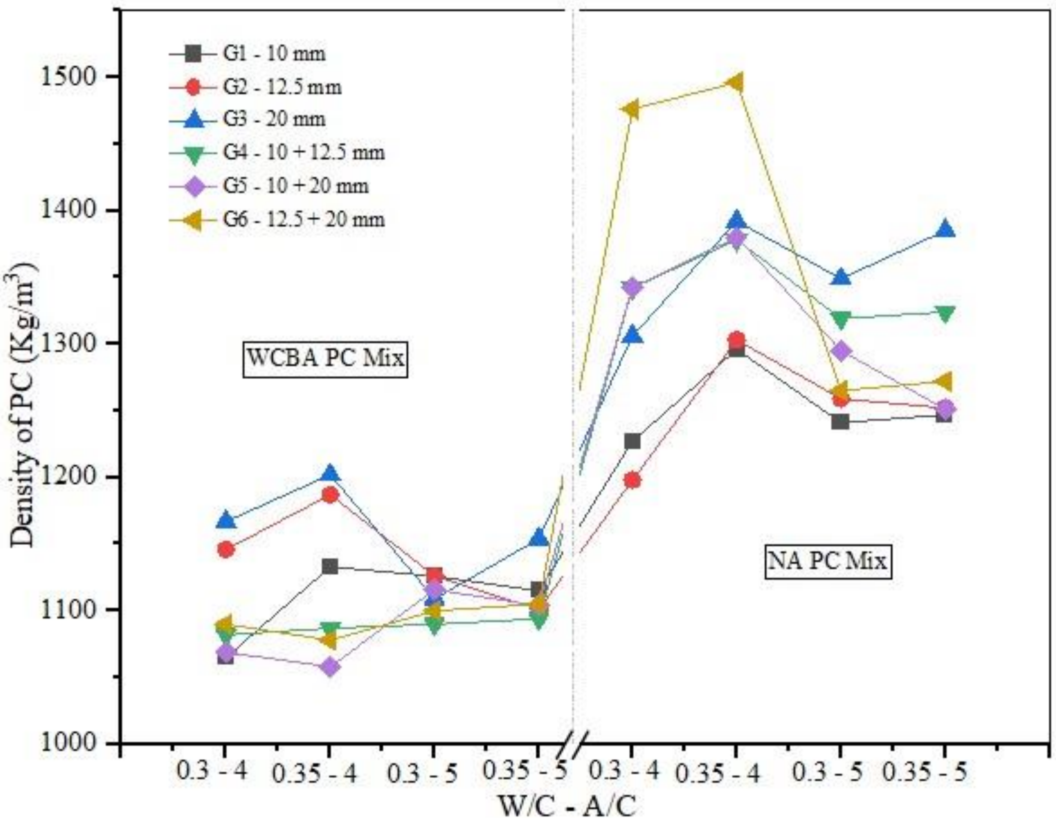

Figure 4.4 Effect of W/C, and A/C ratios on density of PC.

4.2.3 Effect of Aggregate Gradation on Strength of Pervious Concrete

Figures 4.5 and 4.6 show the effect of different aggregate gradations at varying w/c ratio and a/c ratio on the compressive strength of pervious concrete with waste clay brick aggregate and natural aggregate cured till 7 days and 28 days, respectively. With the increase in the aggregate size, the bulk density of aggregate is decreased and this in turn increased the porosity of pervious concrete. A study by (Mahboub, Canler, Rathbone, Robl, & Davis, 2009) reported that the porosity of pervious concrete can be estimated with the knowledge of the bulk density of aggregate, through the existing linear relationship. With the increase in the porosity, the strength of pervious concrete is decreased. Any improvement in the strength of the cement paste with time will not be able to produce any significant change in strength for pervious concrete.

For PCP mixtures, the compressive strength ranges between 3.5 and 28 MPa at 28 days of moist curing (Tennis et al., 2004). In the present study, it was observed that the mean compressive strength of all the mixes at varying gradations, w/c ratios, and a/c ratios was noted to be in the range of 6.04–12.77 MPa for PC mix with NA and 3.94-9.28 MPa for PC mix with WCBA. Amongst all the gradation, G-3 exhibited the lowest compressive strength irrespective of any w/c ratio followed by G-2, G-1, G-6, G-5, and G-4 mixes.

In Fig. 4.5, where it can be observed that the average compressive strength values are becoming reduced with the increased aggregate size of both WCBA and NA. The waste clay bricks have lesser strength properties such as crushing value, impact value, etc., compared to natural ones (refer to Table 4.3), and hence the concrete mixes produced with WCBA become weaker than PC-NA. The typical lower limit of compressive strength for PC mixes is recommended as 3 MPa (ACI 522R, 2010).

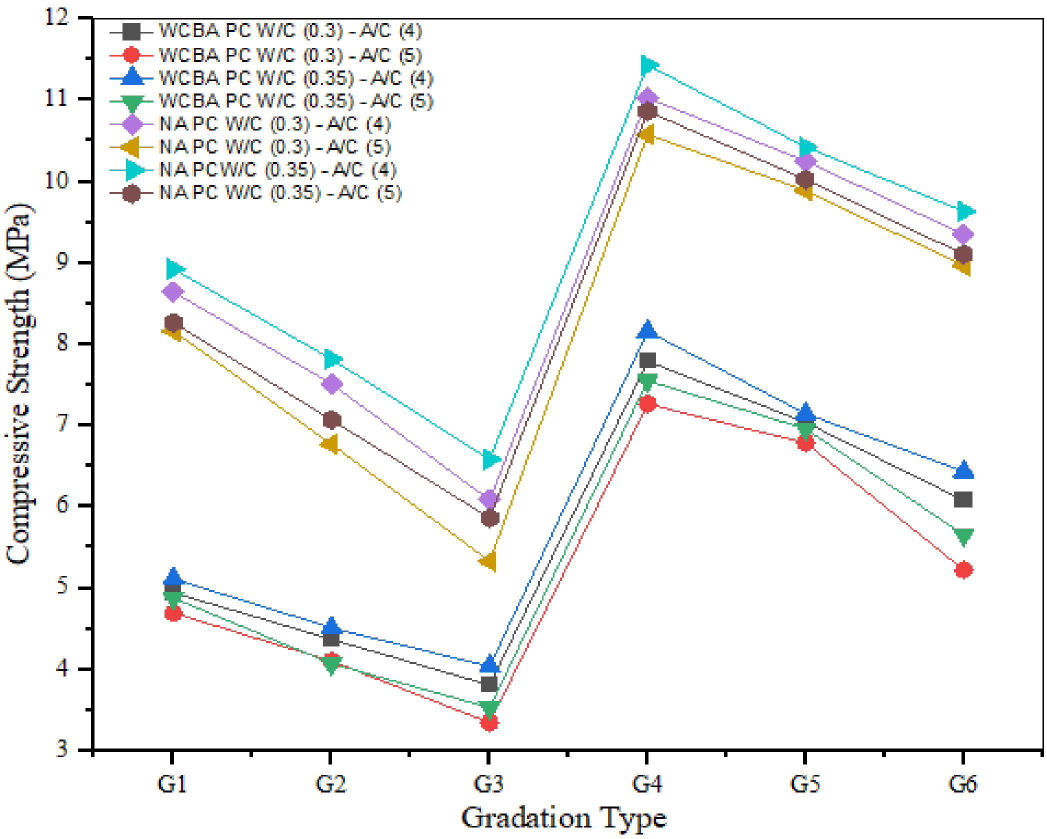

Figure 4.5 Effect of different aggregate gradations on the compressive strength of PC at 7 days of age.

In G-1, G-2, and G-3 gradation consisted of single-sized aggregates among which G-1 consisted of a small amount of fines wherein it was observed that the G-1 mixes exhibited higher compressive strength than the G-2 and G-3 mixes. For instance, the compressive strength of G-1 mixes at w/c–a/c ratios 0.3–4, 0.3–5, 0.35–4, and 0.35–5 was noted to be 9.7, 9.1, 9.9, 9.2 MPa respectively which is 58.8, 59.3, 59.6 and 60.9 times higher than the G-3 mix. This may be due to the fact the G-1 mixes were well graded in nature and consisted of a small amount of fines, and this may have occupied the empty spaces within the PC matrix resulting in a good inter-molecular bonding between the aggregates and hence, a higher compressive strength being achieved by the G-1 mixes as compared to the G-2 and G-3 mixes.

The utilization of binary blended single-sized aggregates G-4 mix also showed higher compressive strength than the G-3 graded mixtures. The G-3 mixes owing to their larger single-sized aggregates 20 mm resulted in a higher concentration of pores and subsequently may have resulted in lower compressive strength than all the considered mixes, whereas, G-4 mixes owing to the use of binary blended single-sized aggregates (50% of 10 mm and 50% of 12.5 mm) may have resulted in a dense aggregate packing, leading to higher compressive strength than the G-3 mixes.

As far as the incorporation of binary blended single-sized aggregates in the PC mixtures is concerned, an increase in the compressive strength was reported as compared to other considered aggregate gradations. For instance, the G-4 graded PC mixtures with NA resulted in a compressive strength of up to 12.77 MPa, whereas the compressive strength value of the G-4 graded PC mix with WCBA was noted to be 9.28 MPa at 28 days of age. G-4, G-5, and G-6 gradation consisted of binary blended single-sized aggregates among which G-4 mixes showed a better interlocking of aggregates as compared to G-5 and G-6. As a result, better interlocking of aggregates, lesser pores, and more compressive strength of G-4 graded PC mixes with NA was noted to be 12.34 MPa, 11.85 MPa, 12.77 MPa, and 12.15 MPa at w/c–a/c ratios 0.30–4, 0.3–5, 0.35–4, and 0.35–5, which is considerably higher than the G-5, and G-6 mixes, respectively.

A similar trend to the compressive strength of PC mixes with NA was also observed compressive strength of PC mixes with WCBA cured till 28 days and is shown in Fig. 4.6. G4-graded PC mixes with WCBA were noted to show the highest compressive strength, followed by G-5, and G-6 mixes, respectively. For instance, the compressive strength of G-4 graded PC mixes with WCBA was noted to be about 8.89 MPa, 8.24 MPa, 9.28 MPa, and 8.55 MPa at w/c–a/c ratios 0.3–4, 0.3–5, 0.35–4, and 0.35–5, respectively, which is considerably higher than the above-mentioned mixes. This indicates that binary blended single-sized aggregates if used in the Pervious concrete mixture could densify the microstructure significantly and ultimately would lead to higher compressive strength but reduced the porosity considerably.

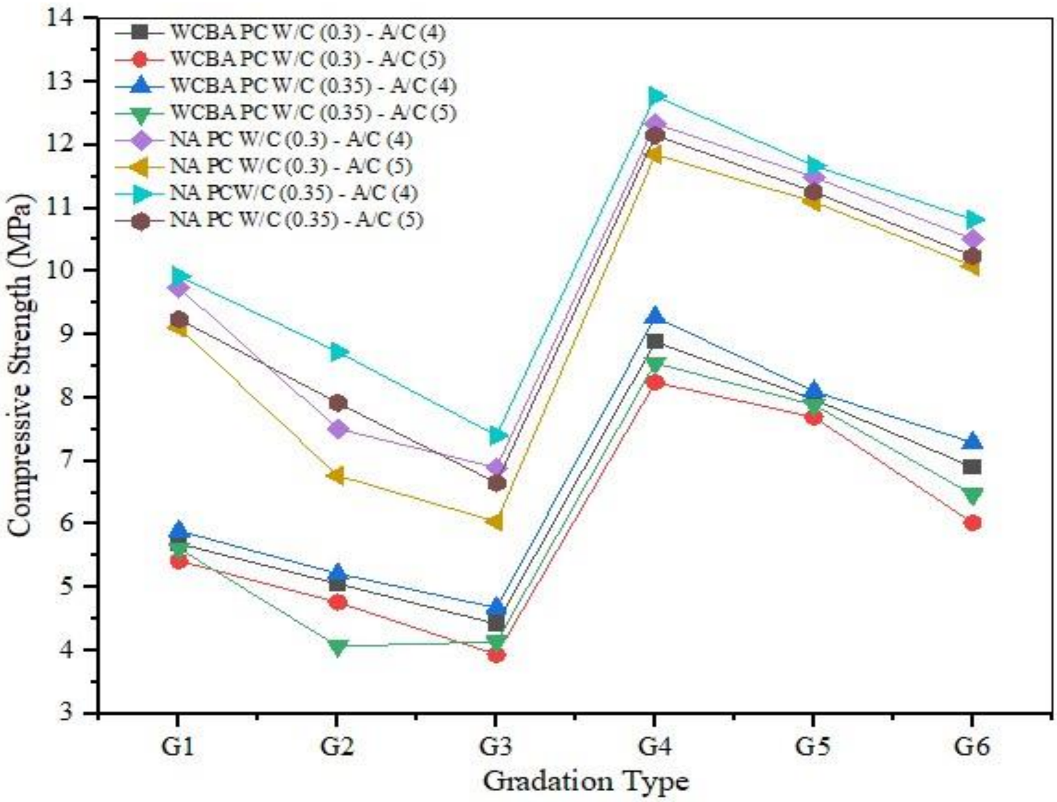

Figure 4.6 Effect of different aggregate gradations on the compressive strength of PC at 28 days of age.

The findings from the present study encourage the utilizing of binary blended aggregates (50% of 10 mm and 50% of 12.5 mm) as the best aggregate gradation for PC mixes since an acceptable balanced relation between the compressive strength and porosity was noted.

4.2.4 Effect of W/C and A/C Ratio on Compressive Strength of Pervious Concrete

The effect of the water-cement ratio on the compressive strength is shown in Figure 4.7. At water-cement ratios of 0.3 and 0.35, the compressive strength increases with the increase of the water-cement ratio. For instance, as the water-cement ratio increased from 0.3 to 0.35, the compressive strength rose approximately 5.61%. In general, the compressive strength changes insignificantly as the water-cement ratio varies. This result is consistent with the test results of (Zhu, Wen, Wang, & Li, 2020).

In the mix ratio, as the water-cement ratio increased, the amount of water increased and the amount of cement decreased. In the water-cement ratio of 0.3, the content of cement mortar was relatively low, and the aggregate could not be wrapped well, resulting in loose filling. Also, the hydration was insufficient, so the compressive strength of pervious concrete was eventually reduced. In the mix ratio, as the w/c ratio increased, the quantity of water increased and the quantity of cement decreased. In the w/c ratio of 0.3, the content of cement mortar was relatively low, and the aggregate could not be wrapped well, resulting in loose filling.

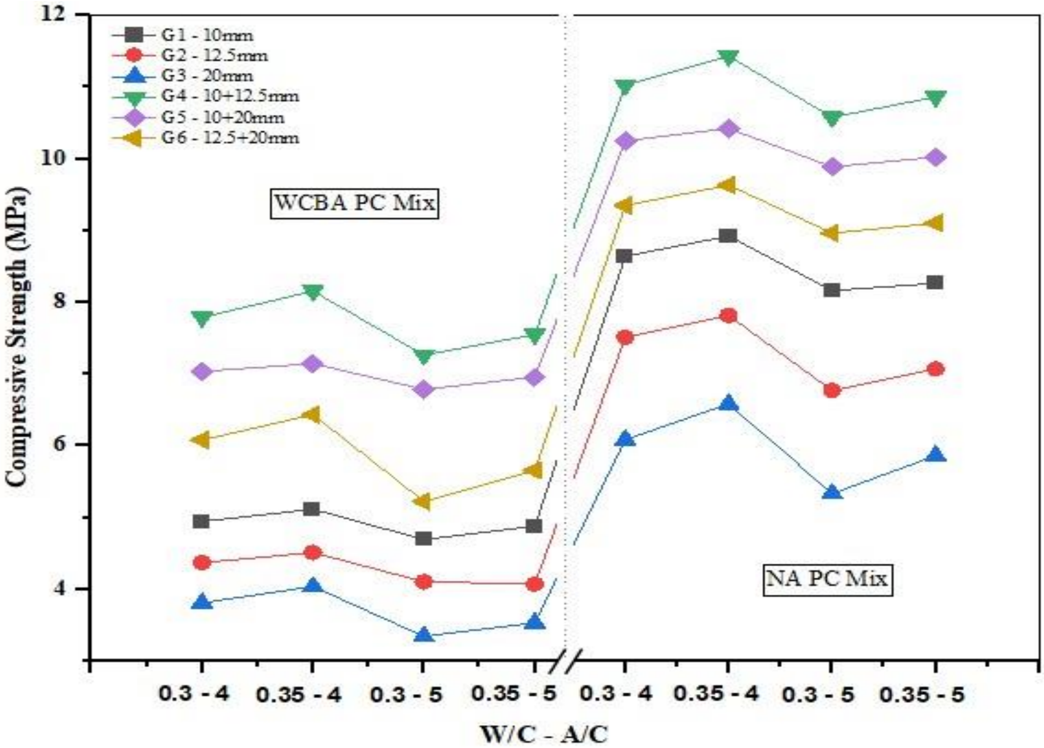

Fig. 4.7 Effect of different w/c ratio on the compressive strength of PC with different aggregate gradation, and a/c proportion at 7 days of age.

Also, the hydration was insufficient, so the compressive strength of PC was eventually reduced. In the W/C ratios of 0.35, it had a certain fluidity, which improved the strength and bonding ability between the aggregates and the concrete saturation. The hydration was more sufficient, and the strength was higher than that of the pervious concrete with a water-cement ratio of 0.3. In the water-cement ratio of 0.35, the fluidity of the mixture was so large that it could easily lead to a slurry. The strength of the concrete structure was increased, but the lifting range was small.

It can also be seen from the influence of the water-cement ratio on porosity in Figure 4.3 that as the water-cement ratio rose, the porosity was gradually reduced, thus increasing the compressive strength, but the increasing scope was very small. In the mix ratio, as the w/c ratio increased, the quantity of water increased and the quantity of cement decreased. In the w/c ratio of 0.3, the content of cement mortar was relatively low, and the aggregate could not be wrapped well, resulting in loose filling. Also, the hydration was insufficient, so the compressive strength of PC was eventually reduced. In the water-cement ratio of 0.35, it had a certain fluidity, which improved the strength and bonding ability between the aggregates and the concrete saturation. The hydration was more sufficient, and the strength was higher than that of the pervious concrete with a water-cement ratio of 0.3. In the water-cement ratio of 0.35, the fluidity of the mixture was so large that it could easily lead to a slurry. The strength of the concrete structure was increased, but the lifting range was small. It can also be seen from the influence of the water-cement ratio on porosity in Figure 4.3 that as the water-cement ratio rose, the porosity was gradually reduced, thus increasing the compressive strength, but the increasing scope was very small.

Figure 4.8 shows the aggregate–cement ratio (A/C) effect on the compressive strength of all porous concrete mixtures. The hardened compressive strength of PC improved with different aggregate gradation and w/c ratios for both A/C ratios. The rate of improvement was significantly higher in A/C ratio 4 than that in 5.

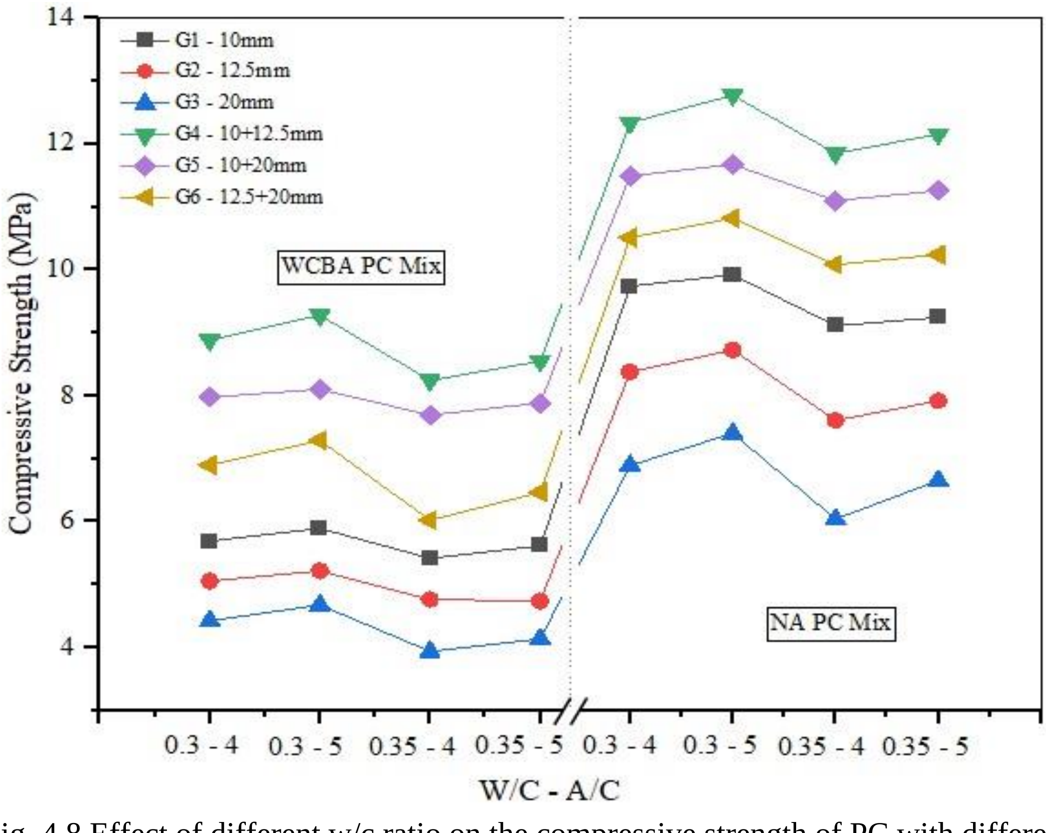

Fig. 4.8 Effect of different w/c ratio on the compressive strength of PC with different aggregate gradation, and a/c proportion at 28 days of age.

For instance, in G-1 gradation WCBA-PC mixes with a w/c ratio of 0.3 at a/c ratios of 4, the compressive strength was noted to be 5.69 MPa, higher than that of G-1 gradation WCBA-PC mixes at a/c ratios of 5 was noted to be 5.42 MPa. This may be because the low A/C ratio had adequate cement paste, which not only filled pores but also coated around aggregates well, and this may have resulted in higher compressive strength.

For instance, in G-4 gradation WCBA-PC mixes at a/c ratios 4, and 5 with a w/c ratio of 0.3, the compressive strength was noted to be 58%, and 56% higher than that of G-3 gradation WCBA-PC mixes. This may be attributed to available cement paste and aggregate gradation with a higher proportion of smaller aggregates which had a relatively higher surface area in G-4 gradation, (i.e., 50% of 10 mm and 50% of 12.5 mm) was higher than G-3 gradation (i.e., 20 mm single-sized aggregate).

Higher surface area enabled adequate coating with cement paste comparatively well in an A/C ratio of 4 that contributed to higher density and compressive strengths. Surface area reduction with the increase in larger aggregates, however, resulted in a low level of coating and hence strength. On the other hand, available cement pastes an A/C ratio of 5.0 was significantly small compared to 4, which was inadequate to cause an impact on density and compressive strength across varying aggregate gradations. The results indicate a satisfactory trend as the compressive strength of PC reduced with an increase in the A/C ratio, producing an effect as the porosity of PC reduced with an increase in the density of PC.

4.2.5 Effect of Aggregate Gradation on Permeability

The effect of aggregate gradation on the water permeability of pervious concrete is shown in Figure 4.9. Firstly, compares three single-sized gradations, G-3 gradation made up of 20 mm single-sized aggregates had slightly higher permeability compared to G-2 gradation consisting of 12.5 mm aggregates and G-1 gradation 10 mm aggregates. For the given W/C ratio and A/C ratio, in G-1 gradation, the increased surface area requires more cement paste to coat the aggregates while a small percentage will fill the inter-granular voids. But, in the G-2 and G-3 gradation, relatively a small amount of cement paste is sufficient to coat the aggregates while larger amounts fill the inter-granular void spaces.

For instance, in G-3 gradation of WCBA-PC mixes at W/C ratios 0.3, and 0.35 with a A/C ratios of 4, and 5 the permeability coefficients were noted to be 0.944 cm/s, 1.121 cm/s, 0.796 cm/s, and 1.105 cm/s higher than that of G-2, and G-1. Further, it can also be interpreted that for a given surface area, the degree of interlocking is higher in the case of smaller aggregates that offer more resistance to compaction resulting in the internal structure with a higher quantity of voids. Another comparison of one single-sized aggregate gradation G-3 (20 mm) with one binary blended single-sized aggregate graded G-6 (50% of 12.5 mm and 50% of 20 mm) pervious concrete mixture. In G-3 gradation, permeability is higher due to the increased porosity and pore size compared to G-6 gradation, which has better packing of aggregates resulting in lower permeability. Lastly, compares three binary blended single-sized aggregates graded pervious concrete mixtures with G-4, G-5, and G-6 gradations. In G-6 gradation, which is a combination of 12.5 mm and 20 mm in equal proportions, permeability is higher due to increased porosity compared to G-5 (50% of 10 mm and 50% of 20 mm) gradation and G-4 (50% of 10 mm and 50% of 12.5 mm) gradation.

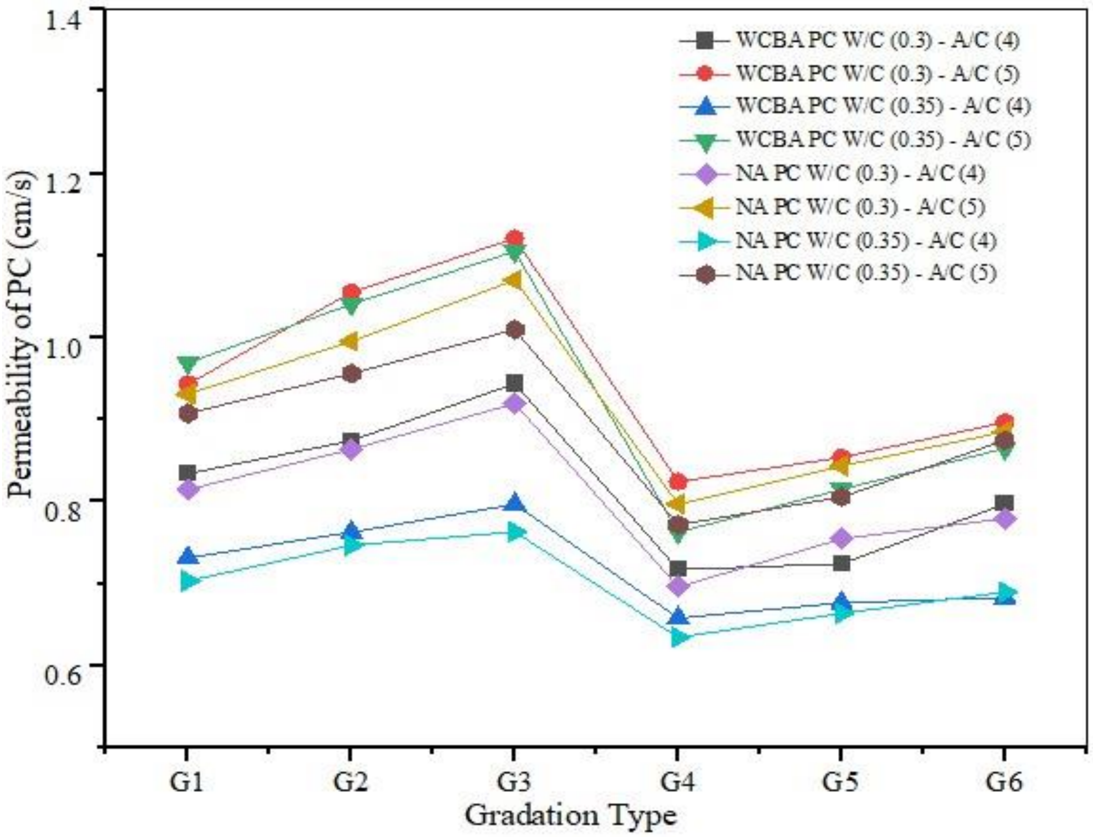

Figure 4.9 Effect of aggregate gradation on the water permeability PC.

The G6 gradation NA-PC mixture has significantly lower water permeability coefficients than the G3 gradation NA-PC at 0.885 cm/s and 1.07 cm/s, respectively. The high values of water permeability coefficients of 0.717–1.121 cm/s were achieved with pervious concretes using WCBA. The water permeability of the NA-PC mixture was lower than that of the WCBA-PC mixture with 0.696–1.07 cm/s.

4.2.6 Influence of W/C Ratio and A/C Ratio on Permeability

For the different aggregate sizes, the water permeability coefficients decreased as binder w/c ratios increased. This is because at low w/c ratio, binders are highly viscous, enabling the binder to fully cover the aggregates. In addition, as the aggregate size increased, the water permeability of pervious concrete increased. For the pervious concrete, four phases (paste, ITZ, coarse aggregates, and designed porosity) exist. Unlike the conventional concrete which adopts mortar to fill the space between aggregates, we only partially fill the space between aggregates by binder for pervious concrete. This concept intentionally makes some porosity inside concrete in order to allow water penetration. Among these four phases, the designed porosity has the worst properties. It has no mechanical strength at all and highest water permeation coefficients. Therefore, the volume fraction of the porosity dominates the behaviors of pervious concrete. When aggregate size is smaller, the initial porosity after packing is smaller. Consequently, when the volume percent of filled voids is the same, the remaining porosity for pervious concrete made with smaller size aggregates is smaller. Therefore, the water permeability coefficient becomes lower. The effect of w/c ratio and a/c ratio on measured permeability of PC is shown in Figure 4.10. As the w/c ratio considered within this study (i.e., 0.3 and 0.35) increased, the degree of lubrication in the PC mixtures increased, which assisted in better densification of the mixture, and hence resulted in lower permeability.

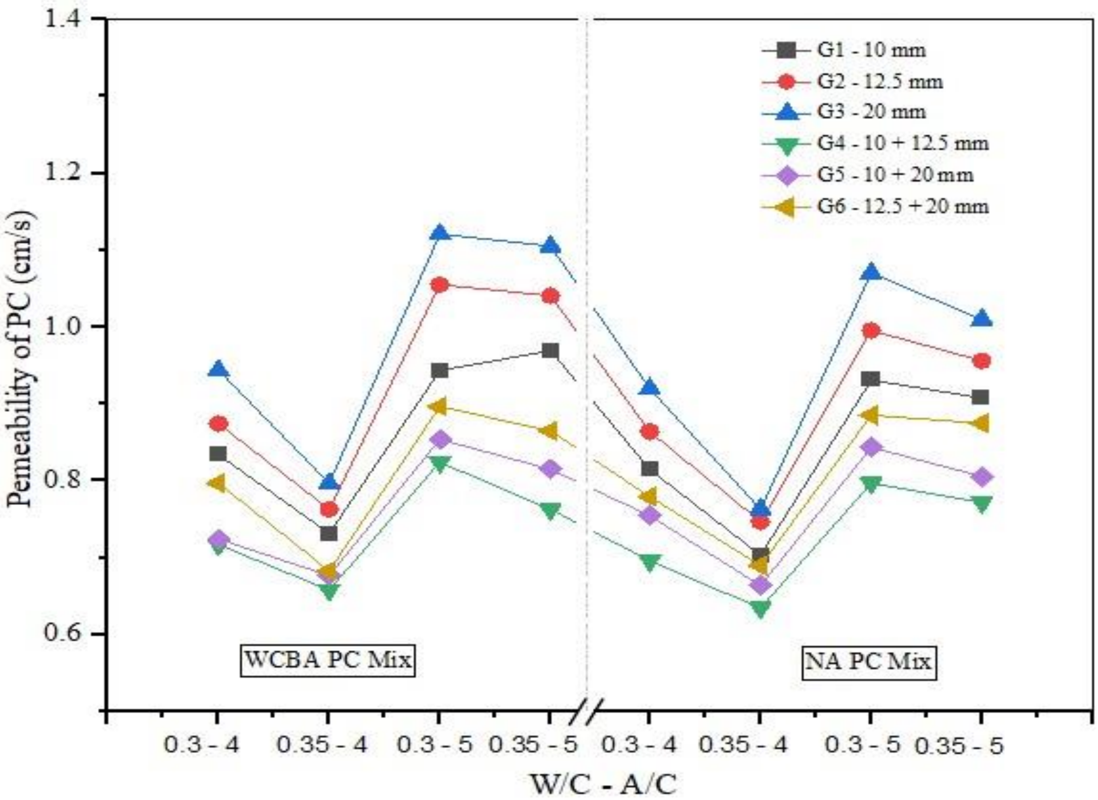

Figure 4.10 Effect of a W/C, and a A/C ratios on the water permeability PC.

At lower w/c ratio (i.e., 0.3), the reduced water content rendered the mix to be harsh that provided higher resistance for compaction resulting in higher permeability. G-1 gradation PC mixes with WCBA resulted higher permeability at lower w/c ratio (i.e., 0.3) than G-1 gradation at higher w/c ratio (i.e., 0.35). For instances, G-1 gradation WCBA-PC mixes at w/c ratios 0.3, and 0.35 with a/c ratio of 4, the permeability coefficient was noted to be 0.834 cm/s, and 0.731 cm/s. Similar effect was also noted in the permeability coefficient values of

PC mixes with NA, at w/c ratios 0.3, and 0.35 with a/c ratio of 4, the permeability coefficient was noted to be 0.814 cm/s, and 0.703 cm/s. Contemporaneously, as A/C ratio increased, the inter-granular void volume reduced due to decreased resistance in compaction offered by the reduced quantity of aggregates. This resulted in lower permeability as shown in Figure 4.10. However, at lower A/C ratio, reduced coating of the cement pastes and increased resistance for compaction given by larger volume of aggregates provided higher permeability of the PC mixtures. It has to be noted that the permeability values obtained at different W/C and A/C ratios are functions of compaction method, and magnitudes may change based on the compaction method. However, the trends with respect to W/C ratio and A/C ratio are expected to be same as also found in this study.

4.1.5 Scanning Electron Microscopy (SEM) Analysis of Pervious Concrete

SEM analyses were performed to examine the interfacial zone between the cement paste and both types of aggregates, natural aggregate and waste clay brick. The results obtained were further substantiated using Scanning Electron Microscopy (SEM) as shown in Figure 4.11.

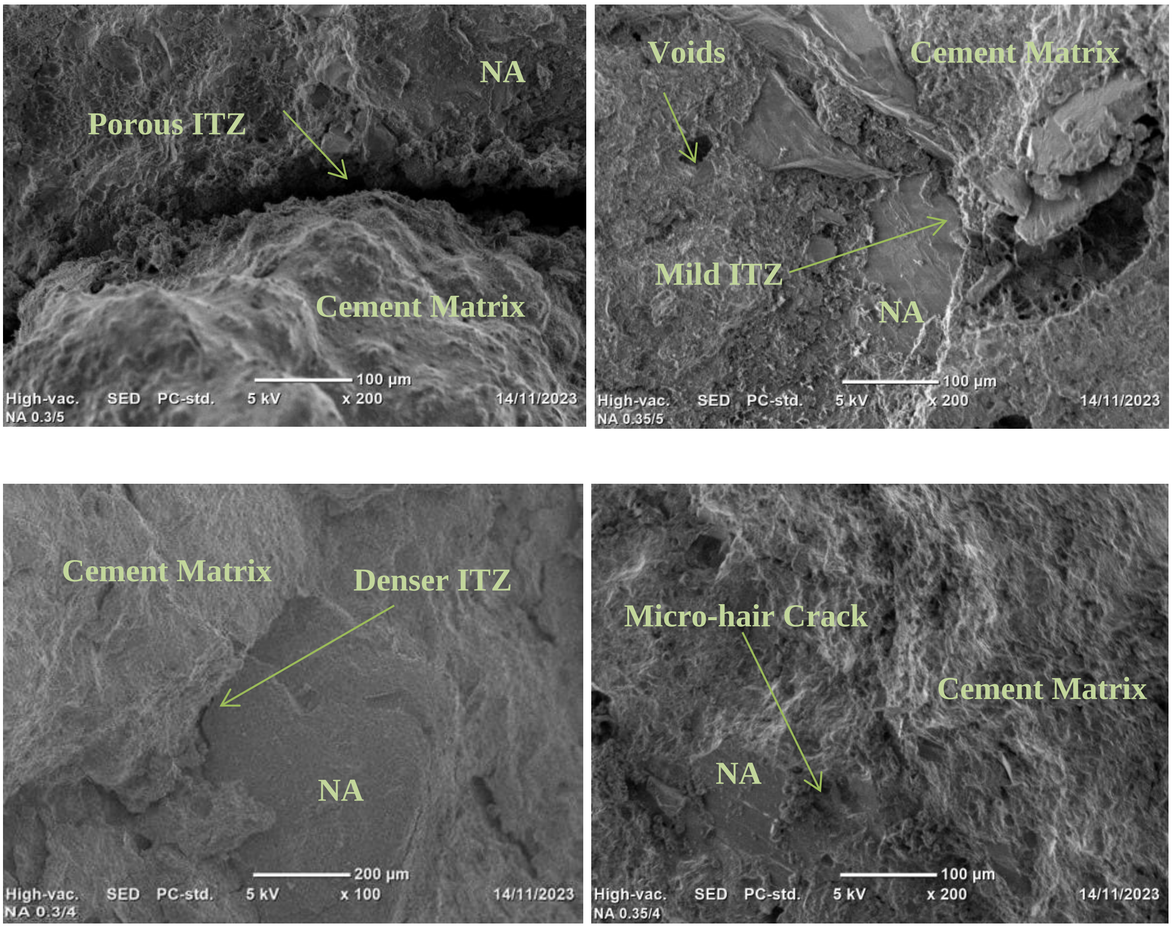

Figure 4.11 SEM image of NA-PC G4 mix a) w/c 0.3, a/c 5 b) w/c 0.35, a/c 5 c) w/c 0.3, a/c 4 d) w/c 0.35, a/c 4.

The NA-PC G-4 mix which contains 0.3, 0.35 w/c ratio and a/c ratio of 4 was seen to have denser surface microstructure and the aggregates were fully coated with thick mortar paste. Also, paste volume in the pores of PC mixture resulted in thin micro hair crack on the surface of the cement matrix. Whereas G-4 mix which contains 0.3, 0.35 w/c ratio and a/c ratio of 5 was seen to have porous and mild Interfacial Transition Zone (ITZ) respectively. This phase could be due to the presence of larger size and well graded aggregates respectively. A G-4 mixes with WCBA-PC showed denser ITZ and good intermolecular bond between aggregates and cement matrix owing to binary blended nature of aggregate as shown Figure 4.12. Similar effect was also noted in the WCBA-PC.

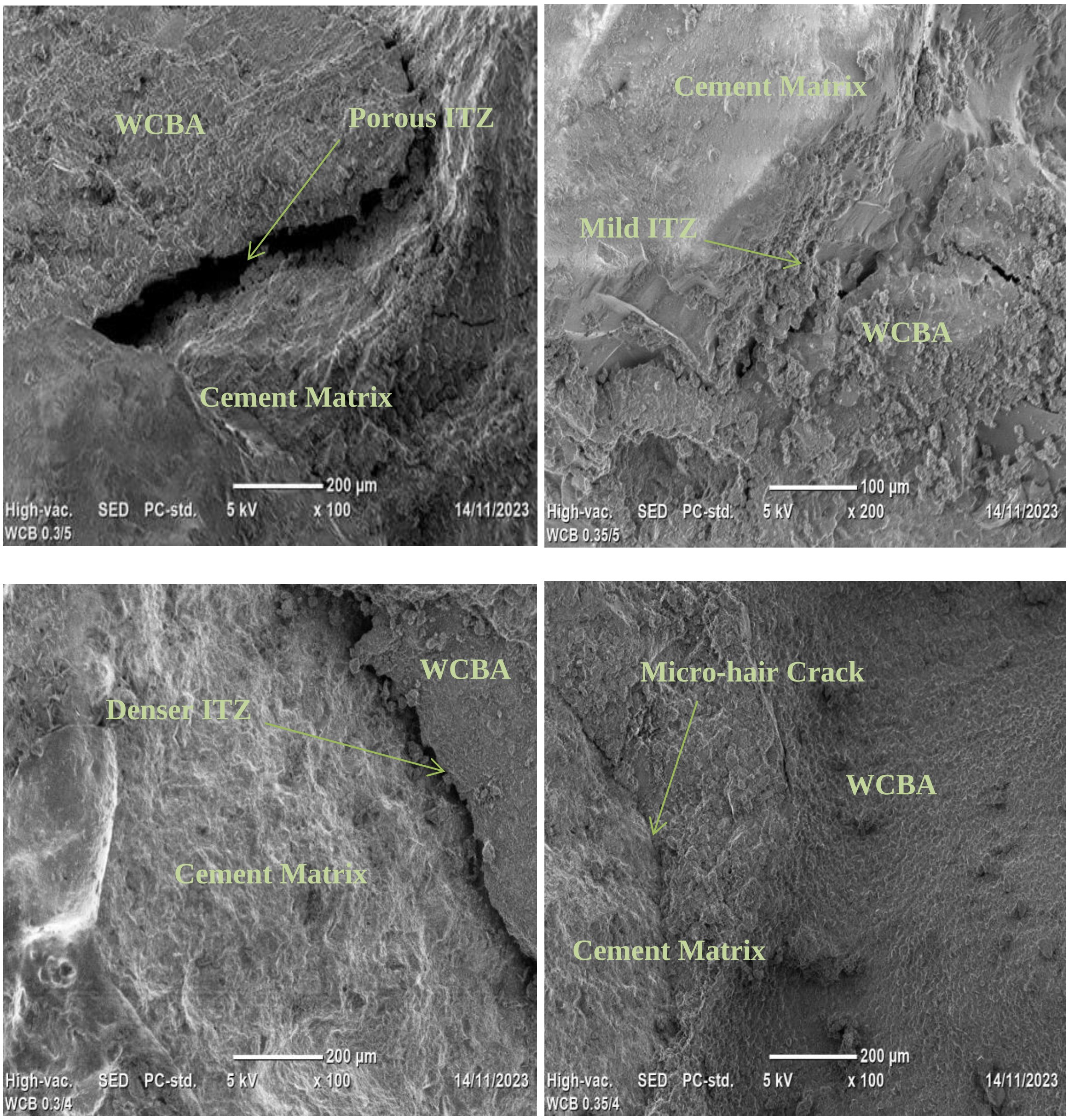

Figure 4.12 SEM image of WCBA-PC G-4 mix a) w/c 0.3, a/c 5 b) w/c 0.35, a/c 5 c) w/c 0.3, a/c 4 d) w/c 0.35, a/c 4.

4.3. A Hybrid Techniques Using Entropy and TOPSIS

This section presents the interpretation of the results obtained by the entropy weighted TOPSIS method and a brief discussion on the findings. The method involves the following steps: formulation of decision matrix, evaluation of weighted Normalized decision matrix, prioritization of alternatives (positive and negative ideal solutions, separation values), and ranking of alternatives.

4.3.1 Formulation of Decision Matrix

The problems involving in multi criteria decision making approach has a cluster of alternatives and criteria essential to be articulated in a matrix format which allows to the systematic evaluation of relationship between the information provided. The formulation of decision matrix based on the alternatives and criteria are illustrated in Table 4.6.

Table 4.6 Decision matrix of WCBA-PC

	Density of PC	Porosity of PC	Compressive strength of PC	permeability of PC	W/C Ratio	A/C Ratio
	C1	C2	C3	C4	C5	C6
A1 (G1-R1)	1065	23.48	5.69	0.834	0.3	4
A2 (G1-R2)	1126	25.30	5.42	0.943	0.3	5
A3 (G1-R3)	1133	23.01	5.89	0.731	0.35	4
A4 (G1-R4)	1115	24.85	5.62	0.969	0.35	5
A5 (G2-R1)	1146	24.89	5.06	0.874	0.3	4
A6 (G2-R2)	1126	26.89	4.76	1.055	0.3	5
A7 (G2-R3)	1187	24.03	5.22	0.762	0.35	4
A8 (G2-R4)	1101	26.22	4.74	1.041	0.35	5
A9 (G3-R1)	1167	26.06	4.43	0.944	0.3	4
A10 (G3-R2)	1109	28.68	3.94	1.121	0.3	5
A11 (G3-R3)	1202	25.75	4.68	0.796	0.35	4
A12 (G3-R4)	1154	27.31	4.14	1.105	0.35	5
A13 (G4-R1)	1082	21.83	8.89	0.717	0.3	4
A14 (G4-R2)	1090	24.18	8.24	0.824	0.3	5
A15 (G4-R3)	1087	21.29	9.28	0.658	0.35	4
A16 (G4-R4)	1094	23.74	8.55	0.762	0.35	5
A17 (G5-R1)	1069	23.10	7.98	0.724	0.3	4
A18 (G5-R2)	1116	24.79	7.69	0.854	0.3	5
A19 (G5-R3)	1058	22.56	8.10	0.676	0.35	4
A20 (G5-R4)	1104	24.41	7.89	0.815	0.35	5
A21 (G6-R1)	1090	24.15	6.90	0.797	0.3	4
A22 (G6-R2)	1100	26.32	6.02	0.896	0.3	5
A23 (G6-R3)	1078	23.77	7.29	0.683	0.35	4
A24 (G6-R4)	1105	25.84	6.47	0.865	0.35	5

m x n matrix is used to define the decision matrix, where m represents alternatives and n represents criteria in which the element D_{ij} (i = 1, 2…, m and j = 1, 2…, n) represents the value of alternative i when it is determined in terms of criterion j. Otherwise it can demonstrate as recital of each alternatives concerning the criteria are expressed by the element D_{ij} in the decision matrix.

4.3.2 Application of Entropy Method

In this section the weights of each criterion are determined by the Entropy method. Firstly, the decision matrix is normalized by using Eq. 3.6 shown in Table 4.7. Then the entropy values are determined for each criterion and entropy weights are calculated by using Eq. 3.7 and Eq. 3.9 shown in Table 4.8.

Table 4.7 Normalized decision matrix of PC with waste clay bricks

	P_{ij}					
	C1	C2	C3	C4	C5	C6
A1	0.03988	0.03964	0.03724	0.04078	0.03846	0.03704
A2	0.04217	0.0427	0.03545	0.04612	0.03846	0.0463
A3	0.04243	0.03883	0.03855	0.03577	0.04487	0.03704
A4	0.04175	0.04195	0.03674	0.04741	0.04487	0.0463
A5	0.04291	0.042	0.03307	0.04275	0.03846	0.03704
A6	0.04217	0.04539	0.03116	0.0516	0.03846	0.0463
A7	0.04445	0.04055	0.03414	0.03729	0.04487	0.03704
A8	0.04123	0.04426	0.031	0.0509	0.04487	0.0463
A9	0.0437	0.04399	0.02895	0.04616	0.03846	0.03704
A10	0.04153	0.0484	0.02577	0.05483	0.03846	0.0463
A11	0.04501	0.04346	0.03059	0.03895	0.04487	0.03704
A12	0.04321	0.04609	0.02708	0.05405	0.04487	0.0463
A13	0.04052	0.03684	0.05813	0.03505	0.03846	0.03704
A14	0.04082	0.04082	0.05392	0.0403	0.03846	0.0463
A15	0.04071	0.03593	0.06068	0.03216	0.04487	0.03704
A16	0.04097	0.04007	0.05592	0.03729	0.04487	0.0463
A17	0.04003	0.03899	0.05217	0.03541	0.03846	0.03704
A18	0.04179	0.04184	0.05032	0.04176	0.03846	0.0463
A19	0.03962	0.03808	0.053	0.03308	0.04487	0.03704
A20	0.04134	0.0412	0.05159	0.03986	0.04487	0.0463
A21	0.04082	0.04077	0.04513	0.03897	0.03846	0.03704
A22	0.04119	0.04442	0.0394	0.04385	0.03846	0.0463
A23	0.04037	0.04012	0.0477	0.03339	0.04487	0.03704
A24	0.04138	0.04362	0.0423	0.04229	0.04487	0.0463

Table 4.8 Entropy values and entropy weights of each criterion

	C1	C2	C3	C4	C5	C6
E_j	0.99983	0.99923	0.99001	0.99573	0.99907	0.99805
W_j	0.00926	0.04236	0.55301	0.2361	0.05157	0.10771

According to the Table 4.8, the C3 (compressive strength of PC) is the most important criterion with the highest entropy weight. C4 (water permeability of PC), C6 (A/C ratio), C1(density of PC), C5 (W/C ratio), and C2 (porosity of PC) follow this criterion respectively.

4.3.3 Evaluation of weighted Normalized Decision Matrix

The normalized decision matrix is identified using the Eq. 3.10 for the values D_{ij} expressed in the matrix. The performance of the concrete mixes is based on all these criteria which are associated with different measurement units and scales.

Table 4.9 Normalized the criteria values

	C1	C2	C3	C4	C5	C6
A1	0.183440	0.003500	0.000848	0.000124	0.000045	0.000596
A2	0.186420	0.003770	0.000808	0.000141	0.000045	0.000745
A3	0.222632	0.003428	0.000878	0.000109	0.000052	0.000596
A4	0.213542	0.003704	0.000837	0.000144	0.000052	0.000745
A5	0.210859	0.003708	0.000754	0.000130	0.000045	0.000596
A6	0.206836	0.004007	0.000710	0.000157	0.000045	0.000745
A7	0.231424	0.003580	0.000778	0.000114	0.000052	0.000596
A8	0.202067	0.003908	0.000706	0.000155	0.000052	0.000745
A9	0.217565	0.003884	0.000660	0.000141	0.000045	0.000596
A10	0.198491	0.004273	0.000587	0.000167	0.000045	0.000745
A11	0.200428	0.003836	0.000697	0.000119	0.000052	0.000596
A12	0.203259	0.004069	0.000617	0.000165	0.000052	0.000745
A13	0.198491	0.003253	0.001324	0.000107	0.000045	0.000596
A14	0.190146	0.003604	0.001228	0.000123	0.000045	0.000745
A15	0.199534	0.003172	0.001382	0.000098	0.000052	0.000596
A16	0.202514	0.003537	0.001274	0.000114	0.000052	0.000745
A17	0.204004	0.003443	0.001189	0.000108	0.000045	0.000596
A18	0.189550	0.003694	0.001146	0.000127	0.000045	0.000745
A19	0.211455	0.003362	0.001208	0.000101	0.000052	0.000596
A20	0.205197	0.003637	0.001175	0.000121	0.000052	0.000745
A21	0.208922	0.003599	0.001028	0.000119	0.000045	0.000596
A22	0.205197	0.003922	0.000898	0.000134	0.000045	0.000745
A23	0.192977	0.003542	0.001087	0.000102	0.000052	0.000596
A24	0.206985	0.003851	0.000964	0.000129	0.000052	0.000745

Since all these criteria with different units of measurement are a concern in the selection of best mix, the criterions are to be normalized for a uniform scale of measure. The criteria values are normalized into a uniform scale with dimensionless units. All the criteria values in the decision matrix are normalized using Eq. 3.10 and it gives the normalized decision matrix. This equation is based on vector normalization. The normalized values are shown in Table 4.9. After normalizing the given criteria, the weighted normalized decision matrix is obtained. Multiplying the weight of the criterion (W_j) with each element in the normalized matrix as shown in Eq. 3.11, gives the weighted normalized decision matrix. The weighted normalized decision matrix is shown in Table 4.10.

Table 4.10 Weighted normalized decision matrix

	V_{ij}					
	C1	C2	C3	C4	C5	C6
A1	0.0016980	0.0001482	0.0004692	0.0000293	0.0000023	0.0000642
A2	0.0017256	0.0001597	0.0004467	0.0000332	0.0000023	0.0000803
A3	0.0020608	0.0001452	0.0004857	0.0000257	0.0000027	0.0000642
A4	0.0019766	0.0001569	0.0004629	0.0000341	0.0000027	0.0000803
A5	0.0019518	0.0001571	0.0004167	0.0000308	0.0000023	0.0000642
A6	0.0019145	0.0001697	0.0003925	0.0000371	0.0000023	0.0000803
A7	0.0021421	0.0001516	0.0004302	0.0000268	0.0000027	0.0000642
A8	0.0018704	0.0001655	0.0003906	0.0000366	0.0000027	0.0000803
A9	0.0020139	0.0001645	0.0003648	0.0000332	0.0000023	0.0000642
A10	0.0018373	0.0001810	0.0003247	0.0000394	0.0000023	0.0000803
A11	0.0018552	0.0001625	0.0003854	0.0000280	0.0000027	0.0000642
A12	0.0018814	0.0001724	0.0003412	0.0000389	0.0000027	0.0000803
A13	0.0018373	0.0001378	0.0007323	0.0000252	0.0000023	0.0000642
A14	0.0017601	0.0001527	0.0006793	0.0000290	0.0000023	0.0000803
A15	0.0018470	0.0001344	0.0007645	0.0000231	0.0000027	0.0000642
A16	0.0018745	0.0001498	0.0007046	0.0000268	0.0000027	0.0000803
A17	0.0018883	0.0001458	0.0006573	0.0000255	0.0000023	0.0000642
A18	0.0017545	0.0001565	0.0006340	0.0000300	0.0000023	0.0000803
A19	0.0019573	0.0001424	0.0006678	0.0000238	0.0000027	0.0000642
A20	0.0018994	0.0001541	0.0006499	0.0000287	0.0000027	0.0000803
A21	0.0019339	0.0001525	0.0005686	0.0000280	0.0000023	0.0000642
A22	0.0018994	0.0001661	0.0004964	0.0000315	0.0000023	0.0000803
A23	0.0017863	0.0001500	0.0006010	0.0000240	0.0000027	0.0000642
A24	0.0019159	0.0001631	0.0005329	0.0000304	0.0000027	0.0000803

4.3.4 Prioritization of Alternatives

The prioritizing method used in TOPSI method is based on the results that are close to ideal solutions. This closeness is measured as a simple Euclidean distance. The best alternative should therefore be within the proximity to the positive-ideal solution and remoteness from the negative-ideal solution simultaneously. The positive ideal solution (V^+) is defined as the best performance value of each criterion and the negative ideal solution (V^-) is defined as the worst performance value of each criterion. The positive-ideal and negative-ideal solutions for all the criteria are shown in Table 4.11.

Table 4.11 Positive solution and negative-ideal solution

V^+	0.001698	0.000134	0.000325	2.31358E-05	2.30531E-06	6.42004E-05
V^-	0.002142	0.000181	0.000764	3.94383E-05	2.68953E-06	8.02504E-05

The n-dimensional Euclidian distance or separation values are then calculated to define the closeness of the alternatives to the ideal solution. Eq. 3.12 gives the separation values of each alternative from the positive-ideal solution S_i^+ and Eq. 3.13 gives the separation values of each alternative from the negative-ideal solution S_i^-. The calculated positive separation values and the negative separation values are shown in Table 4.12.

Table 4.12 Positive and negative separation values

Alt.	Si^+	Si^-	Alt.	Si^+	Si^-
A1	0.00015	0.00053	A13	0.00043	0.00031
A2	0.00013	0.00052	A14	0.00036	0.00039
A3	0.0004	0.00029	A15	0.00046	0.0003
A4	0.00031	0.00034	A16	0.00042	0.00028
A5	0.00027	0.0004	A17	0.00038	0.00028
A6	0.00023	0.00044	A18	0.00032	0.00041
A7	0.00046	0.00034	A19	0.00043	0.00021
A8	0.00019	0.00046	A20	0.00038	0.00027
A9	0.00032	0.00042	A21	0.00034	0.00029
A10	0.00015	0.00054	A22	0.00027	0.00036
A11	0.00017	0.00048	A23	0.00029	0.00039
A12	0.00019	0.0005	A24	0.0003	0.00032

4.3.5 Ranking of Alternatives

After S_i^+ and S_i^- are calculated, the preference value is calculated for each alternative. Preference value (P_i) is defined as the relative closeness to the ideal solution. Using Eq. 3.14, the preference value is calculated for each alternative. The mixture design decision making approach allow various mix factors, mechanical, and water permeability properties to be evaluated concurrently, which enable users to quickly find potential mixture designs. The range of similarity index is always between 0 and 1. The alternative which has the P_i close to 1 is considered as the best result and the alternative which has P_i close to zero is considered the worst result. Table 4.13 gives the preference value for each alternative and ranking the concrete mixes.

Table 4.13 Ranking of WCBA pervious concrete mix

Alt.	P_i	Rank	Alt.	P_i	Rank
A1	0.7863	2	A13	0.4187	20
A2	0.8026	1	A14	0.5211	14
A3	0.425	17	A15	0.3923	23
A4	0.5247	13	A16	0.397	22
A5	0.5946	8	A17	0.4208	19
A6	0.6541	7	A18	0.5649	12
A7	0.4239	18	A19	0.3315	24
A8	0.7106	6	A20	0.4132	21
A9	0.5678	11	A21	0.4587	16
A10	0.7826	3	A22	0.5754	9
A11	0.7358	4	A23	0.5752	10
A12	0.7241	5	A24	0.5168	15

The concrete mixes are then ranked as per the results of preference value. Therefore, in this study the result shows that the mix A2 (G-1 WCBA-PC with W/C ratios 0.3, and A/C ratios 5) has a value with close proximity to one. Pervious concrete (PC) is an emerging construction concept that is a benefit to urban developers as it is the best and most sustainable way to control urban stormwater (Mullaney & Lucke, 2014). Currently, most developed and many developing countries are looking forward to using the PC in urban areas for its advantages from an ecological and hydrological point of view (Imran, Akib, & Karim, 2013).

PC is mainly porous concrete mixes having a certain quantity of voids through which the runoff can be transferred to the lower layers and finally to the groundwater. Around 15–30% of voids are generally present in the PC mixes that can effectively produce an infiltration rate of around 0.1–3.5 cm/s (Chandrappa, Biligiri, & materials, 2016b). However, the presence of these voids drastically affects the strength of PC mixes (Debnath, Sarkar, & Materials, 2019). Hence, pervious concrete pavements cannot be implemented on any good quality service roads such as expressways, highways, or any other connecting roads. The major application of PCs can be found in parking lots, sidewalks, shoulders, etc., where low-strength pavements are also acceptable. The compressive strength of PC mixes generally ranges from 2 to 30 MPa. Therefore, based on the above studies all PC mixes with WCBA as coarse aggregate fulfilled the suggested limit for PC hardened property.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The deficiency of natural aggregates for the growing demand for construction is assisting the search for alternate materials. This study uses WCBA in pervious concrete mixes with the intention of fully replacing the natural aggregates. The influence of aggregate gradation, W/C ratio, and A/C ratio on PC mix design were investigated in this study. PC mixes were casted using the prepared mix design and tested for compressive strength, porosity, and water permeability. Test results were analyzed and eventually a hybrid MCDM were formulated for ranking of the PC mix design.

Based on the results of this study, the following conclusions can be drawn for PC:

- The material characterization shows that the WCBA void ratio, AIV, ACV, LAV, FIV, and EIV is higher than NA. The WCBA porosity contributes significantly to total porosity. The total porosity not only affects the permeability of the mix, but also represents the characteristics of coarse aggregate.
- The use of WCB to replace the natural single-sized aggregates resulted in reductions of compressive strength due to the decrease in the density and weak bonding between the cement paste and the aggregates. However, in the replacement of WCB as coarse aggregates, the compressive strength, porosity and the permeability obtained could still satisfy the requirement of ACI 522 R-10 specification for pervious concrete.
- The use of WCBA had a slight increase on permeability depending on the aggregate gradation, a W/C ratio, and a A/C ratios. In this study, water permeability coefficients of 0.717-1.121 cm/s, and 0.696-1.07 cm/s were achieved with pervious concretes using WCBA and NA, respectively.
- The test results and image analysis (SEM) show that the binary blended aggregate gradation of WCBA (G-4) are very useful for providing adequate porosity and sufficient compressive strength. The water permeability of the PC was found to be mainly affected by the total porosity.
- All the PC mix were ranked based on their closeness index, and the outcome showed that the A2 alternative scored highest closeness index. It showed that entropy weighted TOPSIS was a useful approach to rank the PC mix based on closeness index.

5.2 RECOMMENDATIONS

Theis's research study the effect of aggregate gradation, a W/C ratio, and a A/C ratio on compressive strength, porosity, and permeability. With the basis established in this study, further investigation on the influence of compaction effort, and durability properties of PC could be possible. Although some laboratory tests and image analyses of the PC samples have been conducted in this study, further studies need to be carried out for the overall application of WCBA in PC. Moreover, the cost analysis study of PC with WCBA require future analysis for the practical application of PC with WCBA.

Special Acknowledgment

This research work was funded by grant number ASTU/SM-R/836/23 from Adama science and technology university, Adama, Ethiopia.

6. REFERENCE

ACI 522, R-10, Report on Pervious Concrete. American Concrete Institute, Farmington Hills, Michigan, 2010, 38p

Abed, M., Nemes, R., & Tayeh, B. A. (2020). Properties of self-compacting high-strength concrete containing multiple use of recycled aggregate. *Journal of King Saud University-Engineering Sciences, 32*(2), 108-114.

Akhtaruzzaman, A. A., & Hasnat, A. (1983). Properties of concrete using crushed brick as aggregate. *Concrete International, 5*(2), 58-63.

Alexander, M., & Mindess, S. (2005). *Aggregates in concrete*: CRC Press.

Aoki, Y., Sri Ravindrarajah, R., & Khabbaz, H. (2008). *Environmentally friendly sustainable pervious concrete.* Paper presented at the Futures in Mechanics of Structures and Materials-Proceedings of the 20th Australasian Conference on the Mechanics of Structures and Materials, ACMSM20.

Arhin, S. A., Madhi, R., & Khan, W. (2014). Optimal mix designs for pervious concrete for an urban area. *Int. J. Eng. Res. Technol, 3*(12), 42-50.

Arshad, M. S., & Pawade, P. (2014). Reuse of natural waste material for making light weight bricks. *International Journal of Scientific & Technology Research, 3*(6), 49-53.

Assefa, G., & Gebregziabher, A. (2020). Environmental Impact and Sustainability of Aggregate Production in Ethiopia. *Sandy Materials in Civil Engineering-Usage and Management,* 1-9.

ASTM C, C. (2012). Standard test method for density and void content of hardened pervious concrete. In: ASTM international West Conshohocken, PA.

Bektas, F. (2007). *Use of ground clay brick as a supplementary cementitious material in concrete-hydration characteristics, mechanical properties, and ASR durability*: Iowa State University.

C-16, A. (2016). Standard guide for examination of hardened concrete using scanning electron microscopy. In: ASTM International West Conshohocken, PA.

Chandra, S., & Berntsson, L. (2002). *Lightweight aggregate concrete*: Elsevier.

Chandrappa, A. K., Biligiri, K. P. J. C., & Materials, B. (2016a). Comprehensive investigation of permeability characteristics of pervious concrete: A hydrodynamic approach. *123*, 627-637.

Chandrappa, A. K., Biligiri, K. P. J. C., & materials, b. (2016b). Pervious concrete as a sustainable pavement material–Research findings and future prospects: A state-of-the-art review. *111*, 262-274.

Chen, J., Chu, R., Wang, H., Zhang, L., Chen, X., & Du, Y. J. J. o. c. p. (2019). Alleviating urban heat island effect using high-conductivity permeable concrete pavement. *237*, 117722.

Cui, X., Zhang, J., Huang, D., Liu, Z., Hou, F., Cui, S., . . . Wang, Z. (2017). Experimental study on the relationship between permeability and strength of pervious concrete. *Journal of Materials in Civil Engineering, 29*(11), 04017217.

de Brito, J., & Agrela, F. (2018). *New trends in eco-efficient and recycled concrete*: Woodhead Publishing.

De Pauw, P., Taerwe, L., & DESMYTER, J. (2000). *Concrete and masonry rubble as aggregates for concrete: Something in between normal and lightweight concrete.* Paper presented at the Proceedings of the 2nd International Symposium on Structural Lightweight Aggregate Concrete, ed. Steinar Helland, Ivar Holand and Sverre Smeplass, 18-22 June 2000, Kristiansand (Norway), ISBN 82-91341-37-0.

Deb, P., Debnath, B., Hasan, M., Alqarni, A. S., Alaskar, A., Alsabhan, A. H., . . . Hashim, K. S. J. M. (2022). Development of eco-friendly concrete mix using recycled aggregates: Structural performance and pore feature study using image analysis. *15*(8), 2953.

Debieb, F., & Kenai, S. (2008). The use of coarse and fine crushed bricks as aggregate in concrete. *Construction and Building Materials, 22*(5), 886-893.

Debnath, B., Sarkar, P. P. J. C., & Materials, B. (2019). Permeability prediction and pore structure feature of pervious concrete using brick as aggregate. *213*, 643-651.

Debnath, B., & Sarkar, P. P. J. I. J. o. P. E. (2020). Pervious concrete as an alternative pavement strategy: A state-of-the-art review. *21*(12), 1516-1531.

Deo, O., Neithalath, N. J. C., & Materials, B. (2011). Compressive response of pervious concretes proportioned for desired porosities. *25*(11), 4181-4189.

Dos Santos, B. M., Godoy, L. P., & Campos, L. M. J. J. o. c. p. (2019). Performance evaluation of green suppliers using entropy-TOPSIS-F. *207*, 498-509.

Ge, Z., Gao, Z., Sun, R., & Zheng, L. (2012). Mix design of concrete with recycled clay-brick-powder using the orthogonal design method. *Construction and Building Materials, 31*, 289-293.

Getachew, K. (2017). Laboratory Investigation of Locally Produced Clay Brick Quality and Suitability for Load Bearing Element in Jimma Area, Ethiopia Alemu Mosisa. *Int. J. Eng. Res. Technol, 6*(5), 809-817.

Hassan, I., Abdul-Kareem, O., & Shihab, A. (2014). Effect of using well water as mixing water in concrete. *Al-Rafidain Engineering journal, 22*(5), 17-28.

Hossain, T., Salam, M. A., & Kader, M. A. (2012). Pervious concrete using brick chips as coarse aggregate: An experimental study. *Journal of Civil Engineering (IEB), 40*(2), 125-137.

Hwang, C.-L., Yoon, K., Hwang, C.-L., Yoon, K. J. M. a. d. m. m., & survey, a. a. s.-o.-t.-a. (1981). Methods for multiple attribute decision making. 58-191.

Ibrahim, A., Mahmoud, E., Yamin, M., & Patibandla, V. C. (2014). Experimental study on Portland cement pervious concrete mechanical and hydrological properties. *Construction and Building Materials, 50*, 524-529. doi:https://doi.org/10.1016/j.conbuildmat.2013.09.022

Imran, H., Akib, S., & Karim, M. R. J. E. t. (2013). Permeable pavement and stormwater management systems: a review. *34*(18), 2649-2656.

Jozi, S., Shafiee, M., MoradiMajd, N., Saffarian, S. J. E. m., & assessment. (2012). An integrated Shannon's Entropy–TOPSIS methodology for environmental risk assessment of Helleh protected area in Iran. *184*, 6913-6922.

Kaplan, M. (1959). *Flexural and compressive strength of concrete as affected by the properties of coarse aggregates.* Paper presented at the Journal Proceedings.

Karaman, S., Gunal, H., & Ersahin, S. (2006). Assesment of clay bricks compressive strength using quantitative values of colour components. *Construction and Building Materials, 20*(5), 348-354.

Kazmi, S. M., Abbas, S., Saleem, M. A., Munir, M. J., & Khitab, A. (2016). Manufacturing of sustainable clay bricks: Utilization of waste sugarcane bagasse and rice husk ashes. *Construction and Building Materials, 120*, 29-41.

Kevern, J., Schaefer, V., Wang, K., & Suleiman, M. (2008). Pervious concrete mixture proportions for improved freeze-thaw durability. *Journal of ASTM international, 5*(2), 1-12.

Khalaf, F. M., & DeVenny, A. S. (2004). Performance of brick aggregate concrete at high temperatures. *Journal of Materials in Civil Engineering, 16*(6), 556-565.

Kosmatka, S. H., Panarese, W. C., & Kerkhoff, B. (2002). *Design and control of concrete mixtures* (Vol. 5420): Portland Cement Association Skokie, IL.

Kucche, K., Jamkar, S., & Sadgir, P. (2015). Quality of water for making concrete: a review of literature. *International Journal of Scientific and Research Publications, 5*(1), 1-10.

Kumar, B. V., Ananthan, H., & Balaji, K. (2017). Experimental studies on cement stabilized masonry blocks prepared from brick powder, fine recycled concrete aggregate and pozzolanic materials. *Journal of Building Engineering, 10*, 80-88.

Kumar, S., & Maithel, S. (2016). Introduction to brick kilns & specific energy consumption protocol for brick kilns. *New Delhi: Greentech Knowledge Solutions Pvt. Ltd*, 7-20.

Leite, M., & Santana, V. (2019). Evaluation of an experimental mix proportion study and production of concrete using fine recycled aggregate. *Journal of Building Engineering, 21*, 243-253.

Li, L. G., Feng, J.-J., Zhu, J., Chu, S.-H., & Kwan, A. K. H. J. M. o. C. R. (2021). Pervious concrete: Effects of porosity on permeability and strength. *73*(2), 69-79.

Li, X., Wang, K., Liu, L., Xin, J., Yang, H., & Gao, C. J. P. e. (2011). Application of the entropy weight and TOPSIS method in safety evaluation of coal mines. *26*, 2085-2091.

Li, Z. (2011). *Advanced Concrete Technology*: Wiley.

Maguesvari, M. U., Narasimha, V. J. P.-S., & Sciences, B. (2013). Studies on characterization of pervious concrete for pavement applications. *104*, 198-207.

Mahboub, K., Canler, J., Rathbone, R., Robl, T., & Davis, B. J. A. M. J. (2009). Pervious concrete: Compaction and aggregate gradation. *106*(6), 523.

Makul, N., Fediuk, R., Amran, M., Zeyad, A. M., Klyuev, S., Chulkova, I., . . . Azevedo, A. (2021). Design Strategy for Recycled Aggregate Concrete: A Review of Status and Future Perspectives. *Crystals, 11*(6), 695.

Malhotra, V. (1976). *No-fines concrete-its properties and applications.* Paper presented at the Journal Proceedings.

Mansur, M. A., Wee, T., & Lee, S. (1999). Crushed bricks as coarse aggregate for concrete. *Materials Journal, 96*(4), 478-484.

Marolf, A., Neithalath, N., Sell, E., Wegner, K., Weiss, J., & Olek, J. (2004). Influence of aggregate size and gradation on acoustic absorption of enhanced porosity concrete. *ACI Materials Journal-American Concrete Institute, 101*(1), 82-91.

Meng, T., Wei, H., Yang, X., Zhang, B., Zhang, Y., & Zhang, C. (2021). Effect of Mixed Recycled Aggregate on the Mechanical Strength and Microstructure of Concrete under Different Water Cement Ratios. *Materials, 14*(10), 2631.

Mullaney, J., & Lucke, T. J. C. S., Air, Water. (2014). Practical review of pervious pavement designs. *42*(2), 111-124.

Murdock, L. (1960). The workability of concrete. *Magazine of Concrete research, 12*(36), 135-144.

Neville, A. M. (1995). *Properties of concrete* (Vol. 4): Longman London.

Neville, A. M., & Brooks, J. J. (2010). *Concrete technology* (2nd ed ed.). Harlow, England: Prentice Hall.

Onat, N. C., Gumus, S., Kucukvar, M., Tatari, O. J. S. P., & Consumption. (2016). Application of the TOPSIS and intuitionistic fuzzy set approaches for ranking the life cycle sustainability performance of alternative vehicle technologies. *6*, 12-25.

Padmini, A., Ramamurthy, K., & Mathews, M. (2001). Behaviour of concrete with low-strength bricks as lightweight coarse aggregate. *Magazine of Concrete research, 53*(6), 367-375.

Pettijohn, F. J. (1957). *Sedimentary rocks / by F.J. Pettijohn*. New York: Harper & Brothers.

Poon, C. S., & Chan, D. (2006). Feasible use of recycled concrete aggregates and crushed clay brick as unbound road sub-base. *Construction and Building Materials, 20*(8), 578-585.

Sadek, D. M. (2012). Physico-mechanical properties of solid cement bricks containing recycled aggregates. *Journal of Advanced Research, 3*(3), 253-260.

Sahdeo, S. K., Ransinchung, G., Rahul, K., Debbarma, S. J. C., & Materials, B. (2020). Effect of mix proportion on the structural and functional properties of pervious concrete paving mixtures. *255*, 119260.

Sandanayake, M., Bouras, Y., Haigh, R., & Vrcelj, Z. (2020). Current sustainable trends of using waste materials in concrete—a decade review. *Sustainability, 12*(22), 9622.

Sata, V., Wongsa, A., & Chindaprasirt, P. (2013). Properties of pervious geopolymer concrete using recycled aggregates. *Construction and Building Materials, 42*, 33-39. doi:https://doi.org/10.1016/j.conbuildmat.2012.12.046

Song, M., Zhu, Q., Peng, J., Gonzalez, E. D. S. J. C., & Engineering, I. (2017). Improving the evaluation of cross efficiencies: A method based on Shannon entropy weight. *112*, 99-106.

Tadesse, A. (2013). Effects of firing temperature on physical properties of burnt clay bricks produced around Addis Ababa. *Unpublished M. Sc Thesis. Addis Ababa University*.

Tam, V. W., Soomro, M., & Evangelista, A. C. J. (2018). A review of recycled aggregate in concrete applications (2000–2017). *Construction and Building Materials, 172*, 272-292.

Tennis, P. D., Leming, M. L., & Akers, D. J. (2004). *Pervious concrete pavements* (Vol. 8): Portland Cement Association Skokie, IL.

Torres, A., Hu, J., & Ramos, A. (2015). The effect of the cementitious paste thickness on the performance of pervious concrete. *Construction and Building Materials, 95*, 850-859.

Wang, E., Alp, N., Shi, J., Wang, C., Zhang, X., & Chen, H. J. E. (2017). Multi-criteria building energy performance benchmarking through variable clustering based compromise TOPSIS with objective entropy weighting. *125*, 197-210.

Wongsa, A., Sata, V., Nuaklong, P., & Chindaprasirt, P. (2018). Use of crushed clay brick and pumice aggregates in lightweight geopolymer concrete. *Construction and Building Materials, 188*, 1025-1034.

Yunchao, T., Zheng, C., Wanhui, F., Yumei, N., Cong, L., & Jieming, C. (2021). Combined effects of nano-silica and silica fume on the mechanical behavior of recycled aggregate concrete. *Nanotechnology Reviews, 10*(1), 819-838.

Zachariah, J. P., Sarkar, P. P., & Pal, M. (2021). A study on the moisture damage and rutting resistance of polypropylene modified bituminous mixes with crushed brick aggregate wastes. *Construction and Building Materials, 269*, 121357.

Zakaria, M., & Cabrera, J. (1996). Performance and durability of concrete made with demolition waste and artificial fly ash-clay aggregates. *Waste Management, 16*(1-3), 151-158.

Zhang, L. (2013). Production of bricks from waste materials–A review. *Construction and Building Materials, 47*, 643-655.

Zhao, Y., Gao, J., Chen, F., Liu, C., & Chen, X. (2018). Utilization of waste clay bricks as coarse and fine aggregates for the preparation of lightweight aggregate concrete. *Journal of Cleaner Production, 201*, 706-715. doi:https://doi.org/10.1016/j.jclepro.2018.08.103

Zheng, C., Lou, C., Du, G., Li, X., Liu, Z., & Li, L. (2018). Mechanical properties of recycled concrete with demolished waste concrete aggregate and clay brick aggregate. *Results in Physics, 9*, 1317-1322. doi:https://doi.org/10.1016/j.rinp.2018.04.061

Zhong, R., Leng, Z., & Poon, C.-s. (2018). Research and application of pervious concrete as a sustainable pavement material: A state-of-the-art and state-of-the-practice review. *Construction and Building Materials, 183*, 544-553.

Zhong, R., & Wille, K. (2016). Linking pore system characteristics to the compressive behavior of pervious concrete. *Cement and Concrete Composites, 70*, 130-138.

Zhu, H., Wen, C., Wang, Z., & Li, L. J. M. (2020). Study on the permeability of recycled aggregate pervious concrete with fibers. *13*(2), 321.

7. APPENDIX

Appendix-A

Mix design of pervious concrete

The following mixture proportioning approach can be used to quickly arrive at pervious concrete mixture proportions that would help attain void content of mixed PC when measured in accordance with ASTM C1688 similar to the target value.

Step 1: Determine the dry-rodded unit weight of the aggregate and calculate the void content.

Dry-rodded unit weight of the aggregate (M) = 1060 kg/m^3

Specific gravity (S) = 1.99

Aggregate void content (%) = 100 [(S x W) – M] / (S x W)

= 100 [(1.99 x 1000) – 1060] / (1.99 x 1000) = 47 %

Therefore, aggregate void content is = 47%

Step 2: Estimate the approximate percentage and volume of paste needed. The paste volume (V_p) is then estimated as follows:

V_p (%) = Aggregate Void Content (%) + CI (%) - V_{void} (%)

Where CI = compaction index, and V_{void} = design void content of the pervious concrete mix.

The value of CI can be varied based on the anticipated consolidation to be used in the field. For greater consolidation effort a compaction index value of 1 to 2% may be more reasonable. For lighter level of consolidation, a value of 7 to 8% can be used. NRMCA used a value of 5% to get similar values between measured fresh pervious concrete void content (ASTM C1688) and design void content. Using a smaller value for CI (%) will reduce the paste volume. This study uses 1% compaction index.

V_p (%) = 47 + 1 – 20 = 28%

Therefore, the paste volume is = 0.28 m^3

Step 3: Select the w/c ratio for the paste. According to (NRMC, 2010) recommended values are in the range of 0.25 to 0.36. The W/C ratios for the PC mix that satisfied the compressive strength requirement based on trial mix was found to be 0.3, and 0.35 at A/C ratio of 4.0.

Step 4: Calculate the absolute volume of cement.

$V_c = V_p$ / [1+ (w/c x RD_c)]

Where: RD_c is the specific gravity of cement (3.15)

V_c = 0.28/[1+(0.3x3.15)] = 0.143 m^3

Therefore, the volume of cement is = 0.143 m^3

Step 5: Calculate the volume of water (V_w).

V_w (m3) = V_p – V_c

V_w = 0.28 – 0.143 = 0.135 m3

Therefore, the volume of cement is = 0.135 m3

Step 6: Calculate the volume of SSD aggregate (V_{agg}).

$V_{agg} = 1 – (V_p + V_{void})$

Where: V_{void} is the design void content for the pervious concrete mix.

V_{agg} = 1 – (0.28 + 0.2) = 0.52 m3

V_{agg} = 0.52 m3

Trial batches are prepared to evaluate mix characteristics of the pervious concrete mixture. Make appropriate adjustments are made to account for aggregate moisture content. If paste is high, pick a lower value or change CI (%). Avoid excessive cementitious content should be avoided. The consistency of the paste can be evaluated separately to ensure that it is not too dry or causes paste run down by being too wet. The density of the mixture should be measured in accordance with ASTM C1688 from which the void content is calculated to ensure that values are in line with the design void content. Then evaluate mixture for consistency, specification requirements and placement method used by the pervious concrete contractor.

Adjust to SSD volume by account of aggregate moisture content.

Given that the percentage absorbance (A) of 20.82%.

V_{agg} (SSD) = V_{agg} [1 + (A/100)]

= 0.52 [1 + (20.82/100)] = 0.63 m3

Convert the volumes to weights of ingredients per cubic m3.

Cement (kg/m^3) = $V_c \times RD_c \times 1000$

Water (kg/m^3) = $V_w \times 1000$

SSD Coarse Aggregate (kg/m^3) = $V_{agg} \times RD_{agg} \times 1000$

Convert the volumes to weights of ingredients per cubic m3 and for mix batches:

Cement (kg/m^3) = $V_c \times RD_c \times 1000$

= 0.143 x 3.15 x 1000 = 449 kg/m^3

Cement (kg/m^3) = 449 kg/m^3

Water (kg/m^3) = $V_w \times 1000$

= 0.135 x 1000= 135 kg/m3

Water (kg/m^3) = 135 kg/m^3

SSD Coarse Aggregate (kg/m^3) = $V_{agg} \times RD_{agg} \times 1000$

Where: RD_{agg} is the specific gravity of Coarse Aggregate (1.99)

= 0.63 x 1.99 x 1000 = 1257 kg/m^3

SSD Coarse Aggregate (kg/m^3) = 1257 kg/m^3

Therefore, the adjusted quantities of the constituent materials per m^3 for a W/C ratio of 0.3, and A/C ratio 4 are:

Cement = 1257/4 = 314 Kg

Water = 0.3/314 = 94 Kg

Coarse Aggregate = 1257 Kg

Appendix-B

The 7th day compressive strength test result for PC mixes with WCBA.

Casting Date	Specimen ID.	G-1 (12.5 mm)			G-2 (10 mm)			G-3 (20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
19/5/23	Weight (g)	5843	5944	5938	6252	6311	6274	6195	6243	6231
	Force (KN)	98	99	99	112	112	110	85	86	86
	Compre. Str. (Mpa)	4.34	4.38	4.38	4.96	4.96	4.91	3.79	3.82	3.81
19/5/23	Weight (g)	6067	6088	6098	6274	6312	6301	5849	5833	5876
	Force (KN)	92	93	92	105	105	106	75	76	75
	Compre. Str. (Mpa)	4.09	4.13	4.09	4.68	4.68	4.71	3.33	3.36	3.33
20/5/23	Weight (g)	6741	6752	6782	6486	6539	6488	6725	6838	6698
	Force (KN)	101	104	100	115	114	115	92	91	90
	Compre. Str. (Mpa)	4.48	4.62	4.43	5.13	5.08	5.13	4.07	4.03	4.01
20/5/23	Weight (g)	6472	6466	6584	6522	6438	6557	6486	6449	6464
	Force (KN)	91	91	93	109	110	110	80	79	79
	Compre. Str. (Mpa)	4.04	4.04	4.13	4.86	4.89	4.88	3.55	3.52	3.52

Casting Date	Specimen ID.	G-4 (10+20 mm)			G-5 (10+12.5 mm)			G-6 (12.5+20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
19/5/23	Weight (g)	5851	6036	6012	5757	5914	5833	5687	5724	5833
	Force (KN)	158	159	158	177	177	171	136	136	138
	Compre. Str. (Mpa)	7.01	7.06	7.04	7.86	7.88	7.62	6.06	6.06	6.12
19/5/23	Weight (g)	5828	5763	5645	6023	5903	5965	5501	5575	5532
	Force (KN)	153	152	153	164	163	163	117	117	118
	Compre. Str. (Mpa)	6.78	6.75	6.82	7.29	7.24	7.26	5.21	5.21	5.25
20/5/23	Weight (g)	6024	6177	6287	6107	6086	6041	5963	5845	5851
	Force (KN)	161	160	161	182	184	184	145	144	145
	Compre. Str. (Mpa)	7.15	7.11	7.17	8.11	8.18	8.18	6.45	6.41	6.44
20/5/23	Weight (g)	6084	6075	6135	6069	6047	6056	5812	5649	5687
	Force (KN)	156	157	157	171	170	169	127	128	127
	Compre. Str. (Mpa)	6.95	6.96	6.96	7.58	7.55	7.52	5.65	5.67	5.65

The 7th day compressive strength test result for PC mixes with NA.

Casting Date	Specimen ID.	G-1 (12.5 mm)			G-2 (10 mm)			G-3 (20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
16/5/23	Weight (g)	5962	5928	5864	6309	6324	6263	6205	6183	6195
	Force (KN)	168	171	167	195	195	194	137	137	137
	Compre. Str. (Mpa)	7.48	7.62	7.43	8.66	8.66	8.61	6.09	6.07	6.09
16/5/23	Weight (g)	6090	6082	6102	6294	6282	6184	5873	5843	5812
	Force (KN)	153	151	153	185	185	181	121	120	120
	Compre. Str. (Mpa)	6.79	6.73	6.79	8.22	8.22	8.05	5.35	5.32	5.32
17/6/23	Weight (g)	6634	6742	6687	6536	6594	6476	6767	6784	6729
	Force (KN)	177	177	174	201	201	201	148	148	148
	Compre. Str. (Mpa)	7.87	7.85	7.73	8.92	8.92	8.93	6.59	6.57	6.59
17/6/23	Weight (g)	6426	6453	6372	6565	6473	6498	6464	6495	6358
	Force (KN)	158	158	160	186	186	186	134	131	131
	Compre. Str. (Mpa)	7.04	7.04	7.13	8.26	8.27	8.26	5.95	5.82	5.82

Casting Date	Specimen ID.	G-4 (10+20 mm)			G-5 (10+12.5 mm)			G-6 (12.5+20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
16/5/23	Weight (g)	5896	6051	6042	5746	6085	6075	5689	5741	5798
	Force (KN)	230	231	231	247	249	249	211	211	210
	Compre. Str. (Mpa)	10.2	10.3	10.28	11	11.1	11.05	9.36	9.36	9.33
16/5/23	Weight (g)	5777	5619	5712	6080	5855	5968	5481	5494	5486
	Force (KN)	222	222	223	237	240	237	202	202	202
	Compre. Str. (Mpa)	9.88	9.88	9.91	10.6	10.7	10.5	8.96	8.96	8.97
17/6/23	Weight (g)	6022	6201	6189	6159	6081	6074	5885	5889	5844
	Force (KN)	235	234	234	257	257	257	217	216	217
	Compre. Str. (Mpa)	10.5	10.4	10.4	11.4	11.4	11.4	9.65	9.61	9.64
17/6/23	Weight (g)	6011	6125	6187	6015	6042	6033	5812	5695	5635
	Force (KN)	225	225	226	244	244	245	204	205	205
	Compre. Str. (Mpa)	10	10	10	10.9	10.9	10.9	9.05	9.13	9.13

Appendix-C

The 28th day compressive strength test result for PC mixes with WCBA.

Casting Date	Specimen ID.	G-1 (12.5 mm)			G-2 (10 mm)			G-3 (20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
18/6/23	Weight (g)	5994	6005	6029	6335	6341	6356	6286	6294	6289
	Force (KN)	113	114	114	128	128	127	99	100	100
	Compre. Str. (Mpa)	5.03	5.07	5.07	5.71	5.71	5.66	4.41	4.44	4.43
18/6/23	Weight (g)	6125	6119	6175	6303	6342	6332	5943	5961	5998
	Force (KN)	107	108	107	122	122	122	88	89	88
	Compre. Str. (Mpa)	4.75	4.79	4.75	5.41	5.41	5.44	3.93	3.96	3.93
19/6/23	Weight (g)	6715	6856	6782	6589	6612	6579	6798	6823	6742
	Force (KN)	117	120	116	133	132	133	106	105	105
	Compre. Str. (Mpa)	5.19	5.33	5.14	5.91	5.86	5.91	4.71	4.67	4.65
19/6/23	Weight (g)	6596	6532	6543	6623	6598	6605	6501	6525	6538
	Force (KN)	106	106	108	126	127	126	94	93	93
	Compre. Str. (Mpa)	4.71	4.71	4.8	5.6	5.63	5.62	4.16	4.13	4.13

Casting Date	Specimen ID.	G-4 (10+20 mm)			G-5 (10+12.5 mm)			G-6 (12.5+20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
18/6/23	Weight (g)	5982	6110	6134	5812	6095	5928	5762	5815	5869
	Force (KN)	179	180	180	202	202	196	155	155	156
	Compre. Str. (Mpa)	7.95	8	7.98	8.96	8.98	8.72	6.88	6.88	6.94
18/6/23	Weight (g)	5859	5712	5773	6146	5997	5964	5526	5578	5599
	Force (KN)	173	172	174	186	185	185	135	135	136
	Compre. Str. (Mpa)	7.69	7.66	7.73	8.27	8.22	8.24	6.01	6.01	6.05
19/6/23	Weight (g)	6113	6298	6302	6243	6144	6183	5996	5981	5926
	Force (KN)	182	182	183	208	209	209	164	164	164
	Compre. Str. (Mpa)	8.11	8.07	8.13	9.23	9.3	9.3	7.31	7.27	7.3
19/6/23	Weight (g)	6123	6235	6289	6174	6169	6133	5875	5722	5798
	Force (KN)	177	178	178	193	192	192	145	146	145
	Compre. Str. (Mpa)	7.88	7.89	7.89	8.58	8.55	8.52	6.46	6.48	6.46

The 28th day compressive strength test result for PC mixes with NA.

Casting Date	Specimen ID.	G-1 (12.5 mm)			G-2 (10 mm)			G-3 (20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
14/6/23	Weight (g)	6023	6056	6085	6443	6487	6389	6310	6341	6348
	Force (KN)	188	191	187	220	220	218	155	155	155
	Compre. Str. (Mpa)	8.35	8.49	8.3	9.76	9.76	9.71	6.9	6.88	6.9
14/6/23	Weight (g)	6169	6145	6166	6325	6402	6381	5947	5903	5991
	Force (KN)	172	170	172	206	206	203	136	136	136
	Compre. Str. (Mpa)	7.63	7.57	7.63	9.17	9.17	9	6.06	6.03	6.03
15/6/23	Weight (g)	6722	6718	6784	6645	6682	6728	6846	6829	6883
	Force (KN)	198	197	194	223	223	223	167	166	167
	Compre. Str. (Mpa)	8.78	8.76	8.64	9.92	9.92	9.93	7.41	7.39	7.41
15/6/23	Weight (g)	6565	6584	6537	6623	6687	6607	6538	6556	6543
	Force (KN)	178	178	178	208	208	208	152	149	149
	Compre. Str. (Mpa)	7.89	7.89	7.98	9.24	9.25	9.24	6.74	6.61	6.61

Casting Date	Specimen ID.	G-4 (10+20 mm)			G-5 (10+12.5 mm)			G-6 (12.5+20 mm)		
	Specimen No.	C1	C2	C3	C1	C2	C3	C1	C2	C3
14/6/23	Weight (g)	5915	6132	6115	6122	6156	6182	5755	5729	5871
	Force (KN)	258	259	259	277	278	278	237	237	236
	Compre. Str. (Mpa)	11.45	11.5	11.52	12.29	12.36	12.36	10.52	10.52	10.5
14/6/23	Weight (g)	5846	5835	5814	6118	5968	5903	5562	5593	5543
	Force (KN)	250	250	250	266	268	266	227	227	227
	Compre. Str. (Mpa)	11.09	11.09	11.12	11.82	11.92	11.81	10.08	10.08	10.1
15/6/23	Weight (g)	6058	6064	6102	6256	6142	6188	5941	5933	5923
	Force (KN)	263	262	262	287	288	288	244	243	243
	Compre. Str. (Mpa)	11.7	11.66	11.66	12.76	12.78	12.78	10.84	10.8	10.8
15/6/23	Weight (g)	6025	6033	6087	6141	6087	6166	2987	5744	5812
	Force (KN)	253	253	254	273	273	274	229	231	232
	Compre. Str. (Mpa)	11.25	11.25	11.27	12.15	12.15	12.16	10.19	10.27	10.3

Appendix-D

The 28th day density result for PC mixes with WCBA.

Casting Date	Specimen ID.	G-1 (10 mm)		G-2 (12.5 mm)		G-3 (20 mm)	
	Specimen No.	C1	C2	C1	C2	C1	C2
18/6/23	Dry weight (W_{dry}) (g)	1815	1785	1693	1651	1847	1816
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.156	1.137	1.078	1.052	1.176	1.157
18/6/23	Dry weight (W_{dry}) (g)	1752	1785	1763	1774	1725	1756
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.116	1.137	1.123	1.130	1.099	1.118
19/6/23	Dry weight (W_{dry}) (g)	1841	1886	1771	1788	1916	1857
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.173	1.201	1.128	1.139	1.220	1.183
19/6/23	Dry weight (W_{dry}) (g)	1732	1726	1727	1774	1806	1818
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.103	1.099	1.100	1.130	1.150	1.158

Casting Date	Specimen ID.	G-4 (10+12.5)		G-5 (10+20)		G-6 (12.5+20)	
	Specimen No.	C1	C2	C1	C2	C1	C2
18/6/23	Dry weight (W_{dry}) (g)	1695	1661	1702	1694	1717	1706
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.080	1.058	1.084	1.079	1.094	1.087
18/6/23	Dry weight (W_{dry}) (g)	1781	1722	1710	1712	1717	1738
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.134	1.097	1.089	1.090	1.094	1.107
19/6/23	Dry weight (W_{dry}) (g)	1668	1655	1728	1685	1702	1683
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.062	1.054	1.101	1.073	1.084	1.072
19/6/23	Dry weight (W_{dry}) (g)	1693	1772	1724	1712	1718	1752
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.078	1.129	1.098	1.090	1.094	1.116

The 28th day density result for PC mixes with NA.

Casting Date	Specimen ID.	G-1 (10 mm)		G-2 (12.5 mm)		G-3 (20 mm)	
	Specimen No.	C1	C2	C1	C2	C1	C2
14/6/23	Dry weight (W_{dry}) (g)	1891	1872	1916	1936	2050	2050
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.204	1.192	1.220	1.233	1.306	1.306
14/6/23	Dry weight (W_{dry}) (g)	1969	1984	1953	1945	2108	2128
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.254	1.264	1.244	1.239	1.343	1.355
15/6/23	Dry weight (W_{dry}) (g)	2045	2047	2045	2025	2217	2153
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.303	1.304	1.303	1.290	1.412	1.371
15/6/23	Dry weight (W_{dry}) (g)	1971	1961	1943	1972	2153	2197
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.255	1.249	1.238	1.256	1.371	1.399

Casting Date	Specimen ID.	G-4 (10+12.5)		G-5 (10+20)		G-6 (12.5+20)	
	Specimen No.	C1	C2	C1	C2	C1	C2
14/6/23	Dry weight (W_{dry}) (g)	2087	2126	2095	2119	2306	2328
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.329	1.354	1.334	1.350	1.469	1.483
14/6/23	Dry weight (W_{dry}) (g)	2093	1974	2078	2065	1964	2009
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.333	1.257	1.324	1.315	1.251	1.280
15/6/23	Dry weight (W_{dry}) (g)	2186	2146	2153	2175	2371	2325
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.392	1.367	1.371	1.385	1.510	1.481
15/6/23	Dry weight (W_{dry}) (g)	1938	1991	2067	2089	1986	2007
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Density of PCs (D) (g/cm3)	1.234	1.268	1.317	1.331	1.265	1.278

Appendix-E

The 28th day porosity test result for PC mixes with WCBA.

Casting Date	Specimen ID.	G-1 (10 mm)		G-2 (12.5 mm)		G-3 (20 mm)	
	Specimen No.	C1	C2	C1	C2	C1	C2
18/6/23	Mass of speci. in water (M1) (g)	2050	2000	2200	2150	2250	2200
	Dried mass of spec. in air (M2) (g)	1693	1651	1815	1785	1847	1816
	Appart. density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	23.7	23.2	25.5	24.2	26.7	25.5
18/6/23	Mass of speci. in water (M1) (g)	2150	2150	2150	2200	2150	2200
	Dried mass of spec in air (M2) (g)	1763	1774	1752	1785	1725	1756
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	25.6	24.9	26.4	27.4	28.1	29.3
19/6/23	Mass of speci. in water (M1) (g)	2100	2150	2200	2250	2300	2250
	Dried mass of speci in air (M2) (g)	1771	1788	1841	1886	1916	1857
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	22.0	24.1	23.9	24.2	25.5	26.0
19/6/23	Mass of speci. in water (M1) (g)	2100	2150	2150	2100	2200	2250
	Dried mass of speci in air (M2) (g)	1727	1774	1732	1726	1806	1818
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	24.8	24.9	27.6	24.8	26.1	28.5

Casting Date	Specimen ID.	G-4 (10+12.5)		G-5 (10+20)		G-6 (12.5+20)	
	Specimen No.	C1	C2	C1	C2	C1	C2
18/6/23	Mass of speci in water (M1) (g)	2050	2000	2050	2000	2100	2050
	Dried mass of speci in air (M2) (g)	1702	1694	1695	1661	1717	1706
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	23.2	20.5	23.6	22.6	25.4	22.9
18/6/23	Mass of speci in water (M1) (g)	2050	2100	2150	2100	2100	2150
	Dried mass of speci in air (M2) (g)	1710	1712	1781	1722	1717	1738
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	22.7	25.7	24.5	25.1	25.4	27.2
19/6/23	Mass of speci in water (M1) (g)	2050	2000	2000	2000	2050	2050
	Dried mass of spec in air (M2) (g)	1728	1685	1668	1655	1702	1683
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	21.5	21.1	22.1	23.0	23.2	24.4
19/6/23	Mass of speci in water (M1) (g)	2100	2050	2050	2150	2100	2150
	Dried mass of speci in air (M2) (g)	1724	1712	1693	1772	1718	1752
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	24.9	22.5	23.7	25.1	25.3	26.4

The 28th day porosity test result for PC mixes with NA.

Casting Date	Specimen ID.	G-1 (10 mm)		G-2 (12.5 mm)		G-3 (20 mm)	
	Specimen No.	C1	C2	C1	C2	C1	C2
14/6/23	Mass of speci. in water (M1) (g)	2250	2300	2250	2250	2450	2400
	Dried mass of spec. in air (M2) (g)	1916	1936	1891	1872	2050	2050
	Appart. density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	22.3	24.2	23.9	25.1	26.5	23.3
14/6/23	Mass of speci. in water (M1) (g)	2300	2350	2350	2400	2500	2550
	Dried mass of spec in air (M2) (g)	1953	1945	1969	1984	2108	2128
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	23.1	26.8	25.3	27.5	26.0	27.9
15/6/23	Mass of speci. in water (M1) (g)	2400	2350	2400	2400	2600	2500
	Dried mass of speci in air (M2) (g)	2045	2025	2045	2047	2217	2153
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	23.6	21.7	23.6	23.5	25.4	23.1
15/6/23	Mass of speci. in water (M1) (g)	2300	2350	2350	2350	2550	2600
	Dried mass of speci in air (M2) (g)	1943	1972	1971	1961	2153	2197
	Apparent density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	23.7	25.1	25.1	25.8	26.3	26.7

Casting Date	Specimen ID.	G-4 (10+12.5)		G-5 (10+20)		G-6 (12.5+20)	
	Specimen No.	C1	C2	C1	C2	C1	C2
14/6/23	Mass of speci in water (M1) (g)	2400	2450	2400	2500	2650	2700
	Dried mass of speci in air (M2) (g)	2095	2119	2087	2126	2306	2328
	Appar density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	20.4	22.1	20.9	24.8	22.9	24.7
14/6/23	Mass of speci in water (M1) (g)	2400	2450	2450	2350	2350	2400
	Dried mass of spec in air (M2) (g)	2078	2065	2093	1974	1964	2009
	Appar density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	21.5	25.5	23.7	24.9	25.6	25.9
15/6/23	Mass of spec in water (M1) (g)	2450	2500	2500	2500	2750	2650
	Dried mass of spe in air (M2) (g)	2153	2175	2186	2146	2371	2325
	Appar density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	19.9	21.7	21.0	23.5	25.1	21.7
15/6/23	Mass of speci in water (M1) (g)	2450	2400	2300	2350	2350	2400
	Dried mass of s in air (M2) (g)	2067	2089	1938	1991	1986	2007
	Appa density of water (g/cm3)	1	1	1	1	1	1
	Specimen volume (V) (cm3)	1570	1570	1570	1570	1570	1570
	Porosity of PCs (%)	25.4	20.8	24.1	23.9	24.2	26.0

Appendix-F

The 28th day water permeability test result for PC mixes with WCBA.

Casting Date	Specimen ID.	G-1 (10 mm)		G-2 (12.5 mm)		G-3 (20 mm)	
	Specimen No.	C1	C2	C1	C2	C1	C2
18/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	42	44	41	41	39	37
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.853	0.814	0.874	0.874	0.919	0.969
18/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	38	38	35	33	33	31
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.943	0.943	1.024	1.086	1.086	1.156
19/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	49	49	47	47	45	45
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.731	0.731	0.762	0.762	0.796	0.796
19/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	38	36	36	33	34	31
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.943	0.995	0.995	1.086	1.054	1.156

Casting Date	Specimen ID.	G-4 (10+12.5)		G-5 (10+20)		G-6 (12.5+20)	
	Specimen No.	C1	C2	C1	C2	C1	C2
18/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	50	50	49	50	44	46
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.717	0.717	0.731	0.717	0.814	0.779
18/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	43	44	41	43	41	39
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.833	0.814	0.874	0.833	0.874	0.919
19/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	54	55	52	54	52	53
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.664	0.652	0.689	0.664	0.689	0.676
19/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	47	47	43	45	40	43
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.762	0.762	0.833	0.796	0.896	0.833

The 28th day water permeability test result for PC mixes NA.

Casting Date	Specimen ID.	G-1 (10 mm)		G-2 (12.5 mm)		G-3 (20 mm)	
	Specimen No.	C1	C2	C1	C2	C1	C2
14/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	44	44	41	42	40	38
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.814	0.814	0.874	0.853	0.896	0.943
14/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	39	38	36	36	34	33
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.919	0.943	0.995	0.995	1.054	1.086
15/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	52	50	48	48	46	48
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.689	0.717	0.747	0.747	0.779	0.747
15/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	39	40	37	38	35	36
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.919	0.896	0.969	0.943	1.024	0.995

Casting Date	Specimen ID.	G-4 (10+12.5)		G-5 (10+20)		G-6 (12.5+20)	
	Specimen No.	C1	C2	C1	C2	C1	C2
14/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	51	52	48	47	46	46
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.703	0.689	0.747	0.762	0.779	0.779
14/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	44	46	43	42	41	40
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.814	0.779	0.833	0.853	0.874	0.896
15/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	57	56	54	54	53	51
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.629	0.640	0.664	0.664	0.676	0.703
15/6/23	C/s area of specimen (a) (cm2)	7850	7850	7850	7850	7850	7850
	C/s area of the tube (A) (cm2)	7850	7850	7850	7850	7850	7850
	Length of the specimen (L) (cm)	20	20	20	20	20	20
	Time from h1 to h2 (t) (sec)	48	45	45	44	42	40
	Initial head (h1) (cm)	30	30	30	30	30	30
	Final head (h2) (cm)	5	5	5	5	5	5
	Permeability coefficients (k) (cm/s)	0.747	0.796	0.796	0.814	0.853	0.896

Appendix-G

Pictures

a) Waste clay bricks aggregate

b) Unit weight determination of WCBA

c) Specific gravity determination of WCBA

d) Soaked WCBA

e) Shape tests (FIV and EIV) of WCBA

f) Set up of ALAV testing apparatus

g) Set up of AIV testing apparatus

h) Set up of ACV testing apparatus

i) WCBA at SSD ready for mix

j) PC after being thoroughly mixed

k) Specimens after cast

l) PC specimens covered with plastic sheet

m) PC specimens in curing tank

n) cylinder specimens ready for permeability test

o) Set up of permeability testing apparatus

p) specimens ready for SEM test