ENGINEERING PROPERTIES OF PERVIOUS CONCRETE CONTAINING PALM OIL CLINKER AGGREGATE

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ENGINEERING PROPERTIES OF PERVIOUS CONCRETE CONTAINING PALM OIL CLINKER AGGREGATE

ABSTRACT

In recent time, frequent flooding has been occurring in major cities around the world due to the combination of increased rainfall and high rate of impermeable surface areas. Pervious concrete is widely accepted as an emerging technology for storm water management. This research was focused on adopting locally available waste material in producing eco-friendly pervious concrete. The aim of this study was to develop pervious concrete containing palm oil clinker (POC) coarse aggregates as an alternative replacement for natural aggregates. Mix proportions were based on four different cement contents at a constant water to cement ratio and cement to aggregate ratio respectively. The effects of mix constituents; aggregate size, cement content and curing method on the properties of the concrete were investigated. Two single-sized grades of aggregates were investigated for POC pervious concrete under three curing methods. The volumetric replacement levels of aggregates with POC were 0%, 25%, 50, 75% and 100%. Engineering properties including compressive strength, porosity, permeability, abrasion resistance and density, as well as sustainability efficiency of the concrete were studied. Generally, increasing the cement content led to increased compressive strength, density and abrasion resistance, while porosity and permeability of the concrete reduced. Meanwhile, the effect of increasing the cement content was marginal compared to the effect of incorporating POC aggregate into the concrete mix. POC aggregate properties such as ACV, L.A abrasion value, shape, size and texture played a vital role in the skeleton structure formation of the concrete. POC being a friable material with pores and irregularly shaped negatively affected the engineering properties of the POC pervious concrete. However, POC pervious concrete mixes containing 9.5mm aggregate sizes showed better engineering properties than the mixes with 12.5mm aggregate size. Since abrasion resistance test is dependent not only on compressive strength and porosity of the concrete but also the surface finishing of the concrete, the surface roughness of POC aggregate influenced the outcome of the POC pervious concrete resistance to abrasion. Furthermore, the effect of curing was minimal on the mechanical properties of the concrete. Curing the concrete in air resulted in about 10% loss in compressive strength due to uncontrolled temperature and humidity condition. However, abrasion resistance of the concrete was improved when full water curing was adopted, whereas air curing method was the least effective. Based on the inter-relationship between the compressive strength, porosity and coefficient of permeability of the POC pervious concrete, optimum mix was identified as 25% POC replacement with POC pervious concrete containing 9.5mm nominal size aggregate. This study concludes that the POC pervious concrete is not suitable for structural application due to its reduced strength. However, it could be acceptable for other applications where the concrete will not be subjected to heavy loads. Incorporation of POC into the concrete mix reduced discharge of CO_2 which is dangerous to the environment by 20%.

Keywords: pervious concrete, palm oil clinker, sustainability

SIFAT KEJURUTERAAN KONKRIT TELAP MENGANDUNGI AGREGAT KLINKER KELAPA SAWIT

ABSTRAK

Dewasakini, banjir kerap berlaku di bandar-bandar utama di seluruh dunia kerana taburan hujan yang meningkat dan kadar kawasan permukaan tidak telap yang tinggi. Penmakaian konkrit telap telah diterima secara meluas sebagai teknologi baru untuk pengurusan air ribut. Kajian ini tertumpu kepada penggunaan bahan buangan tempatan sedia ada dalam menghasilkan konkrit telap yang mesra alam. Tujuan kajian ini adalah untuk menghasilkan konkrit telap yang menggunakan klinker kelapa sawit (POC) sebagai agregat kasar menggantikan agregat semula jadi. Campuran konkrit telap ini adalah berdasarkan empat nisbah simen yang berbeza pada nisbah air yang tetap dan nisbah simen kepada nisbah agregat. Kesan kadar campuran; penggredan agregat, kandungan simen dan kaedah pengawetan ke atas sifat konkrit telah dikaji. Dua gred agregat bersaiz tunggal telah digunakan dalam kajian POC konkrit telap bawah tiga kaedah pengawetan. Tahap penggantian isipadu agregat dengan POC adalah 0%, 25%, 50, 75% dan 100%. Sifat kejuruteraan termasuk kekuatan mampatan, keliangan, kebolehtelapan, rintangan lelasan dan ketumpatan, dan kemampanan konkrit telah dikaji. Secara umumnya, meningkatkan kandungan simen membawa kepada peningkatan ketumpatan, kekuatan mampatan dan rintangan lelasan, manakala keliangan dan kebolehtelapan konkrit dikurangkan. Sementara itu, kesan meningkatkan kandungan simen adalah kecil berbanding kesan menggabungkan POC agregat ke dalam campuran konkrit. Sifat agregat POC seperti ACV, nilai lelasan L.A, bentuk, saiz dan tekstur memainkan peranan yang penting dalam pembentukan struktur rangka konkrit. POC menjadi bahan rapuh berliang dan berbentuk tidak sekata menjejaskan ciri-ciri kejuruteraan POC konkrit telap itu. Walau bagaimanapun, campuran POC konkrit telap mengandungi agregat bersaiz 9.5mm telah menunjukkan sifat kejuruteraan yang lebih baik daripada campuran yang menggunakan agregat bersaiz 12.5 mm. Oleh kerana ujian rintangan lelasan bukan sahaja bergantung kepada kekuatan mampatan dan keliangan konkrit, tetapi juga kepada kemasan permukaan konkrit, kekasaran permukaan POC agregat mempengaruhi hasil rintangan POC konkrit telap lelasan. Tambahan pula, pengawetan mempengaruhi ke atas sifat konkrit adalah minimum. Pengawetan konkrit di udara menyebabkan kira-kira 10% kehilangan kekuatan mampatan disebabkan oleh suhu yang tidak terkawal dan keadaan kelembapan. Walau bagaimanapun, rintangan lelasan konkrit bertambah baik apabila pengawetan air sepenuhnya digunapakai, manakala kaedah pengawetan udara adalah yang paling kurang berkesan. Berdasarkan saling hubungan antara kekuatan mampatan, keliangan dan pekali kebolehtelapan konkrit telap POC, campuran optimum POC sebanyak 25% telah dikenal pasti sebagai pengganti dengan konkrit telap POC mengandungi 9.5mm nominal saiz agregat. Kajian ini menyimpulkan bahawa konkrit telap POC tidak sesuai untuk aplikasi struktur kerana kekuatannya rendah. Walau bagaimanapun, ia mungkin boleh diterima untuk aplikasi lain di mana konkrit ini tidak akan tertakluk kepada beban berat. Pemakaian POC ke dalam campuran konkrit akan mengurangkan sebanyak 20% pelepasan CO_2 yang berbahaya kepada alam sekitar.

Kata kunci: Penmakaian konkrit, klinker kelapa sawit, kemampanan

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LIST OF SYMBOLS AND ABBREVIATIONS

ρ	:	Hardened density
a/c	:	Aggregate to cement
AAC	:	Autoclaved aerated concrete
AASC	:	Alkali activated slag cement
ACI	:	American Concrete Institute
ACV	:	Aggregate crushing value
ASTM	:	American Standard for Testing Materials
BA	:	Bottom ash
BS	:	British Standard
CO_2	:	Carbon Dioxide
CPO	:	Crude palm oil
DECC	:	Department for Energy and Climate Change
EAFS	:	Electric arc furnace slag
ETP	:	Economic Transformation Program
f_c	:	Compressive strength
FA	:	Fly ash
GHG	:	Greenhouse gas
ITZ	:	Interfacial zone
k	:	Coefficient of permeability
LA	:	Los Angeles
LWA	:	Lightweight aggregates
LWC	:	Lightweight concrete
LWPC	:	Lightweight pervious concrete
MF	:	Mesocarp fIbre

NA	:	Natural aggregate
NKEA	:	National Key Economic Areas
NWA	:	Normal weight aggregate
NWC	:	Normal weight concrete
OPBC	:	Oil palm boiler clinker
OPC	:	Ordinary Portland cement
OPKS	:	Oil palm kernel shell
OPS	:	Oil palm shell
PA	:	Pumice
POC	:	Palm oil clinker
POFA	:	Palm oil fuel ash
POCP	:	Palm oil clinker powder
RA	:	Recycled aggregate
RBA	:	Recycled block aggregate
RCA	:	Recycled concrete aggregate
RHA	:	Rice husk ash
RW	:	Recycled waste
S.E	:	Structural efficiency
SA	:	Fine sand
SBP	:	Seashell by-products
SDA	:	Sawdust ash
SEM	:	Scanning electron microscope
SSD	:	Saturated surface dry
UPV	:	Ultrasonic pulse velocity
w/c	:	Water to cement
XRD	:	X-ray Diffraction

XRF	:	X-ray Fluorescence

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CHAPTER 1: INTRODUCTION

1.1 Background

Malaysia is a country located in a geologically stable region safe from most natural disasters, such as volcanic activities and earthquakes among others, which its neighbouring countries are exposed to. However, the country is not totally free from natural disasters as major reoccurring disaster of flood often hits the country. Floods are considered as the most natural disaster which inflicts damages worth millions yearly in Malaysia (Aisha, Wok, Manaf, & Ismail, 2015). Due to the geographical characteristics of the country, there is abundance of rainfall occurring annually in all the four regions of the country during the monsoon season. An average rainfall of 2,500mm is recorded annually for all the states in Malaysia, this makes it one of the countries with heaviest rainfall in the world (Khalid & Shafiai, 2015). The basic cause of flood worldwide is as a result of the combined effect of increased rainfall and high rate of impermeable surface areas in major cities. The amount of impervious surfaces and the environmental problems associated with it is likely to increase because of the increasing population of people, approximately 50% of the world, now residing in the urban environments (Mullaney & Lucke, 2013). An impermeable surface will decrease infiltration of rainfall water thereby leading to increased water volume and peak storm water discharges which can result in flash flooding, stream-bank erosion, sewer surcharges, and the need to increase expensive drainage infrastructure capacity (Boogaard, Lucke, & Beecham, 2013; Nguyen, Sebaibi, Boutouil, Leleyter, & Baraud, 2014). Thus, the magnitude and frequency of flood occurrence in Malaysia has increased in recent decades due to fast growing development in the country. Statistics has revealed that about 68% of the country's population resides in urban areas. Thus, thousands of Malaysians are faced with despair every year due to floods. Since the monsoon flood event which occurred in the 1990s, flash flooding are currently identified as the most critical flooding type occurring in urban areas in Malaysia

(Chan, 2015; Mohit & Sellu, 2013). The pool of water on the road during a rainy day resulting from the flooded impermeable surfaces reduces not only the traffic safety of vehicle but that of the foot passenger as well. Consequently, various researches have led to the emergence of different storm water management system for flood control. Some of the methods adopted in the past include planting vegetation to hold excess flood water, floodway construction to divert flood water, retention ponds and reservoir to retain water from flooding, and so on. Other approaches such as water sensitive urban design in Australia, sustainable urban drainage systems in Europe and low impact development in the USA and Japan are being adopted in recent time. As time passed by, researchers are now focused on reducing impermeable surfaces through the use of porous surface in the form of pervious concrete. Pervious concrete is an emerging technology for mitigating impact of urbanization on the environment. Globally, considerable research is being done on pervious concrete and recent studies have indicated that pervious concrete is the best solution for rainfall storm water management and one of the key elements of sustainable development as identified by United State Environmental Protection Agency (Nguyen et al, 2014).

On the other hand, global trend is currently focusing on recovery of reusable waste materials and the utilization of raw materials from waste in construction whenever feasible. This can be done when the means to put waste into an alternative beneficial use is explored. Utilization of these materials will not only reduce the need for landfill for waste disposal but reduce consumption of natural material resources and save cost (Sata, Wongsa, & Chindaprasirt, 2013). Plenty of waste products from the agricultural industry such as palm oil clinker (POC), rice husk ash (RHA), sawdust ash (SDA), palm oil fuel ash (POFA), rubber aggregate and bagasse ash are currently being used in producing different types of concrete. POC is a palm oil mill by-product and is abundantly available in large quantity in Malaysia in the form of waste. They are generally irregularly shaped, porous in nature, with good lightweight characteristics and can serve as a potential construction material due to its physical and chemical properties (Abutaha, Abdul Razak, & Kanadasan, 2016; Kanadasan & Razak, 2014b, 2015; Mohammed, Al-Ganad, & Abdullahi, 2011; Mohammed, Foo, & Abdullahi, 2014). Studies on utilizing POC in pervious concrete have been limited, indicating the relevance of this study. Therefore, this study proposes to exploit the possible use of a locally available agro-waste, palm oil clinker, in the production of pervious concrete due to its environmental benefits.

1.2 Problem statement

In the past few decades, Malaysia has experienced its fair share of floods disaster. Flood is considered as one of the most destructive weather-related problems the country is facing since the 1990s. Monsoon flood and flash flood are the two major types of floods that occur in Malaysia. Recently, one of the most severe floods experienced by the country occurred from December 2014 to January 2015. Over 100s thousand flood victims were displaced from their respective homes with many lives and material possessions lost in the process (Aisha et al., 2015). Due to the fast ongoing development in the country, incidences of flash flood is on the rise particularly in urban areas which is characterized with quite a number of impermeable surfaces (Khan, Shaari, Bahar, Baten, & Nazaruddin, 2014). Since flood is a natural disaster that is beyond the control of human beings, its recurrence remains inevitable and its extent cannot be accurately predicted. However, reducing the presence of impermeable surfaces could help to mitigate its effect on the environment and community at large. Having permeable surfaces will allow storm water from rainfall infiltrate into the ground and channelled to reservoirs thereby decreasing accumulation of water which can lead to flood. Utilization of pervious concrete is deemed as suitable solution due to its high porosity. Pervious concrete is a concrete type which comprises of little or no sand, controlled amount of water, cement and uniformly graded coarse aggregate (JT Kevern, Schaefer, Wang, & Suleiman, 2008;

Nguyen et al., 2014). The coefficient of permeability of pervious concrete typically varies from 6.1mm/s to 0.25mm/s, with 14% to 35% void ratio range and the compressive strength at 28 days is generally between 2.8MPa and 28MPa.

Most of the past studies on pervious concrete have frequently utilized natural aggregate (NA) such as quartzite, dolomite, crushed gravel, granite and limestone among others as coarse aggregate. Meanwhile, there are doubts concerning the use of recycled aggregate (RA) or recycled waste materials (RW) in pervious concrete because of the resulting strength of the concrete. Thus, the use of these waste materials in pervious concrete is rare. However, emphasis should not be on the compressive strength of the concrete, but rather it should be more on pervious concrete porosity and rate of permeability for most of its application (Kuo, Liu, & Su, 2013). Consequently, researchers are starting to identify sustainable materials to be used as alternative aggregate replacement in pervious concrete. Materials such as waste tire rubbers (Gesoğlu, Güneyisi, Khoshnaw, & Ipek, 2014), coal ash (Zaetang, Wongsa, Sata, & Chindaprasirt, 2015), bottom ash and seashell by-products (Nguyen, Boutouil, Sebaibi, Leleyter, & Baraud, 2013), and electric arc-furnace slag (Yeih, Fu, Chang, & Huang, 2015) have been proposed as pervious concrete material suitable for construction such as walkways, road shoulders and parking areas amongst others. Most of these studies have indicated that the properties of pervious concrete containing the various waste materials are acceptable when compared to pervious concrete containing natural aggregates, although, this is dependent on the level and ratio of replacement. Other factors that may influence the performance of pervious concrete is the rationing of the mixture constituents such as aggregate size, cement content, aggregate to cement ratio and water to cement ratio (w/c). Thus, mix constituents are vital to pervious concrete performance. By adopting appropriate concrete materials and mix proportions, the engineering properties of pervious concrete containing RA or RW can be improved significantly (Chen, Wang, Wang, & Zhou, 2013).

This study is an attempt to exploit the use of locally available agro-waste materials in pervious concrete given the abundance availability of agro-waste in Malaysia. The concept of Recycle, Reuse, Reduce and a sustainable environment has been the focus of Malaysian researchers over the last decade. Utilizing waste materials in construction not only helps to save the environment but also preserves the depletion of natural resources. Plenty of waste products from the agricultural industry such as POC, RHA, SDA, POFA, rubber aggregate and bagasse ash are currently being utilized for the production of various concrete types. However, past studies conducted on POC have mainly focused on its use in lightweight concrete, self-compacting concrete, beams and other structural members. This study will serve as a means of exploiting the use of POC in pervious concrete to further broaden its application in concrete. Thus, the study is expected to produce a sustainable pervious concrete which will reflect a good permeability and other characteristics at a reduced cost.

1.3 Significance of the study

This study is proposed to exploit the potential use of POC in pervious concrete due to its environmental benefits. One of the main commodity in Malaysia is the palm oil industry, it is expected that the growth of palm oil productions will be increased tremendously. Thus, as the production of palm oil increased, by-product from this industry which is normally disposed as waste will subsequently increase as well. Studies on utilizing lightweight aggregate and POC in pervious concrete has been limited, indicating the relevance of this study. Past studies have indicated that pervious concrete made with natural aggregates exhibit similar properties with the pervious concrete containing various waste materials, although, the level and ratio of replacement level is a dependent factor. Thus, the incorporation of wastes in producing pervious concrete offers an alternative environment friendly material. Also, incorporation of POC in pervious concrete offers double advantage of reduction in the cost of construction material and also as a means of disposal of waste in ensuring a sustainable environment. It is at this time the above approach is logical, worthy and attributable.

1.4 Objectives of the study

The aim of this study is to develop an eco-friendly pervious concrete using locally available waste material as aggregate replacement. In order to realize the aim of the study, the following objectives have been identified

1. To develop mix proportions for pervious concrete containing palm oil clinker coarse aggregate
2. To investigate the effect of curing and mixture constituents on the engineering properties of the pervious concrete
3. To identify the best mix proportion to obtain the optimum performance of the pervious concrete
4. To evaluate the sustainability efficiency of incorporating palm oil clinker coarse aggregate in pervious concrete

1.5 Scope of the study

The study was focused on producing palm oil clinker pervious concrete. Considering that POC is a weaker aggregate compared to natural aggregates as a result of the voids present inside and on the surface of the material, it is expected that the resulting strength might be low compared to conventional pervious concrete containing natural aggregate. However, since emphasis for pervious concrete are more on the porosity and rate of permeability rather than the compressive strength for most of its application, this is a feasibility study of the worst-case scenario of adopting POC in pervious concrete in order to identify the significant properties as a baseline for its possible engineering application. Once the general properties are better understood, then research on enhancing its mechanical properties and long-term durability can be studied to broaden its engineering application. Consequently, fine aggregate was omitted from the POC pervious concrete mix constituents. Thus, the scope of this research work is summarized as follows:

Firstly, the effect of cement content on the concrete was investigated maintaining a constant cement to aggregate ratio of 0.21. Four different cement contents 400kg/m^3, 350kg/m^3, 300kg/m^3 and 250kg/m^3 were adopted for this study. The concrete's properties investigated were density, compressive strength with age, abrasion resistance, porosity and coefficient of permeability.

Secondly, since aggregates form the structural skeleton of pervious concrete considering the notable void present in the concrete, the study also studied the effect of using different aggregate size on the properties of the concrete. Two single-sized grades of aggregates were investigated for the POC pervious concrete. The volumetric replacement levels of aggregates with POC were 0%, 25%, 50, 75% and 100%. Afterwards, engineering properties including compressive strength, porosity, permeability, abrasion resistance and density were studied. Based on the inter-relationship between compressive strength, porosity and permeability, the optimum mix of the POC pervious concrete was identified. Furthermore, the study also looks into how the concrete will behave under different curing method. The purpose was to determine if the standard curing regime (full water curing) would outperform other curing regimes. Due to the open structure and relatively rough surface of a pervious concrete, evaporation of water from the fresh concrete could be rapid. Casting of pervious concrete may be subjected to hot and dry environment condition depending on the region. This could create problem for fresh and hardened properties of a concrete, because concrete subjected to hot weather conditions often exhibit reduced durability (M. Ibrahim, Shameem, Al-Mehthel, & Maslehuddin, 2013; M. Mannan, Basri, Zain, & Islam, 2002). For these reasons, knowledge on how the POC pervious concrete will respond to different weather is an essential study to look into. The POC pervious concrete was subjected to three curing regimes; full water curing, air curing, and 3 days in water curing. In the case of the 3 days in water curing, the POC pervious concrete was cured in water at room temperature for 3 days prior to it being cured in air till the test days. Engineering properties investigated under the different curing includes compressive strength, density and abrasion resistance.

Lastly, as sustainability is becoming a central point in the life cycle of most practice, the world is focused on reducing CO_2 emission due to its greenhouse effect. Following the summit held in Rio de Janeiro Earth (1992) and Kyoto Protocol in 1997 (Protocol, 1997a, 1997b), reduction of CO_2 has become a global trend. Hence, it is important that the POC pervious concrete satisfy the required mechanical performance without compromising its environmental requirement. Consequently, the sustainability efficiency of the POC pervious concrete will be explored to assess the positive effect of incorporating POC into pervious concrete. In order to eveluate the sustainability efficiency of the concrete, the structural efficiency concept was explored by combining the density and compressive strength components of the concrete to obtain a good platform for comparison at various levels of replacement for the POC pervious concrete mixes with optimum perfromance. Sustainability component was analysed in terms of emission of carbon. The positive effects of POC utilization is expected to be established by combining the evaluation between engineering properties and sustainability aspects.

1.6 Organization of the Report

This thesis is made up of five chapters, where by the first chapter clearly states the motivation and objectives of this work. The second chapter described the relevant literature review, with focus on pervious concrete and palm oil mill waste. Chapter three introduced the characterization of the materials used and the experimental program that was adopted to obtain all the data used for the subsequent chapters. Data obtained and analysis was presented in chapter four with clear representation of data breakdown and detailed discussion of results. The final chapter of this work concluded it all and also presented recommendations for further study.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Floods are one of the most common recurring natural disasters that affect human and its surrounding environment worldwide. The basic cause of flood is as a result of combination of increased rainfall and high rate of impermeable surfaces in major cities (Nguyen et al., 2014). With the continual urbanization and population growth in Malaysia, impervious surface areas cover most part of the cities. Due to the geographical characteristics of the country, there is abundance of rainfall occurring annually in all the four regions of the country (Aisha et al., 2015; Khalid & Shafiai, 2015). Thus, the basic cause of flood in Malaysia is the incidence of heavy monsoon or convective rainfall and the resultant large concentration of runoff which has been exacerbated due to rapid development (Chan, 2015; Mohit & Sellu, 2013). Globally, considerable research has been done which indicates that pervious concrete provides the best solution for storm water runoff management. Thus, United States Environmental Protection Agency has identified pervious concrete as one of the key elements of sustainable development (Nguyen et al., 2013). During the last few years, pervious concrete has attracted more and more attention in concrete industry due to the increased awareness of environmental protection. Pervious concrete pavement have been developed to reduce the runoff rates and growing volumes of storm water collected in urbanized areas (Brattebo & Booth, 2003). They serve as a medium to control storm-water runoff without compromising to ensure a hard surface which can be utilized in urban areas (Scholz, 2006; Scholz & Grabowiecki, 2007).

2.2 Pervious concrete

Pervious concrete (Figure 2.1) has been existing since the mid-way 19th century. However, pervious concrete started gaining more recognition in the 1980s when it was used in Japan as an environmentally friendly material. Since then its applications has extended to other parts of the world (Europe and USA) because of its numerous environmental benefit such as controlling storm-water runoff (Bhutta, Tsuruta, & Mirza, 2012; Putman & Neptune, 2011). The high permeability of pervious concrete creates the ability to significantly reduce storm-water runoff. Thus, pervious concrete has been identified as storm-water Best Management Practice.

Figure 2.1: Pervious concrete slab

The porous structure of the concrete permits air and water percolation through the concrete matrix as seen in Figure 2.2. Also, due to the interconnected pores of the concrete, storm water runoff is reduced and the concrete also performs the role of a filter by the entrapment and degradation of contaminants, such as debris and oils, within and on the structure of the pervious concrete. The lifespan of pervious concrete, porous pavement or permeable surfaces as it is known, in general, depends predominantly on the size of the air voids in the media. The more possibilities for oxidation, the less durability can be achieved. It can be expected that the life of a pervious concrete is shorter than that of an impermeable pavement or surface due to deterioration by runoff, air infiltration, and subsequent stripping and oxidation, as well as hardening of binder (Scholz & Grabowiecki, 2007). Furthermore, it is important to pay close attention to details during mix production, curing and concrete placement of the concrete due to its unique hardened and fresh properties (Putman & Neptune, 2011). By using appropriately-selected aggregates, fine aggregates mixtures, and/or organic intensifiers and by adjusting the concrete mix proportion, strength and abrasion resistance of the concrete can be improved greatly. Previous studies show that gradation, particle size of aggregate, and mass ratio of aggregate to cement are the primary factors affecting porosity, permeability and compressive strength of pervious concrete while water cement ratio has a minor effect on properties of the concrete (Huang, Wu, Shu, & Burdette, 2010; Neithalath, Sumanasooriya, & Deo, 2010). Some advantages of pervious pavement concrete include noise reduction, improved skid resistance, cost reduction, and preservation of native ecosystems, and minimization of heat island effect in large cities (JT Kevern et al., 2008).

Figure 2.2: Water penetrating through the voids of a pervious concrete

2.3 Application of pervious concrete

The unique ability of pervious concrete offers advantages to the environment, public agencies, and building owners by controlling rainwater on-site and addressing storm-water runoff issues. Thus, this new system is more economical in comparison to the traditional impervious pavement and better than using soakaway and rainfall detention ponds (Lian & Zhuge, 2010). According to Tennis, Leming, and Akers (2004), other benefits of pervious concrete include increasing safety of driver by preventing standing water on surface of the road which reduces glare and skidding. Also, the void structure of pervious concrete allows the escape of air between pavement and tire thus producing a lower frequency road noise, which makes the concrete suitable to be used to reduce road noise. Meanwhile in rainy days, the pervious concrete pavement has no plash on the surface and does not glisten at night. This improves the comfort and safety of drivers (Yang & Jiang, 2003). Pervious concrete structural performance and compressive strength is more variable than that of the traditional concrete, and it is mainly dependent on the porosity of the concrete (A. Ibrahim, Mahmoud, Yamin, & Patibandla, 2014). For these benefits to be realized, the pavement must be functioning hydraulically as designed. That is, the pavement should be achieving its design hydraulic conductivity or permeability. A typical indicator for the permeability of the pavement is its porosity (Martin, Kaye, & Putman, 2014). Currently, the permeable concrete pavement is mostly used in car parks because of the light traffic loadings, and bicycle trails as well as footpaths due to its reduced compressive strength (Lian & Zhuge, 2010). Other known applications include artificial reefs, tennis courts, floors/foundations for greenhouses, low water crossings, well linings, slope stabilization, sub base for conventional concrete pavements, patios, tree grates in sidewalks, swimming pool decks, fish hatcheries, aquatic amusement centers, pavement edge drains, seawalls and groins (Deo & Neithalath, 2011; Maguesvari & Narasimha, 2013). However, the most researched amongst its application is its use for storm water runoff which has shown that pervious pavements concrete are effective at reducing the pollutant concentrations found in runoff (Welker, Barbis, & Jeffers, 2012). According to Neithalath et al. (2010), the ability of the concrete to transport large volumes of water through the material structure is the primary benefit it offers thus eliminating or reducing problems related to storm-water runoff as seen in Figure 2.3.

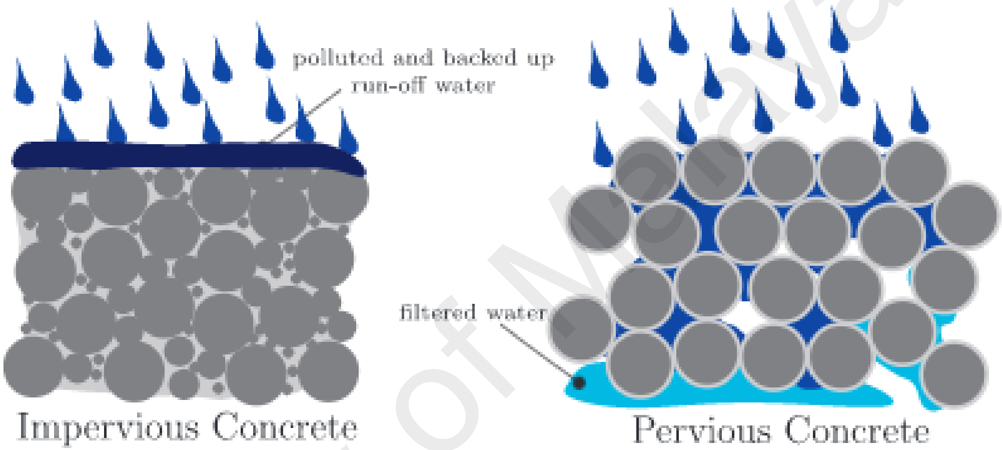


Figure 2.3: Pervious concrete vs impervious concrete (Zhiang 2015)

2.4 Pervious concrete materials

Pervious concrete uses the same materials as conventional concrete (cement, water and aggregate) with the exceptions that the fine aggregate is typically omitted, and the coarse aggregate size distribution (grading) is kept narrow which allows for a particle packing that is relatively low. Thus, this provides the useful hardened properties, but also results in different mixing, placement, compaction and curing considerations for the concrete mix. In some circumstances, chemical admixture and/or supplementary cementitious material could be included into the mix to enhance its performance. Furthermore, excessive paste will decrease the volume of the required pores in the concrete contrary to effect of excessive paste in conventional concrete. Paste volume required for pervious concrete is such that it is sufficient to coat each aggregate particle, creating a workable mixture that can be easily placed and hold the aggregates together without collapsing before the concrete sets (Vancura, MacDonald, & Khazanovich, 2011). However, the workability of fresh pervious concrete compared to conventional concrete is usually decreased as a result of the omission of the fine aggregate (sand).

2.4.1 Effect of aggregate properties

Aggregate properties are vital to the engineering properties of pervious concrete owing that the role of coarse aggregates in the formation of the concrete skeleton structure is important (Ćosić, Korat, Ducman, & Netinger, 2015; L. K. Crouch, 2007). Commonly used gradations of coarse aggregate in pervious concrete include 19mm to 4.75mm, 9.5mm to 2.36mm, 9.5mm to 1.18mm respectively (Ćosić et al., 2015; Jain & Chouhan, 2011; L. K. Crouch, 2007). Obla (2010) stated that single-sized coarse aggregate is normally used in pervious concrete and well graded aggregates are avoided to increase the void content. Meanwhile, larger aggregates provide a rougher surface. Additionally, pervious concrete compressive strength primarily depends on porosity of the concrete, which depends highly on the gradation, shape, and size of the aggregate (Ćosić et al., 2015). Also, pervious concrete durability properties strongly depend on the coarse aggregate texture, angularity and size (Agar-Ozbek, Weerheijm, Schlangen, & van Breugel, 2013). Typically, rounded aggregates produce better engineering properties, although angular aggregates are also generally suitable. Crouch, Pitt, and Hewitt (2007) reported that higher void ratio and compressive strength is attained with a uniformly graded aggregate. The study further stated that a higher compressive strength is achievable with the use of smaller aggregates when compared to using larger aggregates, and this is possible even when porosities of the concrete is similar. Although it has been suggested that a high porosity is produced by increasing the aggregate size, this is not always the case. Larger aggregate will produce larger voids, but due to the reduced surface area per volume for the cement paste to stick to when using larger aggregate size, the concrete voids may be partially filled with excess paste (Crouch et al., 2007; A. Ibrahim et al., 2014). Furthermore, the number of aggregate particles per unit volume of concrete can be increased by using smaller size aggregate. The concrete binding area and the specific surface of the aggregate increases as the aggregate particles increase. Consequently, the concrete strength will improve. Additionally, when the cement quantity in the concrete mix is adjusted accordingly and smaller sized aggregate are used, the strength of the pervious concrete can be significantly enhanced (Huang et al., 2010; Lian & Zhuge, 2010; Yang & Jiang, 2003). Effect of aggregate appear to be more pronounced on the durability and mechanical behavior of pervious concrete when compared to that of the conventional concrete since aggregate take up a substantial volume as high as 80% in the concrete (Chandrappa & Biligiri, 2016)

2.5 Agricultural waste in concrete

According to M. Mannan and Ganapathy (2004), the recycling or utilization of solid wastes generated from most agro-based industries and manufacturing industries is very rewarding. The anxiety about enormous waste production, resource preservation, and material cost has focused attention for the reuse of solid waste. Material recovery from the conversion of agricultural wastes and industrial wastes into useful materials has not only environmental gains, but may also preserve natural resources. Thus, research on the utilization of agro waste materials in concrete to reduce environmental pollution related problems has been on the rise. Many studies has been conducted on various agro waste maetrial mix constituents in concrete production which indicates its acceptable properties compared to natural aggregates. These agro waste materials have been successfully utilized as aggregates, powder materials as replacement for admixtures and cement, example of such waste are coconut and palm kernel shell (Olanipekun, Olusola, & Ata, 2006), oil palm shell (M. A. Mannan & Ganapathy, 2002), palm oil clinker (Abutaha et al., 2016; Kanadasan et al., 2015; Mohammed et al., 2011), palm oil fuel ash, bagasse ash, rice husk ash, (Tangchirapat, Saeting, Jaturapitakkul, Kiattikomol, & Siripanichgorn, 2007), black rice husk ash (Chatveera & Lertwattanaruk, 2011), sugarcane bagasse ash (Payá, Monzó, Borrachero, Díaz-Pinzón, & Ordóñez, 2002) among others. Performance of these aggregates are based on level of replacement into the concrete mixture. Each of the types of agricultural waste has physical and chemical properties, which are suitable for concrete application. For instance, solid agricultural waste as coarse aggregate together with cement matrix can meet design specifications for a low-cost lightweight structures (Teo, Mannan, Kurian, & Ganapathy, 2007). Agricultural wastes can also be used in non-load bearing concrete where compressive strength is not important as in the case of pervious concrete.

2.5.1 Waste aggregate

In order to achieve environmental sustainability, several authors have discussed the use of recycled waste materials and agricultural by-products as aggregate replacement in concrete for construction. Agricultural waste products such as rice husk ash (RHA), sawdust ash (SDA), palm oil fuel ash (POFA), palm oil clinker (POC), rubber aggregate and bagasse ash has been utilized in various types of concrete. Utilization of recycled waste materials (RW) or recycled aggregate (RA) in pervious concrete is rare which could be as a result of doubts concerning the resulting strength of the concrete. However, pervious concrete porosity and rate of permeability should be the main focus for most of its application rather than the concrete compressive strength (Kuo et al., 2013). Consequently, alternative sustainable aggregate materials are being identified by researchers to be used as aggregate replacement in concrete. Sustainable aggregate materials such as tire rubbers waste (Gesoğlu, Güneyisi, Khoshnaw, & Ipek, 2014), coal ash (Zaetang et al., 2015), by-products from seashell (SBP) and bottom ash (Nguyen et al., 2013), and electric arc-furnace slag (Yeih et al., 2015) have been identified as suitable material in pervious concrete construction for applications such as walkways, road shoulders, parking areas amongst others. For instance, SBP is considered as waste in France but adopting this material as partial replacement for aggregate in pervious concrete was considered as an environmentally friendly building material. Findings from Nguyen et al. (2013) study indicated that the mechanical strength of pervious concrete containing SBP could be compared to that of raw pervious concrete pavers without SBP. Also, a compressive strength of 15MPa for pervious concrete seashell by-products based pavers is possible based on the mix parameters used. However, porosity obtained was two times higher than that of ordinary concrete while permeability coefficient was in the range of 3mm/s to 8mm/s (Nguyen et al., 2013). Hesami, Ahmadi, and Nematzadeh (2014) studied the use of RHA as a cement replacement and Polyphenylene sulfide fibers in the production of pervious concrete mixtures. The results indicated a significant increase in compressive, tensile and flexural strengths due to present of the Polyphenylene sulfide fibers and RHA. Also, the w/c ratio of 0.33 significantly increased the mechanical properties of the pervious concrete and reduced the amounts of voids and its permeability. Khankhaje, Salim, Mirza, Hussin, and Rafieizonooz (2016) incorporated coarse aggregate waste material from oil palm industry as natural aggregate replacement to develop a sustainable lightweight pervious concrete. The results indicated that the sustainable lightweight pervious concrete produced is suitable to be used in parking lots and light traffic roads. Furthermore, the water permeability rate of pervious concrete containing the oil palm kernel shell (OPKS) was high, which varied from 4mm/s to 16mm/s with a compressive strength within acceptable range of 6MPa to 12MPa. In another study by In Zaetang, Wongsa, Sata, and Chindaprasirt (2013), three lightweight aggregates (LWA) were used in producing lightweight pervious concrete (LWPC). Diatomite (DA) and pumice (PA) were used as natural lightweight aggregates in pervious concretes. The results were compared to those of LWPC containing recycled LWA from autoclaved aerated concrete (AAC) which indicated that the use of DA, PA, and AAC as coarse aggregates in pervious concrete could reduce the density and thermal conductivity about 3 to 4 times compared with pervious concrete containing natural aggregate. Compressive strengths of LWPCs ranged from 2.47MPa to 5.99MPa at 28days. Meanwhile, the mechanical properties of LWPCs could be improved by increasing the cement paste of the concrete mixtures. LWPC containing DA showed higher mechanical properties and a lower thermal conductivity than those of AAC and PA. However, PA exhibited higher water permeability.

In another study by Zaetang et al. (2015), coal combustion power plant waste aggregate in the form of bottom ash (BA) and fly ash (FA) which was used to produce pervious geopolymer concrete was investigated. FA was used mainly as geopolymer binder and BA as coarse aggregate to produce pervious concrete. The pervious geopolymer concrete containing BA had density and compressive in the range of 1466kg/m^3 to 1502kg/m^3, and compressive strength of 5.7MPa to 8.6MPa respectively. Furthermore, durability of pervious concrete can be improved by incorporation of waste materials into the concrete mixtures. For instance, rubberized pervious concrete produced by Gesoğlu, Güneyisi, Khoshnaw, and Ipek (2014) showed that the concrete ductility and toughness as well as its damping capacity can be improved by replacing fine and coarse aggregates with crump rubber and tire chips. Also, the permeability and the mechanical properties of the concrete was significantly aggravated with the incorporation of the rubber waste but this was dependent on the degree of application according to the rubber type and rate used. Additionally, another study by Gesoğlu, Güneyisi, Khoshnaw, and İpek (2014) indicated that the abrasion resistance of the concrete was significantly enhanced when two types waste from scrap tire rubber, namely tire chips and crumb rubber, were utilized to produce rubberized pervious. Meanwhile, a decrease in the flexural strength of the concrete was recorded due to the rubber chips. Chang, Yeih, Chung, and Huang (2016) investigated the properties of pervious concrete containing alkali activated slag cement (AASC) and electric arc furnace slag (EAFS). It was found that the pervious concrete made with Portland cement had inferior mechanical strengths when compared to the pervious concrete made with AASC. The coefficient of permeability of the pervious concrete containing AASC and EAFS was higher than 0.49cm/s whereas the compressive strength recorded was higher than 35MPa. On the other hand, the pervious concrete made with AASC had a better anti-skid performance in which the British pendulum number recorded was lower than that of the concrete made with Portland cement. Additionally, the pervious concrete made with AASC and EAFS had a sound absorption ratio that reached 0.94 for low frequency noise.

Based on the review of literature so far, most of the studies indicated that the incorporation of waste materials in pervious concrete mix exhibit acceptable properties that are comparable with properties of pervious concrete containing natural aggregates. Although, the level and ratio of replacement is an important factor to consider. Thus, the utilization of wastes in the production of pervious concrete offers an alternative environment friendly material.

2.6 Agricultural waste in Malaysia

Malaysian agricultural industry, over the past decades, has experienced progressive development that has been substantially supporting the country's economy. The product output of the industry has been diversified to processed goods completely from the conventional basic fresh products. At the same time, the manufacturing stages of these goods generates an enormous amount of waste by-products which has prompted serious discussion. In 2010, 80 millions of tonnes of dry solid waste biomass was recorded from the Malaysian oil palm industry and it has been forcasted to increase by an additional

35% million tonnes by the year 2020 (Agensi Inovasi Malaysia, 2011). Over the years, oil palm, cocoa, rubber, coconut and paddy have been planted on thousands of hectares of land which has lead to expansion of the Malaysian agricultural industry. Studies by Michael (2012) and Murphy (2014) show that the total palm oil produced in Malaysia and Indonesia in 2012 was over 57 million tonnes, which amounts to 85% of the palm oil production worldwide. However, there is need for proper disposal of the immense waste generated from each phase of palm oil production. In 2013, the hectares of palm oil planted inceased by 3% when compared to the hectares used for planting in 2012 (Malaysian Palm Oil Board, 2008). Thus, this resulted in production of about 19.22 million tonnes of crude palm oil (CPO). Based on this, the Malaysian palm oil industry plays an integral part in the growth of the country's economy. Statistics show that there are 440 fresh fruit bunch mills in Malaysia in which 247 of the mills is spread across Peninsular Malaysia, and the rest are located in Sarawak and Sabah (Malaysian Palm Oil Board, 2014). Figure 2.4 depicts the different biomass types produced in Malaysia by various industries.

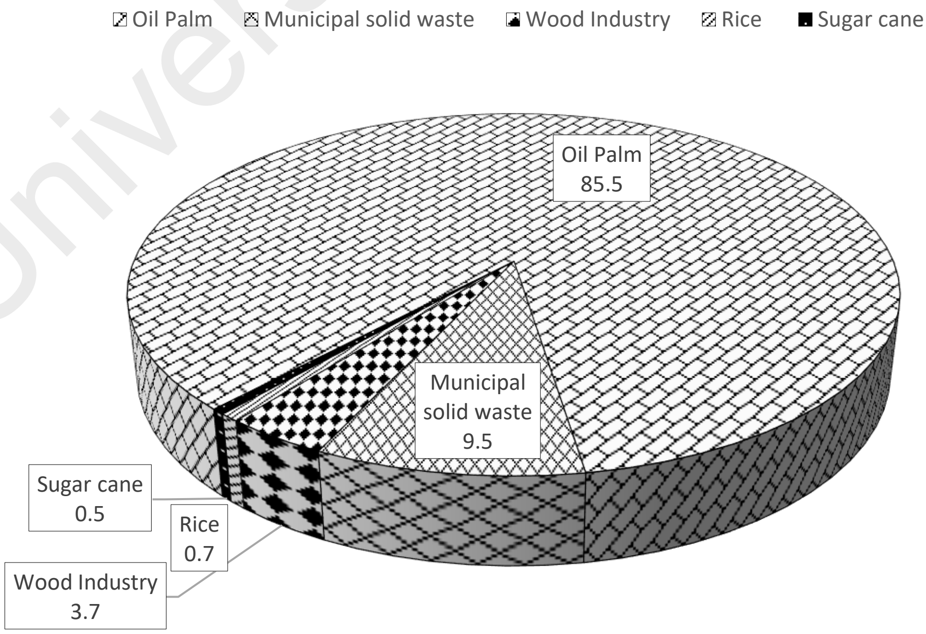


Figure 2.4: Biomass produced by different industries in Malaysia adapted from (Kanadasan & Abdul Razak, 2015)

On the other hand, past studies have indicated that some of the waste generated during and after production process of oil plam production are being reused. For instance, Sumathi, Chai, and Mohamed (2008) stated that the mesocarp fibre (MF) and palm oil shell contains small amount of oil which can be used as a fuel in the production of steam for the operation of the oil palm mill. Their study further stated that when fibre and shell is incinerated in the boiler, steam which can be used in the production of CPO and electricity for the operation of the mill would be generated. Also, Vijaya, Ma, Choo, and Nik Meriam (2008) reported that incineration of shell and MF in the boiler will generate an average approximation of 0.05 tonne of boiler ash per tonne of CPO. However, considering the amount of shell and MF generated from oil palm mill production annually, boiler ash production could also rise proportionally. Thus, the need for an effective system to manage and dispose waste would be on the rise. Some of the most common waste obtained from the oil palm industry include POC, POFA, OPKS and oil palm shell (OPS) which are usually diposed to fill lands cultivating pollution to the society. Generally, POC is obtained at the last stages of burning in boilers in the form of waste byproduct (Kanadasan & Abdul Razak, 2015). Currently, POC is being used to fill potholes in the roads that leads to oil plam estate or often used as landfilling materials.

2.6.1 Palm Oil Clinker (POC)

POC is available abundantly in Malaysia and it has little or no value commercially. It is usually stock piled and disposed as waste as seen in Figure 2.5. Malaysia is one of the largest producers of palm oil in the world and statistics has shown inevitable rapid growth in production due to the increasing demand of vegetable oil globally. An estimated solid waste of about 2.6 million tones is produced annually from the oil palm industry. Consequently, the industry stands as a major contributor to problems related to pollution in the country (Basri, Mannan, & Zain, 1999; M. Mannan & Ganapathy, 2004; Mohammed et al., 2011). However, various studies (Kanadasan & Razak, 2014b, 2015;

Mohammed et al., 2011; Mohammed et al., 2014) have indicated that agro-waste in the form of POC is a potential material that can be used in construction.

Figure 2.5: Palm oil mill waste at factory

Generally, POC is obtained in large chunks as seen in Figure 2.6. POC has an irregular shape, porous in nature and it has a good lightweight characteristic and it is usually obtained from fiber and oil palm shell incineration. POC, when crushed and sieved into appropriate sizes, can be used as an ideal aggregate alternative. One of the advantage of using POC, a lightweight aggregate, in concrete production is the reduced dead load the concrete will have without compromising the target strength of the concrete. This condition is possible because lightweight concrete can reduce the dead load by as much as 35% and still provide the structural strength (Abutaha et al., 2016).

Past studies on the incorporation of POC aggregate in concrete production is limited. For instance, incorporating POC aggregate in the production of self-compacting concrete showed that the concrete can attain almost 68% of the target compressive strength (Kanadasan & Razak, 2014b). Additionally, another study by Kanadasan and Razak (2015) concluded that good ultrasonic pulse velocity (UPV) values can be achieved with concrete containing POC aggregates. Meanwhile, the density of the concrete containing oil palm boiler clinker and oil palm shell concrete reduced by 21%–27% (Shafigh, Mahmud, Jumaat, Ahmmad, & Bahri, 2014), whereas the unit weight of a concrete containing full replacement of natural aggregate with POC aggregates was reduced by 16% (Kanadasan & Razak, 2014a). Additionally, the feasibility study carried out on the use of POC aggregate samples from all states in Malaysia in the production of self-compacting concrete showed that a structural efficiency in the range of 0.035–0.05MPa/(kg/m^3) can be attained, which is similar to control specimen (Kanadasan et al., 2015). Meanwhile, another study revealed that incorporation of POC in producing a lightweight concrete recorded a 13%–31% loss in compressive strength with respect to the control specimens (Ahmad, Hilton, & Mohd Noor, 2007). Furthermore, a satisfactory electrical resistivity values can be achieved with a POC concrete which implies that the durability properties of the concrete is acceptable. Meanwhile, the deflection of a POC concrete beam which was singly reinforced, in which the reinforcement ratio was lesser than 0.5% was satisfactory and within an acceptable range from a structural view point (Mohammed et al., 2014). However, the weight of concrete slab was decreased by 18.3% with the utilization of POC when compared to the conventional concrete slab (Mohammed et al., 2011). Also, Mohammed et al. (2011) study revealed that the structural properties of a POC slab was lower when compared to a conventional slab whereby a lower modulus of elasticity was recorded for the POC concrete. However, the shear performance of conventional concrete beam was similar to that of reinforced POC concrete beam (Mohammed, Foo, Hossain, & Abdullahi, 2013). Also, Kanadasan and Razak (2015) study indicated that incorporating POC as an alternative concreting material can help to sustain the construction industry. A study by Abdullahi, Al-Mattarneh, Hassan, Hassan, and Mohammed (2008) on the trial mix proportions of a POC concrete aimed at determining the properties of POC aggregate, such as specific gravity, water absorption and particle size distribution, accurately revealed that POC aggregate can be utilized in the concrete mix design without the use of admixture.

Figure 2.6: Chunks of palm oil clinker waste

2.6.2 Properties of POC aggregates

Engineering properties of concrete is generally influenced by the physical properties of the aggregate used since aggregate occupies 60% to 75% of the concrete mixture (Kosmatka, Kerkhoff, & Panarese, 2011). Thus, aggregate plays an important role in concrete performance. Besides influencing concrete workability and mechanical properties, aggregate strength, pore structure, size, and gradation also significantly affect hydraulic properties of a pervious concrete. In this study, the investigated physical properties of POC are specific gravity, moisture content, water absorption, aggregate crushing value (ACV) and Los Angeles abrasion value. These properties are compared with other lightweight aggregates and normal weight aggregates (NWAs) properties.

2.6.2.1 Specific gravity

The specific gravity of a given material is often expressed as the ratio of the density of the said material and that of water (Schetz & Fuhs, 1999). Specific gravity of POC varies based on region where it is obtained. From Kanadasan et al. (2015) study, the range of POC specific gravity is around 1.81 to 2.33. The size of the aggregate may also affect the specific gravity of the aggregate where smaller size POC aggregate has higher specific gravity than bigger sizes. However, the specific gravity of POC irrespective of its source within Malaysia did not exceed that of NWA. Conventional aggregates have an apparent specific gravity between 2.6 and 2.7 (Ahmad et al., 2007). Table 2.1 presents some relevant properties of POC aggregate obtained from different sources within Malaysia.

Table 2.1: Physical characteristics of POC across Malaysia (Kanadasan et al., 2015)

State	Specific gravity	Water absorption (%)	Moisture content (%)
Kedah	2.23	1.93	0.17
Kelantan	1.81	4.12	0.25
Terengganu	2.07	2.28	0.04
Penang	2.13	3.05	0.07
Perak	2.11	1.40	0.04
Pahang	2.29	2.34	0.03
Negeri Sembilan	2.33	4.05	0.31
Selangor	2.11	4.10	0.48
Meleka	2.28	1.65	0.02
Johor	2.21	2.37	0.17
Sabah	2.08	2.54	0.05
Sarawak	2.16	5.67	0.04

Other artificial lightweight aggregates such as LECA and Lytag have specific gravity ranging from 0.9 to 0.8, while some LWA such as pumice has specific gravity ranging from 1.7 to 1.3 (Hemmings, Cornelius, Yuran, & Wu, 2009), oil palm kernel shell (OPKS) is around 1.17 to 1.62 (Alengaram, Al Muhit, & bin Jumaat, 2013; Khankhaje et al., 2016) and oil palm boiler clinker is around 1.7 to 2.2 (Aslam, Shafigh, & Jumaat, 2016). However, POC aggregate has specific gravity that is 34% less than the NWA, 61% to 55% higher than the artificial LWAs such as LECA and Lytag, 27% to 28% higher than natural LWAs such as pumice, diatomite and volcanic cinders, 30% to 35% higher than natural LWAs like oil palm kernel shell (OPKS) and 5.5% to 6 higher than natural LWAs like oil palm boiler clinker

2.6.2.2 Water absorption

Based on past studies, organic porous aggregate often has high water absorption due to its porous nature (Ahmad et al., 2007; Aslam et al., 2016). POC being a porous aggregate is expected to show similar characteristics. The humidity of the environment where aggregates are being stored influences the water content to be obtained for such aggregates. However, in a situation where the aggregates have been stored in the laboratory, the aggregates will not absorb water into the particles through the pores present on and inside the aggregate. This is because the aggregate was not being exposed to rainfall which creates moisture. It is important to note that moisture content is of significant importance when designing the concrete mix proportion. Thus, specifying the aggregate water absorption is important otherwise, consistency and workability problems may arise for the concrete (Ahmad et al., 2007).

Table 2.1 shows the water absorption of POC aggregate from different states within Malaysia. It can be seen from the table that POC water absorption range is from 1.40% to 5.67%. This is similar to the water absorption of oil palm boiler clinker with water absorption found in the range of 1.8% to 5.4% as reported by Aslam et al. (2016) and much lesser than that of oil palm kernel shell with water absorption ranging from 14% to 33% reported by Alengaram et al. (2013). Water absorption of NWA is typically found to be in the range of 0.5% to 1% (Neville, 1995). POC aggregate's high-water absorption can be valuable for the mechanical properties of the concrete. Additionally, poor curing regime does not necessarily affect the mechanical properties of a lightweight concrete (LWC) containing porous aggregate when compared to the effect of curing on that of conventional normal weight concrete (NWC) as reported by Al-Khaiat and Haque (1998). This is notable at the early ages, since the pores of the LWAs would retain water required for internal curing. Additionally, it can be seen from the table that the moisture content of POC in this study varied from 0.02% to 0.48% which is similar to that of oil palm boiler clinker with a free moisture content between 0.05% and 1%. Typically, NWA has moisture content ranging from 0.5% to 1% (Aslam et al., 2016). However, oil palm kernel shell has much higher moisture content which varies between 8% and 15%. It should be noted that the moisture content of an aggregate also depends on the humidity of the environment where the aggregate is placed (Ahmad et al., 2007).

2.6.2.3 Aggregate crushing value

The aggregate crushing value gives a relative measure of the resistance of an aggregate to crushing under a gradually applied compressive load. It's the percentage by weight of the crushed (finer) material obtained when the test aggregates are subjected to a specified load under standardized conditions, and it is a numerical index of the strength of the aggregate used in road construction. Aggregates with lower crushing value indicate a lower crushed fraction under load and would give a longer service life to the load and hence a more economical performance. Weaker aggregates if used would get crushed under traffic loads, would produce smaller pieces not coated with binder and these would be easily loosened out resulting in loss of the surface. In short, the aggregates used in road construction must be strong enough to withstand crushing under traffic. Figure 2.7 depicts POC aggregates crushing value variations obtained from several Malaysian states. Due to the porous nature of POC aggregate as well as lightweight characteristics, the load bearing capacity of the aggregate might be affected significantly. Thus, crack propagation will be induced easily due to the highly porous nature of the POC aggregate when compared to the dense cement paste. Thus, occurrence of failure will happen much later with the hardened cement paste and earlier with the aggregate (Kanadasan et al., 2015).

Table 2.2 presents some relevant properties of POC aggregate with other palm oil waste aggregates within Malaysia. Comparing POC aggregates to other waste aggregates from palm oil industry, the ACV of POC aggregates is about 80% to 90% and 66% to 68% higher than OPKS and oil palm boiler clinker (OPBC) respectively. This indicates that POC is a weaker material

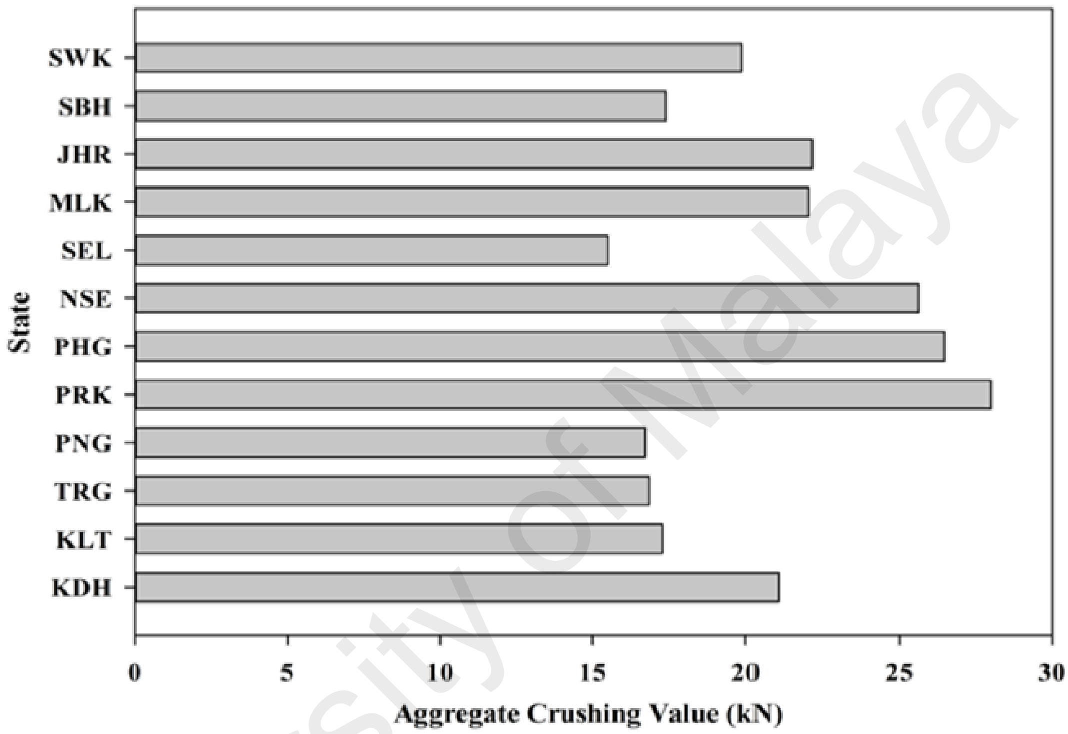


Figure 2.7: Palm oil clinker waste aggregate crushing value for different states in Malaysia (Kanadasan et al., 2015).

2.6.2.4 Los Angeles abrasion value

The aggregate used in surface course of highway pavements are subjected to wearing due to movement of traffic. When vehicles move on the road, the soil particles present between the pneumatic tires and road surface cause abrasion of road aggregates. The steel reamed wheels of animal driven vehicles also cause considerable abrasion of the road surface. Therefore, the road aggregates should be hard enough to resist abrasion. Resistance to abrasion of aggregate is determined in laboratory by Los Angeles (L.A) test machine. The L.A. abrasion test is widely used as an indicator of the relative quality or competence of mineral aggregates. The principle of L.A abrasion test is to produce abrasive action by use of standard steel balls which when mixed with aggregates and rotated in a drum for specific number of revolutions also causes impact on aggregates. The percentage wear of the aggregates due to rubbing with steel balls is determined and is known as L.A. Abrasion Value. Comparing POC aggregates to other waste aggregates from palm oil industry, the L.A abrasion value of POC aggregates is about 23% to 53% and 58% higher than OPKS and OPBC respectively.

Table 2.2: Properties of POC with other palm oil waste aggregates and granite

Author	Material	Specific gravity	Water absorption (%)	Moisture content (%)	Aggregate crushing value	LA abrasion value
This study	POC	1.7 – 1.9	3±2	0.48	56.4	64.8
(Alengaram et al., 2013)	OPKS	1.2 – 1.6	14 – 33	8 - 15	5 – 10	30 - 50
(Aslam et al., 2016)	OPBC	1.7– 2.2	1.8 – 5.4	0.05 – 1.0	18 - 18.8	27.1

2.7 Engineering properties

Pervious concrete engineering properties are deemed important because the concrete's mix design, functional characteristics and its durability is dependent upon it. Based on recent study, the paramount properties of interest for pervious concrete design for its application and functional properties include: density, compressive strength, porosity, coefficient of permeability and resistance to abrasion (Chandrappa & Biligiri, 2016). Typically, pervious concrete mix comprises of binder material in the range of 180kg/m^3 to 350kg/m^3 and coarse aggregates often ranging from 1200kg/m^3 to 1600kg/m^3 (Schaefer, Wang, Suleiman, & Kevern, 2006; Sriravindrarajah, Wang, & Ervin, 2012). The w/c being a very important variable is lower compared to those used in the conventional concrete mix, and has been historically varied over the range of 0.28 to 0.40 with the main intention to provide sufficient cement coating for the aggregates (Chandrappa & Biligiri, 2016; Tennis et al., 2004). Further, the aggregate-to-cement cement to aggregate ratio has been varied in the range of 0.25 to as low as 0.17. Table 2.3

presents the typical mix proportion of pervious concrete used over the last decade based past studies.

Table 2.3: Pervious concrete mix proportion of past studies

Author	Aggregate (kg/m^3)	Cementitious material (kg/m^3)	Water (kg/m^3)	Cement to aggregate ratio	Water to cement ratio
Ghafoori and Dutta (1995a)	1651 1692 1740 1800	412 376 348 300	153 143 135 125	0.25 0.22 0.20 0.16	0.37 0.38 0.39 0.42
Crouch et al. (2007)	1541 1620	344 287	105 87	0.22 0.18	0.3 0.3
John T Kevern, Vernon Ray Schaefer, and K Wang (2009b)	1820 1700 1570 1560	180 260 330 330	50 70 100 100	0.10 0.15 0.21 0.21	0.28 0.27 0.30 0.30
Huang et al. (2010)	1440 1486 1586	320 330 352	112 115 123	0.22 0.22 0.22	0.35 0.35 0.35
Neithalath et al. (2010)	1559 1568 1546 1544	312 314 309 309	103 104 102 102	0.20 0.20 0.20 0.20	0.33 0.33 0.33 0.33
Lim, Tan, and Fwa (2013)	1560 1560 1560 1560	367 242 430 495	110 73 110 148	0.24 0.16 0.27 0.32	0.30 0.30 0.26 0.30
A. Ibrahim et al. (2014)	1600 1800	200 150	70 53	0.13 0.08	0.35 0.35

2.7.1 Density

The density of pervious concrete depends on the properties and proportions of the materials used, and on the compaction procedures used in placement. Generally, pervious concrete has a unit weight which is about 70% of that of a conventional concrete due to the omission of fine aggregate leading to presence of void. In-place densities in the order of 1600kg/m^3 to 2000kg/m^3 are common, which is in the upper range of lightweight concretes. Also, the density of pervious concrete tends to depend on the properties of the aggregate used such as the unit weight, specific gravity and shape of aggregate (Chandrappa & Biligiri, 2016; Chang et al., 2016; Zaetang, Sata, Wongsa, &

Chindaprasirt, 2016). Another factor which determines the density of a pervious concrete is the mix constituents of the concrete. For instance, increasing the cement content would increase the thickness of paste around the aggregate resulting in a higher density irrespective of the mix design methods and compaction (Chang et al., 2016; Zaetang et al., 2013). Also, when the volume of aggregate used is less such that the unit weight will decrease and vice versa when the aggregate size used in the concrete is larger (Chandrappa & Biligiri, 2016; Yeih et al., 2015). Additionally, Ćosić et al. (2015) suggested that a higher amount of smaller aggregate fractions would increase the contact area of the concrete which would yield a higher density concrete mixtures.

2.7.2 Compressive strength

Compressive strength of concrete has been accepted as the most important mechanical property for a structural concrete. Pervious concrete has a 7-day compressive strength which is about 70% to 90% of the compressive strength at 28 days. This strength gain in 7 days is higher when compared to the 7-day strength of conventional concrete, whereby the strength of conventional concrete at 7 days is usually about 65% to70% of the compressive strength at 28 days (Kabir, Hasan, & Miah, 2012). The relationship between concrete composition and compressive strength has long been a matter of interest for researchers. The factors influencing the strength of concrete include the amount and type of cement, w/c ratio, aggregate type and grading, workability of fresh concrete, mineral admixtures used, chemical additives, curing conditions and time, etc. (De Larrard & Belloc, 1997; Kılıç et al., 2008). Although the water cement ratio is one of the important factors for the compressive strength of cement concrete. However, in case of pervious concrete, the above concept may have little significance because water used in pervious concrete is such that it is sufficient to produce the fresh cement paste with a good workability without clogging all the pores. Optimum range of water cement ratio for both strength and permeability point of view ranges from 0.30 to 0.38 (Maguesvari &

Narasimha, 2013). Also, L. K. Crouch (2007) study indicated that strength properties are a function of mix variables, and are less sensitive to w/c ratio, rather more to a/c ratio.

The compressive strength of pervious concrete mixtures tend to be lower than that of the conventional concrete due to the high void ratio and lack of fine aggregate in the concrete (Putman & Neptune, 2011). Due to this low strength compared to the conventional concrete, pervious concrete is not suitable to be used for load bearing structural purposes, rather lightweight concrete application (Lian & Zhuge, 2010). Often the determining factor for designing the target strength is based on the proposed application of the concrete. For instance, a design compressive strength in the range of 10MPa to 13MPa is desired for drainage pavement, parking lots, precast porous concrete products and stone protection (Bhutta et al., 2012; Crouch, Smith, Walker, Dunn, & Sparkman, 2006). Also, compressive strength in the range of 0.69MPa to 6.89MPa and 6.89MPa to 17.24MPa are often employed for insulating concrete and fill concrete respectively (Zaetang et al., 2013). Furthermore, De Larrard and Belloc (1997) pointed out that the strength of pervious concrete is also influenced by the properties of mortar, coarse aggregate and the interface. Since cement paste in pervious concrete is very thin to bond coarse aggregate together, the concrete tends to fail at the binder interface between the aggregates and results in the low compressive strength (Lian & Zhuge, 2010; Yang & Jiang, 2003). Owing to the thin coating of the aggregates with cement, the aggregate type thus plays an important role in the pervious concrete strength development (Lian & Zhuge, 2010). Furthermore, the pervious concrete cement binder strength is low due to the thin layer of the hardened cement paste. The existence of microcracks and pores in the hardened cement paste has a significant influence on the strength of the cement paste. The compressive strength of the concrete is further reduced due to the numbers of microcracks and pores present in the transition zone (Yang & Jiang, 2003). Thus, improving the bond between cement paste and aggregate is vital in order to enhance the compressive strength of the pervious concrete (Zaetang et al., 2016).

Additionally, the coating thickness of the cementing material is an important factor to be considered when pervious concrete performance is being assessed (Chandrappa & Biligiri, 2016). A recent study by Torres, Hu, and Ramos (2015) came up with a novel approach to determine pervious concrete mixtures paste thickness. The method involved correlating the concrete hydrological properties and strength with its cement paste thickness. Evidently, the pore properties, such as porosity, and the strength properties of the concrete decreased and increased respectively, when the paste thickness of the concrete increased. Furthermore, there would be a drop in the strength of pervious concrete due to reduction in cement coating when the size of aggregate used increased. This will occur because the strength of the interface between cement paste and aggregate improves when smaller aggregate size are used (Yang & Jiang, 2003). Also, Torres et al. (2015) suggested that when a high cement content is used in pervious concrete, the aggregate/paste interlock is better because the paste would give a better coating and bond to the aggregates which validates the phenomenon of the improved strength due to cement content. The number of aggregate particles per unit volume of the concrete would increase when smaller size of aggregate is used. As the aggregate particles increase, the specific surface of the aggregate and the binding area increases (Yang and Jiang 2003). Subsequently, the increased contact area will result in strength improvement. Thus, the number of aggregate particles per unit volume of concrete will increase when aggregate grading containing smaller aggregate size is adopted. On the other hand, study by Deo (2011) used a digital microscope to determine pervious concrete paste thickness consisting of varying aggregate size. The study indicated that the paste thickness on the larger aggregate was thicker while a thin coating was observed with the smaller aggregate size and this was attributed to the high contact area observed with the smaller aggregates.

Also, it was found that the compressive strength of the concrete increased with an increase in aggregate size. However, such conclusion contradicts results found in a number of other studies in which those studies indicated that compressive strength will drop with increase in aggregate size. Probably, the variation in mix design method adopted in their respective studies could be the reason for the different conclusion.

Furthermore, Lian, Zhuge, and Beecham (2011) study to establish a quantitative relationship between porosity and compressive strength of porous concrete indicated that the strength of the concrete is mainly influenced by porosity. When the porosity is higher, compressive strength of the concrete reduces. This is because high porosity would lead to a reduced paste thickness which in turns would weaken the aggregate-paste bond strength. Thus, the matrix of the concrete is weakened due to the presence of voids as highlighted by P Chindaprasirt, Hatanaka, Chareerat, Mishima, and Yuasa (2008). Cement paste in pervious concrete unlike conventional concrete only fills the space between aggregates partially. According to Yeih et al. (2015), this is intentional so as to allow existence of porosity inside concrete that will allow water penetration.

2.7.3 Porosity and permeability

Porosity is the ratio of the volume of voids to the total volume of the specimen and its role is important to the outcome of the pervious concrete hardened properties. Ghafoori and Dutta (1995a) stated that the majority of pores in the concrete are formed by the spaces left between coarse aggregates and they are distinguished between porosity and air void content. In their research, the fraction of measurable voids migrated by fluids in their experiments was termed porosity and the sum of measurable voids between aggregates plus entrained or entrapped air in the cement paste was termed air content. In other words, the porosity of pervious concrete could be defined differently. John Kevern, Wang, and Schaefer (2010) study indicated that there are two types of void system in pervious concrete; porosity designed intentionally to facilitate penetration of water and air entrained in the mortar/cementitious material surrounding the aggregate. On the other hand, Montes, Valavala, and Haselbach (2005) defined the pervious concrete porosity as the percentage of void volume with respect to the concrete specimen total volume. In the pervious concrete, there exists some voids that are not effective in allowing water penetrate through the concrete structure. Thus, the active voids that carries water through the material are often referred to as the ‘‘effective voids/porosity’’ (A. Ibrahim et al., 2014). Montes et al. (2005) pointed out that not all the porous spaces are effective in holding and available for fluid flow, which is grouped as the ‘‘inactive porosity’’. Some porous spaces can be isolated (closed off) from other void spaces and will not be able to transmit fluid. This behavior is expected in highly compact or small coarse aggregate (4.75 mm) pervious concrete, as smaller voids have the ability to retain the trapped fluid due to surface tension effects and capillary action. Wimberly, Leming, and Nunez (2001) reported the effective porosity as the fraction of total porosity that was allowed to drain in 30 min, called the ‘‘rapid flow’’ porosity, in which the fluid would rapidly flow, or drain from the pervious concrete sample. However, this method has an increase in variability due to the high possibility of unknowns (Torres et al., 2015). In order to avoid any confusion resulting from differences in ‘‘effective voids’’ definition, Montes et al. (2005) recommended the use of water displacement methodology to determine the total porosity of pervious concrete. This method is based on Archimedes’ principle of buoyancy which states that “the weight of the displaced fluid is equal to the buoyancy force”. Using the displacement method, the total volume, submerged mass and dry mass must be known for the total porosity calculation. Other studies such as Yeih et al. (2015) and A. Ibrahim et al. (2014) on the other hand has determined their total porosity by dividing the difference between the pervious concrete sample submerged weight and the weight of the concrete sample dried in air for 24hrs by the volume of the concrete sample.

Total porosity of pervious concrete was defined as the sum of closed (isolated) porosity and open (connected) porosity by Montes et al. (2005) and their study in agreement with Lian et al. (2011) study indicated that it should be correlated to the compressive directly. Meanwhile Yeih et al. (2015) study suggested that the effective porosity is the primary influence on the permeability of the concrete.

Furthermore, some research has shown that the permeability and compressive strength of the hardened concrete is affected by the effective void and total void content respectively (Chandrappa & Biligiri, 2016; A. Ibrahim et al., 2014; John Tristan Kevern, 2008; Martin et al., 2014; Yang & Jiang, 2003). At higher porosity ratios, water permeability is increased, but the compressive strength is decreased (Ghafoori & Dutta, 1995b). Thus, it is essential to optimize the effective void content in order to achieve the desired strength and permeability. Effective void content in pervious concrete typically ranges from 15% to 35% (ACI-522, 2003). The desired void content may be achieved either by controlling the level of compaction effort and mixture constituents such as the aggregate proportions and cementitious materials (A. Ibrahim et al., 2014; Sonebi & Bassuoni, 2013). Although it is intuitive that increasing aggregate size would produce a higher porosity, this is not always the case. Larger aggregate will produce larger voids, but since the aggregate has less surface area per volume for the cement paste to stick to, excess paste will partially fill in the voids (Crouch et al., 2007). In a recent study, Torres et al. (2015) argued that both the cement paste thickness and the size of aggregate used influences the void of pervious concrete contrarily to the view that it is purely governed by the size of coarse aggregate. The thickness of the aggregate coating is affected by the amount of cement used, which affects the concrete porosity and other mechanical properties. Thus, the feature of the void structure such as the void size, coarse aggregate size, distribution of void, void volume and the amount of cement used dictates the infiltration performance of pervious concrete. Furthermore, w/c is another factor that can determine the outcome of pervious concrete void content. According to Sonebi and Bassuoni (2013) study, a higher volume of paste that was in excess of that needed to encapsulate the aggregate was recorded when the concrete w/c was increased. Surplus paste clogged the open pore structure of concrete, thus reducing the void ratio.

Permeability on the other hand is the most important performance characteristic of pervious concrete, and as with any porous material, transport properties are inherently dependent on the pore structure features (Kayhanian, Anderson, Harvey, Jones, & Muhunthan, 2012). However, it has been common to relate the permeability of pervious concrete to its porosity, primarily because of the ease with which porosity can be measured in such a macro-porous material. The general perception is that permeability of a pervious concrete is influenced by its porosity. However, some studies have argued otherwise. Ćosić et al. (2015) stated that a direct insight into porosity would be beneficial since permeability is influenced not only by the number of pores but also by their distribution and interconnectivity. Thus, having a high porosity does not necessarily suggest that permeability of the concrete would be high because the permeability of the concrete is also a function of the void size and surface area (Montes et al., 2005). Furthermore, Yeih et al. (2015) study has suggested that the effective porosity is the primary influence on the permeability of the concrete. Though there is a general trend of increasing permeability with increasing porosity, this does not necessarily translate to a linear relationship between both. According to Martin et al. (2014) study, a number of studies have looked at the relationship existing between pervious concrete permeability and porosity and each individual studies have often represented this data with an exponential relationship

2.7.4 Abrasion resistance

The abrasion resistance of concrete pavement, which is a surface property test, is defined by the ACI committee 201 (1962) as the ability of the concrete surface to resist wearing away resulting from rubbing and friction of heavy load trucking, sliding, foot traffic skidding and other abrasive materials. It has been recognized that the type of finish, w/c ratio, curing and cement content affects the properties of concrete surface layer. However, the variation in these criteria have been shown to have a lot of influence on the surface abrasion and less on the strength of the concrete. These criteria which include curing method, placement techniques and mixture design are some of the other variables that can directly affect the abrasion resistance of pervious pavement since they determine the likelihood of a raveling incident (Gaedicke, Marines, & Miankodila, 2014a). Additionally, there are two views on the relationship between compressive strength and abrasion resistance of concrete. One of them is that compressive strength is the most important factor governing the abrasion resistance of concrete and while the other is that the abrasion resistance of concrete increases with increasing compressive strength (Atis, 2002, 2003). Also, the abrasion resistance of concrete depends upon the properties of aggregates i.e. the hardness of its coarse aggregates. Pervious concrete made with aggregates having a high L.A. value will show poorer abrasion resistance compared with concrete made with aggregates having lower L.A. value. The influence of aggregate L.A. value is observed to be less pronounced in higher concrete grades than in lower concrete grades (Kumar & Sharma, 2014). This suggests that the abrasion resistance of concrete does not totally depend on its compressive strength, and the crushing value of aggregate is also important. In general, the lower the crushing value, the stronger the aggregate. Thus, any aggregate with low crushing value is beneficial to the abrasion resistance of concrete. The surface texture and crushing value factors affects the strength and abrasion resistance of concrete. The surface roughness affects the interlocking force among aggregates and the bonding between paste and aggregate; the crushing value involves the aggregate strength and directly reflects its wear resistance. With the decrease of Los Angeles abrasion value, the abrasion loss of concrete decreases (B. Li, Ke, & Zhou, 2011). Additionally Zaetang et al. (2016) indicated that increased recycled aggregate and cement paste bond as well as increased paste content will lead to a high pervious concrete strength thus leading to a better resistance to abrasion.

Furthermore, investigations have shown that both surface finishing techniques and curing types have a strong influence on the abrasion resistance of concrete. In general, proper finishing and curing practices are known to enhance the abrasion resistance of concrete considerably (H. Li, Zhang, & Ou, 2006). John T Kevern, Vernon R Schaefer, and Kejin Wang (2009a) investigated how various curing regimes would affect the durability of pervious concrete. They found out that curing the concrete sample under plastic sheets improved its resistance to abrasion when compared to the concrete sample subjected to other surface treatments which includes a non-film evaporation retardant, white pigment and soybean oil curing regime. Additionally, a number of other factors can also have effect on the pervious pavement concrete surface durability. For instance, the aggregate particles in the surface of the material may disjoint if the paste bond with the aggregate is poor. When shear stress is applied to the surface of the pervious concrete pavement causing failure of the paste-aggregate bond, raveling would occur which would affect the concrete uniformity and structure. As a result of the rougher surface texture and open structure of pervious concrete, abrasion and raveling of aggregate particles can be a problem. This is one reason why applications such as highways generally are not suitable for pervious concretes. However, proper compaction and curing techniques will reduce the occurrence of surface raveling (Tennis et al., 2004).

2.8 Optimization of engineering properties

Relationships between the engineering and hydraulic properties of pervious concrete have often been correlated to develop inter-relationships among the concrete properties. Considering that permeability is one of the most important performance characteristic of pervious concrete (Kayhanian et al., 2012), and it is majorly influenced by the porosity of the concrete. Also, pore properties has also been said to be equally important to the strength properties thus it plays an important role in the characterization of the concrete as a sustainable material (Chandrappa & Biligiri, 2016). Hence, it is important is to achieve a continuous network and an adequate void content so that water can easily infiltrate through at an acceptable strength based on the application of the concrete. To this note, some studies has used the relationship between the compressive strength, porosity and permeability to establish the optimum mixture for the best performance of a pervious concrete. The objective is maximizing strength and permeability rate. Joshaghani, Ramezanianpour, Ataei, and Golroo (2015) study showed the relationships among porosity, strength (56-day) and permeability for pervious concrete as seen in Figure 2.8. The study indicated that the relationship plot can be used to estimate the void content needed for mixtures to satisfy the specification requirement for permeability and strength of pervious concrete. In other words, having determined the void ratio (at the point of intersection as seen in Figure 2.8), it would be possible to obtain proper permeability and compressive strength. Also, Maguesvari and Narasimha (2013) used the relationship between the compressive strength, permeability with total void to determine the optimum mix by balancing the compressive strength and permeability. On the other hand, Mohebi, Behfarnia, and Shojaei (2015) used Taguchi design of experiment method to achieve the optimal mixture with maximum compressive strength and abrasion resistance. However, Taguchi method is best suitable to determine the optimal parameters for designing of pervious concrete pavement.

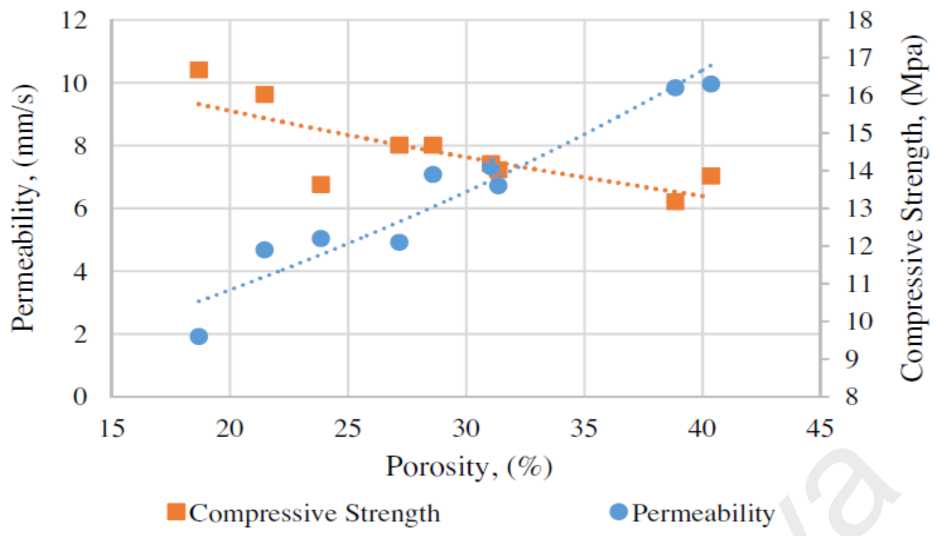


Figure 2.8: Relationship between compressive strength, porosity and permeability (Joshaghani et al., 2015)

2.9 Curing of concrete

Curing is vital for concrete to fully reach its potential in terms of strength and durability (Atiş et al., 2005; Ferreira, de Brito, & Saikia, 2012). The essence of curing is to retain water that would be transferred from concrete to the surroundings within the cement microstructure. This way, the surface of the concrete is shielded from harsh environmental effects such as wind, air moisture and high temperature (Gayarre, Pérez, López, & Cabo, 2014; McCarter & Ben-Saleh, 2001). Thus, proper concrete curing is required to maintain sufficient moisture to allow cement hydration and concrete microstructure develop (Wang, Cable, & Ge, 2006). Also, durability and strength of concrete is affected by the kind of curing regime adopted (ACI, 2000). Many techniques exist to control moisture loss in traditional concrete, although most are not appropriate for pervious concrete. Due to the high porosity of pervious concrete, rapid loss of moisture from the fresh concrete resulting from evaporation can occur. The open structure and relatively rough surface of pervious concrete exposes more surface area of the cement paste to evaporation, making curing even more essential than in conventional concreting (John T Kevern, Schaefer, et al., 2009a). Water is needed for the chemical reactions of the cement and it is critical for pervious concrete to be cured properly (Sabnis, 2015; Tennis et al., 2004). Since the w/c of the concrete is generally low, loss of moisture can result in rapid desiccation, low strength, and excessive surface raveling. Thus, curing is especially important for pervious concrete, because unlike traditional concrete, the bottom of the slab is exposed to air as well as the surface. On the other hand, protecting the surface with even a small measure may provide enough protection to allow proper curing throughout.

Furthermore, casting of pervious concrete may be subjected to hot and dry environment condition depending on the region. In Malaysia, the average daily temperature is estimated to be about 27^{o}C being hot and humid throughout the year (World-weather-and-climate, 2015; World-weather-online, 2015). This could create problem for fresh and hardened properties of a concrete, because concrete subjected to hot weather conditions often exhibit reduced durability (M. Ibrahim et al., 2013; M. Mannan et al., 2002). Putting into consideration the reduced amount of cement and water used in a pervious concrete mix as well as the high porosity, fresh pervious concrete mix may lose moisture rapidly due to evaporation resulting in low strength and rapid desiccation among others (John T Kevern, Schaefer, et al., 2009a)

2.10 Sustainability in construction

In recent time, sustainable development has become the major issue worldwide. The idea is to meet todays' needs without compromising the unborn generations ability to meet their own needs. This involves practices that would lead to the eventual production of high efficiency products, in which mankind and the ecosystem would benefit from (Brundtland, 1987). Sustainable development involves transforming the society and economy progressively. Consequently, satisfying human needs and their aspirations is the major objective of this development (Drexhage & Murphy, 2010). Demands in human life are constantly on the rise in order to fulfil their basic needs, such demands include clean water, shelter, waste disposal, residential and industrial buildings, food, clothing, shelter, safe and rapid transportation for goods and people, energy sources and fresh air (Karim, Zain, Jamil, & Lai, 2011). Thus, United Nations (1992) has provided a comprehensive agenda 21 on actions that should be taken by major groups, organizations and government in all the possible aspect through which the environment is influenced by human. Such actions are to on a global, national and local level. The task is to ensure a balance between environmental and social objectives with the economic development.

However, Malaysian palm oil industry generates million tonnes of waste yearly and its sustainability covers the whole manufacturing system. Thus, sustainability in Malaysian palm oil industry focuses mainly on both international and local acts, process improvement, reverse logistics, regulations and standards, bio-energy and eco-label, zero waste, optimization processes, greenhouse gas (GHG) emissions, energy efficiency, energy generation, renewable energy, food products and consumption, clean production, waste treatment systems, new method of degradation, and life cycle assessment (Ilyana et al., 2015). In fact, it is a worldwide acknowledgement that the modern concrete construction industry has obvious responsibilities such as industrialization, urbanization and infrastructures for the increasing population. Also, it should be noted that the current depletion of natural resources is mainly as a result of its consumption by the construction industry (Mefteh, Kebaïli, Oucief, Berredjem, & Arabi, 2013). Consequently, construction industry worldwide is leaning towards producing a sustainable concrete where the main objectives include reduction of CO_2 gas and pollution, low energy resources development, utilization of waste materials in a more efficient way, flexible structures and buildings that are long lasting, and reduction of energy demand through the development of a thermal mass of concrete (Bravo, de Brito, Pontes, & Evangelista, 2015). Thus, reduction of CO_2 emission is the major sustainable act expected of the construction industry.

On the other hand, the future for Malaysian construction industry indicates that there is light at the end of the tunnel. The government has initiated different programs to ensure that Green Technology implementation will be the strategic engine for Malaysia's economic growth. One of such is the MyHIJAU program. Malaysia's goal of becoming a high-income nation by 2020 needs efforts from every aspect. National Key Economic Areas (NKEAs) was developed to help Malaysia towards their goal by achieving sustainable economic growth and global competitiveness. The government launched the Economic Transformation Program (ETP) on 25th September, 2010 with the goal to elevate the country to develop-nation status by 2020. With the enormous waste generated from the oil palm industry, POC as aggregate replacement in concrete is a way of moving the Malaysian construction industry towards achieving a sustainable environment. From the point of view of energy efficiency, energy required during the preparation stages of natural aggregate would be reduced with the use of POC. Although this is likely best for applications whereby cost savings and reduction of excessive energy consumption is vital. However, incorporating POC as aggregate replacement in concrete will not only reduce consumption of energy, it would also reduce consumption of electricity significantly as well as reduce the processing time used up when compared to process time and method for naturally existing aggregates (Kanadasan et al., 2015).

2.11 Research gap

Despite the amount of research findings which have clearly suggested the possibility of using POC as supplementary aggregate materials in concrete, its use in pervious concrete has been limited. Malaysian researchers have often opted for the incorporation of POC in conventional concrete, self-compacting concrete, high strength concrete and other structural elements such as beams and columns among others. There are indications that different factors such as insufficient knowledge on pervious concrete in general and concerns relating to the physical properties of POC aggregate are some of the barriers limiting the use of POC in pervious concrete. Based on past literatures, there are limited studies on pervious concrete in Malaysia in spite of the various proven studies readily available that has recognized pervious concrete as a sustainable and environmental friendly concrete. Therefore, the utilization of POC in the production of pervious concrete offers an alternative environment friendly concrete and further broadens POC application in concrete which contributes to the green industry initiative being promoted by the Malaysian government. On completion, the study is expected to:

- Reduce the problems related to depleting of raw materials for concrete production.
- Reduce the increasing cost of industrial waste disposal mechanism.
- Develop a pervious concrete for green construction industry initiative.
- Increase the awareness of the environmental and sustainable benefits of pervious concrete

Thus, this proposed study is perceived as a feasible research area since the Government of Malaysia is also encouraging the conversion waste into wealth.

CHAPTER 3: EXPERIMENTAL PROGRAMME

3.1 Introduction

This chapter presents the details of the materials and experimental programme adopted for developing the pervious concrete samples for this study. Due to the lack of standardized mix design method in existence, trial and error approach was adopted to determine the cement to aggregate ratio and w/c used for mix design. The focus of the study was to investigate the way the concrete mix constituents will affect the properties of the concrete. Hence, appropriate methods were adopted to investigate these parameters. Ordinary Portland cement was utilized for all the mixes and two coarse aggregates types were used in the study namely granite and palm oil clinker.

3.2 Materials used

3.2.1 Water

Water used in this study was tap water free from impurities that may affect the properties of the concrete. The water was used for mixing and curing of the concrete.

3.2.2 Cement

Ordinary Portland cement (OPC) equivalent to BS EN 197-1:200 was used throughout the duration of this study as main binding material. OPC was obtained from TYL Cement Sdn Bhd with branding named ‘Orang Kuat’. It has a specific gravity of 3.15 g/cm3. It was supplied in bags with weights of approximately 50kg. The cement was stored in a reserved place to prevent it from moisture. Tests conducted to investigate the properties of the cement include X-ray Fluorescence (XRF), X-ray Diffraction (XRD) and Scanning electron microscope (SEM). The chemical and physical properties of the cement is presented in Table 3.1.

Table 3.1: Chemical and physical properties of OPC and POCP (Kanadasan & Razak, 2015)

Chemical Properties		
Oxides	Cement	POC Powder (POCP)
CaO	64.0	6.37
SiO2	20.3	59.9
SO3	2.61	0.39
Fe2O3	2.94	6.93
Al2O3	5.37	3.89
MgO	3.13	3.30
P2O5	0.07	3.47
K2O	0.17	15.1
TiO2	0.12	0.29
Mn2O3	0.12	0.12
Na2O	0.24	0.24
Others	0.94	0.36
Loss on ignition	1.40	1.89
Physical Properties		
Specific gravity	3.15	2.59
Particle size distribution		
Average size, D (v, 0.5)	27.98µm	20.97µm
Passing 10.48µm (%)	27.58	37.86
Retained 10.48 µm, Passing 48.27 µm (%)	45.80	34.05
Retained 48.27 µm (%)	26.62	28.09

3.2.3 Coarse aggregate

The main objective of this study involves developing an eco-friendly pervious concrete using locally available waste material as coarse aggregate replacement. Thus, two types of coarse aggregates were used in the study namely granite and palm oil clinker.

3.2.3.1 Granite

Crushed granite stones were used as natural coarse aggregates and it was acquired directly from local quarry operated by Kajang Rock Sdn. Bhd. For the purpose of the experimental work, coarse aggregate was sieved into the required size prior to usage and it was divided into 2 single gap-grade as seen in Figure 3.1a. The nominal sizes for the single gap-grades are 9.5mm (4.75mm to 9.5mm) and 12.5mm (9.5mm to 12.5mm). After sieving, the aggregates were stored in plastic bags.

3.2.3.2 Palm Oil Clinker (POC)

The POC utilized in this study was obtained from a local Malaysian palm oil mill. POC was collected in the form of large chunk as seen in Figure 3.1b**,** and then it was crushed into the required aggregate size. A single sized coarse POC with nominal sizes of 9.5mm (4.75mm to 9.5mm) and 12.5mm (9.5mm to 12.5mm) respectively were used as coarse aggregate as shown in Figure 3.1c**.** The POC collected was crushed with a jaw crusher machine and sieved using sieves between 4.75mm and 9.5mm, and 9.5mm and 12.5mm. A maximum size of 12.5mm was adopted for both POC and granite because the jaw crusher used could not produce aggregates of larger sizes. Figure 3.2 shows the coarse POC aggregate that was utilized in this study and it can be seen to have a flaky and irregular shape due to the jaw crusher. Based on its physical properties, POC falls within the criteria for structural lightweight aggregate. According to BSI Document 92/17688 , aggregates with specific gravity lower than 2.2 and bulk density less than 1200kg/m^3 are classified as lightweight aggregates. The unit weight of the POC aggregate is approximately 25% lighter than river sand and 48% lighter than crushed granite stone (Mohammed et al., 2014).

(a)

(b)

(c)

(d)

Figure 3.1: (a) Granite coarse (b) Chunk of POC (c) POC coarse aggregate (d) POCP

3.2.4 Testing of aggregates

Considering that aggregates are vital to the performance of pervious concrete; relevant tests were conducted to investigate the properties of both aggregates used in this research. The physical properties investigated and the test method used for the aggregates tests are summarized in Table 3.2. Since POC is a waste material, it was necessary to wash and dry it so as to remove unwanted particles before it was used as coarse aggregate.

Table 3.2: Test method for aggregates

Physical property	Test method
Sieve analysis	ASTM C 136: 2005
Bulk density	ASTM C 29/C29M: 2009
Specific gravity	ASTM C 127: 2003
Moisture content	BS EN 1097-5: 1997
Water absorption	ASTM C 127: 2003
Aggregate crushing value (ACV)	BS812-110 (1990)
L.A abrasion value	ASTM-C535 (2009)

3.2.4.1 Aggregates sieve analysis

Sieve analysis of the coarse aggregate was conducted to determine the particle size and distribution of the coarse aggregates used in the study as prescribed in ASTM C136 (2005). The primary objective of sieve analysis is to determine the grading of aggregates proposed for the study. The results are used to complement the particle size distribution with applicable specification requirements and to provide necessary data for the control of production of mixtures containing aggregates and various aggregate products. The data was also useful in development of relationship between porosity and packing of the aggregate. The grading of all the coarse aggregates used is summarized in Table 3.3. The aggregates can be seen to be within the acceptable range for nominal size of single-sized aggregate stipulated in BS882:1992 and thus it fulfilled the required parameters.

3.2.4.2 Bulk density, specific gravity and water absorption

Bulk density of aggregates is defined as the mass of aggregates required to fill the container of a unit volume after aggregates are batched based on volume. It depends on the packing of aggregate i.e. either loosely packed aggregates or well dense compacted aggregates. Bulk density would help to understand the possible difference in the concrete density.

Table 3.3: Grading of Aggregates

Sieve size (mm)	Cumulative % by weight passing	
	9.5mm Granite	9.5mm POC
10	100	100
6.3	49	50
5	15	27
4.75	5	6
2	0	3
	12.5mm Granite	12.5mm POC
12.5	100	100
10	44	63
6.3	2	3
4.75	2	2
2	0	0

Additionally, the shape of the particles will also influence very widely because closeness of particles is dependent on the shape of aggregates. In this study, compacted bulk density was reported in accordance to ASTM C29 (2009) by using Equation 3.1. On the other hand, the specific gravity and water absorption of the coarse aggregates used in this study was obtained in accordance with ASTM C127 (2007). The specific gravity of all the coarse aggregates was computed using Equation 3.2

$$Compacted\ bulk\ density\ (\rho) = \frac{A}{V_T} \tag{3.1}$$

$$Specific\ gravity\ = \frac{A}{(A-C)} \tag{3.2}$$

The specific gravity was used for the calculation of the volumes of aggregate required in the various mixtures. Each aggregate has different specific gravity based on the type and size of the material. In addition, water absorption values were used to calculate the change in the mass of an aggregate due to the water being absorbed into the pore spaces within the constituent's particles. Water absorption was determined using Equation 3.2

$$Water\ absorption\ (\%) = \left[\frac{(B-A)}{A}\right] \times 100 \quad (3.2)$$

where *A* is oven dry mass *(g)*, *B* is saturated surface dry mass *(g)*, *C* is submerged mass *(g) and* V_T is the total volume

3.2.4.3 Aggregate crushing value

The aggregate crushing value (ACV) of an aggregate is the mass of material, expressed as a percentage of the test sample. Aggregate crushing value tests was done to evaluate the resistance of both POC and granite aggregate when applied to a gradual compressive load. ACV was computed using Equation 3.3 in accordance with BS812-110 (1990)

$$\text{ACV} = \left(\frac{W_2}{W_1}\right) \times 100 \quad (3.3)$$

where W_1 is the original weight of the aggregate sample before test *(g)* and W_2 is the weight of the aggregate sample passing 1.70 mm sieve *(g).*

3.2.4.4 Los Angeles abrasion value

The Los Angeles (L.A) test is a measure of degradation of mineral aggregates of standard gradings resulting from a combination of actions including abrasion or attrition, impact, and grinding in a rotating steel drum containing a specified number of steel spheres. The L.A. abrasion test is a common test method used to indicate aggregate toughness and abrasion characteristics. This test was carried out as stipulated in ASTM-C535 (2009) and computed using Equation 3.4

$$L.A\ Abrasion\ value = \left[\frac{(W_1 - W_2)}{W_1}\right] \times 100 \quad (3.4)$$

where W_1 is the original weight of aggregate sample *(g)*, W_2 is the weight of aggregate sample retained *(g)* i.e. passing 1.7mm sieve.

Table 3.4: Physical properties of Granite and POC Aggregates

Aggregate type	Aggregate size (mm)	Specific gravity	Aggregate crushing value (%)	Compacted bulk density (Kg/m^3)	Water absorption (%)	LA abrasion value (%)
POC	4.75 – 9.5	1.88	56.40	781	0.78	64.75
	9.5 – 12.5	1.72		747		
Granite	4.75 – 9.5	2.72	18.22	1438	0.55	25.24
	9.5 – 12.5	2.62		1493		

3.2.5 Filler material

Due to the voids present inside and on the surface of the POC coarse aggregate, it was necessary to determine the volume of the additional voids with respect to granite. Consequently, a filler material would be required to pre-coat the surface of the aggregate. Palm oil clinker powder (POCP) has been identified as the suitable filler material to be adopted for this study so as to maximize the application of the palm oil waste. POCP was obtained by ball mill grinding process of POC. The particle size distribution of the POCP is presented in Table 3.1.

3.3 Curing regime

For the purpose of this study, 3 curing regimes (air, full water and 3 days in water curing) were adopted for the POC pervious concrete. For the 3 days in water curing method, the concrete samples were cured for 3 days in water at room temperature prior to it being cured in air until the test days. An average temperature and humidity of 31^{o}C and 71% respectively were recorded for the period of curing for the air cured concrete samples. Figure 3.2 depicts the curing condition. The temperature for the full water curing was kept at room temperature of about 20^{o}C to 25^{o}C.

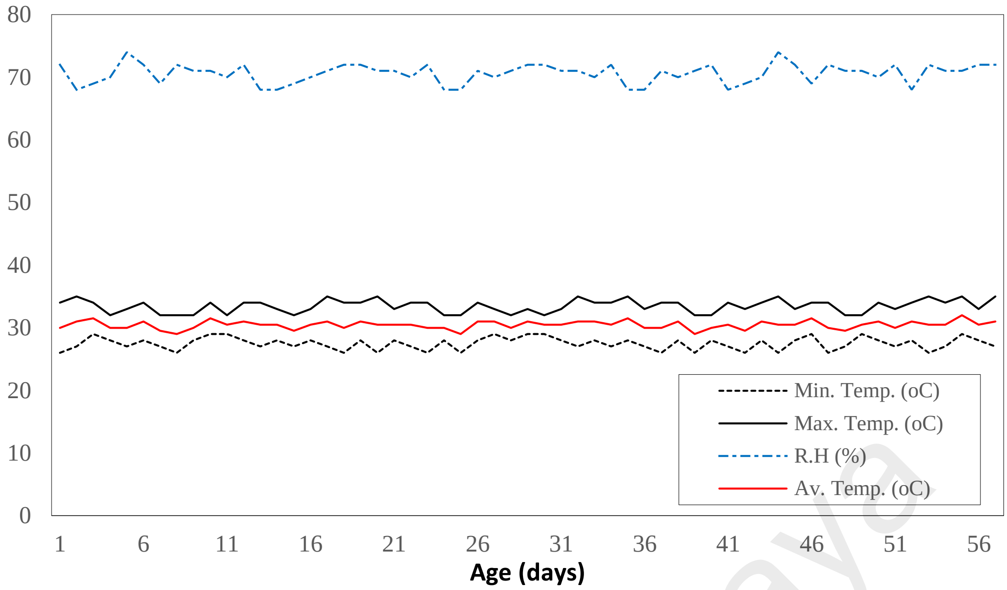


Figure 3.2: Temperature and relative humidity for air curing POC pervious concrete samples

3.4 Experimental programme

3.4.1 Mix proportion

Due to the lack of standardized mix design method in existence, trial and error approach was adopted to determine the cement to aggregate ratio and w/c ratio used for the mix design. The preliminary mix investigation was based on different w/c and cement to aggregate ratio between 0.3 to 0.34 and 0.18 to 0.24 respectively. Mix proportion for all the mixes was then chosen with cement contents of 400kg/m^3, 350kg/m^3, 300kg/m^3, and 250kg/m^3 for the study with two POC coarse aggregate grades. Also, cement to aggregate ratio of 0.21 at a constant water cement ratio of 0.3 was identified to give the best homogeneous mix for the concrete. The selected w/c and cement to aggregate ratio is within the range often used in past studies as seen in Table 2.3. A total of 40 mixes was thus prepared. For all the mixes, Type I OPC complying with British Standard, BS EN 197-1:200 was used as a primary binder. The concrete cubes were tested with age at 3, 7, 28 and 56 days to determine the POC pervious concrete compressive strength and density, while porosity, permeability and abrasion resistance were tested at the age of 28 days.

3.4.1.1 Void calculation for POCP

POC coarse aggregate has visible voids present on it which prompts the need to determine the volume of these voids. Thus, a similar approach by Kanadasan and Razak (2014b) was adopted to calculate the additional voids volume with reference to granite. Figure 3.3 depicts a graphical representation of the concept adopted. The Figure shows that for a given amount of paste, coarse aggregate (X1 and X2 represent equal volume of coarse aggregates) and void, an extra void can be seen from the POC coarse aggregate container due to the porous nature of the POC material. Table 3.5 shows the percentage increment of void at different levels of replacement as a result of the natural porosity of POC coarse aggregate. The final mix proportion for the POC pervious concrete incorporated the resulting void volumes from the calculation. POCP was used to pre-coat the voids present on the surface of the POC coarse aggregate. Figure 3.4 depicts the steps followed to obtain the required POCP volume for the nix proportion at each replacement level.

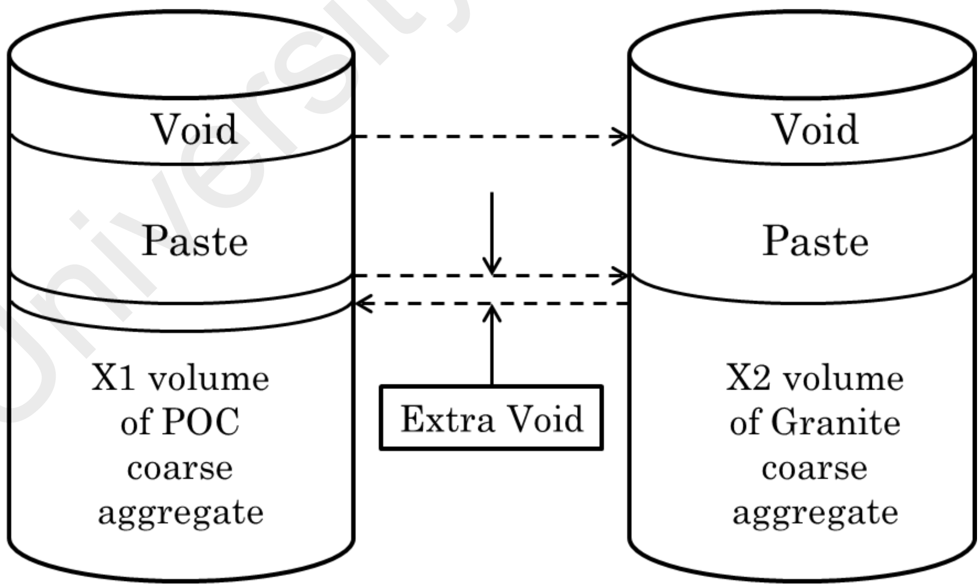


Figure 3.3: Determination of extra voids due to POC coarse

Table 3.5: Total void present on the surface of POC aggregate due to its natural porosity

POC replacement (%)	9.5mm void (%)	12.5mm void (%)
0	0	0
25	3.10	4.78
50	4.63	6.38
75	10.8	13.3
100	16.9	17.6

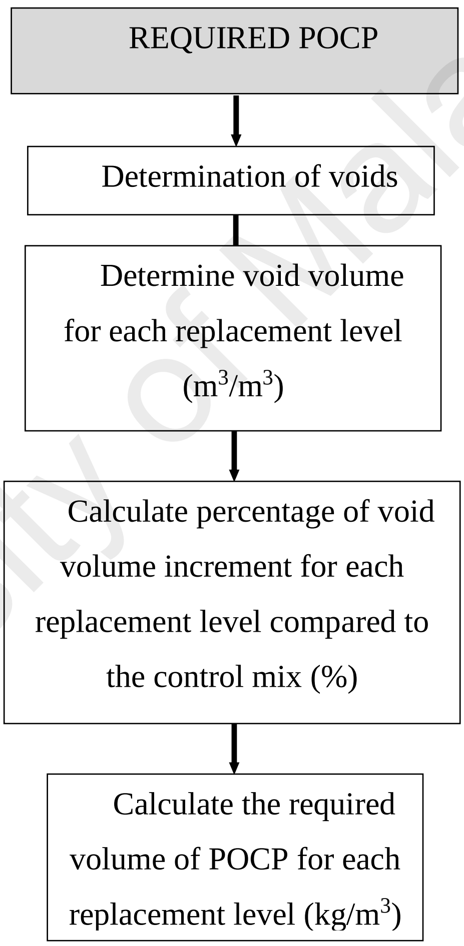


Figure 3.4: Flowchart to obtain POCP for pre-coating POC coarse aggregate

3.4.1.2 POC pervious concrete mix proportion

The mix constituents adopted for the POC pervious concrete mixes include water, cement and POCP was used as a filler material. Other constituents used in all the POC pervious concrete mixes prepared are 2 single gap-graded POC coarse aggregates and granite coarse aggregates. The volumetric replacement levels of natural aggregates with POC were 0%, 25%, 50%, 75% and 100%. A total of 40 mixes were prepared for the POC pervious concrete and the details of these mixes are presented in Table 3.6.

3.4.2 POC pervious concrete mixing and casting

The POC pervious concrete mixes were produced in a rotating drum type mixer. The batching sequence followed these steps:

Step 1: Mixing of POC coarse aggregate with 5% of water and POC powder for the mixes containing POC aggregate for 60 seconds to pre-coat it.

Step 2: Addition of granite, cement and the remaining water, and mixing for 3 minutes

Step 3: Mixture was allowed to rest for 3 minutes

Step 4: Mixing continued further for 2 minutes

Step 5: Consistency test

Once the consistency of the mixture is judged satisfied, the concrete was then cast into 100mm x 100mm x 100mm cubes and 200mm x 100mm cylinder moulds. The POC pervious concrete specimens were de-moulded after 24 hours in accordance with ASTM-C192 (2003) and various samples were cured adopting three curing regimes.

3.4.3 Testing of concrete

3.4.3.1 Fresh properties

The plastic pervious concrete mixture is stiff compared to traditional concrete. Slumps, when measured, are generally less than 20mm, although slumps as high as 50mm have been used. When placed and compacted, the aggregates tightly adhere to one another and exhibit the characteristic open matrix. Thus, fresh concrete properties such as slump are not meaningful for pervious concrete (Sabnis, 2015). However, the consistency test is used to check and control the water content of the concrete.

Table 3.6: POC pervious concrete mix proportions

Aggregate size (mm)	w/c	Cement (kg/m^3)	Components (kg/m^3)	POC replacement ratio (%)				
				0	25	50	75	100
9.5	0.3	400	Granite coarse	1916	1437	958	479	-
			POC coarse	-	331.07	662.14	993.22	1324.30
			POCP	-	13.51	20.24	47.28	73.92
		350	Granite coarse	1676.5	1257.37	838.25	419.12	-
			POC coarse	-	289.69	579.37	869.06	1158.75
			POCP	-	12.08	17.71	41.41	64.69
		300	Granite coarse	1437	1077.75	718.5	359.25	-
			POC coarse	-	248.31	496.61	744.92	993.22
			POCP	-	10.13	15.19	35.42	55.43
		250	Granite coarse	1197.5	898.12	598.75	299.37	-
			POC coarse	-	206.92	413.84	620.76	827.68
			POCP	-	8.45	12.65	29.57	46.18
12.5	0.3	400	Granite coarse	1916	1437	958	479	-
			POC coarse	-	3145	628.92	943.37	1257.8
			POCP	-	20.89	27.89	58.08	76.75
		350	Granite coarse	1676.5	1257.37	838.25	419.12	-
			POC coarse	-	275.15	550.3	825.45	1100.6
			POCP	-	18.29	24.4	50.86	67.16
		300	Granite coarse	1437	1077.75	718.5	359.25	-
			POC coarse	-	235.84	471.68	707.36	943.37
			POCP	-	15.68	20.93	43.60	57.55
		250	Granite coarse	1197.5	898.12	598.75	299.37	-
			POC coarse	-	196.54	393.07	589.61	786.4
			POCP	-	13.06	17.44	36.31	47.97

(a) *Consistency*

This test is used to check and control the water content of the concrete. Consistency of the mixture can be checked by taking a handful of pervious concrete and formed into a ball. If the right water content is used, the concrete will not crumble or lose its void structure as the paste flows into the spaces between the aggregates. If the water is not enough and the concrete becomes too dry, the handful of pervious concrete will collapse. Also, the concrete will become watery and collapse when too much water is used. Figure 3.5 shows a typical scenario for all the cases.

3.4.3.2 Hardened properties

(a) *Hardened density*

The POC pervious concrete hardened density was measured at 3, 7 28 and 56 days, before the compression tests. The obtained densities were calculated as the ratios of identical concrete samples cured in air, 3-day water curing and full water curing regimes. The hardened density was computed using Equation 3.5.

$$\rho = \frac{M}{V} \tag{3.5}$$

where, ρ is the hardened density (kg/m^3), M is the mass of specimen (kg) and V is the volume of specimen (m^3)

(b) *Compressive strength*

Compressive strength test of the concrete samples were carried out in compliance with BS: EN 12390-3 (UNI, 2003). This test was done at the ages of 3, 7, 28 and 56 days on POC pervious concrete cubes of size 100 mm x 100 mm x 100 mm for each mix. The concrete cubes were cast and after 24 hours, they were de-moulded and cured adopting three different regimes; full water curing, 3-day water curing and air curing until days of testing. Full water cured samples were allowed to attain a saturated condition prior to tests. The reported strength value is an average of three samples for the 3, 7 and 56days test and six samples for the 28days test. The compressive strength was calculated by dividing the maximum applied load at failure by surface area of specimen by adopting Equation 3.6

$$f_c = \frac{F}{A_c} \qquad (3.6)$$

where f_c is the compressive strength (MPa), F is the maximum load at failure (N) and A_c is the cross-sectional area of the specimen (mm^2).

(c) *Porosity*

The porosity test was carried out at 28 days of age. The total porosity was determined by dividing the difference between the submerged weight of the pervious concrete sample in the water and the weight after air drying for 24 h (kg) by the sample volume (mm^3) as presented in equation 3.7

$$P = 1 - \left[\frac{(w_1 - w_2)/\rho_w}{v_1} \right] \times 100\% \qquad (3.7)$$

where P is the total porosity of the pervious concrete (%), w_1 is the weight of the air-dried pervious concrete sample for 24 h (kg), w_2 is the submerged weight of the pervious concrete sample underwater (kg), v_1 is the volume of the pervious concrete sample (m^3), and $_w$ is density of water (kg/m^3). A similar approach and equation was also used by (A. Ibrahim et al., 2014) to measure porosity of pervious concrete samples.

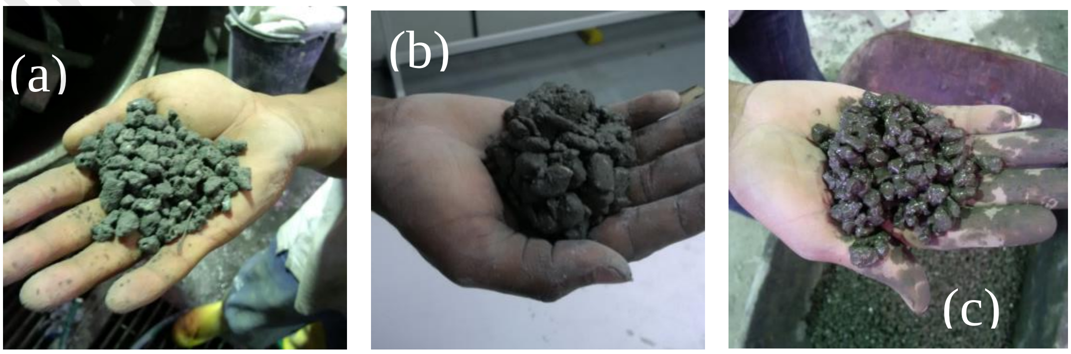


Figure 3.5: Consistency (a) too little water (b) correct amount of water (c) too much water

(d) ***Coefficient of permeability***

This test was carried out after 28 days of full water curing of the concrete samples. As a result of non-standardized method for this test, falling-head apparatus as depicted in Yahia and Kabagire (2014) study was adopted. Similar approach was also adopted by Martin et al. (2014). The test apparatus is shown in Figure 3.6a. In order to ensure that the flow of water went only through the cross-section of the sample and prevent leakage from the sides during testing, a rubber membrane was wrapped around each concrete sample. On completing the test setup, water was allowed to run freely through the specimen prior to commencing the permeability test. This is to ensure that no debris or dust particles clogs the pores of the concrete sample. The test was repeated three times on three identical concrete samples in order to ensure the accuracy of the results. The coefficient of permeability was then computed by adopting Equation 3.8

$$k = \left(\frac{aL}{At}\right)\ln\left(\frac{h_0}{h_1}\right) \tag{3.8}$$

where k is the Coefficient of permeability (mm/s), a is the cross-sectional area of the perspex cylindrical pipe (mm^2), L is the length of concrete sample (mm), A is the cross-sectional area of the concrete sample (mm^2), t is the total time from water levels h_0 to h_1 (secs), h_0 is the initial water level (mm) and h_1 is the final water level (mm).

(e) ***Abrasion resistance***

Surface abrasion resistance was tested at 28 days by the rotating-cutting method in accordance with (ASTM-C944, 1999) as seen in Figure 3.6b. The full water cured samples were allowed to attain a saturated condition before the test and the sample was tested with 98 N load applied. The abrasion resistance test was done for 2 mins each on three sides of one POC pervious concrete sample after contact between the cutter and the surface, totalling to 6 mins per sample. After each abrasion test on each side of the concrete sample, the rotary cutter was brushed clean and a vacuum cleaner was used to blow out any loose debris. An average value based on three different samples were reported. Abrasion resistance mass loss was computed by adopting Equation 3.9

$$M_T = \left[\frac{M_2 - M_1}{M_1}\right] \times 100 \tag{3.9}$$

where M_T is the total mass loss (%), M_1 is the initial mass (kg) and M_2 is the final mass (kg).

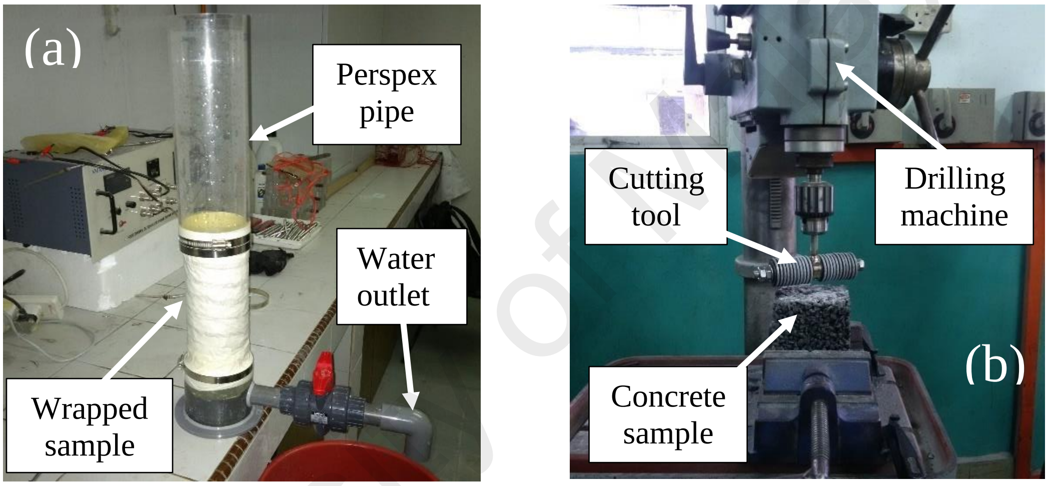


Figure 3.6: Setup for (a) Permeability (b) Abrasion resistance

(f) ***Sustainability efficiency***

Sustainability efficiency is important to understand the effect of incorporating waste aggregates towards enhancing environment quality. In this article, relationship between the structural efficiency and CO_2 emission was adopted to evaluate the sustainability efficiency of the POC pervious concrete mixture. The relationship between the compressive strength and density of the concrete is deemed as the most suitable approach for evaluation of the structural efficiency of the concrete (Choi, Kim, Shin, & Moon, 2006; Kanadasan & Razak, 2015). A good insight on the POC pervious concrete performance will be obtained with structural efficiency evaluation since there exists a good correlation between the reduction in density and the compressive strength of the POC pervious concrete. Structural efficiency was determined using Equation 3.10

$$S.E = \left(\frac{Compressive\ strength}{Density} \right) \tag{3.10}$$

where *S.E* is the structural efficiency, compressive strength and hardened density was considered as results obtained at 28 days. The design mix proportion was adopted for comparison and analysis of the CO_2 emissions for POC mixes. In calculating the amount of CO_2 emitted from the production of $1m^3$ of POC pervious concrete, a similar method adopted by Kanadasan and Razak (2015) to evaluate the greenhouse gas emission of self-compacting concrete (SCC) containing POC aggregates was adopted. Factors put into consideration to determine carbon emission include the CO_2 emission resulting from the transportation of coarse aggregate(s) and cement, as well as the CO_2 emission from the production of cement and aggregate, which was determined using Equations 3.11 and 3.12.

$$TCO_2 = T_T + \sum CO_2 \tag{3.11}$$

where total transportation factor (T_T) is the summation of Transportation of coarse aggregate(s) (T_{CA}) and Transportation of cement (T_C). Also, summation of individual carbon emission $\sum CO_2$ is the sum of carbon emission from the production of cement (CO_2C) and aggregate(s) (CO_2A).

$$T_T = T_{CA} + T_C \text{, and } \sum CO_2 = CO_2C + CO_2A \tag{3.12}$$

Thus, substituting Equation 3.12 into 3.11, Equation 3.11 can be rewritten as below

$$TCO_2 = (T_{CA} + T_C) + (CO_2C + CO_2A) \tag{3.13}$$

The total CO_2 emission for the POC pervious concrete was determined using Equation 3.13. It should be noted that the POC used was collected as a final by-product and it was directly used for all the concrete mixes with no additional treatment. Thus, the carbon emission for POC coarse aggregate was considered to be at the minimum zero level. In this study, the factors for the carbon and transport emission used were based on Mineral Products Association (2012) and DECC (2011) factsheets respectively as presented in Table 3.7. Also, it is expected that for every 1m^3 cube of POC pervious concrete, transportation factors for the aggregates and cement used would be the same. This is because the transportation emission factor is based on the distance covered to obtain the materials used, and all the materials were obtained from a source within a distance not more than 10km. As such, CO_2 transportation emission for all the mix was constant.

Table 3.7: Carbon emission factors based on Mineral Product Association and DECC

Components	CO_2 material emission during production process ($kgCO_2$-e/ton)	CO_2 transportation emission ($kgCO_2$-e/km)
Granite	75	0.22601
POC	-	
Cement	913	

CHAPTER 4: RESULT AND DISCUSSION

4.1 Introduction

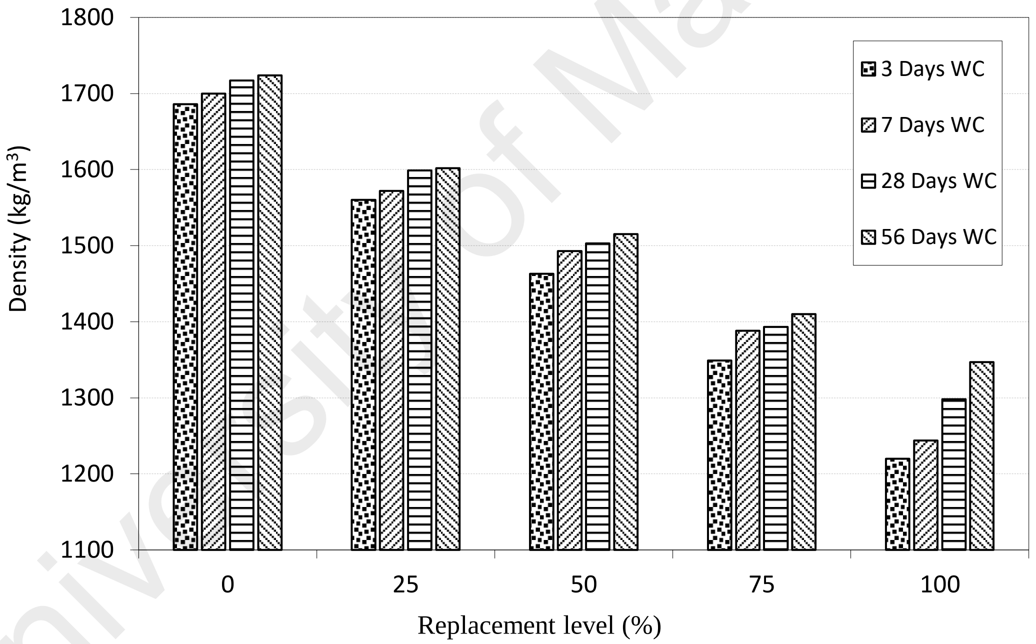
This chapter presents and discusses the experimental outcomes achieved in this study. Mechanical properties of POC pervious concrete are presented. The effects of curing regime and mix constituents such as aggregate size and cement content on the concrete properties are described. The properties investigated are hardened density, compressive strength with age, porosity, permeability coefficient and surface abrasion resistance. Experimental work was analyzed and evaluated on the feasibility of using POC waste in pervious concrete.

4.2 Hardened density of POC pervious concrete

Generally, the density of a concrete depends on the properties, proportions of the materials used, and the compaction procedures used in placement. However, density of a pervious concrete is usually lesser than that of a conventional concrete due to the omission of fine aggregate leading to presence of void. Additionally, unit weight, shape of aggregate also determines the outcome of the hardened density of a pervious concrete. Since POC aggregate has a bulk density almost half of the natural aggregate as seen in Table 3.3, it is expected that the hardened density obtained with incorporation of POC coarse aggregate into the concrete mix will be reduced. Generally, hardened density obtained from the study for the POC pervious concrete at 28 days ranged from 1197kg/m^3 to 1717kg/m^3 and 1166kg/m^3 to 1698kg/m^3 for mixes containing aggregate size of 9.5mm and 12.5mm respectively. This range is similar to the reported values in other pervious concrete research papers, which ranges from 1000kg/m^3 to 2000kg/m^3 (Bumanis, Bajare, & Korjakins, 2013; Chang et al., 2016; Khankhaje et al., 2016; Zaetang et al., 2013).

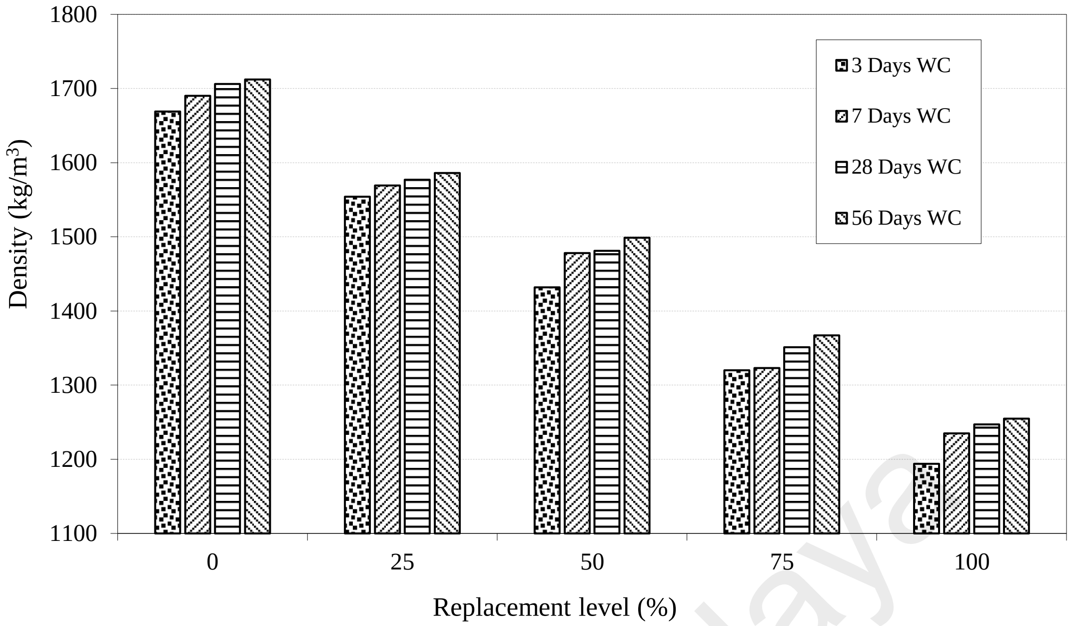
4.2.1 Effects of POC aggregate replacement

Figures 4.1 and 4.2 depict the results of the hardened density obtained for the various POC pervious concrete mixes subjected to full water curing at different cement content for aggregate size of 9.5mm and 12.5mm respectively at 28 days. It can be seen from the Figures that incorporation of POC coarse aggregate into the concrete mixes reduced the density of the concrete. As the percentage of natural aggregate replacement with the POC aggregate increased, there was an increase in the reduction of the concrete's density. Thus, maximum and minimum densities were recorded at 0% and 100% replacement respectively for all the mixes. Since pervious concrete density is relatively dependent on the void in the concrete and the aggregate used (Chandrappa & Biligiri, 2016; Chang et al., 2016; Zaetang et al., 2016), the porous nature of POC aggregate with a reduced unit weight can be said to have directly influenced the lower mass per volume of the POC pervious concrete. Density recorded at 0% replacement was less than 2000kg/m^3 which is equivalent to about 80% of the density of normal concrete. Studies conducted by Kanadasan and Razak (2015) and Abutaha et al. (2016) has shown that incorporation of POC coarse aggregate into a self-compacting and lightweight concrete reduced the density of the concrete, which was related to the POC aggregate porous nature and the reduced unit weight. Table 3.3 shows that POC coarse aggregate has a unit weight which is about 56% lighter than natural aggregate. Similar studies on use of lightweight aggregate from palm oil waste also indicated that increasing the amount of waste in the concrete reduced the density as a result of the lighter weight (about 52%) of the waste aggregate compared to limestone (Khankhaje et al., 2016). Also, the lower specific gravity resulting from the void content and high porosity of POC aggregate contributed to the lower density significantly (Kanadasan et al., 2015). Additionally, when a selected coarse aggregate, characterized with specific weight higher or lesser when compared to natural aggregate, is used to partially or fully substitute natural aggregate in a concrete, it is expected that the concrete's unit weight will either be greater or lesser than unit weight of the control concrete under the same condition (Chang et al., 2016; Yeih et al., 2015). For instance, Chang, Yeih et al. (2016) study showed that the unit weight of the pervious concrete containing electric arc furnace slag aggregate was higher than the control due to the specific weight of individual material where specific weight of gravel and slag were 2.67 and 3.44 respectively. On the other hand, the opposite was the case when oil palm kernel shell was used as natural aggregate replacement in the production of a lightweight pervious concrete in which specific weight of oil palm kernel shell and limestone were 1.3 and 2.7 respectively (Khankhaje et al., 2016).

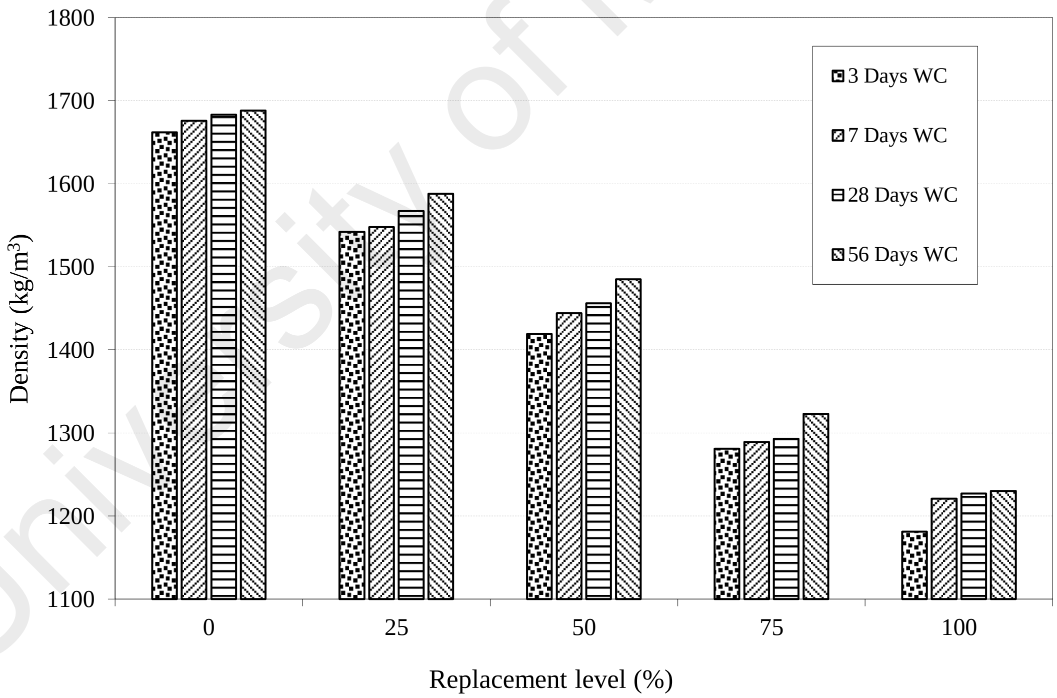


(a)

Figure 4.1: Effect of POC coarse aggregate replacement on the POC pervious concrete density of 9.5mm aggregate size for cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3

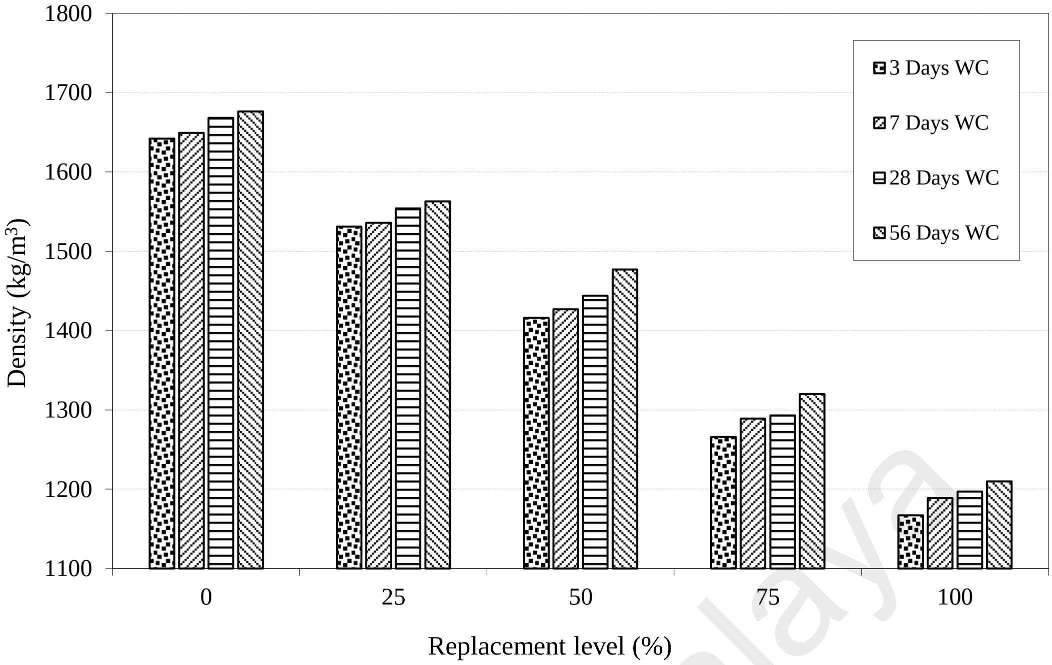


(b)



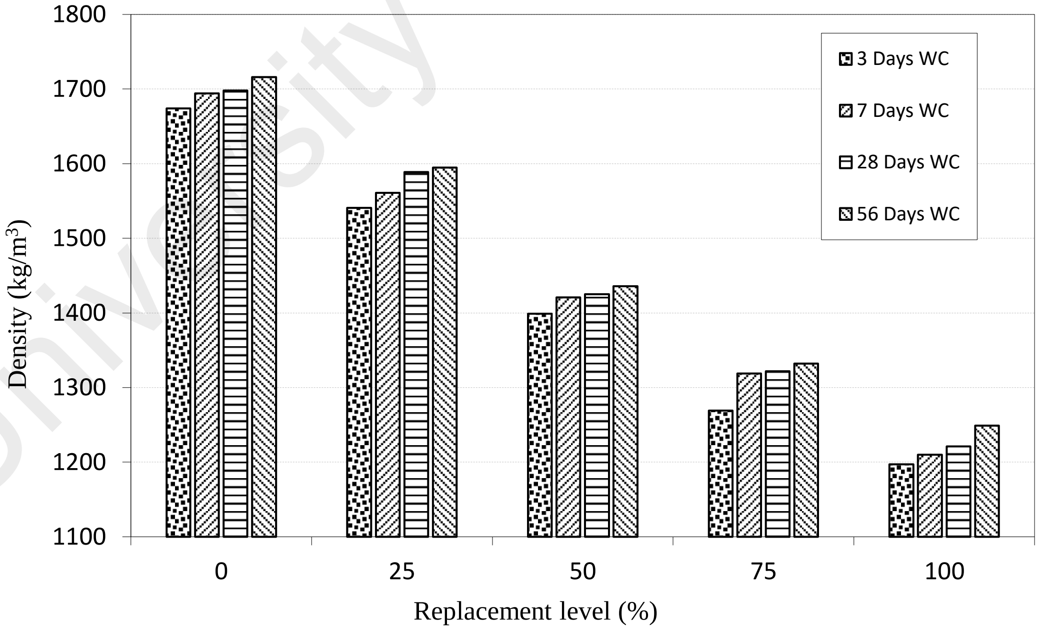
(c)

Figure 4.1, continued



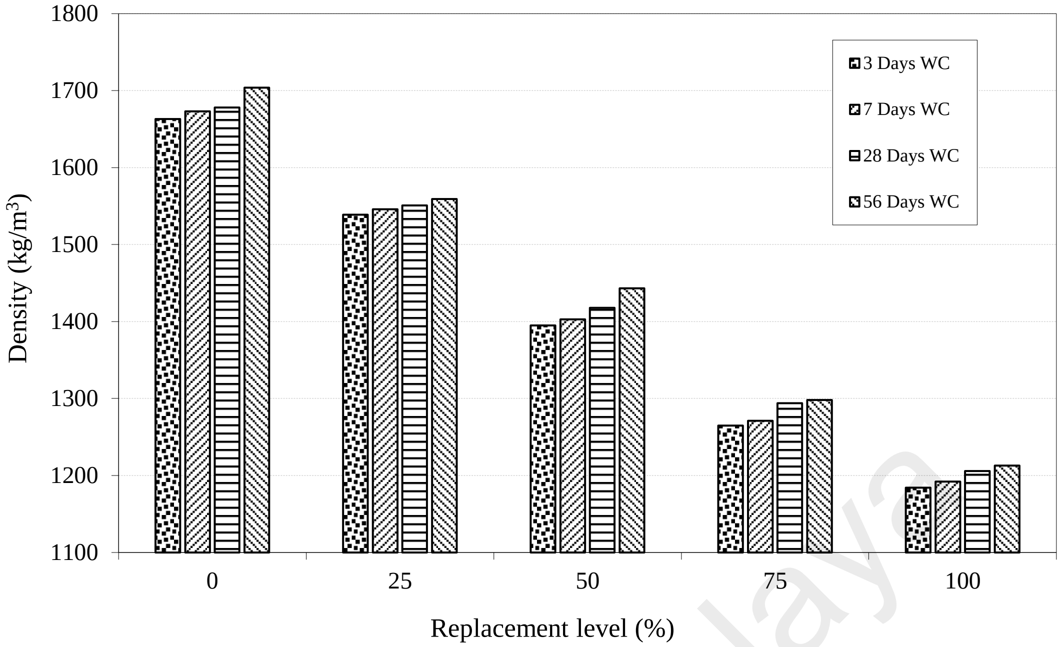
(d)

Figure 4.1, continued

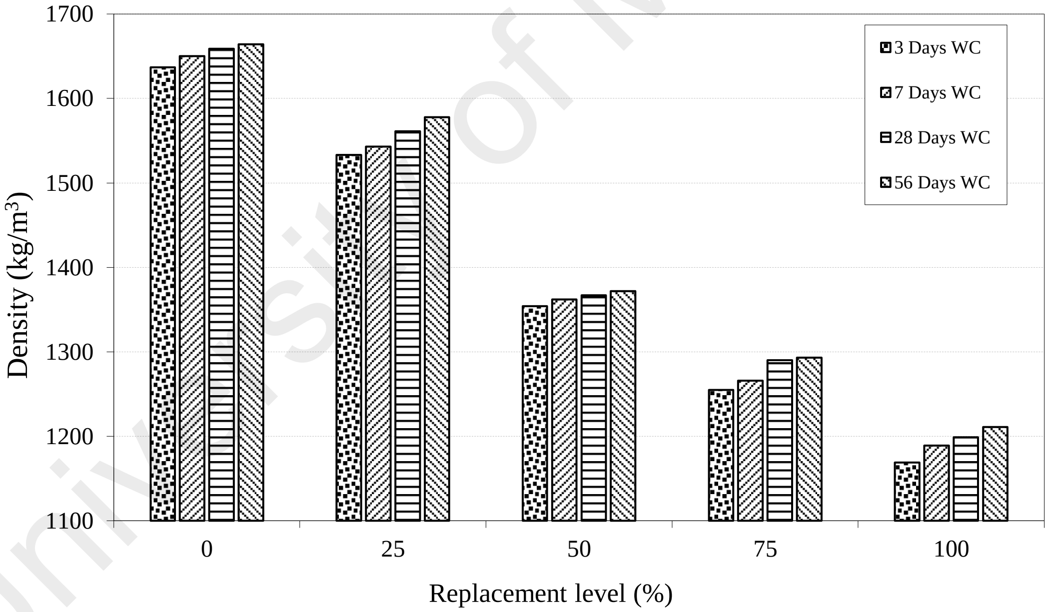


(a)

Figure 4.2: Effect of POC coarse aggregate replacement on the POC pervious concrete density of 12.5mm aggregate size for cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3

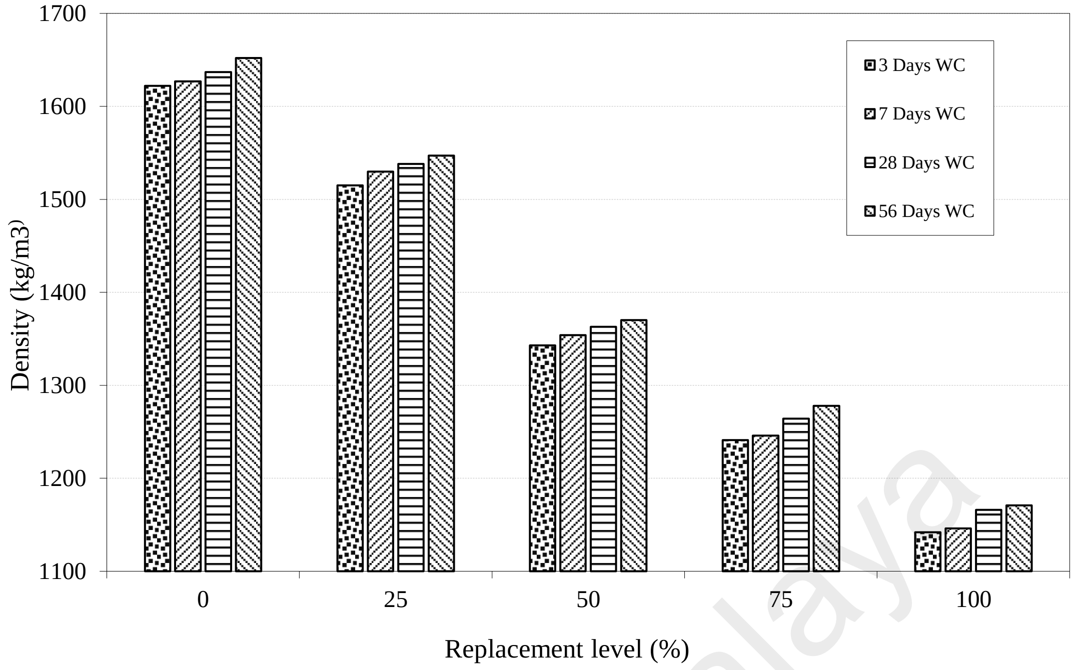


(b)



(c)

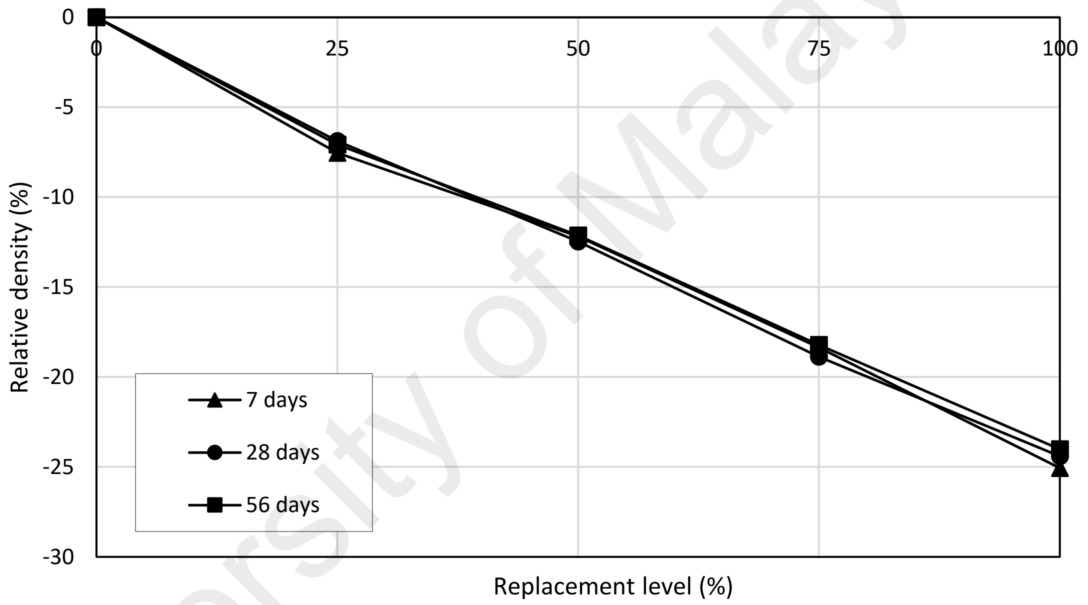
Figure 4.2, continued



(d)

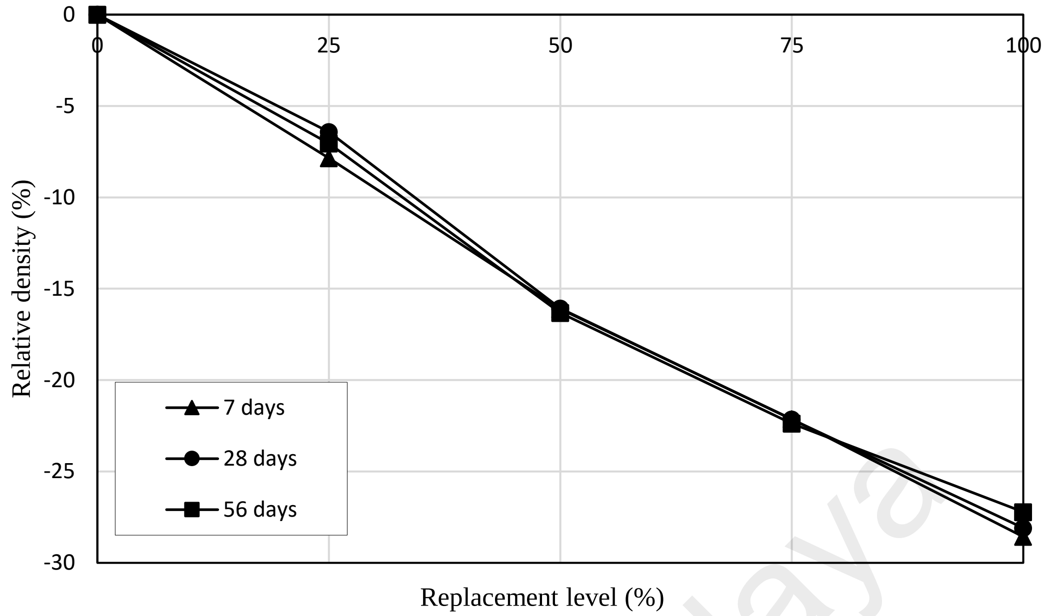
Figure 4.2, continued

Figures 4.3 and 4.4 show the average loss in density resulting from the presence of POC coarse aggregate in the POC pervious concrete mixes for cement content of 400kg/m^3 and 250kg/m^3 at 28 days. The basis for selecting the said cement content was in order to compare the highest and lowest range of densities obtained. It can be seen from both Figures that the POC pervious concrete density decreased irrespective of the age of curing. A maximum reduction of about 25% and 30% was recorded for the POC pervious concrete mix containing 400kg/m^3 cement for the 9.5mm and 12.5mm aggregate size. However, reduction was a bit higher, almost 30%, when the cement content was reduced to 250kg/m^3 for both aggregate grade 9.5mm and 12.5mm. Study conducted by Khankhaje et al. (2016) reported a reduction of about 30% in density due to the presence of oil palm kernel shell in the concrete mix which is similar to the effect of POC aggregate replacement on the POC pervious concrete hardened density. Consequently, this indicates that reducing the cement also affected the outcome of the POC pervious concrete density. The effect of cement content on the density of the concrete is further discussed in the next sub-section accordingly. In general, the density measurements showed that POC pervious concrete can be classified as a lightweight concrete. Concrete whose density is below 2000kg/m^3 may be considered as lightweight concrete (Abutaha et al., 2016; Gesoğlu, Güneyisi, Khoshnaw, & Ipek, 2014; Kanadasan & Razak, 2015; Tennis et al., 2004). Therefore, for applications where energy efficient solutions and lighter weight concrete solutions are required, POC pervious concrete can be used rather than pervious concrete containing natural aggregate.



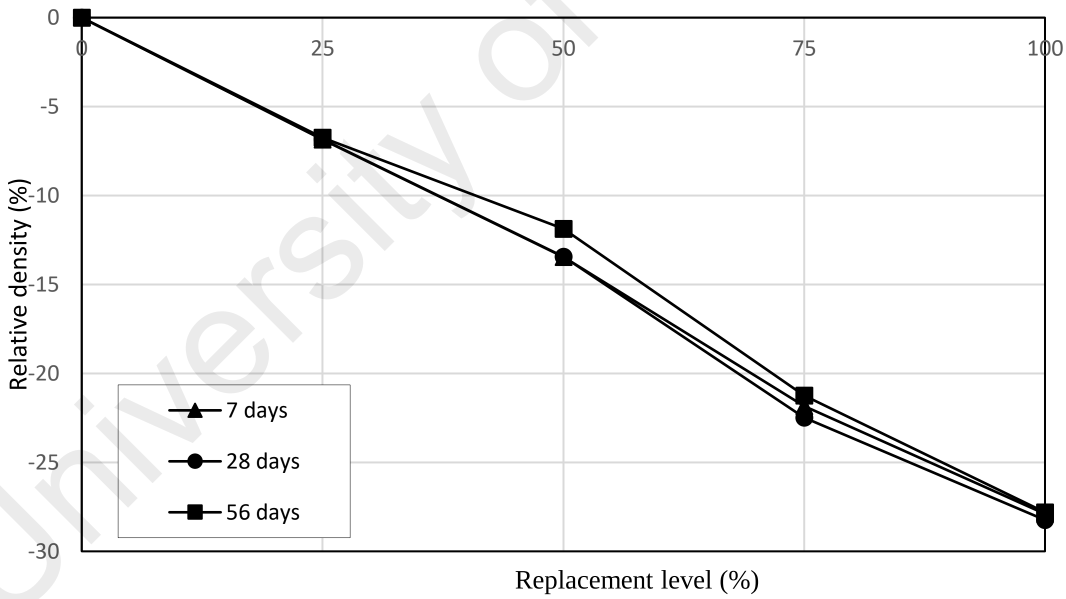
(a)

Figure 4.3: Loss in the POC pervious concrete density with 400kg/m^3 cement content due to POC coarse aggregate replacement for aggregate size (a) 9.5mm (b) 12.5mm



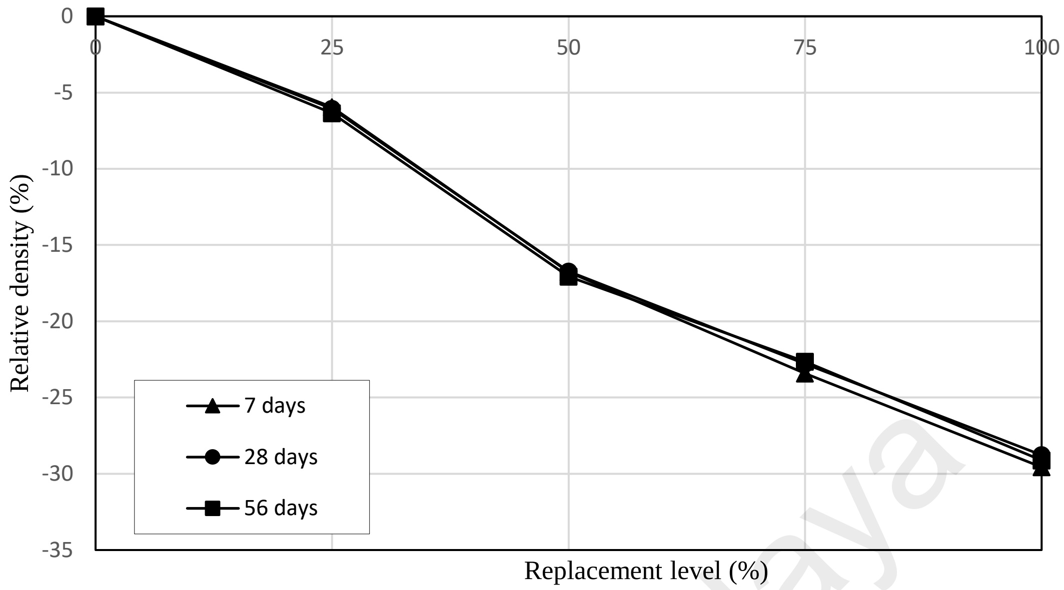
(b)

Figure 4.3, continued



(a)

Figure 4.4: Loss in the POC pervious concrete density with 250kg/m^3 cement content due to POC coarse aggregate replacement for aggregate size (a) 9.5mm (b) 12.5mm



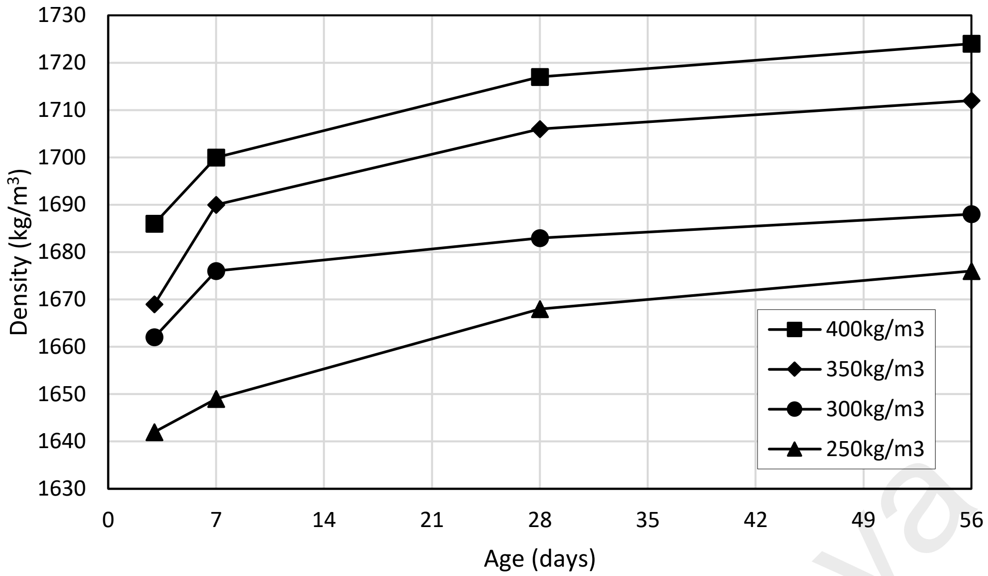
(b)

Figure 4.4, continued

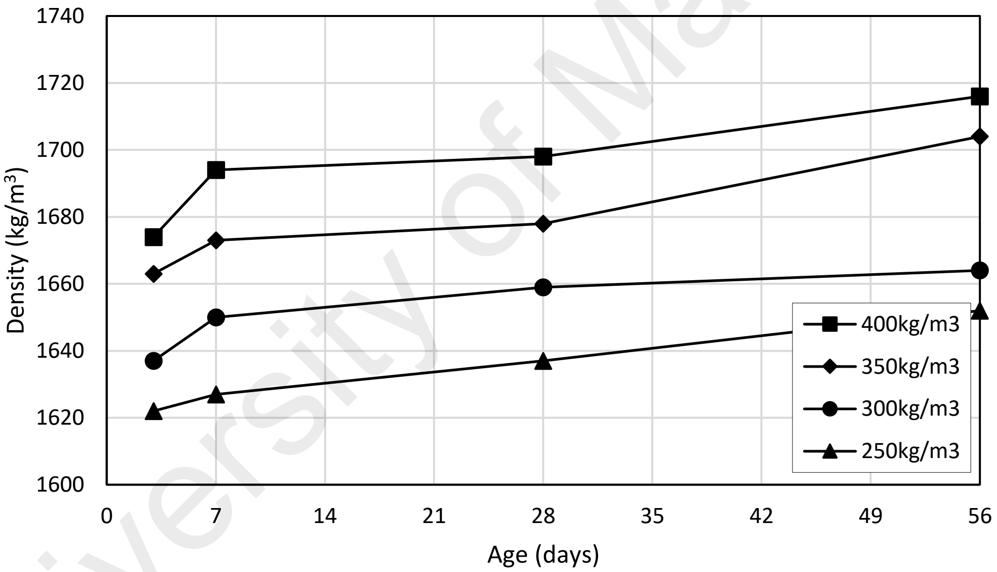
4.2.2 Effects of cement content

The key factors in pervious concrete mixture design are the aggregate gradation, cement to aggregate ratio, and w/c ratio (John Tristan Kevern, 2008). In this study, w/c ratio was kept constant while aggregate gradation and cement content were adjusted. This section discusses the effect of cement content on the density of the POC pervious concrete while the effect of aggregate size will be discussed in the next section. Figure 4.5 shows that the density of the POC pervious concrete increased with higher cement content irrespective of the aggregate size used. The reported density represents the values for control mixes (0% replacement level) at different ages since the effect of POC coarse aggregate on the density of the concrete has been discussed above. As expected, POC pervious concrete mixes containing 400kg/m^3 and 250kg/m^3 cement content had the highest and lowest values of density respectively. Cementitious material in pervious concrete is mainly to sufficiently coat the aggregates in order to increase the concrete's durability. Thus, the increase in the cement paste will increase the coating on the aggregate which in turns will lead to a rise in the density of the concrete. Recent studies have also indicated that increase in cement paste increased the density of the concrete (Chang et al., 2016; Zaetang et al., 2013). It has to be noted that irrespective of the mix design and compaction methods, the paste thickness around the aggregate will increase with an increase in the cement content, which may result in higher mechanical properties such as strength and density but this might defeat the concept of providing better permeability with the use of pervious concrete if care is not taken (Chandrappa & Biligiri, 2016). For instance, if the cement paste is much such that the paste improves the packing of the aggregate, clogging of the concrete pores may occur as a result of the excessive paste settling at the bottom of the concrete. Since pervious concrete is characterized with zero slump and fine aggregate is omitted in this study. The paste used is such that it is sufficient to coat and hold the concrete aggregate in place. Thus, the cement paste was expected not to have any significant effect on the packing of the concrete. Rather, by increasing the cement content, a superior aggregate/paste bond was observed based on visual inspection which suggests that the higher cement content resulted in a better coating of the aggregates. This is similar to what was reported in Torres et al. (2015) study.

Figure 4.6 shows the loss in density resulting from different cement content in the concrete mixes. It can be seen from the Figure that when the cement content of the POC pervious concrete was reduced from 400kg/m^3 to 250kg/m^3, the concrete recorded a maximum loss which was lesser than 5% for both the POC pervious concrete mixes containing 9.5mm and 12.5mm aggregate sizes. This indicates that effect of the cement content on the outcome of the POC pervious concrete density was marginal when compared to the almost 30% loss in density recorded due to the incorporation of POC coarse aggregate.

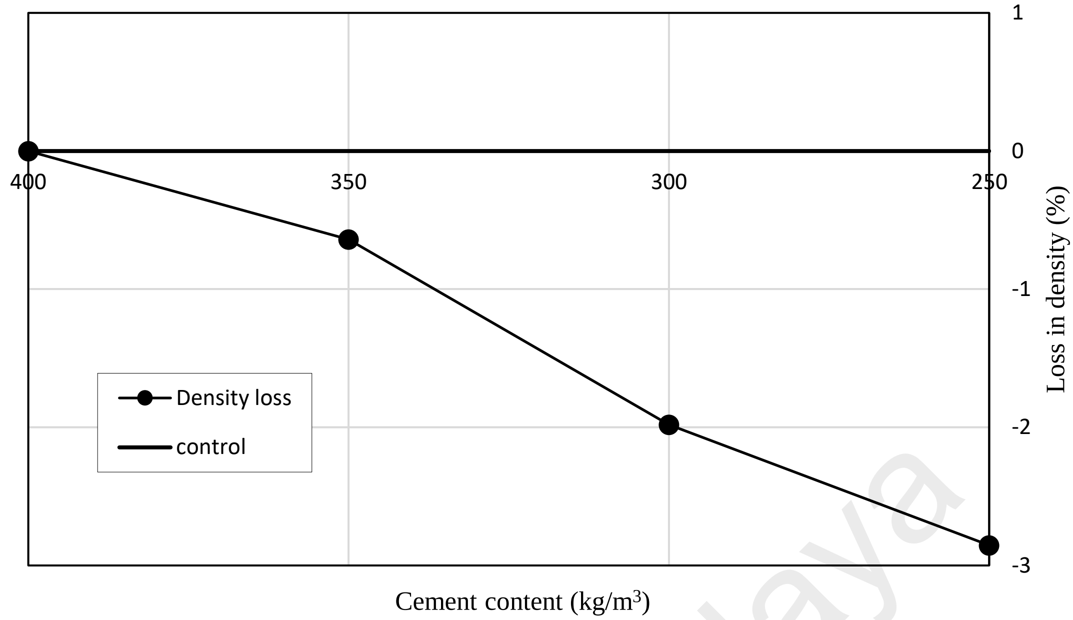


(a)

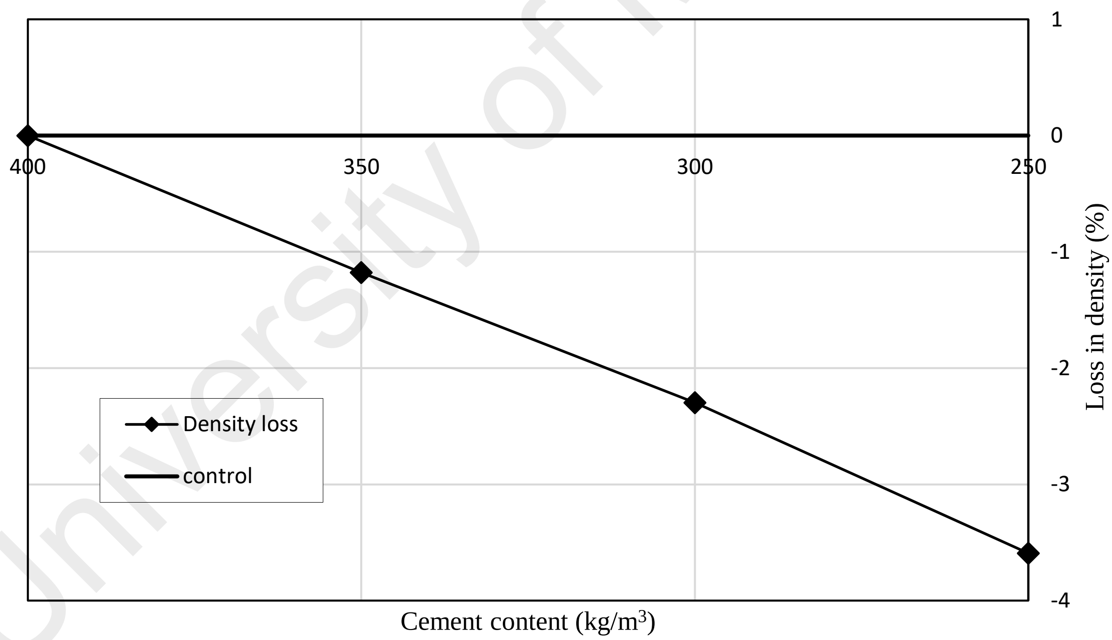


(b)

Figure 4.5: Relationship between varying cement content on the POC pervious concrete density at different ages for aggregate size (a) 9.5mm (b) 12.5mm



(a)

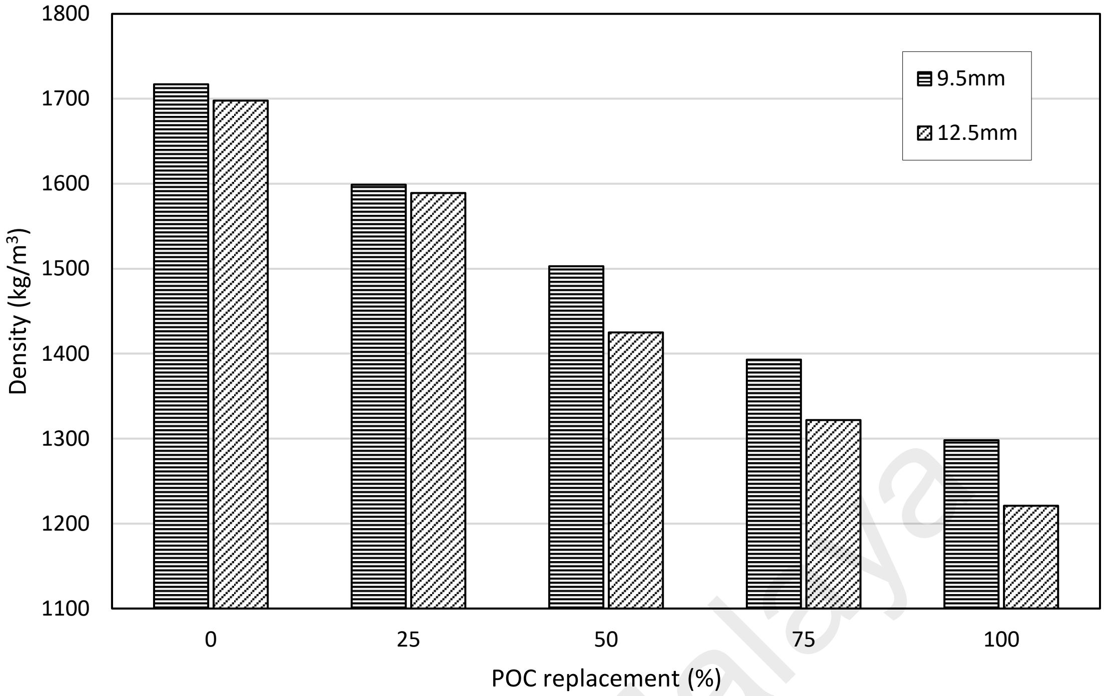


(b)

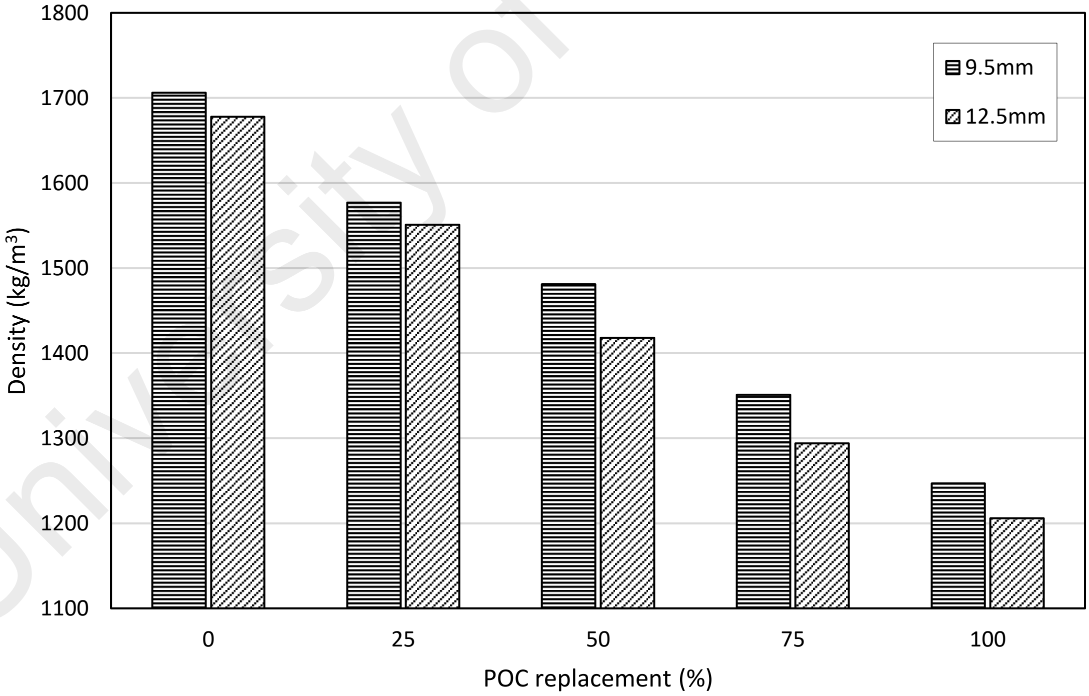
Figure 4.6: Relationship between varying cement content on the POC pervious concrete density at different ages for aggregate size (a) 9.5mm (b) 12.5mm

4.2.3 Effects of aggregate size

Figures 4.7 (a) to (d) shows that using different sizes of aggregate has an effect on the density of the POC pervious concrete. The density values presented were after 28days of full water curing at different POC replacement level. It was observed that the POC pervious concrete mixes containing smaller aggregate size (9.5mm) has higher density compared to the mixes with larger aggregate size (12.5mm). When the aggregate size used in the concrete was larger, the volume of aggregate used became less such that the unit weight decreases. Visual inspection revealed that the number of aggregate particles per unit volume of concrete increased by using smaller size aggregate and vice versa. Thus, the POC pervious concrete unit weight decreased as the aggregate size increased, under the same condition irrespective of cement content or natural aggregate replacement level with POC aggregate. Consequently, mechanical properties of the concrete such as its density can be improved when smaller sized aggregate is used (Chandrappa & Biligiri, 2016; Yang & Jiang, 2003; Yeih et al., 2015). In addition, study conducted by Ćosić, Korat et al. (2015) suggested that a higher amount of smaller aggregate fractions yielded higher density concrete mixtures (Ćosić et al., 2015). Furthermore, the POC pervious concrete loss in density was more evident at 100% POC aggregate replacement level with an average loss of about 5% as a result of using 12.5mm aggregate size with respect to 9.5mm aggregate size as seen from Figure 4.7. This suggest that the effect of aggregate size, similar to effect of cement content, is minimal compared to the effect of POC replacement. Thus, the difference in density values for the POC pervious concrete is visible with increasing replacement level of natural aggregate with POC aggregate for all the mixes irrespective of the cement content.

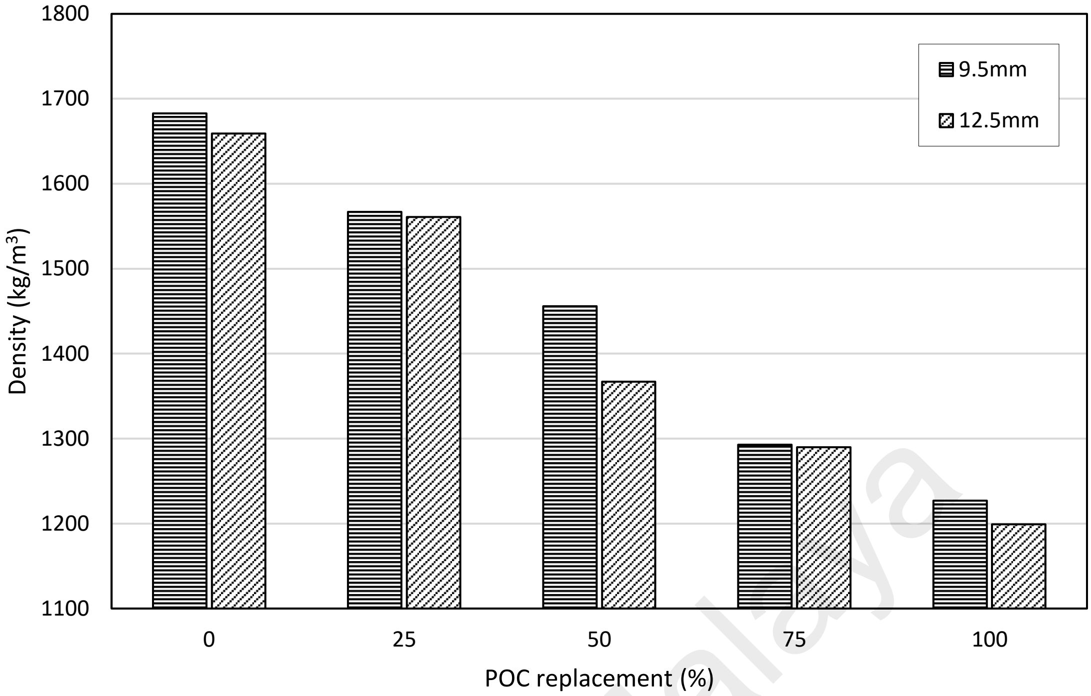


(a)

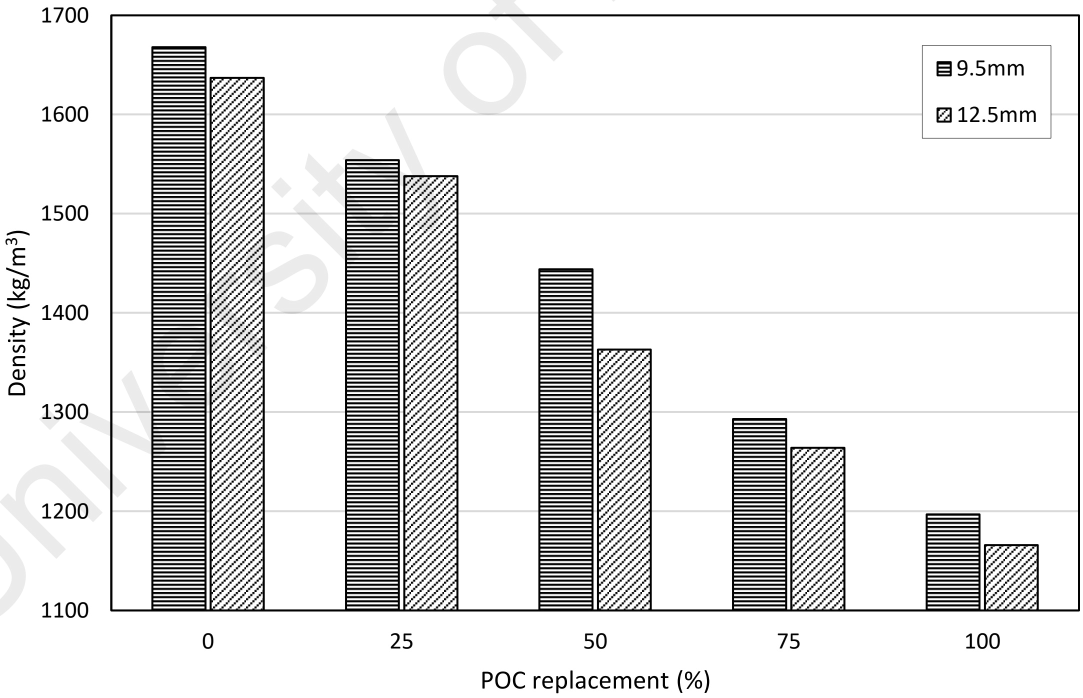


(b)

Figure 4.7: Relationship between varying cement content on the POC pervious concrete density at different ages for cement content(a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3



(c)



(d)

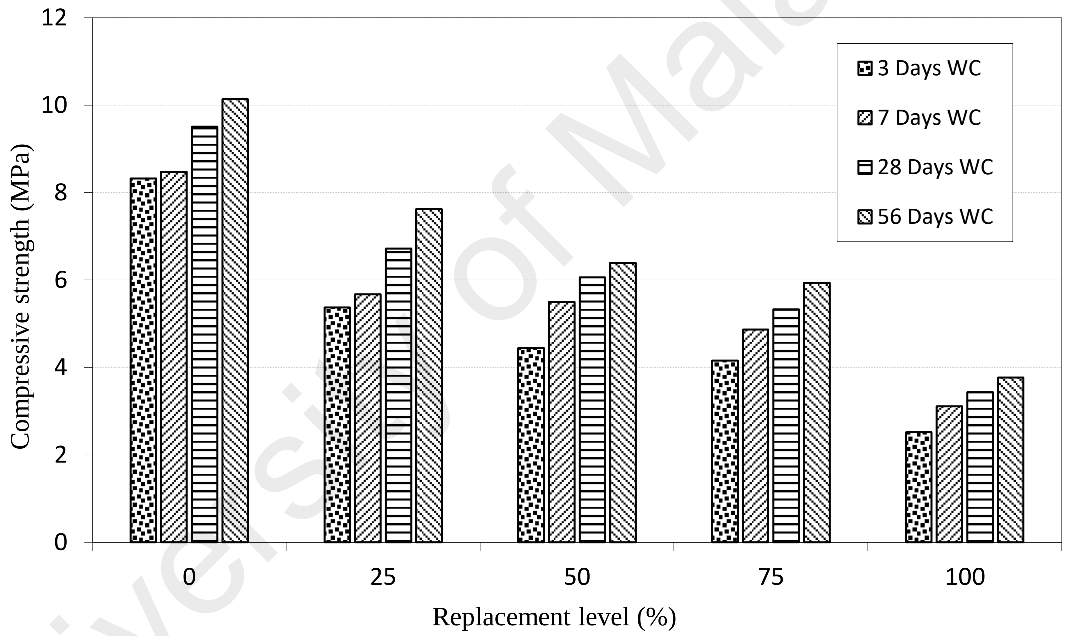
Figure 4.7, continued

4.3 Compressive strength of POC pervious concrete

Generally, pervious concrete has compressive strength lower than conventional concrete due to the presence of high void resulting from lack of fine aggregate (Putman & Neptune, 2011). Owing to the thin coating of the aggregates with cement, the type of aggregate and cement content has a significant role in pervious concrete strength development (Lian & Zhuge, 2010). The compressive strength at 28days is considered as the most vital index for the mechanical performances of concrete. However, emphasis is more on the porosity and permeability rate for pervious concrete rather than the strength for most of its application. On that note, this study starts by examining the influence of aggregate type (POC at selected replacement levels) on the compressive strength.

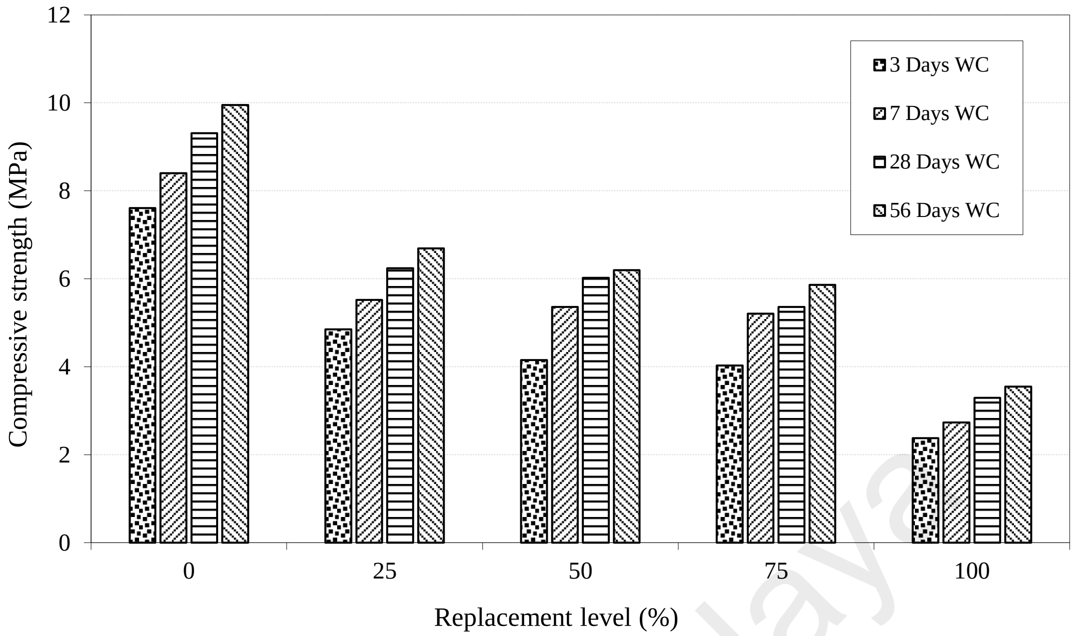
4.3.1 Effects of POC aggregate replacement

Figures 4.8 and 4.9 shows the effect of POC aggregate replacement on the compressive strength development of the POC pervious concrete. The compressive strength of the POC pervious concrete gradually reduced as the incorporation of POC aggregate into the concrete mix increased irrespective of the size of aggregate used and the cement content of the concrete. At 28 days, the control compressive strengths of the POC pervious concrete samples obtained ranged from 9.5MPa to 8.4MPa and 9.3MPa to 8.0MPa for with mixes containing maximum and lowest cement content for the 9.5mm and 12.5mm aggregate size respectively. Meanwhile, the strength values dropped to a minimum range of 3.4MPa to 2.8MPa and 3.3MPa to 2.6MPa for the 9.5mm and 12.5mm aggregate size respectively at full replacement of natural aggregate with POC coarse aggregate. It should be noted that since there exist numerous interconnected pores inside pervious concrete, the pervious concrete compressive strength is expected to be lower than that of a conventional concrete. All the mixes at the age of 7 days had reached 80% to 90% of their 28 days strength which is similar to past studies (Nguyen et al., 2013). The strength gained at 7 days is higher than that for the conventional concrete where 7 days strength is usually about 65% to 70% of the 28-day compressive strength (Chandrappa & Biligiri, 2016). For the POC pervious concrete mix containing 400kg/m^3 cement with aggregate size of 9.5mm, it was observed that the concrete reached about 82% and 80% of its 28-day strength at 7 days when replacement level was 25% and 50% respectively. However, the concrete reached 90% of its 28-day strength at 7 days at full replacement. This trend was similar for the rest of the POC mixes for both aggregate sizes used in the study. As such, as the incorporation of POC aggregate into the concrete mix increased, the rate at which the concrete gained strength gradually increased.

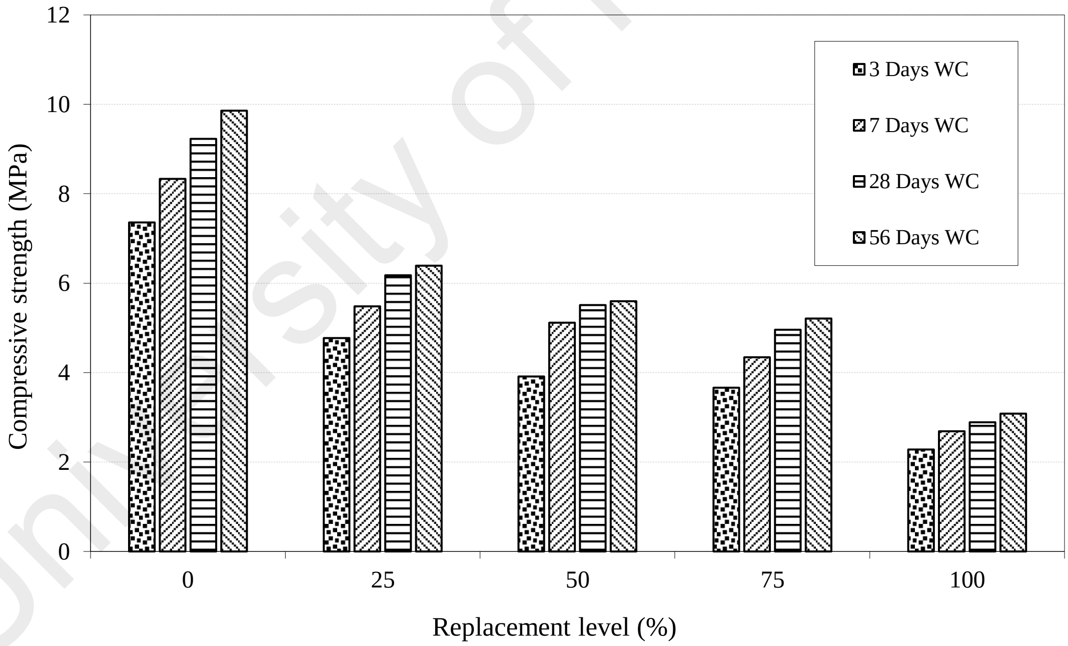


(a)

Figure 4.8: Effect of POC coarse aggregate replacement on compressive strength of 9.5mm aggregate grade at cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3

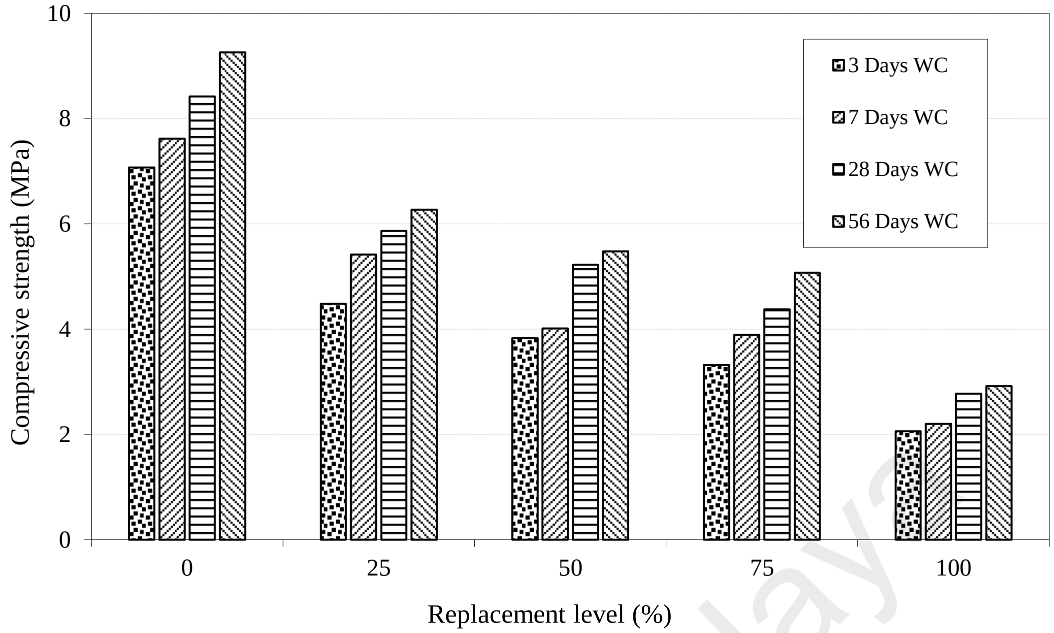


(b)



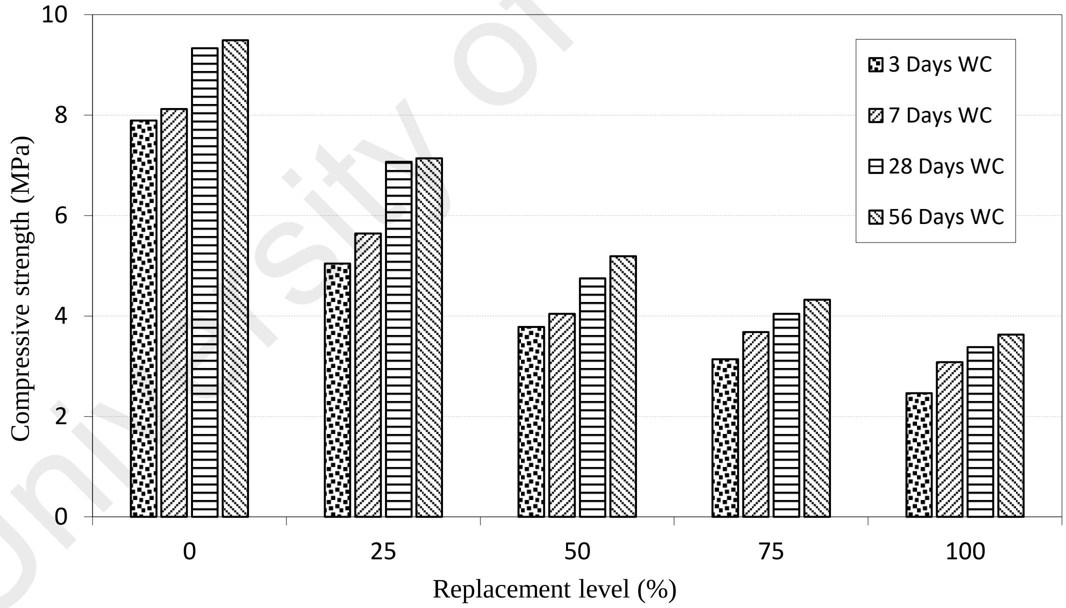
(c)

Figure 4.8, continued



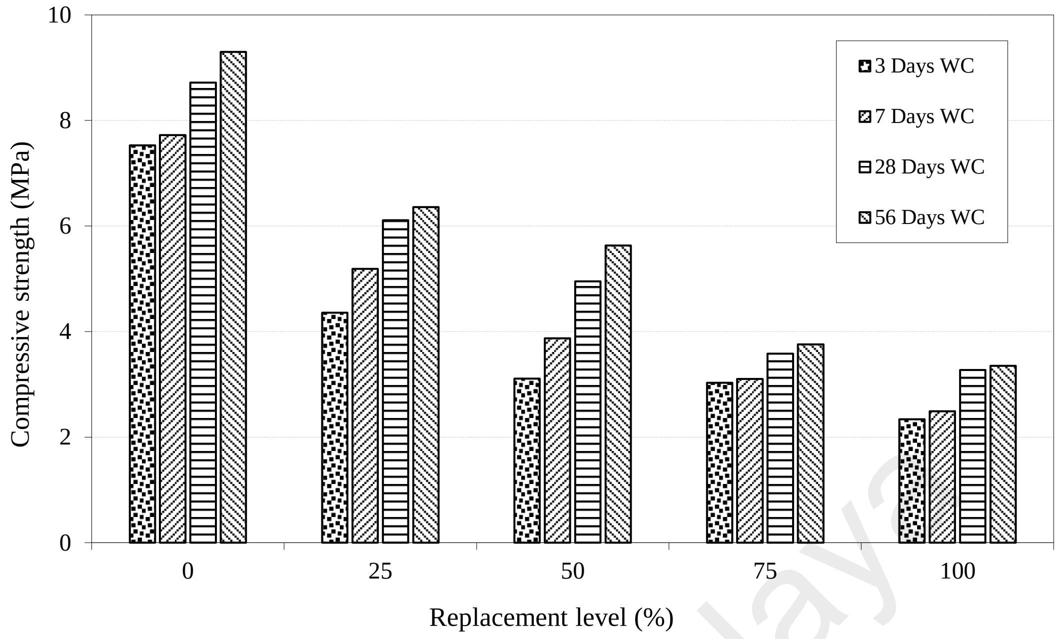
(d)

Figure 4.8, continued



(a)

Figure 4.9: Effect of POC coarse aggregate replacement on compressive strength of 12.5mm aggregate grade at cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3



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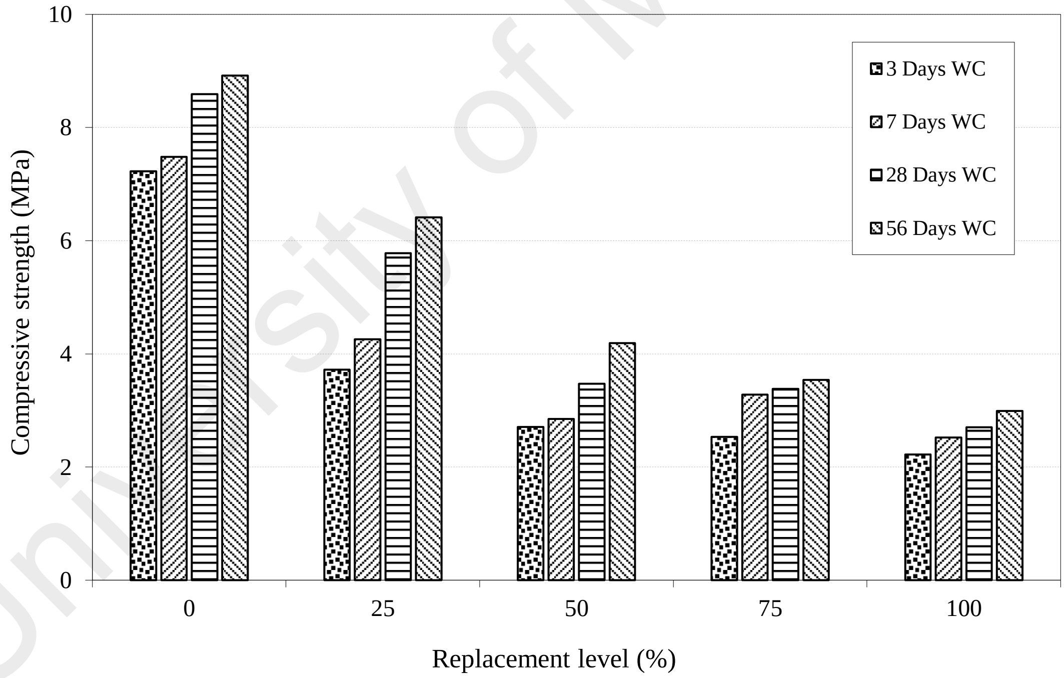
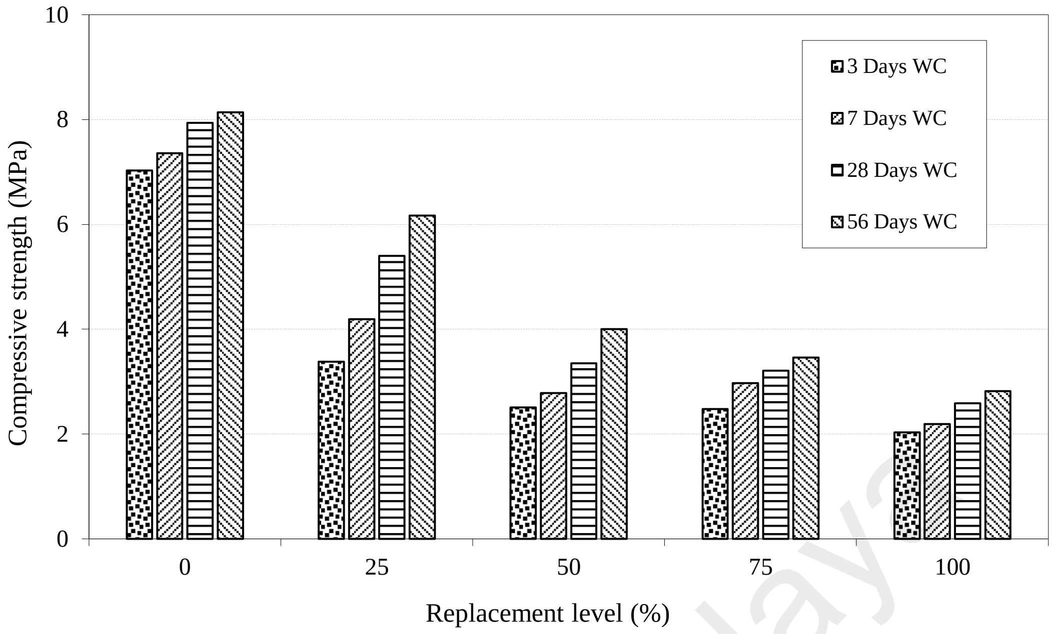


(c)

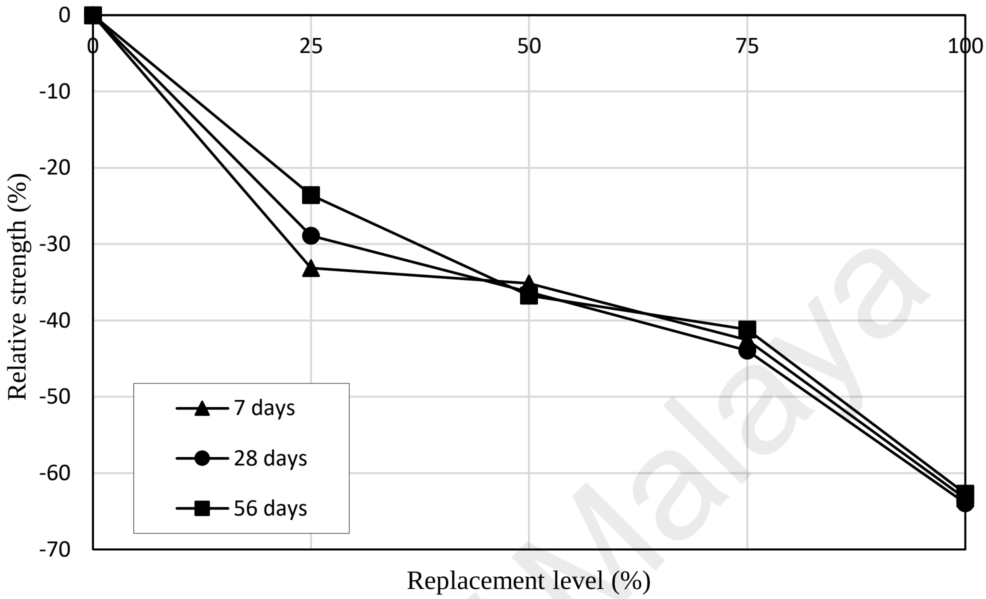
Figure 4.9, continued



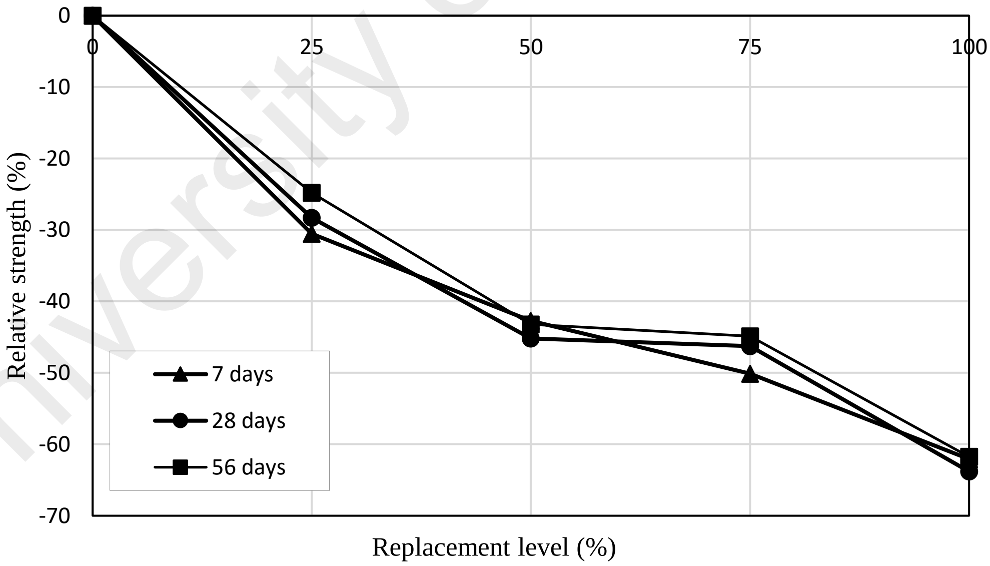
(d)

Figure 4.9, continued

Generally, the range for the compressive strength loss due to POC aggregate replacement was from 23% to 70% where 100% replacement recorded the greatest loss as depicted in Figure 4.11. With a 70% loss in strength, it can thus be said that utilizing POC aggregate resulted in a remarkable reduction in the compressive strength of the concrete. Knowing that POC aggregate has pores inside and on the surface of the material, one can conclude that the porous nature of POC contributed to the loss in strength. This is because the voids present within and on the surface of POC aggregate will make it weaker than a more denser granite thus failing abruptly upon applying load. Although some studies have argued that using a material with rough and porous surface often strengthen the bond between the cement paste and the aggregate. For instance, the use of recycled concrete aggregate and recycled concrete blocks aggregate (materials with rough and irregular shaped surface) increased the compressive strength of the concrete at 60% and 50% replacement of natural aggregate respectively which must have been influenced by the good bond between the paste, and the rough and porous surface of both aggregates compared to normal aggregate (Zaetang et al., 2016).



(a)



(b)

Figure 4.10: Relative compressive strength with age due to POC coarse aggregate replacement for aggregate size (a) 9.5mm (b) 12.5mm

Similarly, the porous nature of using electric arc furnace slag allowed cement paste penetration resulting in a strong interlocking effect and thus improved the compressive strength of the concrete (Chang et al., 2016). It is worth to note that the above statement can only be true when the mechanical properties of the type of aggregates used does not have significant difference. In both study, the difference between the aggregate crushing values of the substituted aggregates and natural aggregate used were not much which indicates that they all had similar mechanical performance. However, if the difference in the aggregates mechanical properties is a lot, the interlocking effect becomes meaningless since its contribution does not supersede the effect of differences in the two aggregates mechanical strength (Chang et al., 2016). Thus, this explains why the theory is not applicable in this study as POC aggregate crushing values varied a lot from that of the natural aggregate used. Similar outcome was observed when OKPS was used as natural aggregate replacement in producing a lightweight pervious concrete. It is because OPKS is more curved and thus resulting in higher void content. Besides, pervious concrete has a limited amount of cement paste and OPKS has hollow sides that are also difficult to fill with cementitious paste (Khankhaje et al., 2016).

Furthermore, since the compressive strength of pervious concrete is greatly affected by the aggregates and its relationship with the interfacial zone (ITZ), failure in pervious concrete occurs through the aggregates (Hesami et al., 2014; Sriravindrarajah et al., 2012). Based on this, the physical characteristics of the aggregate such as shape, size, distribution and texture play important role in controlling the permeability, durability, mechanical properties of pervious concrete because cement paste and aggregate bond is affected by these characteristics (Chandrappa & Biligiri, 2016; Jain & Chouhan, 2011; John T Kevern, Wang, & Schaefer, 2009; Lian & Zhuge, 2010). For instance, study by Lian and Zhuge (2010) concluded that since limestone is more rounded than quartzite, the flaky quartzite particles are more likely to be oriented in one plane under compaction force, and will not handle compression load strength identically in three dimensions. Therefore, it was brittle to resist higher compressive strength (Lian & Zhuge, 2010). Apart from aggregate size, shape, texture and distribution, another property of aggregate that may affect the performance of the concrete is the ACV. According to Kanadasan and Razak (2015), the ACV gives an indirect representation of the aggregate strength which greatly influences the maximum load it can take. Thus, the role of ACV on the outcome of the compressive strength of the POC pervious concrete is important. Table 3.3 shows that the ACV of POC is much higher than the natural aggregates (almost 3 times) resulting in the reduced load the aggregate can withstand which eventually lead to the reduced strength of the POC pervious concrete.

Furthermore, the water absorption of the aggregate is another property which could have contributed to the low strength of the concrete. Lian and Zhuge (2010) revealed that pervious concrete containing quartzite aggregate showed the worst compressive strength compared to that containing limestone aggregate in which the higher water absorption of quartzite was identified as one of the factors that affected the strength. The idea is such that the cement paste around the quartzite aggregate was less viscous to develop a high enough adhesive strength due to its high water absorption when compared to the pervious concrete mixes containing limestone (Lian & Zhuge, 2010). Similar to this study, POC has a higher water absorption than the natural aggregate used as seen in Table 3.3. Additionally, the loading capacity of POC is quite low as a result of the presence of high void inside and on the surface of the POC aggregate. Similar study on use of palm oil waste in pervious concrete revealed that the substitution of gravel with oil palm kernel shell indicated that the curvy and flat shape of the aggregate will disturb the granular arrangement, which subsequently lead to reduced compactness and reduced strength when compared to the round and smooth shape of granite aggregate (Khankhaje et al., 2016). POC, unlike granite whose surface is smooth, has a flaky and rough nature. The load carrying capacity of the aggregate and the interlocking bond between the aggregates may be affected by this inconsistence. A typical failure mode of the POC pervious concrete is depicted in Figure 4.11 (Granite highlighted in red and POC in yellow) in which most of the failure occurred in the POC aggregate.

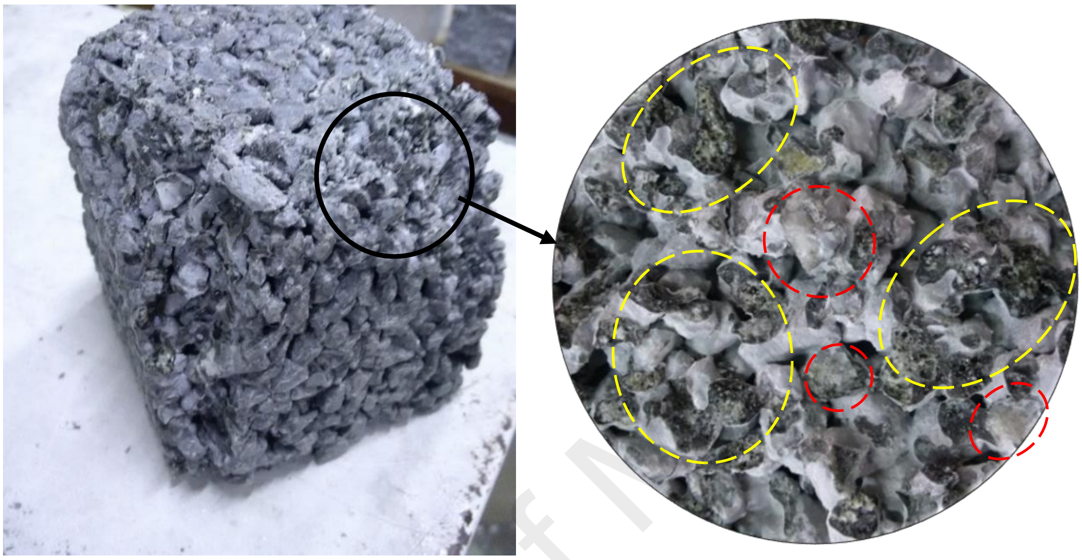
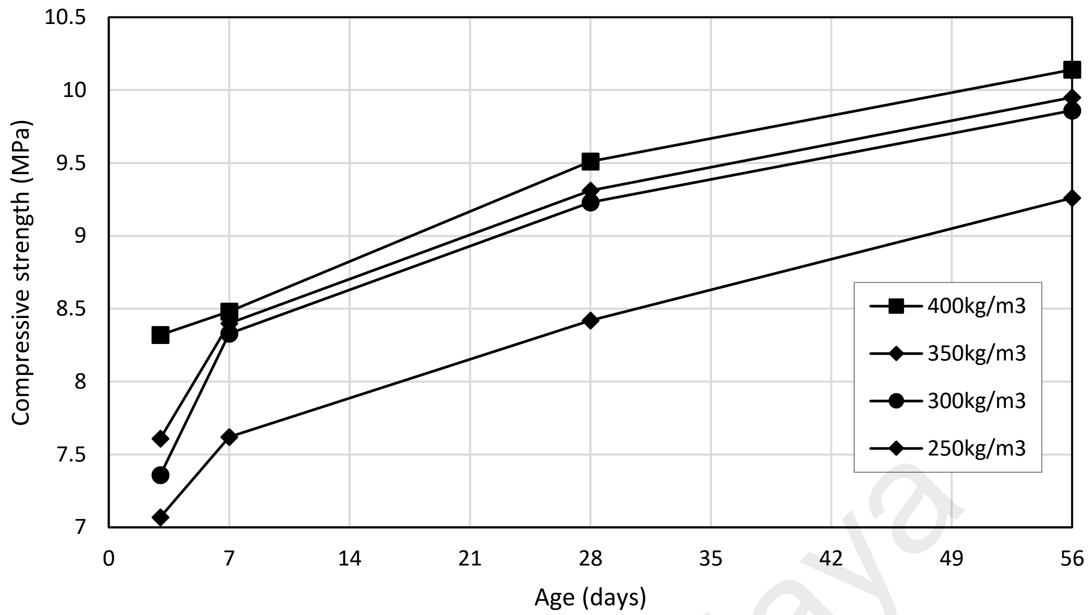


Figure 4.11: Mode of failure of POC pervious concrete

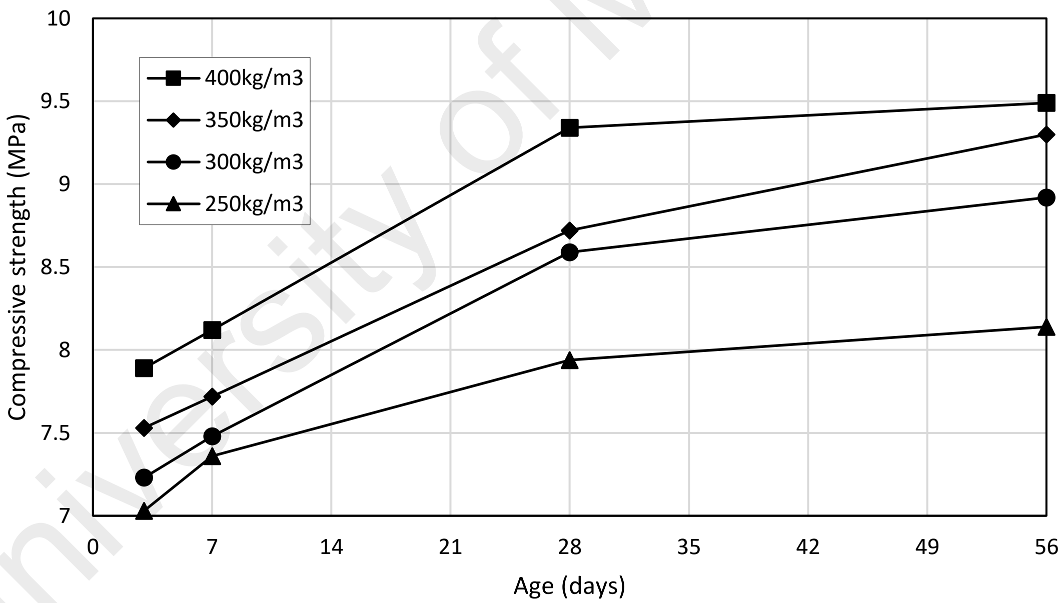
4.3.2 Effects of cement content

The role of binder in pervious concrete is to connect the aggregate pieces together and transfer load throughout the concrete. Too much binder will fill the concrete voids and reduce the required permeability of the concrete. On the other hand, when the binder is too little, it would result in an insufficient connected area required for the concrete strength and durability. Figure 4.12 (a) and (b) shows the effect of using different cement content on the compressive strength of the POC pervious concrete with age for mixes containing 9.5mm and 12.5mm aggregate sizes respectively. The results presented is for the full water curing POC pervious concrete samples only, as the effect of curing on the strength will be discussed in subsequent sections of the study. It can be observed from the Figures that increasing the cement content in the mixes improved the compressive strength of the concrete and vice versa for both aggregate sizes adopted. Also, the mean strength of the POC pervious concrete increased with the age, due to the improved strength of the binder paste with time. This result is expected since increasing the cement content lead to a higher density as discussed earlier. Also, the aggregate/paste interlock is better when a high cement content is used which would give a better coating and bond to the aggregates (Torres et al., 2015). Thus, this explains the ideology of the improved strength due to cement content. However, noting that while increasing the cement content increases the strength, too much cementitious paste thickness will reach a point where it spans from aggregate to aggregate without voids to permit percolation of water thus defeating the purpose of pervious concrete (A. Ibrahim et al., 2014).

Furthermore, it has been established that compressive strength of a concrete is dependent on the combined strength of paste and aggregate as well as void ratio (P Chindaprasirt et al., 2008). However, in the case where the aggregate in the concrete mix has good physical properties, strength of paste becomes an important factor as strength of aggregate is usually higher than that of paste. Thus, when the cement paste coats each aggregate particle thoroughly, a strong bond between them will be developed (Bhutta et al., 2012). The paste will cover the aggregate and act as one unit with air voids formed within the paste matrix which in turns strengthen the ITZ (P Chindaprasirt et al., 2008).



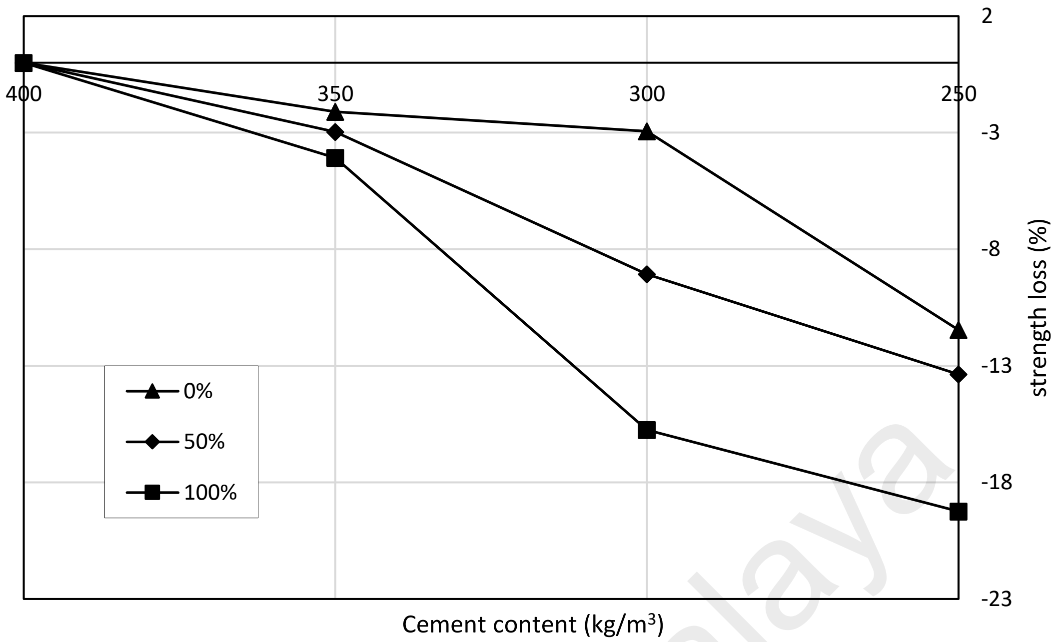
(a)



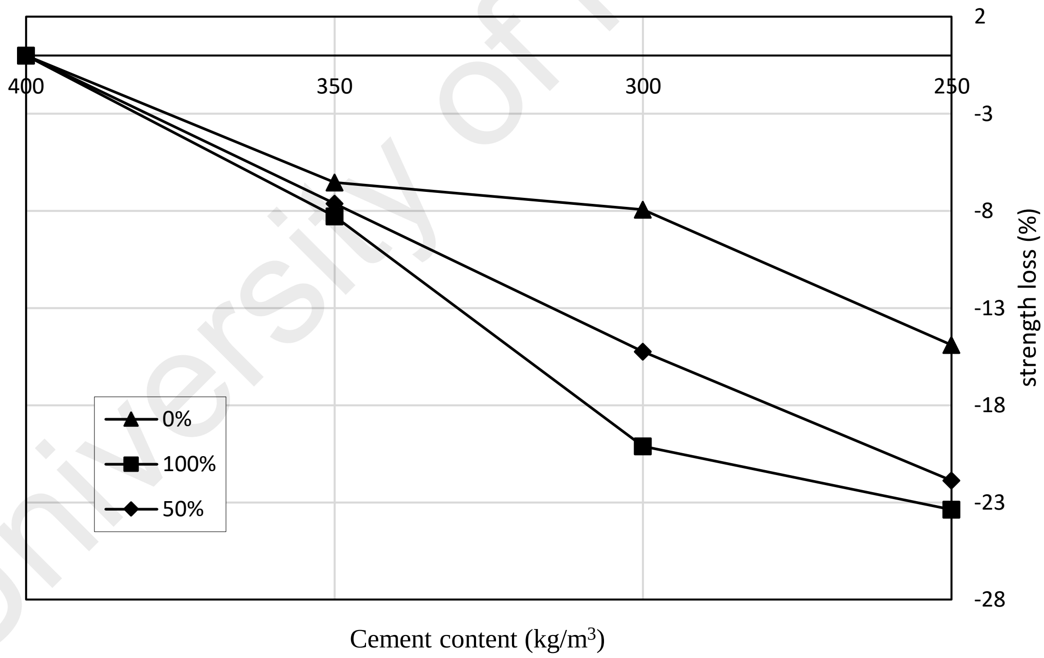
(b)

Figure 4.12: Relationship between varying cement content on the POC pervious concrete compressive strength at different ages for aggregate size (a) 9.5mm (b) 12.5mm

According to Deo and Neithalath (2011), increase in paste volume fraction will increase the thickness of the cement paste layer around the aggregates. Thus, better bonding is formed which will produce increased peak strengths. Though POC aggregate is a friable material which suggests that it would have a bigger effect on the properties of the concrete, the cement content would also contribute to the performance of the paste although such effect might be marginal when compared to the effect of POC aggregate. This is as expected since the compressive strength is primarily affected by the porosity of concrete and type of aggregate used. Thus, any improvement in the cement paste strength can be expected to have minimum effect on the compressive strength of pervious concrete unlike in the conventional concrete where its compressive strength is dependent on the aggregates grading and quality, but mostly on the quality of the binder (Sriravindrarajah et al., 2012). Consequently, maximum loss in strength due to increasing the cement content of the concrete at 0% replacement was about 12% and 15% for the POC pervious concrete with 9.5mm and 12.5mm aggregate sizes respectively as seen in Figure 4.13. The 3% difference could be related to the effect of the aggregate size on the strength of the concrete. However, Figure 4.13 also shows that a maximum loss of about 20% and 23% was recorded at full replacement of natural aggregate with POC aggregate for the POC pervious concrete with 9.5mm and 12.5mm aggregate sizes respectively which suggests that the POC aggregate contributed more to the loss in strength compared to the cement content. Furthermore, the strength of aggregate is usually stronger than the interface between aggregate and cement paste, thus pervious concrete failure normally starts at the binder layer or interface between the aggregate. Thus, the improvement in the cement paste and aggregate bond is important for enhancing the compressive strength of pervious concrete (Zaetang et al., 2016).



(a)



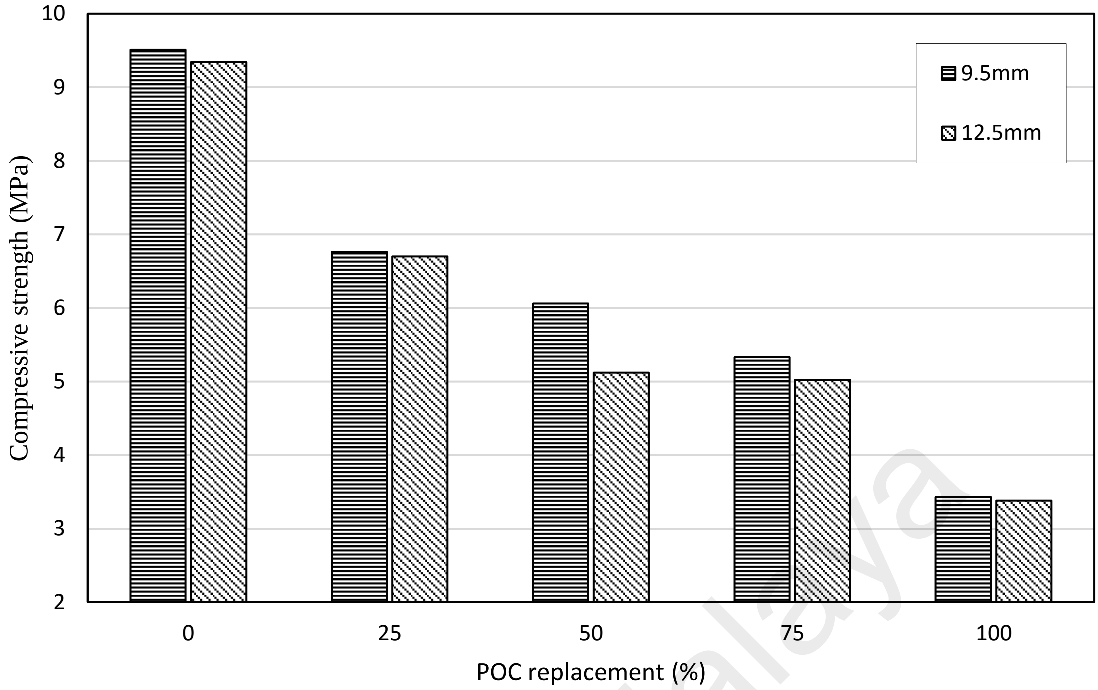
(b)

Figure 4.13: Loss in the POC pervious concrete compressive strength due to varying cement content for aggregate size (a) 9.5mm (b) 12.5mm

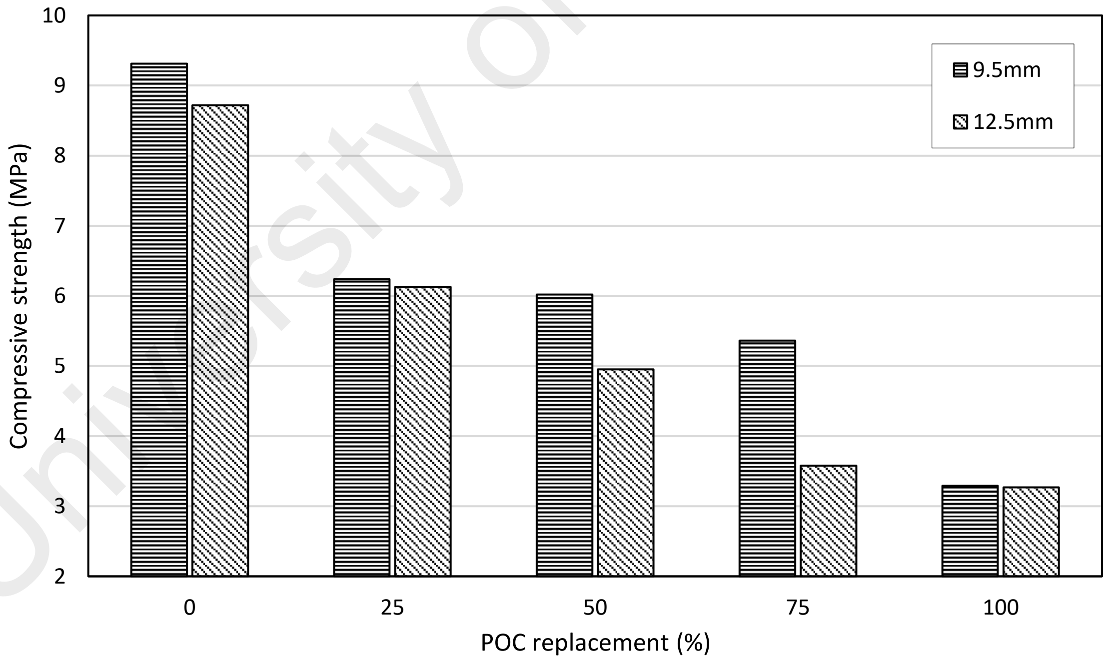
4.3.3 Effects of aggregate size

Two different sizes of aggregate were used in the production of the POC pervious concrete in order to evaluate its effect on the compressive strength of the concrete. From Figure 4.14, it is evident that using bigger size of aggregate affected the compressive strength of the concrete. As expected, the smaller the coarse aggregate size, the higher the compressive strength. Also, when the mix proportion of the concrete are the same, the concrete strength seems to increase with reduction in the size of aggregate. This may be attributed to the fact that the strength of the interface between the cement paste and aggregate will be improved with the use of smaller aggregate size (Yang & Jiang, 2003). The number of aggregate particles per unit volume of concrete will increase by using smaller size aggregate. Thus, the specific surface of the binding area and aggregate increases as the aggregate particles increase (Yang and Jiang 2003). Subsequently, the increased contact area will result in strength improvement. It is believed that the bonding force of cement matrix to aggregates is better when a smaller grade of aggregate is used (Bhutta et al., 2012). Owing to the thin cement coating around the aggregates, the size, type and shape of aggregate has a significant role to play in pervious concrete strength development. Lian and Zhuge (2010) study also indicated that using larger size aggregate over smaller size aggregate reduced the strength of the concrete.

Additionally, it was observed that as the replacement level of natural aggregate with POC aggregate increased, the loss in strength due to aggregate size became more evident which was most noticeable at 50% and 75% replacement level. However, the opposite is the case at 100% replacement level where the loss in strength due to aggregate size was minimal (less than 10%). This can be as a result of the ACV of both materials used. At full replacement, the ACV of POC is the same irrespective of the size and volume of aggregate while the difference between the ACV of POC and natural aggregate at other replacement level is much higher as seen in Table 3.3. It is believed that when the percentage of POC aggregate is equal to or more than the volume of natural aggregate in the mix, the effect of the ACV is noticeable. For instance, the POC pervious concrete would have similar resistance under compression irrespective of the size of aggregate used due to the superior ACV of natural aggregate over POC aggregate because the percentage of natural aggregate is higher than the POC aggregate. However, the high percentage of POC aggregate in the POC pervious concrete at 50% and 75% replacement means the concrete resistance under compression is dependent mainly on the ACV of the POC aggregate based on the high percentage of the POC aggregate. As a result of this, the effect of aggregate size is more visible at 50% and 75% replacement. Average loss in strength due to POC aggregate size was between 30% to 40% at 50% and 75% replacement level for all the mixes while a loss of less than 10% was recorded at other replacement level. Furthermore, visual inspection of the failed specimen as seen in Figure 4.11 shows that failure mostly occurred in the POC aggregate (POC highlighted in yellow and granite in red).

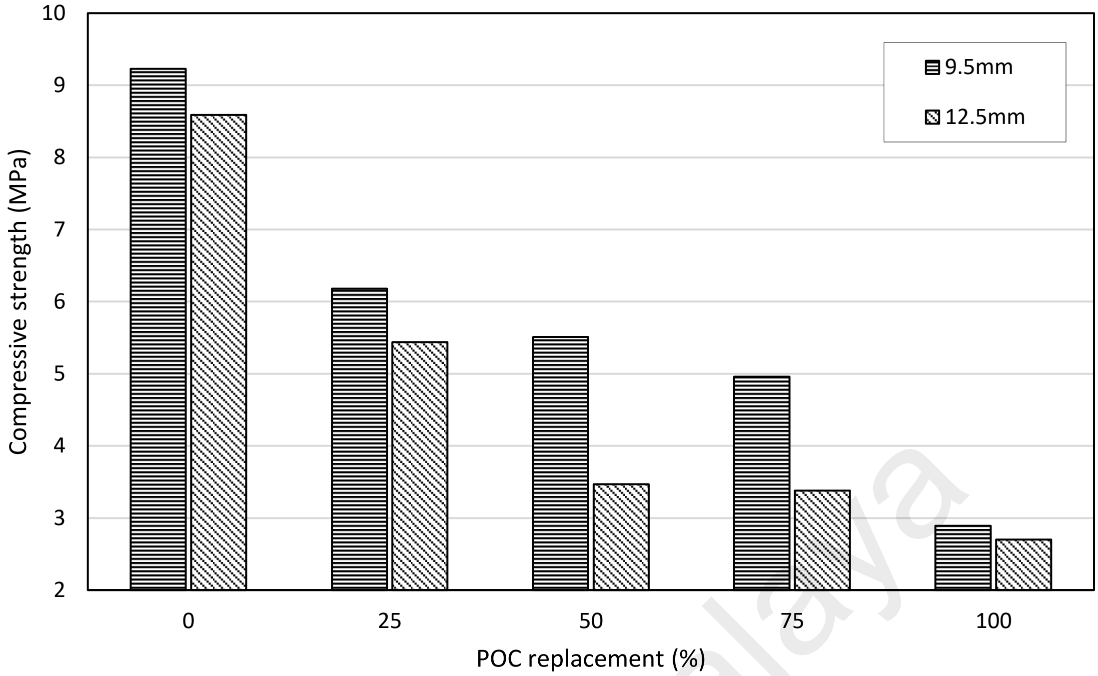


(a)

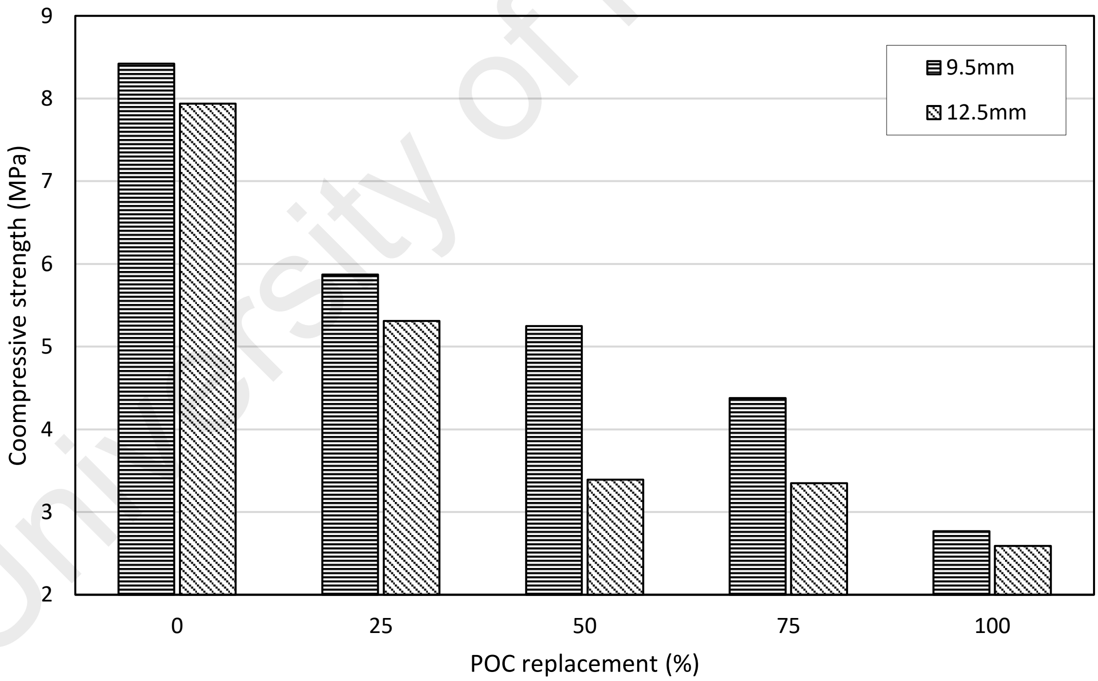


(b)

Figure 4.14: Effect of aggregate size on the POC pervious concrete compressive strength at cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3



(c)



(d)

Figure 4.14, continued

4.3.4 Effect of curing

Figure 4.15 presents the results for the effect of three different curing regimes adopted in this study for the POC pervious concrete at 0% replacement. The aim is to have a clear understanding of the direct effect of the curing on the concrete before incorporation of POC aggregate. An average of 3 samples were tested for each curing regime at 7 days and 56 days while 6 samples were tested at 28 days. Additionally, the compressive strength values of the air cured and 3 days in water cured were compared with standard cured concrete samples (full water curing). Since the strength obtained for the concrete cured in full water and 3 days in water are expected to be the same, the 3-days strength is not reported in the Figure. As expected, the POC pervious concrete compressive strength continued to develop with age irrespective of the curing regime for all the mixes. The highest compressive strength values were recorded when the concrete samples were cured in full water for all the mixes compared to the strength results obtained with 3-days water and air cured concrete samples. Figure 4.15b shows that the strength values obtained with the concrete is lower compared to that of Figure 4.15a. This has already been established to be due to the effect of aggregate size on the concrete. Similar strength values were obtained for the air cured and 3 days in water cured samples in which the strength for air cured concrete samples were slightly lower with a maximum strength loss of about 5% observed for both aggregate sizes with respect to the other two methods. Past studies have indicated that concrete exposed to air curing may experience insufficient water needed for hydration at early stage due to exposure to higher temperatures during this period (Gayarre et al., 2014; Neville, 1995).

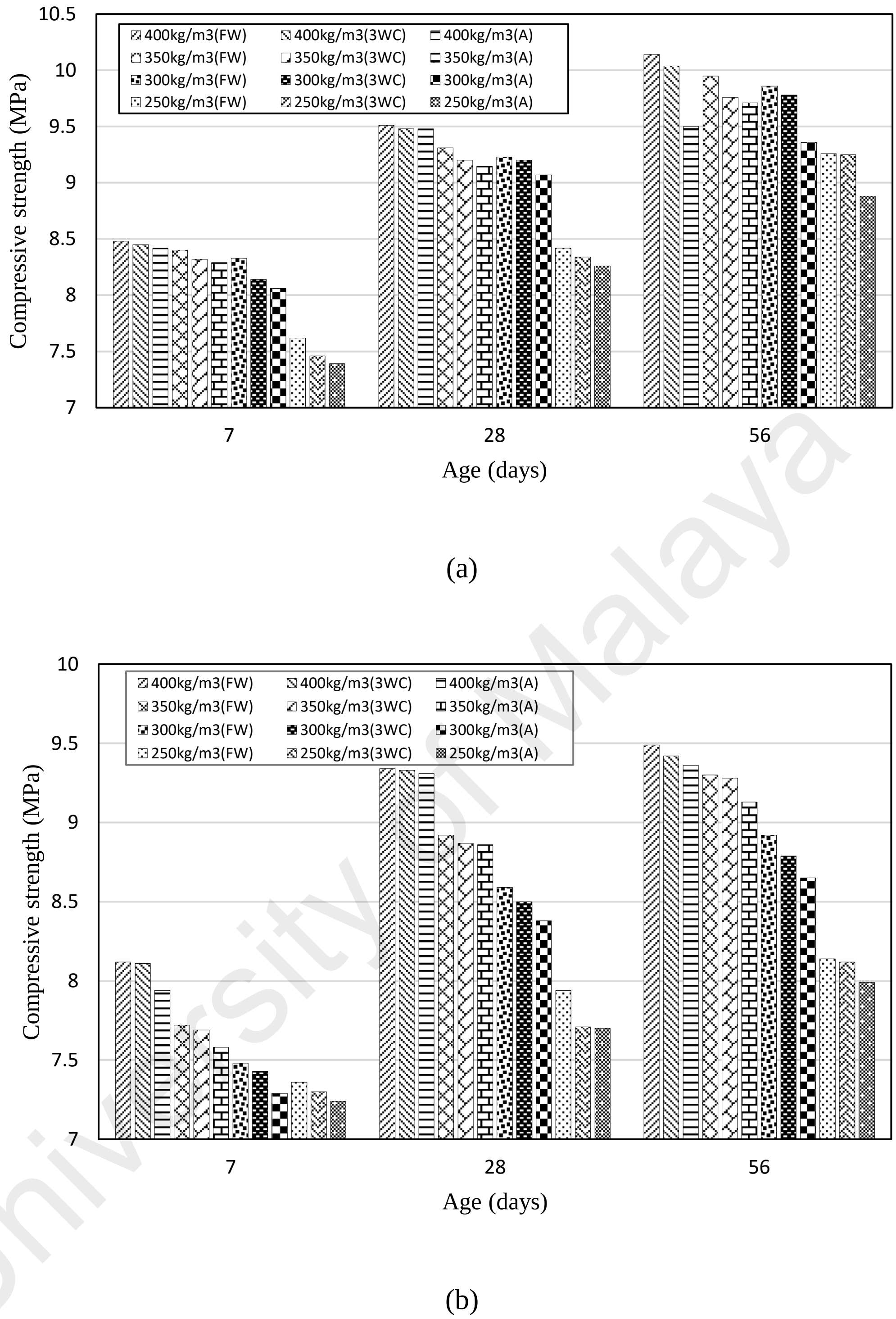
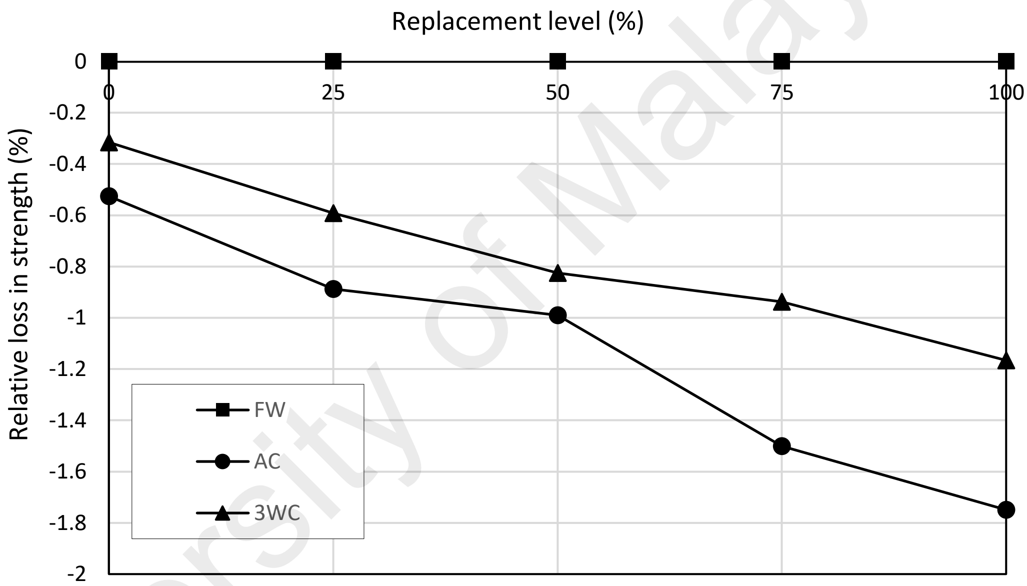


Figure 4.15: Effect of different curing regimes on the POC pervious concrete compressive strength at different cement content for aggregate size (a) 9.5mm (b) 12.5mm

According to Gayarre et al. (2014) study, the loss in strength of the air cured samples when compared to full water cured sample may be due to the uncontrolled conditions of humidity and temperature of the environment. The uncontrolled weather condition could accelerate evaporation of water required for cement hydration at the early stage (Neville, 1995; Zhao, Sun, Wu, & Gao, 2012). Additionally, the presence of high voids in pervious concrete indicates that initial water required for hydration could be lost rapidly at the early stage due to evaporation taken into consideration the low water-cement ratio of pervious concrete mix (John T Kevern, Schaefer, et al., 2009a).

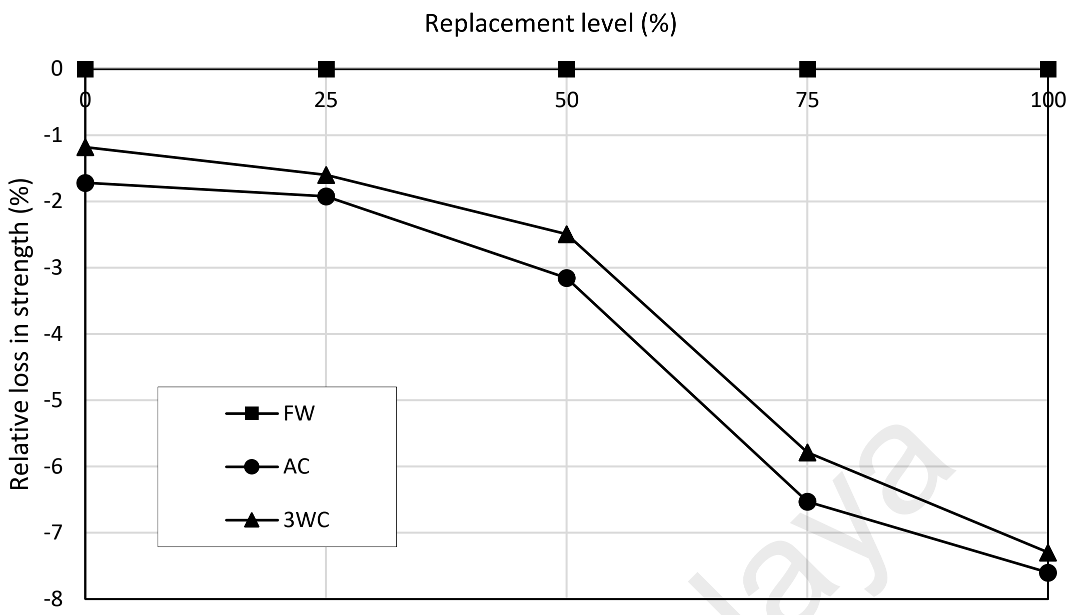
An average temperature and humidity of 30.5^{o}C and 71% respectively was recorded for the period of curing the POC pervious concrete samples in air as seen in Figure 3.2, while the water cured sample were cured at room temperature of 25^{o}C. Thus, it can be said that the weather condition and also the void of the concrete influenced the reduced strength of the air cured POC pervious concrete. However, the high relative humidity the air cured POC pervious concrete was exposed to could have helped minimise the strength loss. According to Bentz and Snyder (1999), water provided for the cement during casting is absorbed by the aggregate at early stages which is later absorb back to the ITZ as cement hydration commences. Thus, the higher water absorption of POC aggregate may have influenced the self-curing properties on the concrete ITZ at later ages. Figures 4.16 and 4.17 show the loss in compressive strength of the air cured and 3-days water cured POC pervious concrete samples at 28 days with respect to the full water cured concrete samples at different replacement levels for mixes containing 9.5mm and 12.5mm aggregates size respectively. It was observed that as the incorporation of POC aggregate increased in the mix, the rate of strength development by the concrete gradually reduced which was most noticeable at 100% replacement. As a result, the concrete had reached almost 90% of its strength at 28 days for 100% replacement. The relatively low strength due to POC aggregate incorporation can be related to the high ACV, void present inside and on the surface of the POC material. These factors influence the maximum load the POC pervious concrete can take (Kanadasan et al., 2015; Kanadasan & Razak, 2014b). As such, a maximum compressive strength of about 8MPa and 7MPa were obtained after

56 days due to the POC aggregate in the mix containing 9.5mm and 12.5mm aggregate sizes respectively. Furthermore, the 28-day compressive strength loss for POC pervious concrete mixes with 9.5mm aggregate size due to air curing and 3 days in water curing with respect to full water cured samples was from 4% to 10% and 3% to 8% respectively. However, the 28-days compressive strength loss values recorded was higher when aggregate size increased to 12.5mm where the strength loss of 8% to 10% and 9% to 12% was recorded for 3 days in water cured and air cured samples respectively.

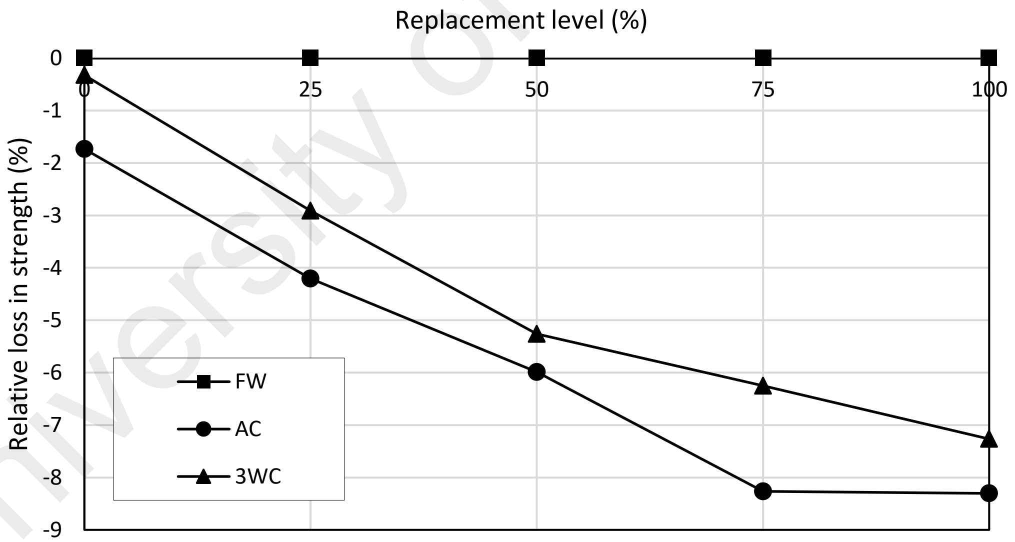


(a)

Figure 4.16: Effect of curing regime on 9.5mm size POC pervious concrete compressive strength at 28 days for cement content of (a) 400kg/m³ (b) 350kg/m³ (c) 300kg/m³ (d) 250kg/m³

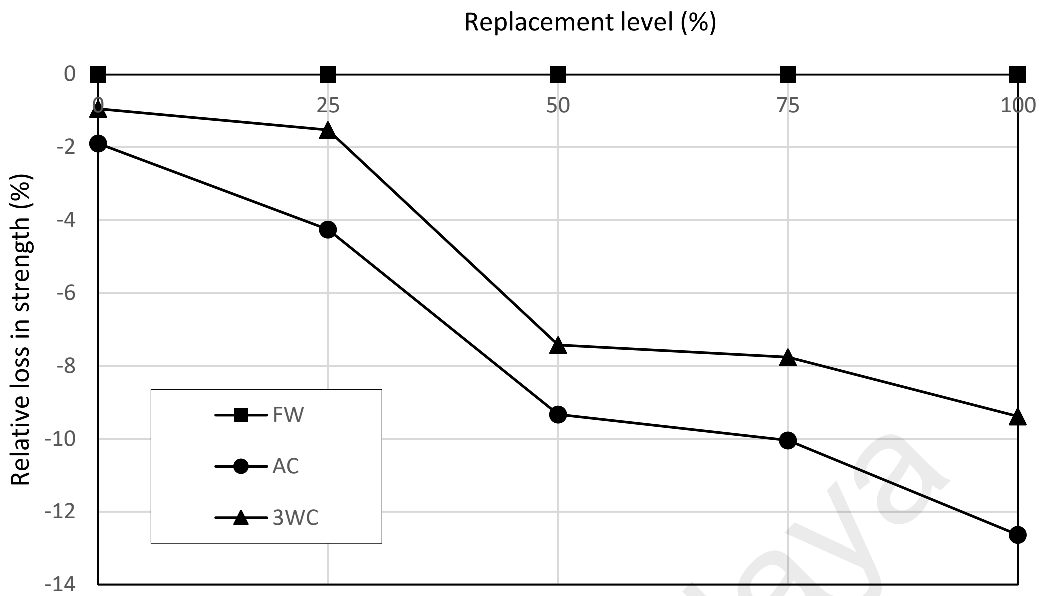


(b)



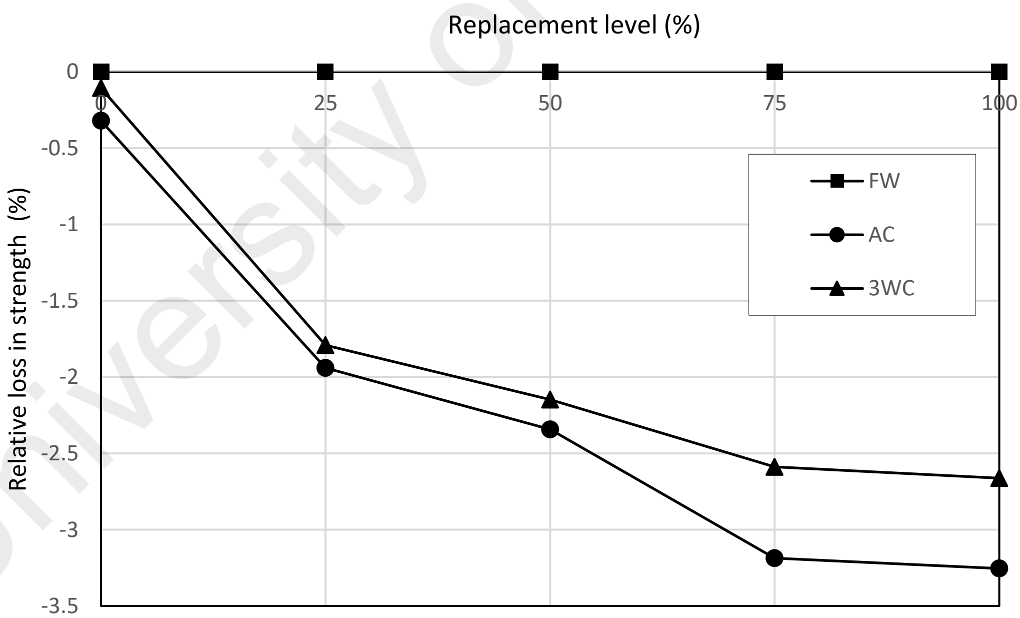
(c)

Figure 4.16, continued



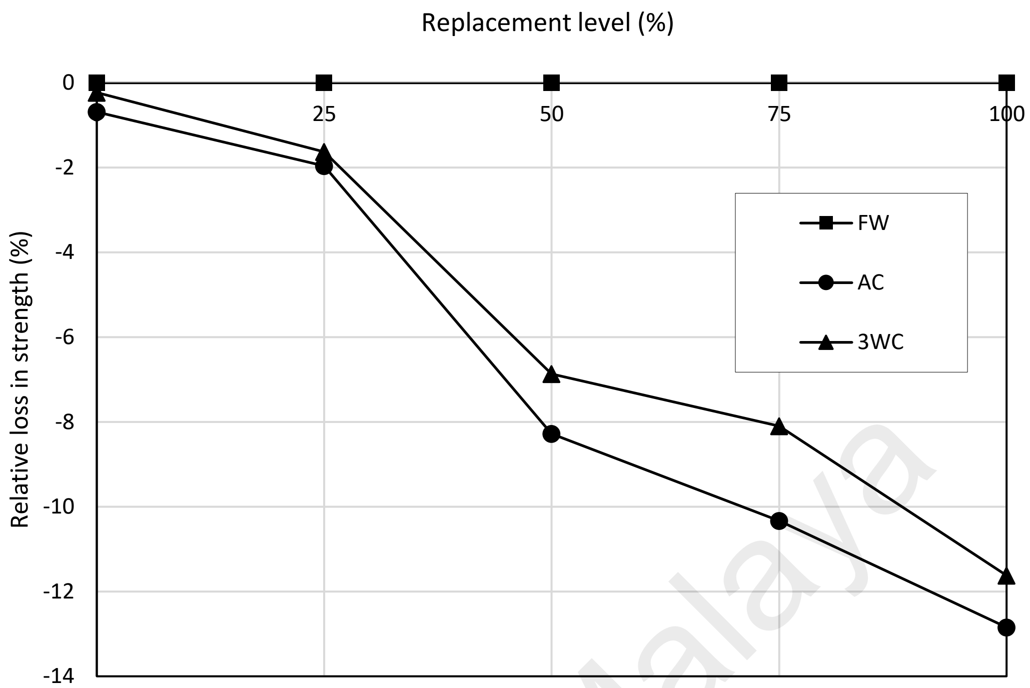
(d)

Figure 4.16, continued



(a)

Figure 4.17: Effect of curing regime on 12.5mm size POC pervious concrete compressive strength at 28 days for cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3



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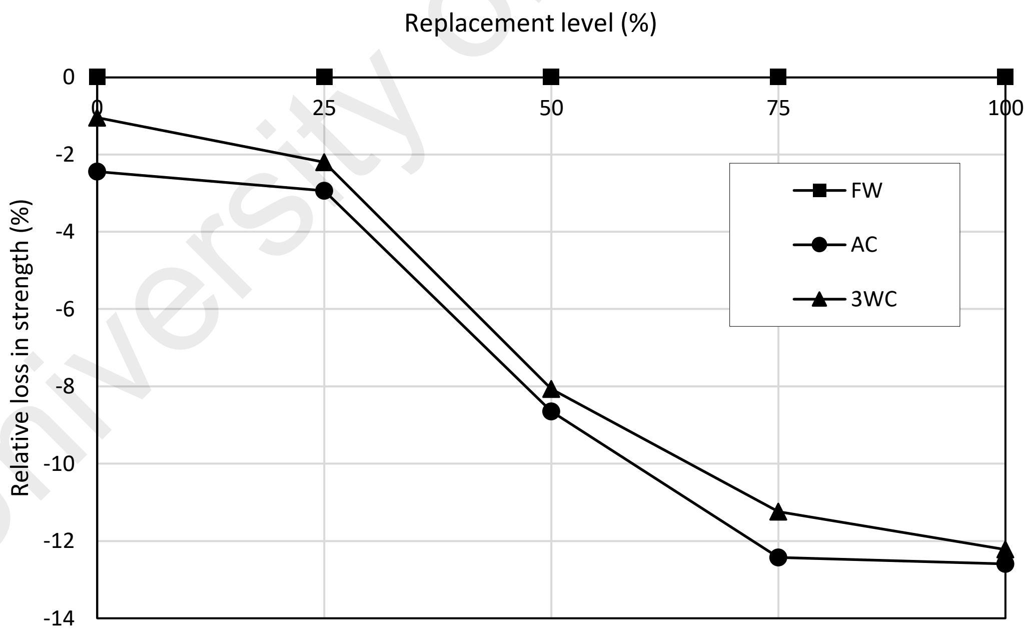
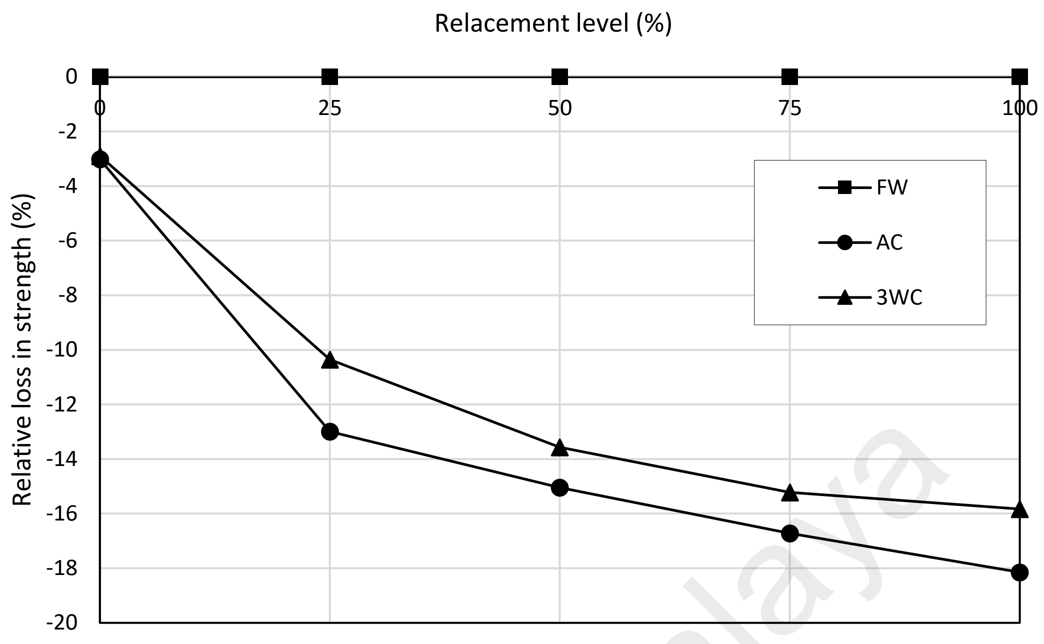


(c)

Figure 4.17, continued



(d)

Figure 4.17, continued

Considering the porous nature of the concrete and the reduced amount of cement in the mix, curing can be said to have had little effect on the outcome of the strength when compared to the loss in strength due to the effect of POC aggregate incorporation. Also, it can be seen from Figure 4.17 that the maximum loss occurred at 100% replacement which suggests that the effect of POC aggregate incorporation supersedes that of the curing method adopted. Generally, strength loss due to POC aggregate incorporation into the mix was in the range of 20% to 70% for all the curing method.

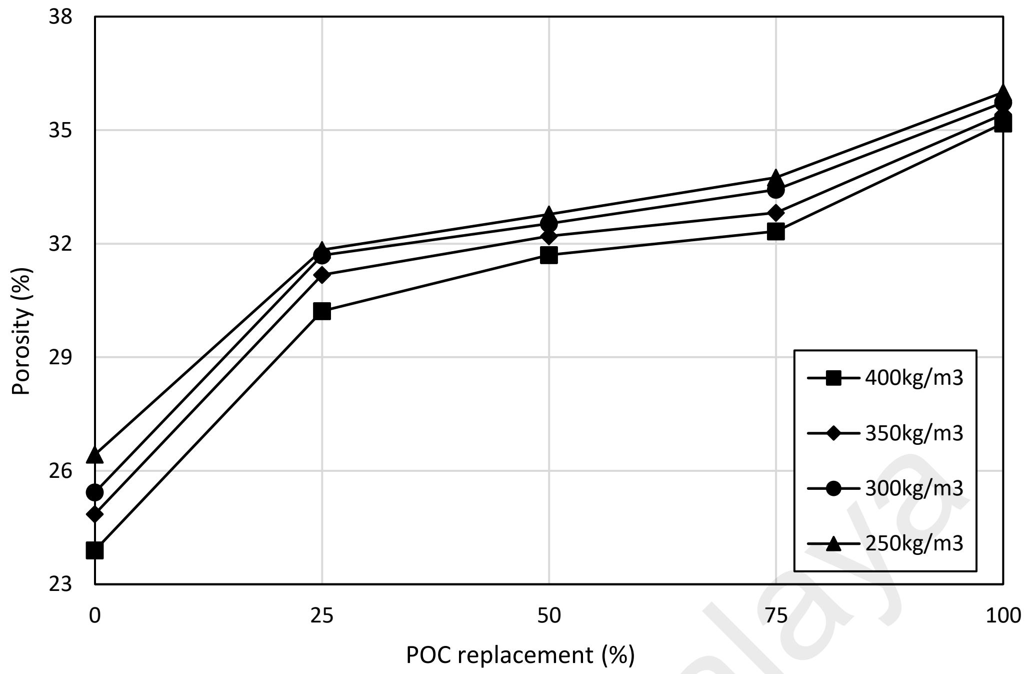
4.4 Porosity of POC pervious concrete

The pore properties of pervious concrete have been adjudged to be important to the strength properties, and thus play an important role in characterizing the material as a sustainable concrete (Chandrappa & Biligiri, 2016). In this study, for clarity, the active voids are defined as the effective porosity since this relates to permeability and the overall air content is accordingly defined as total porosity which relates to the compressive strength of the concrete (Lian et al., 2011). Effective porosity considers the concrete pore roughness, pore-size, construction of the pore space, pore distribution, and the internal pore channel connectivity and tortuosity which makes it more suitable for accurate result (Bonicelli, Giustozzi, & Crispino, 2015). However, it should be noted that the effective porosity was not measured, instead total porosity was measured. Although effective porosity was regularly referred to, this is basically for the purpose of explanation to better understand the porosity obtained for the POC pervious concrete. In this section, the effect of three parameters namely, POC aggregate replacement, cement content and POC aggregate size, on the porosity of the POC pervious concrete were investigated.

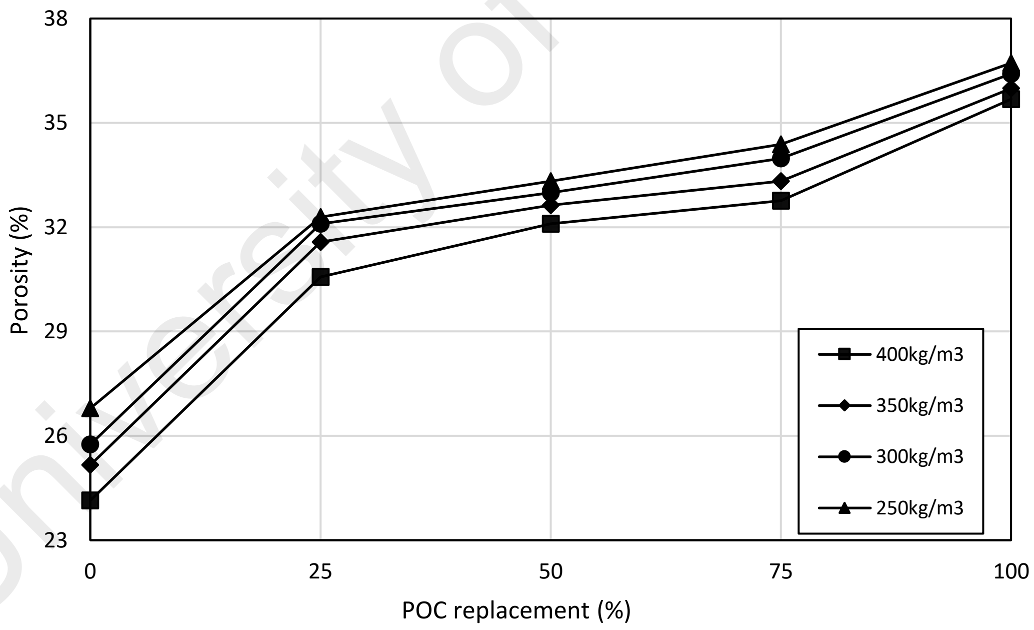
4.4.1 Effects of POC aggregate replacement

A total of 40 mixes, with an average of 3 samples per mix, were investigated for all the POC pervious concrete mixes. Figure 4.18 shows the effect of POC aggregate replacement on the POC pervious concrete porosity mixes. The values of porosity obtained ranged from 23% to 36% and 24% to 37% for the POC pervious concrete mixes with 9.5mm and 12.5mm aggregate size respectively. The stipulated range accepted as stated in ACI-522 (2003) report is between 15% to 35%. The maximum porosity obtained in this study is about 2% above the range stated in the ACI522 report. However, some past studies have recorded porosity as high as 37% and such porosity can still be accepted depending on the application of the concrete (Joshaghani et al., 2015). Figure 4.18 shows that the POC pervious concrete porosity increased for the two aggregate sizes adopted as the level of POC aggregate incorporated into the mix increased. Since POC aggregate is flaky with a rough surface, the level of packing of the aggregate combination for the POC pervious concrete must have contributed to its increased void content. Recent study on the use of OKPS as aggregate in pervious concrete indicated that increasing the replacement level of OKPS in the concrete increased the volume of void of the concrete. The study further highlighted that the granular arrangement of the concrete must have been disturbed by the replacement of coarse aggregate due to the angular shape of OPKS particles (Khankhaje et al., 2016). Similarly, substitution of EAFS as aggregate in pervious concrete also showed that the porosity of the concrete was influenced by the porous nature of EAFS (Yeih et al., 2015).

Although the POC aggregate used in this study was pre-coated with POCP in order to fill the pores on the surface of the material and ensure its surface is smooth, visual inspection revealed that the POCP did not fully coat the pores as expected, thus violating our initial assumptions. The void calculation was based on the concept of particle packing to estimate the amount of powder to fill the pores on the surface of the aggregate without coating other smooth parts of the aggregate. However, it was observed that some of the powder settled at the bottom of the rotating mixing drum even though the POC aggregate were in saturated condition in order to allow the powder stick to the aggregate easily. Figure 4.19 shows a typical POC aggregate revealing the insufficient coating of the aggregate after mixing with POCP. Thus, some of the cement paste must have been used up to coat the available pores due to proper coating which must have led to the increased porosity of the concrete at different replacement level based on the percentage of POC aggregate in the concrete mix. POC pervious concrete mix with 0% POC aggregate recorded the least void for the POC pervious concrete irrespective of the aggregate size and cement content compared to other mixes. Incorporation of POC aggregate increased the void gradually as the level of POC aggregate replacement increased.



(a)



(b)

Figure 4.18: Effect of POC aggregate replacement on the POC pervious concrete porosity at different cement content for aggregate sizes (a) 9.5mm (b) 12.5mm

At 25%, 50%, 75% and 100% replacement, void increased by 26.4% and 26.6%, 32.6% and 33.0%, 35.3% and 35.7%, and 47.2% and 47.8%, for POC pervious concrete mix with 9.5mm and 12.5mm aggregate size. Thus, the variation in the porosity values obtained for both aggregate size showed similar and consistent outcome. Additionally, there is little difference between the values of porosity obtained at 25% and 50% replacement respectively. Also, Table 3.5 depicts similar void due to the natural porosity of POC, which could have influenced the pattern of the mix at both replacement levels.

(a)

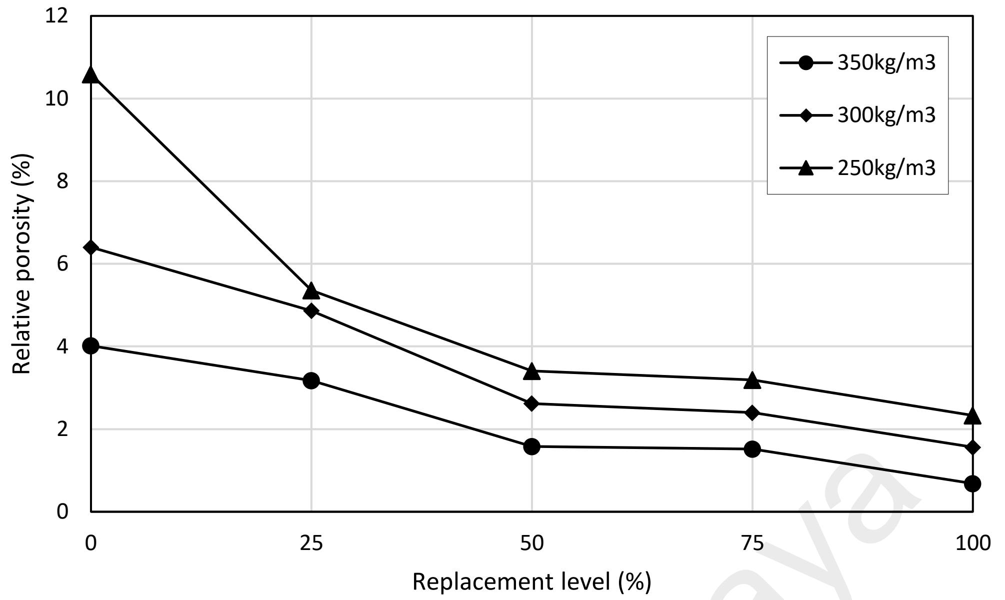
(b)

Figure 4.19: Typical POC coarse aggregate (a) before pre-coating (b) after pre-coating with POCP

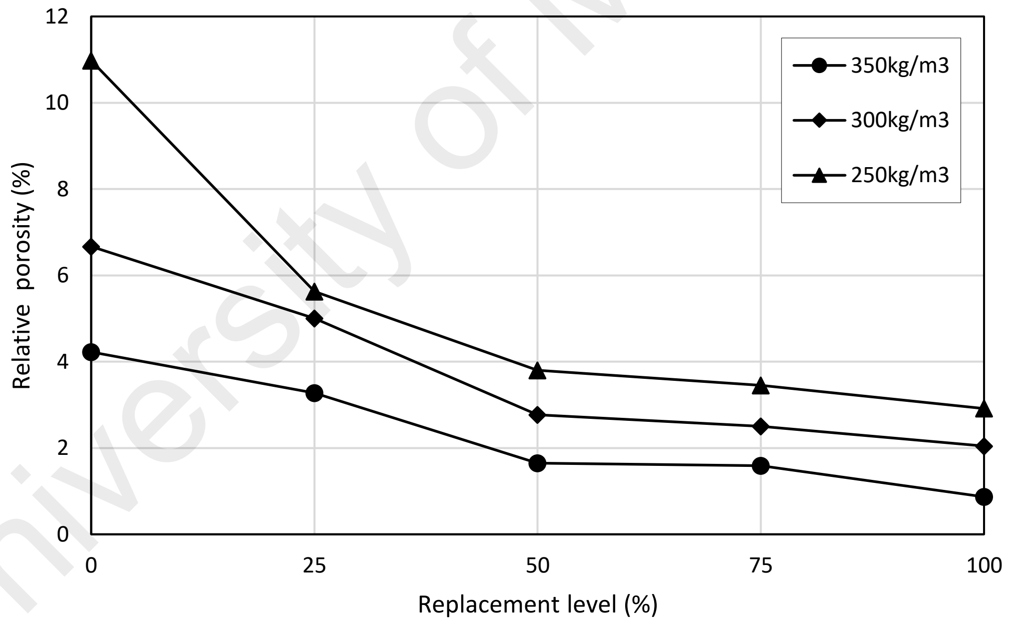
4.4.2 Effects of cement content

When every other parameter is kept constant, it is expected that increasing the cement content of the concrete mix would increase its paste thickness (Torres et al., 2015). As such, the active porosity of the concrete will reduce as the thickness of cementitious paste increased which would decrease the overall porosity of the concrete samples. Figure 4.20 shows that the active porosity of the POC pervious concrete gradually reduced as the cement content increased. POC pervious concrete mixes with low cement content mixtures which results in low paste thickness recorded the highest porosity value for each data group. A recent study by Torres et al. (2015) arrived at similar conclusion. The study further indicated that compaction energy also plays a role in the eventual outcome of the porosity such that the compaction energy simply reduced the concrete porosity and caused more 'bridging' of the paste between the aggregate particles. However, it was also pointed out that the thickness of paste is a function of both the volume of paste and the aggregate surface area. On the other hand, if the cement paste in the mix is too much such that the excess paste fills voids necessary for porosity, the weight of the paste may cause it to accumulate which could result in clogged or sagging cement paste in the concrete and consequently the paste may block the water path and reduce the connected porosity as well as the permeability coefficient of the concrete (Yeih et al., 2015).

Furthermore, taking the porosity of the POC pervious concrete mixes with 400kg/m^3 cement at different POC aggregate replacement level as the control porosity, Figure 4.20 shows that the porosity of the POC pervious concrete containing 9.5mm aggregate size increased by 4.0% at 0% POC aggregate replacement when cement content was reduced to 350kg/m^3. However, the increment reduced gradually as the POC aggregate incorporation into the mix increased whereby porosity increment was less than 1% at full replacement. This could be due to the rough and porous surface of the POC aggregate itself, and lack of sufficient coating by the POCP as expected. Further reducing the cement content to 250kg/m^3 resulted in a higher porosity increment of 10.6% and 2.3% when POC replacement was at 0% and 100% respectively. Similarly, the same pattern was observed with the POC pervious concrete mix containing aggregate size of 12.5mm. Although similar, the percentage of porosity increment was slightly higher in this case due to the size of the aggregate. In this case, porosity increased by 4.2% and 0.9% when cement content was reduced from 400kg/m^3 to 350kg/m^3 at 0% and 100% POC replacement. However, porosity further increased by 11.0 % and 2.9% when cement content was reduced from 400kg/m^3 to 250kg/m^3 at 0% and 100% POC replacement



(a)



(b)

Figure 4.20: Effect of cement content on the porosity of POC pervious concrete for aggregate size (a) 9.5mm (b) 12.5mm

4.4.3 Effects of aggregate size

The result of the effect of using different aggregate size on the porosity of the POC pervious concrete is presented in Figure 4.21. The Figure shows the percentage increment in void as POC aggregate replacement increased for the concrete mixes with respect to its cement content. The POC pervious concrete porosity gradually increased with the use of a larger aggregate size irrespective of the cement content. Increasing the aggregate size would reduce the required volume of aggregate based on the respective unit weight (Chandrappa & Biligiri, 2016; Yeih et al., 2015). Zhong and Wille (2016a) study indicated that a larger aggregate size would increase the pore size of the concrete leading to a decrease in the number of pores per unit volume of the concrete. The study further stated that an increase in pore size will lead to a decrease in the number of pores per unit volume resulting in a reduced contact area between the aggregates covered by the cementitious matrix, assuming unchanged total porosity. However, the effect of the aggregate size was concluded to be marginal. Similar outcome was reported by Huang et al. (2010) in which porosity difference was less than 5% as a result of using three different aggregate sizes of 4.75mm, 9.5mm and 12.5mm nominal sizes. From Figure 4.21, it can also be seen that effect of increasing the aggregate size from 9.5mm to 12.5mm nominal size recorded a porosity difference less than 5%.

Additionally, it was found in another study that the initial porosity for gravel was lesser for the EAFS under the same size condition when both materials were compared. However, the EAFS porous nature greatly influenced the total initial porosity (Yeih et al., 2015). Table 3.5 shows that POC aggregate of 12.5mm has more pores on its surface when compared to the 9.5mm size. The reason is similar to Yeih et al. (2015) observation. It was observed during the void calculation for both aggregate size that the 12.5mm POC has a higher packing when compared to the 9.5mm. Thus, this was reflected on the outcome of the void present in the aggregate. Also, using smaller size of aggregate has been suggested to allow proper packing which means the aggregate will be able to fit into the pore of each other as in the case when OPKS was used in the production of lightweight pervious concrete (Khankhaje et al., 2016).

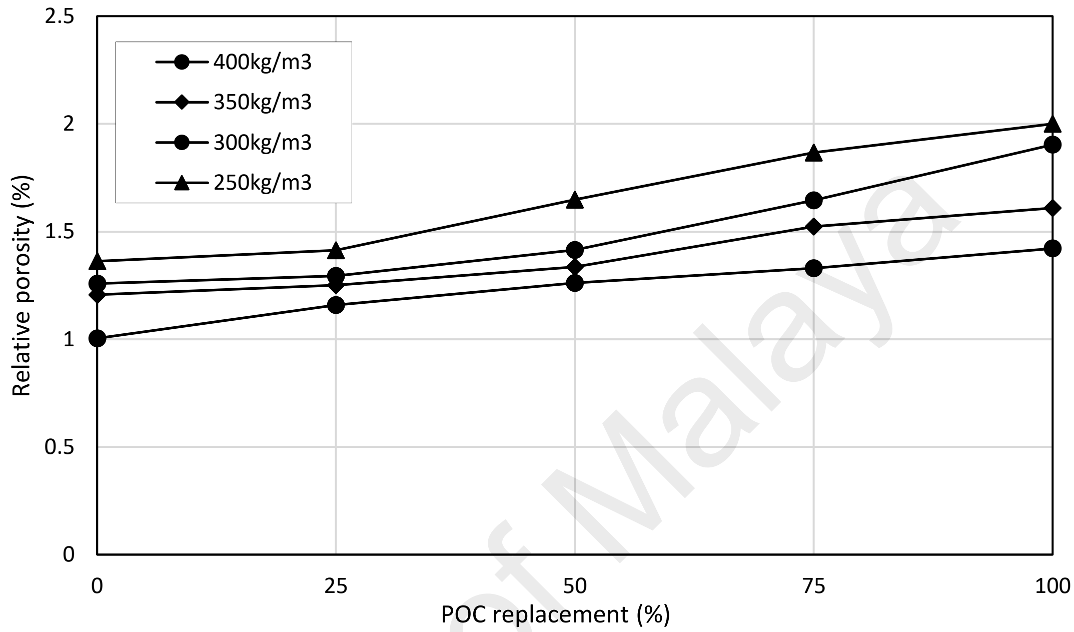


Figure 4.21: Effect of aggregate size on POC pervious concrete porosity at different cement content

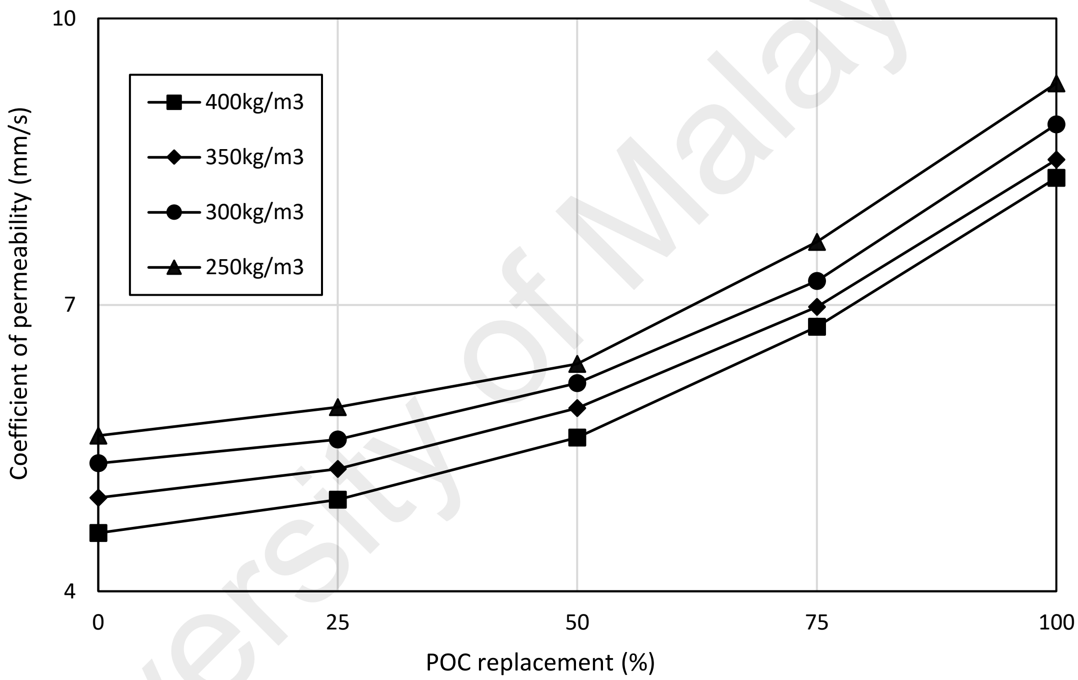
4.5 Coefficient of permeability of POC pervious concrete

Water permeability is a major index for evaluating the performances of pervious concrete. Thus, it is important to achieve a continuous network and an adequate void content that will allow easy passage for water. Based on this, it was necessary to evaluate the coefficient of permeability of the POC pervious concrete under the selected parameters for this study. Some studies have established that the permeability of a pervious concrete is dependent on the effective porosity of the concrete (Deo & Neithalath, 2011; Gaedicke, Marines, & Miankodila, 2014b; Huang et al., 2010; Kayhanian et al., 2012). Thus, the effective porosity of the POC pervious concrete is expected to determine the pattern of its permeability. Although, a recent study has suggested that compaction method also influences the effect of effective porosity distribution on the permeability of the concrete (Martin et al., 2014). The effect of compaction is expected to have marginal outcome on the POC pervious concrete due to the reduced compaction the concrete was subjected to i.e. 10 seconds on vibration table. The study examines the influence of POC aggregate type and size as well as the effect of different cement content on the water permeability coefficient of the POC pervious concrete.

4.5.1 Effects of POC aggregate replacement

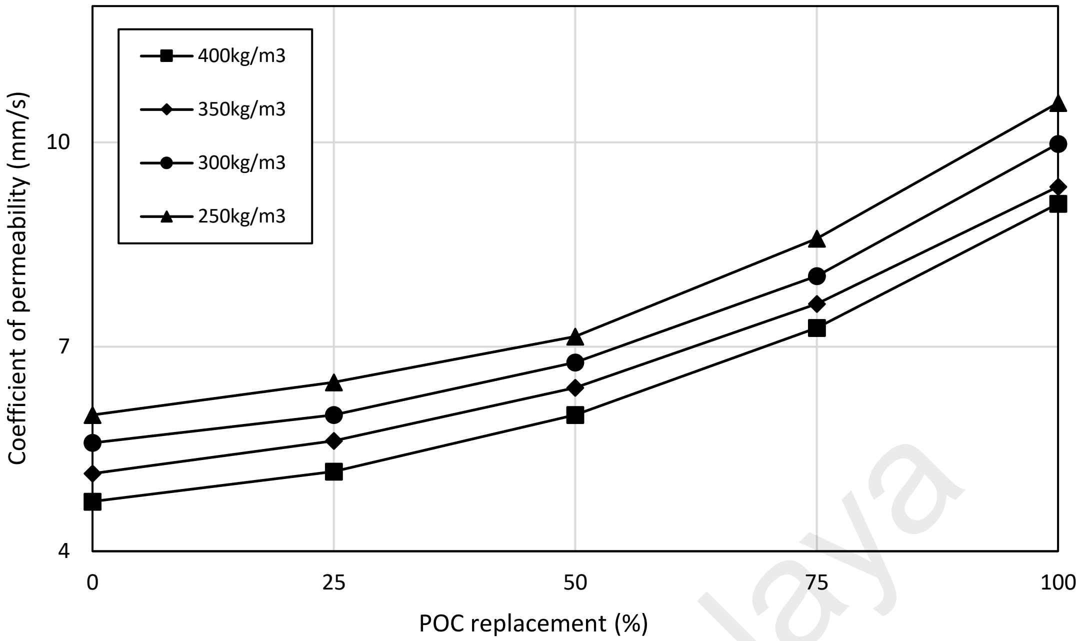
According to Figure 4.22, the permeability of the POC pervious concrete gradually increased with incorporation of POC aggregate in the concrete mix irrespective of aggregate size and cement content. These results can be interpreted based on the POC pervious concrete porosity which increased with the level of POC aggregate introduced (Figure 4.20). Permeability coefficient values obtained ranged from 4.6mm/s to 9.3mm/s and 4.7mm/s to 10.6mm/s for the POC pervious concrete mixes containing 9.5mm and 12.5mm aggregate size respectively. Permeability is dependent on the pore size present in the concrete and the concrete porous network i.e. effective porosity.

Due to the lack of standardized code for pervious concrete, some studies (Lian & Zhuge, 2010; Tennis et al., 2004), have suggested that the acceptable flow rates for water through pervious concrete are typically from 2 mm/s to 5.4 mm/s which suggests that the maximum permeability coefficient values obtained in this study exceeds the maximum acceptable range. However, the POC pervious concrete coefficient of permeability values are within the range obtained in other studies usually in the range of 2mm/s to 12mm/s (Cheng, Hsu, Chao, & Lin, 2011; Prinya Chindaprasirt, Nuaklong, Zaetang, Sujumnongtokul, & Sata, 2015; Khankhaje et al., 2016; Nguyen et al., 2013). On the other hand, some studies have recorded higher permeability coefficient of 40mm/s (Zouaghi, Nakazawa, Imai, & Shinnishi, 1999) and 35mm/s (Meininger, 1988) which was still within acceptable porosity range of 35%. However, the former associated it to the effect of head loss on the outcome of the result. Additionally, it has been stated in the previous section of the study that the rough and flaky nature of POC pervious concrete will also contribute to the increasing permeability coefficient with POC aggregate incorporation compared to the concrete with granite (control) since the surface of the granite aggregate is smooth. Similar outcome was reported when EAFS (Yeih et al., 2015) and OPKS (Khankhaje et al., 2016) were used in production of pervious concrete.



(a)

Figure 4.22: Effect of POC aggregate replacement on the POC pervious concrete coefficient of permeability at different cement content for aggregate size (a) 9.5mm (b) 12.5mm

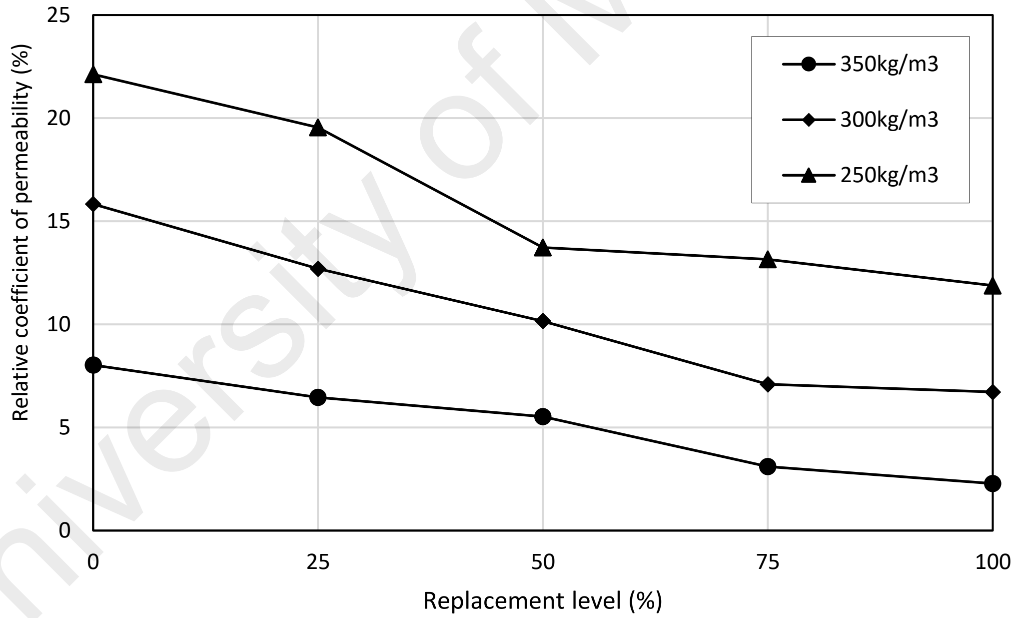


(b)

Figure 4.22, continued

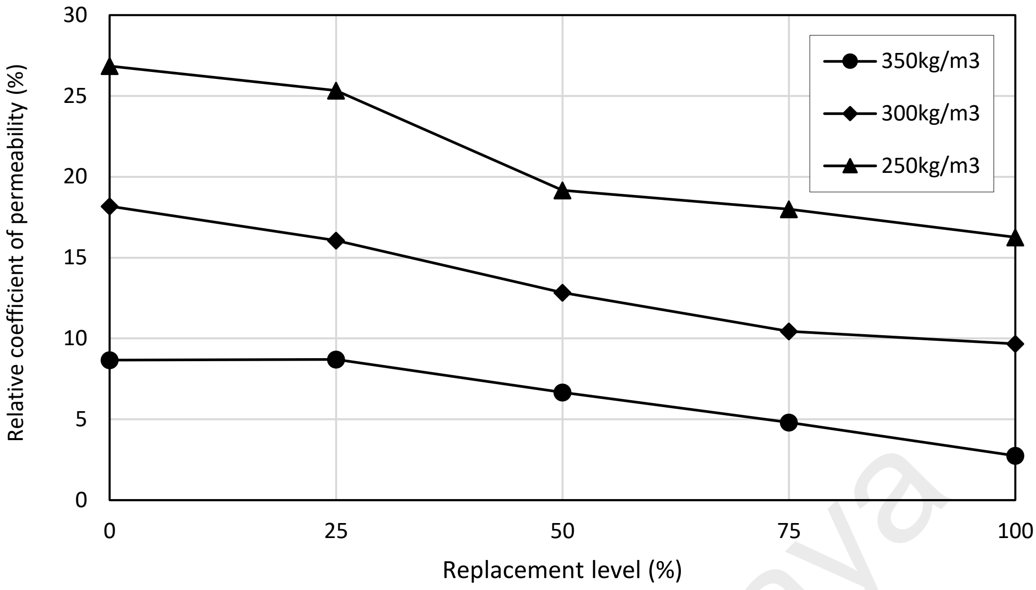
4.5.2 Effects of cement content

Based on the effect of cement paste on the porosity of the POC pervious concrete, it is expected that increasing the cement content would reduce the permeability coefficient of the concrete. Thus, Figure 4.23 shows that as the cement content increased, resulting in higher cementitious paste thickness, the coefficient of permeability of the POC pervious concrete reduced irrespective of the aggregate size and POC replacement level. This result is based on the theory that as the cement paste gets larger, the effective pores of the concrete will get smaller (Torres et al., 2015). Taking the permeability coefficient of the POC pervious concrete mixes with 400kg/m^3 cement at different POC aggregate replacement level as the control, Figure 4.27 shows that the coefficient of permeability of the POC pervious concrete containing 9.5mm aggregate size increased by 8% at 0 % POC aggregate replacement when cement content was reduced to 350kg/m^3. However, the increment reduced gradually as the POC aggregate incorporation into the mix increased whereby porosity increment was less than 2% at full replacement. This was expected as the pattern is similar to what was observed with the porosity of the concrete. Further reducing the cement content to 250kg/m^3 resulted in a higher permeability coefficient increment of 22% and 12% when POC aggregate replacement was at 0% and 100% respectively. Similarly, the same pattern was observed with the POC pervious concrete mix containing aggregate size of 12.5mm. Although similar, the increment in permeability coefficient was slightly higher in this case due to the size of the aggregate. In this case, permeability coefficient increased by 9% and 3% when cement content was reduced from 400kg/m^3 to 350kg/m^3 at 0% and 100% POC aggregate replacement. However, permeability coefficient further increased by 26% and 16% when cement content was reduced from 400kg/m^3 to 250kg/m^3 at 0% and 100% POC replacement



(a)

Figure 4.23: Effect of cement content on the POC pervious concrete coefficient of permeability for aggregate size (a) 9.5mm (b) 12.5mm



(b)

Figure 4.23, continued

4.5.3 Effects of aggregate size

Using different aggregate size affected the coefficient of permeability of the POC pervious concrete similar to how it affected the porosity of the concrete. Figure 4.24 shows the percentage increment in coefficient of permeability as POC aggregate replacement increased for the concrete mixes with respect to its cement content. Also, the POC pervious concrete coefficient of permeability increased resulting from the increased effective porosity when 12.5mm aggregate size was used. Yeih et al. (2015) study also indicated that the water permeability coefficient increased as the size of aggregate used in pervious concrete increased. This is because larger aggregate size will result in a higher volume of void after packing which therefore leads to a greater coefficient of permeability. Furthermore, Jain and Chouhan (2011) prepared pervious concrete mix using smaller size of aggregates in comparison to the mix produced with larger size aggregate and similar outcome was reported. Their study suggested that the sizes of pores rather than total porosity in the concrete section has more influence on the flow of water from pervious concrete. Based on this, visual inspection revealed that the POC pervious concrete prepared using larger size particles produced pores larger in size which in turn causes higher permeability irrespective of the cement content.

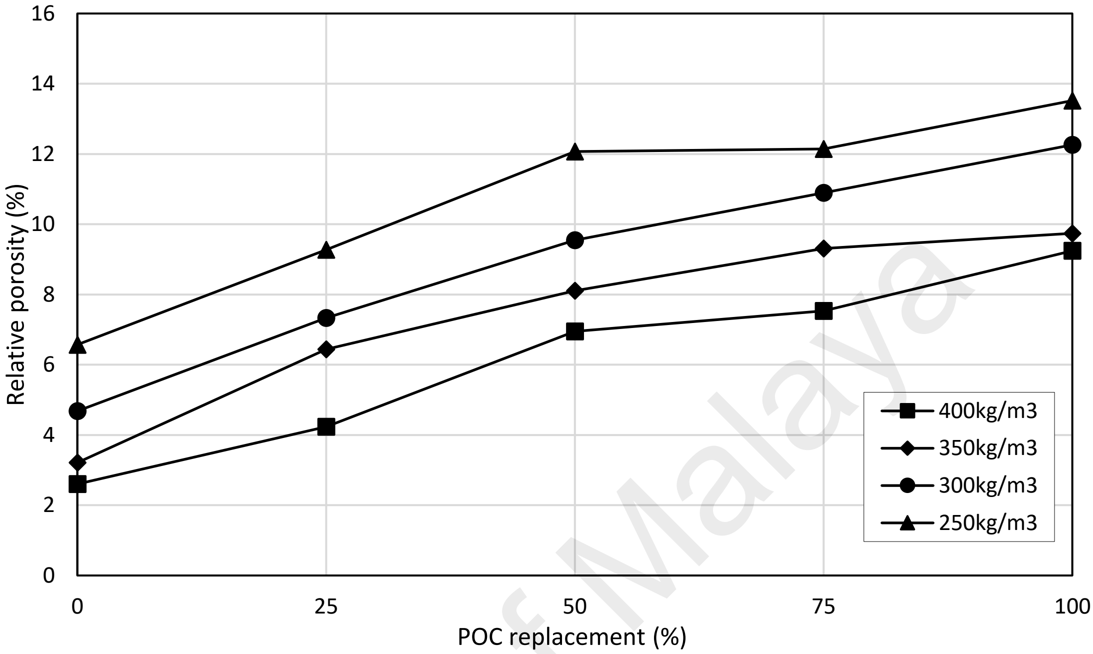


Figure 4.24: Effect of aggregate size on the POC pervious concrete coefficient of permeability at different cement content

Figure 4.24 also reveals that maximum increment in the POC pervious concrete coefficient of permeability was recorded when the cement content was least at full replacement of granite with POC aggregate. On the other hand, the minimum increment was obtained at highest cement content as expected. The POC pervious concrete coefficient of permeability increased by 2.8%, 7% and 9.2% at 0%, 50% and 100% replacement level when cement content was 400kg/m^3. Meanwhile, the increment rose to 6.5%, 12% and 13.5% at 0%, 50% and 100% replacement level when cement content was reduced to 250kg/m^3. Among the three parameters considered for the coefficient of permeability of the POC pervious concrete, the effect of cement paste thickness happens to be more pronounced when compared to the effect of POC aggregate replacement and aggregate size. However, the latter had a marginal effect on the coefficient of permeability of the POC pervious concrete among the last two parameters. It should be noted that POC aggregate porous nature also influenced the outcome of the effect of cement content on the POC pervious concrete effective porosity which directly affected the coefficient of permeability of the concrete.

4.6 Abrasion resistance of POC pervious concrete

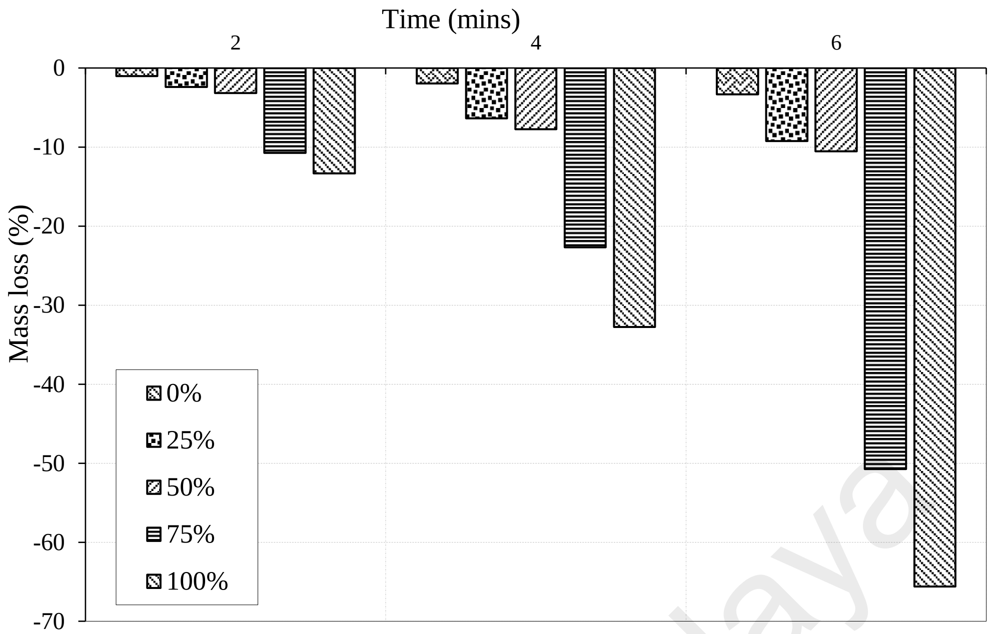
Surface abrasion resistance is considered as one of the most important factor to be investigated to ensure that pervious concrete has a long and good service life. Abrasion resistance of concrete generally depends upon its compressive strength, surface finishing, hardness at surface zone of the concrete, paste-aggregate bond and curing method (Prinya Chindaprasirt et al., 2015; Gaedicke et al., 2014a; B. Li et al., 2011; Singh, Nagar, Agrawal, Rana, & Tiwari, 2016). The better surface abrasion resistance is presented by a lower average weight loss value. In this section, the effect of four parameters namely POC aggregate replacement, cement content, curing method and POC aggregate size, on the surface abrasion resistance of the POC pervious concrete were investigated. However, the test for the POC pervious concrete samples containing aggregate size of 12.5mm was not successful in which over 50% loss in mass was measured before the minimum 2 minutes time stipulated in the ASTM-C944 (1999) standard. As such, the test could not be completed for mixes containing this size of aggregates. This could be as a result of the large void, reduced contact area and weak compressive strength associated with these mixes. Thus, the binder could do little to resist the pressure of the cutting tool from breaking the bond within the aggregates easily indicating that there may be a poor paste-aggregate bond with the concrete. Consequently, the results discussed are for the POC pervious concrete containing 9.5mm aggregate size only

4.6.1 Effects of POC aggregate replacement

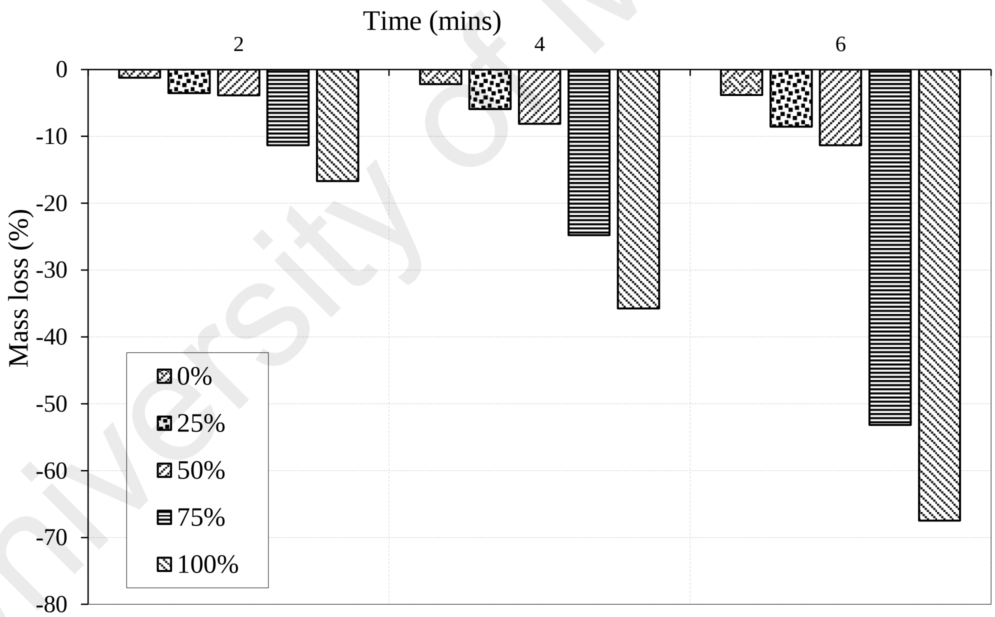
Mass loss occurred in the form of paste removed from the aggregate surface, followed by removal of individual aggregate piece as a whole resulting from abrasion of the aggregate as seen in Figure 4.25.

Figure 4.25: A typical POC pervious concrete specimen before (LHS) and after (RHS) abrasion resistance test

Based on the results from Figure 4.26, the average mass loss of concrete samples obtained after 6mins tests were between 1% and 70%, with the most notable loss occurring at full replacement of granite with POC aggregate. It can be seen from Figure 4.26 that mass loss became more evident as POC aggregate exceeded granite in the mix (i.e. >50%) irrespective of the cement content and curing method. This is an indication that the paste-aggregate bond of the POC pervious concrete becomes weaker as POC substitution increased in the mix which could be as a result of the irregular shape and pores present on the surface of the aggregate.

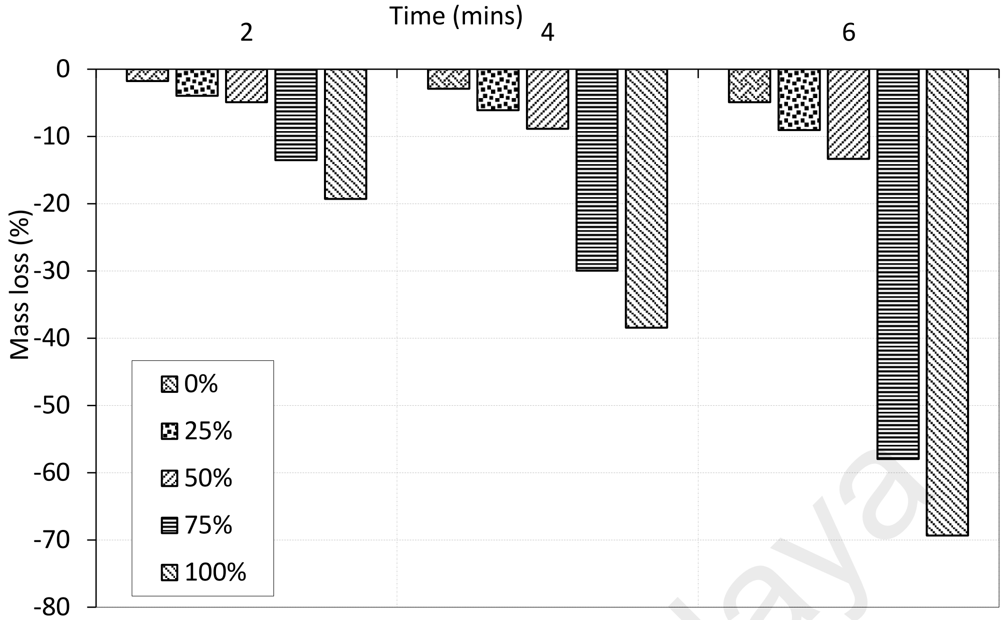


(a)



(b)

Figure 4.26: Effect of POC aggregate replacement on the POC pervious concrete abrasion resistance for different cement content at (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3



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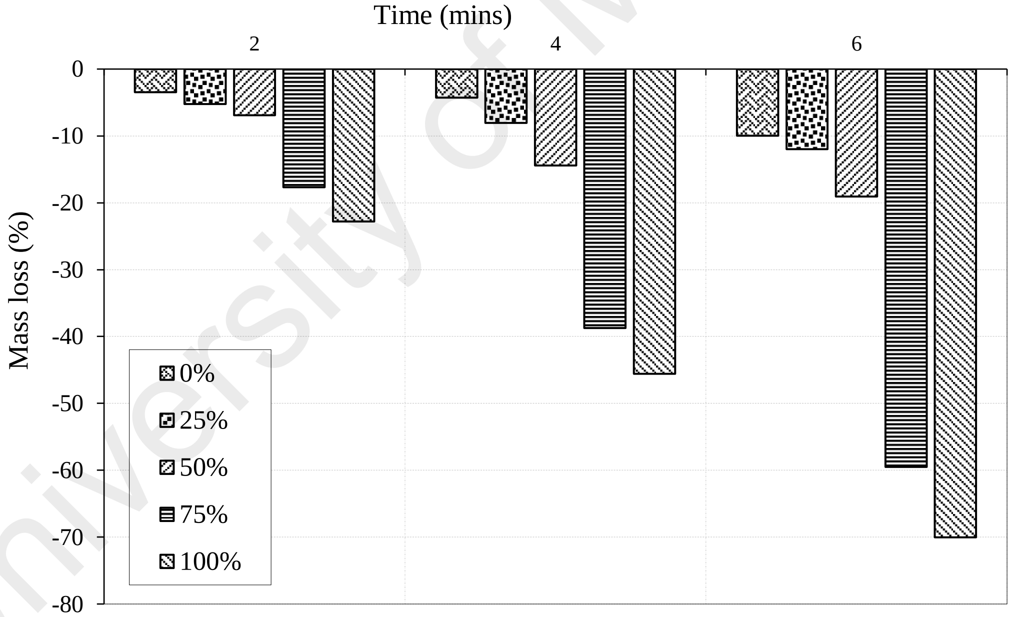


(d)

Figure 4.26, continued

POC aggregate has an ACV and LA abrasion value which is almost 3 times that of granite. This indicates that POC, a friable material, is much weaker than granite leading to the weaker resistance under abrasion. Once the L.A abrasion value of aggregate is greater than 50%, the abrasion performance of concrete gets influenced significantly especially when the concrete contains partial or full replacement of aggregate (Kumar & Sharma, 2014), unlike when the L.A abrasion value is less than 30% as in the case of granite which is 25% in this study. Table 3.2 shows that POC has LA abrasion value of about 60% (>50%), its effect on the POC pervious concrete abrasion resistance is therefore expected. Furthermore, other studies have also indicated that LA abrasion value is directly related to the concrete abrasion resistance in which a decrease in L.A abrasion value will result in decreased abrasion loss of concrete (Kılıç et al., 2008; B. Li et al., 2011). Although these studies were focused on conventional concrete which is denser (more paste which plays major role on the mechanical properties of the concrete) when compared to pervious concrete with limited paste content. One can however argue that if the effect of aggregate L.A abrasion is significant on conventional concrete, it is expected to be even more significant on pervious concrete considering the porous nature of the concrete. On the other hand, Zaetang et al. (2016) study reported that using recycled block aggregate (RBA) as coarse aggregate in pervious concrete had a significant effect on the surface abrasion resistance of the concrete because of its 52% L.A abrasion value which exceeded the allowed stipulated value in ASTM-C33 (2003). In the study, RBA weakness became a dominant factor and increasing the RBA content beyond 20% resulted in the reduction of the concrete surface abrasion resistance. Thus, the weakness of recycled concrete started to play a significant role once the optimum replacement level was exceeded. Furthermore, it has been indicated that the ASTM-C944 (1999) method is sensitive to surface finishing of the concrete and the dressing wheels will roll properly without getting caught when rounded aggregate is used (Gaedicke et al., 2014a). It is expected that the POC pervious concrete would record significant mass loss with increase in POC replacement considering the rough flaky nature of the POC surface. Thus, when POC was less in the mix, the mass loss was less.

4.6.2 Effects of cement content

Generally, increasing the cement content in the POC pervious concrete resulted in reduced porosity and increased compressive strength due to the increased paste thickness and stronger paste-aggregate bond respectively. Also, recalling that the abrasion resistance of pervious concrete is dependent on the compressive strength as well as paste to aggregate bond. Consequently, it is expected that POC pervious concrete mixes with higher cement content will have better resistance to abrasion. Similarly, study by Zaetang et al. (2016) also reported that abrasion resistance of the concrete was improved due to the pervious concrete increased strength resulting from the improved bond between cement paste and recycled aggregate as well as the pervious concrete increased paste content. Also, a similar outcome was reported when three different natural aggregates types were used in the production of pervious concrete. For all the three aggregate types, increasing the paste content had a beneficial effect i.e. the mass loss was reduced by 52%. These notable reduction in mass loss was related to the reduced porosity of mixes containing high paste mixtures (Gaedicke et al., 2014a). The ITZ between paste and aggregate is improved when more cement content is used in the concrete. Thus, this enhancement of the bonding generates a better abrasion response in concrete materials (Gaedicke et al., 2014b; Longhi, Gonzalez, Rahman, Tighe, & Sangiorgi, 2015).

Figure 4.27 shows that the effect of the cement content is marginal when compared to the effect of POC aggregate. Maximum mass loss of 10% occurred with least cement content of 250kg/m^3 due to cement content unlike the 70% mass loss obtained due to POC aggregate incorporation. Meanwhile, mass loss reduced to about 3% when cement content was increased to 400kg/m^3. However, reduction in mass loss due to POC incorporation for mixes containing 400kg/m^3 cement content was 65% which is still a significant loss.

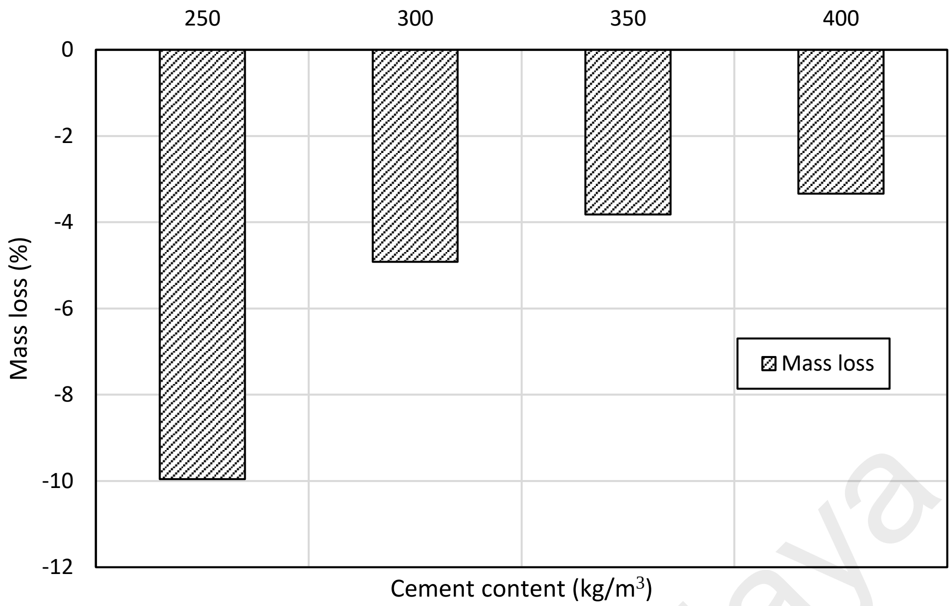
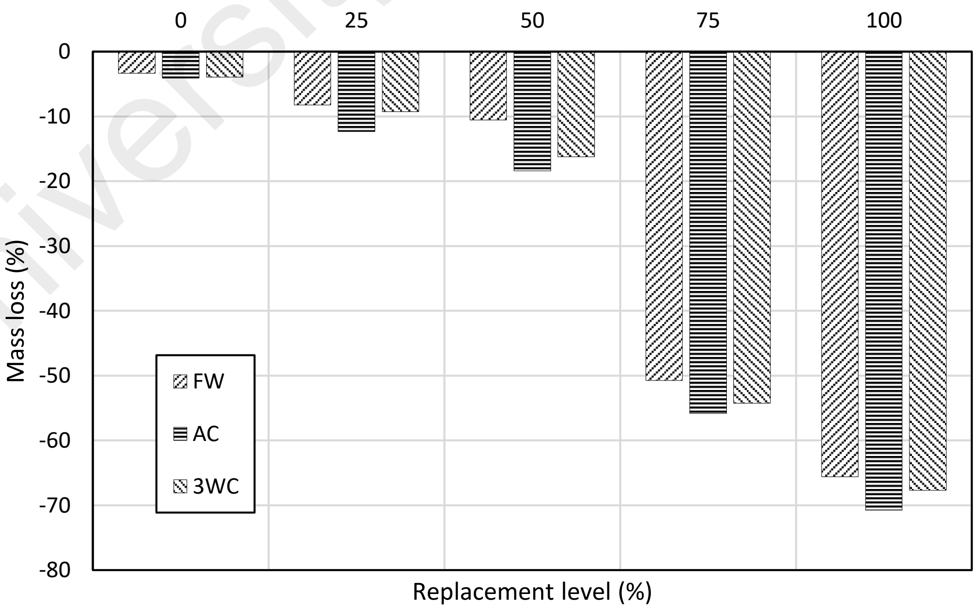


Figure 4.27: Effect of cement content on the POC pervious concrete abrasion resistance

4.6.3 Effects of curing

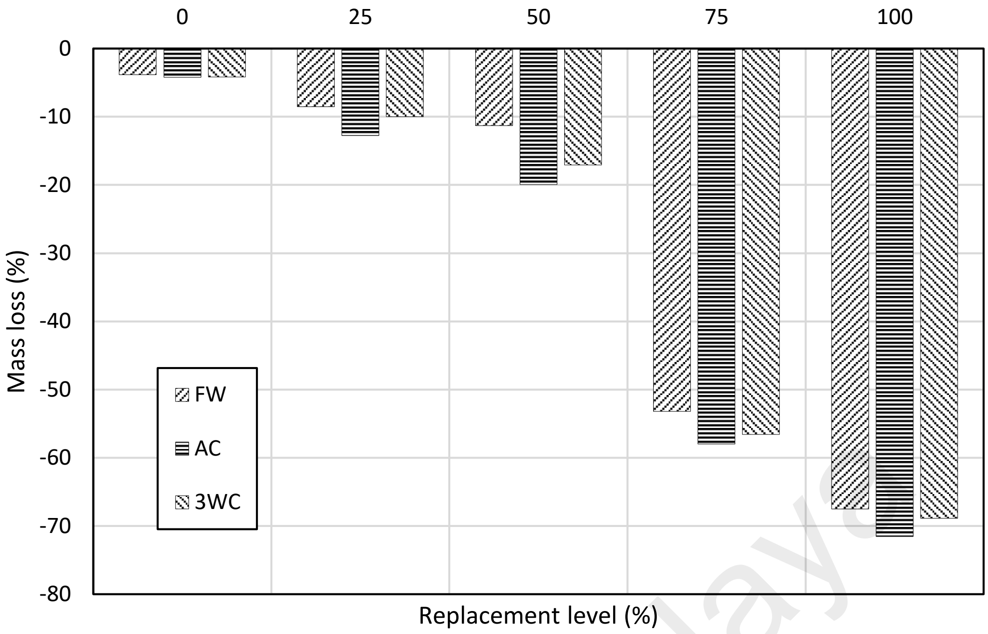
Figure 4.28 shows that mass loss gradually increased for the POC pervious concrete for all the method of curing adopted as the incorporation of POC aggregate replacement level into the mix increased irrespective of the cement content. It can also be observed from the Figure that the mass loss recorded for the POC pervious concrete samples under full water curing was similar to that cured for 3 days in water. However, mass loss increased when the POC pervious concrete was cured in air which may be as a result of the uncontrolled temperature and relative humidity the samples might have been exposed to. The uncontrolled temperature and relative humidity could accelerate evaporation of water required for cement hydration at the early stage as a result reducing the compressive strength of the concrete (Neville, 1995; Zhao et al., 2012). A similar outcome was observed by John T Kevern, Schaefer, et al. (2009a). Taking the full water cured POC pervious concrete as control, mass loss increased by a maximum of 6% and 3% for POC pervious concrete containing cement content of 400kg/m^3 when cured in air and 3 days in water cured respectively. However, the mass loss further increased to 12% and 9% for air cured and 3 days in water cured when cement content was reduced to 250kg/m^3.

Additionally, focusing on the control mixes without POC aggregates, the increase in mass loss of the concrete ranged from 0.2grams to 0.7grams and 0.1gram to 0.6grams as a result of curing the concrete samples in air and 3 days in water respectively when compared to full water cured samples. This suggests that curing had a marginal effect when the same aggregate type was used. However, when the substitution level of POC coarse aggregate into the concrete mix was 50% and above, the mass loss became more evident. This can be attributed to the weakness of the POC aggregate due to its physical properties and porous nature. Table 3.5 shows that POC coarse aggregate has poor ACV and L.A abrasion resistance compared to granite. Both the ACV and L.A abrasion value are important parameters which influences the way concrete will perform under abrasion. Based on this, it can be said that the properties of the aggregate and cement content both played a vital role compared to the effect of curing on the POC pervious concrete resistance to abrasion. The effect of curing can therefore be said to be marginal which is consistent with previous study by Schaefer and Kevern (2011).

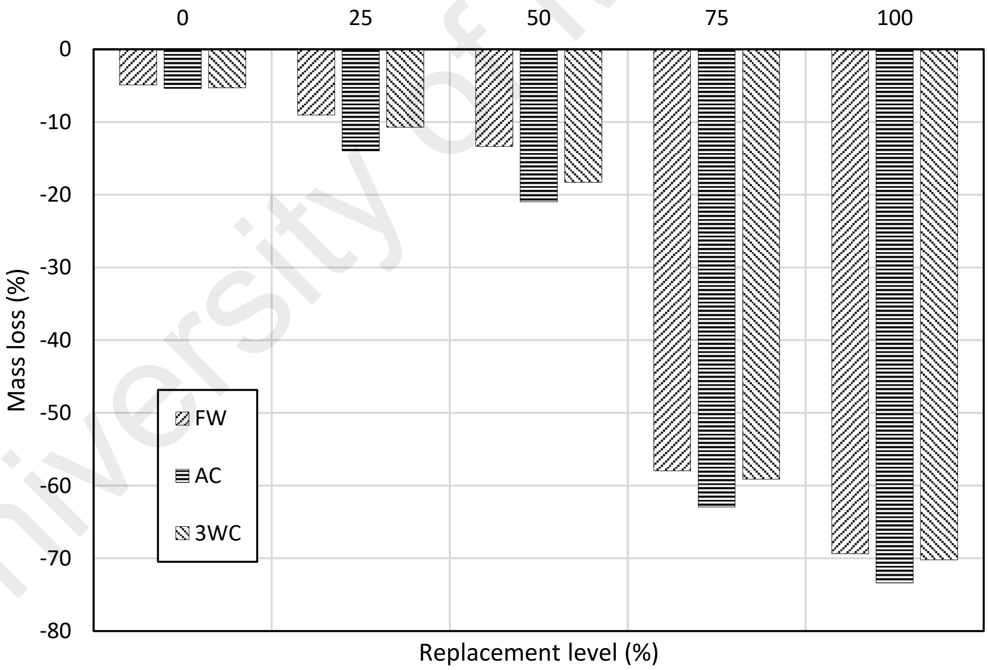


(a)

Figure 4.28: Effect of curing regime on 9.5mm size POC pervious concrete abrasion resistance at 28 days for cement content of (a) 400kg/m^3 (b) 350kg/m^3 (c) 300kg/m^3 (d) 250kg/m^3

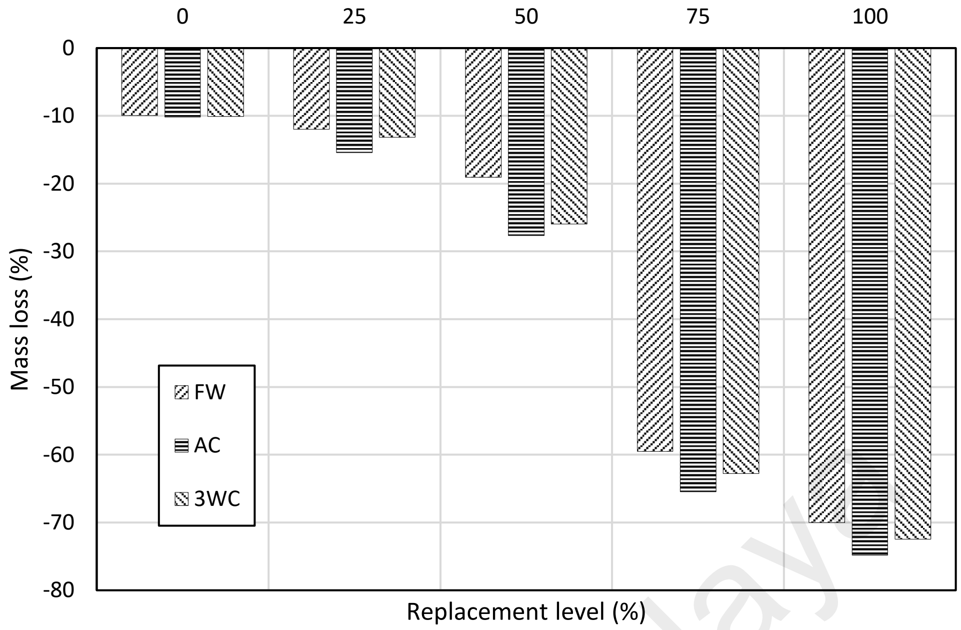


(b)



(c)

Figure 4.28, continued



(d)

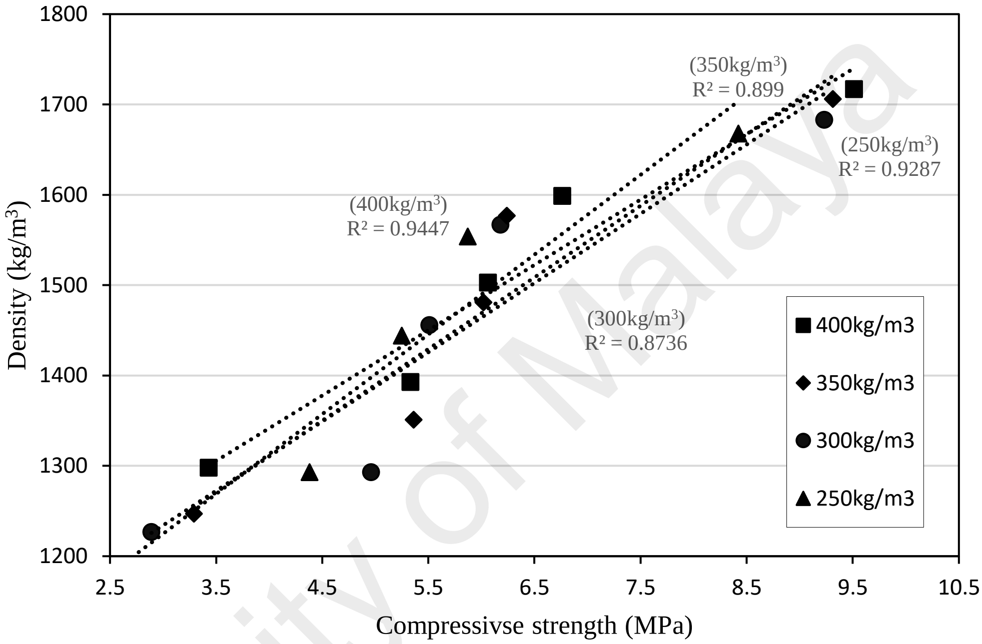
Figure 4.28, continued

4.7 Relationship between engineering properties of POC pervious concrete

Considering that pervious concrete is different from conventional concrete in terms of its mix design, mixing process and engineering properties. It is important to understand how the properties influence each other. Past studies have indicated that the relationships among pervious concrete properties are similar to those of conventional concrete (Hesami et al., 2014; Schaefer, Kevern, & Wang, 2009). Thus, this section will discuss the relationship between the engineering properties of the POC pervious concrete.

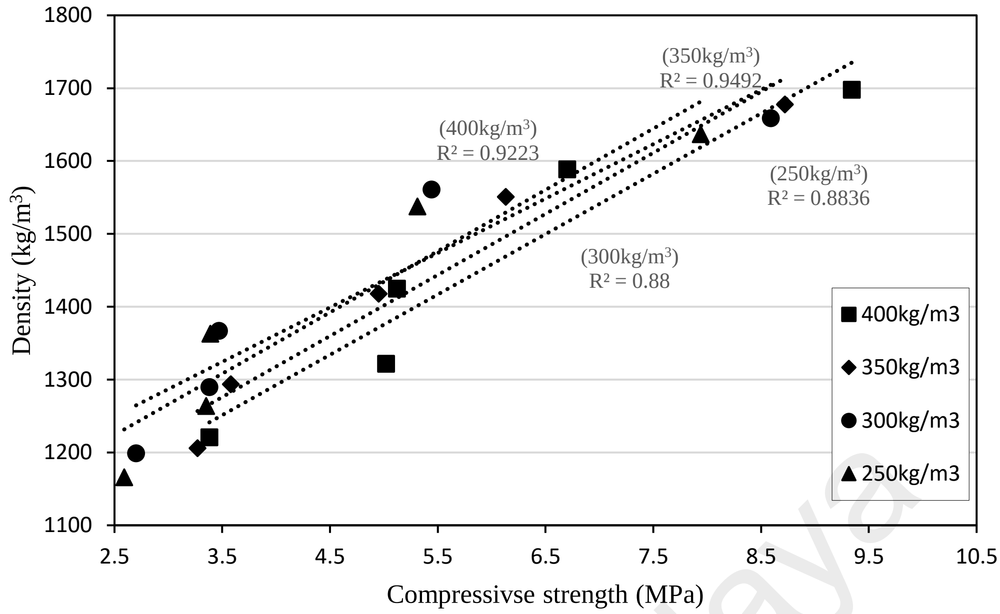
4.7.1 Density and compressive strength

The unit weight of POC aggregate is about 43% lighter than that of crushed granite stone (Kanadasan & Razak, 2014b). As a result, density of the concrete reduced as replacement of natural aggregate with POC coarse aggregate increased. Figure 4.29 (a) and (b) shows the relationship between the POC pervious concrete density and compressive strength for mixes containing 9.5mm and 12.5mm aggregate size respectively. A trend line has been added to show the general relationship between the density and compressive strength of the concrete which reveals that it is linear in nature with a R^2 value ranging from 0.87 to 0.95 indicating a strong relationship. Thus, the compressive strength of the concrete gradually drops as the density of the concrete reduced. This pattern was observed with POC pervious concrete containing 9.5mm and 12.5mm aggregate size respectively irrespective of the varying cement content.



(a)

Figure 4.29: Relationship between compressive strength and density at 28 days for aggregate size (a) 9.5mm (b) 12.5mm



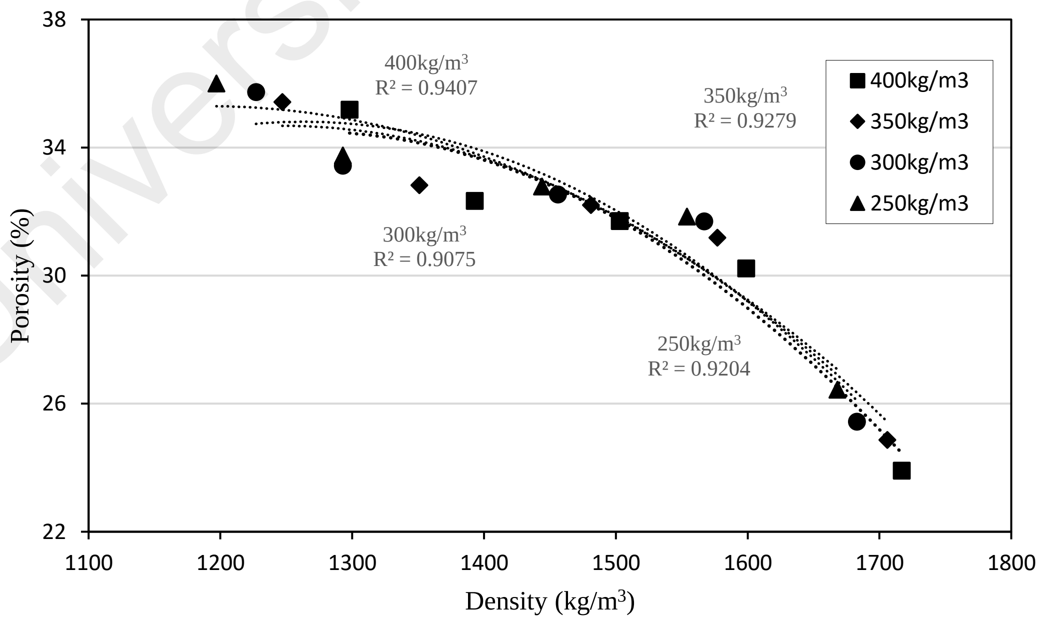
(b)

Figure 4.29, continued

4.7.2 Density and porosity

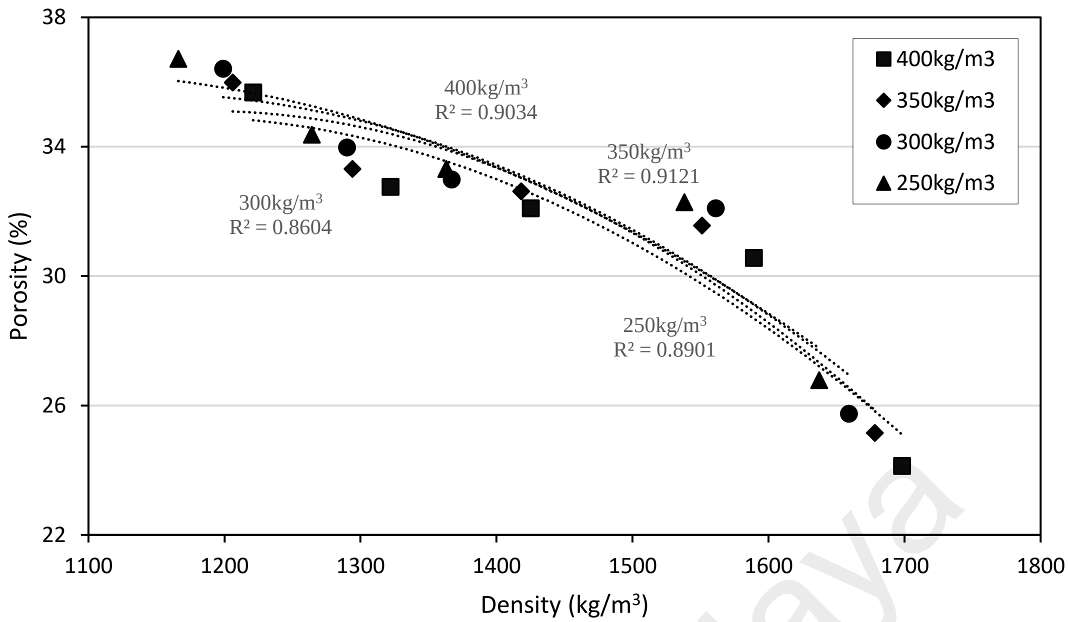
Figure 4.30 shows the effect of density on porosity for all POC pervious concrete mixtures. The unit weight of each POC pervious concrete specimen was computed by dividing each specimen weight by their respective volume. The relationship between the porosity and density was analyzed, and a polynomial equation was found to appropriately represent the correlation. The results indicate a satisfactory trend as the density increased with reduction in porosity irrespective of the aggregate size and cement content in the POC pervious concrete mix. Due to POC coarse aggregate physical characteristics which indicates that the material can be classified as a lightweight aggregate, it is expected that the POC pervious concrete reduced density would increase porosity. POC is flaky and rough in nature different from natural aggregate with a round surface. The smooth surface of natural aggregate would allow for an optimum packing density in contrast to POC coarse aggregate. Similar outcome was observed when Khankhaje et al. (2016) studied the use of OPKS in place of gravel in pervious concrete production. The study revealed that the incorporation of OKPS to substitute gravel was able to increase the pervious concrete total void content. Since the shape of natural gravel is round, an optimum packing density was obtained in the mixture. Contrarily, the shape of OPKS is curvy and flat which prevented proper packing and disturbed the granular arrangement of the aggregates in the concrete mix. Thus, this lead to a reduced compactness unlike natural aggregates.

Gaedicke et al. (2014b) study shows that type of aggregate affected the relationship between porosity and unit weight. The finding of the study was more pronounced when comparing the lower unit weight of recycled concrete aggregate block (RCAB) mixtures with virgin aggregate mixtures. Contrarily, the porosity versus unit weight relationship of both pea gravel and limestone mixtures was similar. The bulk specific gravity of each aggregate was concluded to have caused these. For instance, pea gravel and limestone have similar bulk specific gravity of 2.57 and 2.61, while the bulk specific gravity of RCAB was a considerably lower at 2.42.



(a)

Figure 4.30: Relationship between POC pervious concrete density and porosity at 28 days for aggregate size (a) 9.5mm (b) 12.5mm

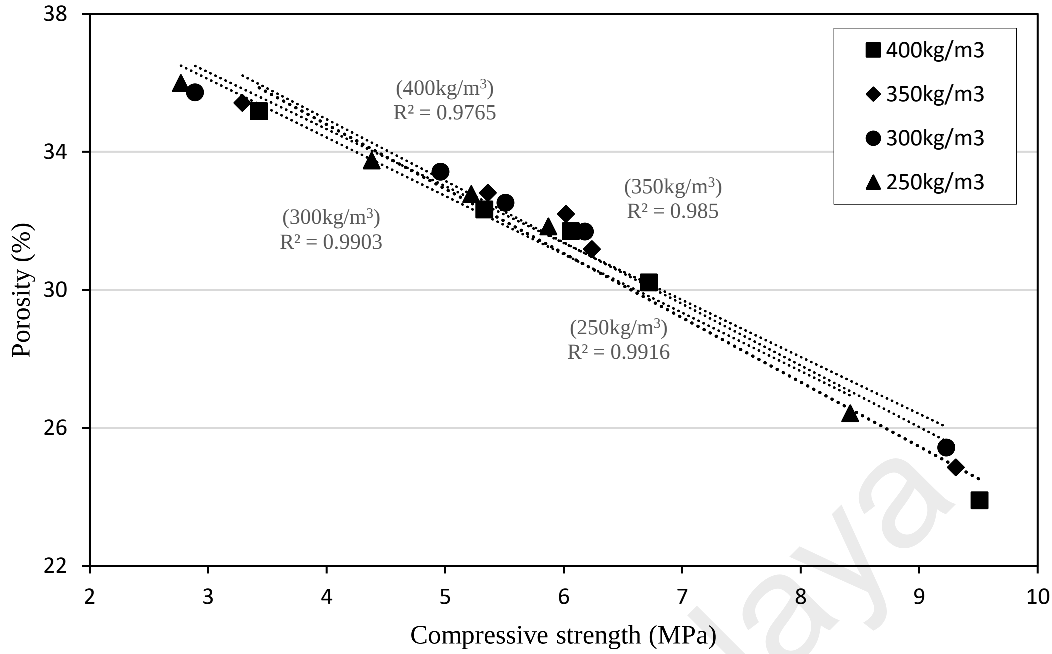


(b)

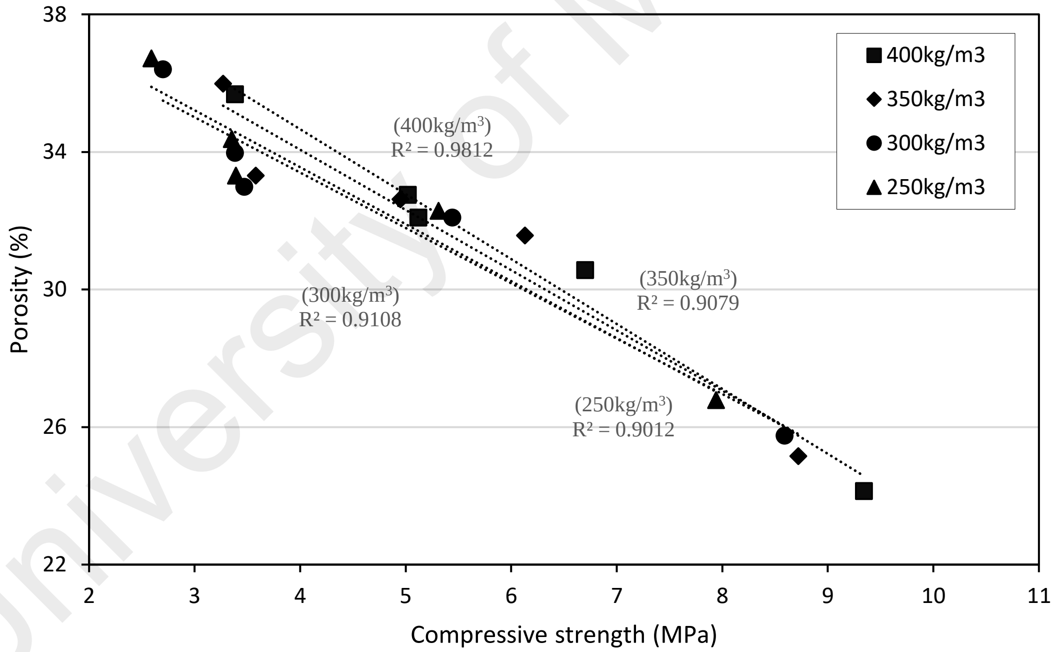
Figure 4.30, continued

4.7.3 Porosity and compressive strength

Following the earlier discussion, it is clear that influence of mixture constituents such as aggregate size and shape, cement content on compressive strength of the POC pervious concrete are not as significant when compared with the influence of porosity of the concrete. It is clear that for the POC pervious concrete, the type of aggregate influenced the relationship between strength and porosity due to the porous nature of POC coarse aggregate. Based on this, the porosity values obtained ranged from 23% to 36% and 24% to 37% for the POC pervious concrete mixes containing 9.5mm and 12.5mm aggregate size respectively. Meanwhile, the average compressive strength of the POC pervious concrete samples obtained ranged from 9.51MPa to 2.77MPa and 9.34MPa to 2.59MPa for mixes containing 9.5mm and 12.5mm aggregate size respectively. The high porosity and low strength is expected for these mixtures due to the mixture lacking fine aggregate. Figure 4.31 shows a linear relationship between the void present in the concrete and its compressive strength. A good correlation can be observed with R^2 value ranging from 0.90 to 0.99 indicating a strong relationship.



(a)



(b)

Figure 4.31: Relationship between POC pervious concrete porosity and compressive strength at 28 days for aggregate size (a) 9.5mm (b) 12.5mm

The highest compressive strength value was recorded at 0% replacement because the concrete porosity was least at this replacement level. Also, there was a gradual loss in compressive strength of the concrete irrespective of the cement content and aggregate size as substitution of natural aggregate with POC increased resulting in increased porosity. Compressive strength reduced to 3.43MPa and 2.77MPa when POC was fully substituted into the concrete mix at maximum and minimum cement content respectively for the POC pervious concrete mix containing 9.5mm aggregate size. Similar outcome was observed with the POC pervious concrete containing 12.5mm aggregate size. Consequently, the reduced paste thickness weakened the aggregate-paste bond when the porosity is higher. This indicates that presence of voids weakened the concrete matrix as highlighted by P Chindaprasirt et al. (2008). Cement paste in pervious concrete unlike conventional concrete only fill the space between aggregates partially. According to Yeih et al. (2015), the intent of this is to create void inside concrete so as to intentionally allow penetration of water. Thus, porosity has the worst effect on the engineering properties of a pervious concrete because it has the highest water permeation coefficient and no mechanical strength. Therefore, pervious concrete behavior is dominated by the volume fraction of the porosity (Yeih et al., 2015). For the conventional concrete, the concrete property is dominated by the ITZ property since the weakest part in concrete is the ITZ. However, porosity is the weakest part for pervious concrete which directly determines the compressive strength of a pervious concrete (Gaedicke et al., 2014b; Yeih et al., 2015). Additionally, the nature of POC aggregate is such that it has external and internal interconnected void (Kanadasan et al., 2015). The external interconnected pores of POC, unlike the internal voids, are visible to the eyes. Figure 4.32 shows a typical 20µm magnification of POC aggregate microstructure. Although the POC pervious concrete aggregate was pre-coated during the process of casting, it is believed that the coating did not completely fill the internal voids present in the aggregate as seen in Figure 4.33 and is thus more pronounced on the aggregate surface. Thus, internally connected void of the POC aggregate would result in a quick crack propagation and failure when the concrete is subjected to applied load.

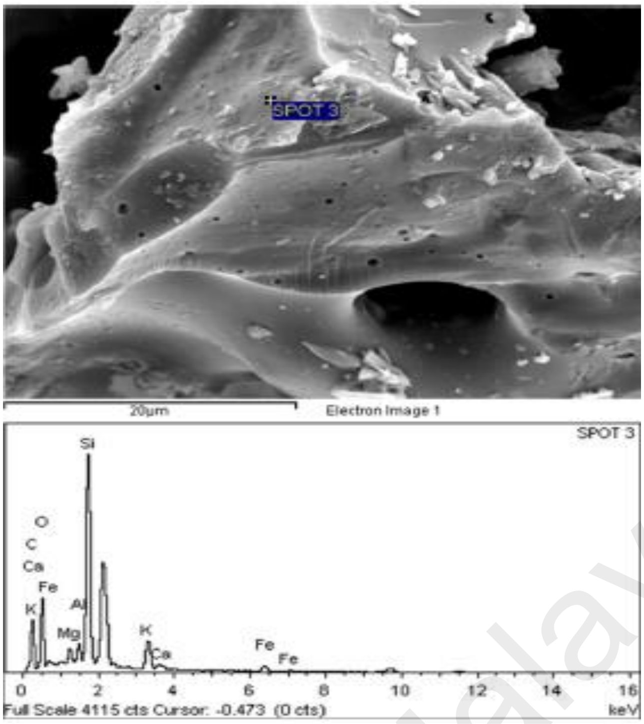


Figure 4.32: POC aggregate internal micro-pores structure (Kanadasan et al., 2015)

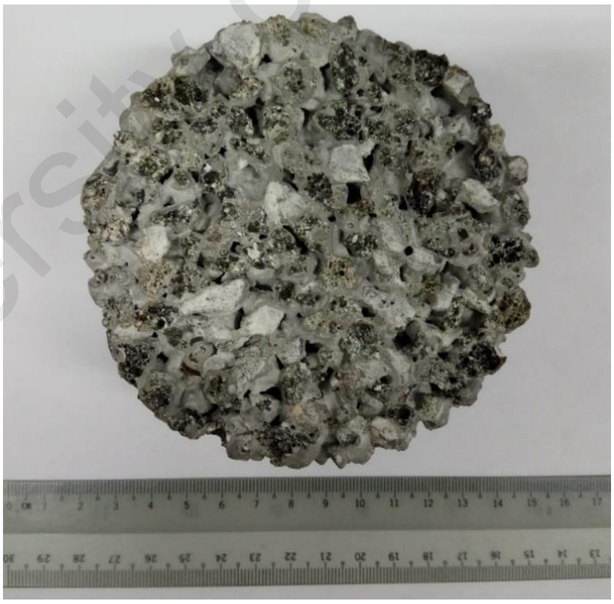


Figure 4.33: Cross-section of POC pervious concrete sample revealing POC internal voids

Furthermore, some researchers correlate effective porosity with compressive strength. However, it is the total porosity that influences the compressive strength. The total porosity is defined as the ratio of total pore volume to the total volume. The total porosity takes into account the volume of non-accessible pores (Vnap). The volume of non-accessible pores may be further divided into non-connected pores left in the space between aggregates (Vncp) and the pores in the matrix (Vmp). Figure 4.34 illustrates the pore system in pervious concrete (Zhong & Wille, 2016a, 2016b).

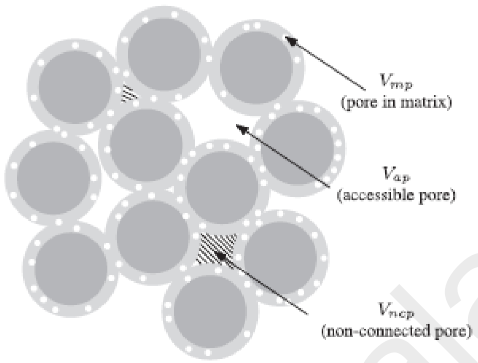
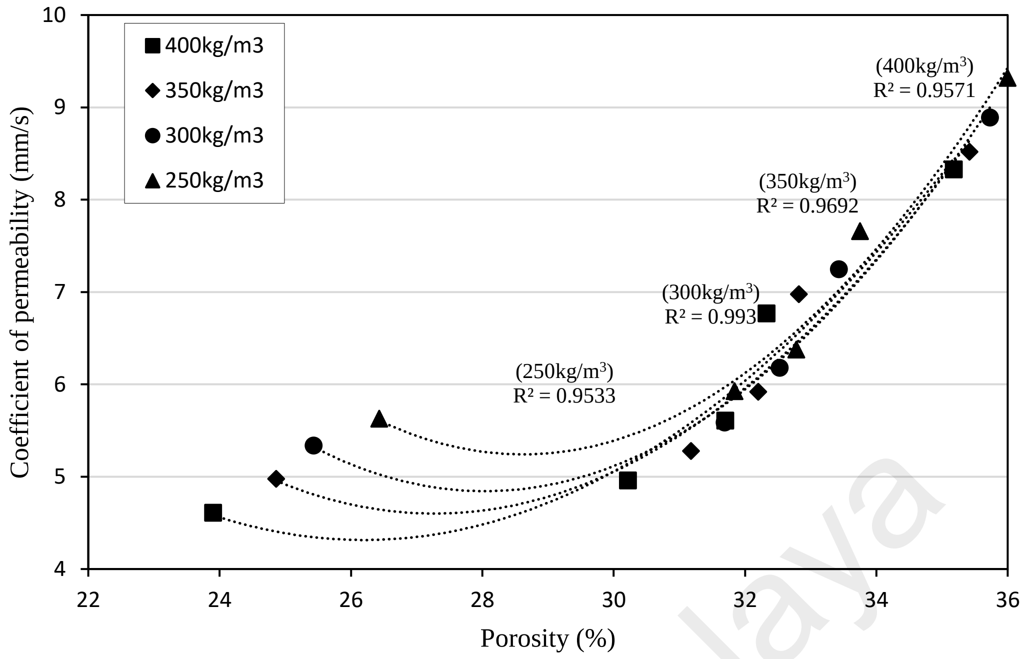


Figure 4.34: Typical pervious concrete pore system (Zhong & Wille, 2016b)

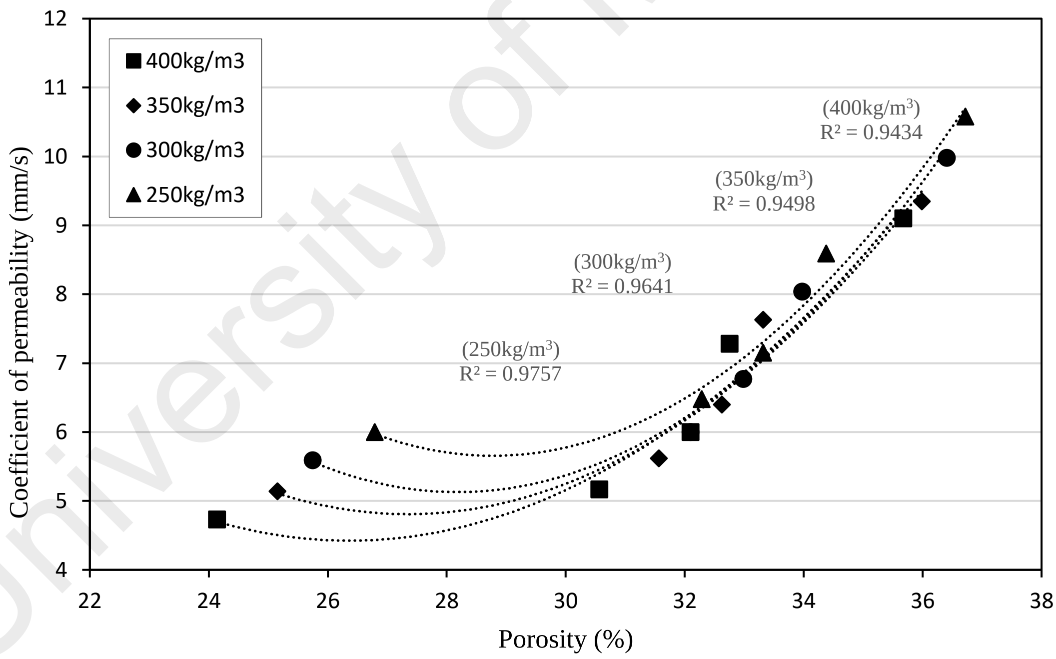
4.7.4 Porosity and coefficient of permeability

Pervious concrete has the unique ability to allow water infiltrate through its microstructure which makes it stand out among other concrete. Consequently, achieving an adequate porosity becomes important to allow easy passage of water through the concrete structure. Based on this, water permeability is important for the performance evaluation of a given pervious concrete. Regardless of aggregate size and cement content, the coefficient of permeability of the POC pervious concrete samples increased as the porosity of the concrete mix increased. Figure 4.35 shows the relationship between the permeability coefficient and porosity for the two aggregate sizes used in this study. For the range of porosities measured, the correlation was best represented with a polynomial equation. Similar relationship was reported by Yahia and Kabagire (2014). The range of permeability obtained was between 4.61mm/s to 9.32mm/s and 4.73mm/s to 10.58mm/s for POC pervious concrete mixes containing 9.5mm and 12.5mm aggregate size respectively.

Permeability coefficient of the POC pervious concrete was least at 0% POC coarse aggregate replacement irrespective of the cement content and aggregate size. However, the high void present in the concrete ensured that a significant increase was recorded at 100% replacement. For instance, when porosity increased from 23% to 30% at 0% POC incorporation, coefficient of permeability increased by 7% for POC pervious concrete mixes containing 9.5mm aggregate size. Meanwhile at 100% POC replacement, permeability increased by 80% when porosity increased to 35%. On the other hand, coefficient of permeability increased by 9% and 92% at 0% and 100% POC incorporation respectively for the POC pervious concrete mixes containing 12.5mm aggregate size even though the porosity increment observed was similar to that of the POC pervious concrete mixes containing 9.5mm aggregate size. Consequently, it shows that the size of aggregate used has an influence on the relationship between the porosity and coefficient of permeability. This could be as a result of the packing of the aggregates which must have affected the effective porosity of the concrete. Based on the concept behind effective porosity as explained by Lian, Zhuge et al. (Lian et al., 2011; Zhong & Wille, 2016b), effective porosity is believed to determine how water would permeate through the matrix of the concrete. Similar outcome was observed in a recent study whereby coefficient of permeability rose from 0.0186m/s to 0.0241m/s at a constant porosity of 38% when aggregate size increased from 9.5mm to 12.5mm (A. Ibrahim et al., 2014). Additionally, the authors believe that a better relationship would have been obtained if ‘‘effective’’ porosity is measured instead of total porosity.



(a)



(b)

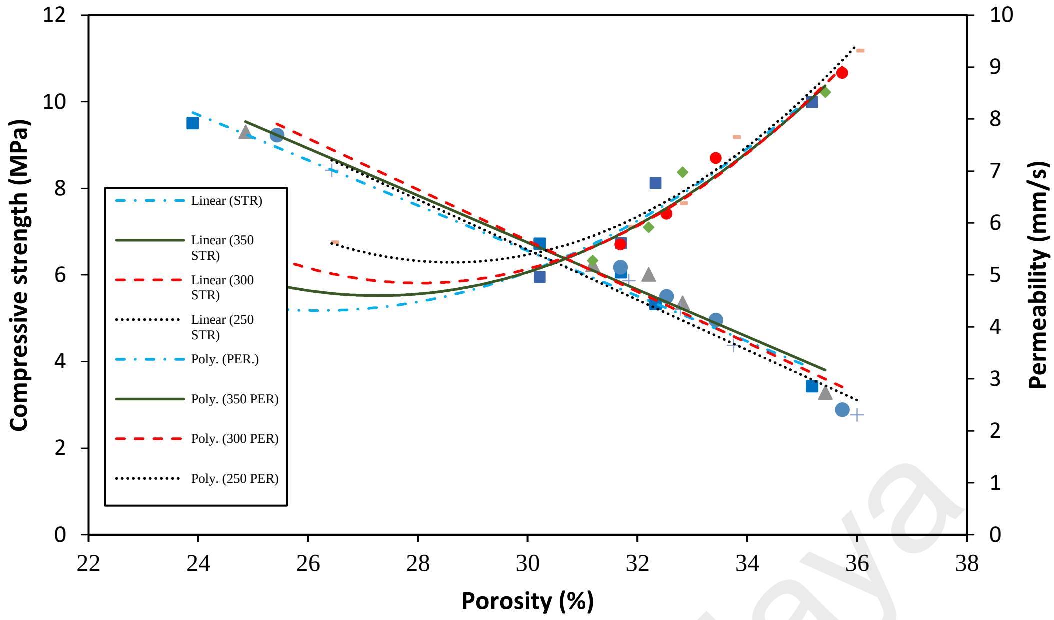
Figure 4.35: Relationship between porosity and coefficient of permeability at 28 days for aggregate size (a) 9.5mm (b) 12.5mm

4.8 Optimum mix for POC pervious concrete

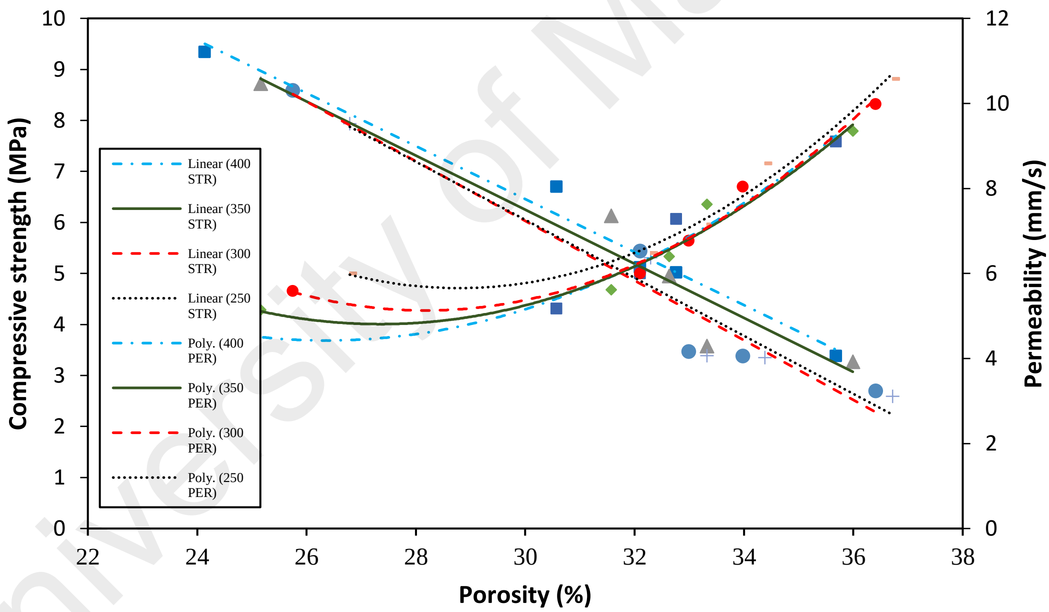
For a pervious concrete, engineering properties such as compressive strength, porosity and permeability are important for most of its application. It has been established that there exists a direct relationship between these three properties with both compressive strength and permeability being influenced by the porosity of the concrete. Based on this, some studies (Joshaghani et al., 2015; Maguesvari & Narasimha, 2013; Schaefer & Kevern, 2011) have suggested that a balance between these three properties can be used to determine the optimum mix for the concrete performance.

4.8.1 Relationship between compressive strength, porosity and coefficient of permeability

Figure 4.36 shows the relationships between the porosity, 28-days compressive strength and permeability for the POC pervious concrete. The Figure shows that permeability and compressive strength increased and decreased respectively when the concrete porosity increased. By evaluating the compressive strength, permeability and porosity of the concrete, the optimum mix for the POC pervious concrete was determined. Based on Figure 4.36 (a), compressive strength range between 6MPa to 7MPa with porosity range of 28% to 32% at permeability between 4.5mm/s to 5.5mm/s is the optimum performance for the POC pervious concrete mixes containing 9.5mm aggregate size irrespective of the cement content. On the other hand, it can be seen from Figure 4.36 (b) that the values obtained for the optimum performance of POC pervious concrete containing 12.5mm aggregate size was slightly different. In this case, compressive strength range between 4.5MPa to 5.5MPa with permeability between 6mm/s to 7mm/s at porosity range of 30% to 34% is the optimum performance irrespective of the cement content.



(a)



(b)

Figure 4.36: Relationship between compressive strength, porosity and coefficient of permeability at 28 days for aggregate size (a) 9.5mm (b) 12.5mm

With reference to the values above, POC pervious concrete mixes containing 25% POC coarse aggregate replacement has been identified as optimum for the POC pervious concrete containing 9.5mm aggregate size for each cement content. However, POC pervious concrete mix with 400kg/m^3 cement content has the closest value compared to the average optimum range obtained as presented in Table 4.1. Thus, this has been identified as the best mix among the POC pervious concrete mixes containing 9.5mm aggregate. As expected, POC pervious concrete mixes containing 12.5mm aggregate size exhibited a different outcome. POC pervious concrete mixes containing 25% POC coarse aggregate replacement has been identified as optimum for POC pervious concrete containing 12.5mm aggregate size for cement content of 250kg/m^3 and 300kg/m^3. However, POC pervious concrete mixes containing 50% POC coarse aggregate replacement has been identified as optimum for POC pervious concrete containing 12.5mm aggregate size for cement content of 350kg/m^3 and 400kg/m^3. Based on Table 4.1, POC pervious concrete mix with 300kg/m^3 cement content at 25% replacement level has the closest value compared to the average optimum range. Thus, it has been identified as the best mix among the POC pervious concrete mixes containing 12.5mm aggregate size. Although the POC pervious concrete optimum compressive strength range for both mixes containing 9.5mm and 12.5mm aggregate size indicates that the concrete might not be suitable for structural application. A design compressive strength in the range of 10MPa to 13MPa is desired for drainage pavement, parking lots, precast porous concrete products and stone protection (Bhutta et al., 2012; Crouch et al., 2006). However, the lower strength of the POC pervious concrete could be acceptable for applications where the concrete will not be subjected to heavy loads such as walkways and pedestrian trials as suggested in past studies (Crouch et al., 2006; Zaetang et al., 2013).

Table 4.1: Engineering properties for optimum mix and actual experimental results

Cement content (kg/m^3)	POC replacement level (%)	Average optimum range			Actual experimental values		
		Porosity (%)	Coefficient of Permeability (mm/s)	Compressive strength (MPa)	Porosity (%)	Coefficient of Permeability (mm/s)	Compressive strength (MPa)
POC pervious concrete containing 9.5mm aggregate size							
400	**25**	**30.5**	**5.2**	**6.3**	**30.2**	**5.0**	**6.7**
350	25	30.7	5.3	6.5	31.2	5.3	6.2
300	25	30.8	5.3	6.5	31.7	5.6	6.2
250	25	30.3	5.5	6.6	31.8	5.9	5.9
POC pervious concrete containing 12.5mm aggregate size							
400	50	32.2	6.4	5.5	32.1	6.0	5.1
350	50	32.0	6.2	5.2	32.6	6.4	4.9
300	**25**	**31.6**	**6.0**	**5.0**	**32.1**	**6.0**	**5.4**
250	25	31.4	6.3	5.3	32.3	6.5	5.3

The optimum mix compressive strength for the POC pervious concrete falls within the suggested range in ACI 522 (2003). Research conducted by other researchers have shown similar results. For instance, sustainable lightweight pervious concrete was produced by partially replacing limestone with OPKS by mass (Khankhaje et al., 2016). The study reported permeability coefficient of 4mm/s to 16mm/s and a compressive strength of 6MPa to 12MPa at a target void of 20%. The optimum mix was at 25% replacement. Considering that OKPS and POC are palm oil waste with similar lightweight characteristics, it would be expected that a similar outcome in terms of engineering properties is obtained. However, it should be noted that the study with OKPS incorporated about 15% fine aggregate by weight of coarse aggregate in order to enhance the properties of the concrete which is the reason for superior properties compared to this study.

Additionally, the properties of pervious concretes containing two types of recycled aggregates; recycled concrete aggregate (RCA) and RBA were studied by Zaetang et al. (2016). The RBA and RCA at 40% and 60% replacement level was optimum whereby the respective compressive strength was 17MPa and 15MPa. Void content obtained for RBA and RCA optimum replacement was 20% and 24% while coefficient of permeability was 8mm/s and 9.8mm/s respectively. The improved strength compared to this study could be as a result of the reduced void obtained as well as the LA abrasion value of RBA and RCA of 52% and 43.3% respectively as compared to that of POC (64.7%) as seen in Table 3.3. However, the coefficient of permeability obtained in this study is acceptable and similar to the study on RCA and RBA.

Furthermore, Zaetang et al. (2013) investigated the use of LWA for making LWPC. Diatomite (DA) and pumice (PA) were used as natural LWAs in pervious concrete in which the results were compared to those of lightweight pervious concrete containing recycled LWA from autoclaved aerated concrete (RA). The study reported void content of 15.6% to 31.8% with compressive strength and coefficient of permeability of 2.47MPa to 5.99MPa and 13mm/s to 47mm/s respectively. Figure 4.37 shows that the PA and RA aggregate have similar porous and irregular surface to POC. However, the LA abrasion values differ where DA, PA and RA has L.A abrasion values of 52.6%, 66.2% and 89.9% respectively. Based on the similar properties of POC with these lightweight aggregates, it can be seen that POC showed better engineering properties at optimum replacement.

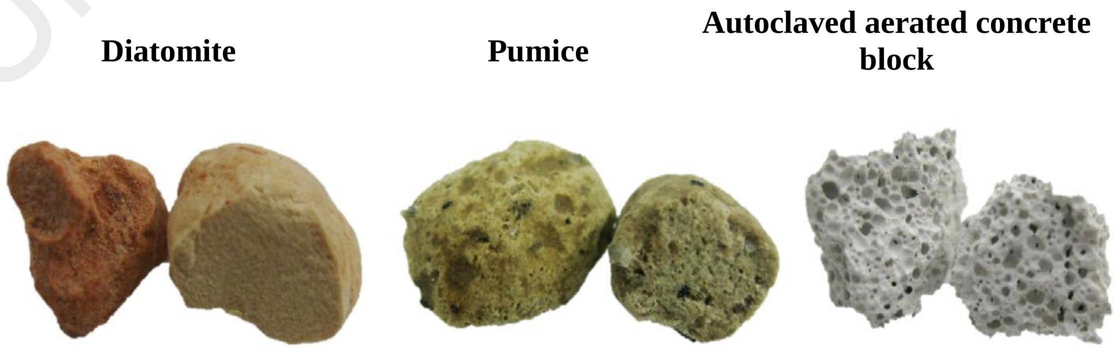


Figure 4.37: Particle shapes of lightweight aggregate (Zaetang et al., 2013)

Prinya Chindaprasirt et al. (2015) investigation on the use of recycled lightweight aggregate from waste autoclaved aerated concrete block to make LWPC reported 28 days compressive strength of 1.9MPa to 4.1MPa with void ratio of 14% to 24% which produced coefficient of permeability of 1.7mm/s to 11.6mm/s. Although the additions of both fine sand (SA) and fly ash (FA) at 10% to 30% by weight of cement in LWPC were effective for increasing the compressive, a high LA abrasion value of 90% ensured that the effect of both SA and FA on the strength of the concrete was minimal.

Additionally, Nguyen et al. (2013) reported permeability coefficient of 3mm/s to 8.4mm/s and 31.8% to 34.9% for porosity which shows similar result to this study. However, a compressive strength of 15MPa was recorded which is superior to this study. The high strength is believed to be as a result of the type of cement and the low w/c ratio used. On the other hand, A. Ibrahim et al. (2014) investigated the properties of pervious concrete without fine aggregate which contains two different size of aggregates. The result of the study showed that 6.95MPa was the maximum value of compressive strength obtained. This was obtained with the mix containing 9.5mm aggregate size with 250kg/m^3 cement content. Coefficient of permeability obtained at void content of 30% was 15mm/s.

4.9 Sustainability efficiency of POC pervious concrete

Sustainability efficiency of the POC pervious concrete at various replacement levels for the POC pervious concrete optimum mix was evaluated through simplified proportioning between the carbon emissions and the structural efficiency of the respective mixes**.** Althoguh POC pervious concrete optimum mix were identified based on two different aggregate sizes, the sustainability efficiency of the POC pervious concrete optimum mix containing 12.5mm aggregate size is not discussed in this section. This is because the surface abrasion resistance test was not successful. As such, it cannot be said to have fully fullfilled all the mechanical properties expected of it.

Figure 4.38 shows the relationship between the structural efficiency of the concrete and POC replcament for the POC pervious concrete with optimum mix. It can be seen from the Figure that there was significant reduction with increased POC replacement in the mix which is most evident at full replacement level. This is similar to what was reported by Kanadasan and Razak (2015) when POC was used in the production of self compacting concrete. Compressive strength of the POC pervious concrete reduced with respect to the density of the concrete which may be as a result of the POC aggregate inability to withstand a high load because of its considerable interconnected porosity and shape. For a typical concrete mix containing lightweight aggregate, the density decreases resulting in decreased compressive strength and such tendency is evaluated upon the structural efficiency (Choi et al., 2006). Hence, the effect of using lightweight aggregate such as POC is expected to reflect on the structural efficiency of the concrete. Furthermore, Figure 4.38 also shows that the structural efficiency of the concrete was similar between 25% and 50% and a slight drop at 75% POC replacement. However, the structural efficeincy further dropped by 50% at full replacement level. Meanwhile, the structural efficiency dropped by 24% compared to the control at 0% replacement level for the optimum POC replacement level of 25%. The structural efficiency of POC pervious concrete varied depending on the replacement level of natural aggregate with POC coarse aggregate. POC pervious concrete showed acceptable structural efficiency values at 0% POC replacement. At full replacement level, the POC pervious concrete attained an approximate value of 50% of the control concrete structural efficiency. By integrating both the engineering aspects and environmental impact, a satisfactory output was recorded for the mixes incorporating POC aggregate.

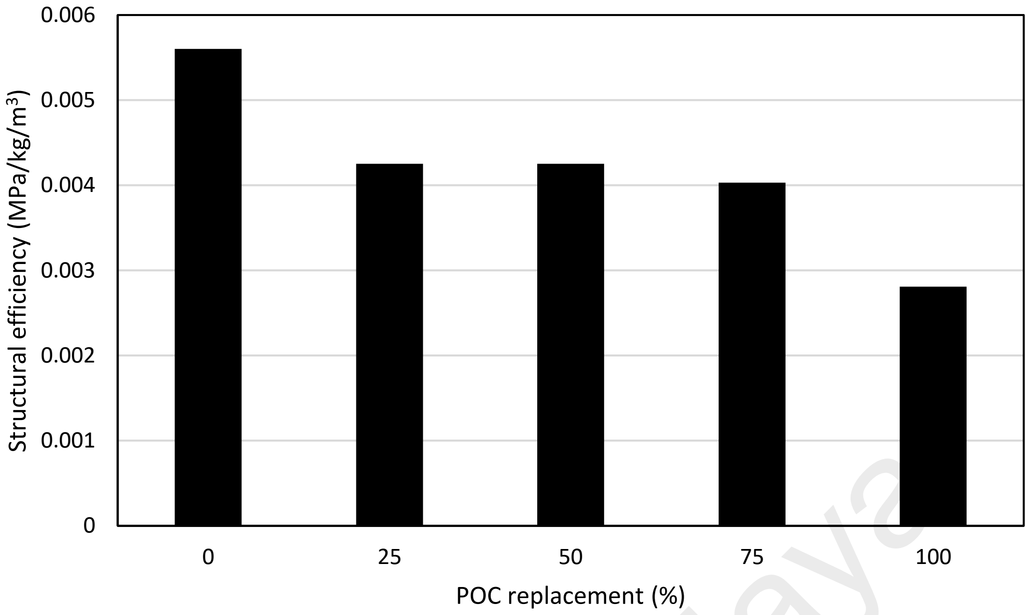


Figure 4.38: Relationship between the Structural Efficiency and POC replacement

The relationship between the CO_2, POC replacement and structural efficiency for the POC pervious concrete optimum mix can be seen in Figure 4.39. CO_2 emissions showed some reduction as POC was incorporated into the mixes. Since evaluation is carried out at a constant cement content for the POC pervious concrete containing the optimum mix while POC coarse aggregate varied at every replacement level, a clear indication as to how POC would affect CO_2 emission was obtained. At 100% replacement, a maximum reduction of approximately 20% was recorded compared to the control at 0% POC replacement. This pattern is similar to that reported in Kanadasan and Razak (2015) study where a carbon emission reduction of 22.62% was obtained at full replacement with POC compared to the control mix. Similarly, incorporation of OPS, another oil palm waste, in geopolymer concrete in Islam, Alengaram, Jumaat, Bashar, and Kabir (2015) study also revealed that the carbon footprint of OPS geopolymer concrete was about 50% to 60% lower compared to conventional concrete. On the other hand, CO_2 emission reduction at POC pervious concrete optimum mix replacement of 25% was less than 10%. Thus, incorporating POC into concrete mix will help reduce the discharge of CO_2 which is harmful to the environment.

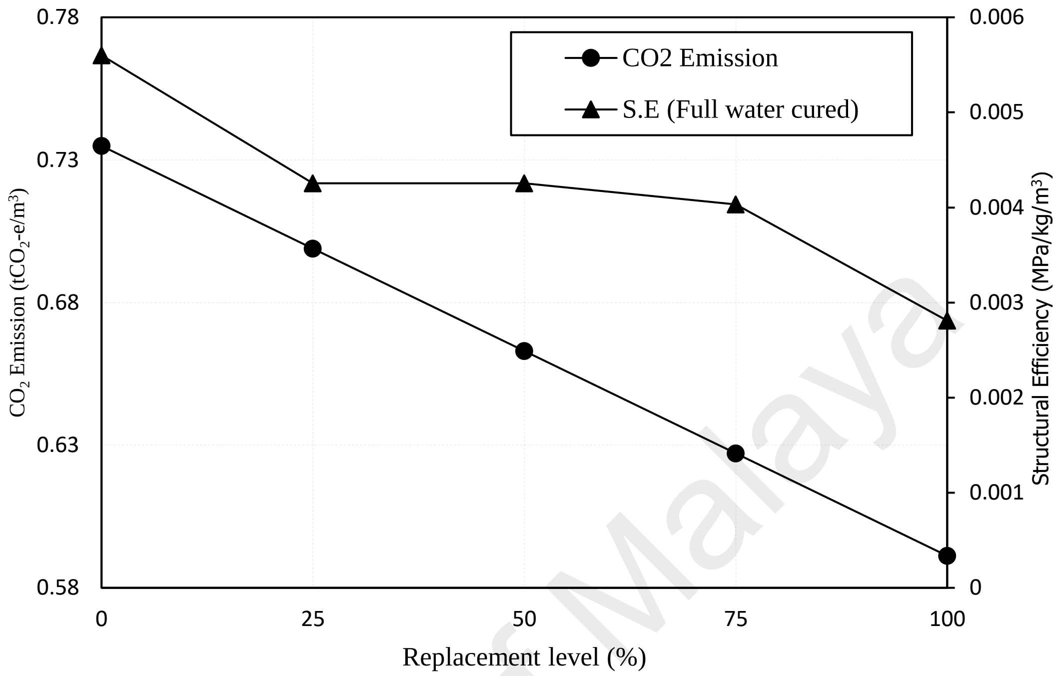


Figure 4.39: Relationship between the CO_2 emission, POC replacement and Structural Efficiency

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Pervious concrete is a new technology gaining attention worldwide. Thus, there is no standardized method for mix design. Consequently, a trial and error method was adopted to develop the mix proportion in this study. The mix proportion used was based on four cement contents and two aggregate sizes in order to study the effects of varying the mixture constituents on the concrete engineering properties. Consistency tests was used to check and ensure that the w/c ratio adopted was satisfactory. Thus, the mix proportion was based on a fixed w/c ratio of 0.3 whereas the c/a was kept constant at 0.21. Natural aggregate was replaced with POC coarse aggregate by volume at different levels of replacement which are 25%, 50%, 75% and 100% respectively. Due to the angular and flaky nature of POC aggregate, the aggregate is characterized with interconnected voids both externally and internally. Thus, POCP was used as a filler material to fill the visible voids on the aggregate surface. POCP was selected to further maximise the use of palm oil waste in the concrete production. The volume of POCP required to pre-coat the POC aggregate at the selected replacement levels was determined using a similar approach used in past studies. However, this method was modified to suit the purpose of this study. Consequently, the void volume obtained based on this method was incorporated to develop the final mix proportion for the POC pervious concrete.

Based on the second objective of the study to investigate the effect of adopting different curing regimes and varying mixture constituents on the properties of the POC pervious concrete, it was observed that the effect of curing regimes was marginal. Among the three curing regimes adopted, POC pervious concrete samples subjected to full water curing showed the best result in terms of compressive strength and abrasion resistance, while the air cured concrete samples showed the worst results. The uncontrolled temperature and relative humidity of curing the concrete in air could have accelerated evaporation of water required for cement hydration at the early stage. As a result, the concrete was weak under compression load and resistance to abrasion. Meanwhile, cementitious material in pervious concrete is mainly to provide the aggregate with sufficient coating in order to increase the concrete durability. Thus, increasing the cement paste increased the coating on the aggregate which in turns lead to a rise in the density, compressive strength, and resistance to abrasion while porosity and coefficient of permeability of the concrete reduced. On the other hand, the use of smaller aggregate size improved the engineering properties of the concrete. Although such improvement is not pronounced, as similar outcomes were recorded in most of the cases. However, the larger aggregate size failed under resistance to abrasion due to the large voids, reduced contact area and a poor paste to aggregate bond. Thus, the abrasion resistance tests of the POC pervious concrete containing large aggregate size could not be completed. The concrete sample collapsed before the minimum time stipulated in the standard was attained. Considering the three mixture parameters investigated, the effect of using different curing regimes had the least effect on the engineering properties of the POC pervious concrete. Meanwhile, effect of varying the cement content and using different aggregate size showed similar outcomes. Consequently, the notable differences recorded in the engineering properties of the POC pervious concrete was observed to be as a result of the physical properties of the POC aggregate such as shape, size, texture, water absorption and the ACV.

By evaluating the inter-relationship between the compressive strength, porosity and coefficient of permeability, the study was able to determine the POC pervious concrete mix with the best mechanical properties which has been defined as the optimum mix in line with the third objective of the study. Compressive strength in the range of 6MPa to 7MPa with permeability coefficient between 4.5mm/s to 5.5mm/s at a porosity range between 28% to 32% was identified as the optimum performance for the POC pervious concrete mix containing 9.5mm aggregate size. Thus, POC pervious concrete mix with 400kg/m^3 cement content containing 25% replacement of POC aggregate falls within the range of the inter-relationship evaluated. Furthermore, due to the inability to test the abrasion resistance of the POC pervious concrete mix containing 12.5mm aggregate size, further investigation such as structural efficiency and carbon emission were not carried out. Thus, optimum performance of the POC pervious concrete can be obtained with the mix containing 9.5mm aggregate. However, an optimum compressive strength of 6.7MPa for the POC pervious concrete indicates that the concrete might not be suitable for structural application. The relationship between the concrete structural efficiency and POC replcament for the POC pervious concrete with optimum mix shows that the structural efficiency of the concrete dropped by 24% drop for the optimum replacement level compared to the control. This suggests that the POC pervious concrete is more suitable for non-structural applications. Additionally, the POC pervious concrete may not be suitable for some non-structural applications such as drainage pavement, precast porous concrete products, stone protection and parking lots because a higher design compressive strength is desired for such applications. Nevertheless, the POC pervious concrete optimum strength could be acceptable for applications where the concrete would not be subjected to heavy loads such as bicycle path and pedestrian trial. By comparing the optimum mix of the POC pervious concrete with pervious concrete from past studies which incorporated different lightweight aggregates in their concrete production, it was observed that the POC pervious concrete optimum mix fared well among them.

Lastly, it is important for the POC pervious concrete to satisfy its engineering properties as well as environmental requirement in order to function properly. Thus, sustainability efficiency analysis revealed that there was significant reduction with increased POC replacement in the POC pervious concrete optimum mix. It was observed from the relationship between the structural efficiency, POC replacement and carbon emission that the concrete carbon emission reduced as POC was incorporated into the mix. At 100% replacement, carbon emission reduction of approximately 20% was recorded compared to the control at 0% POC replacement. On the other hand, CO_2 emission reduction at the identified POC pervious concrete optimum mix replacement of 25% was less than 10%. Nevertheless, discharge of CO_2 which is dangerous to the environment was reduced with incorporation of POC into concrete mix.

5.2 Limitations of the Study

Study on pervious concrete is not a famous area of research in Malaysia and there were some limitations encountered during the execution of this study. Due to its lack of popularity, some of the equipment and apparatus used for tests were either modified or fabricated. For instance, abrasion resistance complying with ASTM C1688 was not available. There was need to modify the existing drilling machine to suit the tests. Also, there is no standard apparatus for conducting permeability for pervious concrete. The apparatus used was thus fabricated with reference to past studies. Furthermore, the selected aggregate size for the POC pervious concrete was limited to maximum of 12.5mm nominal size because the jaw crusher used in breaking the chunks of POC waste does not allow for larger sizes.

5.3 Recommendations

Generally, the current study was aimed at investigating the possibility of using palm oil mill waste in the form of palm oil clinker (POC) as an alternative coarse aggregate in the production of eco-friendly pervious concrete. POC is porous aggregate with lightweight characteristics and its application in concrete has been investigated by various researchers. Based on the outcome of this study, the significant potential of using POC in pervious concrete warrants further investigation especially on long-term durability and how to enhance the properties of the concrete to broaden its engineering application.

Some of the areas that requires investigation by future researchers include enhancing the engineering properties of the concrete such as compressive strength, and more importantly its resistance to abrasion. Once this is successfully improved, other engineering properties such as split tensile strength, flexural strength, modulus of elasticity can be investigated appropriately. Meanwhile, improving the mechanical properties of the concrete must be done in such a way as not to compromise other properties of the concrete such as porosity and coefficient of permeability. Some past studies have shown that pervious concrete can serve as a suitable insulating concrete, so it would be interesting to see how the POC pervious concrete would perform with respect to this. Furthermore, it would be worth investigating how the incorporation of fine aggregate at given percentage (10±3%) would affect the engineering properties of the concrete. Additionally, past studies have indicated that three types of aggregate can be obtained from palm oil mill waste in the form of POC namely POC coarse and fine aggregate as well as POC powder. In this study, POCP was utilized as a filler material. Meanwhile, past studies have indicated that it can serve as cement replacement. Also, POC fine has been successfully used as fine aggregate replacement in concrete. Consequently, investigation on the possible use of both POC fine and powder as fine aggregate and cement replacement respectively would be an area of research worth looking into. Such utilization is believed to further promote an eco-friendly pervious concrete. Another interesting area of research to further broaden the application of oil palm waste in pervious concrete worth studying is the utilization of a combination of other oil palm waste by-products as aggregate replacement in pervious concrete. Oil palm waste such as POFA, OKPS, palm oil waste fiber, OPS, OPBC amongst others have proven to enhance the engineering properties of various types of concrete and building components. However, a combination of two or more of these materials in pervious concrete could improve the engineering properties of the concrete in terms of strength and long-term durability. Also, studies on long term durability such as clogging of the concrete should be carried out appropriately.

Lastly, there exists no standardized method for pervious concrete mix design and the conventional approach of varying mixture proportion through trial and error does not give a clear picture of the role played by the individual mixture constituents on the optimum performance of the concrete. Currently, statistical analysis is being used to present and explore interactions between parameters affecting one phenomenon because of its precision. Thus, using statistical tools such as factorial Design of Experiments (DOE) in civil engineering has prominent potential because it would broaden the perspective of designers and engineers about the parameters that affect concrete performance. It would be interesting to see how such statistical tools can be employed to developed and optimize pervious concrete mix design.

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LIST OF PUBLICATIONS

1. **Effect of palm oil clinker incorporation on properties of pervious concrete.** Hussein Adebayo Ibrahim & Hashim Abdul Razak (2016). Construction and Building Materials, 115: 70-77. **(Q1)**
2. **Strength and abrasion resistance of palm oil clinker pervious concrete under different curing method**. Hussein Adebayo Ibrahim, Hashim Abdul Razak & Fuad Abutaha (2017). Construction and Building Materials 147: 576-587· **(Q1)**
3. **Optimizing pervious concrete mixture proportion using response surface methodology**. Hussein Adebayo Ibrahim, Hashim Abdul Razak & Fuad Abutaha. Article in review Construction and Building Materials **(Q1)**