2-1-2014

Properties of Portland cement pervious concrete

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Recommended Citation

APA Citation

El-Tawil, F. (2014).*Properties of Portland cement pervious concrete* [Master’s thesis, the American University in Cairo]. AUC Knowledge Fountain.
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MLA Citation

El-Tawil, Farrah Abdel Aziz. *Properties of Portland cement pervious concrete*. 2014. American University in Cairo, Master's thesis. *AUC Knowledge Fountain*.
https://fount.aucegypt.edu/etds/1230

The American University in Cairo

School of Sciences and Engineering

PROPERTIES OF PORTLAND CEMENT PERVIOUS CONCRETE

A Thesis Submitted to

The Department of Construction & Architectural Engineering

in partial fulfillment of the requirements for the degree of

Master of Science in Construction Engineering

By

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The American University in Cairo

June 2013

DEDICATION

This thesis is lovingly dedicated to the memory of my mother and truest friend, Hanaa El-Bannany, who has always emphasized the importance of education and relentlessly supported and motivated me throughout her life but unfortunately, could not live to see this dream come true. Her being was a mark of love, care, and sacrifice. Gone now but never forgotten, I will miss her always and love her forever.

ACKNOWLEDGEMENTS

I am greatly indebted to several people without whom this dissertation might not have been completed.

First and foremost I owe my sincerest gratitude to my supervisor, Prof. Dr. Mohamed Nagib Abou Zeid, who has supported me throughout my thesis with his patience and knowledge and who has endured the many obstacles I faced during the course of finalizing my thesis. His kind yet strict guidance and his professional scientific attitude have greatly contributed to formatting the ideas developed during the research; it has been an honor for me to have Dr. Nagib as my sponsor.

I would also like to thank my examining committee, Prof. Dr. Gouda Ghanem Dean of the Faculty of Engineering at El Shorouk Academy, Prof. Dr. Emad Imam professor of hydraulic and water resources engineering at The American University in Cairo, and Prof. Dr. A. Samer Ezeldin Professor and Director of the Graduate Program at the Construction Engineering and Architecture Department at The American University in Cairo.

I am also very thankful to Dr. Mohamed Nour Assistant Professor of Environmental Engineering at The American University in Cairo for his support and help on the environmental portion of this thesis and Dr. Mohamed Rashwan and Eng. Ahmed Samir for their support and valuable advice.

Moreover, I am also very grateful to the concrete laboratory personnel who helped me continuously during this study. Special thanks to Ragab and Haytham for their tremendous assistance in the laboratory. Without the help of Mr. Ragab, this work could not have been undertaken in such a short period of time.

My gratitude for the blessing and support received from my father, Abdel Aziz El-Tawil, cannot be expressed by mere words as he has been my role-model for hard work, persistence, and personal sacrifices throughout my life. He has always encouraged me to set high goals and instilled in me the confidence to achieve them.

I would also like to thank my husband, Ahmed Adel, who has been supportive of my work and who nurtured this project and treated it as if it was his own. This thesis would not have been possible without Ahmed's support and assistance.

My love and admiration go to my lovely little sister, Malak El-Tawil, for her encouragement during this study and for being the enlightenment of my life.

Last but not least, I offer my regards and blessings to each and every person, whether from AUC or outside, who supported me in any respect during the completion of this project and again to my family whom this thesis would not have been possible without their encouragement.

ABSTRACT

Portland Cement Pervious Concrete (PCPC) is an innovative type of concrete that contains little or no fine aggregates thus creating a substantial void content which allows concrete to be water permeable. PCPC thus can be used for drainage, recharging groundwater, reducing storm water and possibly filtering some pollutants. Proper employment of PCPC has been recognized by the U.S. Environmental Protection Agency (EPA) as a Best Management Practice. Yet, this type of concrete has not been yet considered in the Egyptian market.

This study aims primarily at producing PCPC using local materials and achieving better understanding of mechanical properties, durability and potential applications. To meet that objective, concrete mixtures were prepared using 250, 350 and 450 kg of cement with different aggregates gradations, plasticizing admixtures, and silica fume. Fresh concrete tests as well as compressive and flexural strength tests were conducted. Water flow, chloride permeability, chemical durability, resistance to elevated temperature, and the potential of water purification and reduction of bacteria were examined.

The results of this study investigation reveal that the PCPC can be produced using local materials and allow sizable flow of water throughout. PCPC has undergone a reduction of strength up to 48% when compared with conventional concrete. However, the reduction in strength still allows concrete to be produced at the lower bound of permits many of these mixtures to be used in structural concrete. Moreover, PCPC seems to possess a potential for water purification particularly for oil/grease contaminants. PCPC have witnessed an average reduction of 98.6% of TSS, 92.2% of bacteria, and 14.6% of lead when 98% of used vehicle oil was removed from the simulated water sample. Further research works as well as pilot trials need to be conducted to explore the full potential of PCPC in concrete applications requiring permeability of fluids and some purification of pollutants.

Keywords: Pervious Concrete, No-fines, Porous Concrete, Storm-Water Management, and Water Purification)

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Background

Conventional concrete or specifically ordinary Portland cement concrete (OPCC) used worldwide in the construction industry may at some instances reveal disadvantages that are specific to a certain application. Thus, different parties within the construction industry may be encouraged to use special concrete types, which overcome general limitations of conventional concrete, depending on their different interests. Planners may have special requirements for the environment, the client/owner may have concerns for lower running or energy costs, an architect may have special criteria for colors, surface finish, textures, appearance, or innovation whereas engineers may need to apply new norms or special technical requirements, and last but not least contractors may have special application limitations during construction. For example, light weight concrete was developed to solve issues like reduction of dead loads, making savings in foundations and reinforcement, improving thermal properties and fire resistance, saving on transporting and handling precast units on site, and reduction of formwork whereas shot/sprayed concrete was designed to enable contractors to cast concrete in areas where formwork is not applicable such as tunneling, rock and slope consolidation, high performance linings, and repair and refurbishment works. Table 1.1 illustrates the six categories grouping special concretes according to its advantages.

Comparing special concrete types with conventional concrete, they are usually less standardized or even not standardized at all. Special concretes have their own advantages and disadvantages and need special knowledge and experience to apply adequately and define the relevant characteristics during the design stage (Construction Competence & Consulting, 2013)

Table 1.1 Special concrete types (Construction Competence & Consulting, 2013)

Functional Application	Pavements Tunnel Maritime Structures Under-water Structures Floors
Design Properties	High Strength Concrete Very High Strength Concrete Early Strength Concrete Lightweight Concrete High Density Concrete Low Shrinkage Concrete / Shrinkage Compensating Concrete High Ductile Concrete
Construction	Self-Compacting Concrete or Self Consolidating Concrete Shot Concrete or Sprayed Concrete Pumping Concrete Low Heat concrete
Decorative	Exposed Concrete Exposed Aggregates Colored Concrete Painted Concrete Textured Concrete Translucent Concrete
Durability	Water Proof Concrete Freeze Thaw Salt Resistant Concrete Fire Resistant Concrete Chemical Resistant Concrete Sealed Concrete
Sustainability	Recycled Aggregate Concrete Slag Concrete Insulating Concrete Recyclable Concrete Pervious Concrete

One of the special concretes categorized under sustainability advantages is Portland Cement Pervious Concrete (PCPC), sometimes referred to as “no-fines concrete”, “porous concrete”, “permeable concrete”, “pervious concrete”, “gap-graded concrete” and “enhanced-porosity concrete” is basically concrete that contains little or no fine aggregates/sand. The concrete produced is thus harsh, of low workability and a slump as low as “zero” with and an open-cell structure. This open-cell structure results in a highly interconnected void content of 15 to 35% that consequently creates a porous/permeable concrete with distinctive properties. As per the National Ready Mixed Concrete Association (NMRCA) "*In pervious concrete carefully controlled amounts of water and cementitious materials are used to create a paste that forms a thick coating around aggregate particles. A pervious concrete mixture contains little or no sand, creating a substantial void content. Using sufficient paste to coat and bind the aggregate particles creates a system of highly permeable, interconnected voids that drains quickly*".

The permeability of Portland cement pervious concrete varies with the void content, aggregate size, and density of the mixture allowing 81-730 Liters of water per minute to pass through each square meter, Figure 1.1 and Figure 1.2 illustrates the texture/open-cell structure of Portland cement pervious concrete and a sample draining water respectively. Due to the high void content of pervious concrete, it is considered to be a light-weight concrete with unit weight usually ranging from 1600 to 1900 kg/m^3 compared to the unit weight of conventional concrete which is typically around 2300 kg/m^3. Furthermore, the compressive strength of pervious concrete is limited where it lies between 2.8 and 28 MPa (400 to 4000 psi). The same way, tensile and flexural strengths also tend to be significantly lower than those of standard concrete (NMRCA, 2004).

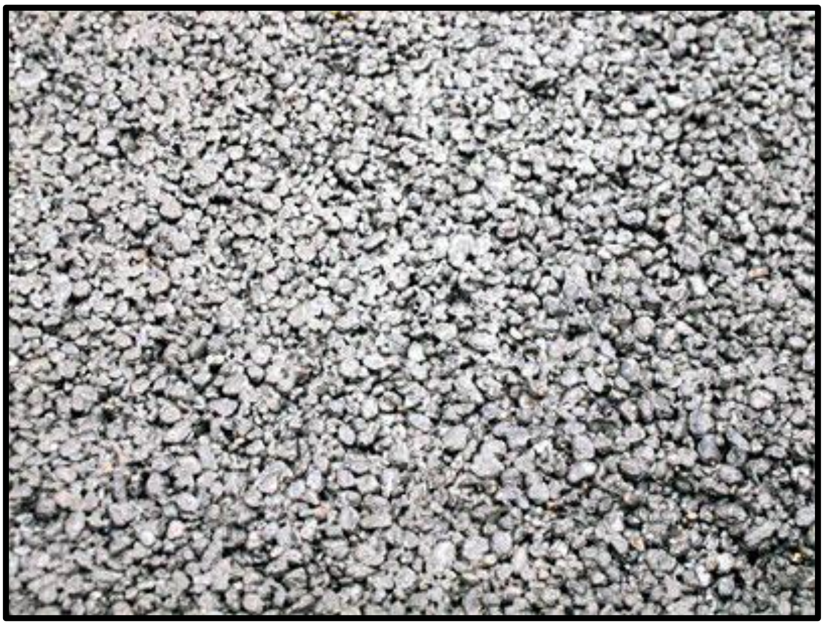


Figure 1.1 Texture of pervious concrete (NRMCA, 2011)

Figure 1.2 Pervious concrete draining water (NRMCA, 2011)

1.2 Development, Advantages, and Disadvantages

When water from rainfalls and snowmelts flow over land, paved streets, parking lots, and building rooftops, or any other impermeable surface and does not seep into the ground, storm-water runoff is created. As the runoff flows over those surfaces it collects dirt, debris, chemicals, sediment, heavy metals (from the brake linings of cars), hydrocarbons (from vehicle oils and asphalt pavements), and other pollutants creating a point source for pollution. Usually storm water drains wash this polluted runoff to rivers and streams rather than to treatment facilities thus negatively impacting natural water resources by increasing algae content, harming aquatic life, and necessitating expensive treatments to make the water drinkable thereafter. Storm water runoff can also cause flooding and erosion, destroy habitat, and contribute to combined sewer overflows (Tennis et. al., 2004)

Attempting to tackle such serious pollution concerns, the U.S. Environmental Protection Agency (EPA) and many other authorities currently require stricter storm water management practices and are tapering environmental regulations. Hence, real estate development is becoming a burden on property owners due to the size and expense of the necessary drainage systems.

Amendments to the Clean Water Act (1999) mandating governmental and private entities to manage storm water runoff, both quantitatively and qualitatively, has driven recent interest in the use of permeable paving materials for pavements in the United States to reduce storm water runoff and improve the quality of storm water, thus Pervious concrete is becoming one of the most practical solutions (Iowa State University Report, 2006). The proper use of pervious concrete has also been recognized as a "Best Management Practice" by the U.S. Environmental Protection Agency (EPA) because of its competence in reducing storm water runoff (Neptune and Putman, 2010). As a result of decreasing the volume of storm water runoff, Portland cement pervious concrete reduces the necessity of separate storm water retention ponds and permits the use of smaller capacity storm sewers reducing financial burden on real estate developers.

Pervious concrete is a pioneering material with many environmental, economic, and structural advantages. The major environmental advantages of Portland cement pervious concrete will be further discussed in chapter 2 but are summarized as follows (Abou Zeid et al., 2010; Iowa State University Report, 2006):

- Cutting down the volume of storm water runoff released into storm sewers.
- Enhancing quality of storm water runoff as it naturally filters storm water and can reduce pollutant loads entering into streams, ponds, and rivers.
- Preserving natural ecosystems through maintaining aquifer levels due to directly recharging groundwater, alleviating contaminants from watersheds, and reducing the urban heat-island effect (since Portland cement pervious concrete is lighter in color than conventional asphalt surfaces and because it has an open-cell structure, it does not absorb and store heat and then radiate it back into the environment)
- Lessening the need for irrigation water as it directs more water to tree roots and landscapes.

- Reduces skid resistance and risks associated with refreezing of puddles while providing a tidy surface during the day by absorbing excess water during rainfall and snowmelt events and is consequently safer for drivers and pedestrians.
- Reducing noise as open-cell structure and interconnected void content of the porous pavement causes porous pavements to absorb the sound.
- Inhibiting defects on sidewalks by allowing trees to cultivate without a root heave.

Pervious concrete as a material might not be substantially more expensive than conventional concrete, however Portland cement pervious concrete pavements are usually much thicker (because it is designed for a weaker sub-grade) and thus the initial cost is much higher. Although the initial cost for the construction of pervious concrete pavements is usually higher than it is for typical pavements (asphalt and concrete), the overall costs including installation and life-cycle costs can be considerably lower due to (NMRCA, 2011):

- Lower installation costs as the use of Portland cement pervious concrete for pavements eliminates the need of constructing underground piping and storm drains for water runoff.
- Permits the use of existing sewer systems even when accommodating new residential and commercial developments.
- Portland cement pervious concrete, when properly constructed, is a highly durable paving material requiring minimal maintenance and thus has lower life-cycle costs.
- Increasing land utilization through avoiding occupation of retention ponds and other water-retention and filtering systems to large land areas.

The reported shortcomings of pervious concrete involve cleaning to unclog voids to restore porosity (through vacuum sweeping or pressure washing), risk of contaminating groundwater, lower compressive strength, higher initial cost, difficulty of placing and finishing and thus the need for specialized labor, low durability upon exposure to chemical attacks, and surface raveling (Abou Zeid et al., 2010; Iowa State University Report, 2006).

1.3 Applications

Portland cement pervious concrete, Portland cement pervious concrete, has been utilized in Europe, Australia, and the Middle East for over a century. In 1852, Portland cement pervious concrete was employed in the construction of two houses and a sea-groin in the United Kingdom (Ghafoori and Dutta, 1995). Portland cement pervious concrete then became common for applications such as cast-in-place load-bearing walls of single and multistory houses, prefabricated panels, and stem-cured blocks after World War II. In Europe Pervious Concrete had been used in limited applications including parking areas, roof pavements, tennis court slabs, and some minor roads whereas in the United States it has mainly been used in pavement applications such as a surface paving material for parking lots, permeable base course, edge drains, and greenhouse floors (Ghafoori and Dutta, 1995). Although the history of Portland cement pervious concrete goes back to 1852, as with any new product, it has had to prove itself.

Pervious concrete has been used in landscaping for urban and garden paths, footpaths in country parks, rural trails and other recreation areas, and riverside paths. Its color is aesthetically more appealing to rural settings than that of tarmac and asphalt. It is ideal for sections which cannot be drained or which is subject to stream/river erosion (NMRCA, 2011).

Pervious concrete pavements has been used for a few decades in England and the United States for light-duty pavement applications (residential streets, parking lots, driveways, and sidewalks) while it is commonly used in Europe and Japan for roadway applications as a surface course to improve skid resistance and reduce traffic noise (Abou Zeid et al., 2010). Despite the fact that pervious concrete can be used for a surprising number of applications, its current most important use is in pavements either full-depth pavements or as a surface layer. Table 1.2 summarizes Portland cement pervious concrete applications listed by most of the literature:

Table 1.2 Portland cement pervious concrete applications (Schaefer, et al., 2006)

Low-volume pavements	Residential roads, alleys, and driveways
Concrete overlays for highway pavements	Foundations/floors for greenhouses, fish hatcheries, aquatic centers, and zoos
Sidewalks and pathways	Tennis courts
Low water crossings	Parking lots
Sub-base for conventional concrete	Slope stabilization
Artificial reefs	Tree grates in sidewalks
Channel/Well linings	Hydraulic structures
Patios	Groins and seawalls
Pavement edge drains	Walls (including load-bearing)
Noise barriers	Curb and gutter

The above listed applications of PCPC have been the most common. However, a recent study discussed the use of a special type of permeable concrete, that fractures into small fragments when exposed to impact loading while having sufficient static strength, to be used in protective structures such as safety walls or storages for explosives (Agar-Ozbek et al., 2013).

1.4 Construction

The choice of materials in the concrete mixture as well as the practices used to cast and finish pervious concrete pavements is different than that associated with conventional impervious pavements. In pervious concrete mixtures, fine aggregates are excluded from the mixture while water and cementitious materials must be carefully proportioned to create a paste that is sufficient to coat and bind the coarse aggregate particles. Excess water will cause paste to drain down while insufficient water can hamper adequate curing of the concrete and lead to a premature raveling (aggregates loosely attached to the surface initially which pop out due to traffic loading) surface failure. On average, pervious concrete has water to cement (w/c) ratio of 0.28 to 0.40 and void content of 15 to 25%.

Due to the stiff consistency of pervious concrete, special attention is required during transportation and placement. Portland cement pervious concrete mixtures should be transferred as quickly and as close as possible to where it needs to be and discharged into place within one hour after initial mixing.

Such zero-slump needs some of care while casting to avoid filling voids. Placement should be continuous and spreading and strike-off should be rapid as can be seen in Figure 1.3 and Figure 1.4.

Figure 1.3 Pervious concrete placement (NRMCA, 2011)

Figure 1.4 Pervious concrete compaction (NRMCA, 2011)

A fair face surface makes conventional concrete supreme whereas the rough harsh surface is vital for the purpose of Portland cement pervious concrete. Therefore, pervious concrete finishing techniques are very different as well. Contractors have to make sure not to seal the surface and ultimately close pore spaces that allow water to filter through the pavement. (Drotleff L. and Eberly D., 2011).

Within a maximum of 20 minutes after placing, compacting, and jointing curing should take place since pervious concrete pavements have a high tendency for plastic shrinkage cracking. The sub grade must be dampened before concrete is poured to prevent it from absorbing moisture from the concrete. Following placement, the most common curing practice is fog misting followed by plastic sheeting for at least seven days as illustrated in Figure 1.5 (NMRCA; www.perviouspavement.org).

Figure 1.5: Pervious concrete curing by plastic sheeting (NRMCA, 2011)

1.5 Statement of the Problem

In light of the aforementioned advantages and disadvantages of pervious concrete, it evidently offers a practical solution to several dilemmas in the construction industry while meeting the intensifying environmental demands for Sustainable and Low Impact Development.

While a substantial amount of work have investigated various properties of Portland cement pervious concrete (aggregate gradation and size, void ratio, strength, admixtures), scarce studies were conducted on durability, water purification potential, and probable economic merit which are of urgent priority towards securing widespread application for Portland cement pervious concrete. Moreover, not many studies were held to investigate the use of Portland cement pervious concrete in Egypt utilizing locally available materials.

1.6 Work Objective and Scope

The key objective of this work is to study the characteristics of Portland cement pervious concrete made in Egypt utilizing locally available materials and examining the mechanical properties, permeability, water purification potential, and long term properties of Portland cement pervious concrete attempting to highlight how to establish a Portland cement pervious concrete mixture which compromises between the mechanical properties and the permeability of the pervious concrete to achieve pervious concrete mixtures which are of good mechanical properties whilst sufficiently permeable.

To attain the aforesaid objectives, thirteen Portland cement pervious concrete mixtures are prepared. The mixtures are to be categorized according to cement content. Three categories are to be utilized containing 250, 350, and 450 kg/m^3. Those three categories symbolize poor quality, medium-quality, and high-strength concrete mixtures respectively as used in the construction industry in Egypt. Under each category different aggregate gradations will be investigated; single-sized 12.5mm coarse aggregate, single-sized 9.5mm coarse aggregate, and graded coarse aggregates of size “1” all with no fine aggregates. Two water/cement (w/c) ratios (0.30 and 0.40) are to be used; 0.30 for poor quality mixtures, 0.30 for medium-quality mixtures, and 0.40 for high-strength concrete mixtures. Three conventional concrete mixtures (containing fine aggregates) are to be prepared to act as control mixtures for this investigation. One mixture was prepared with 10% silica fume to explore the effect of silica fume on the Portland cement pervious concrete. Plasticizer and superplasticizer were used for mixtures with w/c of 0.30 and 0.40 respectively to improve the workability of the Portland cement pervious concrete.

Properties of hardened concrete to be assessed are compressive strength at 3, 7, 28, 56, and 90 days and flexural strength at 28 days. Furthermore, durability of Portland cement pervious concrete mixtures is to be assessed through testing for resistance to exposure to elevated temperatures, chemical soundness, rapid chloride permeability, and ponding of concrete plates. The water purification potential of the Portland cement pervious concrete is to be tested using a common pollutant and bacteria. A preliminary study on economic merits of Portland cement pervious concrete will also be prepared to evaluate economic benefits of utilizing Portland cement pervious concrete in Egypt.

The second chapter of this study will exemplify preceding work conducted by researchers on the properties and uses of Portland cement pervious concrete. The third chapter will demonstrate comprehensively the methodology conducted in the experimental program of this study. The subsequent chapter will thus demonstrate results generated via experimentation and will also encompass the study for economic merit of application of Portland cement pervious concrete. Finally, the fifth and last chapter analyzes the experimental results and derives conclusions based on the findings of this study. Chapter five also provides some recommendations for future work and for the construction industries.

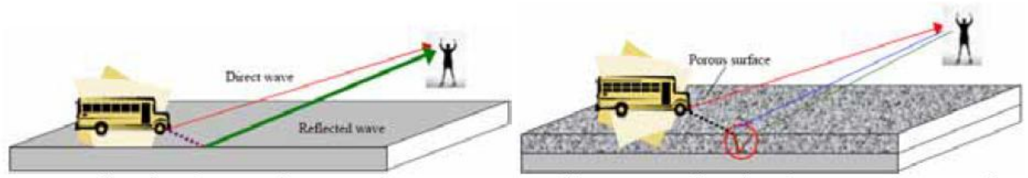
CHAPTER 2: LITERATURE REVIEW

Portland Cement Pervious Concrete (PCPC) is a unique construction material with numerous environmental, economic, and structural advantages. Although pervious concrete has been in use for more than 50 years in diverse applications, the recent EPA regulations issued to support the federal clean water legislation are renewing the interest of many entities for revisiting applications of this unique material and therefore the use of PCPC has been emergent in the recent years. However, because pervious concrete has its own unique properties that significantly differs from that of conventional concrete, the process of mixture design, placing, and curing must be planned and properly executed to achieve the required results. As any other material, PCPC has its disadvantages which may be bypassed if utilized in a proper manner and appropriate application.

The literature review of this study primarily includes PCPC advantages, disadvantages, and applications, as well as constituents, and mixture proportions. Furthermore, a sight on previous research held attempting to investigate, improve, or optimize on one or more of PCPC properties and how each of those properties affect one another.

2.1 Advantages of Portland Cement Pervious Concrete

The major environmental advantages of PCPC as explained by Abou Zeid et al. (2010), National Ready Mix Concrete Association (2005), and Iowa State University Report (2006) include cutting down the volume of storm water runoff released into storm sewers and preserving natural ecosystems through maintaining aquifer levels due to directly recharging groundwater. Since pervious concrete is lighter in color than conventional asphalt surfaces and because it has an open-cell structure it does not absorb and store heat and then radiate it back into the environment thus reducing the urban heat-island effect especially in large cities where most areas are paved with impervious construction materials; the heat island causes the significant energy consumption up to 12% and higher urban temperatures (Bin Tong, 2011). Pervious concrete also cuts down on the quantity of irrigation water required as it directs more air and water to tree roots and landscapes while inhibiting defects on sidewalks by allowing trees to nurture with no root heave. PCPC reduces noise as the difference in arrival time between direct and reflected sound waves, caused by the open-cell structure and interconnected void content of the porous pavement, causes porous pavements to absorb the sound as illustrated in Figure 2.1. Moreover, it reduces skid resistance and risks associated with refreezing of puddles while providing a tidy surface during the day by absorbing excess water during rainfall and snowmelt events and is consequently safer for drivers and pedestrians. Figure 2.2 illustrates a comparison of post-snowstorm asphalt surface and PCPC surface, pervious concrete accelerates the melting of snow and allows the water to drain instantly, these photos were taken within minutes of each other in two parking lots in Denver when both lots were plowed in the morning after an overnight snow storm.



(a) Wave reflection from a dense surface (b) Wave reflection from a porous surface

Figure 2.1 Reflection of sound waves resulting from moving vehicles (Iowa State University Report, 2006)

Figure 2.2 Left asphalt parking lot, right PCPC parking lot (NRMCA, 2011)

Another leading environmental advantage of pervious concrete is its potential in enhancing the quality of storm water runoff as it naturally filters storm water and can reduce pollutant loads entering into streams, ponds, and rivers thus can "treat" the pollution prior to release (Tennis et. al. 2004). As quoted by Bin Tong (2011), up to 75% of the total urban contaminant loads can be reduced by using PCPC pavement. PCPC provides "*first-flush pollution control and storm water management*" and has therefore been recognized as a Best Management Practice by the U.S. Environmental Protection Agency (EPA) (NRMCA, 2004). Taghizadeh and et. al. (2007) investigated water purification using a pilot study with a vertical porous concrete filter using the low overflow rate of river water which revealed that an adequate efficiency of about 90-100 % was obtained for decreasing the coliform bacteria. Another more recent study has presented that Portland cement pervious concrete mixtures have screened 70% to 80% of grease and oil pollutants and thus recommends the use of PCPC for drainage systems in gas stations, oil containers, and factories or industries where oil is present (Abou Zeid et. al., 2010). The same study also examined the capability of PCPC in eliminating harmful metals specifically zinc where the results did not exceed 18% removal. Another study was held in the University of Essen in Germany by Dierkes to examine heavy metal retention within a porous pavement structure. Porous pavement structures with four different subbase materials were tested in rigs and additional tests were carried out in a pilot-scaled test bed consisting of porous concrete blocks loaded by sprinklers with synthetic runoff with dissolved heavy metals. The study concluded that if porous pavements are planned and constructed carefully, groundwater seems not to be endangered by trace metals in the road-runoff as porous pavements for storm water infiltration from parking lots and residential streets showed a very high affectivity to trap dissolved heavy metals in the runoff.

Economically, the overall material cost of Portland cement pervious concrete might not be substantially more expensive than conventional concrete but because it is designed for a weaker sub-grade PCPC pavements are usually much thicker and thus the initial material cost is much higher. Also due to its low workability it is labor intense and thus its installation cost is higher than that of asphalt or conventional concrete. Although the initial cost for the construction of pervious concrete pavements is usually higher than it is for typical pavements (asphalt and concrete), the overall costs including installation and life-cycle costs can be considerably lower (NMRCA, 2005). This can be attributed to creating more efficient land use by eliminating the need for underground piping, storm drains, retention ponds, swales, and other storm water management systems thus reducing the overall project costs on a first-cost basis (Tennis et. al, 2004). Furthermore, when properly constructed, PCPC is a highly durable paving material requiring minimal maintenance and thus has lower life-cycle costs (NMRCA, 2004).

From a structural standpoint as expounded by NRMCA (2004), although the compressive strength of PCPC is much lower than that of conventional concrete it can attain strengths greater than 20 MPa (3000 psi) which is sufficient for its applications. Furthermore, strength and durability can be enhanced through special mix designs including supplementary cementitious materials, such as silica fume and fly ash, and installing subgrade and subbase levels of course and/or fine aggregates beneath the pavement. Because pervious concrete mixtures are stiff with least amounts of water and therefore very low workability, it develops sooner and much smaller amount of drying shrinkage occurs in the placement of pervious concrete than in conventional concrete.

2.2 Disadvantages of Portland Cement Pervious Concrete

Though the above mentioned environmental, economic, and structural advantages of PCPC have been the mainspring of its growing use all over the world, like any material pervious concrete also has shortcomings that have not been fully resolved. These deficiencies in addition to the absence of uniform standards have also been delaying the application of PCPC in novel and more innovative applications. The drawbacks of PCPC listed hereunder necessitates further research to solve these problems (Abou Zeid et. al., 2010; Iowa State University Report, 2006; Tong, 2011):

- the relatively low compressive and flexural strengths of pervious concrete hindered its usage for heavy traffic roadways and highways;
- although the overall costs including installation and life-cycle costs can be considerably lower for pervious concrete as opposed to conventional concrete, the high initial cost remains a drawback for many users;
- the clogging of pervious concrete pavement can considerably decrease its drainage ability, routine maintenance and cleaning through sweeping or vacuuming to restore porosity effectively and timely may be costly;
- PCPC has lower resistance to freeze-thaw cycles than conventional concrete;
- PCPC is more vulnerable to chemicals attack than conventional concrete; and
- due to installation problems, placement of PCPC is labor intensive and skilled specialized labor is essential.

Users were reluctant to utilize pervious concrete in the past due to its relatively high failure rate attributed to poor design, inadequate construction techniques, low permeability soil, heavy construction traffic, and poor maintenance (Joung et. al., 2008). During the past decade many studies have been carried out attempting to increase the mechanical properties, enhance free-thaw durability, concrete properties, and construction techniques developments.

2.3 Portland Cement Pervious Concrete Constituents

The permeability of PCPC is created by the exclusion of fine aggregate from the conventional concrete mixture, where slight amounts or no fine aggregate is included in the mixture. Portland cement pervious concrete is therefore comprised of coarse aggregate, cementitious materials, water, admixtures, and, in some cases, fibers. In this section, the above-mentioned constituents of pervious concrete is discussed.

2.3.1 Cementitious Materials

Similar to conventional concrete, pervious concrete employs Portland cements in accordance with ASTM C 150 and C 1157 and blended cements conforming to ASTM C 595 and C 1157). Additionally, supplementary cementitious materials (SCMs) such as fly ash, pozzolans (ASTM C 618), and ground-granulated blast furnace slag (ASTM C 989) may be used to alter concrete performance, setting time, rate of strength development, porosity, permeability, etc. Typical ranges of cementitious materials in pervious concrete mixtures 270 to 415 kg/m^3 (450 to 700 lb/yd^3) according to NRMCA (2004).

2.3.2 Aggregates

The primary component of PCPC is the coarse aggregate. Typical coarse aggregate quantities in a pervious concrete mixtures range from 1400 to 1550 kg/m^3

(Mahboub K., et al., 2009). Generally the strength of concrete does not rely on the aggregate strength as failure of concrete specimens in a compression test usually occurs at the aggregate-paste interface where the bond strength is weaker than both the strength of the paste and the strength of the aggregate. Yet, in pervious concrete the cement paste is limited and the aggregate rely on the contact surfaces between one another for strength (Chopra et. al., 2007). Accordingly harder aggregate, such as granite or quartz, would yield higher compression strength than a softer aggregate like limestone as can be seen in Table 2.1 quoted by Chopra et. al. (2007) from an older study. The coarse aggregates employed in pervious concrete mixtures are generally either rounded aggregates (gravel) or angular aggregates (crushed stone) studies have shown that higher strengths are achieved by means of utilizing gravel (Iowa State University Report, 2006; Tennis et. al., 2004).

According to Tennis et. al. (2004), commonly used gradations of coarse aggregate include gap-graded or narrowly-graded coarse aggregates in accordance with ASTM C 33 "Standard Specification for Concrete Aggregates" No. 67 (19.0 to 4.75 mm), No. 8 (9.5 to 2.36 mm), or No. 89 (9.5 to 1.18 mm) sieves and ASTM D 448 "Specification for Crushed Stone, Crushed Slag and Gravel for Water bound Base and Surface Courses of Pavements". Moreover, single-sized aggregate up to 25 mm (1 in.) has been used since larger aggregates provide a rougher surface thus increasing increases skid resistance. For applications like low-traffic pavements and parking lots, smaller sized aggregates are preferable as their looks are more appealing. The smaller the aggregate size, the higher the compressive and flexural strengths but in this case strength is traded off with permeability as permeability decreases with the decrease in aggregate size.

Table 2.1 Relationship between 28 day compressive strength and aggregate type (Chopra et. al., 2007)

Type of Aggregate	Dry Density		Compressive Strength	
	kg/m^3	lb./ft^3	MPa	psi
Rounded Quartzite Gravel	1842	115	8.62	1250
Irregular Flint Gravel	1586	99	4.83	700
Crushed Limestone	1826	114	6.89	1000
Crushed Granite	1697	106	7.58	1100

Fine aggregates are excluded from a PCPC mixture because it is believed to minimize the percentage of voids and thus reduces permeability. Nevertheless, Researchers have concluded that incorporating 5% to 10% fine sand, as a mass ratio of fine aggregate to coarse aggregate, is optimal to improve strength without significantly affecting porosity (Iowa State University report, 2006). A recent study concluded that the mixtures containing 7% fines had the highest strength in the groups of mixtures examined (Abou Zeid et. al., 2010).

Typical ranges of coarse aggregates in pervious concrete mixtures are 1190 to 1480 kg/m^3 (2000 to 2500 lb/yd^3) with an aggregate to cement ratio of 4 to 4.5:1 by mass according to NRMCA (2004). Proper values of aggregate to cement ratio (a/c) is mostly governed by the application, mixture materials, and properties required. Excessively high a/c ratios cause weak interconnection between the particles whereas too low a/c ratios cause a heavy paste layer around aggregates occupying void spaces and sequentially reducing permeability as illustrated in Figure 2.3. The ratio of 4.76:1 was found to provide particle coverage with no excess cement according to Iowa State University Report (2006).

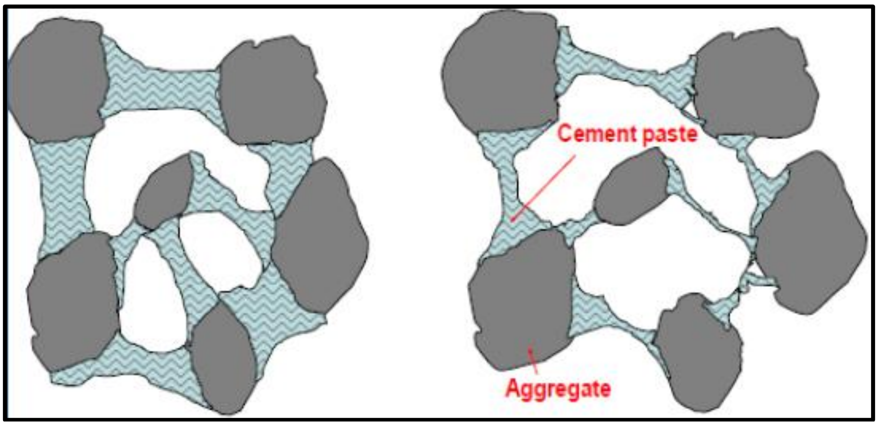


Figure 2.3 Left lower a/c ratio and right higher a/c ratio (Tong, 2011)

2.3.3 Water

Water is the most crucial constituent for all concrete. Water hydrates the cement to form the bond between the aggregate which sequentially gives concrete its strength and also creates a workable substance. Because Portland cement pervious concrete is sensitive to changes in water content, the precise quantity of water is critical and thus field fine-tuning is generally necessary (CIP 38).

According to NRMCA (2004) the typical w/c ratio for pervious concrete mixtures is in the range of 0.27 to 0.34 whereas other literature have indicated that this range goes up to 0.45 (CIP 38). Lower w/c ratios significantly reduces workability of PCPC and causes inadequate cohesion due to reducing the bonds between the particles as can be seen in Figure 2.4. Moreover, a water content that is too low will also impede suitable curing of the concrete and lead to a premature raveling surface failure (CIP 38). On the other hand, higher w/c ratios may lead to over-workable mixtures encouraging segregation and consecutively lower permeability due to blockage of the voids.

Figure 2.4 PCPC water content (a) too little water, (b) proper amount of water, and (c) too much water (NRMCA, 2011)

2.3.4 Chemical Admixtures

As in conventional concrete, chemical admixtures may be used in pervious concrete to attain enhanced or different properties. Retarders or hydration-stabilizing admixtures are commonly used to overcome problems associated with the rapid setting time of Portland cement pervious concrete whereas a high range water reducer is always used to assist in the placement of the pervious concrete mixture by acting like a lubricant between interlocking aggregates due to its low workability. Air-entraining admixtures have been used in countries where freeze-thaw is a concern to reduce damage in pervious concrete. Viscosity modifying admixtures are useful in preventing drain-down of the paste (Phillips J., 2009). Chemical admixtures used must conform to ASTM C 494 whereas ASTM C 260 governs air-entraining admixtures.

2.4 Pervious Concrete Mixture Proportioning

Although Portland cement pervious concrete is comprised of the same constituents as conventional concrete, its characteristics have mandated the mixture proportioning to develop as an “art form” rather than a fixed practice. A successful mixture for pervious concrete always meets the requirements for strength for loadings, permeability for acceptable hydrological function, freeze-thaw resistance, and clogging resistance with minimal maintenance cost (Kevern et. al., 2009). Water-to-cement ratio (w/c) and aggregate-cement ratio (a/c) are the key measures affecting the mechanical and hydrological properties of Portland cement pervious concrete and upon which the mix design is based. Table 2.2 summarizes the effect of w/c and a/c ratios on properties and performance of PCPC while Table 2.3 illustrates material proportions for typical PCPC.

Table 2.2 Effects of w/c and c/a ratio on PCPC Properties (Tong, 2011)

Ratio	Proper Values	Low	High
w/c	0.27-0.30 (by weight)	• Low workability • Low strength • Low flexural strength • Low elastic modulus • Low freeze-thaw-durability	• Low permeability • Low void ratios • Eliminate the anticipated hydraulic function • Eliminate the effective service life
c/a*	0.18-0.22 (by volume)		

*The aggregate-cement ratio (a/c) is inverted for illustration purposes

Table 2.3 Typical materials proportions in pervious concrete (NRMCA, 2011)

Materials	Proportions, kg/m^3 (lb/yd^3)
Cementitious materials	270 to 415 (450 to 700)
Aggregate	1190 to 1480 (2000 to 2500)
w/c (by mass)	0.27 to 0.34
a/c (by mass)	4 to 4.5:1
Fine : coarse aggregate ratio (by mass)	0 to 1:1

2.5 Portland Cement Pervious Concrete Properties

Table 2.4 recaps the Portland cement pervious concrete properties found in the literature where the void ratio of PCPC ranges from 11% to 35%, with a 28-day compressive strength between 5.5 and 32 MPa (800 - 4650 psi), permeability between 5 and 883 $L/m^2/min$ (12 - 2120 in./hr.), flexural strength between 1.03 and 7.48 MPa (150 - 1085 psi), and unit weight between 1602 and 2211 kg/m3 (100 - 139 lb./ft3). Nevertheless, the permeability of the mixture with the highest compressive strength was not reported (Iowa State University Report).

2.5.1 Unit Weight

Unit weight is the preferred measurement for fresh quality of pervious concrete because slump test has not been expressive due to the stiffness of the mixtures as compared to traditional concrete. Slumps, when measured, are generally less than 20 mm (¾ in.). According to Tennis et. al. (2004) the fresh density of pervious concrete is an indicator of the mechanical and hydrological properties, and provides the best routine test for monitoring quality. Unit weights of pervious concrete mixtures are approximately 70% of conventional concrete mixtures commonly between 1600 and 2000 kg/m^3 (100 lb/ft^3 to 125 lb/ft^3), which is in the upper range of lightweight concretes (NRMCA, 2004). In-place densities are contingent upon the mixtures, mixing materials and compaction levels and procedures.

2.5.2 Porosity and Permeability

The interconnected void structure of PCPC enables the movement of water within the hardened concrete. The relationship between strength and porosity is inversely proportional where highly porous mixtures commonly yields lower strength and vice versa. According to Tennis et al. (2004), PCPC with void ratios between 15% and 25% produce strength values greater than 13.8 MPa (2000 psi) with a permeability of about 200 L/m^2/min (480 in./hr.). Permeability values up to 600 L/m^2/min (1440 in./hr.) were reported for PCPC mixtures with a void ratio exceeding 20% (Iowa State University Report, 2006). Figure 2.5 illustrates the relationship between strength, void ratio, and permeability as established by Schaefer et. al. (2006).

Table 2.4 PCPC properties presented from literature (Iowa State University Report, 2006; Tong, 2011)

Void Ratio (%)	Unit Weight kg/m^3 (lb./ft^3)	Permeability L/m^2/min (in/hr.)	Compressive Strength MPa (psi)	Flexural Strength MPa (psi)	Reference
11-15	-	15-105 (36-252)	-	4.18-7.48 (606-1085)	Kajio, 1998
20-30	1890-2082 (118-130)	-	17.6-32 (2553-4650)	3.87-5.69 (561-825)	Beeldens, 2001
15-35	-	-	-	2.5-3.9 (363-566)	Olek et al., 2003
19	-	-	26 (3771)	4.4 (638)	Beeldens et. al., 2003
-	-	-	19 (2756)	-	Tamai and Yoshida, 2003
15-25	1602-2002 (100-125)	120-315 (288-756)	5.5-20.7 (800-3000)	1.03-3.79 (150-550)	Tennis et al., 2004
18-31	-	-	11-25 (1595-3626)	-	Park, 2004
15-25	1600-2000 (100-125)	120-320 (288-770)	3.5-28 (500-4000)	1-3.8 (150-550)	NRMCA, 2005
18.3-33.6	1668-2097 (104.1-130.9)	59-289 (142-694)	12.2-25.2 (1771-3661)	1.41-2.9 (205-421)	Wang et al., 2006
15.6-24.4	-	38-286 (91-687)	16.4-22.5 (2385-3260)	-	Delattee, 2009
11.2-33.6	1579-2211 (98.6-138)	5-883 (12-2120)	5.4-27.8 (784-4027)	1.39-2.96 (201-429)	Schaefer et al, 2008

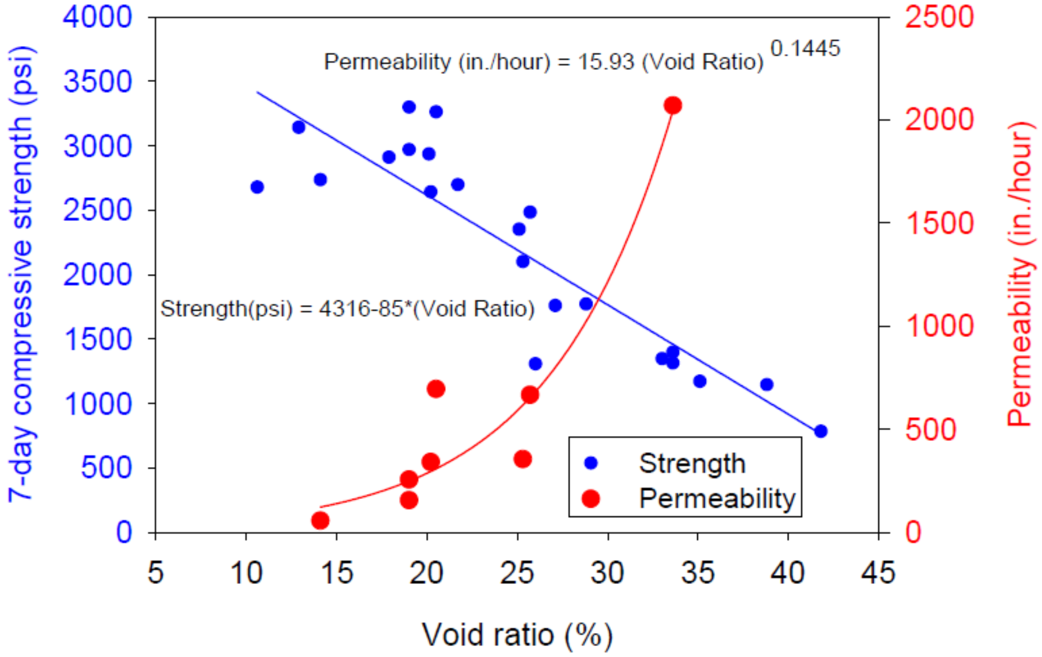


Figure 2.5 Relationship between strength, void ratio, and permeability (Schaefer et. al., 2006)

Porosity and Permeability rely on the pore structure of pervious concrete. According to Tong (2011) studies on the pore structure of pervious concrete included four factors which are pore volume, pore size, pore distribution and the connectivity of the pores. Studies on pore structure benefit the understanding of the freeze-thaw durability of pervious concrete, permeability prediction, and clogging.

2.5.3 Compressive, Flexural, and Split Tensile Strengths

The mechanical properties are the chief criteria for the structural design of pavements. Due to the high void ratio of pervious concrete, the mechanical properties including compressive and flexural strength are constantly inferior to that of conventional concrete. The method and amount of compaction and the porosity are the two principal factors that affects the mechanical properties of PCPC. Mechanical properties are enhanced through the:

1. increase of fresh unit weight,

2. increase of fine aggregates in mixtures, and
3. the application of high compaction effort.

However, the hydraulic performance decreases with the increase of strength of pervious concrete.

Pervious concrete mixtures can develop compressive strengths in the range of 3.5 MPa to 28 MPa (500 to 4000 psi), which is appropriate for a widespread variety of applications (NRMCA, 2005). Pervious concretes with enhanced static strengths (at the range of 30 – 50 MPa) were produced by modifying the compositional properties as well as the method of compaction (Agar-Ozbek et al., 2013) also high strength pervious concrete (32 to 46 MPa) can be achieved through both SCM-modification, using silica fume (SF) and superplasticizer (SP) and polymer-modification (Chen et al., 2013). As with any concrete, the properties and combinations of specific materials, as well as placement techniques and environmental conditions, will dictate the actual in-place strength. This implies that drilled cores are the best measure of in-place strengths, as compaction differences make cast cubes and/or cylinders less demonstrative of the cast concrete.

Although the typical applications utilizing pervious concrete does not require the measurement of flexural strength for design, flexural strength is an important mechanical property of concretes. In pervious concretes flexural strength varies between about 1 MPa and 3.8 MPa (150 psi and 550 psi). Many factors guide the flexural strength of pervious concrete predominantly the degree of compaction, porosity, and the aggregate-to-cement (a/c) ratio.

As for splitting tensile strength, Tong (2011) stated that the relationship between splitting tensile strength and compressive strength for pervious concrete is between 12% and 15% of the compressive strength.

2.5.4 Shrinkage

Values on the order of 0.002 have been reported for the drying shrinkage of pervious concrete which is approximately half that of conventional concrete mixtures. However, drying shrinkage of pervious concrete develops sooner. This phenomenon can be attributed to the low paste and mortar content. As a consequence of this lower shrinkage and the surface texture pervious concrete structures at some instances are made without control joints and allowed to crack randomly (Tennis et. al, 2004).

2.5.5 Durability of PCPC

Although PCPC was perceived to have no freeze-thaw durability due to its porosity, several studies indicated that freeze-thaw resistance of pervious concrete is subject to the saturation level of the voids in the concrete at the time of freezing. The interconnected void structure of pervious concrete offers adequate space for expansion consequently minimizing the excessive pressure exerted on the concrete when water is present inside the voids at freezing temperatures. A study was carried out at Iowa State University (2006) to develop an optimal mix design for PCPC in cold weather climates. Several concrete mixtures with assorted aggregate types and gradations as well as admixtures were investigated using strength tests as a function of time and freeze-thaw resistance according to ASTM C666, procedure A, in which samples were frozen and thawed in saturated conditions. The test was completed when the sample reached 300 cycles or 15% mass loss. Results of the testing showed that (Iowa State University report, 2006):

- PCPC failure when subjected to freeze-thaw cycles is due to either aggregate deterioration or cement paste matrix failure.
- Incorporating fine aggregates in mixtures enhanced freeze-thaw resistance.
- Mixtures comprising single-sized river gravel and 7% fines displayed the best performance when subjected to freeze-thaw cycles.
- Compaction energy has a significant effect on the freeze-thaw durability of PCPC. Samples prepared at regular compaction energy failed through the

aggregate, while failure through aggregate and paste was observed for mixtures prepared at low compaction energy.

The open structure of pervious concrete marks it as more vulnerable to aggressive acid and sulfate chemical attacks than conventional concrete. According to Tennis et. al. (2004), pervious concrete can be used in areas of high-sulfate soils and ground waters if isolated from them. Placing the pervious concrete over a 6-inch (150-mm) layer of 1-inch (25-mm) maximum top size aggregate provides a pavement base, storm water storage, and isolation for the pervious concrete.

Abrasion and surface raveling can be a problematic due to the rougher surface texture and open structure of pervious concrete. Therefore applications such as highways are generally not suitable for pervious concretes.

2.6 Different Previous Studies on PCPC

This section aims to provide a brief sight on various previous researches held attempting to investigate, improve, or optimize on one or more of Portland cement pervious concrete properties.

2.6.1 Durability and Maintenance

Yang Z. (2011) investigated the durability of pervious concrete under recurring freezing and thawing, wet-dry environments, and salt applications to simulate field conditions. This study examined the effects of materials, mixture proportions, and curing conditions on the freezing-and-thawing durability of pervious concrete. The study determined that air curing causes an intense reduction in the freezing-and-thawing durability as compared with water curing. Moreover, Silica fume additions are observed to improve the performance of water-cured pervious concrete during slow freezing and thawing while causing a significant drop in the performance of air-cured specimens. Polypropylene fibers ware seen to enhance the resistance of pervious concrete to repeated freezing and thawing, whereas salt applications are noted to aggravate the deterioration. In addition, wet-dry cycles are found to slow down the freezing-and-thawing damage development when the duration of the wet cycle is less than 3 days.

2.6.2 Mix Designs

Mahboub et. al. (2009) provided a practical tool to allow estimation of the porosity of the pervious concrete based on its aggregate bulk density during design of PCPC when using crushed limestone.

Sumanasooriya et. al. (2010) utilized a computational procedure to predict the permeability of 12 different pervious concrete mixtures from three-dimensional material structures reconstructed from starting planar images of the original material.

2.6.3 Specifications and Test Methods

Mahboub et. al. (2009) examined the compaction and consolidation of pervious concrete where the study presented cylindrical specimen preparation techniques that will produce laboratory specimens that are similar to the field pervious concrete slab. The study concluded that the customary method of rodding cylinders does not accurately represent a roller-compacted pervious concrete slabs where pneumatically pressing the pervious concrete cylinders at 10 psi (0.07 MPa) correlated well to specimens cored from roller-compacted pervious concrete.

2.6.4 Structural Design and Properties

Ghafoori et. al. (1995) investigated the physical and engineering characteristics of various PCPC mixtures where mixtures subjected to impact compaction were studied under unconfined compression, indirect tension, and static modulus of elasticity. The effect of impact-compaction energies, consolidation techniques, mixture proportions, curing types, and testing conditions on physical and engineering properties were also studied. The study concluded that the strength of no-fines concrete is strongly related to its mixture proportion and compaction energy. A sealed compressive strength of 20.7 MPa (3,000 psi) can readily be achieved with an aggregate cement ratio of 4.5:1 or less and a minimum compaction energy of 165 J/m

(4,303 ft-lb/cu ft). The splitting tensile-compressive relationship followed a pattern similar to that of conventional concrete. No-fines concrete had a lower modulus of elasticity than conventional concrete. The ultimate drying shrinkage of compacted no-fines concrete was found to be approximately 280 x 10", about half that typically expected in conventional concrete. Air-entrained no-fines concrete exhibited a higher resistance to freezing and thawing than non-air-entrained mixtures.

Andrew et. al. (2010) attempted to define the effects of aggregate size and gradation on the unit weight, strength, porosity, and permeability of pervious concrete mixtures. The water-cement ratio (w/c) and cement-aggregate ratio (c/a) were kept constant at 0.29 and 0.22, respectively, with a design unit weight of 2002 kg/m^3 (125 lb./ft3). Fifteen different aggregate gradations were tested and categorized according to nominal maximum aggregate sizes of 9.5, 12.5, and 19.0 mm (0.38, 0.49, and 0.75 in.) and had a range of uniformity coefficients Cu. The results indicated that as the porosity increased, strength decreased and permeability increased. As the gradation became less uniform or single-sized and more well-graded the strength also increased, whereas the porosity and permeability decreased.

CHAPTER 3: EXPERIMENTAL WORK

3.1 Introduction

The experimental program herein was designed to study mechanical properties, permeability, and long term properties (durability) of Portland cement pervious concrete, attempting to reach a point where balance is made between the mechanical properties and the porosity of the pervious concrete to achieve pervious concrete mixtures which are of good mechanical properties.

Thirteen mixtures were prepared under three categories with cement contents of 250, 350, and 450 kg/m^3. Those three categories represent low-quality, moderate-quality, and high-strength concrete mixtures used in the construction industry. Mixtures under each category were prepared using 12.5 mm, 9.5 mm, and graded coarse aggregates of size “1” with no fine aggregates. Two water/cement (w/c) ratios (0.30 and 0.40) were used. Three mixtures, one in each category, were prepared with fine aggregates to stand as the control mixture or the bench mark of this investigation. One mixture was prepared with 10% silica fume to explore the effect of silica fume on the Portland cement pervious concrete. A Plasticizer a superplasticizer were used for mixtures with w/c of 0.30 and 0.40 respectively to improve the workability of the Portland cement pervious concrete. Figure 3.1 summarizes the mixtures prepared for the experimental program.

Compressive strength at 3, 7, 28, 56, and 90 days was evaluated using cubes whereas beams were used to measure flexural strength of mixtures at 28 days. Furthermore, elevated temperatures resistance, chemical soundness, rapid chloride permeability, and ponding of concrete plates were performed to give an indication of the durability of the mixtures. In addition, the water purification potential of the Portland cement pervious concrete was tested using a common pollutant and bacteria.

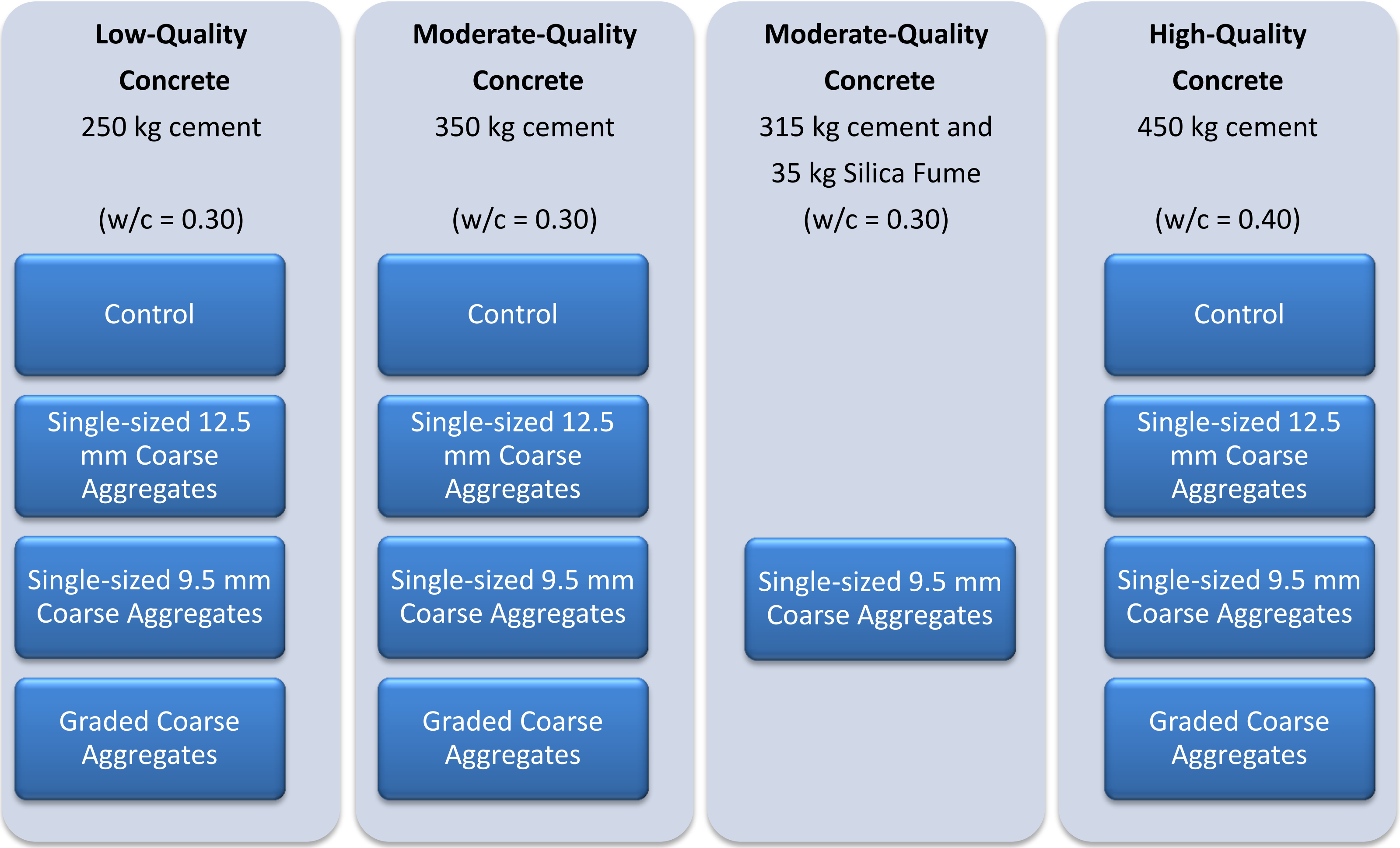


Figure 3.1 Breakdown of concrete mixtures prepared

3.2 Materials

Materials consumed within this experimental program (cement, coarse aggregates, fine aggregates, silica fume, plasticizer, and superplasticizer) were of local origin and have been acquired from the Egyptian market. These elements can be summarized as follows:

3.2.1 Portland Cement

Ordinary Portland Cement Type I was used in the preparation of the concrete mixtures for this study. The cement was procured from “Tourah Cement Company”, CEM I 42.5 R, manufactured according to the Egyptian standards ES 4756/1-2007 and complies with ASTM CI50. The physical, mechanical, and chemical properties of the type I Portland cement used are illustrated in Table 3.1.

Table 3.1 Physical, mechanical, and chemical properties of Portland cement

Property	Test Result	Product Data	ASTM C 150	Standard
Physical & Mechanical Properties				
Normal Consistency	23.10 %	-		ASTM C 187
Blaine Fineness	361.3 m^2/kg	-	280 m^2/kg	ASTM C 204
Setting Time				ASTM C 191
Initial Set	1 hrs., 29 min	≥ 60 min	> 45 min	
Final Set	2 hrs., 15 min	-	< 6 hrs., 15 min	
Specific Gravity	3.15	-	3.14 - 3.16	ASTM C 188
Compressive Strength				ASTM C 109
3 Days	21.0 MPa	≥ 20 MPa	12.4 MPa	
7 Days	28.4 MPa	-	19.3 MPa	
28 Days	-	≥ 42.5 MPa	N/A	
Soundness	-	≤ 10		
Chemical Properties				
Loss on Ignition	-	≤ 5%		
Insoluble Residue	-	≤ 5%		
Sulphate (SO_3)	-	≤ 4%		
Chloride Content	-	≤ 0.1%		

Product Data Sheet, 2008 Suez Cement Copyright, http://www.suezcement.com.eg

3.2.2 Silica Fume

Silica fume from Sika Company was used with an average SiO_2 content of 92%. Chemical composition and physical properties of silica fume are shown in the following Table 3.2 after Abou-Zeid (1990).

Table 3.2 Typical properties of silica fume Abou-Zeid (1990)

Chemical Composition	**% Weight**	
	From	**To**
SiO_2	90	94
C	0.8	2
Fe_2O_3	0.3	1
$A1_2O_3$	0.2	0.6
Na_2O	0.8	1.8
K_2O	1.5	3.5
MgO	0.3	3.5
S	0.2	0.4
Physical Property	**Value**	
Color	Light grey	
Specific Weight	2.2 t/m^3	
Volume wt. Uncompacted	0.15 - 0.3 t/m	
Volume wt. Compacted	0.4 - 0.6 t/m	
Specific Surface	20 m^2/g	
Particle Size (guiding values)	20% < 0.05 microns 70% < 0.10 microns 95% < 0.20 microns 99% < 0.50 microns	

3.2.3 Fine Aggregates

Natural sand brought from “Premix Company” Batch Plant, located at Mokkattam, was used for the three Control mixtures. The sand had a fineness modulus of 2.88 and a bulk specific gravity of 2.50. The measured absorption was 1.3%. Sieve Analysis for the Fine Aggregates was conducted according to ASTM C 33; the results realized are tabulated in Table 3.3 and illustrated in Figure 3.2.

Table 3.3 Sieve analysis results for fine aggregates

Sieve No./Size		Tested Fine Aggregate	% Passing Cumulative ASTM C 33 Limits Min (%)	ASTM C 33 Limits Max (%)
# 4	4.75 mm	99.0	95.0	100.0
# 8	2.36 mm	86.0	80.0	100.0
# 16	1.18 mm	66.0	50.0	85.0
# 30	0.6 mm	41.0	25.0	60.0
# 50	0.3 mm	14.0	10.0	30.0
# 100	0.15mm	5.0	2.0	10.0
# 200	0.075mm	0.6	-	3.0

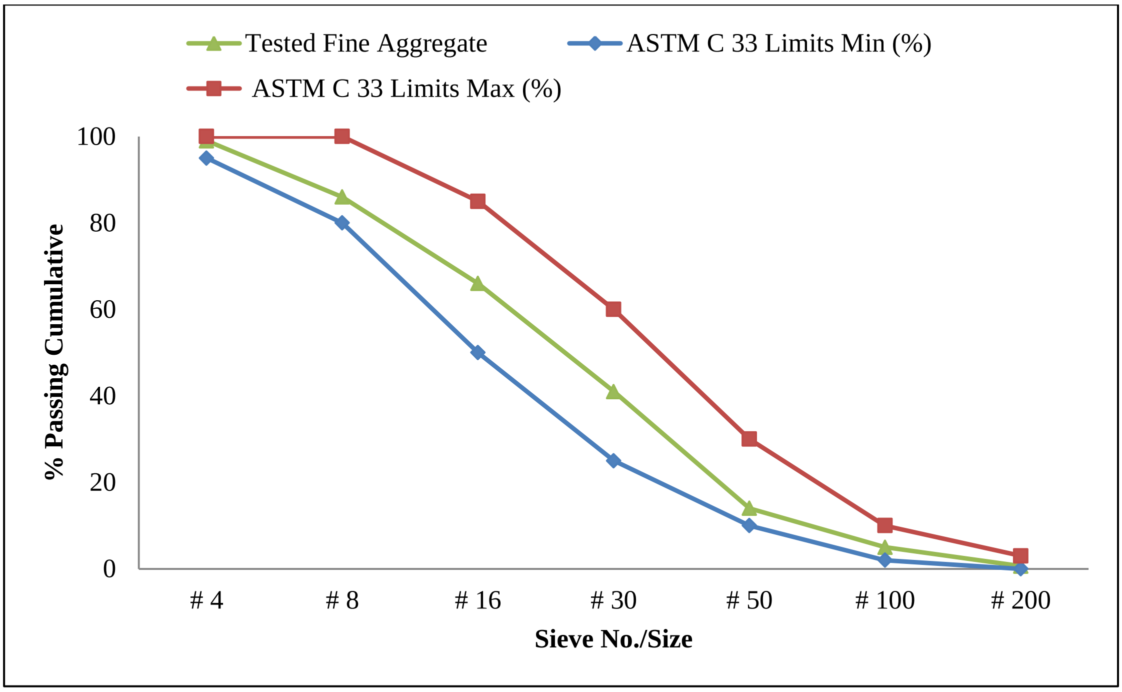


Figure 3.2 Sieve analysis for fine aggregates

3.2.4 Coarse Aggregates

Crushed dolomite acquired from “Premix Company” Batch Plant, located at Mokkattam, was used during the course of the experimental work of this study. In the Egyptian market, it is a trend to identify coarse aggregate as “size 1” or size 2”.

Coarse Aggregate “1” and “2” had a bulk specific gravity of 2.54. The percentage absorption measured was 1.23%. Sieve Analysis for the Coarse

Aggregates was conducted according to ASTM C 33; the results realized are tabulated in Table 3.4 and

Table 3.5 and illustrated in Figure 3.3 and Figure 3.4 for coarse aggregates types “1” and “2” respectively.

Nonetheless, the natural gradation of coarse aggregates is considered of minor significance for this study as it is one of the factors investigated. Three gradations were used to investigate the effect of the particle size distribution on the properties and durability of Pervious Portland Cement Concrete. The first and second gradation schemes utilized were single-sized coarse aggregates retained on 1/2 in (12.5 mm) sieve and 3/8 in (9.5 mm) sieve respectively. The third scheme utilized Coarse Aggregate “1” as is. Accordingly, upon the procurement of the aggregate materials from their sources, they were sieved to separate the aggregate according to particle sizes 12.5 mm and 9.5mm.

Table 3.4 Sieve analysis results for coarse aggregates type ‘1”

Sieve No./Size		% Passing Cumulative		
		Tested Coarse Aggregate 1	ASTM C 33 Limits Min (%)	ASTM C 33 Limits Max (%)
3/4 in	19 mm	100.0	100.0	100.0
1/2 in	12.5 mm	94.0	90.0	100.0
3/8 in	9.5 mm	57.0	40.0	70.0
# 4	4.75 mm	11.0	-	15.0
# 10	2 mm	2.0	-	5.0
# 200	0.075 mm	0.1	-	1.0

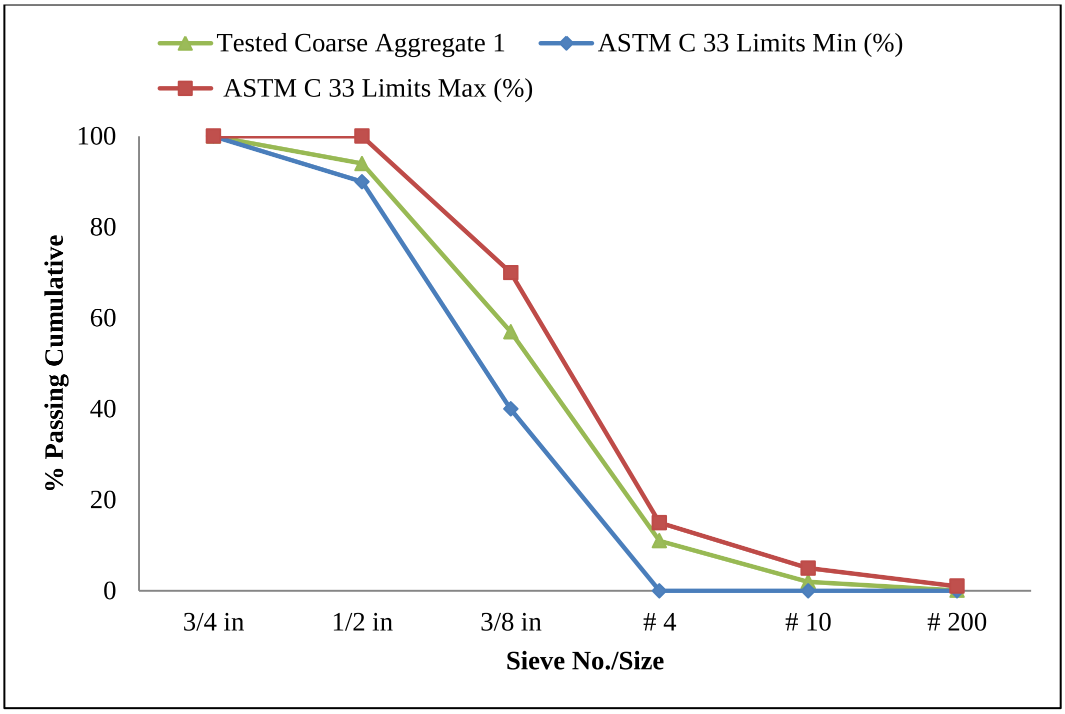


Figure 3.3 Sieve analysis for coarse aggregates type “1”

Table 3.5 Sieve analysis results for coarse aggregates type ‘2”

Sieve No./Size		% Passing Cumulative Tested Coarse Aggregate 2	ASTM C 33 Limits Min (%)	ASTM C 33 Limits Max (%)
1.5 in	38 mm	100.0	100.0	100.0
1.0 in	25 mm	94.0	90.0	100.0
3/4 in	19 mm	72.0	40.0	85.0
1/2 in	12.5 mm	36.0	10.0	40.0
3/8 in	9.5 mm	14.0	-	15.0
# 4	4.75 mm	3.0	-	5.0
# 200	0.075 mm	0.5	-	1.0

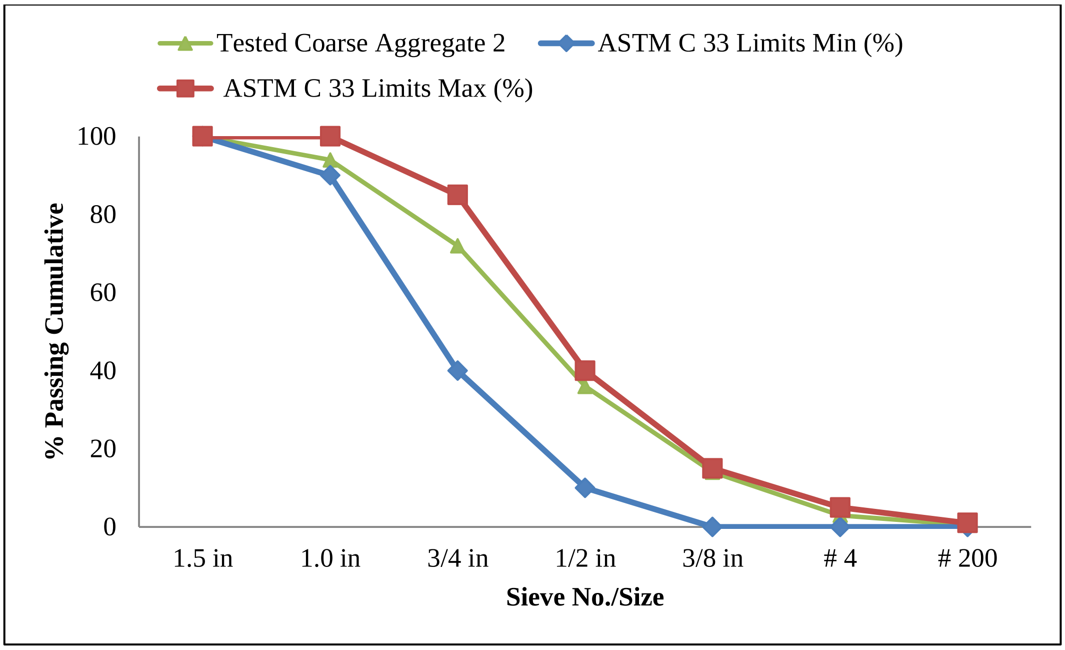


Figure 3.4 Sieve analysis for coarse aggregates type "2"

3.2.5 Chemical Admixtures

To enhance workability of Portland cement pervious concrete mixtures, a plasticizer was used for mixtures with w/c of 0.30 while a superplasticizer was used for mixtures with w/c of 0.40. The chemical used, Sikament®163, was procured from Sika Company. Sikament®163 is a highly effective water-reducing agent and superplasticizer complying with ASTM C494 Type F and B.S.5075 Part 3 1983 for superplasticizer with an approximate density of 1.17 kg/L. The dual action Sikament®163 promotes accelerated hardening with high early and ultimate strengths.

Sikament®163 was dosed at 0.6% by weight of cement to act as a plasticizer for mixtures with w/c of 0.30 and 1.5% by weight of cement to act as a superplasticizer for mixtures with w/c of 0.40; it was added to the mixing water prior to its addition to the aggregates.

3.2.6 Water

Cairo's municipal tap water was utilized during the entire experimental program for mixing and curing concrete and for testing.

3.2.7 Pollutants

The Clean Air Act requires EPA to set National Ambient Air Quality Standards for six common air pollutants. These universally found pollutants are particle pollution, ground-level ozone, carbon monoxide, sulfur oxides, nitrogen oxides, and lead as per the U.S. Environmental Protection Agency (EPA). These pollutants are harmful to human wellbeing and the environment, and may also cause property damage. For the purpose of this study, Lead was used to test the potential of Portland cement pervious concrete for purification water from pollutants.

The potential of Portland cement pervious concrete for filtration of bacteria is examined since bacteria is always present in organic materials and waste washed out by storm water or rains. The coliform source used was a random sample of waste water from a manhole at the American University in Cairo.

Used vehicle oil was used to measure the potential of PCPC to purify water including oil/grease. Moreover, the pH of the testing water was altered to reach 5.5 to resemble the PH of acid rain so as to examine the potential of PCPC to raise the pH of water.

3.3 Mix Designs

As discussed in section 3.1, Thirteen mixtures were prepared in three categories with total cement content of 250, 350, and 450 kg/m^3 those three categories represent poor-quality, medium-quality, and high-strength concrete mixtures used in the construction industry. Mixtures under each category where prepared using 12.5mm, 9.5mm, and graded coarse aggregates of size “1” with no fine aggregates. Two water/cement (w/c) ratios (0.30 and 0.40) were used. Three mixtures, one under each category, were prepared with fine aggregates to stand as the control mixture or the bench mark of this investigation. One mixture was prepared with 10% silica fume to explore the effect of silica fume on the Portland cement pervious concrete. Plasticizer and superplasticizer were used for mixtures with w/c of 0.30 and 0.40

respectively to improve the workability of the Portland cement pervious concrete. Table 3.6 presents the weight proportions of the mixtures used.

The Mixture I.D. could be elaborated as follows: The first part is either "250" for cement content 250 kg/m^3, "350" for cement content 350 kg/m^3, "350S" for cement content 350 kg/m^3 including silica fume, or "450" for cement content 450 kg/m^3. The second part is "C", "12.5", "9.5", or G representing Control mixture (including fine and graded coarse aggregates size), single-sized coarse aggregates size 12.5mm, single-sized coarse aggregates size 9.5mm, or graded coarse aggregate size "1" respectively. The last part is "N", "P", or "SP" representing no admixtures, plasticizer, or superplasticizer respectively.

3.4 Experimental Program

The experimental program can be grouped into five main categories as follows: (1) constituent materials testing, (2) fresh concrete testing, (3) hardened concrete testing, (4) long-term properties' (durability) testing, and (5) environmental (Water purification potential).

3.4.1 Aggregate Testing

Coarse and fine aggregates used for the experimental program in hand have been tested in accordance with the ASTM standard specifications for the following tests listed in Table 3.7.

Table 3.6 Concrete mixture proportions

Mixture I.D.	Water (kg)	Air Content (%)	w/c	Portland Cement (kg/m^3)	Silica Fume (kg/m^3)	Fine Aggregate (kg/m^3)	Coarse Aggregate (kg/m^3)	c/a	Plasticizer (kg/m^3)	Superplasticizer (kg/m^3)	Additional Water (Absorption)
250-C	75	2	0.3	250	0	756	1329	0.12	0	0	25.65
250-12.5-N	75	20	0.3	250	0	0	1640	0.15	0	0	20.17
250-9.5-N	75	20	0.3	250	0	0	1640	0.15	0	0	20.17
250-G-N	75	20	0.3	250	0	0	1640	0.15	0	0	20.17
350-C	105	2	0.3	350	0	689	1240	0.18	0	0	23.73
350-12.5-P	105	20	0.3	350	0	0	1483	0.24	2.1	0	18.24
350-9.5-P	105	20	0.3	350	0	0	1483	0.24	2.1	0	18.24
350S-9.5-P	105	20	0.3	315	35	0	1483	0.21	2.1	0	18.24
350-G-P	105	20	0.3	350	0	0	1471	0.24	2.1	0	18.09
450-C	180	2	0.4	450	0	593	1067	0.27	0	0	20.42
450-12.5-N	180	20	0.4	450	0	0	1212	0.37	0	0	14.91
450-9.5-SP	180	20	0.4	450	0	0	1212	0.37	0	6.75	14.91
450-G-N	180	20	0.4	450	0	0	1212	0.37	0	0	14.91

Table 3.7 Aggregate testing ASTM standard references

Standard Test Method for	Active ASTM Standard
Sieve Analysis of Fine and Coarse Aggregates	**ASTM C136 - 06**
Materials Finer than 75 µm (No. 200) Sieve in Mineral Aggregates by Washing	**ASTM C117 - 04**
Clay Lumps and Friable Particles in Aggregates	**ASTM C142 / C142M - 10**
Density, Relative Density (Specific Gravity), and Absorption of Fine Aggregate	**ASTM C128 - 07a**
Test Method for Density, Relative Density (Specific Gravity), and Absorption of Coarse Aggregate	**ASTM C127 - 07**

3.4.2 Portland Cement Testing

Ordinary Portland cement has been tested in accordance with the ASTM standard specifications for the following properties listed in Table 3.8.

Table 3.8 Portland cement testing ASTM standard references

Standard Test Method for	Active ASTM Standard
Amount of Water Required for Normal Consistency of Hydraulic Cement Paste	**ASTM C187 - 11e1**
Time of Setting of Hydraulic Cement by Vicat Needle	**ASTM C191 - 08**
Density of Hydraulic Cement	**ASTM C188 - 09**
Fineness of Hydraulic Cement by Air Permeability Apparatus	**ASTM C204 - 11**
Strength of Hydraulic Cement Mortars (Using 2 in. or [50 mm] Cube Specimens)	**ASTM C109 / C109M - 11a**

3.4.3 Concrete Preparation

A conventional drum mixer was utilized for concrete mixing. The drum mixer had a capacity of 0.06 m^3 but due to the low workability of Portland cement pervious concrete mixtures and the status of the mixer, a maximum volume of 0.035 m^3 was prepared per round.

The ingredients; coarse aggregates, cement, fine aggregates (if any), silica fume (if any) were mixed together in their dry condition for 5 minutes. To eliminate dusting while mixing, half the portion of the aggregates was placed under the cement and the other half above the cement before dry mixing. Water was then added gradually while the mixing process continued for an additional 5 minutes. If the mixture was to include a plasticizer/superplasticizer, Sikament®163 was dosed and added to the mixing water prior to its addition to the aggregates as per the manufacturer's recommendation on the product data sheet.

Immediately upon completion of the mixing process for concrete, concrete was poured in oil-brushed molds as illustrated in Figure 3.5.

Due to the nature of Portland cement pervious concrete mixtures, low workability, heavy vibration might cause segregation. Thus, the molds were heap-filled and then placed on the vibrating table where low intensity vibration took place for 15 seconds. The molds were left intact for 24 hours as shown before they were disassembled. The concrete specimens were then kept in the curing room until they became ready for testing.

Figure 3.5 Different specimens cast for each mixture

3.4.4 Fresh Concrete Testing

Immediately after mixing, fresh concrete properties including Slump, temperature, air content, and unit weight were tested according to ASTM standards as per Table 3.9.

Table 3.9 Fresh concrete testing ASTM standard references

Standard Test Method for	Active ASTM Standard
Slump of Hydraulic Cement Concrete	**ASTM C143 / C143M - 10a**
Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete	**ASTM C138 / C138M - 10b**
Temperature of Freshly Mixed Hydraulic Cement Concrete	**ASTM C1064 / C1064M - 11**
Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method	**ASTM C231 / C231M - 10**

3.4.5 Hardened Concrete Testing

Mechanical properties of hardened concrete were investigated through studying compressive strength of cubes at 3, 7, 28, 56 and 90 days and flexural strength of beams at 28 days as per the following standards.

- Compressive strength tests of concrete cubes were conducted at 3, 7, 28, 56, and 90 days according to BS 1881-116:1983 “Testing Concrete; Method for Determination of Compressive Strength of Concrete Cubes” on the ELE compressive testing machine with a maximum capacity of 3000 KN.
- Flexural strength of concrete beams was conducted at 28 days according to ASTM C78 / C78M - 10 “Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)” using the ELE Machine.

3.4.6 Durability Testing

Long term properties/durability of Portland cement pervious concrete Durability performance was studied through the following tests: (1) Rapid Chloride

Permeability Test according to ASTM C1202 - 10 “Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration”, (2) Chemical Soundness of Concrete, (3) Elevated Temperature Resistance (using standard cubes after 90-days compressive strength), (4) water permeability, and (5) Ponding test according to ASTM C1543 - 10a “Standard Test Method for Determining the Penetration of Chloride Ion into Concrete by Ponding”.

Indication of Concrete's Ability to Resist Chloride Ion Penetration

Rapid Chloride Permeability Test (RCPT) is the common name for the test conducted to electrically indicate the concrete's ability to resist chloride ion penetration. According to ASTM C1202 - 10 concrete specimens are subjected to a 60 V applied DC voltage for 6 hours using the apparatus and the cell arrangement shown in Figure 3.6.

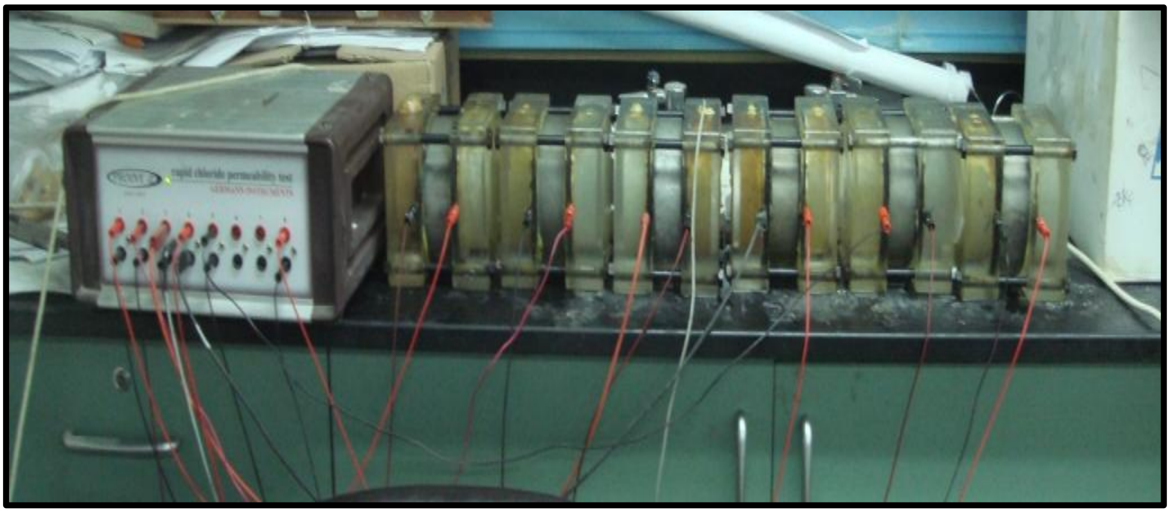


Figure 3.6 RCPT Apparatus

Three 56-days old standard cylindrical concrete specimens (50 mm thick and 100 mm diameter) for each of the thirteen concrete mixtures were prepared using a cutting machine; original molds were 70 mm thick, as shown in Figure 3.7. It is worth mentioning that the cutting process involved spraying water during the cutting process to facilitate cutting and eliminate dust. The specimens were then water-saturated and set up in the apparatus as shown in Figure 3.8 and Figure 3.9. The apparatus accommodates 8 cells per run, however 2 cells were out of order at the time the test was conducted. Thus, the test was planned to be performed on two mixtures at a time.

The apparatus, shown in Figure 3.6, includes cells in which the water-saturated concrete specimens are tightly attached to two reservoirs one containing a 3.0% NaC1 solution (positive pole) and the other containing a 0.3 N NaOH solution (negative pole). The poles are connected to a control unit which is consecutively linked to a computer. "PROOVE IT" is the computer software regulating the test (starting/shutting down the cells, recording results, and producing a final test/result report). The total charge passed is determined and this is used to rate the concrete according to the criteria included as shown in Table 3.10 as per ASTM C1202 - 10 (The better/less porous the concrete, the less passing charges recorded in coulombs signifying low permeability categorization).

Table 3.10 Chloride ion penetrability based on charge passed

Charge Passed (Coulombs)	Chloride Ion Penetrability
> 4,000	High
2,000 - 4,000	Moderate
1,000 - 2,000	Low
100 - 1,000	Very Low
< 100	Negligible

Figure 3.7 Cutting specimen

Figure 3.8 Vacuum Saturation of Specimen

Figure 3.9 Setting up RCPT Cells

Chemical Soundness of Concrete

Small concrete (5x5x5 cm) specimens were used for investigating the effect of the exposure of Portland cement pervious concrete to salts and acids. Two groups each composed of three samples from each concrete mixture, as per Figure 3.10, were exposed to chemicals. The first group was exposed to a 10% concentrated sulphuric acid (H_2SO_4) solution whereas the second set was exposed to a super-saturated solution of magnesium sulphate ($MgSO_4$).

Figure 3.10 Specimen sets prepared for chemical durability

For concrete specimens tested for vulnerability to acid, specimens are washed thoroughly to remove any dust or suspended matter. The samples are oven-dried for 24 hours at a temperature of 110℃, and then they are weighed and placed in containers where they will be submerged in the 10% concentrated sulphuric acid (H_2SO_4) solution for 28 days as can be seen in Figure 3.11. After 28 days, the samples are washed, oven-dried (for 24 hours at a temperature of 110℃), and reweighed to calculate the percentage loss in mass due to exposure to the acid.

The methodology adopted for testing chemical soundness against salts was slightly different. The concrete specimens were immersed in super-saturated magnesium sulphate solution for 18 hours as can be seen in Figure 3.12, after which they were drained, washed, oven-dried (for 24 hours at a temperature of 110℃), and re-immersed in the solution. This cycle was repeated 5 times, after the fifth cycle the samples are dried to constant weight and the mass loss resulting from the chemical exposure is calculated.

Figure 3.13 illustrate concrete specimen submerged in acid after seven days while Figure 3.14 shows samples after the first cycle of immersing in salt. while Figure 3.15 illustrate the final visual inspection of the samples just before they are weighed after the test is performed.

Figure 3.11 Specimens immersed in acid

Figure 3.12 Specimens immersed in salt

Figure 3.13 Specimen submerged in acid for 7 days

Figure 3.14 Specimen washed after first salt cycle

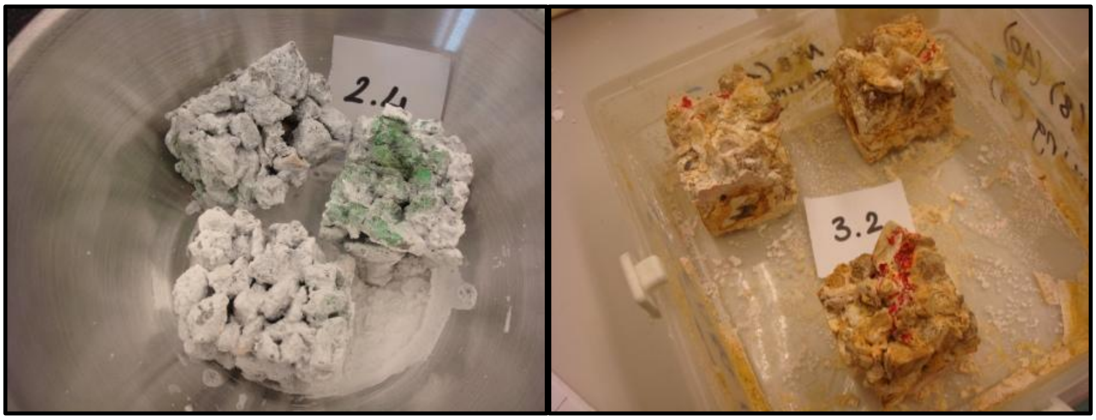


Figure 3.15 Cubes after chemical durability test

Resistance of concrete to exposure to elevated temperature

The objective of this test was to explore the effect of exposure to elevated temperatures on the compressive strength of Portland cement pervious concrete to determine whether a specific Portland cement pervious concrete mixture design would yield better resistance to elevated temperatures. Three samples from each concrete mixture (90-days old) were exposed to heat for eight hours at 500^0C. The oven was allowed to cool down over night to avoid any cracking in the specimens due to sudden cooling thus making it impractical to perform the compressive strength test. Visual inspection was conducted in order to describe any noticeable remarks on the heated/burnt cubes. The compressive strength was then conducted as per BS 1881-116:1983.

Water Permeability of Portland cement pervious concrete

Due to the fact that pervious concrete is a special type of concrete with a high porosity, typical permeability tests performed on conventional concrete, assuming conventional concrete was impermeable, was deemed unreliable. A simple experiment was designed to compare the porosity of different concrete mixtures studied.

Concrete plates (300 x 300 x 80 mm) were supported above a digital scale. 1000 mL of water were measured in a flask and poured through the concrete plate into a container on the scale. The time taken for the water to pass through the specimen was recorded via a stopwatch as can be seen in Figure 3.16. In order to eliminate the personal errors due to manually pouring the water, the stopwatch wasn't stopped except when the scale remained constant.

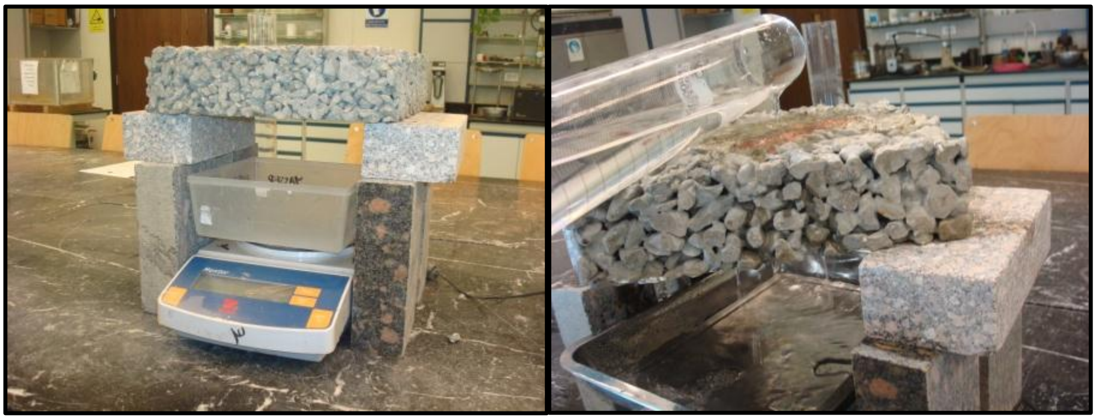


Figure 3.16 Apparatus designed to measure permeability

Penetration of Chloride Ion into Concrete by "Ponding"

Penetration of Chloride Ion into Concrete by Ponding was conducted according to ASTM C1543 - 10a. Concrete plates (300 x 300 x 80 mm) were cast and cured for 28 days. The top surface was bermed and ponded with a salt solution for 90 days. The samples are then crushed for the chloride content of each layer to be determined. Unfortunately, due to the high porosity of Portland cement pervious concrete mixtures, the test could not be conducted as the water passes through the plate and the salt solution level of, 15 cm, could not be maintained.

3.4.7 Water Purification Potential

The water purification potential of Portland cement pervious concrete was examined using Lead as a common pollutant and bacteria. One old standard cylindrical concrete specimen (70 mm thick and 100 mm diameter) for each of the ten Portland cement pervious concrete mixtures was prepared using a cutting machine;

original molds were 100 mm thick. It is worth mentioning that the cutting process involved spraying water during the cutting process to facilitate cutting, cool the cutting disc and eliminate dust. The specimen were then secured inside 100 mm diameter PVC pipes using silicon to avoid drainage of water through the sides as shown in Figure 3.17. Each sample was washed thoroughly using four liters of water to assure uniformity of results and eliminating purification due to absorption of the water as shown in Figure 3.18.

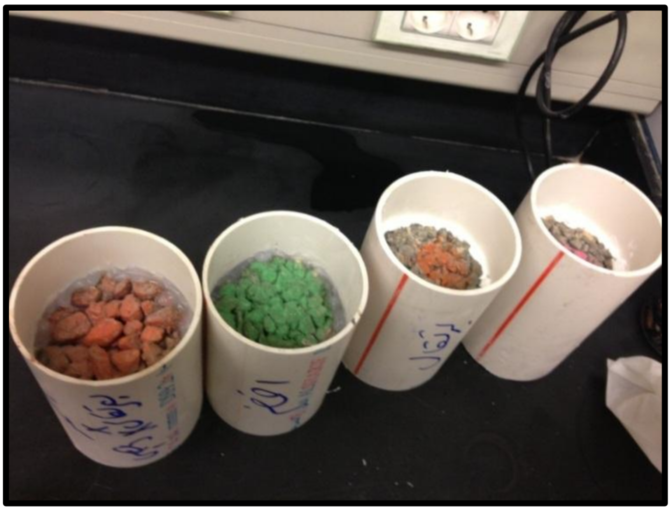


Figure 3.17 Specimen for testing water purification potential

Figure 3.18 Washing the specimen

For the first round of testing, four specimen where tested with a simulated water sample consisting of one liter of distilled water, 5 mg/lt. lead, and 5 ml of waste water (coliform source) was prepared. Because Lead added to the water is dissolved in nitric acid, the PH of the simulated water sample was found to drop to 2.6. The PH of the water was modified to 5.5 to resemble acid rain through adding sodium hydroxide solution as can be seen in Figure 3.19. A 100 ml raw sample was taken from the simulated water sample to act as the benchmark for pollutant contents. The simulated water was then passed through the specimen and a 250 ml sample of the water that passed through was then collected for testing the pollutant content after filtration through the Portland cement pervious concrete specimen.

The water samples were then analyzed to measure the Lead content, bacteria content, and pH before and after passing through the specimen. Figure 3.20 and Figure 3.21 illustrate the preparation of samples and the incubator for measuring bacteria content of water samples.

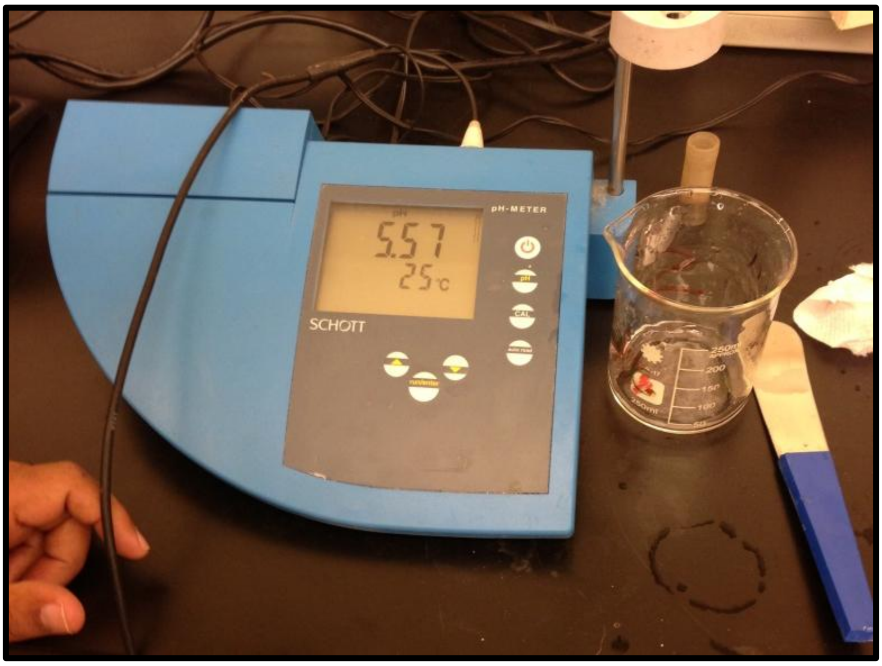


Figure 3.19 Measuring PH of the simulated water sample

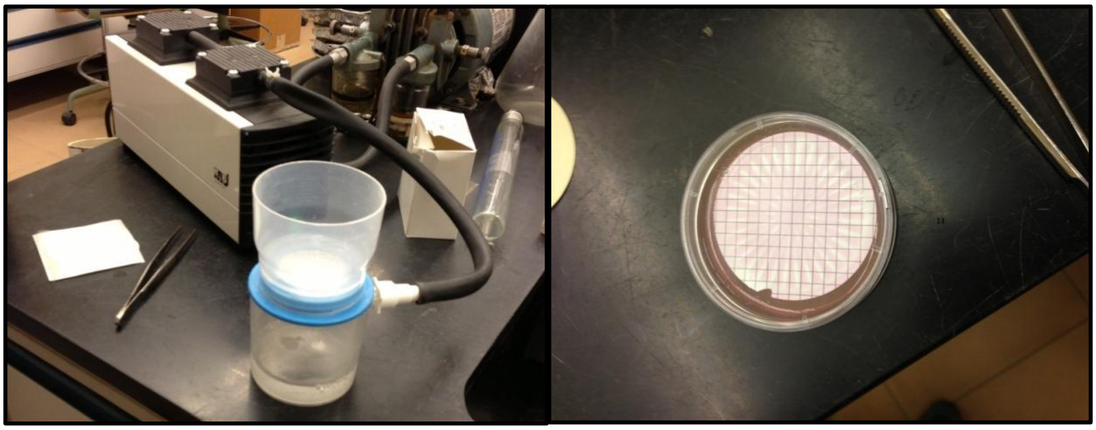


Figure 3.20 Preparation of media for measuring bacteria

Figure 3.21 Incubator for bacteria growth

After testing the four specimen illustrated in Figure 3.17 for water purification potential, the test was run again on all 10 PCPC mixtures using one liter of a simulated water sample containing 1 L of distilled water, 5 mg/L of lead (10 ml of lead standard solution 1000 mg/L concentration), 5 ml of used vehicle oil, and 20 ml of coliform source.

CHAPTER 4: RESULTS AND ANALYSIS

The conducted experimental work includes four major sections that comprise fresh concrete testing, hardened concrete testing, durability, and environmental control potential testing (Water purification potential). The results of the experimental work carried out are demonstrated and discussed in this chapter.

4.1 Fresh Concrete Properties

Fresh concrete properties have been evaluated to examine the effect of aggregate size and gradation, cement content, and water-to-cement ratio on the workability (slump), unit weight, air content, and temperature of concrete. In this section the results for fresh concrete properties tested are presented and discussed. Table 4.1 provides the results of these fresh concrete properties conducted on the fresh Portland cement pervious concrete samples of the various concrete mixtures designed in this study.

4.1.1 Workability

The results of the slump tests are listed in Table 4.1 and illustrated in Figure 4.1 and Figure 4.2 for each of the thirteen mixtures with different cement contents, water-to-cement ratios, and aggregate sizes and gradations.

Normally the slump test is suitable for slumps of medium to high workability; slump in the range of 25 – 125 mm, the test fails to determine the difference in workability in stiff mixtures which have zero slumps, or for wet mixtures that give a collapse slump. It can be seen in Figure 4.1 that nine of the thirteen mixtures have fallen between a range of 0 and 25 mm and one mixture 450-9.5-SP gave a collapse slump. Only three mixtures had a slump in the medium to high workability range of 25 – 125 mm.

Table 4.1 Fresh concrete properties

Mix ID	Aggregate Size	Portland Cement (kg)	Silica Fume (kg)	w/c	Admixtures	Slump (mm)	Unit Weight (kg/m^3)	Fresh Concrete Air Content (%)	Temperature of Fresh Concrete (^{0}C)	
									Room Temp.	Mix Temp.
250-C	Control	250	-	0.30	-	0	1798	3.3	22	25
350-C		350	-	0.30	-	0	1964	5.7	23	26
450-C		450	-	0.40	-	25	2320	4.2	22	25
250-12.5-N	Single-sized 12.5 mm CA and No Fines	250	-	0.30	-	115	1513	0.5	23	25
350-12.5-P		350	-	0.30	Plasticizer	120	1940	2.4	24	25
450-12.5-N		450	-	0.40	-	20	2013	3.8	23	25
250-9.5-N	Single-sized 9.5 mm CA and No Fines	250	-	0.30	-	0	1496	0.7	24	26
350-9.5-P		350	-	0.30	Plasticizer	0	1686	1.5	24	25
350S-9.5-P		315	35	0.30	Plasticizer	0	1667	1.6	24	26
450-9.5-SP		450	-	0.40	Superplasticizer	220	2063	3.5	24	25
250-G-N	Well Graded CA and No Fines	250	-	0.30	-	145	1547	1.7	24	25
350-G-P		350	-	0.30	Plasticizer	0	1616	1.0	24	27
450-G-N		450	-	0.40	-	10	2067	3.3	23	29

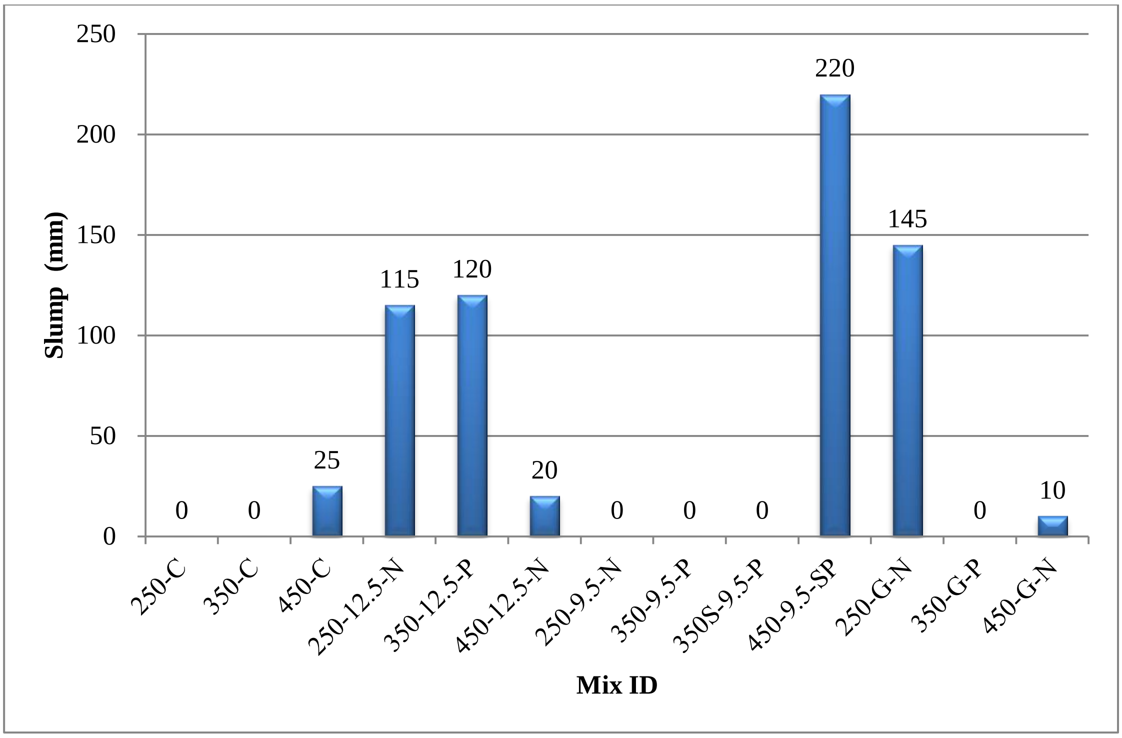


Figure 4.1 Slump of all concrete mixtures

However upon a closer inspection of the results it can be noticed that the two Portland cement pervious concrete mixtures which had a slump in the medium to high workability range of 25 – 125 mm included one-sized coarse aggregates of the larger size, 12.5 mm where the mixture with 350 kg of cement included a plasticizer. Also as can be seen, mixture 250-G-N gave a slump of 145 mm but this result cannot be attributed to a specific trend as mixtures with 250 kg cement are not generally expected to be very workable. The mixture that give a collapse slump, 450-9.5-SP, included a Superplasticizer in addition to a w/c ratio of 0.40.

It is also worth mentioning that even the control mixtures gave zero slump with the exception of mixture 450-C which yielded a 25 mm slump. Control mixtures with 250 kg cement content and 350 kg cement content both had a water-to-cement ratio of 0.3 and well graded coarse and fine aggregates. Portland cement pervious concrete mixtures were designed to represent poor quality, medium-quality, and high-strength concrete mixtures used in the construction industry which aligns with the results obtained for slump of the control mixtures being zero for dry poor quality and medium-quality mixtures and within range for the high-strength concrete although the medium-quality mixture should have produced a higher slump.

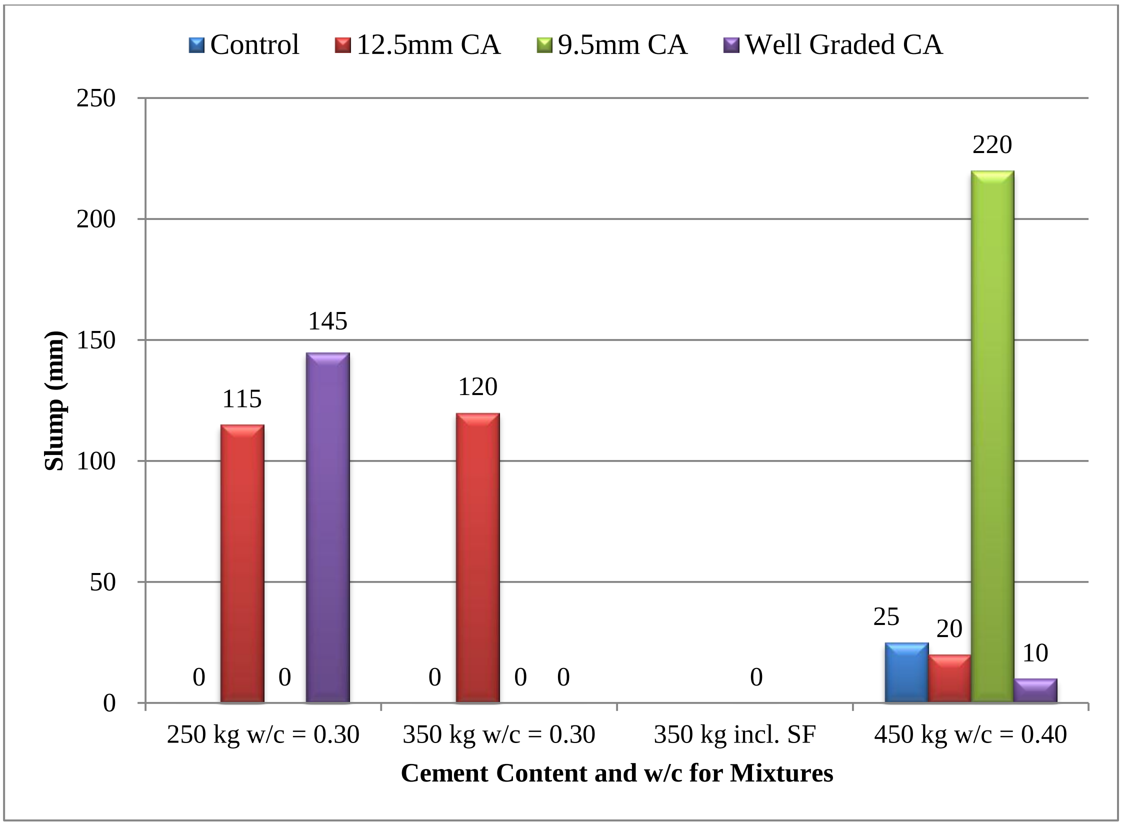


Figure 4.2 Slump classified by cement content of mixtures

Figure 4.3 illustrates one of concrete mixtures which gave a zero slump, while Figure 4.4 illustrates the mixture which gave a collapse slump.

In summary, the concrete produced is harsh with low workability and a slump as low as zero, and generally less than 25 mm. To increase workability of Portland cement pervious concrete, admixtures must be used but with caution to avoid very loose concrete which may segregate and/or thus loose the major advantage of being permeable.

Figure 4.3 Mixture with zero slump

Figure 4.4 Mixture with collapse slump

4.1.2 Temperature

Temperature is measured to determine conformance to temperature limits in a specification and is a required test when strength test specimens are prepared. It is permitted to measure the temperature of concrete in place when it is not measured in conjunction with strength tests. In general, the room temperature during mixing ranged between 22^0C to 24^0C whereas the temperature of fresh concrete ranged between 25^0C to 29^0C. As illustrated in Figure 4.5, all mixtures followed a very normal trend of a temperature just slightly higher than room temperature.

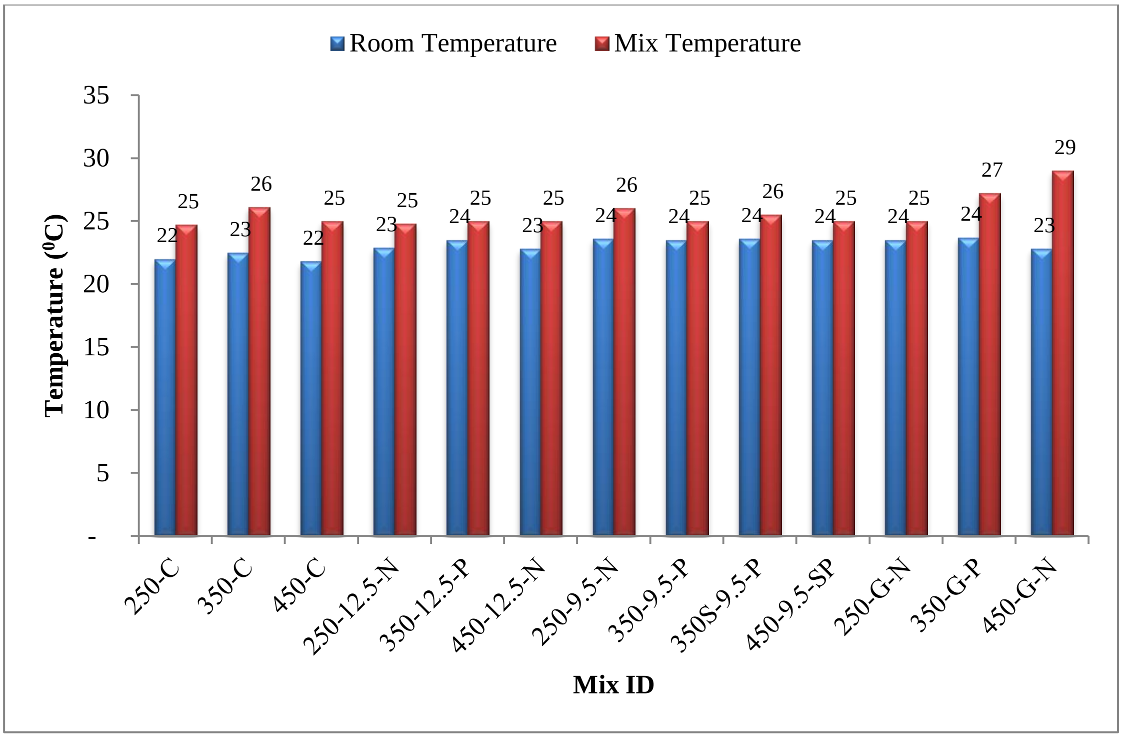


Figure 4.5 Temperature of fresh concrete

4.1.3 Unit Weight

The results of the unit weight are recorded in Table 4.1 and illustrated in Figure 4.6 through Figure 4.8 for the thirteen mixtures studied. Examining Figure 4.6, it can be observed that the unit weights range was between 1496 and 2067 kg/m^3 for all the ten Portland cement pervious concrete mixtures studied, which follow the conclusions made from the literature review, whereas the control mixtures yielded higher unit weights which ranged of 1798 to 20 kg/m^3.

It could be noticed from Figure 4.7 that there is a trend between the unit weight and the cement content of the concrete mixtures. As cement content increases, the unit weight increases for concrete samples with different sizes and gradations of coarse aggregates. For instance, the mixtures with 250 kg cement content has yielded unit weights ranging from 1496 to 1547 kg/m^3 whereas mixtures with 350 kg cement content yielded unit weights ranging from 1616 to 1940 kg/m^3 and the same applies to mixtures with 450 kg cement content which exhibited unit weights in the range of 2013 to 2067 kg/m^3.

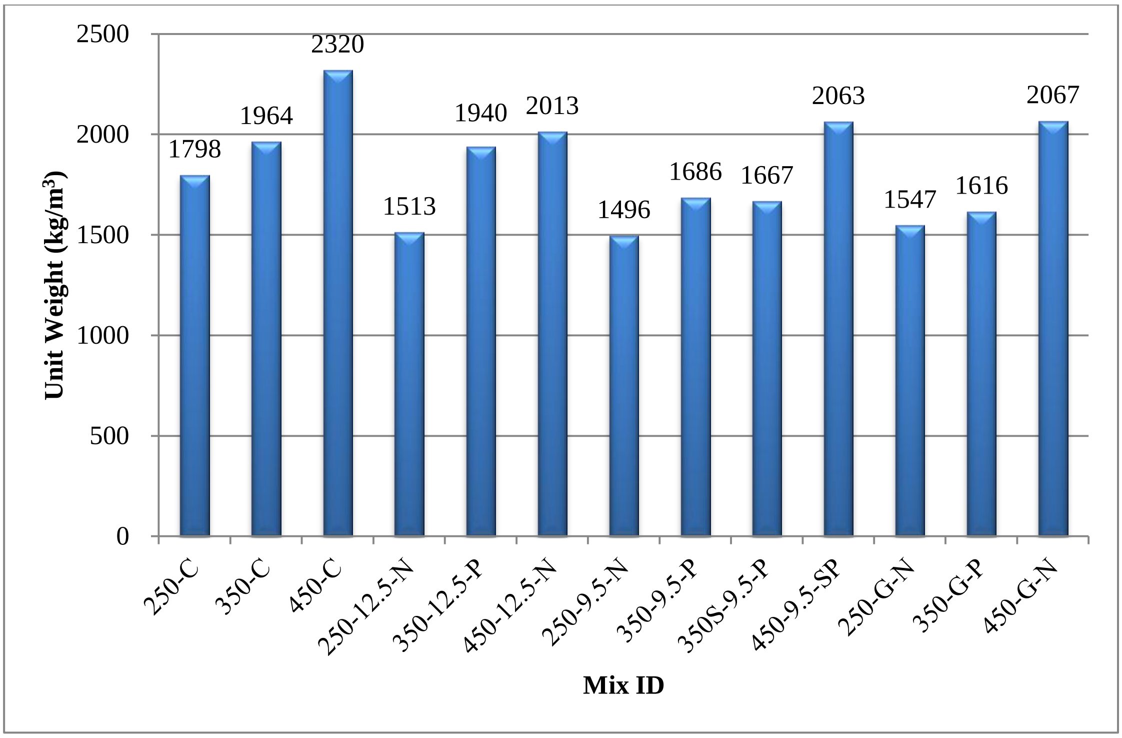
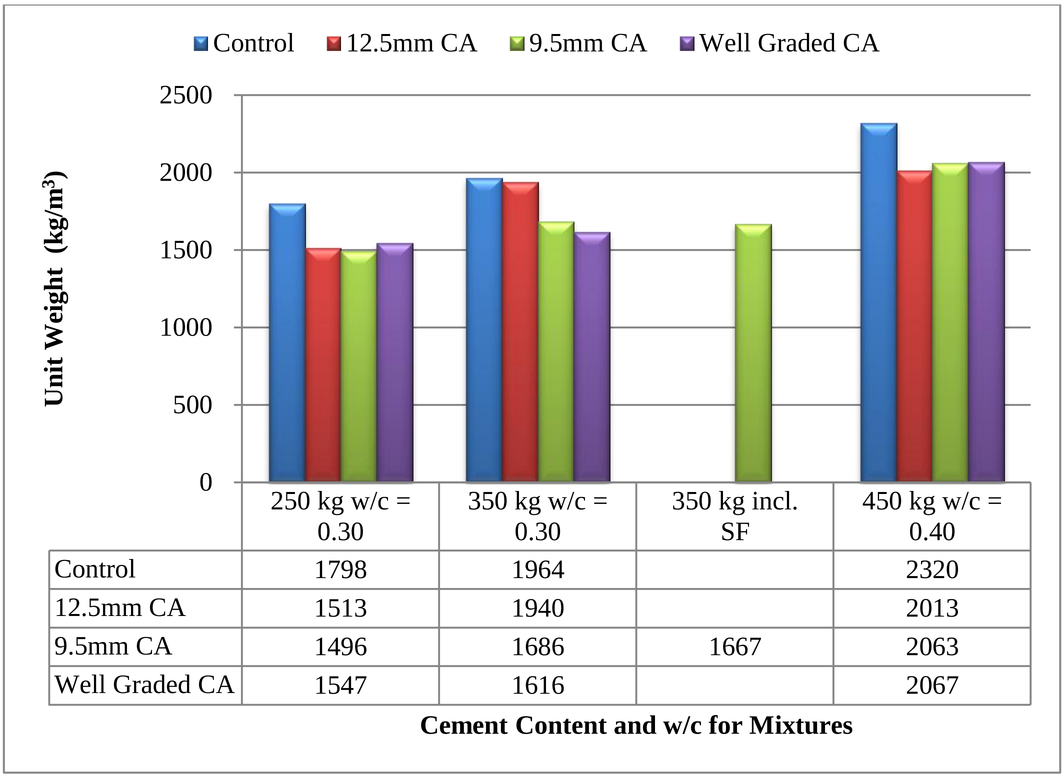


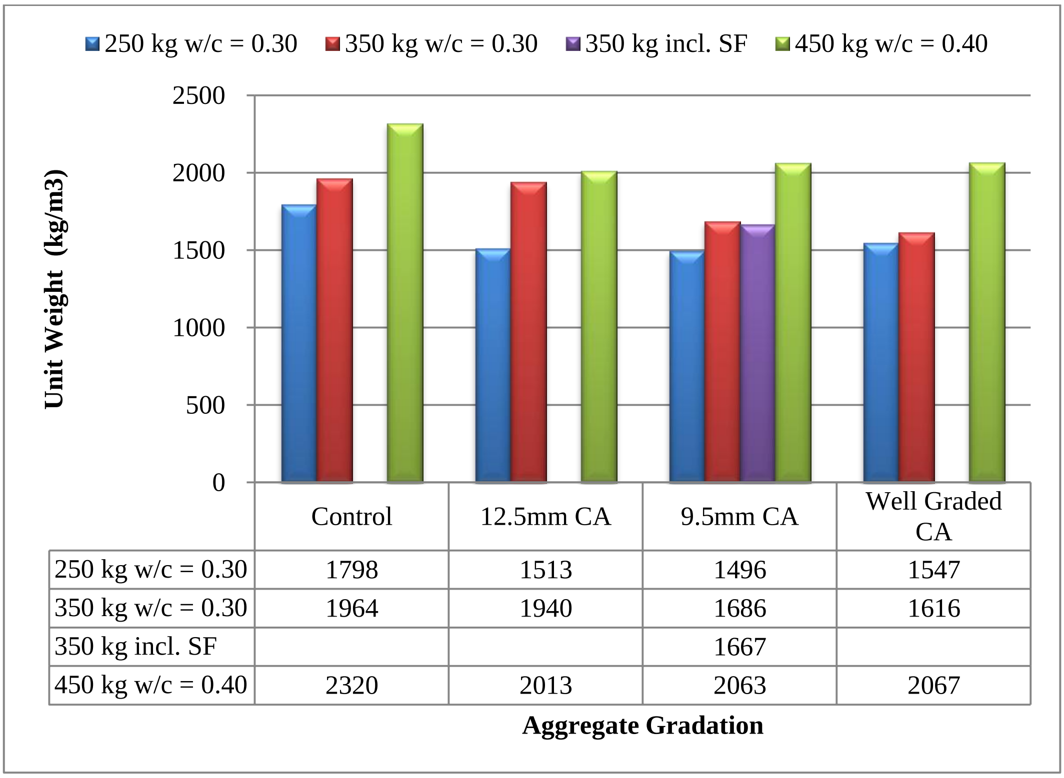
Figure 4.6 Unit weight of all concrete mixtures

Moreover, it is also noticeable from Figure 4.8, that the concrete mixtures with the same cement content with single-sized 12.5 mm coarse aggregates are heavier than the corresponding 9.5 mm concrete blends with the exception of the mixtures with 450 kg cement where the mixtures with single-sized 9.5 mm coarse aggregates are heavier than the corresponding 12.5 mm but with a negligible difference. For example, the mixture 350-12.5-P had a unit weight of 1940 kg/m^3 while the corresponding mixture with smaller sized aggregate 350-9.5-P had a unit weight of 1686 kg/m^3 at the same cement content.



	250 kg w/c = 0.30	350 kg w/c = 0.30	350 kg incl. SF	450 kg w/c = 0.40
Control	1798	1964		2320
12.5mm CA	1513	1940		2013
9.5mm CA	1496	1686	1667	2063
Well Graded CA	1547	1616		2067

Figure 4.7 Unit weight classified by cement content



	Control	12.5mm CA	9.5mm CA	Well Graded CA
250 kg w/c = 0.30	1798	1513	1496	1547
350 kg w/c = 0.30	1964	1940	1686	1616
350 kg incl. SF			1667	
450 kg w/c = 0.40	2320	2013	2063	2067

Figure 4.8 Unit weight classified by aggregate gradation

4.1.4 Air Content

The air contents of the fresh Portland cement pervious concrete samples of different mixtures are illustrated in Figure 4.9 through Figure 4.11. Air Content for Portland cement pervious concrete mixtures ranged between 0.5% and 3.8% whereas air content for the control mixtures ranged between 3.3% and 5.7% as can be realized from Figure 4.9.

On the whole, PCPC fresh concrete air content did not considerably differ from that of conventional concrete mixtures. Figure 4.10 demonstrates that the trends for air content follow that of unit weight, as cement content increases, the air content increases for concrete samples with different sizes and gradations of coarse aggregates. Figure 4.11 shows that the concrete mixtures with the same cement content with 12.5 mm coarse aggregates have higher air content than that of the corresponding mixture with 9.5 mm aggregates. Mixtures with well-graded aggregates displayed a lesser air content than that of both mixtures with 12.5 mm and 9.5 mm aggregates. For example, air content for mixtures 350-12.5-P, 350-9.5-P, and 350-G-P were 2.4%, 1.5%, and 1.0%. Similarly air contents for mixtures 450-12.5-N, 450-9.5-SP, and 450-G-N were 3.8%, 3.5%, and 3.3% respectively. Mixtures with cement content of 250 kg did not follow this trend; in fact the trend was reversed were mixtures 250-12.5-N, 250-9.5-N, and 250-G-N yielded 0.5%, 0.7%, and 1.7% respectively. Figure 4.11 also shows that the addition of silica fume did not significantly affect the air content of the mixture as the air content for 350-9.5-P was 1.5% while mixture 350S-9.5-P yielded 1.6%.

However, it is to be mentioned that this air content does not represent the measure of the void content resulting from the open-cell structure of Portland cement pervious concrete in the hardened state but rather represents the air content between the aggregate particles and the binding mortar.

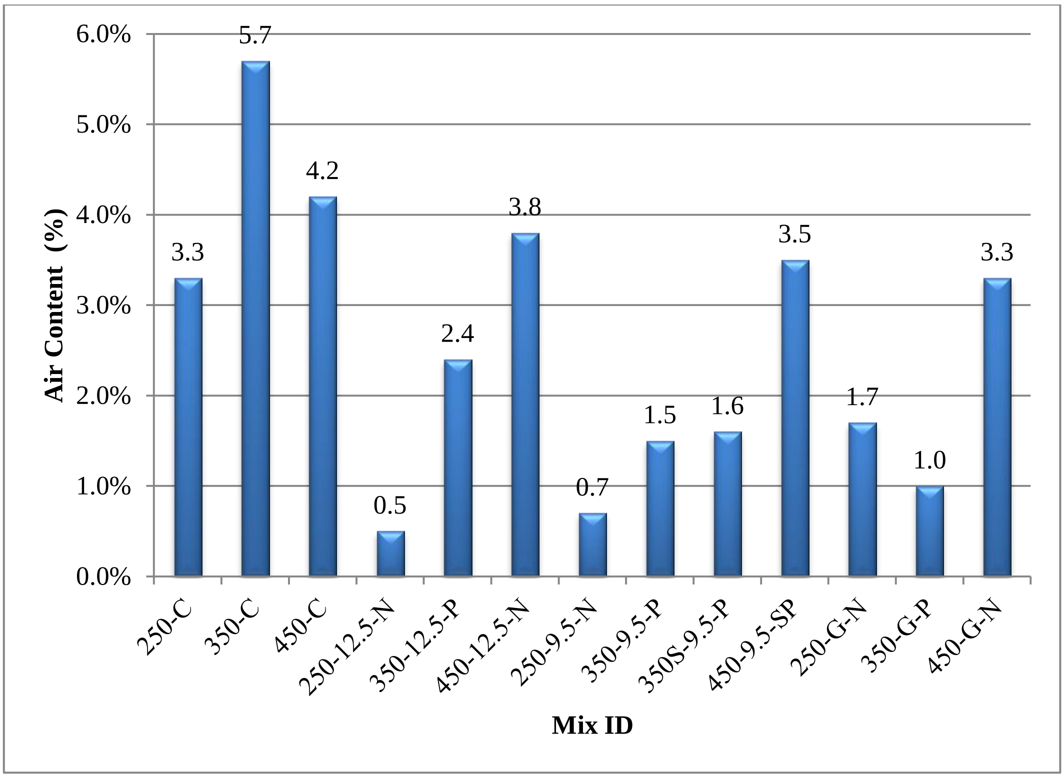


Figure 4.9 Air content of all concrete mixtures

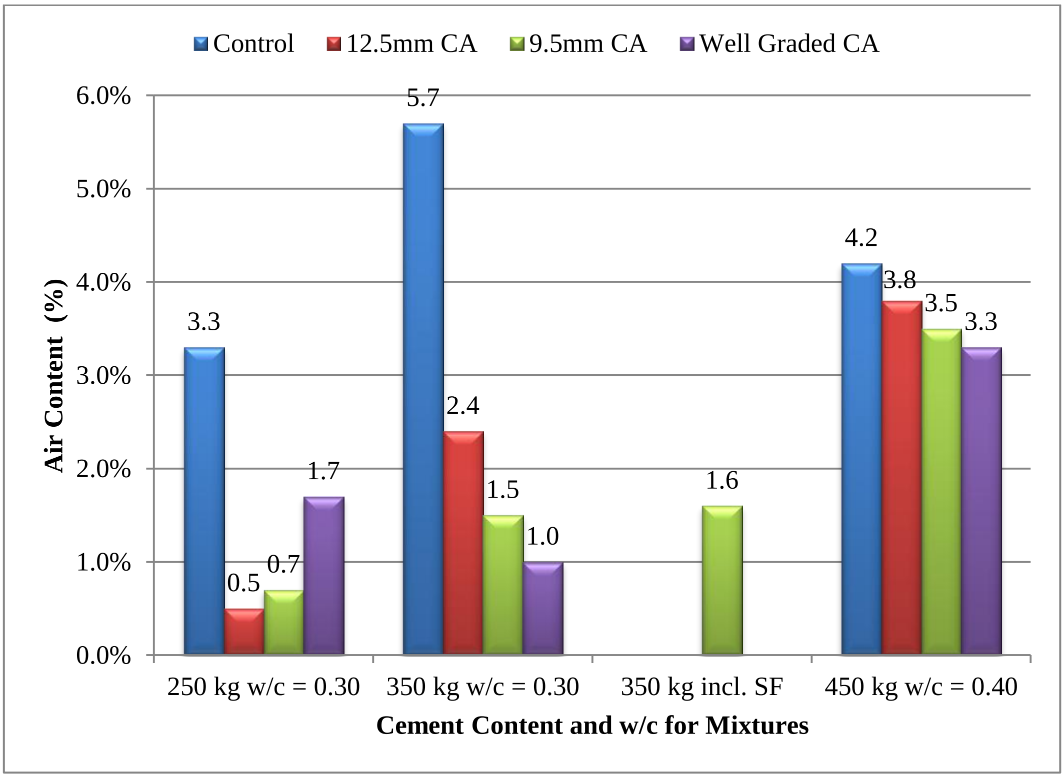


Figure 4.10 Air content classified by cement content

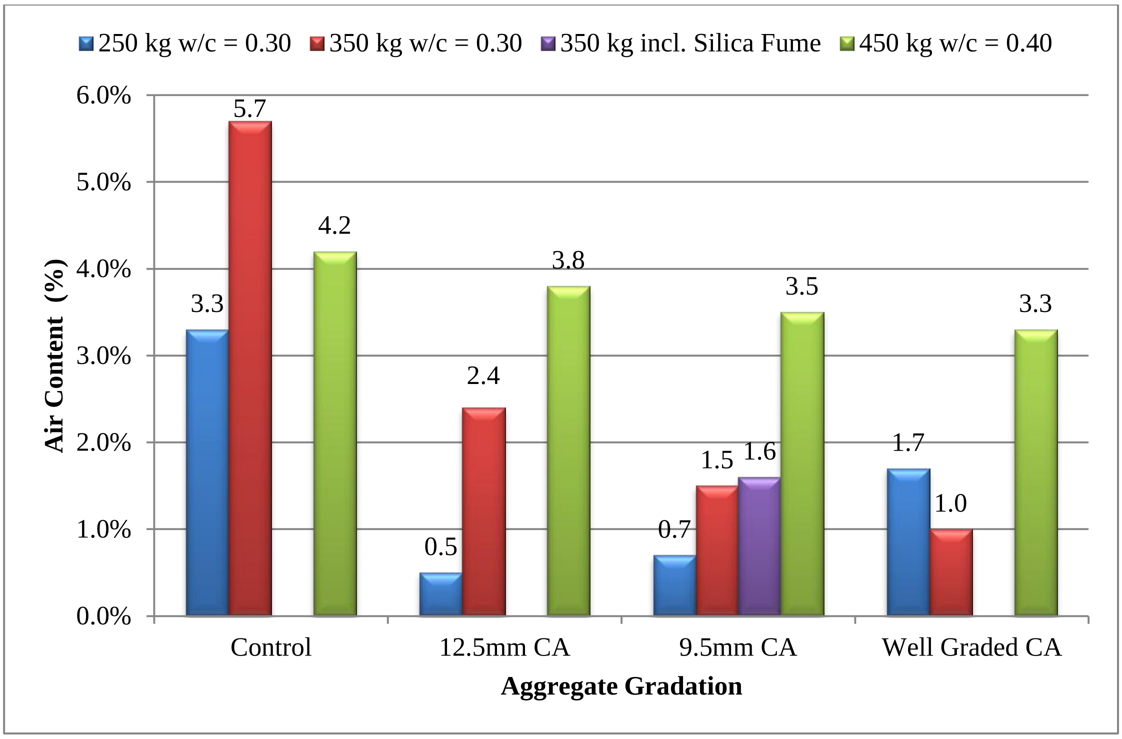


Figure 4.11 Air content classified by aggregate gradation

4.2 Hardened Concrete Properties

To study the influence of aggregate size and gradation, cement content, and w/c ratio on the hardened concrete properties, compressive strength of cubes and flexural strength of beams was investigated. In this section the results of hardened concrete tests are presented and discussed.

4.2.1 Compressive Strength

The average cube compressive strengths results at the ages of 3 ,7, 28, 56, and 90 days for all of the concrete mixtures are tabulated in Table 4.2 and Table 4.3 and studied in Figure 4.12 through Figure 4.18. The coefficient of variation represents the ratio of the standard deviation to the median.

At a glance, the results from Table 4.3 and Figure 4.12, the control mixtures prepared with low w/c ratios while including both coarse and fine aggregated were harsh mixtures that did not yield expected values for compressive strength. This may be attributed that the quantity of water was insufficient to provide full hydration.

Table 4.2 Compressive strength cube results and coefficient of variation

Mix ID	Compressive Strength Test Results																			
	3 Days				7 Days				28 Days				56 Days				90 Days			
	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV
250-C	5.9	7.6	0.6	33	6.6	20.6	0.7	20	6.8	33.6	1.2	21	6.8	57.9	2.8	7	6.8	38.2	2.0	12
	6.6	20.1			6.1	14.5			6.6	31.6			6.8	63.7			6.6	51.2		
	6.0	15.8			6.3	14.3			6.5	18.9			6.3	68.1			6.6	44.8		
250-12.5-N	5.5	28.0	1.8	39	5.6	47.2	1.8	11	5.4	50.6	2.3	5	5.3	36.9	2.4	29	5.3	95.8	3.2	29
	5.4	35.7			5.4	38.1			5.5	56.3			6.0	73.6			5.0	60.9		
	5.9	61.0			5.1	38.4			5.4	51.6			5.4	51.9			5.1	57.3		
250-9.5-N	4.6	12.6	0.4	36	5.0	17.9	0.7	19	3.9	15.7	0.8	11	4.9	20.3	1.0	7	4.6	20.6	1.0	3
	5.1	3.7			4.9	18.1			4.2	20.6			5.0	22.8			5.1	21.6		
	4.4	10.5			4.1	10.6			4.2	18.4			4.9	23.9			4.8	22.4		
250-G-N	4.9	17.5	0.8	17	4.1	3.7	0.3	53	4.5	19.3	1.1	20	5.0	19.9	1.0	5	5.0	20.3	1.0	12
	4.5	13.7			4.8	11.6			4.9	22.6			5.0	21.9			4.8	20.3		
	5.1	21.0			4.5	6.2			5.2	30.2			5.2	22.7			5.0	25.4		
350-C	7.2	88.7	2.8	33	6.7	72.0	3.5	6	6.9	124.8	5.3	20	6.4	79.0	6.7	28	7.1	178.0	6.4	18
	6.6	52.7			7.1	84.2			6.8	148.1			6.8	180.9			6.8	121.8		
	6.3	50.1			6.7	77.8			6.5	87.6			7.2	193.2			6.9	133.4		
350-12.5-P	6.7	178.8	8.3	13	6.6	214.9	10.2	38	7.1	309.1	18.2	51	6.6	164.4	14.6	75	6.8	353.1	15.5	6
	7.0	217.5			7.3	336.3			7.3	631.3			7.4	578.8			7.1	373.1		
	6.4	163.4			6.5	135.6			6.7	285.6			7.0	239.2			6.8	318.1		

Table 4.2 Compressive strength cube results and coefficient of variation

	3 Days				7 Days				28 Days				56 Days				90 Days			
	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV	Cube wt. (kg)	Result (kg)	Avg. (Mpa)	CV
350-9.5-P	6.4	72.3	3.2	5	6.2	130.8	5.6	4	5.9	78.1	2.9	18	6.0	128.4	5.2	23	5.9	123.7	6.8	19
	5.9	75.9			6.1	119.5			5.6	47.8			5.6	75.8			6.2	145.0		
	5.9	67.8			6.4	130.6			5.6	69.8			6.1	145.4			6.4	188.9		
350-G-P	5.3	43.2	2.3	20	5.7	59.9	2.5	5	5.0	59.1	2.8	16	5.5	100.8	3.6	19	5.6	74.7	3.4	1
	5.4	47.6			5.3	58.4			5.2	74.9			5.7	74.9			5.4	75.5		
	5.5	64.8			5.5	52.8			4.8	52.6			5.5	68.1			5.4	76.1		
350S-9.5-P	5.5	50.0	2.5	22	5.5	58.3	3.3	56	5.7	82.4	3.5	22	5.7	78.7	3.8	56	5.9	84.5	3.9	3
	5.8	70.9			5.5	42.9			5.6	100.7			5.1	34.7			5.8	89.1		
	5.4	45.6			6.0	118.4			5.5	56.2			6.0	142.8			5.6	91.2		
450-C	8.1	589.9	28.1	22	8.3	678.4	26.8	10	8.0	735.5	33.3	4	8.1	881.7	38.4	11	8.1	1246.0	45.8	16
	7.5	809.2			7.7	591.8			8.2	723.8			7.8	741.5			7.7	887.8		
	8.2	495.1			8.6	537.0			7.8	787.1			8.2	968.2			7.8	954.9		
450-12.5-N	7.4	328.1	14.8	29	7.7	541.1	15.9	44	7.3	400.8	22.4	30	7.0	262.5	22.3	32	7.7	785.0	33.2	7
	7.8	450.1			7.2	229.1			7.7	684.0			7.6	555.1			7.7	785.3		
	7.4	217.5			7.2	302.1			7.6	424.8			7.6	686.2			7.6	670.9		
450-9.5-SP	7.4	465.1	15.2	30	7.3	415.2	16.0	12	7.7	656.6	28.4	8	7.7	357.8	15.0	17	7.4	672.3	31.6	7
	7.0	196.7			7.2	331.7			7.9	694.8			7.2	396.7			7.8	777.9		
	7.4	366.6			7.3	334.9			7.5	566.2			8.0	255.3			7.6	684.2		
450-G-N	7.2	353.5	14.2	12	7.1	279.6	11.5	6	7.8	368.5	17.6	11	7.0	700.5	29.7	23	7.2	456.3	20.0	1
	7.8	341.9			7.5	249.3			7.1	368.8			7.7	455.9			7.2	451.4		
	7.7	263.3			7.0	247.3			7.6	451.6			6.5	849.9			7.0	444.4		

Table 4.3 Compressive strength results at 3, 7, 28, 56, and 90 days

Mix ID	Aggregate Size	Portland Cement (kg)	Silica Fume (kg)	w/c	Admixtures	Compressive Strength (MPa)				
						3-day	7-day	28-day	56-day	90-day
250-C	Control	250	-	0.30	-	0.64	0.73	1.25	2.81	1.99
350-C		350	-	0.30	-	2.84	3.47	5.34	6.71	6.42
450-C		450	-	0.40	-	28.06	26.77	33.28	38.39	45.76
250-12.5-N	Single-sized 12.5 mm CA and No Fines	250	-	0.30	-	1.85	1.83	2.35	2.41	3.17
350-12.5-P		350	-	0.30	Plasticizer	8.29	10.17	18.16	14.55	15.47
450-12.5-N		450	-	0.40	-	14.75	15.89	22.36	22.28	33.20
250-9.5-N	Single-sized 9.5 mm CA and No Fines	250	-	0.30	-	0.40	0.69	0.81	0.99	0.96
350-9.5-P		350	-	0.30	Plasticizer	3.20	5.64	2.90	5.18	6.78
350S-9.5-P		315	35	0.30	Plasticizer	2.47	3.25	3.55	3.80	3.92
450-9.5-SP		450	-	0.40	Superplasticizer	15.24	16.03	28.41	14.96	31.62
250-G-N	Well Graded CA and No Fines	250	-	0.30	-	0.77	0.32	1.07	0.96	0.98
350-G-P		350	-	0.30	Plasticizer	2.31	2.53	2.76	3.61	3.35
450-G-N		450	-	0.40	-	14.20	11.50	17.61	29.72	20.03

Also 28-day compressive strength for Portland cement pervious concrete mixtures ranged from 0.3 MPa to 28.4 MPa with the lowest values corresponding to mixtures with low content of cementious materials and increasing with the increase of the cementitious materials content of the concrete mixtures. For instance, Portland cement pervious concrete mixtures with one-sized 12.5 mm coarse aggregates exhibited a 28-day compressive strength of 2.3, 18.2, and 22.4 MPa and mixtures with one-sized 9. 5 mm coarse aggregates yielded 0.8, 2.9, and 28.4 MPa at cement contents of 250, 350, and 450 kg respectively. The same trend applies to mixtures with well graded coarse aggregates.

The addition of silica fume to mixtures with 350 kg cement and one-sized 9.5 mm coarse aggregates slightly enhanced the strength as the 28-day compressive strength for mixture 350-9.5-P was 2.9 MPa whereas mixture 350S-9.5-P yielded 3.5 MPa. At 28 days the mixtures representing low quality concrete, including 250 kg cement, yielded slightly lower compressive strength values when compared to the control mixture, with the exception of mixtures with single-sized 12.5 mm coarse aggregates that exhibited a 28-day compressive strength value higher than that of the control mixture. The same trend applies to mixtures representing medium quality concrete.

For mixtures representing high quality concrete, the control mixture yielded higher 28-day compressive strength than the mixtures with one-sized 12.5 mm, one-sized 9.5 mm, and well graded aggregates. Moreover, mixtures with one-sized 12.5 mm aggregates yielded 28-day compressive strength lower than that of the corresponding mixtures with one-sized 9.5 mm which was not the case with mixture groups containing 250 kg and 350 kg of cement.

Table 4.4 represents Compressive strength relative gain/loss to control mixtures, when looking at Table 4.4 one can notice that at 28 days age the highest percentage of gain in compressive strength was witnessed by mixtures containing one-sized 12.5 mm coarse aggregates at 250 kg and 350 kg cement gaining compressive strength by 88% and 240%, respectively when compared to the control mixture compressive strength value at that age. A similar trend can be depicted for the same mixtures at 3, 7, 56, and 90 days with the exception that mixture 250-12.5-N lost strength by 14% relative to the control mixture compressive strength value at that age. Such exceptions can be attributed to the random structure and void content of Portland cement pervious concrete mixtures which can at many instances reveal awkward results. Mixture 350-9.5-P also showed relative percentage gains to the control mixture compressive strength of 13%, 63%, and 6% at 3, 7, and 90 days respectively. The percentage loss were displayed at 3, 7, 28, 56, and 90 days aged concrete mixtures with graded coarse aggregates.

Examining ratios calculated in Table 4.5, the 3-to-90 day strength ratio for the Portland cement pervious concrete mixtures, one can notice that almost all Portland cement pervious concrete mixtures gained between 30 to 60 % in average of their final 90 day strength values except mixtures with graded coarse aggregates that attained an average of 70% of its final strength in the first three days (more than the control mixture that achieved an average of 50% in the same time frame). Moreover, the 7-to-90 day strength ratio it can be noted that almost all Portland cement pervious concrete mixtures gained between 30 to 80 % in average of their final 90 day strength values, however it can also be noticed that the higher strength gain for all Portland cement pervious concrete mixtures was at 3-days. The 28-to-90 day strength ratio shows that the average strength for all Portland cement pervious concrete mixtures was 80% with the exceptions of mixtures 350-12.5-P and 250-G-N which gained 110% of the final 90-day compressive strength. This case is very common for the 56-to-90 day strength ratio where seven mixtures yielded 56-day compressive strength equal to or greater than compressive strength at 90 days. Again this phenomenon cannot be attributed to any specific reason but the unsystematic void content of mixtures which at many cases yield unexplained results.

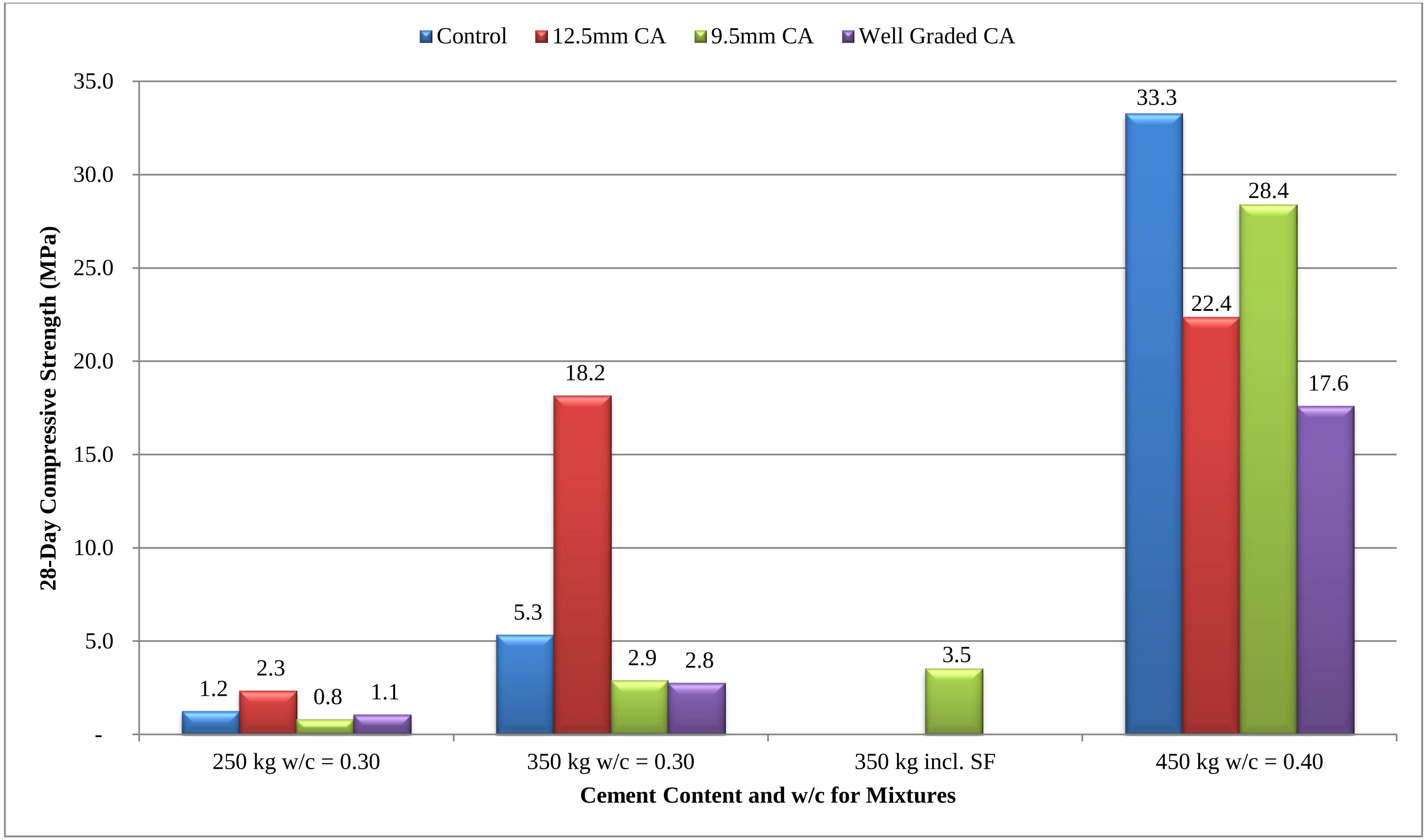


Figure 4.12 28-day compressive strength classified by cement content

Table 4.4 Compressive strength relative gain/loss to control mixtures

Mix ID	Aggregate Size	Compressive strength test results (MPa) and percentage relative gain to control mixtures									
		3-day	Relative Gain / Loss	7-day	Relative Gain / Loss	28-days	Relative Gain / Loss	56-day	Relative Gain / Loss	90-day	Relative Gain / Loss
250-C	Control	0.64	-	0.73	-	1.25	-	2.81	-	1.99	-
350-C		2.84	-	3.47	-	5.34	-	6.71	-	6.42	-
450-C		28.06	-	26.77	-	33.28	-	38.39	-	45.76	-
250-12.5-N	Single-sized 12.5 mm	1.85	1.87	1.83	1.50	2.35	0.88	2.41	-0.14	3.17	0.59
350-12.5-P		8.29	1.92	10.17	1.94	18.16	2.40	14.55	1.17	15.47	1.41
450-12.5-N		14.75	-0.47	15.89	-0.41	22.36	-0.33	22.28	-0.42	33.20	-0.27
250-9.5-N	Single-sized 9.5 mm	0.40	-0.38	0.69	-0.06	0.81	-0.35	0.99	-0.65	0.96	-0.52
350-9.5-P		3.20	0.13	5.64	0.63	2.90	-0.46	5.18	-0.23	6.78	0.06
350S-9.5-P		2.47	-0.13	3.25	-0.06	3.55	-0.34	3.80	-0.43	3.92	-0.39
450-9.5-SP		15.24	-0.46	16.03	-0.40	28.41	-0.15	14.96	-0.61	31.62	-0.31
250-G-N	Well Graded	0.77	0.20	0.32	-0.56	1.07	-0.14	0.96	-0.66	0.98	-0.51
350-G-P		2.31	-0.19	2.53	-0.27	2.76	-0.48	3.61	-0.46	3.35	-0.48
450-G-N		14.20	-0.49	11.50	-0.57	17.61	-0.47	29.72	-0.23	20.03	-0.56

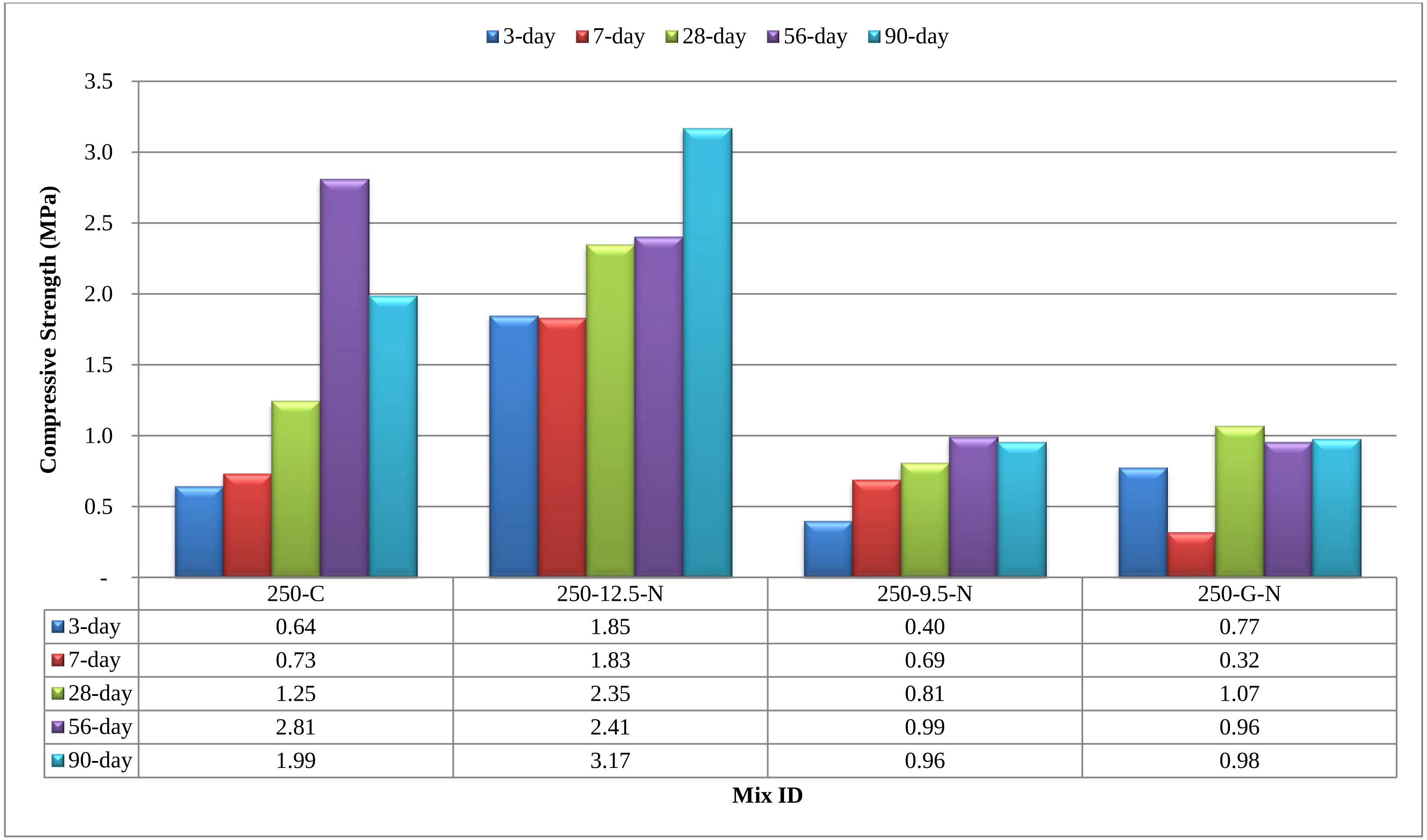
Table 4.5 Compressive strength gain ratios

Mix ID	Aggregate Size	Compressive strength test results (MPa) and strength gain ratios								
		3-day	3/90 Ratio	7-day	7/90 Ratio	28-days	28/90 Ratio	56-day	56/90 Ratio	90-day
250-C	Control	0.6	0.3	0.7	0.4	1.2	0.6	2.8	1.4	2.0
350-C		2.8	0.4	3.5	0.5	5.3	0.8	6.7	1.0	6.4
450-C		28.1	0.6	26.8	0.6	33.3	0.7	38.4	0.8	45.8
250-12.5-N	Single-sized 12.5 mm CA	1.8	0.6	1.8	0.6	2.3	0.7	2.4	0.8	3.2
350-12.5-P		8.3	0.5	10.2	0.7	18.2	1.2	14.6	0.9	15.5
450-12.5-N		14.8	0.4	15.9	0.5	22.4	0.7	22.3	0.7	33.2
250-9.5-N	Single-sized 9.5 mm CA	0.4	0.4	0.7	0.7	0.8	0.8	1.0	1.0	1.0
350-9.5-P		3.2	0.5	5.6	0.8	2.9	0.4	5.2	0.8	6.8
350S-9.5-P		2.5	0.6	3.3	0.8	3.5	0.9	3.8	1.0	3.9
450-9.5-SP		15.2	0.5	16.0	0.5	28.4	0.9	15.0	0.5	31.6
250-G-N	Well Graded CA	0.8	0.8	0.3	0.3	1.1	1.1	1.0	1.0	1.0
350-G-P		2.3	0.7	2.5	0.8	2.8	0.8	3.6	1.1	3.4
450-G-N		14.2	0.7	11.5	0.6	17.6	0.9	29.7	1.5	20.0

By inspecting the results in Figure 4.13, it can be noticed that Portland cement pervious concrete mixtures with 250 kg cement content mixtures are gaining compressive strength steadily over time although Portland cement pervious concrete mixtures seem to gain strength quicker relative to the control mixture of the same category. The mixtures with one-sized 12.5 mm coarse aggregates appear to have higher compressive strength values when compared to the control, one-sized 9.5 mm coarse aggregates, well graded aggregates mixtures. Mixtures with one-sized 9.5 mm coarse aggregates and well graded aggregates mixtures achieved equivalent final 90-day strength significantly lower than that of the control mixture and the mixture with one-sized 12.5 mm coarse aggregates. Also all Portland cement pervious concrete mixtures with 250 kg cement content yielded comparable values for 28, 56, and 90 day compressive strength with the exception of one-sized 12.5 mm coarse aggregates which significantly gained strength again at 90 days. This aligns with the conclusions depicted from the strength gain ratios previously discussed. Exactly the same trend applies to compressive strength results for mixtures with 350 kg cement as per Figure 4.14. The 350 kg cement group of mixtures included a mixture incorporating silica fume, although at 28-days silica fume seemed to have enhanced the compressive strength of the Portland cement pervious concrete mixture with on-sized 9.5 mm coarse aggregates, the final strength at 90 days shows otherwise where the 90 days strength for mixtures 350-9.5-P and 350S-9.5-P were 6.8 and 3.9, respectively.

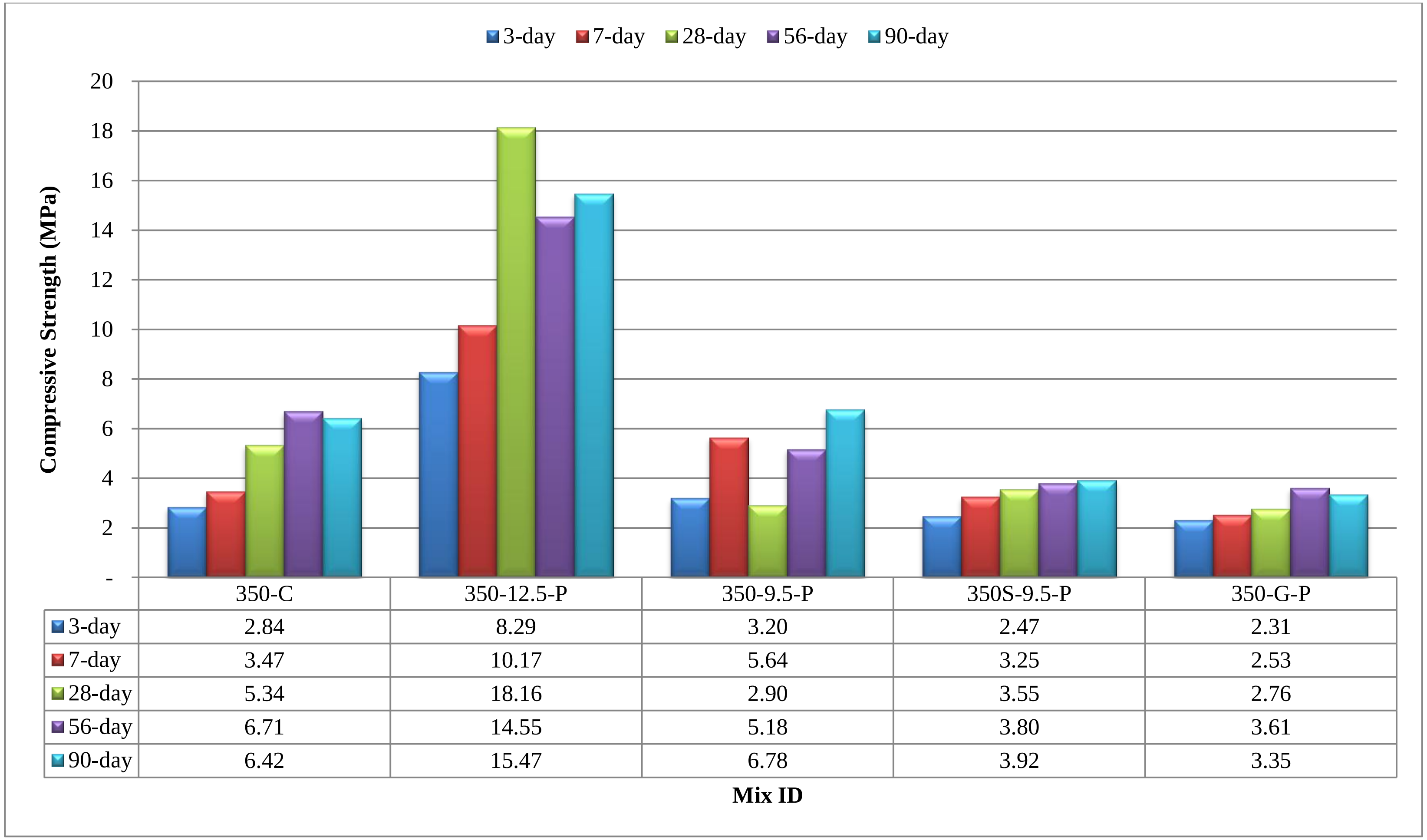
Figure 4.15 shows that the trend for mixtures representing high quality concrete were slightly different as the control mixture showed the highest strength values and mixtures with one-sized 12.5 mm and 9.5 mm coarse aggregates showed similar final 90-day strengths where mixture 450-12.5-N and 450-9.5-SP yielded 33.2 MPa and 31.6 MPa, respectively. However it is to be mentioned that incorporating a superplasticizer mixture 450-9.5-SP may have resulted in a lower compressive strength as the mixture was too wet that it caused segregation and blockage of the bottom voids in some of the samples.

Figure 4.16 through Figure 4.18 illustrates the compressive strength for mixtures grouped by their aggregate size and gradation, a very noticeable conclusion can be drawn when comparing all three figures, at the same aggregate size and gradation the increase of the cement content of the mixture exponentially increases the compressive strength of the Portland cement pervious concrete. For example, mixtures 250-12.5-N, 350-12.5-N, and 450-12.5-N yielded 90-day compressive strengths of 3.2 MPa, 15.5 MPa, and 33.2 MPa, respectively where mixtures 250-9.5-N, 350-9.5-P, 450-9.5-SP produced 90-day compressive strengths of 1.0 MPa, 6.8 MPa, and 31.6 MPa, respectively and compressive strength for mixtures with well graded coarse aggregates was 1.0 MPa, 3.4 MPa, and 20 MPa for mixtures 250-G-N, 350-G-P, and 450-G-N in that order.



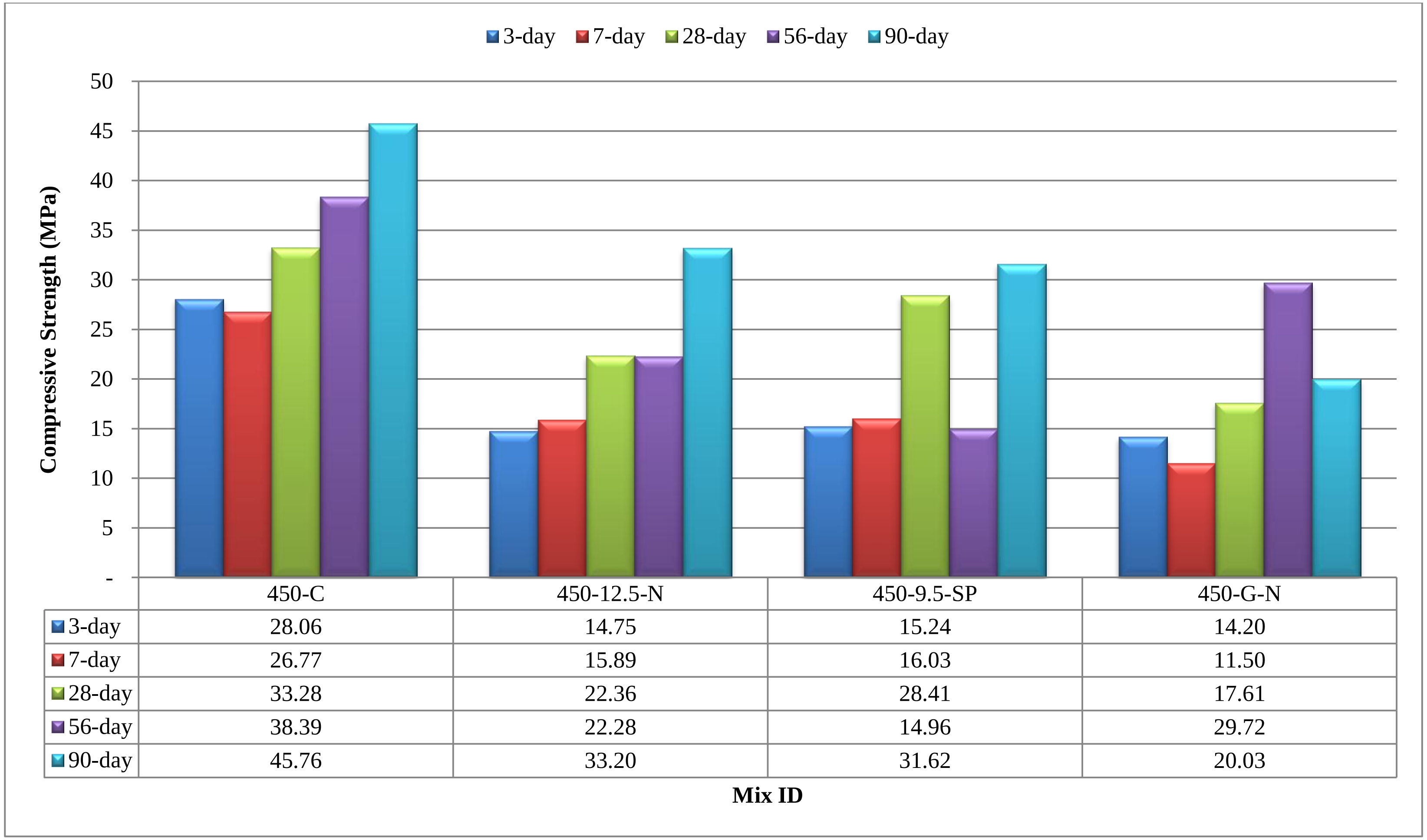
	250-C	250-12.5-N	250-9.5-N	250-G-N
3-day	0.64	1.85	0.40	0.77
7-day	0.73	1.83	0.69	0.32
28-day	1.25	2.35	0.81	1.07
56-day	2.81	2.41	0.99	0.96
90-day	1.99	3.17	0.96	0.98

Figure 4.13 Compressive strength for mixtures with 250 kg cement



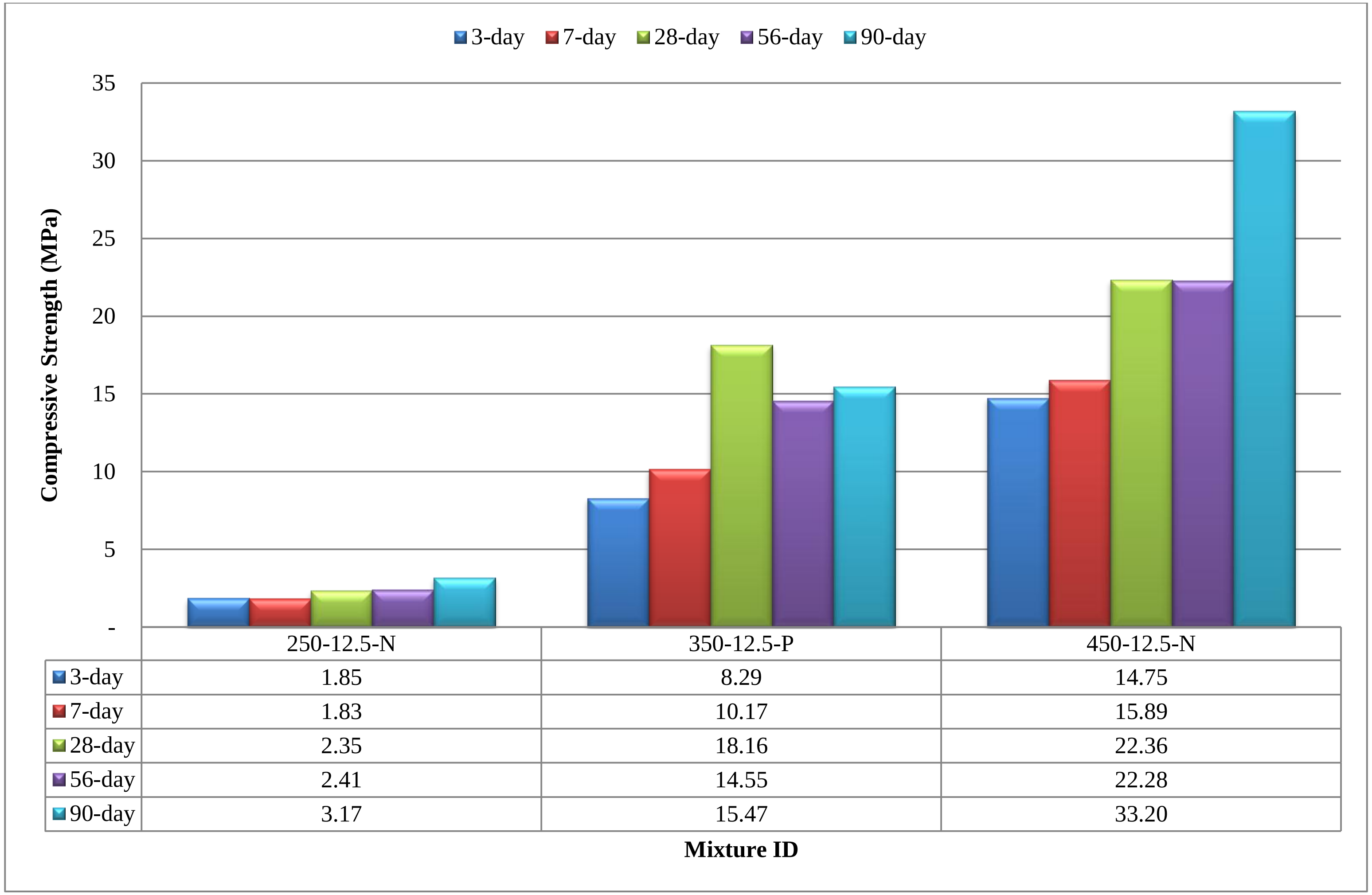
	350-C	350-12.5-P	350-9.5-P	350S-9.5-P	350-G-P
3-day	2.84	8.29	3.20	2.47	2.31
7-day	3.47	10.17	5.64	3.25	2.53
28-day	5.34	18.16	2.90	3.55	2.76
56-day	6.71	14.55	5.18	3.80	3.61
90-day	6.42	15.47	6.78	3.92	3.35

Figure 4.14 Compressive strength for mixtures with 350 kg cement



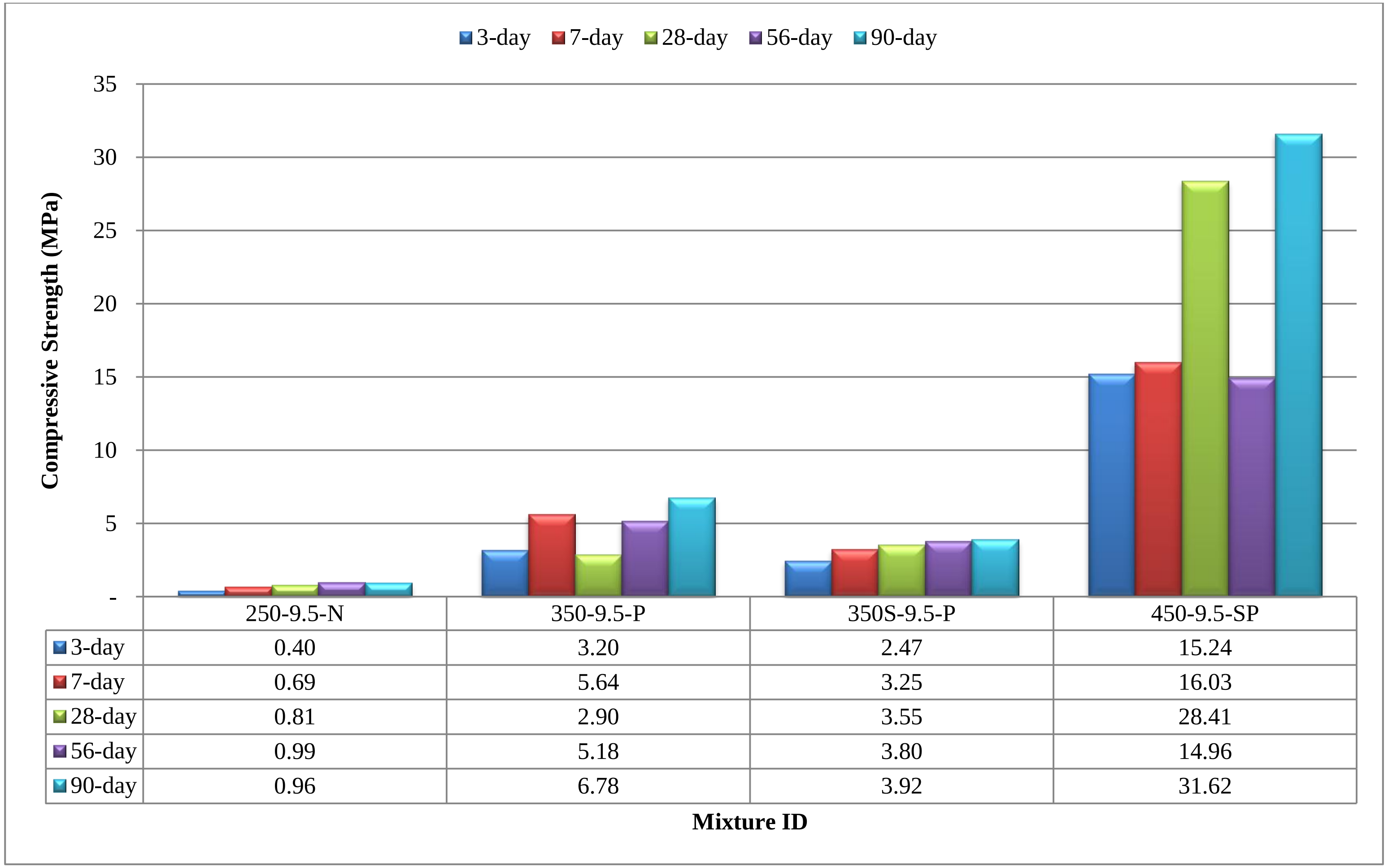
	450-C	450-12.5-N	450-9.5-SP	450-G-N
3-day	28.06	14.75	15.24	14.20
7-day	26.77	15.89	16.03	11.50
28-day	33.28	22.36	28.41	17.61
56-day	38.39	22.28	14.96	29.72
90-day	45.76	33.20	31.62	20.03

Figure 4.15 Compressive strength for mixtures with 450 kg cement



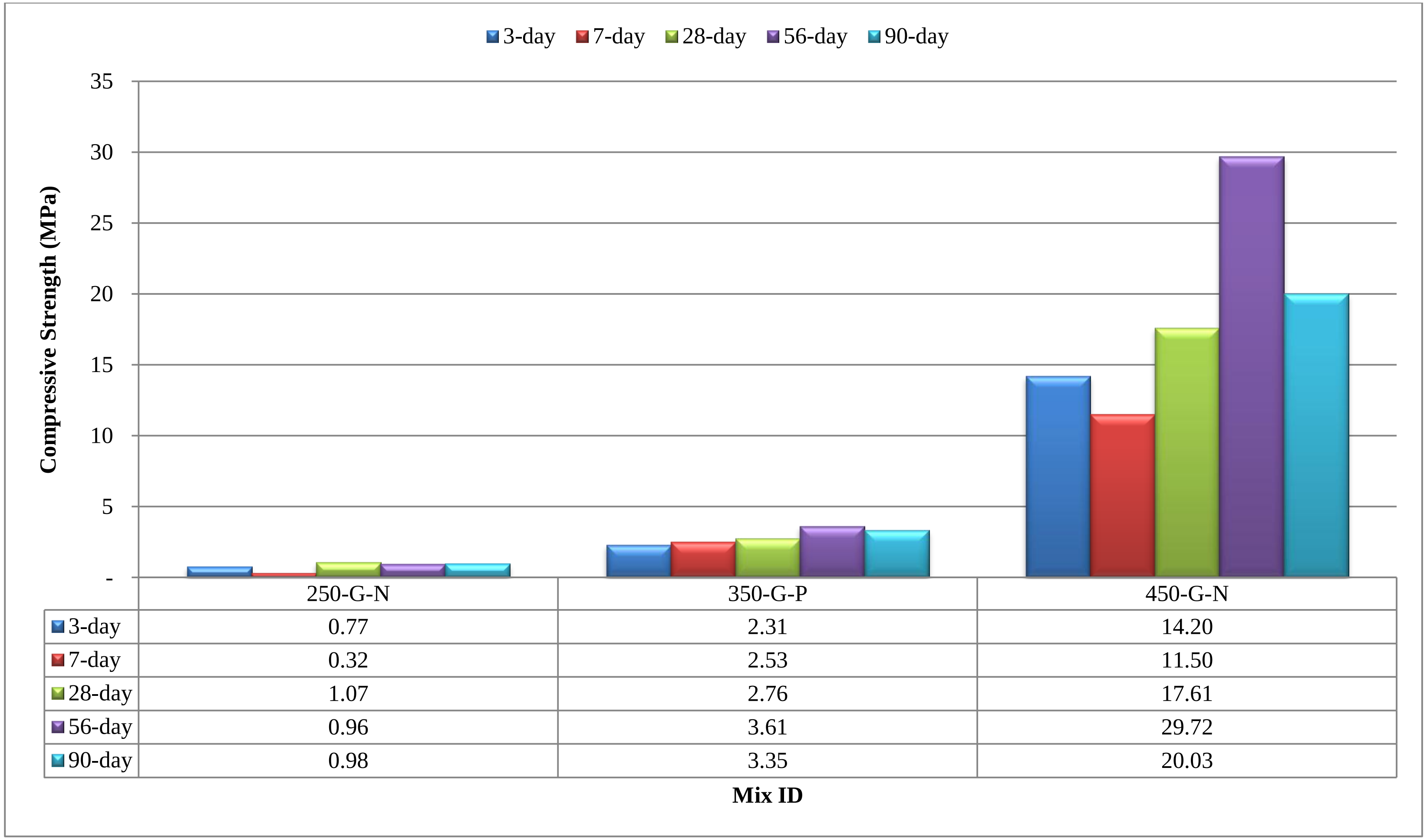
	250-12.5-N	350-12.5-P	450-12.5-N
🟦 3-day	1.85	8.29	14.75
🟥 7-day	1.83	10.17	15.89
🟩 28-day	2.35	18.16	22.36
🟪 56-day	2.41	14.55	22.28
🟦 90-day	3.17	15.47	33.20

Figure 4.16 Compressive strength for mixtures with 12.5 mm aggregates



	250-9.5-N	350-9.5-P	350S-9.5-P	450-9.5-SP
3-day	0.40	3.20	2.47	15.24
7-day	0.69	5.64	3.25	16.03
28-day	0.81	2.90	3.55	28.41
56-day	0.99	5.18	3.80	14.96
90-day	0.96	6.78	3.92	31.62

Figure 4.17 Compressive strength for mixtures with 9.5 mm aggregates



	250-G-N	350-G-P	450-G-N
3-day	0.77	2.31	14.20
7-day	0.32	2.53	11.50
28-day	1.07	2.76	17.61
56-day	0.96	3.61	29.72
90-day	0.98	3.35	20.03

Figure 4.18 Compressive strength for mixtures with graded aggregates

4.2.2 Flexural Strength

Flexural strength was tested for all concrete mixtures as a measure of the tensile strength of concrete. Two unreinforced concrete beams with dimensions 75 cm x 15 cm x 15 cm were casted for each of the thirteen concrete mixtures and tested at 28 days for their ability to resist failure in bending. The flexural strength is expressed as Modulus of Rupture (R) in psi (MPa) and was determined by using a simple beam with third point loading as recommended by ASTM C 78.

Because the fracture initiated in the tension surface within the middle third of the span length, the modulus of rupture was calculated for each mixture at the ages of 28 days and presented in Table 4.6 using equation [4.1]:

$$R = PL/bd^2 \qquad [4.1]$$

Where:

R = Modulus of Rupture, MPa

P = maximum applied load indicated by the testing machine, N

L = span length, 600 mm

b = width of the specimen, 150 mm

d = depth of the specimen, 150 mm

Table 4.6 lists the modulus of rupture values achieved by the concrete mixtures prepared in this study at an age of 28 days cured in the laboratory curing room. The results of the modulus of rupture are illustrated for all the mixtures at cement contents of 250, 350, and 450 kg and different aggregate sizes and gradations in Figure 4.19 through Figure 4.23.

Table 4.6 Modulus of rupture for concrete mixtures

Mix ID	Aggregate Size	Portland Cement (kg)	Silica Fume (kg)	w/c	Admixtures	Flexural Strength (kg.F)			Coefficient of Variation (%)	Max Load at 28 Days (N)	Modulus of Rupture (MPa) $R=PL/bd^2$
						Beam 1	Beam 2	Average			
250-C	Control	250	-	0.30	-	290	288	289	0.7	2834	0.50
350-C		350	-	0.30	-	652	574	613	13.6	6011	1.07
450-C		450	-		-	2283	2290	2287	0.3	22 423	3.99
250-12.5-N	Single-sized 12.5 mm	250	-	0.30	-	874	400	637	118.5	6247	1.11
350-12.5-P		350	-	0.30	Plasticizer	1923	2383	2153	23.9	21 114	3.75
450-12.5-N		450	-	0.40	-	2203	1954	2079	12.7	20 383	3.62
250-9.5-N	Single-sized 9.5 mm	250	-	0.30	-	219	190	205	15.3	2005	0.36
350-9.5-P		350	-	0.30	Plasticizer	1177	990	1084	18.9	10 626	1.89
350S-9.5-P		315	35	0.30	Plasticizer	510	653	582	28.0	5703	1.01
450-9.5-SP		450 kg	-	0.40	Superplasticizer	2734	2560	2647	6.8	25 958	4.61
250-G-0	Well Graded	250 kg	-	0.30	-	186	275	231	47.8	2260	0.40
350-G-P		350 kg	-	0.30	Plasticizer	634	654	644	3.2	6315	1.12
450-G-N		450 kg	-	0.40	-	1847	2548	2198	38.0	21 550	3.83

Through a quick preview of the experimental results acquired for the modulus of rupture from Table 4.6 and Figure 4.19, one can notice that at 28 days Portland cement pervious concrete mixtures yielded R values in the range of 0.36 MPa to 4.6 MPa which are as high as or in range of the control mixtures which yielded results varying from 0.50 MPa to 3.99 MPa.

Figure 4.20 show that on the whole, the modulus of rupture increases with the increase of the cement content of the concrete mixtures. R values for mixtures with cement content of 250 kg ranged from 0.36 MPs to 1.1 MPa where mixtures with 350 kg cement content yielded R values ranging from 1.07 MPa to 3.75 MPa and mixtures with 350 kg cement content yielded R values ranging from 3.62 MPa to 4.61 MPa. Further observations can be deduced from Figure 4.21, for the group of mixtures with 350 kg cement the mixture with one-sized 12.5 mm coarse aggregates yielded the highest R value followed the mixture with one-sized 9.5 mm coarse aggregates and well graded aggregates, respectively where all three Portland cement pervious concrete mixtures yielded a modulus of rupture value higher than that of the control mixture. The same trend applies for mixtures with 250 kg cement except that the mixture with well graded coarse aggregates yielded an R value higher than that of the mixture with one-sized 9.5 mm aggregates. For mixtures with 450 kg a different trend occurred, the highest R value was attributed to the mixture with one-sized 9.5 mm coarse aggregates followed by that with well graded aggregates and the mixture with one-sized 12.5 mm coarse aggregates came in the last place where only the mixture with one-sized 9.5 mm coarse aggregates yielded an R value higher than that of the control mixture.

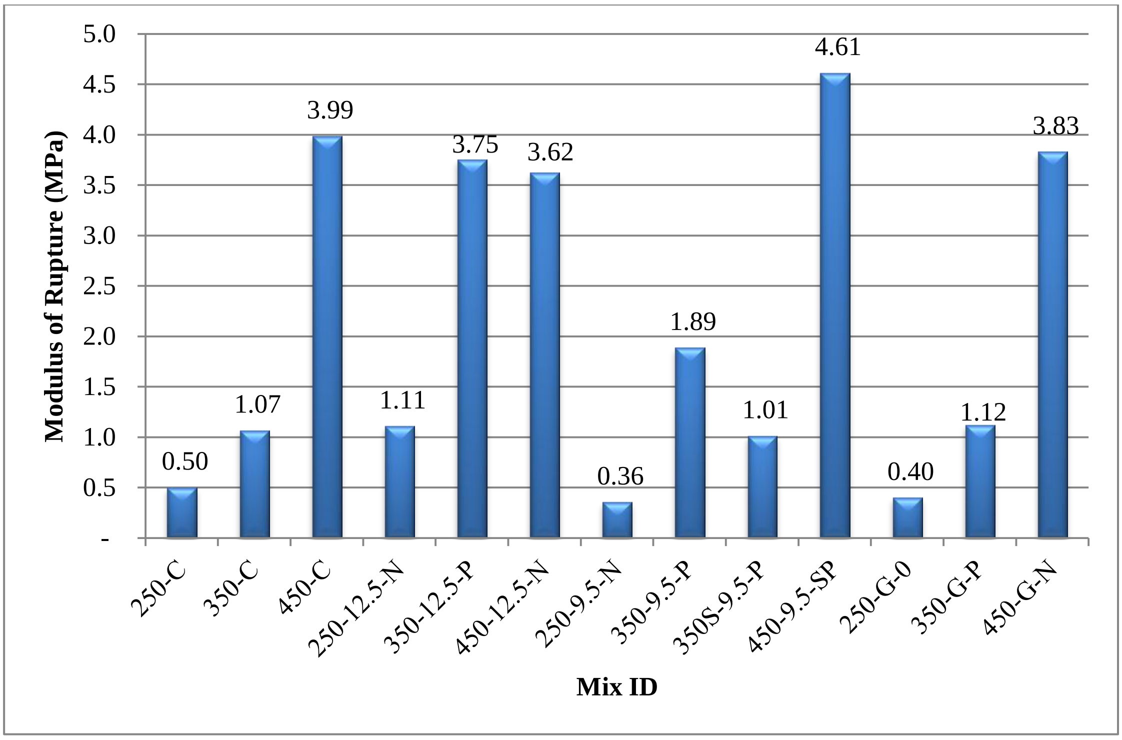


Figure 4.19 Modulus of rupture for all concrete mixtures

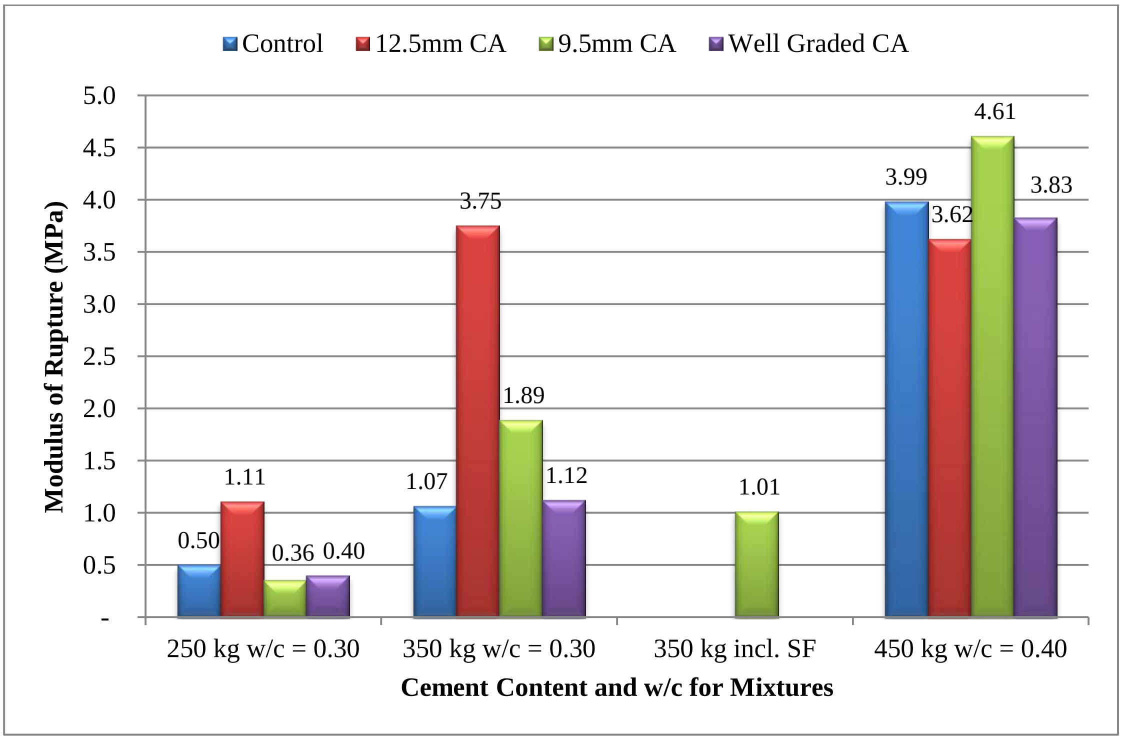


Figure 4.20 Modulus of rupture classified by cement content

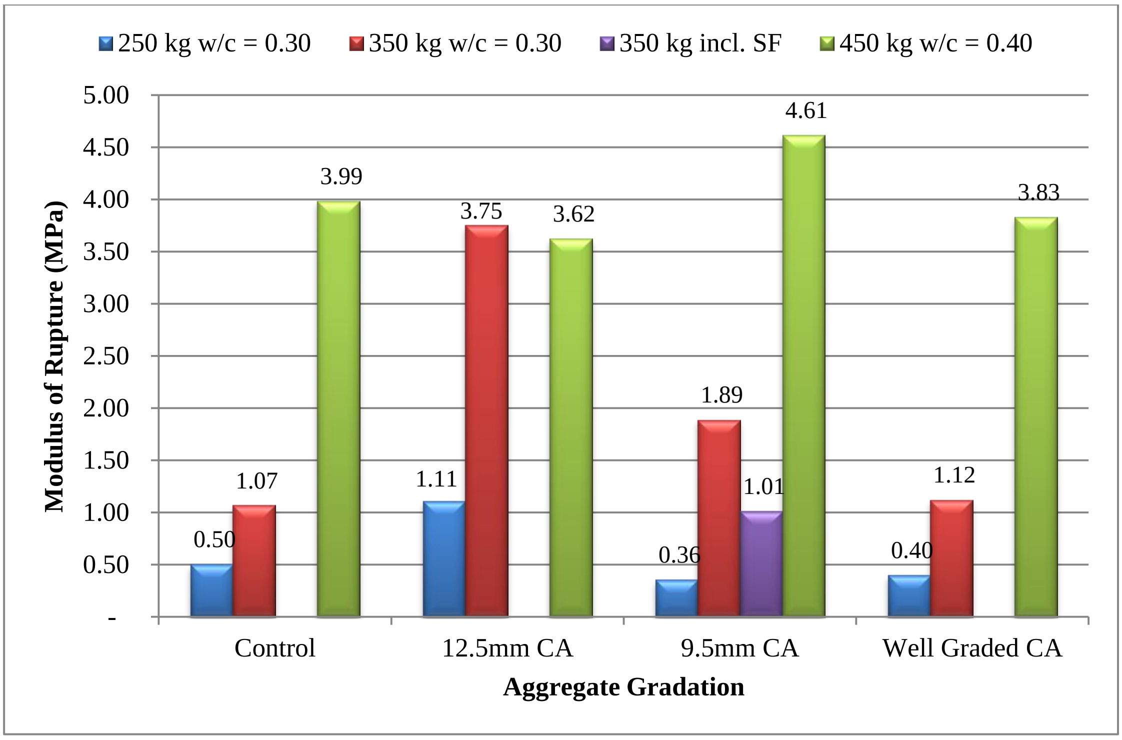


Figure 4.21 Modulus of rupture classified by aggregate size and gradation

ASTM C 78 specifies that results of two properly conducted tests by the same operator on beams made from the same batch sample should not differ from each other by more than 16 %. However, many of the test results gave a coefficient of variation of test results exceeding 16% as illustrated in Figure 4.22. This phenomenon is probably attributed to the fact that due to the open-cell structure of Portland cement pervious concrete mixtures, flexural strength is not only dependent on the strength level of the beams but may fracture due to surface raveling or improper binding of the coarse aggregates together. Conventional concrete mixtures 250-C, 350-C, and 450-C conveyed a coefficient of variation of test results less than 16% which confirms the above-mentioned phenomenon.

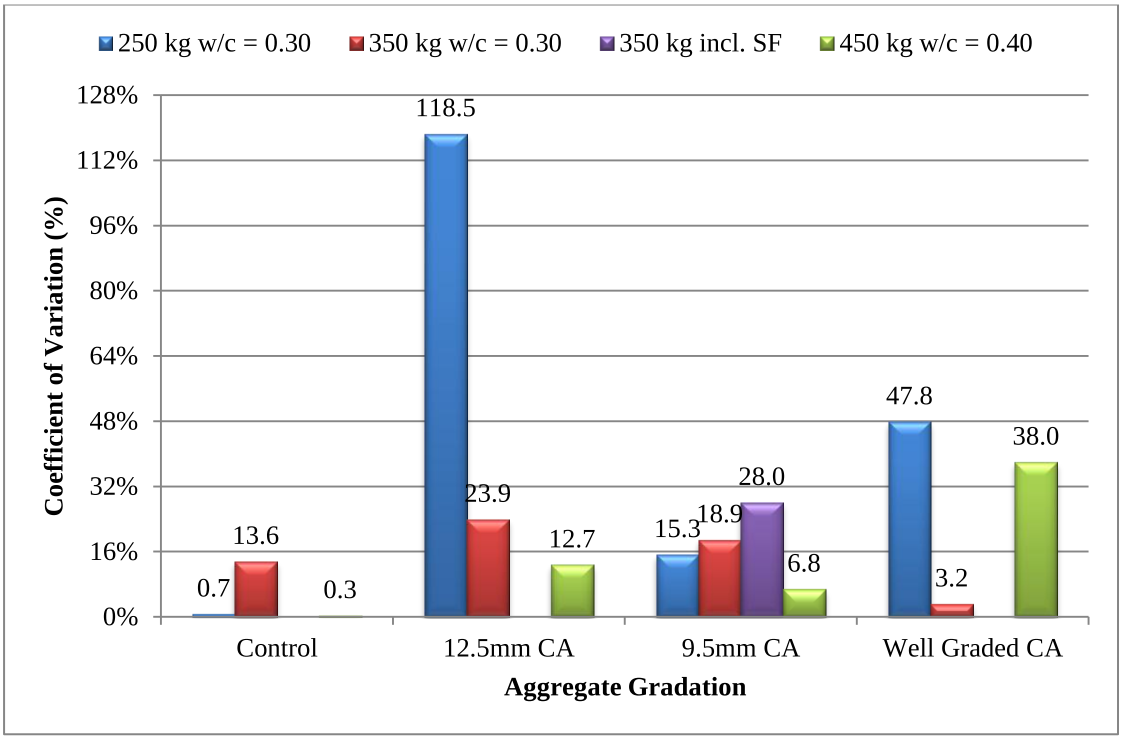


Figure 4.22 Coefficient of variation for flexural strength of beam samples

Endeavoring to forecast the flexural strength based on the experimental compressive strength values of Portland cement pervious concrete, equations that belong to several design codes were employed to be able to establish a connection, if any, between flexural and compressive strengths within the parameters of this study.

The Egyptian code specified the relationship between flexural strength and compressive strength values for concrete mixtures aged 28 days as per equation [4.2].

$f_{ctr}= 0.6 \sqrt{} f_{cu}$ [4.2]

Where:

f_{ctr}= predicted modulus of rupture in MPa

f_{cu}= experimental cube compressive strength in MPa

As per the American Concrete Institute, committee for high strength concrete ACI 363, the equation used to forecast the modulus of rupture for concrete having compressive strength values within the range of 21 and 83 MPa is as follows:

$$f_{ctr}= 0.94 \sqrt{f_{c'}} \qquad [4.3]$$

Where:

f_{ctr}= predicted modulus of rupture in MPa

$f_{c'}$= experimental cylindrical compressive strength in MPa

The third empirical relationship was developed for high performance concrete by Burg to calculate the modulus of rupture for both moistly and air cured specimens. Equation [4.4] calculates the R for moistly cured specimens based on the experimental cylindrical compressive strength.

$$f_{ctr}= 1.03 \sqrt{f_{c'}} \qquad [4.4]$$

Where:

f_{ctr}= predicted modulus of rupture in MPa

$f_{c'}$= experimental cylindrical compressive strength in MPa

All the above mentioned empirical formulas were used to calculate the modulus of rupture of different concrete mixtures aged 28 days. These empirical values were then compared to the flexural strength experimental values attained so as to be able to judge which formula will be appropriate for calculating R values of Portland cement pervious concrete.

The Burg and ACI equations use the cylindrical compressive strength values to estimate the flexural strength. On the other hand, the Egyptian Code equation uses the compressive strength values of cubes. Because this study did not incorporate testing the compressive strength of cylindrical specimen for mixtures and to avoid inconsistency and allow for impartial comparison all the equations were based on cube compressive strength. Accordingly, the equations were reworked based on the cube to cylinder compressive strength ratio of 0.75% as follows:

Egyptian Code Equation: $f_{ctr}= 0.6 \sqrt{f_{cu}}$ [4.5]

ACI 363 Equation: $f_{ctr}= 0.81 \sqrt{f_{cu}}$ [4.6]

Burg Equation: $f_{ctr}= 0.89 \sqrt{f_{cu}}$ [4.7]

The experimental modulus of rupture and the forecasted modulus of rupture (calculated using the Egyptian code, ACI 363 committee and the study program of Burg) are listed in Table 4.7 and illustrated in Figure 4.23.

Table 4.7 Modulus of rupture calculated by several formulae

Mix ID	Aggregate Gradation	Experimental 28-days (MPa)		Predicted F_{ctr} (MPa)		
		F_{cu}	F_{ctr}	Egyptian Code	ACI 363	Burg
250-C	Control	1.2	0.50	0.67	0.90	0.99
350-C		5.3	1.07	1.39	1.87	2.06
450-C		33.3	3.99	3.46	4.67	5.13
250-12.5-N	Single-sized 12.5 mm CA	2.3	1.11	0.92	1.24	1.36
350-12.5-P		18.2	3.75	2.56	3.45	3.79
450-12.5-N		22.4	3.62	2.84	3.83	4.21
250-9.5-N	Single-sized 9.5 mm CA	0.8	0.36	0.54	0.73	0.80
350-9.5-P		2.9	1.89	1.02	1.38	1.52
350S-9.5-P		3.5	1.01	1.13	1.53	1.68
450-9.5-SP		28.4	4.61	3.20	4.32	4.74
250-G-0	Well Graded CA	1.1	0.40	0.62	0.84	0.92
350-G-P		2.8	1.12	1.00	1.35	1.48
450-G-N		17.6	3.83	2.52	3.40	3.74

From Figure 4.23 it is apparent that the Burg and ACI equations cannot be used for forecasting of the modulus of rupture for Portland cement pervious concrete mixtures. Although the Egyptian code formula generated the most conservative forecasted values for the modulus of rupture with many of the actual experimental values being higher, several experimental values were still lower than that calculated using this formula. This observation may be attributed to the fact that the formulas were derived for 28-day compressive strength values of mixtures higher than 20 MPa whereas most of the 28-day compressive strength results for Portland cement pervious concrete mixtures where lower than this range. Figure 4.23 confirms that all formulas, specially the Egyptian code formula, may be applicable to Portland cement pervious concrete mixtures with 28-day compressive strength results higher than 20 MPa.

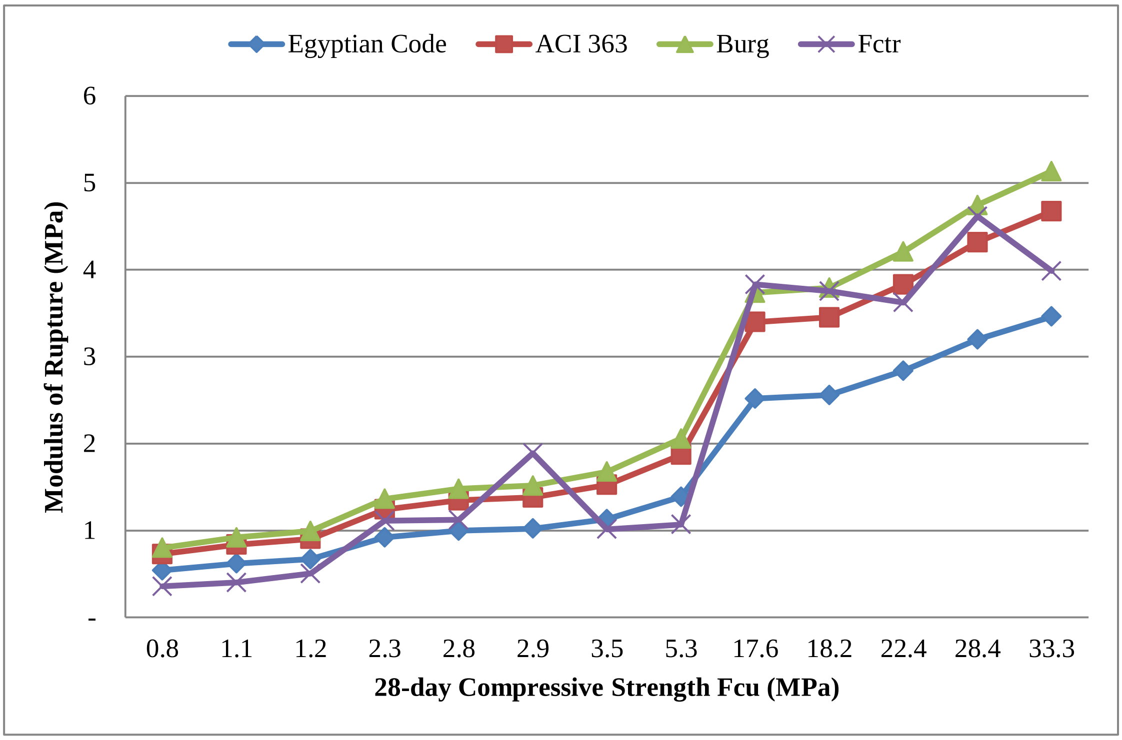


Figure 4.23 Experimental vs. calculated R values for all mixtures

Figure 4.24 is an attempt to derive and equation specific to pervious concrete, however this equation needs further verification through various other mixtures and results.

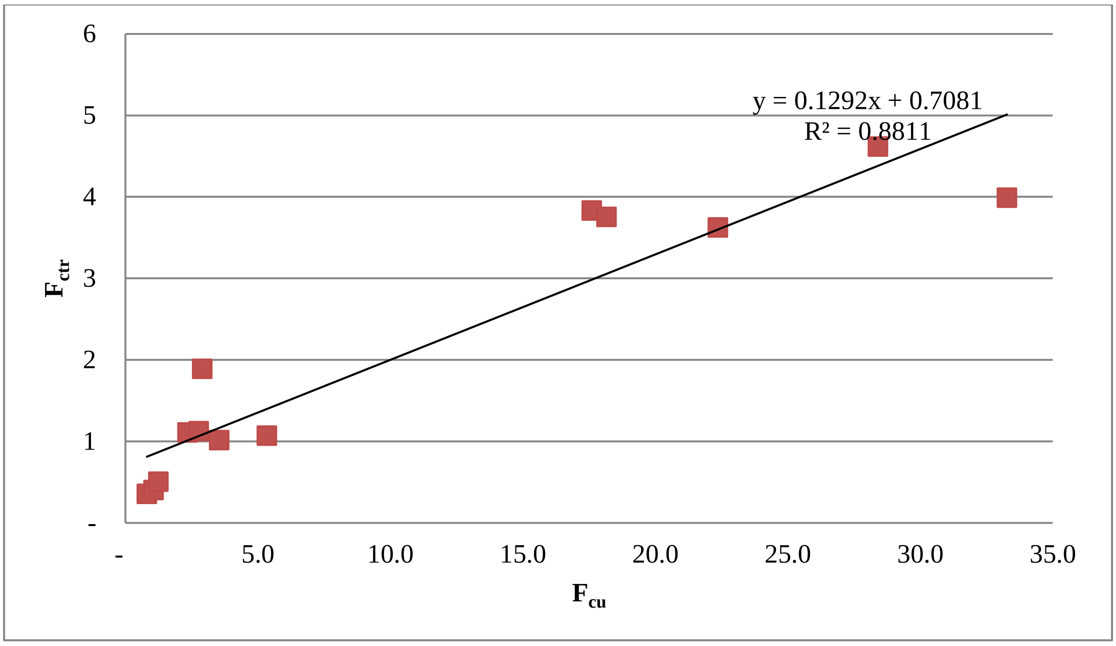


Figure 4.24 Equation for predicted R values for pervious mixtures

4.3 Durability Testing

Durability of Portland cement pervious concrete was studied through the following tests: (1) Rapid Chloride Permeability Test, (2) Chemical Soundness of Concrete, (3) Fire Resistance (using standard cubes after 90-days compressive strength), (4) water permeability, and (5) Ponding test.

4.3.1 Rapid Chloride Permeability Test

This study endeavored to evaluate concrete resistance to chloride penetration via the Rapid Chloride Permeability test for 56 days aged concrete specimens. Three 56-days old standard cylindrical concrete specimens (50 mm thick and 100 mm diameter) for each of the thirteen concrete mixtures were prepared using a cutting machine. The cutting process involved spraying water during the cutting process to facilitate cutting and eliminate dust.

The apparatus accommodates 8 cells per run, however 2 cells were out of order at the time the test was conducted. Thus, the test was planned to be performed on two mixtures at a time.

Unfortunately, due to the void structure and high permeability of Portland cement pervious concrete no results were achieved through the Rapid Chloride Permeability Test. The experiment gave an error due to the fact that the 3.0% NaC1 solution (positive pole) and the 0.3 N NaOH solutions (negative pole) in the two reservoirs of the test apparatus mixed instantaneously as can be seen in Figure 4.25. Accordingly the computer software regulating the test, PROOVE IT, did not generate any results as it has been originally designed to test permeability of conventional non-permeable concrete.

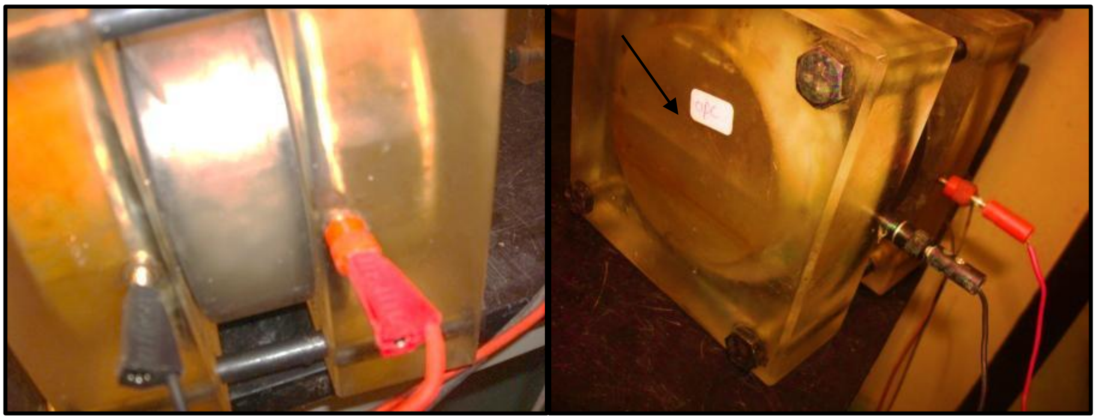


Figure 4.25 Rapid chloride permeability test reservoirs

4.3.2 Chemical Durability of Concrete

The Chemical durability of the concrete mixtures was evaluated though testing their chemical soundness when soaked in two different chemicals; 10% concentrated sulphuric acid (H_2SO_4) and a super-saturated solution of magnesium sulphate (MgSO4). For investigating the effect of the exposure of Portland cement pervious concrete to acids and salts, two groups each composed of three small concrete cubes (5x5x5 cm) from each concrete mixture were exposed to the chemicals. The samples were sharply saw-cut from originally 150 x 150 x 150 mm cubes to avoid the initiation of internal cracks.

For concrete specimens tested for vulnerability to acid, specimens are washed thoroughly to remove any dust or suspended matter. The samples are oven-dried for 24 hours at a temperature of 110℃, and then they are weighed and placed in containers where they will be submerged in the 10% concentrated sulphuric acid (H_2SO_4) solution for 28 days. After 28 days, the samples are washed, oven-dried (for 24 hours at a temperature of 110℃), and reweighed to calculate the percentage loss in mass due to exposure to the acid.

The methodology adopted for testing chemical soundness against salts was slightly different. The concrete specimens were immersed in super-saturated magnesium sulphate solution for 18 hours after which they were drained, washed, oven-dried (for 24 hours at a temperature of 110℃), and re-immersed in the solution. This cycle was repeated 5 times, after the fifth cycle the samples are dried to constant weight and the mass loss resulting from the chemical exposure is calculated.

Table 4. 8 illustrates the weight loss of the different replicas tested for chemical durability in addition to the coefficient of variation representing the ratio of the standard deviation to the median of the results. Table 4.9 presents the average weight losses due to submerging the samples in sulphuric acid and magnesium sulphate respectively. Figure 4.26, Figure 4.27, Figure 4.31, and Figure 4.32 illustrate the average percentage of weight losses for the examined mixtures under exposure to acids and salts.

On the whole, as can be seen in Figure 4.26, there is no specific trend for the mass loss of concrete specimen when immersed in acid specifically when attempting to compare against the percent loss in the control mixtures. This phenomenon could be attributed to the random distribution of voids in the concrete mixture which lead to different patterns of seepage of acid within the specimen. However, it can be observed from Figure 4.26 and Figure 4.27 that generally and with some exceptions the aggregate gradation and size did not affect the percentage of mass loss when exposed to acid as much as the cement content did. For instance, percent mass loss ranged between 61% to 100% for mixtures with 250 kg, 10% to 100% for mixtures with 350 kg cement, and 7% to 22% for mixtures with 450 kg of cement. In other words for the group of mixtures with the same cement content the three or four mixtures with different aggregate gradations and sizes attained roughly the same loss in mass as a result of being immersed in sulphuric acid for 28 days. Mixture 450-12.5-N attained the lowest percentage of mass loss while mixtures 250-C, 350S-9.5-P, 250-G-N, and 350-G-P attained the highest percentage of mass loss, 100%, among all investigated mixtures. Another observation was that the difference in average mass loss was wider between the mixtures representing low quality concrete as opposed to those representing medium and high quality concrete.

Mixtures containing 250 kg of cement yielded 100% loss for both the control mixture and the mixture with well graded aggregates and 61% for the mixture with single-graded 12.5 mm aggregates. The mixture with one-sized 9.5 mm aggregates could not be tested as all attempts to prepare the specimen failed due to surface raveling. As for mixtures containing 350 kg of cement percent mass loss was 40%, 38%, and 10% for the control mixture, mixture with single-graded 12.5 mm aggregates, and mixture with single-graded 9.5 mm aggregates respectively but 100% for the mixture with well graded aggregates. The 450 kg cement mixtures yielded improved results and unpredictably percent mass loss for Portland cement pervious concrete mixtures was lower than that of the control mixture for this group.

Table 4. 8 Chemical durability specimen weights

Mix ID	H2SO4				MgSO4			
	Weight (g)				Weight (g)			
		Initial	Final	%Loss		Initial	Final	%Loss
250-C	1	213.5	0.0	100.0	1	227.5	0.0	100.0
	2	241.5	0.0	100.0	2	220.5	0.0	100.0
	3	204.0	0.0	100.0	3	228.5	0.0	100.0
		Average		100.0		Average		100.0
250-12.5-N	1	227.0	34.0	85.0	1	230.0	232.0	(0.9)
	2	219.5	117.0	46.7	2	238.0	240.5	(1.1)
	3	217.0	106.0	51.2	3	230.5	236.0	(2.4)
		Average		61.0		Average		(1.4)
250-G-N	1	136.5	0.0	100.0	1	95.0	97.5	(2.6)
	2	154.0	0.0	100.0	2	129.5	131.5	(1.5)
	3	158.0	0.0	100.0	3	125.0	129.0	(3.2)
		Average		100.0		Average		(2.5)
350-C	1	230.5	165.5	28.2	1	215.5	227.0	(5.3)
	2	249.5	196.5	21.2	2	220.0	244.0	(10.9)
	3	219.5	63.0	71.3	3	219.0	241.0	(10.0)
		Average		40.2		Average		(8.8)
350-12.5-P	1	255.0	133.0	47.8	1	235.5	237.0	(0.6)
	2	232.0	129.5	44.2	2	257.0	258.0	(0.4)
	3	226.5	179.0	21.0	3	222.0	223.5	(0.7)
		Average		37.7		Average		(0.6)
350-9.5-P	1	222.0	213.5	3.8	1	210.0	213.5	(1.7)
	2	192.5	167.5	13.0	2	206.5	211.0	(2.2)
	3	212.0	183.5	13.4	3	180.0	183.5	(1.9)
		Average		10.1		Average		(1.9)
350-G-P	1	204.5	0.0	100.0	1	182.0	184.5	(1.4)
	2	171.5	0.0	100.0	2	168.5	172.5	(2.4)
	3	196.0	0.0	100.0	3	179.0	182.0	(1.7)
		Average		100.0		Average		(1.8)
350S-9.5-P	1	187.0	0.0	100.0	1	204.5	208.5	(2.0)
	2	207.5	0.0	100.0	2	201.5	203.5	(1.0)
	3	208.0	0.0	100.0	3	197.0	202.0	(2.5)
		Average		100.0		Average		(1.8)
450-C	1	285.5	212.5	25.6	1	276.5	282.0	(2.0)
	2	301.5	240.5	20.2	2	305.0	307.5	(0.8)
	3	287.0	228.5	20.4	3	266.0	271.5	(2.1)
		Average		22.1		Average		(1.6)

Table 4. 8 Chemical durability specimen weights

Mix ID	H_2SO_4				$MgSO_4$			
	Weight (g)				Weight (g)			
		Initial	Final	%Loss		Initial	Final	%Loss
450-12.5-N	1	300.0	283.0	5.7	1	245.5	249.5	(1.6)
	2	272.5	249.0	8.6	2	289.0	291.0	(0.7)
	3	277.5	255.5	7.9	3	292.0	296.5	(1.5)
		Average		7.4		Average		(1.3)
450-9.5-SP	1	324.5	262.0	19.3	1	290.5	299.5	(3.1)
	2	323.0	281.5	12.8	2	228.0	284.5	(24.8)
	3	246.5	214.5	13.0	3	300.5	324.0	(7.8)
		Average		15.0		Average		(11.9)
450-G-N	1	236.5	197.0	16.7	1	240.0	249.0	(3.8)
	2	239.5	218.0	9.0	2	232.5	240.0	(3.2)
	3	253.0	211.5	16.4	3	245.5	251.0	(2.2)
		Average		14.0		Average		(3.1)

Table 4.9 Percentage weight loss of specimens tested for chemical soundness

Mix ID	Mix Short Number	Aggregate Size	Portland Cement (kg)	Silica Fume (kg)	w/c	Admixtures	% Weight Loss Sulphuric Acid	% Weight Loss Magnesium Sulphate
250-C	1.0	Control	250		0.30	-	100.00	100.00
350-C	2.0		350	-	0.30	-	40.25	-8.76
450-C	3.0		450	-	0.40	-	22.06	-1.63
250-12.5-N	1.1	Single-sized 12.5 mm CA and No Fines	250	-	0.30	-	60.96	-1.44
350-12.5-P	2.1		350	-	0.30	Plasticizer	37.67	-0.57
450-12.5-N	3.1		450	-	0.40	-	7.41	-1.29
250-9.5-N	1.2	Single-sized 9.5 mm CA and No Fines	250	-	0.30	-	-	-
350-9.5-P	2.2		350	-	0.30	Plasticizer	10.09	-1.93
350S-9.5-P	2.4		315	35	0.30	Plasticizer	100.00	-1.83
450-9.5-SP	3.2		450	-	0.40	Superplasticizer	15.03	-11.90
250-G-N	1.3	Well Graded CA and No Fines	450	-	0.30	-	100.00	-2.46
350-G-P	2.3		250	-	0.30	Plasticizer	100.00	-1.81
450-G-N	3.3		350	-	0.40	-	14.03	-3.07

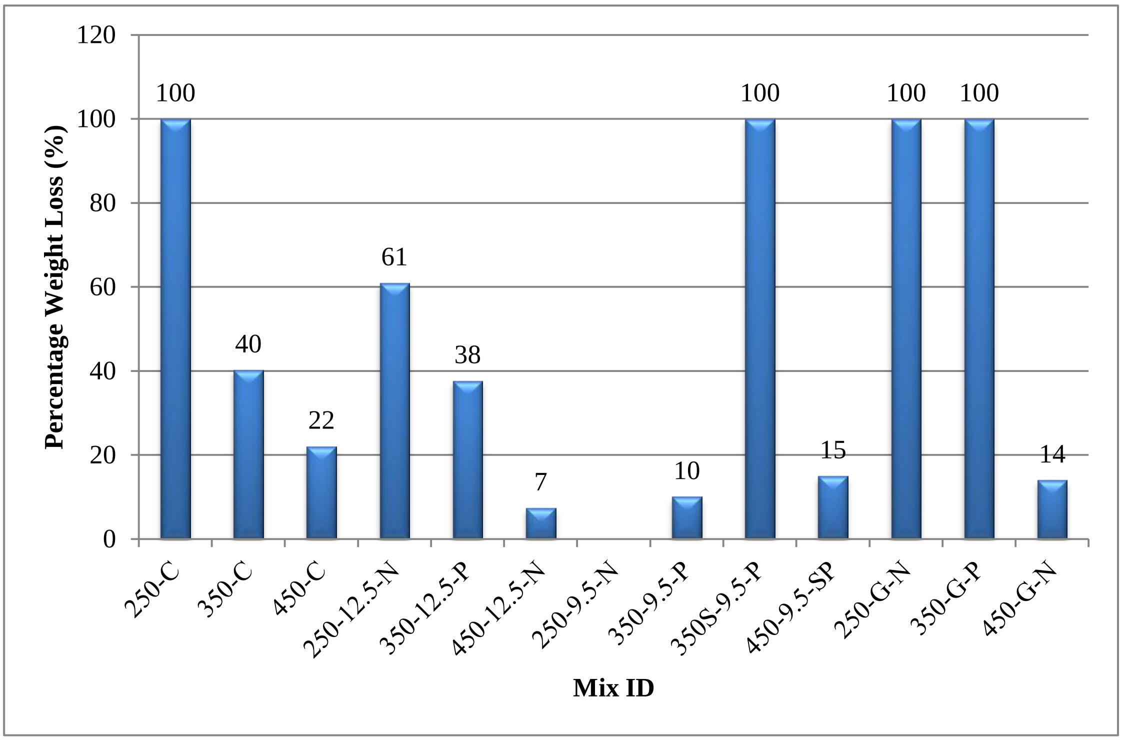


Figure 4.26 Average weight loss for specimens submerged in H_2SO_4

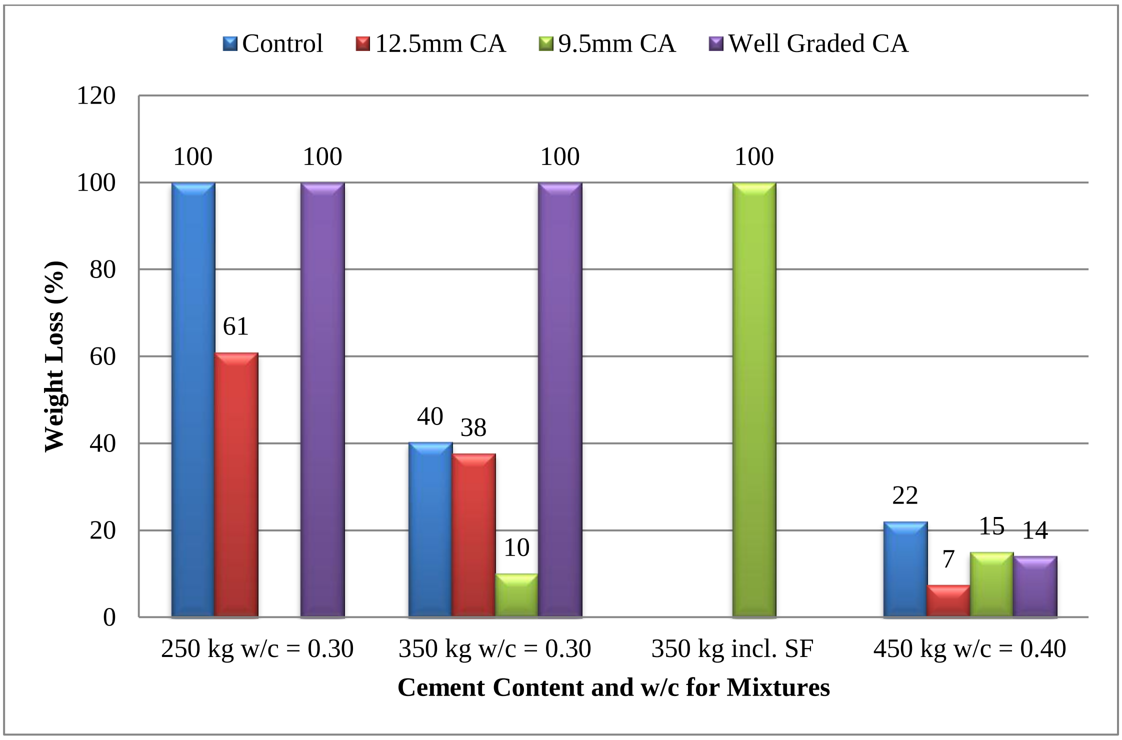


Figure 4.27 Weight loss for specimens submerged in H_2SO_4 by cement content

Visual previews for the immersed samples were captured and illustrated in Figure 4.28 through Figure 4.30. The interesting observation in the visual previews is the final profile of the samples which yielded 100% mass loss. Those samples have completely decomposed.

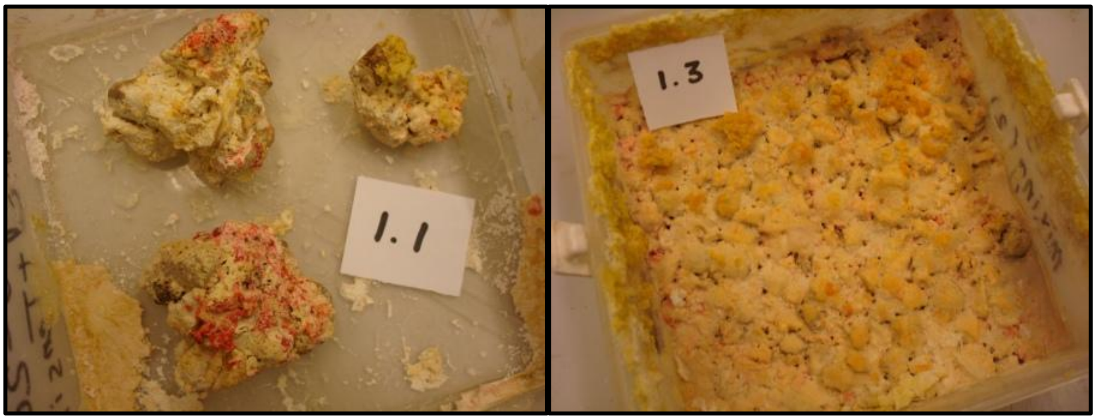


Figure 4.28 Specimens for 250 kg cement mixtures after soaking in acid

Figure 4.29 Specimens for 350 kg cement mixtures after soaking in acid

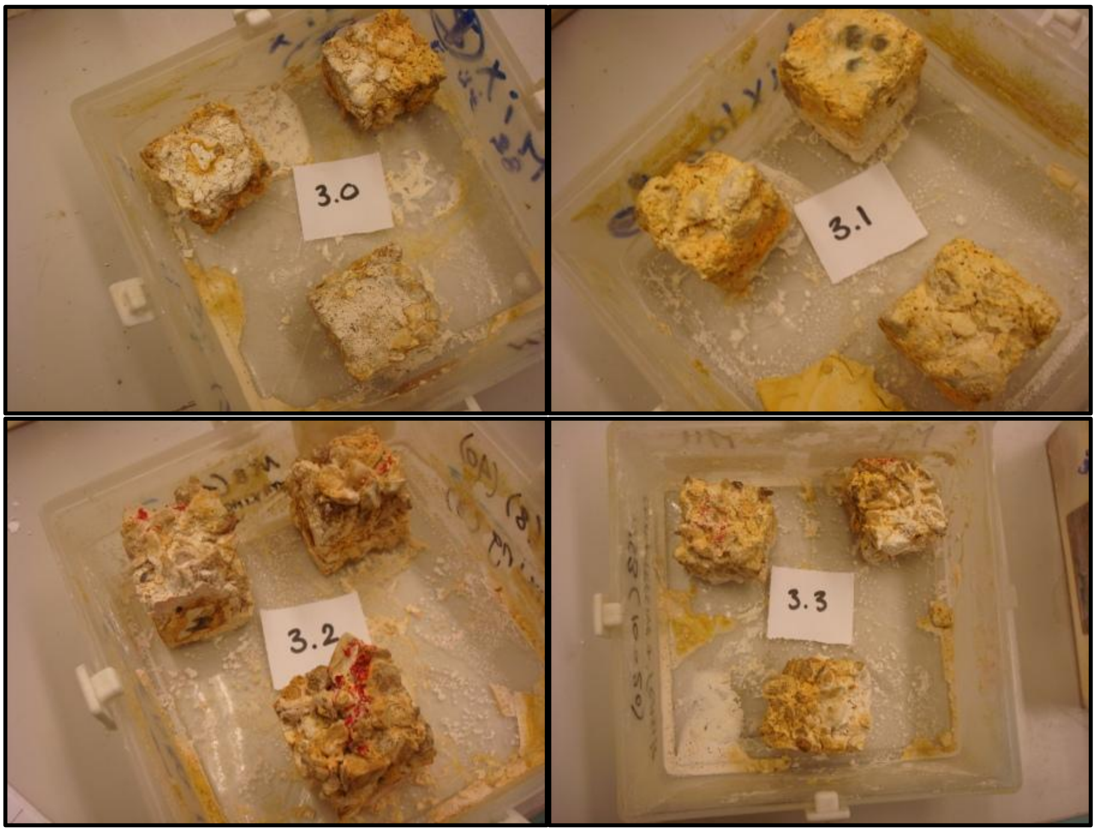


Figure 4.30 Specimens for 450 kg cement mixtures after soaking in acid

As for specimen submerged in magnesium sulphate, Figure 4.31, and Figure 4.32 illustrate the average percentage of weight losses for the examined mixtures under exposure to salt. When inspecting the abovementioned figures it can be observed that the specimen did not lose mass but in fact absorbed the salt and gained mass.

The mass gain percentage in the case of magnesium sulphate ranged from 0.6% to 11.9%. Upon closer inspection, the mixtures with one-sized 12.5 mm aggregates were noticed to have attained less mass gain percentage when compared to mixtures with one-sized 9.5 mm aggregates and well graded aggregates. However, the mass loss of the concrete specimens resulting from exposure to magnesium sulphate was noted not to follow a specific pattern. Visual previews for the immersed samples were captured and illustrated in Figure 4.33 through Figure 4.35 where no major observation was seen except for the sedimentation of salt on the samples. It is worth mentioning that the control mixture with 250 kg of cement expressed 100% loss, illustrated as zero for presentation purposes, as it broke down into pieces and thus could not be weighed.

The mixture with the highest increase in weight, swelling, was mixture 450-9.5-SP which included a superplasticizer. The effect of chemical admixtures on the chemical durability of pervious concrete should be further examined.

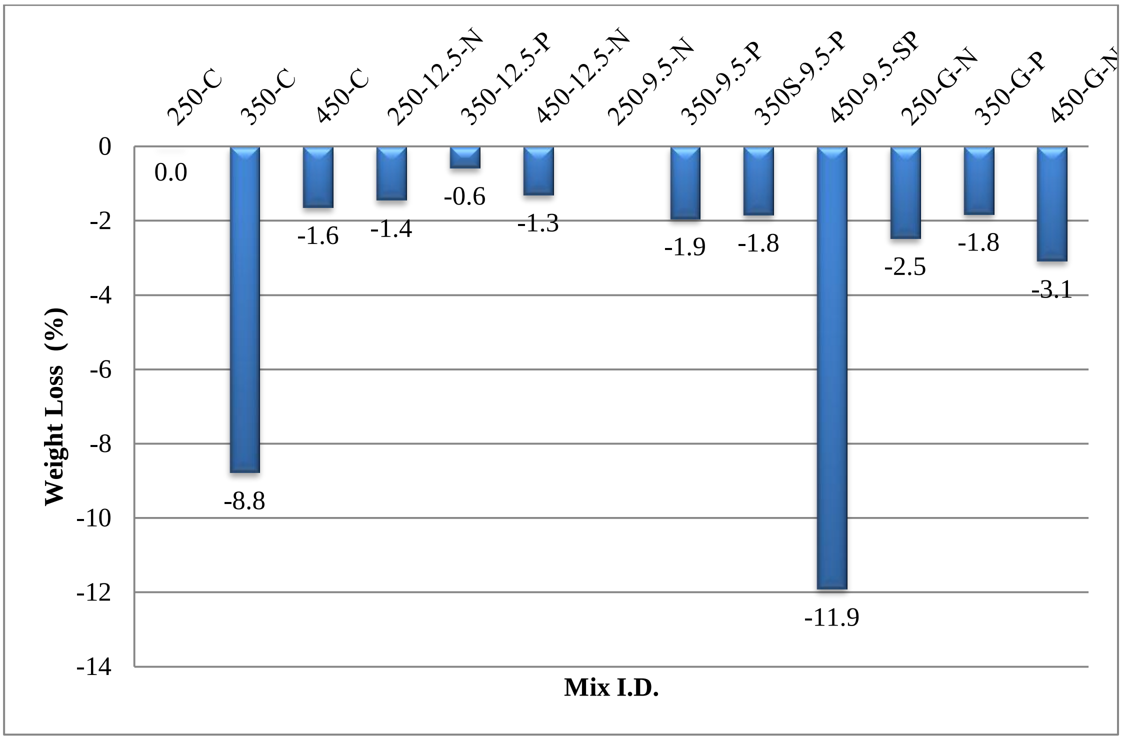


Figure 4.31 Average weight loss for specimens submerged in $MgSO_4$

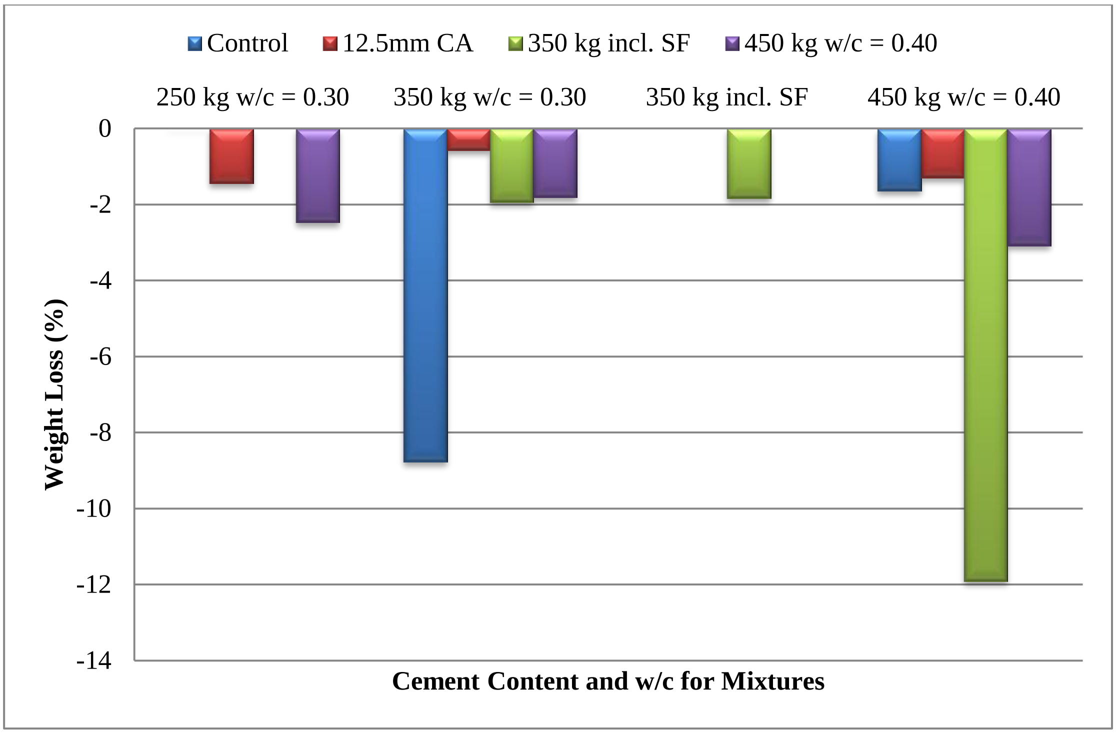


Figure 4.32 Weight loss for specimens submerged in $MgSO_4$ by cement content

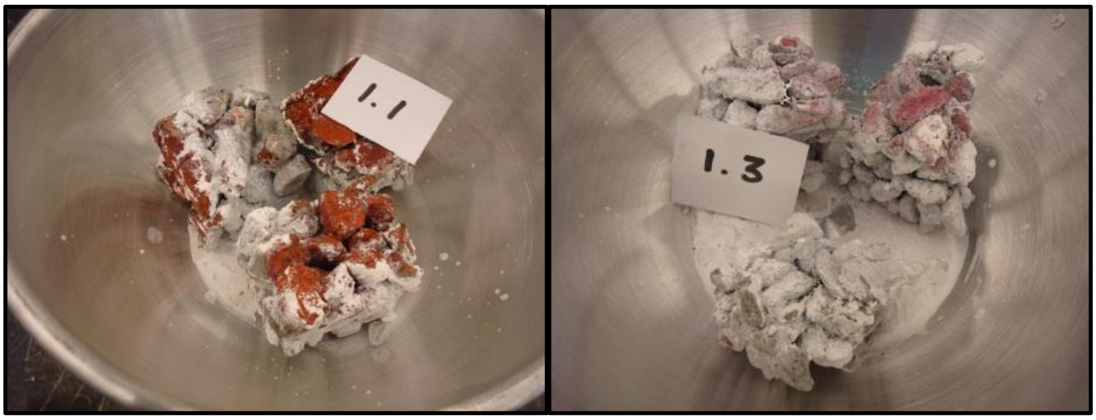


Figure 4.33 Specimens for 250 kg cement mixtures after soaking in salt

Figure 4.34 Specimens for 350 kg cement mixtures after soaking in salt

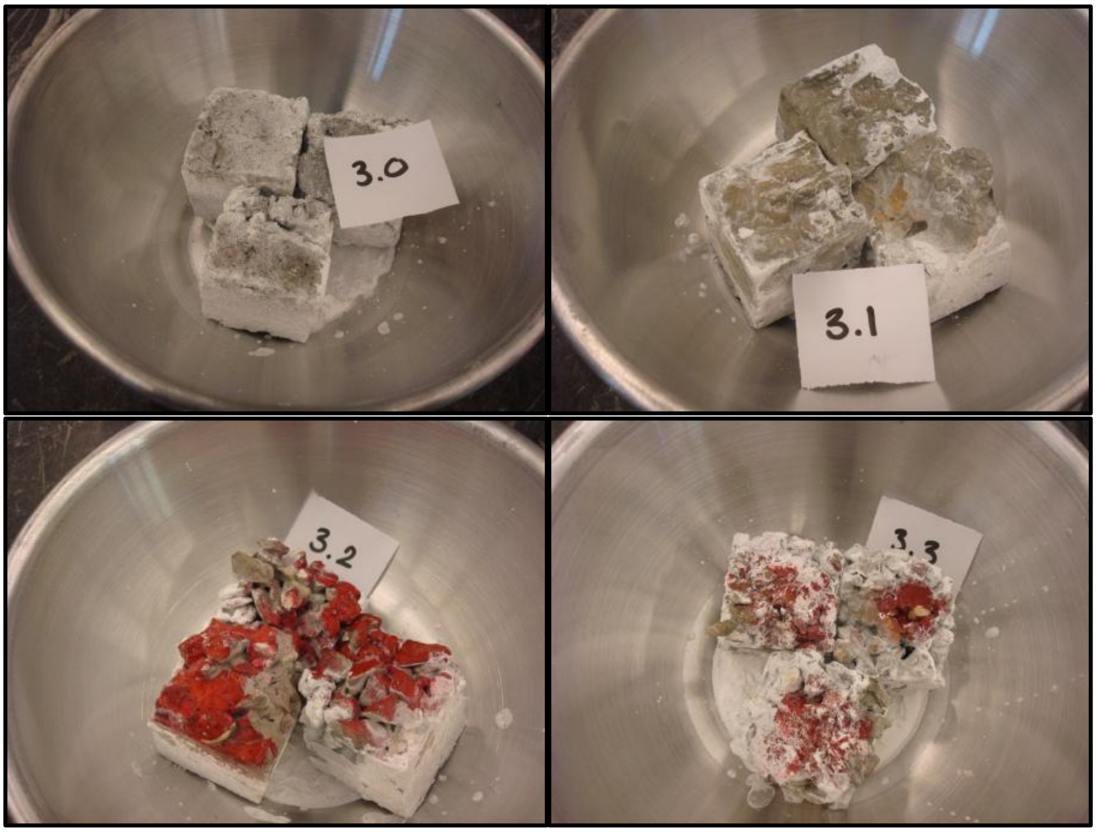


Figure 4.35 Specimens for 450 kg cement mixtures after soaking in salt

4.3.3 Resistance to Elevated Temperatures

To explore the effect of exposure to elevated temperatures on the compressive strength of Portland cement pervious concrete and whether a specific mix design would yield better resistance to elevated temperature. Three standard cubes from each concrete mixture (90-days old) were exposed to heat for eight hours at 500^0C. The oven was allowed to cool down over night to avoid any cracking in the specimens due to sudden cooling thus making it impractical to perform the compressive strength test. Visual inspection was conducted in order to describe any noticeable remarks on the heated cubes. The compressive strength was then conducted as per BS 1881-116:1983. Table 4.10 illustrates the compressive strength results for the replicas tested for resistance to elevated temperatures while Table 4.11 lists the compressive strengths of cubes exposed to heat whereas Figure 4.36 through Figure 4.39 illustrate the comparison of the compressive strength before and after exposure to elevated temperature to compressive strength of cubes before exposure to elevated temperatures.

Examining Table 4.11 and Figure 4.36, it can be seen that with no exceptions all mixtures lost strength. The percentage loss due to exposure to elevated temperature lied in the range of 5% to 38% with the exception of mixtures 250-12.5-N and 350-9.5-P which yielded loss in strength of 72% and 45%, respectively. Those may be attributed to inconsistencies in the specimen specially that the coefficient of variation for mixture 250-12.5-N before exposure to heat is 29%. Comparing Figure 4.37 and Figure 4.38, the trend for compressive strength for mixtures before and after exposure to elevated temperature is exactly the same where 90-day compressive for Portland cement pervious concrete mixtures ranged from 0.96 MPa to 33.20 MPa for mixtures before exposure to elevated heat and 0.68 MPa to 25.57 MPa for mixtures exposed to elevated heat with the lowest values corresponding to mixtures with low content of cementious materials and increasing with the increase of the cementitious materials content of the concrete mixtures.

Table 4.10 Exposure to temperature compressive strength cube results and CV

Mix ID	Not exposed to elevated temperature				After Exposure to Heat at 500^{0}C				
	Cube wt.	Result (kg)	Avg. (Mpa)	CV (%)	Cube wt.	Cube wt.	Result (kg)	Avg. (Mpa)	CV (%)
350-12.5-P	6.8	353.1	15.5	6	7.2	6.9	292.6	10.7	16
	7.1	373.1			6.6	6.3	211.9		
	6.8	318.1			6.6	6.4	220.8		
350-9.5-P	5.9	123.7	6.8	19	5.7	5.4	67.9	3.7	15
	6.2	145.0			5.8	5.6	84.9		
	6.4	188.9			5.9	5.7	99.0		
350S-9.5-P	5.9	84.5	3.9	3	5.8	5.5	50.7	2.5	7
	5.8	89.1			5.8	5.5	60.7		
	5.6	91.2			5.7	5.5	59.0		
450-9.5-SP	7.4	672.3	31.6	7	7.2	6.8	593.9	19.5	29
	7.8	777.9			7.3	6.9	382.4		
	7.6	684.2			7.7	6.8	338.6		
350-G-P	5.6	74.7	3.4	1	5.5	5.3	53.6	2.3	30
	5.4	75.5			5.5	5.2	30.3		
	5.4	76.1			5.6	5.4	68.8		
250-9.5-N	4.6	20.6	1.0	3	5.2	5.1	16.9	0.7	9
	5.1	21.6			5.0	4.8	15.0		
	4.8	22.4			4.4	4.3	13.8		
450-12.5-N	7.7	785.0	33.2	7	7.7	7.2	635.4	25.6	36
	7.7	785.3			8.0	7.4	821.1		
	7.6	670.9			7.1	6.6	269.8		
450-G-N	7.2	456.3	20.0	1	6.9	6.4	318.6	15.5	31
	7.2	451.4			7.6	7.0	481.1		
	7.0	444.4			7.0	6.5	247.0		
250-12.5-N	5.3	95.8	3.2	29	5.2	5.0	21.0	0.9	6
	5.0	60.9			5.4	5.2	20.0		
	5.1	57.3			4.9	4.8	18.3		
250-G-N	5.0	20.3	1.0	12	5.1	4.9	23.1	0.7	31
	4.8	20.3			4.6	4.5	12.3		
	5.0	25.4			5.0	4.8	14.9		
350-C	7.1	178.0	6.4	18	6.7	6.4	122.3	6.0	15
	6.8	121.8			6.8	6.6	160.8		
	6.9	133.4			6.7	6.5	120.2		
450-C	8.1	1246.0	45.8	16	7.8	7.4	900.0	43.3	7
	7.7	887.8			8.1	7.6	1058.0		
	7.8	954.9			7.9	7.4	963.0		
250-C	6.8	38.2	2.0	12	6.4	6.2	29.1	1.5	19
	6.6	51.2			6.5	6.3	30.4		
	6.6	44.8			6.7	6.4	42.2		

Table 4.11 Compressive strength at 90 days before and after exposure to heat

Mix ID	Aggregate	Portland Cement (kg)	Silica Fume (kg)	w/c	Admixture	90-day Compressive Strength (MPa)		Percentage Loss (%)
						Before Exposure to Heat	After Exposure to Heat	
250-C	Control	250	-	0.30	-	2.0	1.5	24
350-C		350	-	0.30	-	6.4	6.0	7
450-C		450	-	0.40	-	45.8	43.3	5
250-12.5-N	Single-sized 12.5 mm CA and No Fines	250	-	0.30	-	3.2	0.9	72
350-12.5-P		350	-	0.30	Plasticizer	15.5	10.7	31
450-12.5-N		450	-	0.40	-	33.2	25.6	23
250-9.5-N	Single-sized 9.5 mm CA and No Fines	250	-	0.30	-	1.0	0.7	29
350-9.5-P		350	-	0.30	Plasticizer	6.8	3.7	45
350S-9.5-P		315	35	0.30	Plasticizer	3.9	2.5	36
450-9.5-SP		450	-	0.40	Superplasticizer	31.6	19.5	38
250-G-N	Well Graded CA and No Fines	250	-	0.30	-	1.0	0.7	24
350-Graded-P		350	-	0.30	Plasticizer	3.4	2.3	33
450-G-N		450	-	0.40	-	20.0	15.5	23

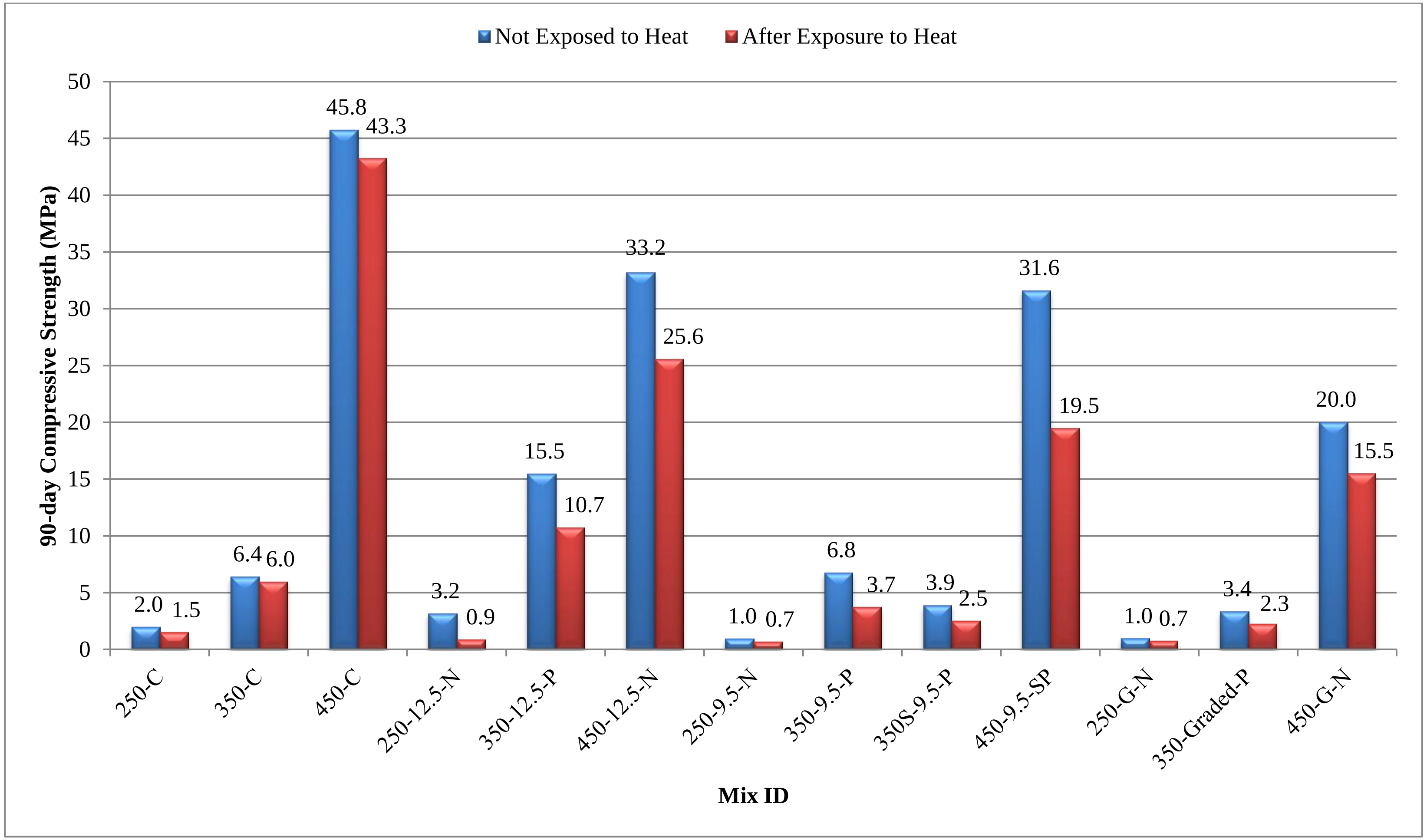


Figure 4.36 Compressive strength at 90-days before and after exposure to heat

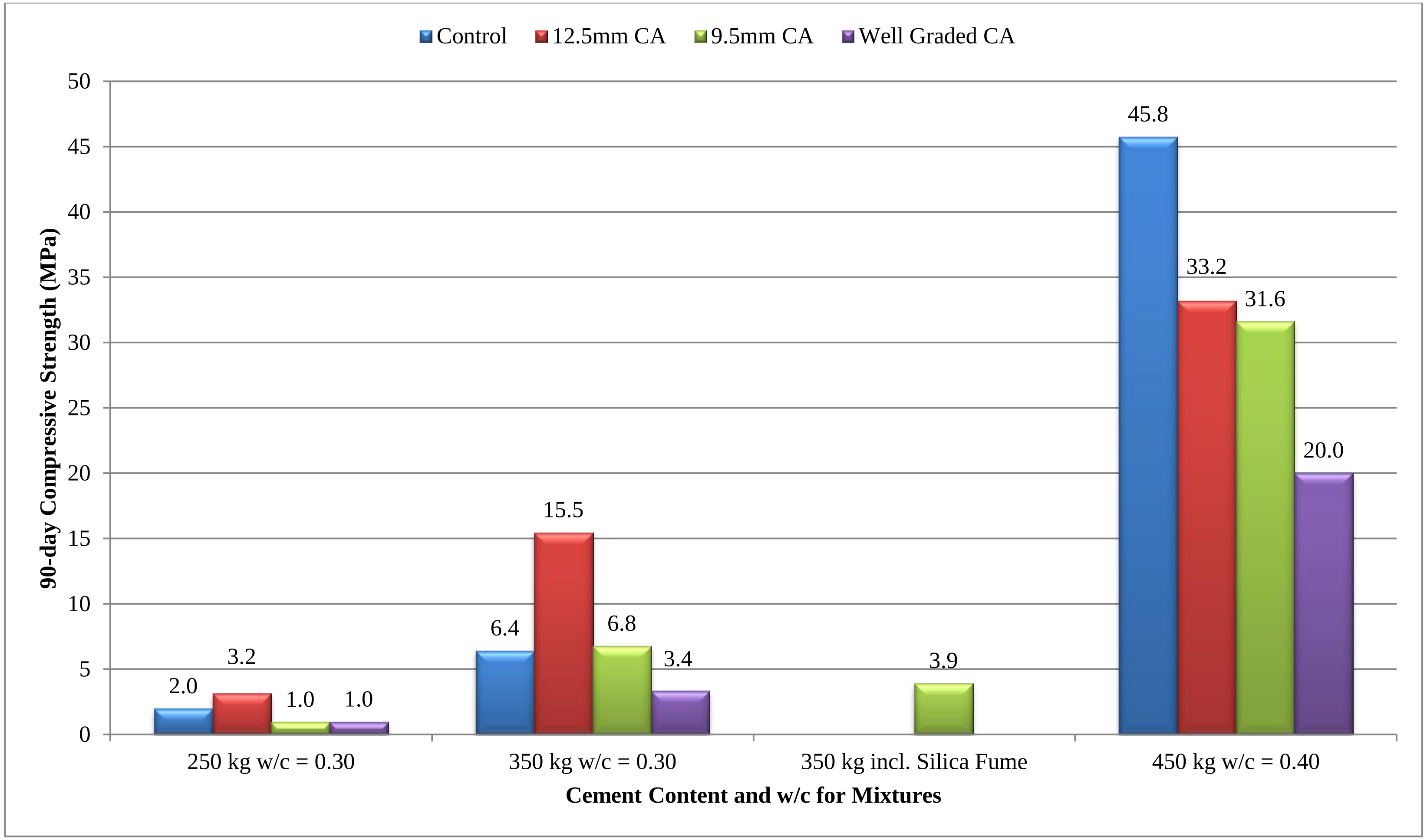


Figure 4.37 90-days Compressive strength for mixtures not exposed to heat

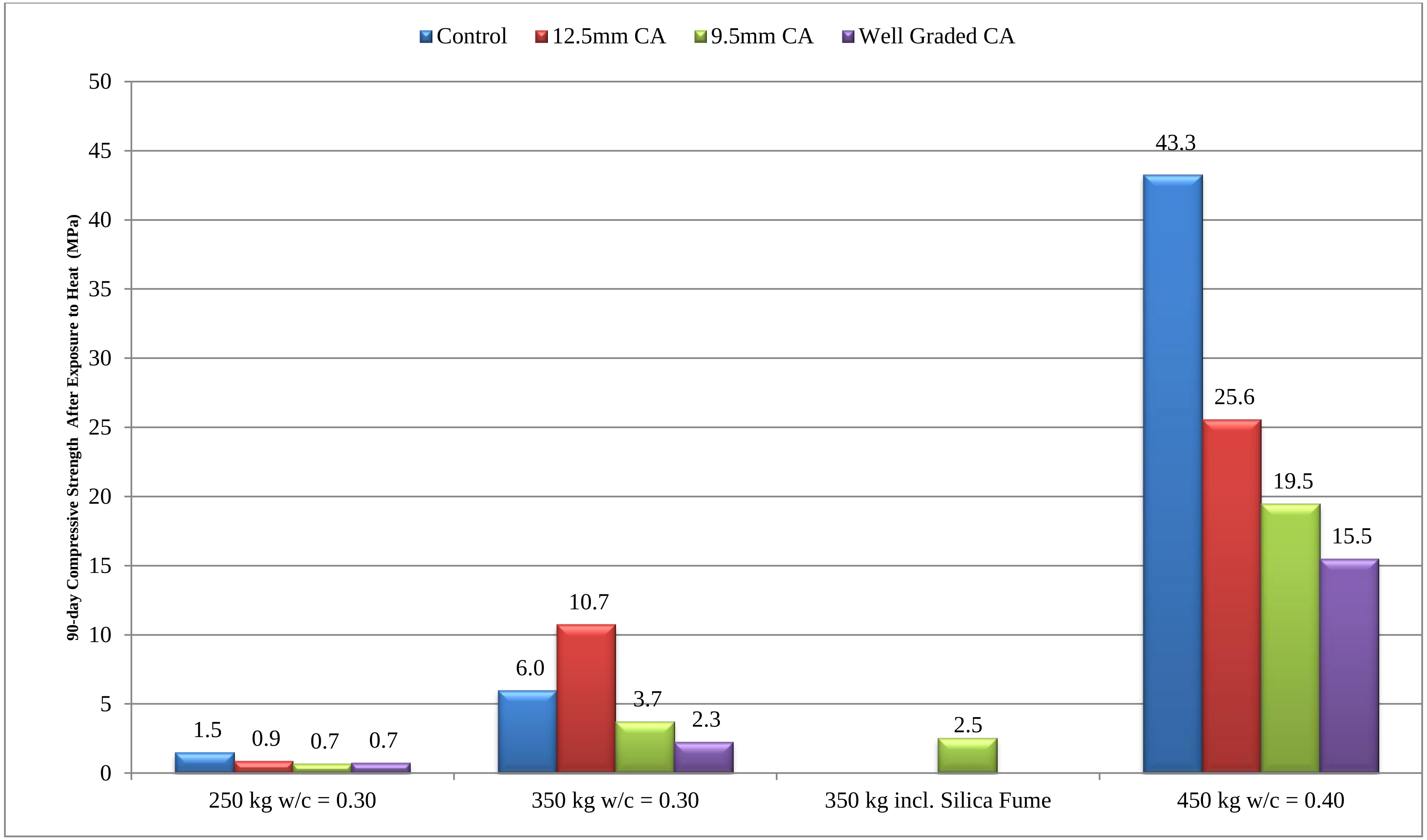


Figure 4.38 90-days Compressive strength for mixtures exposed to heat

Figure 4.39 illustrates the percentage loss in compressive strength due to exposure to heat. The average loss in compressive strength for control mixtures, mixtures with one-sized 12.5 mm CA, mixtures with one-sized 9.5 mm CA, and mixtures with well graded CA was 12%, 42%, 37%, and 26%, respectively whereas after eliminating exceptions the averages are 12%, 27%, 34%, and 26%. This means that mixtures with one-sized 12.5 mm coarse aggregate and mixtures with well graded coarse aggregates have yielded the least percentage loss in compressive strength due to exposure to elevated heat. This observation can be attributed to the fact that mixtures with well graded coarse aggregates are the most similar to control mixtures and those with one-sized 12.5 mm coarse aggregate have proven to be the strongest of Portland cement pervious concrete mixtures through previous strength and durability testing.

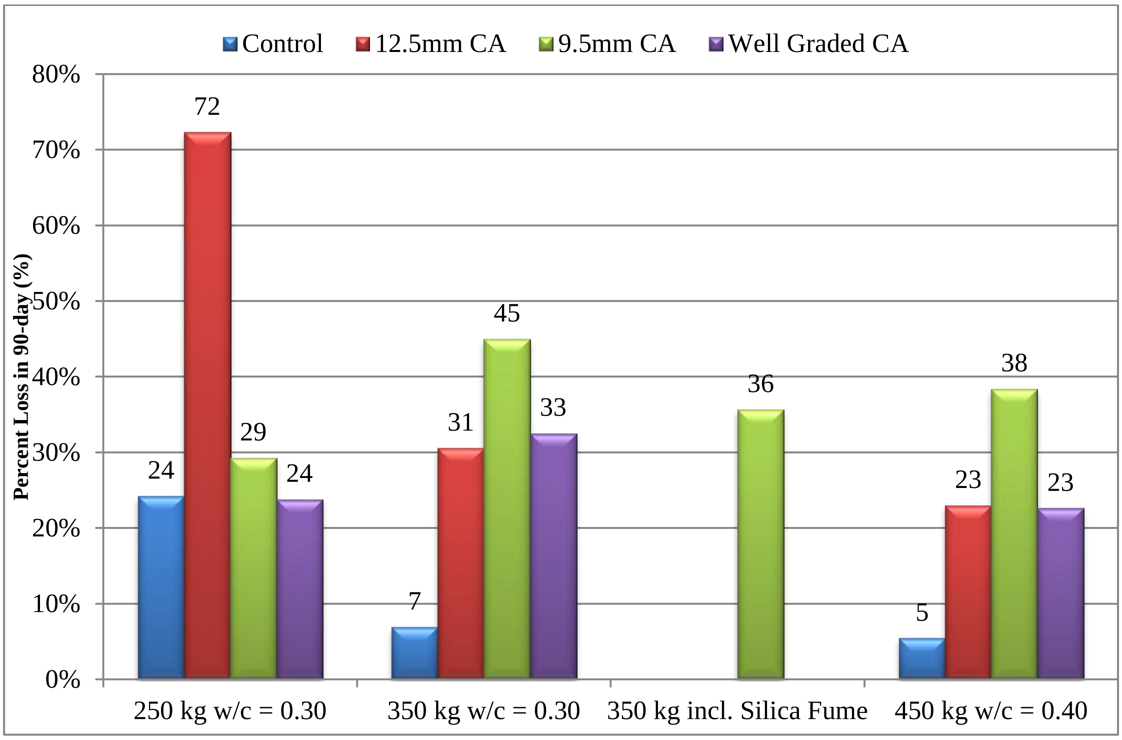


Figure 4.39 Percentage loss in compressive strength due to exposure to heat

4.3.4 Water Permeability

As highlighted in section 4.3.1 above, pervious concrete is a special type of concrete with a high porosity and accordingly typical permeability tests performed on conventional concrete such as RCPT was deemed unreliable. A simple experiment was designed to compare the porosity of different concrete mixtures studied.

Concrete plates (300 x 300 x 80 mm) were supported above a digital scale. 1000 ml of water were measured in a flask and poured through the concrete plate into a container on the scale. The time taken for the water to pass through the specimen was recorded via a stopwatch. In order to eliminate the personal errors due to manually pouring the water, the stopwatch was not stopped except when the scale remained constant; the experimental procedure described is illustrated in Figure 4.40.

Figure 4.40 Experimental procedure designed to study permeability of PCPC

Table 4.12 illustrates the results obtained from the permeability test designed while Figure 4.41 through Figure 4.43 and Figure 4.46 illustrate the time taken for water to pass through the specimen for all Portland cement pervious concrete mixtures, the amount of water that actually passed through the specimen respectively, the amount of water passed, retained, and lost, and the water flow rate for Portland cement pervious concrete mixtures expressed in l/m^2/min, respectively.

At a glance it can be noticed that mixtures with 250 kg cement passed the water quickest as opposed mixtures with 350 kg and 450 kg of cement. Figure 4.41 shows that mixtures with 250 kg of cement required average time of 34 sec for the water to pass through the specimen as opposed to 79 sec and 105 for mixtures with 350 kg and 450 kg of cement, respectively. The mixture incorporating silica fume needed less time than the equivalent mixture without silica fume where water passed through the specimen in 43 sec for mixture 350S-9.5-P and 73 sec for mixture 350-9.5-P. It could also be noticed that mixtures within the same group of mixtures with one-sized 12.5 mm coarse aggregate required more time than those with one-sized 9.5 mm coarse aggregates and well graded aggregates in that order.

A similar observation can be made from Figure 4.42 where mixtures with 250 kg cement passed a larger volume of water as opposed mixtures with 350 kg and 450 kg of cement. Mixtures with 250 kg of cement passed an average volume of 911 ml of water versus 904 ml and 635 ml for mixtures with 350 kg and 450 kg of cement ,respectively. The mixture incorporating silica fume passed a smaller volume of water than the equivalent mixture without silica fume where 936 ml of water passed through the specimen for mixture 350S-9.5-P and 954 ml passed through the specimen for mixture 350-9.5-P.

Table 4.12 Test results for water permeability of PCPC mixtures

Mix ID	Aggregate Size	Weight (kg)	Time (Sec)	Water Passed (g)	Weight of Wet Specimen (kg)	Water Retained (g)	Loss (g)	Flow Rate (L/m^2/min)
250-12.5-N	12.5 mm CA	12	38	965	12	30	5	609
350-12.5-P		14	109	847	14	80	73	186
450-12.5-N		15	114	598	15	30	372	126
250-9.5-N	9.5 mm CA	8	33	935	8	-	65	680
350-9.5-P		14	73	954	14	10	36	313
350S-9.5-P		12	43	936	12	40	25	522
450-9.5-SP		15	102	517	15	40	443	122
250-G-N	Well Graded CA	11	32	834	11	110	56	626
350-G-P		11	54	911	11	-	90	405
450-G-N		13	98	789	13	70	141	193

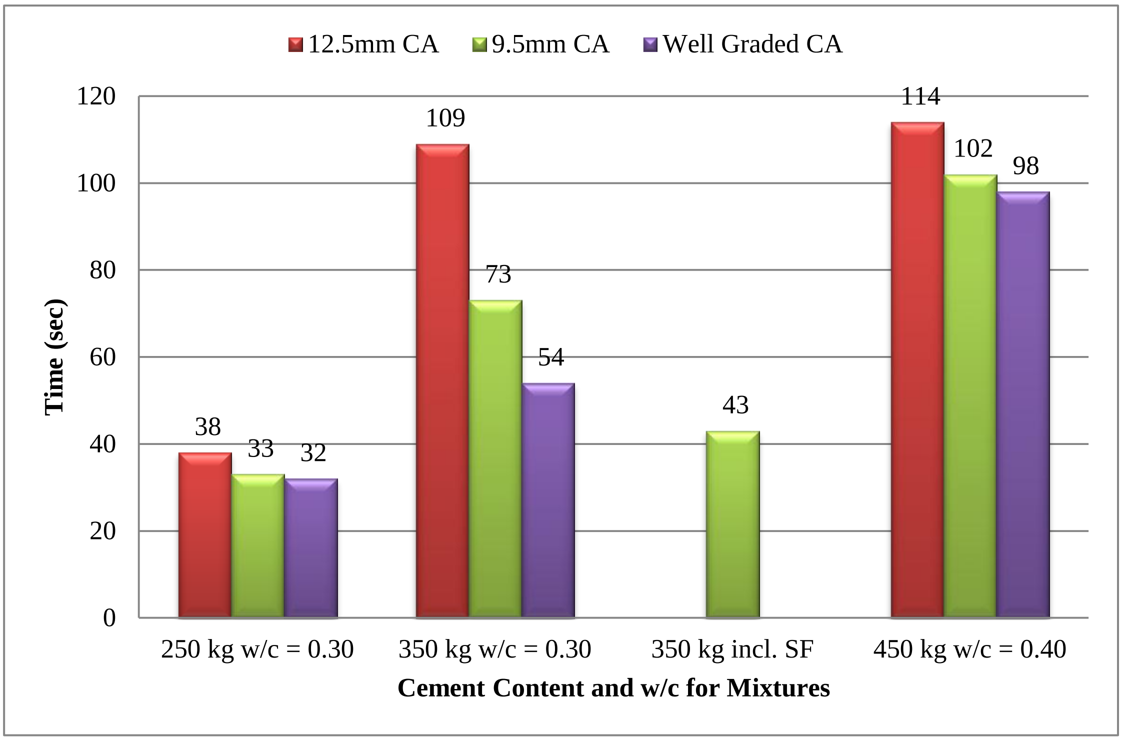


Figure 4.41 Time taken for water to pass through the specimen

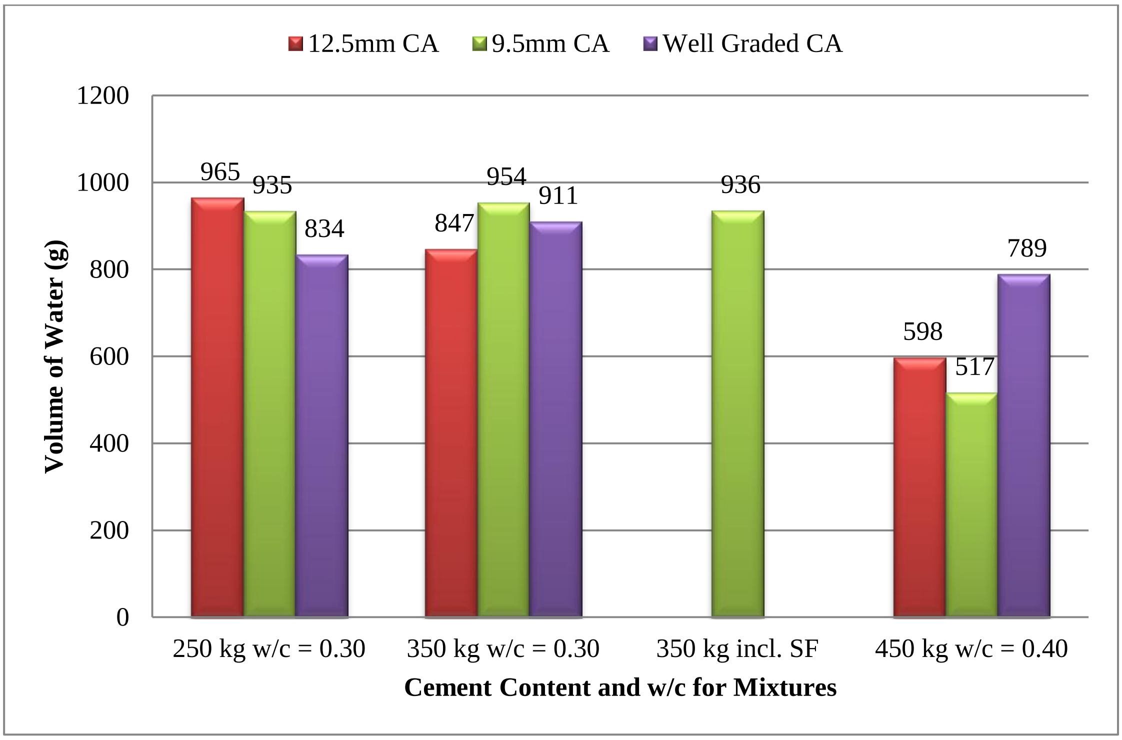


Figure 4.42 Volume of water that passed through the specimen

Figure 4.43 illustrates the total volume of water poured into the Portland cement pervious concrete specimen to show the percentage of water passed, retained by specimen, or lost. It can be seen from Figure 4.43 that all mixtures with 250 kg and 350 kg cement content have passed an average of 91% of the volume of water poured into the specimen as opposed to mixtures with 450 kg of cement which only passed an average of 63%. An average of 4% of the volume of water was retained in the specimen for all mixtures. The major variance occurred for the percentage of water lost which averaged 4%, 6%, and 32% for mixtures with 250 kg, 350 kg, and 450 kg cement content, respectively. This phenomenon could be attributed to the irregular structure of voids within the specimen and the porosity of the bottom of the specimen where water which could not pass through the bottom of the specimen seeped to the sides and escaped through. It is inevitable to mention here that mixtures with 450 kg cement and w/c ratio of 0.4 where significantly more workable than other mixtures and this lead to blockage of pores at the bottoms of the samples as can be seen in Figure 4.44 and Figure 4.45.

Figure 4.46 illustrates the water flow rate through Portland cement pervious concrete mixtures where it ranged from 122 L/m^2/min to 680 L/m^2/min aligning with the ranges deduced from the literature review with the smallest flow rate for mixtures with 450 kg cement and increasing with the decrease of cement content and w/c ratios of the mixtures. However, it is inevitable to mention that those results are specific to 80 mm thick cross sections. The effect of aggregate size and gradation seem to have no specific trend or effect on the water flow rate within the Portland cement pervious concrete mixtures. However, this trend is not well defined and needs further investigations specifically to eliminate the effect of the blockage of the bottom voids of the specimen due to segregation or binding material sinking to the bottom.

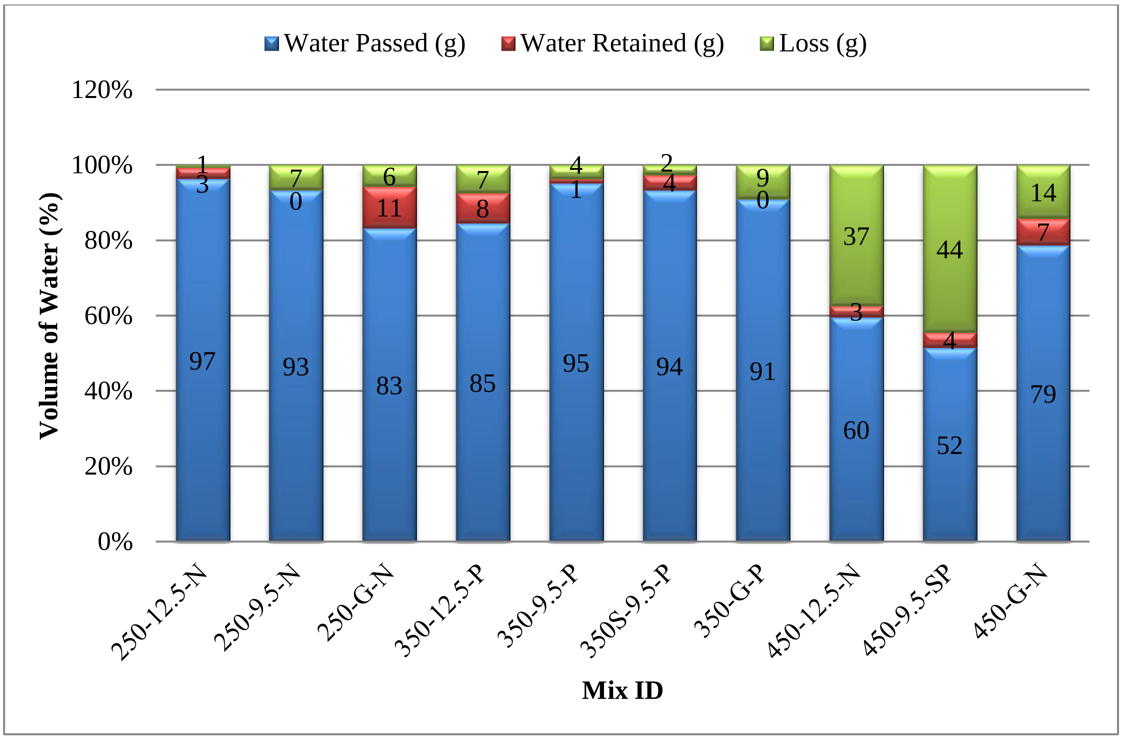


Figure 4.43 Volume of water passed, retained, and lost

Figure 4.44 Impermeable bottom of specimen

Figure 4.45 Water seeping through sides of the sample

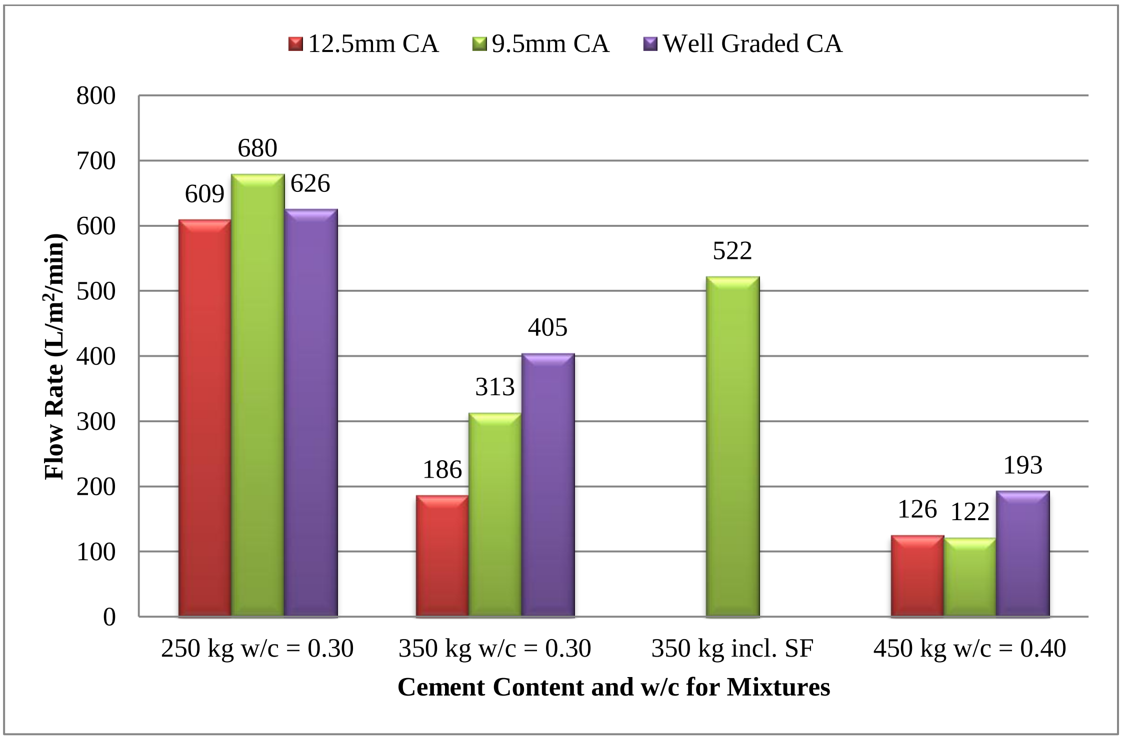


Figure 4.46 Water flow rate for mixtures (L/m^2/min)

4.4 Water Purification Potential

Filtration is an essential procedure that separates suspended particle matter from water. With the various engineering applications of filtration, all mechanical filtration approaches function by passing the solution or suspension through a permeable membrane or medium, upon which the solid particles are retained on the surface or within the pores of the medium, while the fluid, referred to as the filtrate, passes through. Most pollutants, such as viruses and heavy metals may be accompanied with particles (Taghizadeh, et al., 2007). According to Abou Zeid, PCPC mixtures have a good potential in reducing pollutants specifically pollutants like grease and oil and the ability of PCPC to remove harmful metals such as zinc is fair. The ability of PCPC in reducing pollutants of the concrete mixtures was evaluated through testing water purification potential of PCPC mixtures using used vehicle oil, lead as a common heavy metal pollutant, and bacteria with modifying the pH of the water to resemble acid rain.

The first round of tests held yielded no results for bacteria elimination as the coliform source used appeared to contain no bacteria. The effect of PCPC media on the pH of the water also seemed to be negligible as filtered water with original pH of 5.5 yielded results in the range of 5.6 to 5.7. The results of first round of testing lead elimination are tabulated in Table 4.13 and illustrated in Figure 4.47.

Table 4.13 Water purification potential for Lead

Mix ID	Lead mg/L		% Eliminated
	Blank	Result	
250-12.5-N	5.00	4.922	1.6%
350S-9.5-P	5.00	4.631	7.4%
350-9.5-P	5.00	4.813	3.7%
350-G-P	5.00	4.484	10.3%

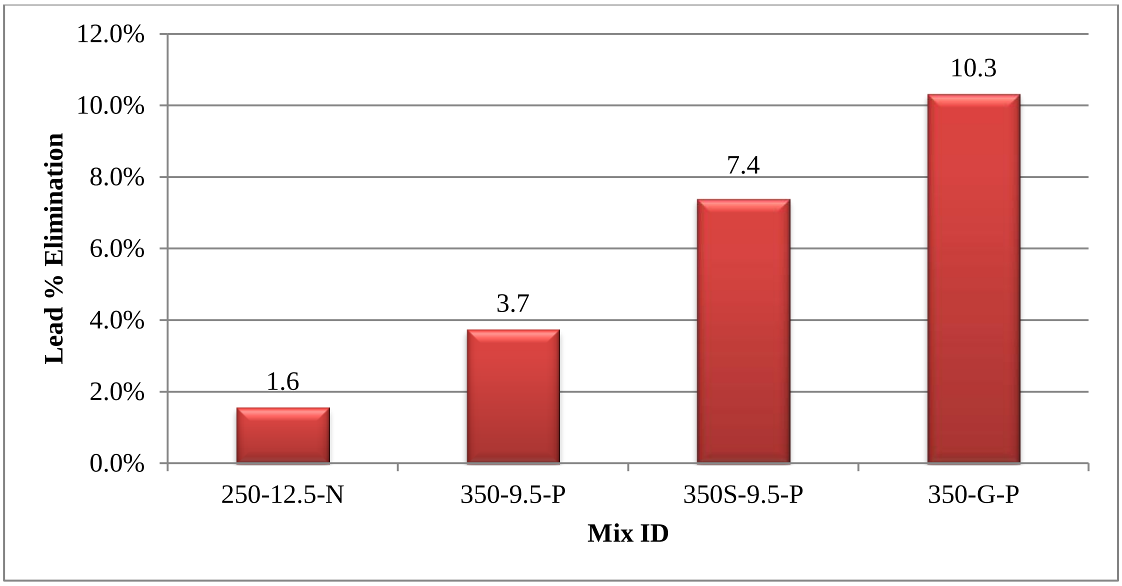


Figure 4.47 Percent elimination of lead from the filtrate

As can be seen from Table 4.13 and Figure 4.47, PCPC mixtures have a potential in reducing harmful metals such as lead although it did not exceed 10.5% removal. Silica fume seems to have enhanced the ability of mixtures to reduce lead as mixture 350S-9.5-P eliminated 7.4% of the lead content whereas the corresponding mixture without SF eliminated only 3.7%. Despite the fact that only four PCPC mixtures were tested for water purification potential in the first round, mixtures with smaller aggregate size and/or graded aggregates seem to have an enhanced potential for reducing pollutants.

Another round of testing was held on the same four specimen with a different coliform source where the media for the raw water sample as well as the effluent water from the four samples tested showed no evidence of a decrease in bacteria as can be seen in Figure 4.48.

Mixture 350-G-P was then retested, as it showed the highest filtration rate for lead, with a diluted coliform source. Only Total Suspended Solids (TSS) and bacteria were examined where the PCPC mixture decreased the TSS of the filtrate from 120 mg/L to 90 mg/L (30% elimination) and again no evidence showed decrease in bacteria as the results were similar to that shown in Figure 4.48.

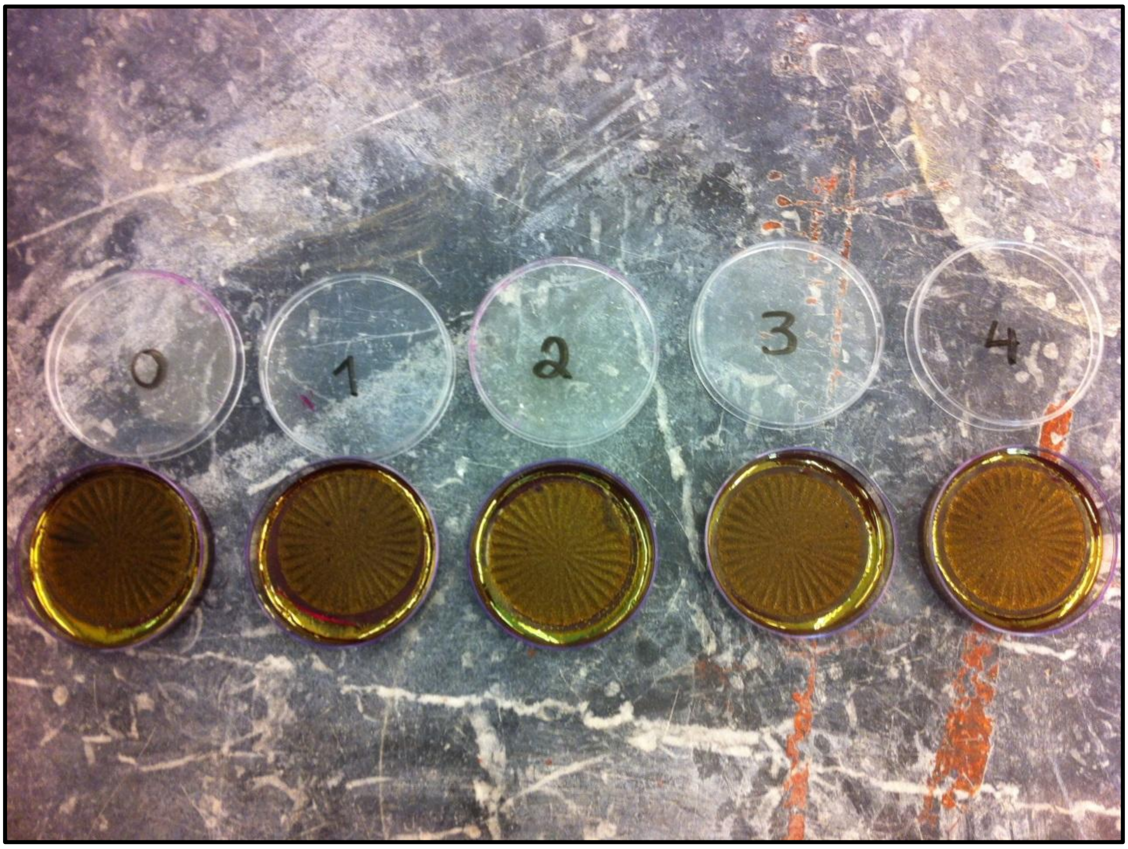


Figure 4.48 Bacteria count

Finally all 10 PCPC mixtures were tested for water purification potential with one liter of a simulated water sample containing 1 L of distilled water, 5 mg/L of lead (10 ml of lead standard solution 1000 mg/L concentration), 5 ml of used vehicle oil, and 20 ml of coliform source. The results of PCPC pollutant elimination are tabulated in Table 4.14 and illustrated in Figure 4.50.

Generally, the PCPC have good potential in reducing pollutants such as oil and grease, suspended particles, harmful heavy metals such as lead, and bacteria. From Figure 4.50 it can be observed that PCPC has eliminated an average of 98.6%, 92.2%, and 98.6% of TSS, bacteria, and oil respectively. PCPC also has a potential in reducing heavy metal pollutants such as lead with removal as high as 14.6%. Visually one can notice the considerable level of water purification. Specimen for mixtures with 450 kg of cement were not sufficiently permeable to achieve water purification results as can be seen in Figure 4.49.

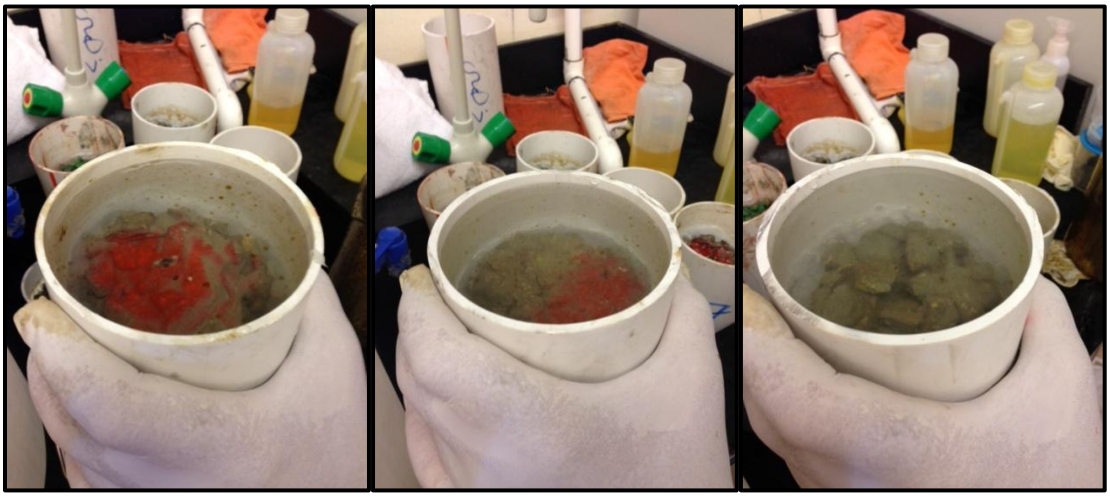


Figure 4.49 specimen for 450 kg cement mixtures

The mixture with silica fume seems to have a higher potential to reduce lead than that of the corresponding mixture that contains no silica fume where 10.8% and 13.7% of the lead was eliminated from the filtrate of mixtures 350-9.5-P and 350S-9.5-P respectively. Moreover, Mixtures made with smaller sized aggregate or graded aggregates seem to have a greater potential for reducing pollutants.

It is important to mention that the purification procedure for lead needs to be further investigated. Lead included in the simulated water sample was dissolved in nitric acid, accordingly the filtration could not have occurred mechanically. The filtration of lead may have been caused by adsorption, specifically when oil was not included in the simulated water sample.

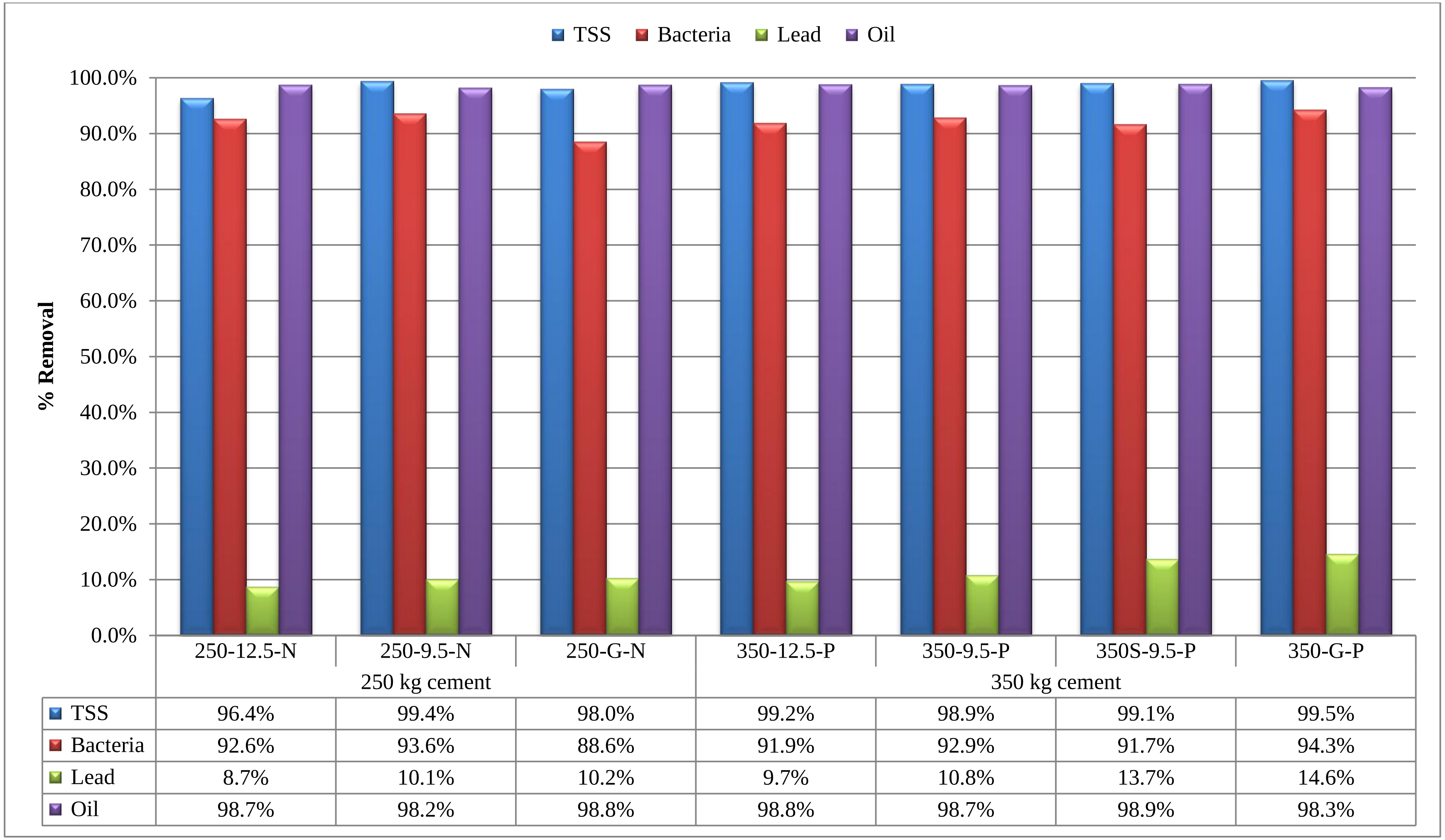
It can also be noticed from the results of the several rounds of testing that when oil/grease is contained within filtrate, the results for elimination of TSS and bacteria are enhanced significantly. Despite the short duration for water passing through the pervious concrete specimen and thus the short contact time between the water and the specimen, reduction of pollutants has took place. However, the limited work of this study did not reveal a well-defined pattern for the relationship between water purification and the water flowablity. Moreover, flowability rates deduced from this test are only specific to 70 mm thick cross sections.

The time taken for the one liter of the simulated water sample to pass through the specimen was recorded and accordingly the permeability was calculated again to reconfirm values achieved in section 4.3.4 above. Figure 4.51 illustrates flow rate calculated for the 100 mm diameter cylinders whereas Figure 4.52 illustrates a comparison of results for both approaches of flow rate calculations. The water flow rate through Portland cement pervious concrete mixtures measured for 100 mm discs ranged from 223 to 688 L/m^2/min as opposed to previous results yielding 122 to 680 L/m^2/min. The highest flowrate achieved in this test corresponds to the mixture with 250 kg cement and well graded aggregates where in the earlier test it corresponded to the mixture with 250 kg cement and single-sized 9.5 mm aggregates. Specimen for mixtures with 450 kg cement were impermeable in this test and thus yielded no results for flowability whereas in the previous test results in the range of 167 L/m^2/min. were reported. The results for flow rate for both experiments align with the ranges deduced from the literature review with the smallest flow rate for mixtures with highest cement content and increasing with the decrease of cement content and w/c ratios of the mixtures. The variances between the flow rates deduced from the two different tests may be attributed to the inconsistent void structure and the difference in specimen size and thickness.

It is inevitable to mention that the flowability calculated herein might not be representative of the actual flowability of a pervious concrete structure due to the fact that when applied the water does not flow from the sample to the air but rather to another soil/subbase system with different permeability and resistance. Further testing procedures are recommended to establish a more representative value for flowability when applied in real life.

Table 4.14 PCPC pollutant elimination

Mix ID	Aggregate Size	Time (sec.)	TSS		Bacteria		Lead		Oil		Flow Rate ($L/m^2/min$)
			mg/L	% Removed	Col./ 100mL	% Removed	mg/L	% Removed	mg/L	% Removed	
Raw Water			2632		840		5.27		3863		
250-12.5-N	Single-sized 12.5 mm	23.47	96	96.4	62	92.6	4.81	8.7	49	98.7	325
350-12.5-P		34.27	22	99.2	68	91.9	4.76	9.7	45	98.8	223
450-12.5-N		-	-	-	-	-	-	-	-	-	-
250-9.5-N	Single-sized 9.5 mm	17.10	16	99.4	54	93.6	4.74	10.1	68	98.2	447
350-9.5-P		18.20	30	98.9	60	92.9	4.70	10.8	50	98.7	420
350S-9.5-P		22.20	24	99.1	70	91.7	4.55	13.7	42	98.9	344
450-9.5-SP		-	-	-	-	-	-	-	-	-	-
250-G-N	Graded	11.10	52	98.0	96	88.6	4.73	10.2	48	98.8	688
350-G-P		12.32	12	99.5	48	94.3	4.50	14.6	65	98.3	620
450-G-N		-	-	-	-	-	-	-	-	-	-



	250-12.5-N	250-9.5-N	250-G-N	350-12.5-P	350-9.5-P	350S-9.5-P	350-G-P
	250 kg cement			350 kg cement			
🟦 TSS	96.4%	99.4%	98.0%	99.2%	98.9%	99.1%	99.5%
🟥 Bacteria	92.6%	93.6%	88.6%	91.9%	92.9%	91.7%	94.3%
🟩 Lead	8.7%	10.1%	10.2%	9.7%	10.8%	13.7%	14.6%
🟪 Oil	98.7%	98.2%	98.8%	98.8%	98.7%	98.9%	98.3%

Figure 4.50 PCPC pollutant removal results

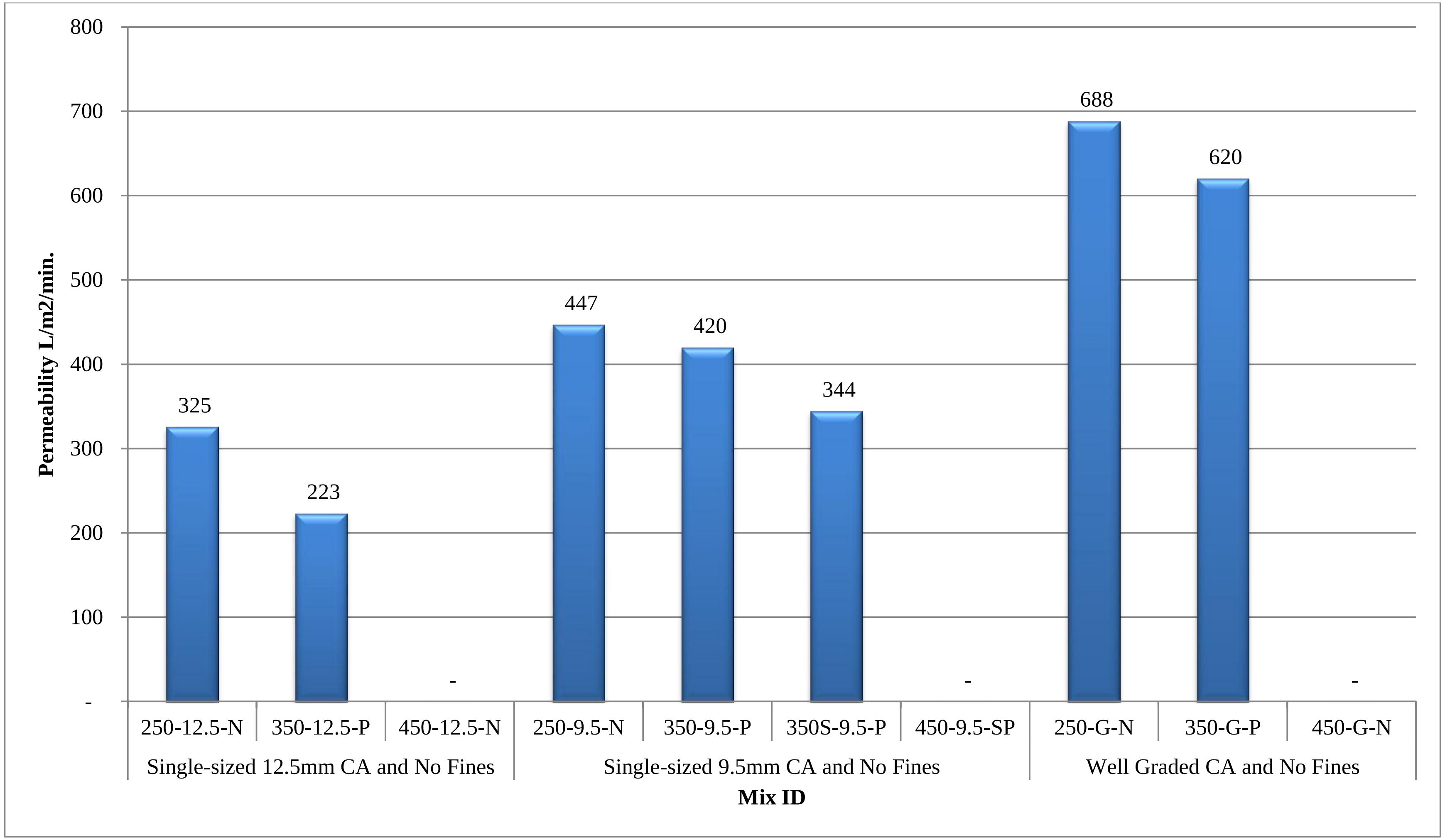


Figure 4.51 Permeability of PCPC Discs

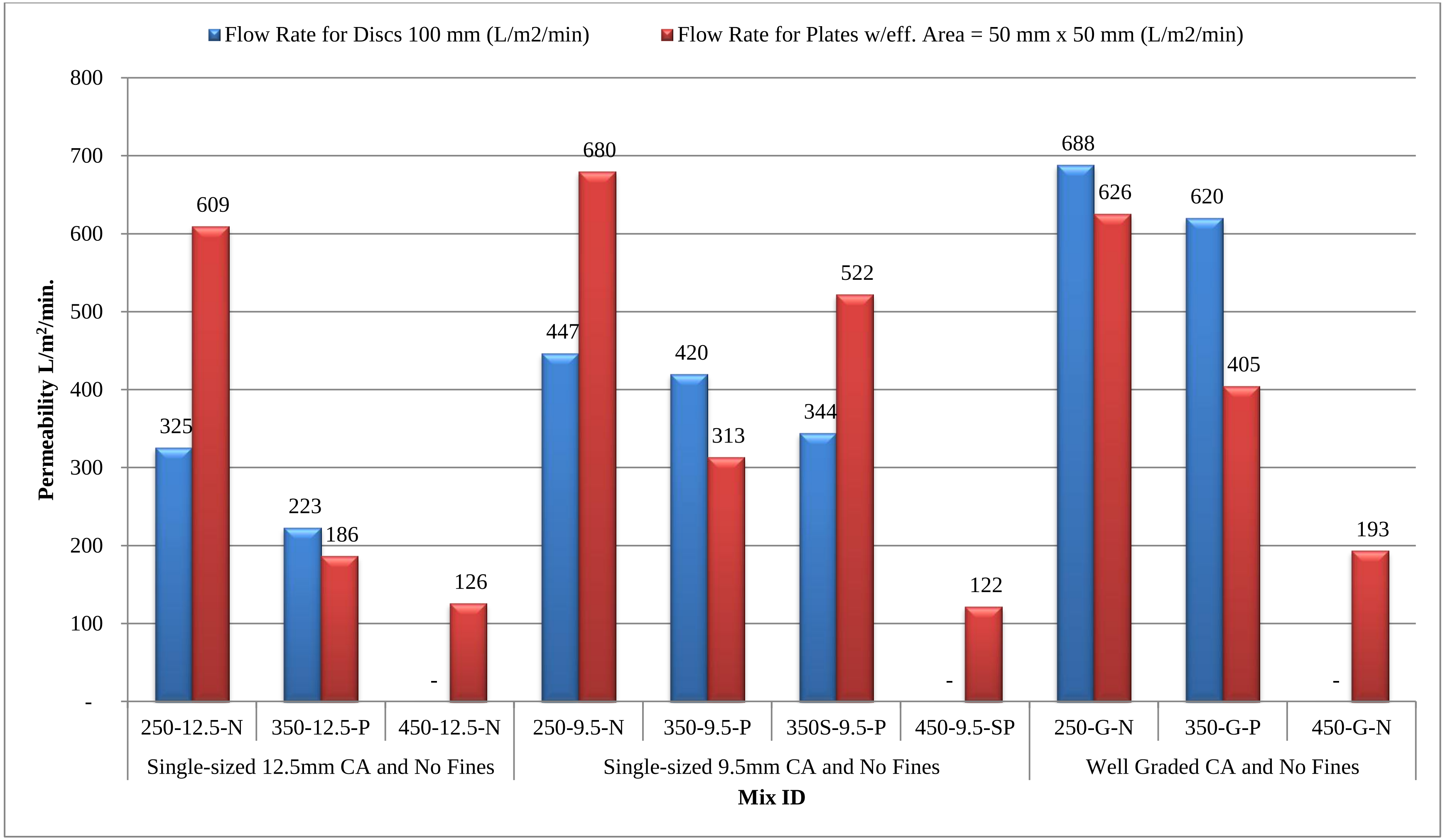


Figure 4.52 Flow rate for different specimen size and type

The effect of aggregate size and gradation in the later test seem to affect the flowability of water through the specimen as illustrated in Figure 4.51. Graded aggregates seem to enhance permeability followed by one-sized 9.5 mm aggregates as opposed to the earlier test were a well-defined trend or effect on the water flow rate was obvious. However, taking inconsistencies in specimen and test results into account, PCPC mixtures generally allow a significant amount of water to flow through where the thickness of the specimen was not considered in the flow rate calculations.

Adjusting the concrete mix design to allow for a lower flow rate may result in further reduction of pollutants. Hence, it is advisable to adjust the mix proportions to achieve an adequate flow rate together with the targeted level of water purification and also mechanical properties.

4.5 Potential Applications

In light of the aforementioned results of water purification, PCPC has a potential use in oil and related industries, food industries involving oil and organic/bacterial waste, gas stations, maintenance workshops disposing a substantial amount of oil waste, and shipyards.

4.6 Economic Merit

As elaborated in chapter 2, while the cost of material and installation cost of pervious concrete might be somewhat higher than that of conventional concrete, there are counterweighing savings for large projects because the need for underground piping, storm drains, retention ponds, swales, and other storm water management systems is eliminated. Moreover, the feasibility of a pervious concrete system increases under the following circumstances:

- high/sufficient flow rate/permeability,
- rainy zones or areas of frequent flooding,
- high cost of drainage and plumbing systems,

- occasional damage/corrosion of conventional drainage systems,
- high risk of accidents and other economic losses due to water accumulation and/or ponding on roadways, and
- health and pollution hazards due to water ponding and stagnation.

The cost of a concrete system can be calculates as follows:

$$Cost = Capital\ Cost + Operation\ and\ Maintenance + Environmental\ Cost + Hydrological\ Cost \qquad [4.1]$$

Both conventional and pervious systems incur capital and operation cost. Conventional concrete systems incur additional environmental and hydrological costs.

The capital cost is the material, labor, and equipment cost for installing the concrete which is higher in the case of pervious concrete as illustrated in Table 4.15 and Table 4.16. In Table 4.17 and Table 4.18 a cost comparison for a 1000 m^2 parking lot constructed using conventional rigid pavement (150 mm concrete pavement, 100 mm capillary water barrier, 100 mm base course, and 150 mm subgrade layer) and pervious concrete has been done. The assumed pervious concrete design is illustrated in Figure 4.53 after Tong (2011). The capital cost for pervious concrete is 49% more expensive than that of conventional concrete.

Table 4.15 Cost of materials for conventional concrete mixture per for 1 m^3

Item	Qty.	Unit	Price (L.E.)	Cost (L.E.)
Cement	0.45	ton	550.00	247.50
Water	190	L	0.003	0.57
Coarse Aggregates	0.41	m^3	187.50	76.88
Fine Aggregates	0.32	m^3	84.00	26.88
Total				**351.83**

Table 4.16 Cost of materials for pervious concrete mixture per for 1 m^3

Item	Qty.	Unit	Price (L.E.)	Cost (L.E.)
Cement	0.45	ton	550.00	247.50
Water	165	L	0.003	0.50
Coarse Aggregates	0.85	m^3	187.50	159.38
Fine Aggregates		m^3	84.00	-
Total				**407.37**

Table 4.17 Cost estimate for 1000 m^2 conventional parking lot in Egypt

Item	Qty.	Unit	Unit Price (L.E.)	Total (L.E.)
Material				
150 mm Subgrade Layer	180	m^3	37.50	6,750.00
100 mm Base Course	120	m^3	187.50	22,500.00
100 mm Capillary Water Barrier	100	m^3	180.00	18,000.00
150 mm Concrete Pavement	180	m^3	351.83	63,328.50
Subtotal				110,578.50
Equipment				
Concrete Paver	180	1	0.98	176.12
Curing Machine	180	1	0.21	37.38
Dump Truck	180	1	0.13	22.89
Backhoe	180	1	0.32	57.68
Water Tanker	180	1	0.20	35.31
Aggregate Base Course Equipment	120	1	35.78	4,293.00
Subtotal				4,622.38
Labor				
Concrete Finisher Forman	180	1	0.14	25.07
Concrete Finisher	180	8	0.07	103.32
Carpenter	180	5	0.06	54.23
Helper	180	5	0.04	32.18
Subtotal				214.79
Grand Total Capital Cost				**115,415.67**

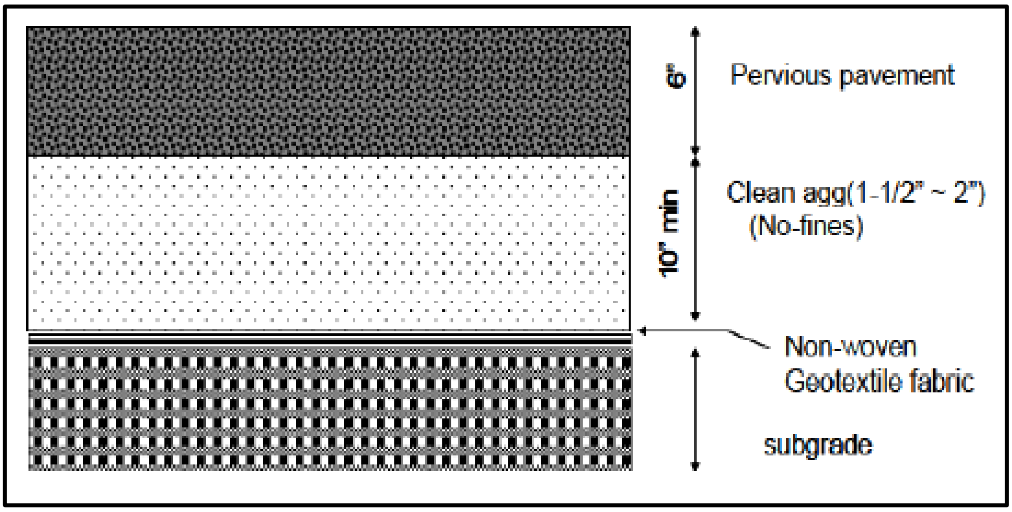


Figure 4.53 Pervious concrete design for heavy traffic (Tong, 2011)

Table 4.18 Cost estimate for 1000 m^2 pervious parking lot in Egypt

Item	Qty.	Unit	Unit Price (L.E.)	Total (L.E.)
Material				
300 mm Base Course	360	m^3	187.50	67,500.00
100 mm Capillary Water Barrier	100	m^3	180.00	18,000.00
150 mm Pervious Concrete Pavement	180	m^3	407.37	73,326.60
Subtotal				158,826.60
Equipment				
Vibrator Screed	180	1	0.85	153.23
Curing Machine	180	1	0.68	121.50
Truck Mixer	180	1	0.62	111.38
Water Tanker	180	1	0.64	114.75
Aggregate Base Course Equipment	360	1	35.78	12,879.00
Subtotal				13,379.85
Labor				
Civil Forman	180	1	0.28	50.13
Concrete Finisher	180	5	0.14	129.15
Carpenter	180	5	0.12	108.45
Helper	180	10	0.07	128.70
Subtotal			0.61	416.43
Grand Total Capital Cost				**172,622.88**

Operation and maintenance of pervious concrete is also more expensive than that for conventional concrete as long-term maintenance is required by routine quarterly vacuum sweeping for removal of fine sediments from the paved surface to optimize permeability. According to the EPA (1999), four inspections per year involving proper jet hosing and vacuum sweeping treatments are needed for the maintenance of a pervious concrete surface.

However, although needs many socioeconomic studies to quantify, the environmental costs are incurred for the conventional concrete system. Environmental costs include requirements for additional investment in drainage systems to comply with environmental regulations of fees/fines for noncompliance. Environmental costs also include the savings caused by the reduced urban heat island effect (LEED Sustainable Sites Credit 7.1) as less energy is consumed to light the parking area as well as to cool a building on peak energy-demand days due to the decreased ambient temperatures caused by the more reflective pavement. Moreover, additional hydrological costs are saved such as the cost of rain water collected and used and the cost of preventing damages caused by storm water runoff though costs for treating the collected water for reuse may be incurred. Therefore, a pervious concrete system may be feasible on the long run. The following case studies were reported to have incurred cost savings due to utilizing pervious concrete.

1. The North Central Pennsylvania Asphalt Project Case Study

The North Central Pennsylvania Asphalt Project constructed a 1465 square meter (15774 square feet) parking lot which was originally designed with an underground detention system and asphalt paving; one catch basin and one water quality unit. The detention system was constructed of plastic storm chambers. The cost associated with the impervious system was compared to 150 mm (6 in.) of pervious concrete with a 300 mm (12 in.) gravel storage base as illustrated in Table 4.19 which illustrates that a cost saving of almost 20% was incurred due to utilizing pervious concrete.

Table 4.19 Traditional as opposed to pervious project cost comparison

Cost Item	Traditional Design	Pervious Concrete Design
Detention System Costs	$56,094.99	
Asphalt Paving Costs	$57,350	
Pervious Concrete and 300 mm Gravel Retention		$91,201
Project Total	**$113,444.99**	**$91,201***

http://www.specifyconcrete.org/assets/docs/PACA_pervious_insert_sheet.pdf

2. Stratford Place Residential Project Case Study

The Stratford Place residential project, the community of Sultan, Washington, was the first in Washington to use pervious concrete for all its surfaces. Initially, three or four driveways were poured to get the sense for placing the pervious concrete, and then set out to place 2972 square meters (32,000 square feet) throughout Stratford Place including driveways, sidewalks, and the main street. The construction also included 20 new homes with a 6 m (20 ft.) wide roadway and 1.2 m (4 ft.) integrally colored sidewalks. Pervious concrete was used as a 2-part on-site storm water management system consisting of pervious concrete pavement 200 mm (8 in.) and a coarse gravel retention layer 200 mm (8 in.) for storm water storage. An initial soils site survey and site specific storm water calculations for volume and duration were held as the basis of the design of the retention/recharge area include.

The benefits of pervious concrete for storm water management and other green solutions are many. Moreover, many construction costs were eliminated with the use of pervious concrete. As per Concrete Network (2013), the use of pervious concrete at the Stratford Place residential project resulted in an overall cost saving exceeding $260,000 in construction costs as it eliminated costs for storm water catch basins, embeds, and piping infrastructure labor, Interior plat curbing, asphalt roadway system, and the storm water system. Moreover the builder reclaimed two additional lots versus land used for detention vaults.

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the materials, techniques and other parameters associated with this work and taking inconsistencies in some of the results into account, the following conclusions can be drawn:

1. Of the limited number of mixtures studied, mixtures with 350 kg cement and one-sized 12.5 mm aggregates seem to have compensating mechanical and hydrological properties with a slump of 120 mm, unit weight of 1940 kg/m^3, 28-day compressive strength of 18.16 MPa, Flexural strength 3.75 MPa, and moderate water flowability, chemical durability, and resistance to elevated temperatures. Yet, different applications may require a different combination of properties. For example, compensating further compressive strength for permeability or vice versa.
2. Fresh Portland cement pervious concrete (PCPC) has lower slump than conventional concrete. The validity of the slump test itself is questionable when applied to PCPC mixtures.
3. The PCPC has significantly less unit weight than conventional concrete that can be as low as 1500 kg/m^3. PCPC mixtures made with higher cement content and mixtures with single-sized 12.5 mm coarse aggregates yielded relatively higher unit weight compared to other PCPC mixtures.
4. On the whole, fresh concrete temperature as well as air content did not vary significantly for the PCPC compared to conventional concrete mixtures. The air content measured in the fresh state does not reflect the actual void content in the hardened state.
5. The PCPC mixtures produced in this study allowed for water permeability and drainage with water passing percent as high as 91%. However, the limited

work of this study did not reveal a well-defined pattern of water flowablity and mix design proportioning.

6. Almost all PCPC mixtures suffered a sharp drop in compressive strength at all ages. However, mixtures made with 450 kg of Portland cement still can attain strength as in the lower bound of structural concrete. Low w/c and the use of fine aggregates resulted also low strength results.
7. The PCPC attained 80% of the final 90 day strength at 28 days with a few exceptions that reached 110% of their final compressive strength at 28 days. Introducing silica fume had contradicting strength patterns after 28 and 90 days.
8. At 28-day, PCPC mixtures yielded modulus of rupture ranging from 0.36 MPa to 4.6 MPa which are similar or higher than control mixtures. The modulus of rupture increased with the increase of the cement content. These values were not as typical as ones predicted empirically.
9. Due to the massive void content, the rapid chloride permeability test did not result in meaningful results for the tested PCPC mixtures. Other tests need to employed to assess PCPC permeability.
10. Cement content is an influential factor for chemical durability of PCPC. On the whole, PCPC made with 450 kg cement had relatively best performance when exposed to sulfuric acid. Increase in mass when specimens submerged to magnesium sulfate is likely due to crystallization.
11. The chemical durability of pervious concrete mixtures soaked in hydrochloric acid or magnesium sulphate did not exhibit a well-defined trend. This could be due to the random distribution of voids in the concrete.
12. Loss in compressive strength due to elevated temperature exposure was in the range of 5 to 38%. Mixtures with one-sized 12.5 mm coarse aggregate and mixtures with well graded coarse aggregates have yielded the least loss.

13. Flow rate through Portland cement pervious concrete mixtures ranged from 122 to 688 L/m^2/min. which is in agreement of previous work. Lowest flow rate were witnessed for mixtures made with 450 kg cement, high w/c ratio of the mixtures with no pronounced effect for the aggregate size and gradation.
14. The PCPC have good potential in reducing harmful metals such as lead with higher potential for silica fume mixtures to reduce lead. PCPC mixtures had good potential in reducing oils, TSS, and bacteria as high as 98.9%, 99.5, and 14.6% respectively.
15. Mixtures made with small sized aggregate or graded aggregates seem to have a higher potential for reducing pollutants.

5.2 Recommendations for Future Research Work

Similar to other studies in new fields, several recommendations for future work need to be addressed as follows:

- The findings herein of this study needs to be validated by wider scale studies involving diverse constituent materials, larger sets of specimens and an expanded scope of experimental work.
- The effect of specimen preparation and compaction techniques on the permeability and performance of PCPC need to be further investigation.
- Both chemical and mineral admixtures need a closer look in order to rationalize their use and maximize their benefits in PCPC.
- There is a true need to develop a form of correlation between PCPC mix proportions and expected water flow, expected mechanical properties, and potential water purifications.
- Long-term properties including creep, fatigue, and extended abrasion resistance need to be examined for PCPC mixtures.

- The potential for water purification should be examined through a wider scope of testing incorporating different pollutants and eliminating other variables within the test.
- A long-term water purification test shall be held to examine the effect of accumulated pollutants and suspended particles on the clogging of the pervious surface in addition to the effect of time on the leaching potential of pollutants retained in the concrete.
- Microscopic studies are recommended in order to better understand the pore structure and the void distribution of PCPC concrete mixtures.
- Pilot experiments and prototypes in parts of highways or sidewalks are recommended in which feasibility and economic merits are to be better addressed.

5.3 Recommendations for the Construction Industry

- Concrete users need to consider PCPC in applications such as parking lots, highway shoulders, pedestrian pavements, and industrial hangers particularly when pollutants are present.
- The industry needs to have a closer look in applications of Portland cement pervious concrete where reduction of pollutants is of an essence.
- It is recommended to include a provision in the Egyptian Code for PCPC with some clear guidelines for its production. This is of particular interest in Green Code provisions where environmental merits are highly considered.
- A full-scale feasibility study is recommended for applicators in which alternative materials and drainage and purification systems are put in comparison.

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