USE OF EXCESS PASTE THEORY AND IMAGE ANALYSIS TO INVESTIGATE PROPERTIES OF PERVIOUS CONCRETE

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ABSTRACT

USE OF EXCESS PASTE THEORY AND IMAGE ANALYSIS TO INVESTIGATE PROPERTIES OF PERVIOUS CONCRETE

Pervious concrete is a type of special concrete that is formed with interconnected pores. It is able to pass the stormwater through its pores in order to control surface runoff and groundwater effectively. Due to the environmental benefits of pervious concrete, the usage of it has been increased day by day. In this thesis, the properties of pervious concrete by using excess paste theory and image analysis method were investigated.

Concrete mixtures were prepared with four different aggregate gradations by combining three aggregate sizes (4-8 mm, 8-12.5mm and 12.5-16 mm), three different volume of paste to the volume of aggregate ratios (0.39, 0.42, and 0.45) and superplasticizer in three different ratios (0.5%, 0.7%, and 0.9%). For the determination of paste thickness in pervious concrete, excess paste theory and image analysis were used. For the determination of surface area of aggregate AutoCAD ReCap and some models were used. For the determination of fresh properties of pervious concrete, slump test, the density test of fresh pervious concrete and rheological measurements of cement paste were done. Permeability, compressive and flexural strength, abrasion resistance, density test, and void content tests were performed on hardened pervious concrete.

To sum up, just as paste thickness results, the ratio volume of paste to the volume of aggregate, aggregate gradations, and the usage ratios of superplasticizer affected the performance of concrete. Results showed that increasing paste to aggregate ratio and superplasticizer dosage caused more workable concrete, more paste thickness, less permeability, less void, and more compressive strength.

ÖZET

GEÇİRİMLİ BETON ÖZELLİKLERİNİN ARTIK HAMUR TEORİSİ VE GÖRÜNTÜ ANALİZİNİ KULLANARAK İNCELENMESİ

Geçirimli beton, normal betondan farklı olarak birbiriyle bağlantılı gözenekler oluşturan özel bir beton türüdür. Yüzeydeki akışı ve yeraltı suyunu etkin bir şekilde kontrol edebilmek için yağmur suyunu gözeneklerden geçirebilir. Geçirimli betonun çevresel faydaları nedeniyle kullanımı artmıştır. Bu tez çalışmasında, atık hamur teorisi ve görüntü analiz yöntemi kullanılarak geçirimli betonun özellikleri incelenmiştir.

Beton karışımları üç farklı agrega grubunun (4-8 mm, 8-12.5 mm ve 12.5-16 mm) değişik oranlarda karıştırılmasıyla elde edilen 4 farklı gradasyonda, üç farklı çimento hamuru hacmi, agrega hacmi oranında (0.39, 0.42 ve 0.45) ve farklı oranlarda kimyasal katkı maddeleri içermektedir. (% 0.5,% 0,7 ve% 0,9) süperakışkanlaştırıcı ile hazırlanmıştır. Geçirimli betonda hamur kalınlığının belirlenmesi için, atık hamur teorisi ve görüntü analizi, ayrıca agrega yüzey alanının belirlenmesinde AutoCAD ReCap ve bazı modeller kullanılmıştır. Geçirimli betonun taze özelliklerinin tespiti için, çökme testi, taze geçirimli betonun yoğunluk testleri ve çimento hamurunun reolojik ölçümleri yapılmıştır. Sertleşmiş geçirimli betonun özelliklerinin tespiti için, geçirimlilik, basınç ve eğilme dayanımı, aşınma direnci, yoğunluk testi ve boşluk muhtevası testleri yapılmıştır.

Sonuç olarak, çimento hamuru hacmi agrega hacmine oranının, agrega dağılımlarının ve süperakışkanlaştırıcı kullanım oranlarının betonun performansını etkilendiği bulunmuştur. Sonuçlar, çimento hamuru hacmi agrega hacmine oranı ve süperakışkanlaştırıcı kullanım oranı artıkça, daha işlenebilir bir beton ile sonuçlandığını, daha fazla çimento hamur kalınlığı, daha az geçirimlilik, daha az boşluk oranı ve daha fazla basınç dayanımı ile sonuçlanmıştır.

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CHAPTER 1

INTRODUCTION

1.1 Object

Using high amount of paste in pervious concrete reduces the permeability while low amounts of paste reduce the concrete strength. In other words, paste thickness in pervious concrete requires to be optimized. This study aims to investigate a new methodology for finding a possible relationship between paste thickness and the mechanical and physical properties of pervious concrete based on excess paste theory and image analysis. Determining the surface area of aggregates and paste thickness around the aggregates is a difficult task. This study also aims to find simpler methods to achieve these goals.

To see the effects of different paste thickness on concrete, different types of aggregate gradations and different ratios of paste volume to aggregate volume were selected to investigate. In addition, different amounts of superplasticizer contents were prepared to understand the effects on workability, paste thickness and rheological behavior of cement paste.

For explaining relationships between paste thickness and properties of pervious concrete, the permeability, abrasion resistance, compressive and flexural strength, rheological properties of cement paste, slump flow, flakiness index, fresh and hardened density, and their void content tests were carried out.

1.2 Scope

In order to reach the objectives stated above, the thesis consisted of mainly four stages:

In the first stage, concrete mixtures were prepared with four different aggregate grading, which were obtained by combing three different aggregate sizes (4-8mm, 8-12.5mm, and 12.5-16mm). Moreover, the ratio of paste volume to aggregate volume was set to three different values as 0.39, 0.42, and 0.45. Water/cement ratio and superplasticizer content were fixed to 0.33 and 0.5% by the weight of cement. In all these mixtures, slump, density abrasion resistance, permeability, void content, compressive and tensile strength were determined.

In the second stage, one mixture from the first stage was selected and superplasticizer content was changed. The usage of superplasticizer content was varied as 0.5%, 0.7%, and 0.9% (by the weight of cement). Also, same tests listed above were carried out on the concrete. The rheological parameters of the pastes containing different superplasticizer content were determined in this stage as well.

Third stage consisted of the determination of the surface area of aggregates and the paste thickness around the aggregates. Some simple methods found in the literature and some image analysis methods were employed to achieve these goals. Tests and analyses were performed on the aggregate and the concrete images of the cut sections of the concrete specimens obtained in the first two stages.

Finally, relations between the paste thickness and concrete properties were investigated.

CHAPTER 2

GENERAL INFORMATION

2.1 Pervious Concrete

Pervious concrete is a special concrete type that contains cement, water, coarse aggregate, and too little or no sand. Due to the lack of sufficient fine aggregates, it has a very porous structure that allows water to drain to the underlying soil (Figure 2.1) and it supplies more air and water permeability by creating continues void when compared to conventional concrete [1]. The porosity of pervious concrete ranges between 15% and 35%, and water flow rate through pervious concrete is change according to aggregate size and density of density of mixture, but it is generally change between 81 to 730 l/min/m^2) [2, 3]. Therefore, due to its high drainage capacity, the pervious pavement has been applied to manage the capacity of urban runoff.

Figure 2.1 Pervious concrete

The drainage capacity or rate depends mainly on aggregate size and amount of ingredients. Therefore, the pervious concrete mix design is very important to obtain a balance between voids, strength, paste content, workability, and permeability. The amount of cement used in pervious concrete generally ranges between 110-330 kg/m^3.

The increase in the amount of cement in pervious concrete can improve the strength while this can reduce the permeability of pervious concrete. It is important to provide sufficient cement paste to bind the aggregates and achieve the required strength while keeping the pores open for good permeability. Generally, the aggregate content in pervious concrete is between 1500- 1800 kg/m^3 and optimum D_{max} is 12.5 mm. The D_{max} value is generally limited to 22 mm. The reason for this limitation is to provide sufficient surface area for aggregate bonding, which can affect the mechanical and physical performance of the pervious concrete. The water-cement ratio is generally chosen at a range of 0.30-0.40 since a high-viscosity paste is needed to coat the aggregate surface, prevent drain-down of paste and ensure the bonding of aggregate surfaces [3]. Some studies concluded that the optimum water-cement ratio could be ranged 0.32 to 0.34 for pervious concrete, but some studies stated that the optimum water-cement ratio depends on many factors such as mixing time, compaction techniques or energy, and using of admixture [4, 5].

The unit weight of the fresh previous concrete is 30% less than conventional concrete and it is generally between 1600-2000 kg/m^3. Therefore, pervious concrete can be classified as lightweight concrete. Concrete working time is ranged from 20 to 60 minutes. In addition, compressive strength of pervious concrete is generally between 2.8 to 28 MPa and flexural strength varies from 1 MPa to 4 MPa [3, 6].

Pervious concrete has many environmental benefits and therefore, the use of pervious concrete has been increasing day-by-day [7]. For example, the main pervious concrete is that it has interconnected voids, which are ranged from 15-30% such that these voids are allowed infiltration of rainwater to underground [3, 7]. In addition, there are two types of pore system for pervious concrete, which are active and inactive pores. Active pores are those, which allow the water to easily move, while inactive pores do not allow water transmission by withholding the trapped water due to surface tension effects and capillary actions [4].

Generally, pervious concrete structures are designed in two ways: hydrological design and structural design. In hydrological design, the pervious concrete is composed of a permeable surface, the subbase layer which under earth surfaces and the impermeable stratum at the bottom of the subbase layer. In some studies, drainage channels can also be constructed between the sub-base layer and the impermeable stratum. The purpose of using this drainage channel or pipes is to manage a higher volume of stormwater and distribute it to another stratum or places [3, 8]. Void amount in pervious concrete affects infiltration rates and compressive strength. For the determination of the proper void amount, proper mix design optimization is needed. Many studies have concluded that the properties and performance of pervious concrete depend on water-cement ratio, aggregate to cementitious materials ratio, aggregate sizes and gradations, binder material type, and compaction techniques [8, 9]. Many researchers studied the effect of different aggregate types by keeping aggregate grading and amount unchanged. It was found that aggregate strength, particle shape, and particle texture affect the strength of concrete since aggregate can have a load transfer mechanism [5, 9, 10]. In addition, it was concluded that this variation might have been caused by differences in aggregate properties, which are the strength, particle shape, and particle texture. Moreover, they made their studies on a single size aggregate gradation, which means that all aggregates have the same size, then variation in gradation of aggregate size increased, the compressive strength of pervious concrete increased, but further increasing the aggregate gradation can lead to a decrease in compressive and flexural strength [5, 9].

Pervious concrete contains water, cement, admixtures, and coarse aggregate. A small amount of fine aggregate, typically 5 to 7 percentages, is used to increase freeze-thaw durability and improve mechanical properties [11]. Mix design of pervious concrete requires establishing the balance between strength and infiltration rate. Although pores can favor the flow rate through the concrete, they can cause low strength. For the proper mixture, design can be needed to proper optimization of the composition of pervious concrete and need to proper materials selection. Use of 5-7% fine aggregate by weight of total aggregate, the strength of pervious concrete increased, but it should be noted that the addition of fine aggregate reduces the permeability of concrete. As in the normal concrete, the interfacial transition zone is the weakest zone, the use of admixtures such as silica fume and superplasticizer can improve the weakest zone by distributing non-uniform thickness on the aggregate surfaces [7]. Similar to conventional concrete, the use of superplasticizer in the mixture reduces water demand and develops workability in pervious concrete. In addition, the use of mineral admixtures and superplasticizer improves compressive strength, on the other hand, the use of silica fume was found to decrease the permeability of pervious concrete due to its fineness [7]. In the literature, the optimum water-cement ratio could be ranged 0.32 to 0.34 for pervious concrete [7], but some researchers that the optimum water to cement ratio depends on many factors which were mixing time, compaction techniques or energy, and using of admixtures [4, 9]. For the pervious concrete, the rheology of pervious concrete was studied and found that permeability of pervious concrete is related to the viscosity of cement paste. When plastic viscosity is increased, the paste flow in pervious concrete decreased [4]. Moreover, the influence of cement paste on the performance of pervious concrete mixtures and understanding of some of factors that influence pervious concrete, different aggregate types, water-cement ratio, and mineral admixtures were used. At the end of the study, when w/c increase, the flow of concrete increase and the addition of superplasticizer and mineral admixtures such as fly ash generally led to an increase in flow at the same water-to-cement ratio [9]. In addition, the unit weight of the fresh pervious concrete was seen to increase with increasing cement-to-aggregate ratio, but porosity was shown to decrease with increasing cement-to-aggregate ratio. Moreover, for paste film thickness, the study concluded that the addition of superplasticizer developed thicker paste thicknesses around the aggregate with increasing cement-to-aggregate ratio. Lastly, the study also showed that the aggregate source significantly influenced the performance of pervious concrete [9, 12].

Another factor that affects pervious concrete properties is curing. Curing time and conditions are important because the evaporation of the mixing water through an open void structure of pervious concrete and incomplete hydration can lead to plastic shrinkage cracking, reduction in compressive strength and a weak structure [12]. Due to its strength insufficiency, pervious concrete was limited to applications such as pavements footpaths, and bicycle trails, low volume traffic roads [5, 9]. Consequently, proper curing of pervious concrete can be achieved by using plastic coverings.

Compaction method is another important factor that affects the performance of pervious concrete. Reduced compaction energy could result in lower unit weight, increased void ratio, increased permeability and reduced compressive strength [10]. Therefore some studied investigated that three different laboratory compaction techniques were compared to each other (using standard proctor hammer, dropping of the mold at a 5 cm height on the surface and tamping with 16-mm diameter rod [8]. It was concluded that for rodding technique, the pores were not filled with concrete due to the high stiffness of pervious concrete mixtures, therefore there is no accumulation of cement paste at the bottom of the mold [8]. On the other hand, the use of standard proctor hammer and dropping of the mold showed similar performance on the pervious concrete poured in the field. The using proctor hammer can cause breakage of aggregates and the proper compaction is made by using vibration techniques. Briefly, there is no standard compaction technique for all given mixtures. The proper compaction technique can depend on the mixture proportions [5].

The performance of pervious concrete is affected by clogging, as well. Clogging can be an important problem of pervious concrete at the design stage and/or in time during its service life. At the design or casting stage, clogging can occur by an accumulation of cement paste at the bottom of the concrete layer due to over-compaction and/or high fluidity of the paste. For this type of clogging, a thin laitance layer at the bottom of the pervious concrete can be observed, and strength of the concrete can decrease. Another clogging problem that occurs during the service life of concrete is due to the gradually accumulated of sediments or wastes. In both cases, the ability of pervious concrete to infiltrate water is reduced. Moreover, clogging is a very important problem, which can be controlled at the design stage of the concrete by proper proportioning and compaction of the concrete or it can be prevented during the service life by cleaning the voids via using dry vacuuming or pressure washing, which can restore up to 90% of the infiltration capacity of a pervious concrete pavement [1, 13, 14].

2.2 History

Pervious concrete is named also as “permeable” or “porous concrete”. According to ACI 522-10 report, the first user of pervious concrete is the building of two houses in the United Kingdom in 1852 and these structures only consisted of coarse aggregate and cement. After a while, pervious concrete was used in Scotland as residential construction. The end of 1942, over 900 houses had been constructed with pervious concrete. Later years, the use of pervious concrete had been increased in Germany, Holland, France, Belgium, Spain, Venezuela, and Australia. In Australia, the first use is known to be in 1946 [3].

After World War 2, the pervious concrete became used more popular [3]. It had been used in Florida and other southeastern countries, which have been constructed from the 1970s to control runoff, erosion, and flooding. There are a number of examples using permeable pavement in Florida because it has heavy storms and they need to reduce large amounts of stormwater, so Florida has been a leader in the construction of pavements using pervious concrete [3].

There are hundreds of projects that have been completed statewide, with many pavements in service for more than 10 years. In California, pervious concrete is primarily being used to pave parking lots. It is also becoming a practical alternative for subdivision streets, sidewalks, and golf cart paths. Another example of using pervious pavement is in the Pacific Northwest, most of the annual precipitation comes from rainfall events of less than an inch. Because of this situation, a stormwater management system using pervious concrete can be very effective at reducing total runoff and increasing the amount of filtered groundwater [3, 9].

2.2.1 Advantages and Disadvantages of Pervious Concrete

Use of pervious pavement provides many advantages especially from environmental point of view. For instance, pervious concrete helps to restore groundwater, reduce pollution of loam, prevent erosion, control local storm sewer systems and control the life cycle of a biological asset in the aquatic ecosystem and terrestrial ecosystem (Figure 2.2, and Figure 2.3). Use of pervious concrete enables filtering of stormwater into the soil as a groundwater source, so the flow of water on the surface can be managed and it can maintain aquifer levels in the soil. It integrates paving and drainage, providing a great solution for stormwater management; therefore, it reduces the amount of land needed to manage stormwater runoff and it decreases the budget needed for collection and detection systems for untreated stormwater runoff and sewer system [15]. In addition, due to its porous structure, it can absorb the noise of vehicles and reduces noise pollution in the environment [15]. Moreover, owing to the increasing impervious surface in the world, it can be difficult to replace heat and moisture with the air. This fluctuation in the air system can cause a problem to adjust the temperature and humidity of the earth's surface and because of this problem, the greenhouse system is formed [15]. In addition, pervious concrete pavements can be reducing the urban heat-island effect. Because of its light color and open-graded structure, it does not absorb or store heat and dissipate back into the environment like a typical asphalt pavement. In brief, it provides energy saving. In addition, the pollution of streams or rivers due to gases waste, oil, mud sedimentation wastes, and rubber particles due to the cars is reduced, and it prevents the contamination of watersheds and ecosystem and eliminates hydrocarbon pollution from asphalt pavements and sealer [14].

Figure 2.2 Pervious concrete (Source: [6])

On the other hand, there are also some disadvantages of pervious concrete. One of them is the maintenance of pervious concrete due to the clogging problem. Its repairing should be made regularly by vacuum, sweeping and pressure washing system, but the effectiveness and performance of these repairing systems are controversial. In addition, its rough-textured and honeycombed surface can be a problem for high traffic intensity roadways and it can result with the wheel wear of the vehicles, which may cause to debone aggregate in the concrete surface. Moreover, the strength of pervious concrete is not very high when compared to other types of roadways; therefore, it is not proper to use it for high-traffic pavements such as highways. Lastly, there is not enough standard specification to construct pervious concrete [2].

Figure 2.3 Manage to stormwater (Source: [6])

Despite these disadvantages, there are many application areas of pervious concrete which are listed below [2, 6, 15]:

1. Walkways (Figure 2.4) and pedestrian footpaths
2. In parking lots and parks pathways (Figure 2.5)
3. At driveways; low-traffic areas (Figure 2.6)
4. In pool decks (Figure 2.7)
5. In Patios
6. At entertainment centers, tennis courts, and zoo
7. Hydraulic structures
8. Greenhouses
9. In the drainage areas at margin of sidewalks
10. Structural wall application for lightweight thermal insulations
11. For slope stabilization (Figure 2.8)
12. Artificial reefs
13. Bridge embankments
14. Foundations
15. Sewage treatment plant sludge beds
16. Spur and seawalls
17. In bevel areas to reduce hydrostatic pressure
18. In noise barriers to absorb the voice due to voids
19. At landscape design and other decorative usage areas
20. In the drying of the clothes industry or other materials that can need a drying process in the industry

Figure 2.4 Walkways (Source: [6])

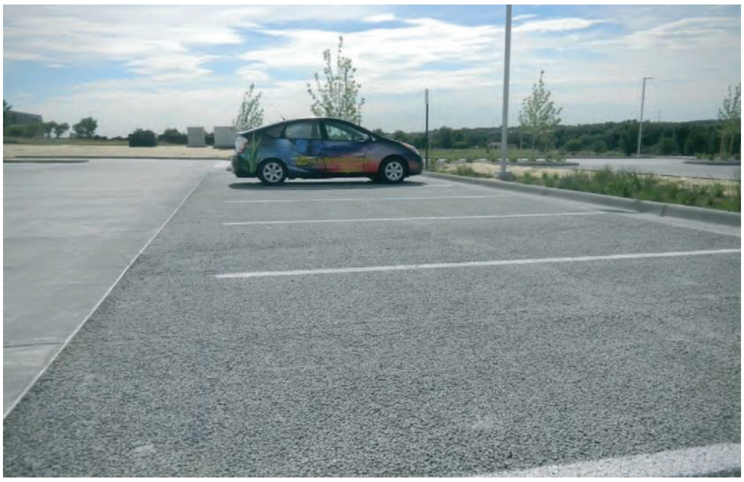

Figure 2.5 Parking areas (Source: [6])

Figure 2.6 Driveways (Source: [6])

Figure 2.7 Swimming pool decks (Source: [6])

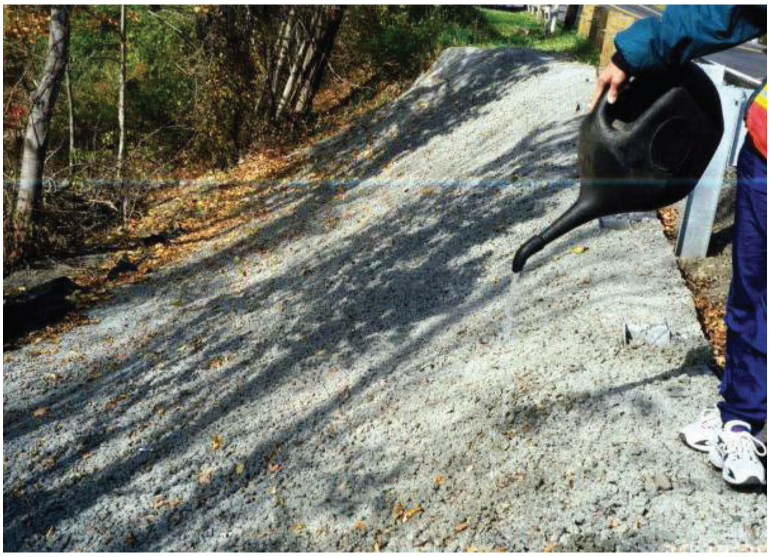

Figure 2.8 For slope stabilization (Source: [16])

2.3 Materials

Pervious concrete fundamentally consists of cementitious materials, aggregate, and water. The properties and proportions of ingredients in pervious concrete affect performance of pervious concrete.

2.3.1 Cementitious Materials

Generally, Portland cement is preferred in pervious concrete. Fly ash, ground granulated blast furnace slag, and silica fume can be used. For the mix design of pervious concrete, the amount of cementitious materials is more important than the type of binder. A high amount of binder can cause clogging, reduce voids and decrease the permeability.

2.3.2 Aggregate

Aggregates occupy approximately 70% of concrete volume in conventional concrete; therefore, the role of aggregate in concrete is very important. Aggregates strongly influence concrete's fresh and hardened properties, mixture proportions, and the economy. The functions of aggregate in the concrete is to provide a mass of particles which are suitable to resist the action of applied loads and show better durability then cement paste alone and it provides a relatively cheap filler for the cementing material Also, it reduces volume changes resulting from setting and hardening process and from moisture changes during drying. That is why aggregate properties are important. Aggregate properties, such as grading, durability, particle shape, surface texture, abrasion resistance, unit weight, and absorption capacity, amount of contamination, surface moisture and surface area are among the factors that can affect concrete performance in terms of workability, bleeding, segregation, strength, permeability, and durability. For example, using flaky and elongated particles in concrete can reduce strength and durability of concrete and produce stiff mixtures as against using rounded aggregates. To define aggregate shape, there are many indexes, which are sphericity, shape factor, aspect ratio, elongation ratio, flatness ratio, and flakiness index. These expressions give information about the 3D shape of aggregates by measuring the longest (L), intermediate (I), and shortest (S) distance [17, 18].

Sphericity can be calculated from Equation 2.1.

$$\sqrt[3]{\frac{\mathbf{I} * \mathbf{S}}{\mathbf{L}^2}} \tag{2.1}$$

Shape factor can be calculated from Equation 2.2.

$$\frac{\mathbf{S}}{\sqrt[2]{\mathbf{I} * \mathbf{L}}} \tag{2.2}$$

Aspect ratio (L/I) is a ratio of the longest dimension to the intermediate dimension of aggregate [18].

Elongation ratio (I/L) is a ratio of the intermediate dimension to the longest dimension of aggregate [18].

Flatness ratio (S/I) is a ratio of the shortest dimension to the intermediate dimension of aggregate [18].

Flakiness index is an index to express flaky particles in terms of percentage of mass in the tested sample (More detailed information on flakiness index will be given in section 3.3.1.2.).

Just like normal concrete, the role and performance of aggregate are so important. Because they affect compressive strength, flexural strength, and permeability of pervious concrete, those are the most important properties for pervious concrete. For the pervious concrete, maximum aggregate size, elongation, and flatness of aggregate and surface area of aggregate can determine the performance of pervious concrete. According to the ACI report, the maximum aggregate size is limited by 22 mm and according to the literature, the selection of aggregate gradation is generally preferred a single sized grading or grading between 9.5 and 19 mm. the aggregate used should meet requirements of ASTM C 33 [3, 6, 19].

The Surface Area of Aggregate:

Surface area of aggregates is an important parameter for the performance of pervious concrete. Therefore there are lots of methods to determine the surface area of coarse aggregate [17]:

1. Laser-based technique
    a. Laser scanning
    b. Circular track meter
2. Visualization technique
    a. X-ray tomography
    b. Image processing
    c. Photogrammetry
3. Volumetric technique
    a. Sand patch
    b. Outflow meter
4. Fractional dimensional method
5. Packing density method
6. Particle size distribution: Sieve analysis
7. Nitrogen adsorption or measurement of heat of immersion

Laser-based and visualization technique is rapid, repeatable, and accurate, however, it is complex, and can be expensive. Volumetric technique is inexpensive, simple, and portable but on the other hand, it is slow and the repeatability is low. As in normal concrete, 70% of the volume of pervious concrete is composed of aggregate and it consists of coarse aggregate surrounded by a thin layer of cement paste. The ingredients of materials in pervious concrete such as cement affect the aggregate coating thickness, which has an effect on porosity and mechanical properties of the concrete. Therefore, to find the thickness of the paste, the surface area of the aggregate should be known. To determine the surface area of the aggregate, the simplest method is the sieve analysis test. For the determination of aggregate properties, several standards are identified as follows:

ASTM C 33 is a standard for concrete aggregates, but it is not enough to identify all properties of aggregates [19].

ASTM D 5821 is a standard for identifying particle shape of coarse aggregate, but this standard is based on visual observations by calculating fractured faces which means angular, rough, or broken surface of an aggregate particle created by crushing [20].

ASTM D 3398 is a method that covers the determination of the particle index of aggregate as an overall measure of particle shape and texture characteristics and it provides an index value to the relative particle shape and texture characteristics of aggregates and those characteristics that may affect the performance of road and paving mixtures [21].

ASTM D 4791 covers the determination of the percentages of flat particles, elongated particles, or flat and elongated particles in coarse aggregates. Elongated particles of aggregates have a ratio of length to width greater than a specified value. Flat and elongated particles have a ratio of length to thickness greater than a specified value. Flat particles have a ratio of width to thickness greater than a specified value [22]. The other methods are ASTM C 136 [23] which is an sieve analysis of aggregate and TS EN 933-3 [24] which introduces flakiness index as will be described Chapter 3.

There is direct relationship between the surface area of aggregate to paste thickness and flow characteristics of concrete [17]. For a given concrete mixture with known cement paste volume, the thickness of the excess paste coating the aggregate particles can be found after the determining or calculating the surface area of aggregate. Some of the researchers assumed that aggregate has a spherical or cubic shape for designing concrete mixture [25]. Due to its irregular shape, the calculation of aggregate surface area is difficult, therefore many researchers investigated how to calculate or determinate the surface area of aggregate and other shape properties [25]. Some researchers used Martin’s and Ferret’s diameter to calculate the surface area of coarse aggregate. Ferret’s diameter is a distance between two opposite sides of the particle onto projection. The distance was measured parallel to the fixed direction and Martin’s diameter bisects the image area on to projection where the direction should be the same for all particles. These diameter methods are based on the projected area of an irregular shape of particles. At the end of the study, Martin’s and Ferret’s diameter technique was compared to sieve analysis and then concluded that these diameters lead to an approximate measure of surface area and give the most realistic circularity. Moreover, when compared to nitrogen adsorption and heat of immersion technique, it is an easy method to determine the surface area of aggregates [25].

The physical and chemical properties of aggregate such as surface texture, angularity, dirtiness, and strength affect the performance of concrete. Due to its irregular shapes and rough surface textures, determination of the surface area of aggregate is difficult [11].

With the development of technology, the use of image analysis techniques or programs in 2D or 3D has been increased to characterize aggregate properties [26] and researchers studied the parameters of coarse aggregate (angularity, surface area, texture, etc.) which affect the particle packing of aggregate [26]. The study in [26] involved model simulation of aggregate by using BLOKS3D which is a program in discrete element method (DEM) that is capable of three dimensional modeling and determining particle angularity classes (low, medium high). The results indicated that DEM simulations showed a good model to study and optimize aggregate gradations. Also in this study, the analysis was used to identify the flatness and elongation ratio, angularity index, and surface texture index. Another image analysis method, which is an aggregate imaging system (AIMS), was used in to determine properties of fine and coarse aggregate, and the results were discussed for hot mix asphalt performance. It concluded that using of AIMS to analysis aggregate texture, angularity surface area in three-dimensional forms was made in a short time and the operator error was minimum [27, 28]. AIMS consist of one camera and two different types of lighting schemes to take photos of aggregate from different viewpoints. AIMS make analysis of aggregate shape and angularity on black and white images, but for texture, it uses grey images. In addition to study, aggregate characteristics were evaluated in 3D form by using 3D image analysis and the results were grouped by using artificial neural network models

[27, 28]. The study was concluded that using digital technology to determine aggregate properties gave accurate and faster results. Using x-ray computed tomography equipment estimated aggregate properties such as surface area, angularity, roundness, texture, etc. [27-29]. The study resulted that when compare to result of x-ray computed tomography give nearly same results to ASTM D 4791 [22] which is a standard to determination elongated and flatness or neither elongated nor flatness of coarse aggregates. Also, it concluded that using of x-ray computed tomography gave accurate results, and it was easy method to determination of aggregate properties [29]. In addition to use, the digital system is set a scanning camera system to take aggregate images for determining aggregate features such as angularity, perimeter, fractured face number, flakiness, and elongation. For using 2D images studied aggregate morphologic characteristics and compare the gradation curve results which was obtained by sieve analysis results to image analysis results [30]. Moreover, in this research, authors developed an empirical model using simple physical properties of hot mix asphalt (HMA) to estimate surface area of aggregate blend in HMA and by using 3D laser imaging system modified surface area was installed, then the calculated surface area of aggregates in samples was compared to other established methods which were used to calculate surface area of HMA [31]. Also, it investigated the determination of HMA properties. For this, the relationship between the fractal dimension, which is related to surface areas of coarse aggregates, and mechanical properties of asphalt (flow, marshal stability,) concrete was established [17]. In addition, the shape properties of natural and crushed aggregates by using image analysis were investigated after did that, the result of image analysis and fractional dimensions was compared. At the end of this study, it concluded that the surface area of crushed aggregate was more than natural aggregate.

2.3.3 Water

For pervious concrete, the amount of water is very important and pervious concrete should be proportioned with a low water-cement ratio, which is generally ranged from 0.30 to 0.40. Using excess amount of water will cause drainage of the paste and lead to clogging of the pore system. This can also cause less compressive strength due to less amount of paste on the aggregate surface (weak transition zone). In addition, the moisture condition of the aggregate used in pervious concrete is very important and sensitive, because it can affect water to binder ratio.

2.3.4 Admixtures

Pervious concrete frequently contains admixtures such as superplasticizer, viscosity-modifying admixtures (VMA) and rheology-modifying admixture (RMA). Superplasticizer is used to improve fresh and hardened properties of pervious concrete just like normal concrete. For example, using of water-reducing admixtures (based on naphthalene sulphonate and polycarboxylate) increase the workability at low w/c ratio and it is used to extend workability by decreasing the rate of cement hydration and reduce excessive heat of hydration during earlier ages. Retarding admixtures overcome the stiff mixture, which has a low water to cementitious ratio. VMA can supply a cohesive paste mixture to prevent to drain of the paste into down and air entraining admixtures (AEA) is generally used to protect to freeze/thaw degradation in cold climates [10, 11, 32]. Also, color or pigment additives can be used in liquid form or powdered form. Some companies suggest using integral colorants.

2.4 Construction

The construction of the pervious concrete is not difficult, but it is different from conventional concrete. Due to the stiff structure and too short setting time, it needs special transportation and placement. The pavement structure includes a pervious concrete (PC) layer at the top that contains a high amount of air voids of the total volume [33]. The high air void content allows free drainage of water through the layer. Generally, the PC layer thickness is chosen 15 and 30 cm in Figure 2.9 which are changed by application areas [3].

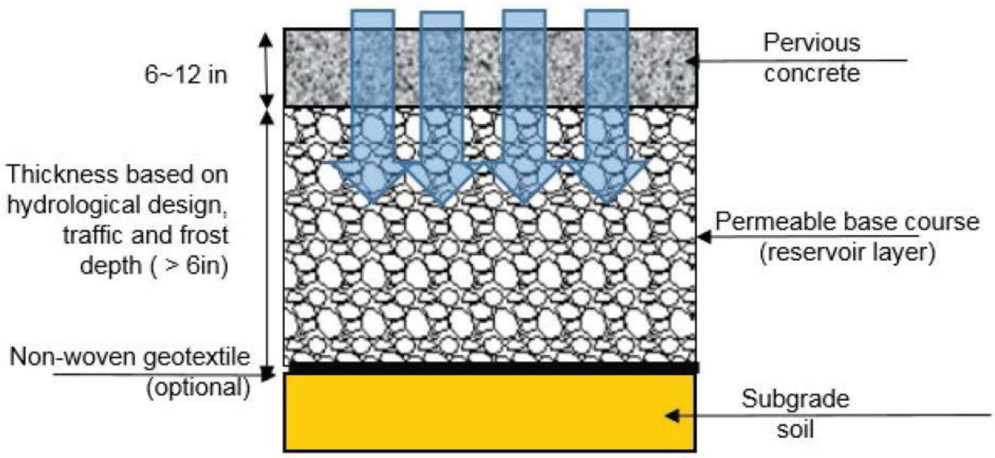

Figure 2.9 Typical cross section of a pervious concrete pavement (Source: [36])

According to Washington Aggregate and Concrete Association (WACA), PC layer thickness ranges 10-13 cm, for sidewalks/pathways, 13-15 cm ,for residential driveways parking lots, and 20-25 cm for areas with heavier truck traffic [34]. On the other hand, According to Ready Mixed Concrete Association of Turkey [6], for the heavier traffic concentration, the pervious concrete pavement cannot be suggested for traffic safety and comfort because of the low compressive, tensile strength, and its rough surface of PC. But for sidewalks and bicycle road PC layer thickness can be suggested 12.5–15 cm and sublayer thickness is 0-15 cm, for the low traffic volume and parking lots, PC layer thickness can be 15-20 cm and the sublayer thickness can be 15-30 cm and lastly, for the not low and not too high traffic volume, PC layer thickness can be suggested at 20 to 25 cm and the sublayer thickness can range between 20-40 cm. Generally, the pervious concrete surface is placed at the top of the pervious pavement system. The pervious concrete surface is constructed on the subbase layer. If it needs, the drainage system can be constructed under the base layer to discharge water [6] (Figure 2.10 and Figure 2.11).

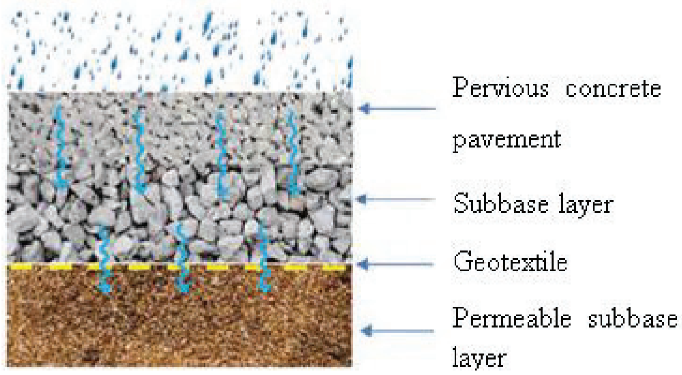

Figure 2.10 Pervious pavement structure (Source: [6])

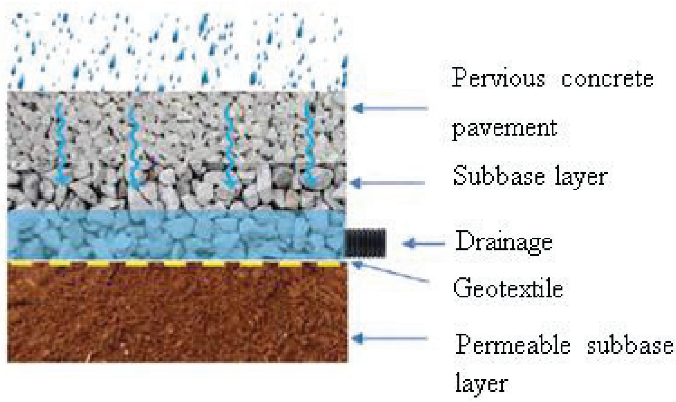

Figure 2.11 Pervious pavement structure with a drainage system (Source: [6])

The thickness of the pervious concrete and subbase layer that is the place of the constructed to it depends on the traffic volume and loads, local environmental parameters such as precipitation, evaporation, soil infiltration rates. For example, for permeable ground, the sublayer thickness is 15 cm, but for impermeable soil, this thickness 30 cm [6].

2.5 Placement of Concrete

As in normal concrete, the construction of pervious concrete consists of the same steps (placement, compaction, jointing, finishing, and curing). For placement, generally, the truck mixer is used (Figure 2.12), but the important point is that pervious concrete placement should be done quickly due to low water content and having less workable structure. The time necessary for workable pervious concrete is 20 minutes (without any addition of retarder admixture) [6, 35].

Figure 2.12 Placement of pervious concrete (Source: [6])

After the placement of pervious concrete, compaction which is the main parameter that affects the performance of pervious concrete is made [5]. Insufficient compaction causes low-strength and surface raveling, on the other hand over-compaction can cause reduction of void content and paste drain down [10]. Pervious concrete pavements are generally compacted by roller, motorized roller template, and vibration (at very low frequency) in situ (Figure 2.13 and Figure 2.14) and in the laboratory; rodding and vibration (at very low frequency) are generally used.

Figure 2.13 Compaction of pervious pavement (Source: [6])

Figure 2.14 Compaction of pervious pavement (Source: [6])

In normal concrete, when the concrete road is poured, the control joints are added to prevent cracking, however, for the previous concrete, there is no need to add joints because the voids in pervious concrete prevent to enlarging of cracking. In addition, the shrinkage of the pervious concrete is less than conventional concrete, but according to the Ready Mixed Concrete Association of Turkey [6], joint cutting still should be done. The recommended joint cutting range is recommended six meters. Joints should not be in the form of a false joint, and it should cover 1/3 or 1/4 of the coating thickness.

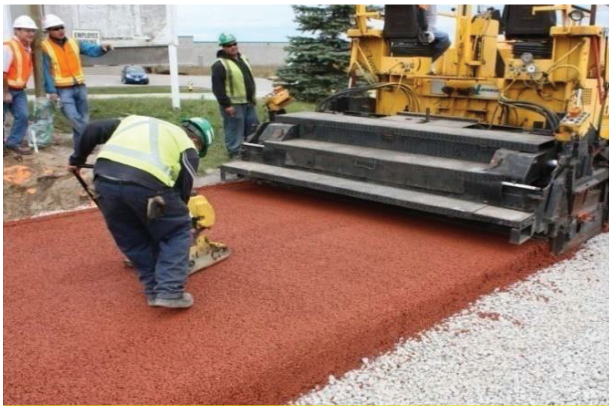

Figure 2.15 Compaction of reddish pervious pavement (Source: [35])

In addition, the finishing step of pervious concrete is involved as a part of the consolidation process. The finishing process is not the same as normal concrete. For example, Advanced Concrete Pavement Technology (ACPT) stated that “normal concrete finishing procedures, such as with bull floats and trowels should not be performed for pervious concrete.” but according to the Ready Mixed Concrete Association of Turkey [6], the surface of pervious concrete can be leveled by trowel (Figure 2.15).

After the finishing operation, the curing of pervious concrete should be done properly, because it influences the mechanical features of pervious concrete as a normal concrete. If these steps are not done properly, it can cause some problems just like normal concrete such as less strength or less durable pervious concrete. Generally, the plastic sheet is used [11]. It was found that liquid membrane curing compounds are not used for protection of pervious concrete because it cannot hold surface moisture and prevent evaporation of the pervious concrete mixture water [35]. In addition, after immediately pouring concrete, acrylic, or non-paraffin based special curing materials (soybean oil emulsions, etc.) can be preferred for curing operations of pervious concrete [9, 11].

For the production of pervious concrete as a pavement, The American Concrete Institute has prepared a report which includes some guideline sand limitations on how to construct and testing it [3]. Some of these standards are ASTM C 1688 (standard test method for density and void content of freshly mixed pervious concrete), ASTM C1701 (standard test method for infiltration rate of in place pervious concrete), ASTM C1747, (standard test method for determining potential resistance to degradation of pervious concrete by impact and abrasion), ASTM C 1781 (standard test method for surface infiltration rate of pervious unit pavement system) and ASTM C1754, (standard test method for density and void content of hardened pervious concrete) [36-40].

2.6 Maintenance

Over time, sand, dirt, vegetation, vehicle's wastes, and other debris can accumulate into voids of pervious concrete and it reduces the porosity of pervious concrete. Therefore, the regular or periodical maintenance can be necessary to prevent clogging of pervious concrete. For the clogging, the vacuum (Figure 2.16) or pressure washing (Figure 2.17) can be used for the cleaning of voids system.

Figure 2.16 Cleaning of pervious concrete by vacuuming (Source: [6])

Figure 2.17 Cleaning of pervious concrete by vacuuming (Source: [6])

2.7 Excess Paste and Paste Thickness

By using the volume of cement paste, the paste thickness and excess paste can be calculated. When the volume proportion of cement paste increases, it apparently shows that it improves the mechanical properties of pervious concretes, in terms of compressive strength, abrasion and freeze-thaw resistance.

The excess paste in a concrete mixture is defined as the paste in excess of the amount required filling the void volume in the granular phase. It can enhance the workability of the concrete. The volume of the excess paste is generally used for estimating the flow properties of concrete.

For pervious concrete, paste thickness can be calculated by the ratio of paste volume to the surface area of aggregates. Some researchers calculated the surface area of aggregate by different techniques like assuming spherical aggregate shape or computed tomography. Therefore, for evaluating the thickness of pervious concrete, there are two analysis techniques: using software programs or calculating manually by hand measurements. For both cases, there are advantages and disadvantages which are that using of software-based analysis may not be able to recognize some features, for example, to distinguish between void spaces and paste software analyze techniques requires scanning of each sample with a high-resolution scanner for seeing all features are visible. In addition, the image needs to be processed and imported into a software package capable of sophisticated measurements. Lastly, the software may not understand where to make the measurements from, in regards to each edge of the aggregate or edge of the paste, but project coordinator could possibly overcome most of these problems. On the other hand, by doing using this technique will take lots of time and for the uniformity of results. For example, a study in [41] for calculating paste thickness, they used a manual hand technique, which was started with using the AutoCAD software program, and then a two-dimensional linear grid system was built in AutoCAD software program. This grid system consisted of horizontal and vertical lines and the amount of these lines, and space of size between two parallel horizontal or vertical lines in this grid system is adjusted according to the size of the aggregate. Then grids were printed on a transparent plastic film, which used for overhead projector slides. The grids were placed on top of each cross-section of pervious concrete. After doing that, paste thickness was measured with a digital caliper. The measurements were taken a distance between two horizontal lines and two vertical lines. To do that, the operator began with the first horizontal line at the top of the sample and working from left to right measuring across each horizontal line. Consequently, the paste thickness was defined as a distance the length (along the grid line) of the paste until a void or piece of aggregate was encountered, at which point the process was repeated each time a cementitious paste edge was observed. To identify paste thickness a single value, an average of all measurements was taken to paste thickness [41].

The mix design and production of pervious concrete are more complex and it involves several factors affecting material performance. As in normal concrete, the 70% the volume of pervious concrete is composed of aggregate and it consists of coarse aggregate surrounded by a thin layer of cement paste., therefore, the ingredients of materials in pervious concrete such as cement affects the aggregate coating thickness, which has an effect on porosity and other mechanical properties of the concrete. Therefore, many researchers investigated this topic. Anthony Torres at all, though that there is a correlation between the cementitious paste thicknesses to the performance of pervious concrete with using two different aggregate size (9.54-6.35mm), three paste content (low, medium, high) and different compaction energy levels, therefore the paste thickness was analyzed by cross-sectional analysis of the hardened concrete and hand measurements. The study was constructed on a correlation between the porosity versus the cement paste thickness and the study resulted with a thicker cement coating will lead to a lower percolation rate by reducing the porosity, on the other hand, this could have an effect on other desirable mechanical properties, such as strength, absorption, freeze/thaw capabilities, durability, etc. Therefore, adjusting the number of ingredients and compaction energy can inherently affect the paste thickness around the aggregate. Thicker paste thickness was occurred around the coarse aggregate due to its low surface area. To sum up there is a linear relationship between paste thicknesses to paste volume, compressive strength, and flexural strength. On the other hand, there is an inverse relationship between paste thickness to pore sizes, and permeability [9]. Other researchers that are found an empirical relationship for determination paste volume and required slump value [42]. It is related to paste volume, paste composition and content and all of these parameters significantly affect fresh concrete properties [42]. On the other hand, were coming up with a threshold value to achieve minimum workability of the mixture to using water reducing admixture [43]. This value is equal to 1.5 times more paste by volume required to fill voids between solid particles. Another approach to solving the problem is based on water film thickness and paste film thickness of coating aggregate particles and there are similar ideas between excess paste theory and thickness approach. Also for determination of paste thickness were set a relationship between o characteristics of SCC which are slump flow and strength of SCC to water film thickness and paste film thickness [44]. The another researchers studied that the combined effects of WFT (water film thickness), PFT (paste film thickness) which was defined to excess paste to solid surface area ratio and MFT (mortar film thickness) was investigated on the effects of fresh properties of concrete by different combinations of paste volume, water/cement ratio and fine/total aggregate ratio [45]. Their study has resulted with a higher packing density of aggregate particles would reduce the volume of voids to be filled with paste and higher packing density of aggregate need more excess paste for a given paste volume and w/c. also the study was showed excess paste and excess water would increase the workability of concrete. Because it provides a lubricating effect on aggregate particles to easily move for a given paste volume and w/c and the writers were concluded that surface area of aggregate affects the thickness of paste on the aggregate, for fine aggregate which has large surface area could need to thin paste thickness or for coarse aggregate. It has a smaller surface area than fine aggregate could have thick paste thickness [41].

2.8 Rheology of Cement Paste

After the mix design of concrete, (transporting, placing, consolidating, finishing, spreading pouring, etc.) are important factors to affect the mechanical and physical properties of concrete. All of these factors depend on the rheology of materials.

Rheology is the study of flow and deformation rate of fluids under acting forces. The measurement of rheological properties is applied to the fluid structure. It is related to stress, time, strain, and rate of strain. The study of the rheology of concrete gives us some information about the properties of fresh concrete such as deformation, the behavior of the mixture, and the placement of mixed concrete. Rheological parameters are yield stress and plastic viscosity, which are measured with a rheometer.

The action of shear stresses is related to yield stress, which is needed to initiate flow. It calculated by intersection point on the stress axis on the torque–rotational speed graph and another parameter is plastic viscosity, which is the slope of the graph. There are several models about the explanation of fresh concrete behavior by using rheometer. The most used one is the Bingham model (Figure 2.18). Bingham fluid model is as follows Equation 2.3.

$$\tau = \tau_0 + \eta \frac{d\gamma}{dt} \quad (2.3)$$

Where τ is shear stress, dγ/dt is shear rate; η is plastic viscosity and τo is yield stress.

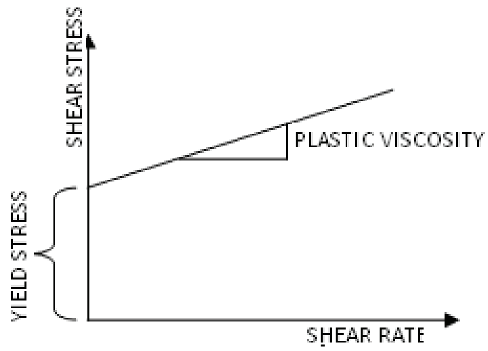

Figure 2.18 Bingham's equation for a fluid (Source: [46])

The yield stress is shear stress required to initiate flow and the plastic viscosity is resistance to flow once the concrete is flowing. The yield stress correlates with the slump value, but the plastic viscosity is not measured by using of slump test. Because plastic viscosity occurs after the yield stress overcomes. The existence of the plastic viscosity helps explain why concretes with the same slump may behave differently during placement [46].

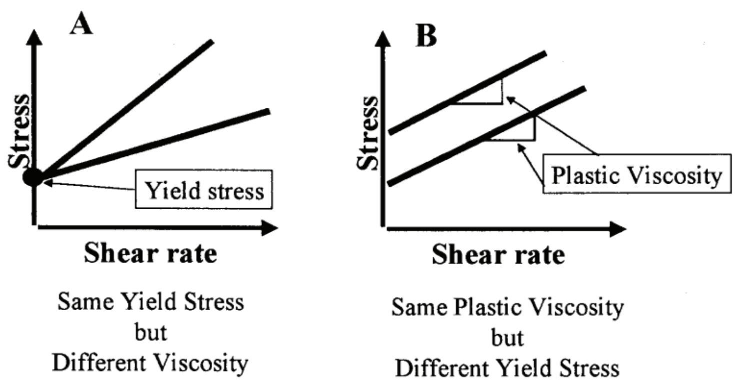

Figure 2.19 Concrete rheology (Source: [46])

Some liquid materials can show different behavior like shear thinning and shear thickening (Figure 2.20).

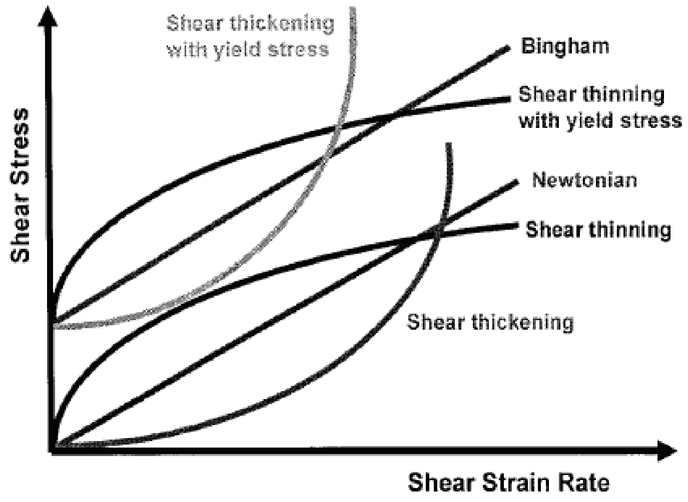

Figure 2.20 Common used flow curves (Source: [48])

For a shear thickening material, viscosity increases with increasing shear rate, on the other hand, a shear thinning material viscosity decreases with increasing shear rate. The flow curves can be described with various theories and the Bingham model is one of them. For example, Modified Bingham (MB) and Herschel-Bulkley (HB) model are some of the other theories to describe flow properties. Such models are summarized in Table 2.1.

Table 2.1 Rheological models for concrete

Model	**Equation**
Newtonian	$\tau = \eta\dot{\gamma}$
Power Equation	$\tau = A\dot{\gamma}^n$
Bingham	$\tau = \tau_0 + \eta\dot{\gamma}$
Herschel-Bulkley	$\tau = \tau_0 + K\dot{\gamma}^n$
Modified Bingham	$\tau = \tau_0 + \eta\dot{\gamma}^{n_1} + A\dot{\gamma}^{n_2}$

Where τ is shear stress, $\dot{\gamma}$ is shear rate, τ_0 is yield stress; η is viscosity and n_1, n_2, A, K are constants. The Power equation can be used to describe shear thinning (n<l) or shear thickening (n>l) behavior, but Herschel-Bulkley equation can be used to explain shear thinning or shear thickening with using yield stress. Modified Bingham model is a combination of Power equation and Herschel-Bulkley equation.

In a rheometer test process, an increase of shear rate (up curve) is followed by a decreasing shear rate (down curve) as shown in Figure 2.21. The ascending curve does not approximate the Bingham model. It has been recognized by researchers that a certain amount of time is necessary for cementitious materials to reach the equilibrium state. The downward flow curves generally follow the Bingham model well, which is because the time to attain equilibrium at a given shear rate is shorter when going from a higher to a lower shear rate [47]. Hence, the down part of the flow curve is generally used to calculate the parameters of flow and torque resistance.

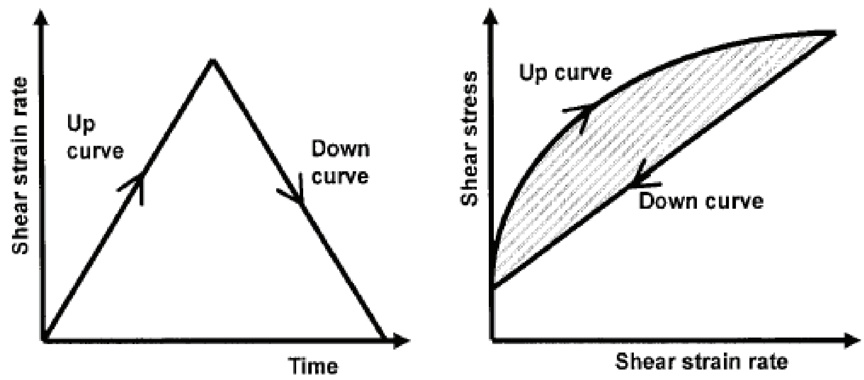

Figure 2.21 Thixotrophy behavior and hysteresis loop (Source: [48])

There are some factors that affect the rheological properties of concrete or cement paste such as the amount of water, properties and amount of cement, properties, and proportion of fine and coarse aggregates, type an amount of mineral and superplasticizer, the temperature of the cement paste, mixing time, method, and time (when water and cement made a reaction). When water content increases, yield stress and viscosity of fresh concrete will decrease, but it can cause segregation and bleeding.

The study in [47] studied the effect of water-reducing admixture content for proper mechanical and hydraulic behavior of pervious concrete. To do that, the aggregate and cement content was fixed ratio. In addition, by using an optical microscope, the thickness of paste coating on the surface of the aggregate in pervious concrete was examined. The research resulted in the effects of paste rheological properties on compressive strength, flexural strength, porosity, and permeability were analyzed. Consequently, the results showed that at the first stage, the mechanical properties of pervious concrete increase with increasing plastic viscosity, but then it showed decreasing behavior. To sum up, the rheological properties of pervious concrete can play a role to adjust a balance between strength and permeability of pervious concrete.

Another research in [48] was done to investigate the effect of mineral additives on the performance of the concrete. The effect of fly ash and blast furnace slag content (10%, 20%, and 30%) on the mechanical and hydraulic behavior of pervious concrete was studied [48]. The research showed that using of fly ash increased apparent viscosity, but it decreased porosity, compressive strength (for 28D, but for 60D it increased) and permeability. On the other hand, using slag did not cause any significant change for apparent viscosity, but it showed the same results when using of fly ash in pervious concrete for compressive strength, permeability, and porosity. The study in [47] investigated the rheological behavior of highly flowable mortar and they found that increasing water-cement ratio would reduce yield stress and apparent viscosity and the rheological properties of mortar or paste is dependent on the type and amount of supplementary cementitious materials at same w/c ratio [49]. They also correlated yield strength and apparent viscosity with excess water to the solid surface ratio.

CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 Materials

In this study, the materials of pervious concrete consisted of cement, water, aggregate, superplasticizer and color at different proportions.

3.1.1 Cement

Portland cement (CEM-I 42.5 R), confirming to EN197-1 [50], was used in this study. Properties of the portland cement are summarized in Table 3.1 and Figure 3.1.

Table 3.1 Properties of portland cement

	Portland cement
CaO (%)	73.84%
SiO_2 (%)	2.02%
Al_2O_3 (%)	7.32%
Fe_2O_3 (%)	2.66%
MgO (%)	2.66%
K_2O (%)	0.48%
Na_2O (%)	9.02%
SO_3 (%)	1.56%
P_2O_5 (%)	0.10%
MnO (%)	0.03%
CuO (%)	0.16%
Specific gravity	3.1
Initial Setting time (min)	153
Final Setting time (min)	266

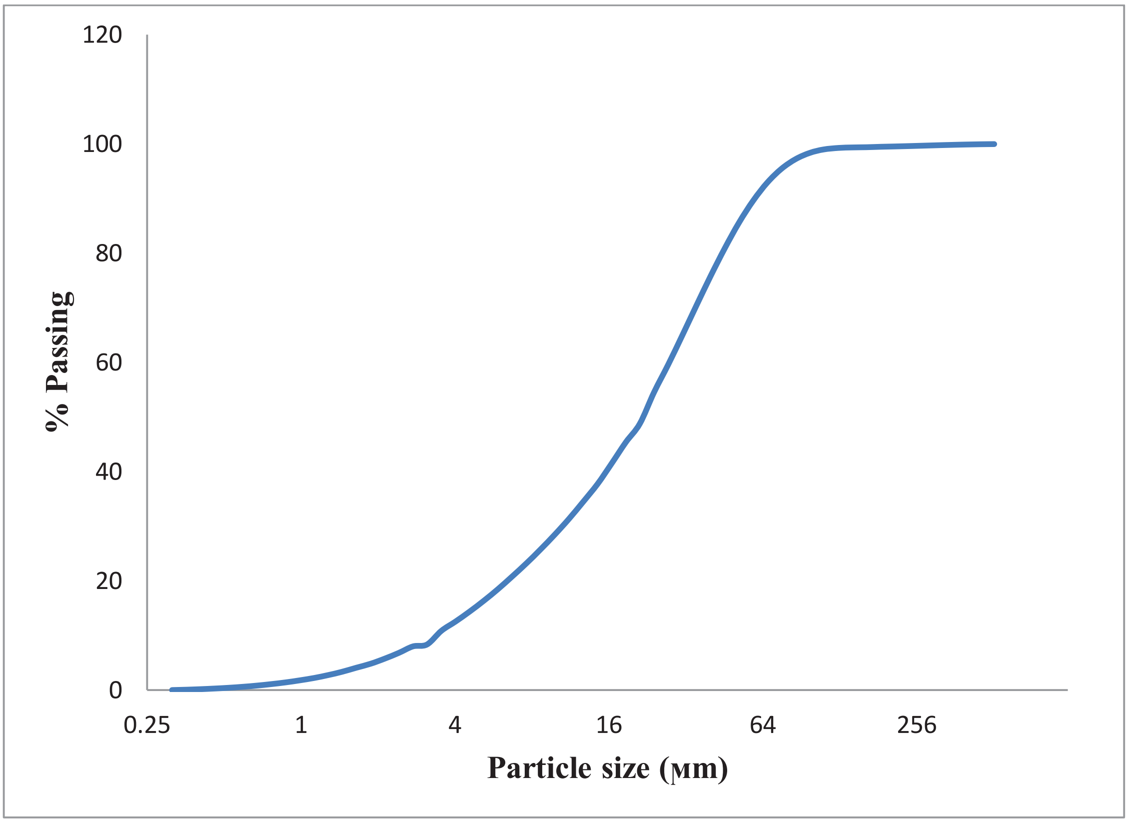

Figure 3.1 Particle size distribution of cement

3.1.2 Aggregate

Crushed limestone aggregate with a size range of 4 mm-16 mm was obtained from a local supplier. As-received properties of the aggregate, which were determined according to ASTM C 127 [51] and ASTM C 29 [52]. The physical properties of aggregates are given in Table 3.2, Table 3.3, and Figure 3.2.

Table 3.2 Physical properties of aggregate

Properties	**4-16 mm**
Bulk specific gravity	2.65
Apparent specific gravity	2.69
Water absorption (%)	0.92
Bulk density (kg/m^3)	1602
Voids (%)	39.56

Table 3.3 Sieve analysis of the aggregate

Sieve opening size (mm)	% Passing
16	100
12.5	81.17
8	39.55
4	8.30
2	3.26
1	2.44
0.5	2.18
0.25	1.58
0.125	1.17

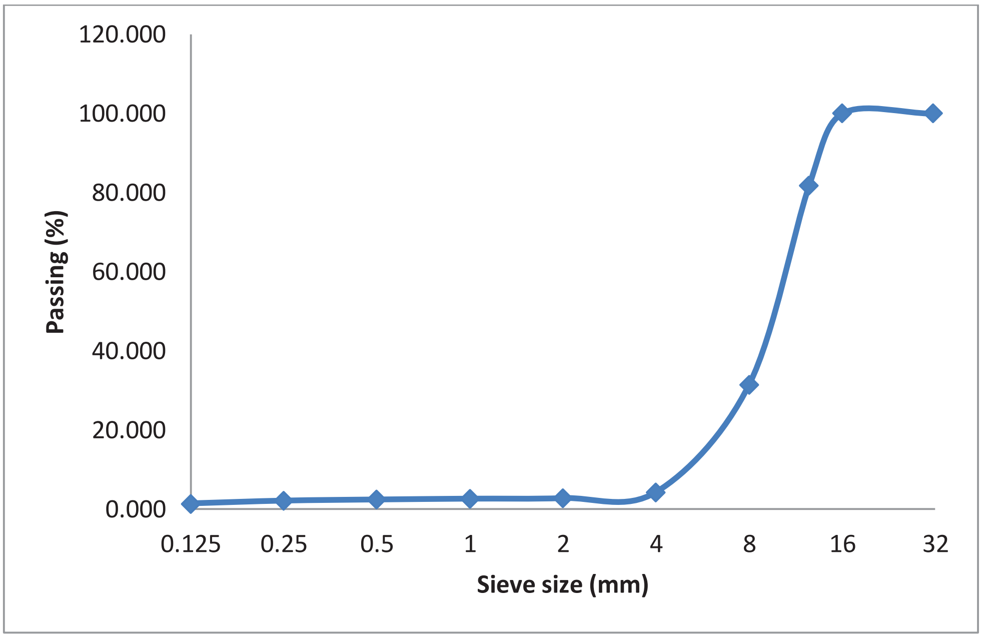

Figure 3.2 Gradation curve of aggregate

3.1.3 Superplasticizer

A naphthalene sulphonate based superplasticizer (Nanoplast M 50), conforming to TS EN 934-2 [53], was used. It was obtained from LYKSOR A.Ş. The typical dosage recommended by the manufacturer was 0.8% to 1.5% of the weight of cementitious materials. The properties of the superplasticizer obtained from the manufacturer are summarized in Table 3.4.

Table 3.4 Properties of the superplasticizer

Color and Form	Brown – Liquid
Chemical structure	Naphthalene sulphonate
Density (kg/l)	1.09-1.13 at 20°C
Chlorine content	Max. 0.1%
Alkaline content	Max. 0.5%
pH	5-9
Conformance	TS EN 934-2

3.2 Mix Design

In this thesis, in order to study the factors that may affect mechanical and physical properties of pervious concrete, several mixtures were prepared by varying mainly three mix-design parameters:

1. Volume of paste-to-volume of aggregate ratio (V_p/V_a)
2. Gradation
3. Superplasticizer contents

These parameters are among the most important ones to alter the void content, paste thickness around aggregates and clogging possibility in the pervious concrete.

The mix design was prepared at two sections. The first section was prepared at same water to cement ratio (0.33), same SP dosage (wt. 0.5% by the weight of the cement), and red pigment content (powdered form) (wt. 2.5% by the weight of the cement). The reason for using red pigment was to differentiate paste and aggregate during image analysis to give the color into the concrete. Three different V_p/V_a values were selected as 0.39, 0.42, and 0.45, which are typical values for pervious concrete according to the literature review. In order to obtain different aggregate gradations, firstly, as-received aggregate was sieved and the aggregate was separated into different size groups as 4-8 mm, 8-12.5 mm and 12.5-16 mm. Then, these aggregate groups were mixed in different proportions to obtain 4 different aggregate grading as seen in Table 3.5. Therefore, a total of 12 mixtures were obtained by varying V_p/V_a and aggregate grading (Table 3.6).

Table 3.5 Gradation schema of an aggregate

	Gradation of aggregate (%)			**Unit weight of the aggregate gradation (kg/m^3)**	**Void content in aggregate gradation (%)**
	4-8 mm	**8-12.5 mm**	**12.5-16 mm**		
Gr 1	20	40	40	1602	39.6
Gr 2	20	0	80	1627	38.6
Gr 3	0	100	0	1586	40.1
Gr 4	0	50	50	1598	39.7

Table 3.6 Mixture design of pervious concrete with superplasticizer

Superplasticizer content (wt. % of cement)	**V_p/V_a**	**Gradation of aggregate (%)**		
		4-8 mm	**8-12.5 mm**	**12.5-16 mm**
0.5%	0.45	20	40	40
0.7%	0.45	20	40	40
0.9%	0.45	20	40	40

In the second section, after taking the results of these 12 mixtures, one mixture design in Table 3.6 was chosen to see the effect of superplasticizer contents on the performance of pervious concrete. This choice or suitability was preferred as the best compressive strength result and most pervious concrete among 12 mixtures. Three different types of superplasticizer contents were used in the selected mixture design which were 0.5%, 0.7% and 0.9% (by the weight of the cement content) in Table 3.7.

Consequently, a total of 14 mixtures were prepared as seen in Table 3.6. This Table also shows the relative proportions of the ingredients of mixtures prepared in this study.

Table 3.7 The proportion ratios of ingredients in each mixture

		Aggregate gradation (mm)							
	V_p/V_a	4-8	8-12.5	12.5-16	Water	Cement	Total Aggregate	Pigment	SP
1	0.39	20	40	40	1.00	3.00	13.30	0.075	0.015
2	0.39	20	0	80	1.00	3.00	13.30	0.075	0.015
3	0.39	0	100	0	1.00	3.00	13.30	0.075	0.015
4	0.39	0	50	50	1.00	3.00	13.30	0.075	0.015
5	0.42	20	40	40	1.00	3.00	12.35	0.075	0.015
6	0.42	20	0	80	1.00	3.00	12.35	0.075	0.015
7	0.42	0	100	0	1.00	3.00	12.35	0.075	0.015
8	0.42	0	50	50	1.00	3.00	12.35	0.075	0.015
9	0.45	0	100	0	1.00	3.00	11.53	0.075	0.015
10	0.45	20	0	80	1.00	3.00	11.53	0.075	0.015
11	0.45	0	100	0	1.00	3.00	11.53	0.075	0.015
12	0.45	0	50	50	1.00	3.00	11.53	0.075	0.015
13	0.45	20	40	40	1.00	3.00	11.53	0.075	0.209
14	0.45	20	40	40	1.00	3.00	11.53	0.075	0.271

3.3 Methods

In this section, aggregate shape properties, surface area of aggregate, the calculation method of the paste thickness, rheology of cement paste and concrete will be explained how to complete their experiments

3.3.1 Aggregate Shape Properties

The aggregate shape properties are very important that affect performance of pervious concrete, therefore, particle size distribution of aggregate, flakiness index and crushing strength of aggregates were calculated.

3.3.1.1 Sieve Analysis

As-explained previously, the as-received 4-16 mm aggregate was sieved to produce aggregate with three different size groups, which are 4-8 mm, 8-12.5 mm, and 12.5-16 mm. The sieve analysis was performed by using the 1m x 2m sieves as shown in Figure 3.3.

Figure 3.3 Sieves

3.3.1.2 Flakiness Index

Flakiness index of coarse aggregate was determined according to TS EN 933-3 [24]. For sample preparation 4.5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5 mm aperture-size test sieves (Figure 3.4, and Figure 3.5) were used. The experiment consists of two processes. Firstly, the aggregates were separated d_i/D_i in giving particle size distribution by standard sieves used in sieve analyzing test according to TS EN 933-1 [24] part 1. Each particle size distribution was sieved for using grid sieve sets in Figure 3.5 (Flakiness Index Sieve EN) which opening sieve size should be Di/2. The total flakiness index was calculated as the percentage of total mass passed through the grid sieve to total dry initial mass. d_i/D_i represents the fraction of the particle size at i^{th} class.

Figure 3.4 Grid sieve

Figure 3.5 Grid sieve sets

3.3.1.3 Crushing Strength Value

The purpose of this experiment is to determine the crushing value of aggregate by using compressive strength test machine. This test is performed by placing an aggregate between two parallel plates of a testing machine and applying compression until failure [54-57]. 15 particles were used for each size fraction and crushing strength values were calculated from Equation 3.1 [58, 59].

$$\boldsymbol{\sigma} = \frac{\mathbf{2.8} * \mathbf{P}}{\boldsymbol{\pi} * \mathbf{X^2}} \tag{3.1}$$

Where X is the distance between two parallel plates of the testing machine just before loading, P is the maximum load before failure and 2.8 is the shape factor.

3.3.2 Excess Paste Theory

As mentioned earlier in Chapter 2, the excess paste in a concrete mixture beyond that required to fill the void volume in the granular phase can enhance the workability of the concrete (Figure 3.6). The volume of excess paste ($V_{paste,\ ex}$) can be calculated as follows Equation 3.2, 3.3, 3.4, 3.5, and 3.6.

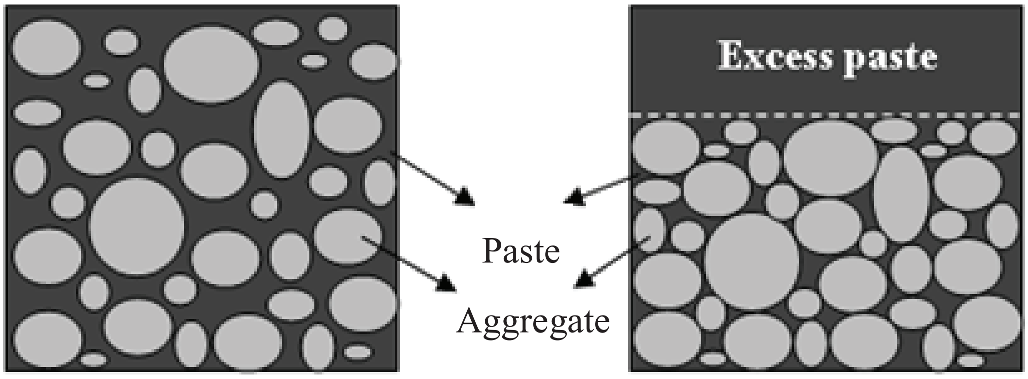

Figure 3.6 Schematic representation of excess paste

$$V_{concrete} = V_{aggregate} + V_{paste} \tag{3.2}$$

$$V_{concrete} = V_{aggregate} + V_{paste,ex} + V_{void} \tag{3.3}$$

$$V_{void} = \left(V_{concrete} - V_{paste,ex}\right) * (\text{void ratio}) \tag{3.4}$$

$$V_{concrete} = V_{aggregate} + V_{paste,ex} + \left(V_{concrete} - V_{paste,ex}\right) * (\text{void ratio}) \tag{3.5}$$

$$V_{paste,ex} = V_{concrete} - \frac{V_{aggregate}}{1 - (\text{void ratio})} \tag{3.6}$$

Where, $V_{concrete}$, $V_{aggregate}$, V_{paste}, and V_{void} are the volumes of concrete, aggregate, paste, and void among the aggregate particles, respectively. The void ratio is determined experimentally from the unit weight test of the aggregate according to ASTM C 29, but in this study, pervious concrete is also consisted of the porous structure, therefore instead of volume of excess paste, the volume of paste was used. The volume of the excess paste was used in this study for estimating paste thickness.

Paste Thickness

In this study, pervious concrete consists of porous structure, therefore instead of volume of excess paste, the volume of paste was used. The volume of paste was used in this study for estimating paste thickness. Once the excess paste volume is calculated, a parameter called paste thickness (t_p) can be introduced. It represents the mean thickness of the paste on an aggregate particle. Paste layer on the aggregates, t_p can be expressed as Equation 3.7.

$$t_p = \frac{\text{Volume of excess paste}}{\text{Total surface area of aggregates}} \tag{3.7}$$

In this approach, the thickness of the paste is assumed to be uniform (or same) for all aggregate particles, regardless of the dimension of the aggregate particle. For the calculation of the paste thickness, t_p, the summation of the $n_i*s_i*D_i$ values for each aggregate class is needed. This value was changed by applying a hypothesis and the details will explain in Chapter 4. All this calculation was performed other grading type and V_p/V_a ratio. Then using solver add-in at Excel program, the surface area of each aggregate group and coefficient factors were evaluated.

3.3.3 Image Analysis with AutoCAD ReCap Program

To calculate paste thickness by using excess paste theory, firstly, the surface area of the aggregate is needed. Therefore, aggregate images were taken by a digital camera (Canon EOS 600D) with 5184*3456 resolutions for every aggregate gradation and totally, 30 images were loaded in the software program (AutoCAD ReCap) with adjusting the scale of the images. After doing some regulations and trimming on the images, the software program gives the volume and surface area of the aggregate (Figure 3.7).

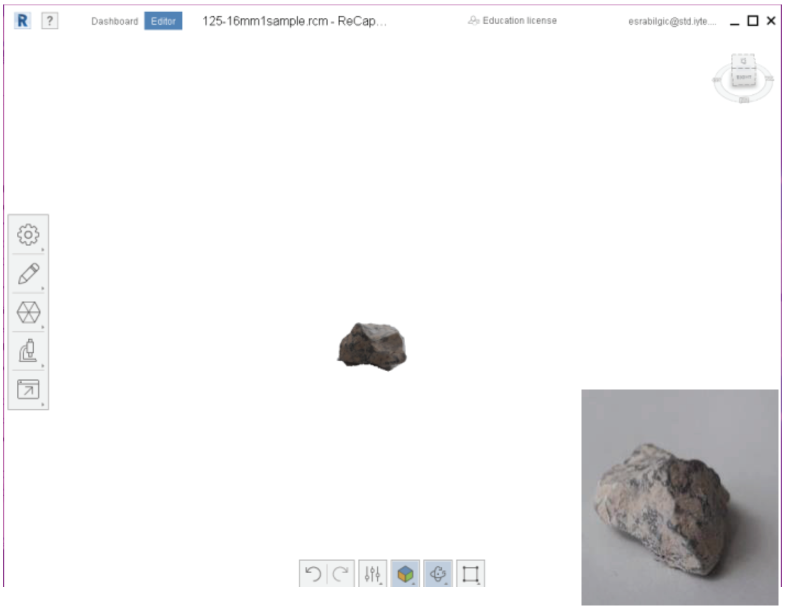

Figure 3.7 Aggregate sample

3.3.4 Paste Thickness

Paste thickness is defined as the average thickness of cementitious paste that accumulates around each surface of aggregates. There are different techniques to measure or calculation of paste thickness, but generally, it classified in two categories that are by using software based or manual hand measurements. There are several advantages and disadvantages by using both of them. Software system analysis is not perceived extraneous features like voids spaces and it requires a high-resolution scanner system to comb out each sample for detecting all features of each sample. Lastly, the software may not understand where to make the measurements from, in regards to each edge of the aggregate or edge of the paste. On the other hand, by using the manual method, these deficiencies can be eliminated, but it can require more time for evaluating all features of each sample. Therefore, by using both system in one method for calculating paste thickness, it can be eliminated all drawbacks during calculation processes.

In this study, paste thickness measured by the maximum length from the edge of an individual aggregate to the outermost edge of the cement paste, which surrounds that individual piece of aggregate. The paste thickness is surrounding aggregate particles was determined based on a procedure based on the studies described in [41]. Firstly, two grid patterns were constructed in AutoCAD program that forms a two-dimensional linear grid system. These linear grid systems consisted of 17 vertical and 17 horizontal lines and distance of spacing between horizontal and vertical lines was adjusted according to the maximum size of aggregate in different aggregate gradations. Then grid system placed on the cross section of sample image as seen Figure 3.21. The images were obtained by taking an image from a half of hardened density sample, specimens used for unit weight tests were divided into two parts along the whole length of the sample and they were taken by a digital camera (Canon EOS 600D) with 5184*3456 resolutions for each sample and load the software program with adjusting the scale of the images that are 500 scale and 0 degree of rotation. The reason for construct a grid system is done consistent measuring at each sample. Images were taken to set an experimental setup as Figure 3.9 and Figure 3.10. The digital camera was put between two rulers and then taken the photograph of samples. The reason for the set such experimental setup to obtain the same scale of the images for every sample. Then, by using AutoCAD software program a two-dimensional linear grid system was constructed. Afterward, the paste thickness was measured distances which taken to calculate in the same plane as the photograph between two horizontal lines and between two vertical lines. To do that, the operator began with the first horizontal line at the top of the sample and working from left to right measuring throughout each horizontal line. Consequently, the paste thickness was defined as a length (along the gridline) of the paste until a void or piece of aggregate was encountered, at which point the process was repeated each time a cementitious paste edge was observed [41, 60]. The same procedure was done for each vertical line. Figure 3.10 demonstrates a single measurement being taken along a solitary horizontal line. Each line may have approximately 3-15 measurements per line. Finally, the length of each past thickness and the corresponding line were recorded. To identify paste thickness a single value and eliminate errors during paste thickness process, an average of all measurements along a horizontal and vertical gridline was taken to representing paste thickness for one mixture. In addition, to see paste thickness easily, the red color pigment was added in each mixture (powdered form) (wt. 2.5% by the weight of the cement) to give the color into concrete for easily identification of paste thickness at image analyze. Otherwise, the cut paste thickness and aggregates would be both in gray. Therefore, to distinguish paste thickness from aggregate, the red pigment was used in each mixture.

Figure 3.8 Experimental setup to take a picture of the specimens

Figure 3.9 Specimen using for calculating paste thickness

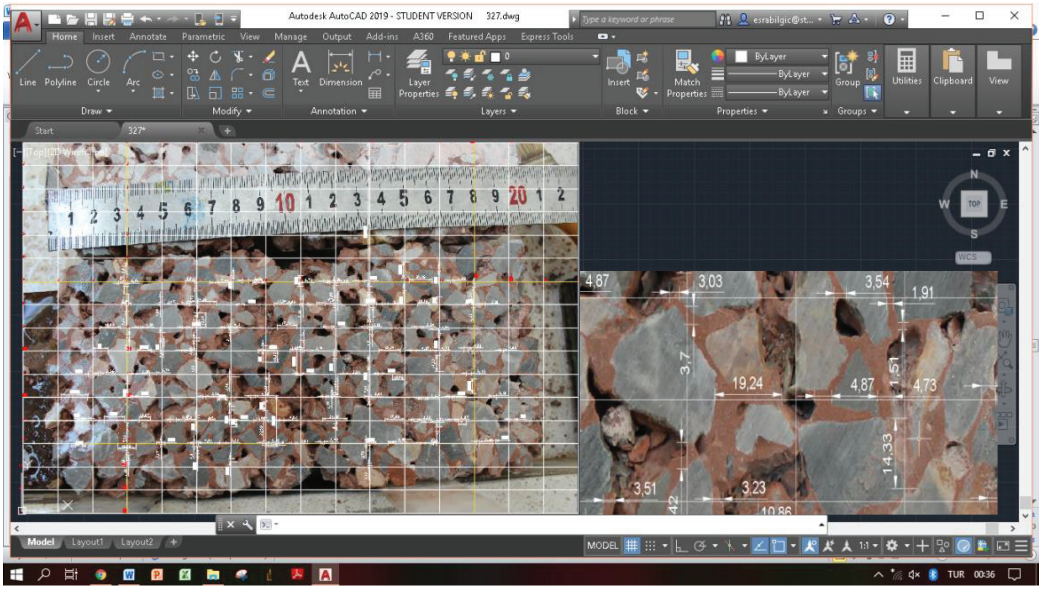

Figure 3.10 Gridline system in AutoCAD

3.3.5 Rheology of Cement Paste

There were three different superplasticizer contents in the mixtures (0.5%, 0.7% and 0.9% of the cement weight) as explained previously. The rheology of these three different paste types was determined by Discovery hybrid rheometer (AR 2000) shown in Figure 3.11 at constant w/c (0.33). Plastic viscosity and yield stress of the cement pastes were determined at different admixture contents. During the test, shear rate was increased then decreased gradually. The rheological measurements were made for the data taken during the decreasing stage.

Figure 3.11 Discovery hybrid rheometer (AR 2000) model

3.3.6 Fresh Pervious Concrete

Slump test, unit weight of freshly mixed pervious concrete and void content tests were performed for determination of properties of fresh pervious concrete.

3.3.6.1 Slump

The pervious concrete has a low water-cement ratio; therefore, it has a stiff mixture compared to normal concrete. Slump flow test was done according to ASTM C 143 [61] procedure. With the same procedure applied for conventional concrete, pervious concrete was placed into the cone in 3 layers and each layer is rodded 25 times. Then the cone is removed vertically and the collapse of the concrete was measured with a ruler from the top surface of the slump cone.

3.3.6.2 Unit Weight and Void Content of Fresh Pervious Concrete

In the literature, the unit weight of pervious concrete mixtures is approximately 70% of traditional concrete mixtures. For determining the fresh density of pervious concrete, ASTM C 1688 was used. Freshly mixed pervious concrete was placed into a 5-liter cylindrical container in two layers and each layer was rodded 25 times. Then, the surface of consolidated fresh pervious concrete was stroked off with glass plate. The mass of freshly mixed concrete was measured to calculate the density by dividing the concrete mass to the volume of the cylindrical container (Figure 3.12) [36]. Finally, density and the percentage of voids in freshly mixed concrete were calculated as Equation 3.8, Equation 3.9, and Equation 3.10.

$$\mathbf{T} = \frac{\mathbf{M_s}}{\mathbf{V_s}} \tag{3.8}$$

$$\mathbf{D} = \frac{\mathbf{M_c} - \mathbf{M_m}}{\mathbf{V_m}} \tag{3.9}$$

$$U\,(\%) = \frac{T - D}{D} * 100$$

(3.10)

Where M_s is total mass all materials batched (kg), M_m is mass of the measure (kg), M_c, mass of the measure filled with concrete (kg), V_m, volume of the measure (m^3), V_s, sum of the absolute volumes of the component ingredients in the batch (m^3), D, density (unit weight) of concrete (kg/m^3), T, theoretical density of the concrete computed on an air free basis (kg/m^3) and U is the percentage of the voids content in fresh pervious concrete [36].

Figure 3.12 Density of freshly mixed pervious concrete

3.3.7 Hardened Pervious Concrete

Unit weight and void content of the hardened concrete, permeability, abrasion resistance, flexural and compressive strength were performed for determination of properties of hardened pervious concrete.

3.3.7.1 Unit Weight and Void Content of the Hardened Concrete

The unit weight of hardened pervious concrete changes between 1600 kg/m^3 and 2000 kg/m^3 according to literature. Unit weight and void content of hardened concrete mixtures were determined based on the procedure described in ASTM C 1754M-12 [40]. For each mixture, two 10cm x 20cm cylindrical specimens were prepared (Figure

3.13) and they were cast into their molds in two equal layers each of which were rodded 25 times. Then, the specimens were kept in the mold for three days to gain strength and they are stored in water at 20°C for four days. At the end of 7 days, the dimensions of the cylindrical specimens were measured to calculate the specimen volume. Then the specimens were dried in the oven for 24h to obtain constant mass. Afterward, the specimens were immersed in a water bath to determine the volume of solids in the specimen. Finally, using these measured values, the density and void content was calculated using Equation 3.11 and Equation 3.12.

$$\mathbf{Density} = \frac{\mathbf{K} * \mathbf{A}}{\mathbf{L} * \mathbf{D^2}}$$

(3.11)

$$\mathbf{Void}\ (\%) = \left[\mathbf{1} - \left[\frac{\mathbf{K} * (\mathbf{A} - \mathbf{B})}{\boldsymbol{\rho}_{\mathbf{water}} * \mathbf{D^2} * \mathbf{L}}\right]\right] * \mathbf{100}$$

(3.12)

Where A is defined as dry mass of the specimen in g, D is the average diameter of the specimen in mm, L is the average length of the specimen in mm, K is a 1 273 240 in SI units, B is submerged mass of the specimen in g, and finally, ρ water is defined as the density of water at the temperature of the water bath in kg/m^3 [40].

Figure 3.13 Sample to measure the hardened density of pervious concrete

3.3.7.2 Permeability

According to literature, the flow rate of pervious concrete can change 81 L/m²/min to 730 L/min/m² or permeability coefficient varies from 0.2 mm/s to 5.4 mm/s [3]. In this study, permeability was measured according to ASTM C 1701 [37] and ASTM C 1781 [39]. The purpose of these standards is to measure the water infiltration rate of in-place pervious concrete.

This test was performed on hardened pervious pavements with 60cmx60cmx8cm dimensions (Figure 3.14 and Figure 3.15). At an age of 7 days, a ring with a diameter of 29.5cm, (Figure 3.16), was placed on the center of the pavements. To measure the infiltration rate, two lines were marked inside of the ring at a distance of 1.0 and 1.5 cm from the bottom of the ring. The outer periphery of the ring was sealed with silicon to prevent leakage of water from the bottom of the ring (Figure 3.16). Before pouring water, the pervious pavement was wetted to eliminate absorption of water by the concrete. The 18 kg of water was poured on to the pervious pavement so that the water level inside the ring remained between the marked lines (Figure 3.16). The time necessary to pour 18 kg of water was recorded (Figure 3.17). Finally, the permeability rate (I) (mm/hr) was calculated by using Equation 3.13, which is given in ASTM C 1701 [37].

$$\mathbf{I} = \frac{\mathbf{K} * \mathbf{M}}{\mathbf{t} * \mathbf{D}^2} \tag{3.13}$$

Where K is 4 583 666 000 (in SI units), M (kg) is mass of infiltrated water, D (mm) is inside diameter of infiltration ring and lastly, t (s) defines the time required for 18kg water to infiltrate the concrete [37].

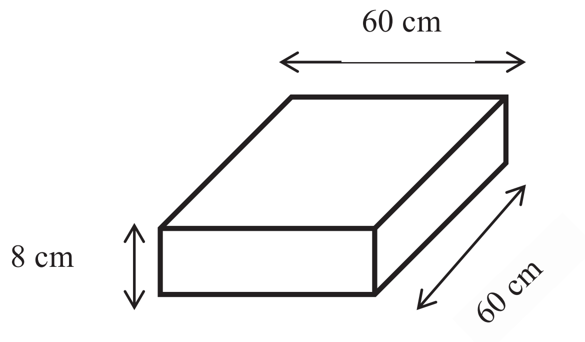

Figure 3.14 Dimensions of the pervious pavement

Figure 3.15 The mold for pervious pavement

Figure 3.16 Insulation ring with aerogel to measure permeability rate

Figure 3.17 The mechanism to measure the permeability of pervious pavement

3.3.7.3 Abrasion

Due to its open structure and rough surface, abrasion can be a problem for pervious concrete when exposed to the high traffic load. Therefore, pervious concrete applications have to be checked for abrasion resistance. In this study, abrasion test was performed according to ASTM C 1747M-13 [38]. This method involves determining the potential resistance to degradation of pervious concrete by measuring the mass loss of specimens that were exposed to the combined action of impact and abrasion in a Los Angeles test machine (Figure 3.18). Higher potential resistance to degradation is associated with lower mass loss. In this study, three 10cmx10cm cylindrical specimens were prepared for each mix design by placing the concrete in two layers that were rodded 25 times. They were cured three days in their molds, and then moist cured for 3 days. After waiting in the laboratory conditions for 1 day, the mass of the specimens were measured. Then, three specimens were put into the Los Angeles test machine without steel balls. After 500 revolutions, the amount of materials retained on 1-inch sieve was determined (Figure 3.19). The potential resistance to degradation by impact and abrasion was expressed as the percentage mass according to the following Equation 3.14.

$$\mathbf{Mass\ loss}\ (\%) = \frac{\mathbf{Mass\ of\ the\ orginal\ three\ specimens - \ Final\ mass\ retainedon\ the\ 1\ inch\ sieve}}{\mathbf{Mass\ of\ the\ orginal\ three\ specimens}} * \mathbf{100} \tag{3.14}$$

Figure 3.18 Los Angeles test machine

Figure 3.19 1-inch sieves

3.3.7.4 Flexural Strength

The flexural strength for pervious concrete ranges between 1- 4 MPa according to the literature. For determining flexural strength, three beam specimens with 7 cmx7 cmx25 cm dimensions were prepared for each mix design. These beams were placed into the molds in two layers and each layer was rodded 25 times. The specimens were demolded after 1 day. Then they placed in the curing room until 28 days. These specimens were tested under central point loading according to ASTM C 78 [62] (Figure 3.20). The test was performed by using a deformation controlled the universal testing machine with 250 KN capacity and the loading rate was 0.1 mm/sec.

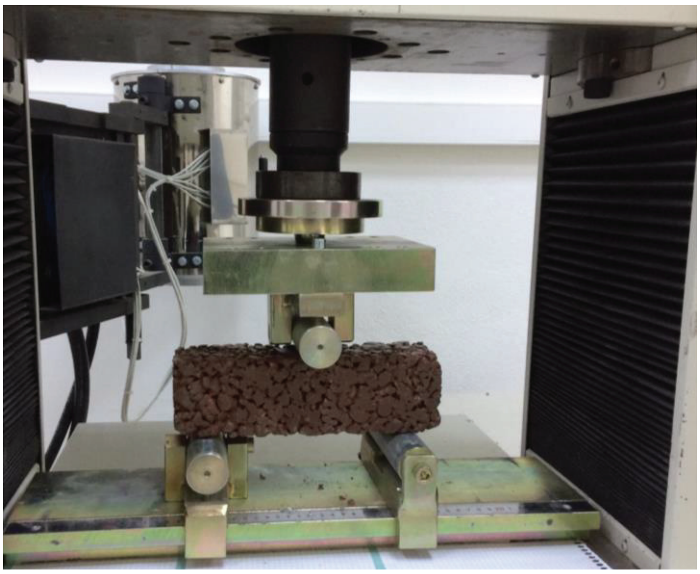

Figure 3.20 Testing machine

3.3.7.5 Compressive Strength and Bond Strength

As with any concrete, the properties and combinations of specific materials, as well as placement techniques and environmental conditions, will influence the strength of pervious concrete. In the literature, the 28-day compressive strength of pervious concrete was changed between 2.8 to 28 MPa [3].

In this study, to measure the compressive strength, six cube specimens with 15*15*15 cm dimensions were made for each mix design. Three of these specimens were for 7 days and the other three were for 28 days. The fresh samples were placed into the molds in two equal layers by rodding each layer 25 times. All of the specimens for determining compressive strength were waited in the molds for three days to gain strength. Then, they were cured in water in the curing room until 7 and 28 days. Currently, there is no ASTM test standard for compressive strength of pervious concrete; therefore, the test was performed according to the procedure for normal concretes, which is ASTM C 39 [63]. Therefore, as normal concrete determining compressive strength value, the same procedure was done for determining the compressive strength of pervious concrete except for delay time at the end of compressive strength loading. In this study, for delay time at the end of compressive strength loading, % F_{max} was chosen %70. This value was determined by our experiment and preliminary studies.

When pervious pavement or concrete was broken or exposed to any damage, the repair is an important task. In addition, as normal concrete, when pouring or placing the concrete, there may be a time lag of truck or mixer and therefore cold joint can occur. Therefore, the bonding of two layers was tested as well. One the cubic mold was first filled with half of the mold, which was placed at 45 degrees on the ground surface, and it waited into 15*15*15 cm cubic specimen during three days as seen in Figure 3.21. After the gaining initial strength during three days, other rest of the mold was filled by pervious concrete and it waited in the mold for three days. At the end of 6 days, the sample was removed from the mold and put into curing room for 1 day. Total curing time was 7 days, so the compressive strength of this sample was tested at the end of 7 days. By using the 2000 KN capacity compression testing machine shown in Figure 3.22.

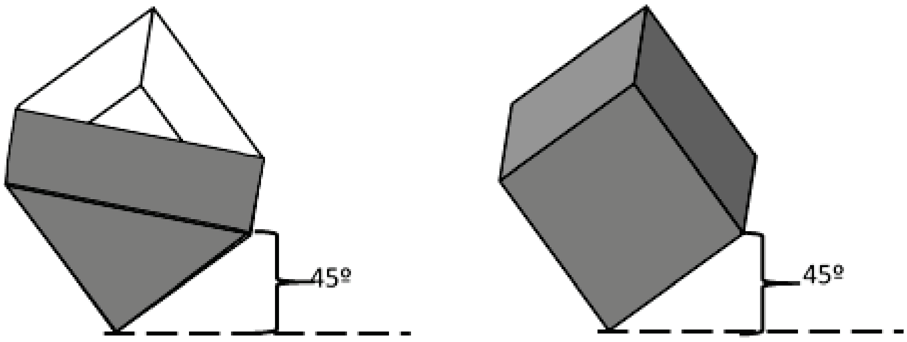

Figure 3.21 Pouring method for bonding test

Figure 3.22 Compressive strength test machine

CHAPTER 4

RESULT AND DISCUSSION

This study was divided into four stages. In the first stage, concrete mixtures were prepared with four different aggregate grading, which were obtained by combing three different aggregate sizes (4-8 mm, 8-12.5 mm, and 12.5-16 mm). Moreover, ratio of paste volume to aggregate volume was set to three different values as 0.39, 0.42, and 0.45. Water/cement ratio and superplasticizer content was fixed to 0.33 and 0.5% by the weight of cement. In all these mixtures, slump, density abrasion resistance, permeability, void content, compressive and tensile strength were determined. To understand the effects of superplasticizer on pervious concrete, the superplasticizer content was changed at different amounts (0.5%, 0.7%, and 0.9% by the weight of cement). The rheological parameters of the pastes and some tests listed above were carried out on the concrete in the second stage. The third stage consisted of some simple methods and image analysis that were applied to find the surface area of aggregates and the paste thickness around the aggregates. Finally, the relationships between the paste thickness and concrete properties were investigated.

4.1 Effect of V_p/V_a and Aggregate Gradation on Properties of Pervious Concrete

In this section, results will be discussed at when concrete is a fresh or hardened form.

4.1.1 Fresh Pervious Concrete

To understand effects of V_p/V_a on the performance of fresh pervious concrete, slump cone test, unit weight and void content of the fresh pervious concrete were investigated.

4.1.1.1 Slump Cone Test

After the mixing of the concrete, the slump test was done. The slump value of pervious concrete mixtures varied between 19±2 cm due to the addition of superplasticizer. Figure 4.1 shows the slump test concretes with Gr 3 type grading but with different V_p/V_a. The results are shown in Table 4.1. Figure 4.1 show that the slump of the concrete did not vary significantly with V_p/V_a and grading type. However, the superplasticizer content increased the slump values as expected. (As seen in Table 4.2). the addition of superplasticizer performed lubrication effects on the aggregate. The reason of addition to superplasticizer content, firstly show that when increase superplasticizer dosage, the paste moves with aggregate and accumulate into ground. The second reason is that addition of superplasticizer increase the physical and mechanical properties of pervious concrete.

Table 4.1 Results of the fresh pervious concrete at same superplasticizer content (0.5%)

V_p/V_a	Grading type	Slump Value (cm)	Fresh Density (kg/m^3)	Fresh Density Void (%)
0.39	Gr 1	19.8	1881	24.1
0.39	Gr 2	18.2	1870	28.6
0.39	Gr 3	18.2	1847	27.1
0.39	Gr 4	20.0	1859	24.6
0.42	Gr 1	17.8	1852	23.8
0.42	Gr 2	18.0	1846	28.5
0.42	Gr 3	18.6	1803	27.0
0.42	Gr 4	20.7	1835	25.3
0.45	Gr 1	16.5	1959	19.0
0.45	Gr 2	19.3	1959	23.2
0.45	Gr 3	19.0	1945	19.7
0.45	Gr 4	19.2	1955	19.9

$V_p/V_a = 0.39$ $V_p/V_a = 0.42$ $V_p/V_a = 0.45$

Figure 4.1 Slump flow test at the same gradation (Gradation 3)

Table 4.2 Results of fresh pervious concrete at different superplasticizer contents

V_p/V_a	Superplasticizer content (%)	Grading type	Slump Value (cm)	Fresh Density (kg/m^3)	Fresh Density Void (%)
0.45	0.5	Gr 1	16.5	1959	19.0
0.45	0.7	Gr 1	20.5	1963	20.2
0.45	0.9	Gr 1	21.5	2086	15.2

4.2.1 Unit Weight and Void Content of the Fresh Pervious Concrete

After the slump test, the fresh unit weight of pervious concrete mix was measured using the procedure as before described in Chapter 3. The results of the fresh unit weight testing are included in Figure 4.2 (See Table 4.1 and 4.2 as well). This Figure indicated that the highest fresh unit weight was reached when $V_p/V_a = 0.45$ and the lowest fresh unit weight was $V_p/V_a = 0.42$ for the same gradation. In addition, the lowest fresh unit weight was at gradation 3 and the highest fresh unit weight was at gradation 1 at same V_p/V_a ratio. Moreover, when V_p/V_a ratio was equal to 0.39 and 0.42, the fresh unit weight of the pervious concretes was closer to each other. All these results showed that both of the V_p/V_a and aggregate gradation affected fresh unit weight.

The void content in freshly mixed pervious concrete was calculated according to ASTM C 1688 [36]. In this study, the void content in freshly mixed pervious concrete was varied between 19.0 to 28.6% (Figure 4.3). For all V_p/V_a ratios, the highest void content was obtained for gradation 2 or the lowest void content was obtained for gradation 1 (Figure 4.4). In addition, when V_p/V_a ratios were equal to 0.39, and 0.42, the void content changed very little. Consequently, when increasing the V_p/V_a ratios until 0.42 value, the unit weight of the fresh pervious concrete and void content did not change significantly, but the change was more when V_p/V_a reached at 0.45 ratios.

Normally, hypothesized an increase in cement paste content would occupy more volume within the pervious concrete structure; therefore, cause a reduction in the volume of pores. However, in this study, for V_p/V_a ratios of 0.39, and 0.42, the void content in freshly mixed pervious concrete nearly the same. This situation can be explained as follows: increase in the amount of cement paste per unit aggregate volume would occupy more volume up to a critical point within the pervious concrete structure, and at that critical point the cement paste just coats the aggregate surfaces, but after that critical point it may start to fill the voids between aggregate, and reduce the volume of pores.

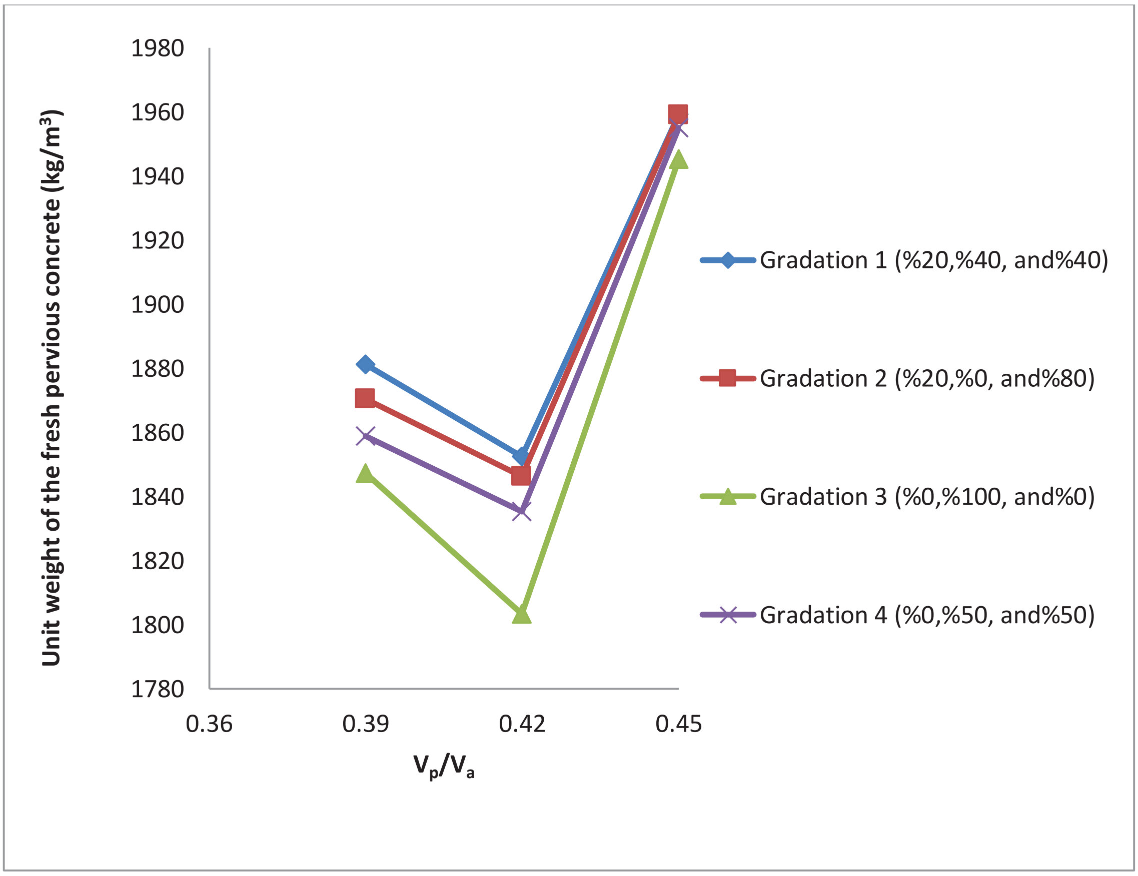

Figure 4.2 The unit weight of the fresh pervious concrete at different V_p/V_a ratios

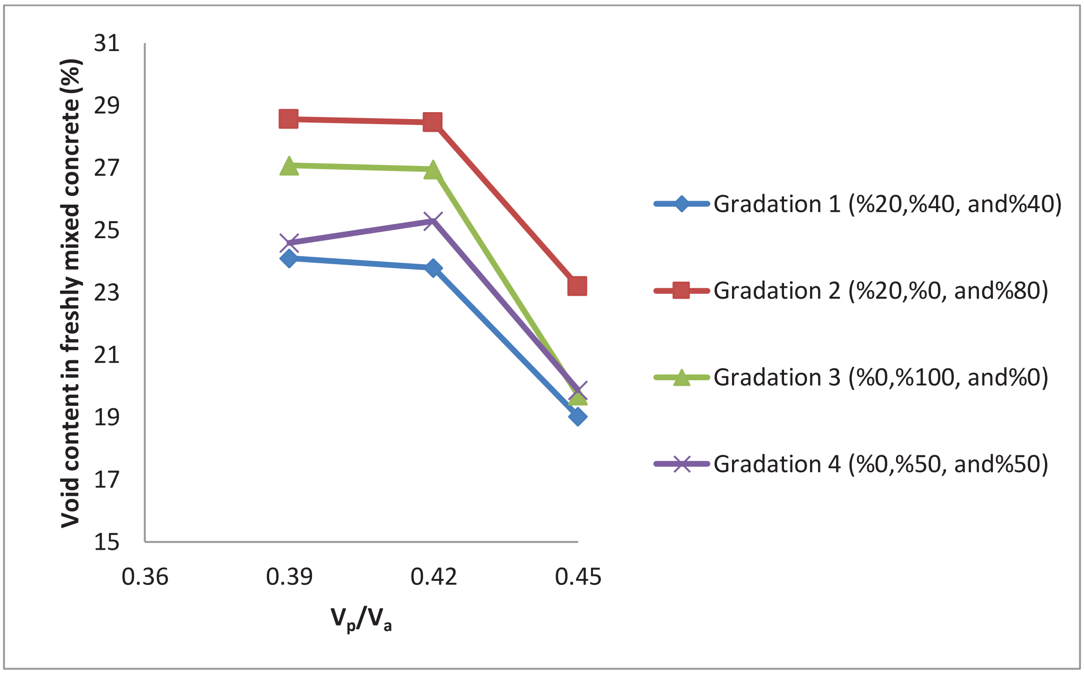

Figure 4.3 The void content in freshly mixed pervious concrete at different V_p/V_a

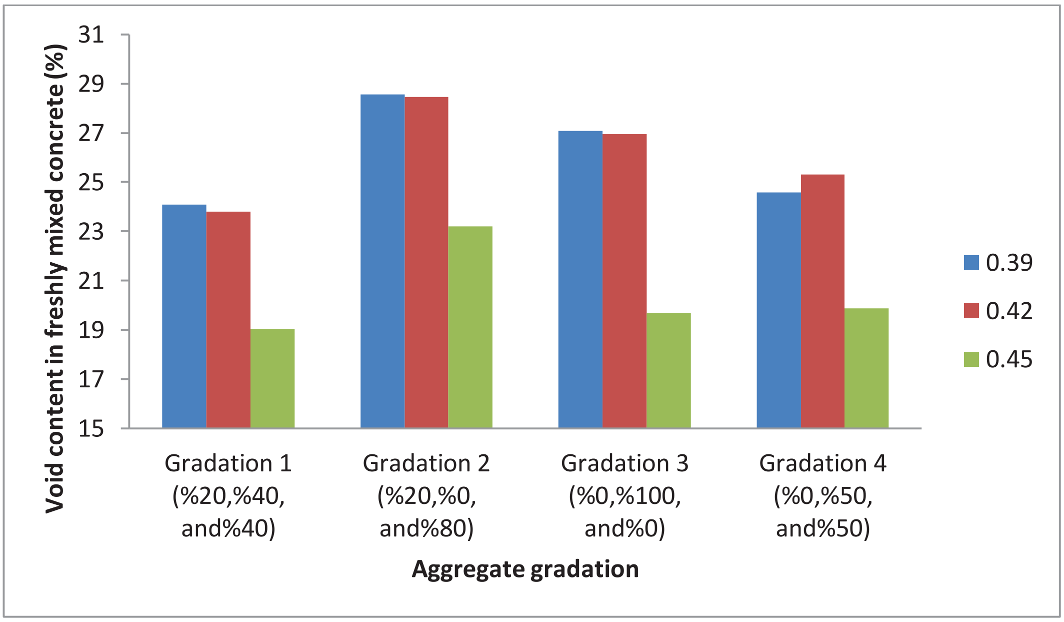

Figure 4.4 The void content in freshly mixed pervious concrete at different gradations

The relation between aggregate unit weight (for different gradings) and unit weight of fresh concrete can be seen in Figure 4.5. It was found that for V_p/V_a = 0.45, the unit weights of the fresh pervious concrete were highest at each aggregate gradation. For the same aggregate gradation, the order of the unit weight of the fresh pervious concrete is the same for different V_p/V_a ratios.

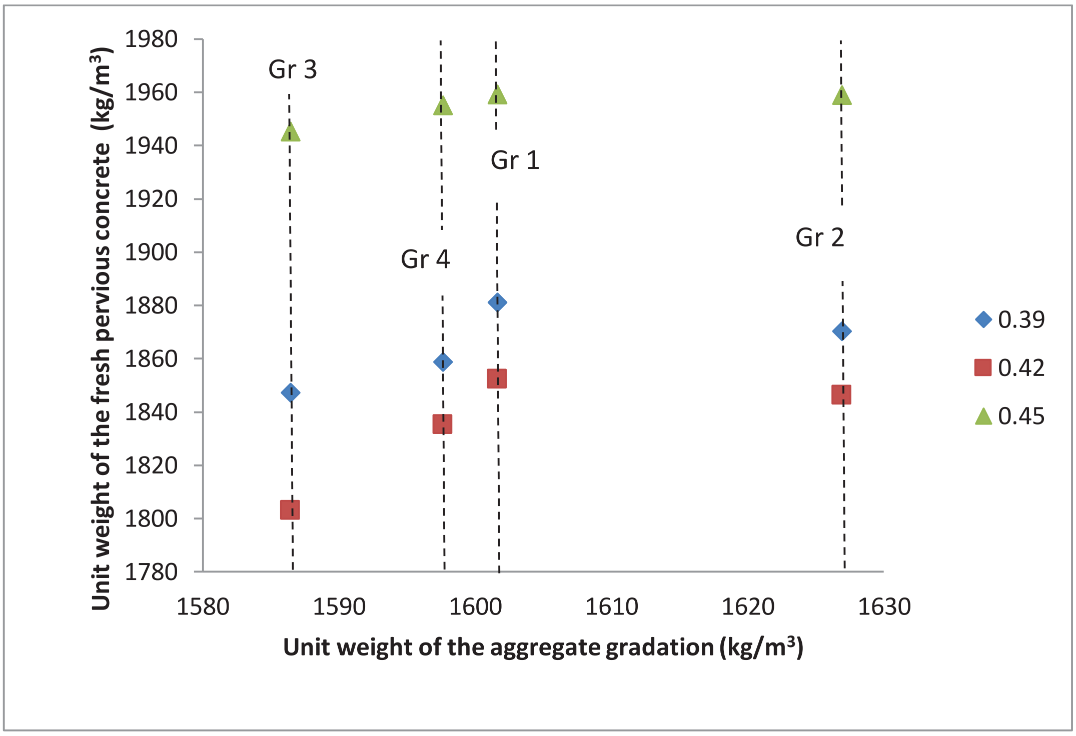

Figure 4.5 The relationship between the unit weight of the fresh concrete and aggregate

4.1.2 Hardened Pervious Concrete

Unit weight and void content of the hardened concrete, permeability, abrasion resistance, flexural and compressive strength were discussed for the determination of properties of hardened pervious concrete

4.1.2.1 Hardened Density and Void Content

The density and void content of the hardened pervious concrete depends on many factors. In this study, hardened density varied with the combination of aggregate gradation and cement paste. When V_p/V_a = 0.39, the highest hardened density was observed gradation 2, but V_p/V_a = 0.42, the hardened density was the lowest value at gradation 2 (Figure 4.6 and Figure 4.7). In addition, except for gradation 4, the gradation 1, 2, and 3 resulted in nearly same hardened density at when V_p/V_a = 0.45. Finally, as unit weight results of the fresh pervious concrete, the hardened density of pervious concrete was highest, when V_p/V_a = 0.45 at each aggregate gradation. The results are shown in Table 4.3.

Table 4.3 Results of Hardened pervious concrete at same superplasticizer content(0.5%)

V_p/V_a	Gradation Type	Beam σ (MPa)	Bond σ (MPa)	7D σ (MPa)	28D σ (MPa)	Permeability rate (cm/s)	Hardened Density (kg/m^3)	Hardened Density void (%)	Mass Loss (%)
0.39	Gr 1	3.62	7.76	7.70	9.40	2.74	1838	27	43
0.39	Gr 2	2.65	6.50	6.53	8.80	1.88	1886	28	60
0.39	Gr 3	2.30	6.23	7.06	8.90	2.31	1661	34	64
0.39	Gr 4	1.95	3.57	7.92	10.44	4.93	1700	33	65
0.42	Gr 1	2.55	7.40	7.42	7.99	4.09	1788	29	97
0.42	Gr 2	2.27	7.42	6.82	7.82	2.89	1661	36	68
0.42	Gr 3	2.54	6.68	6.66	8.06	3.26	1733	28	100
0.42	Gr 4	2.84	7.42	7.60	8.91	3.12	1795	24	41
0.45	Gr 1	4.15	13.3	13.41	16.02	2.81	1875	24	40
0.45	Gr 2	5.11	15.2	15.26	17.26	1.81	1898	25	30
0.45	Gr 3	2.94	11.5	12.64	14.00	2.17	1899	24	47
0.45	Gr 4	3.87	11.9	12.88	15.68	2.45	2004	19	39

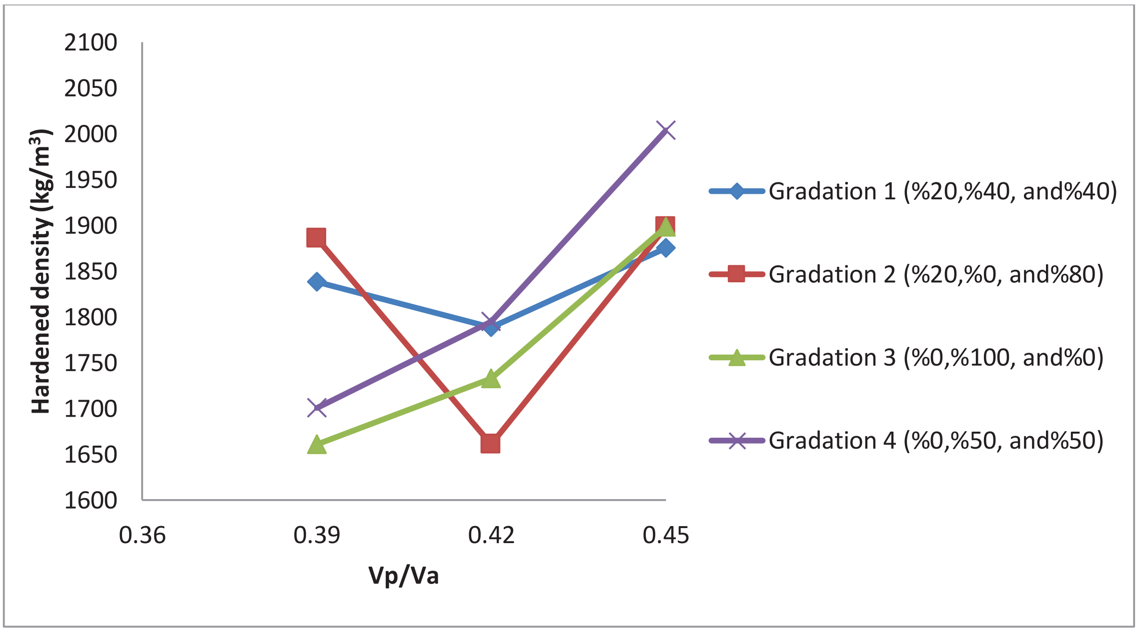

Figure 4.6 The unit weight of the hardened pervious concrete at different V_p/V_a

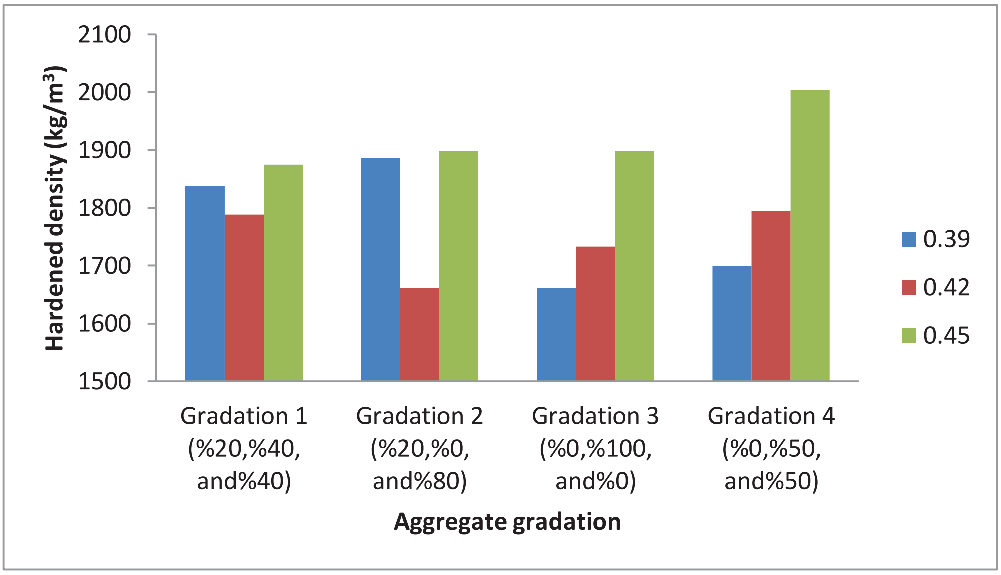

Figure 4.7 The unit weight of the hardened concrete at different gradations

The void content in hardened pervious concrete can affect the permeability and compressive strength. In this study, the void content in hardened concrete was changed between 19-36 % as seen in Figure 4.8 According to the results, void content decreased with increasing V_p/V_a for gradation 3, and 4.

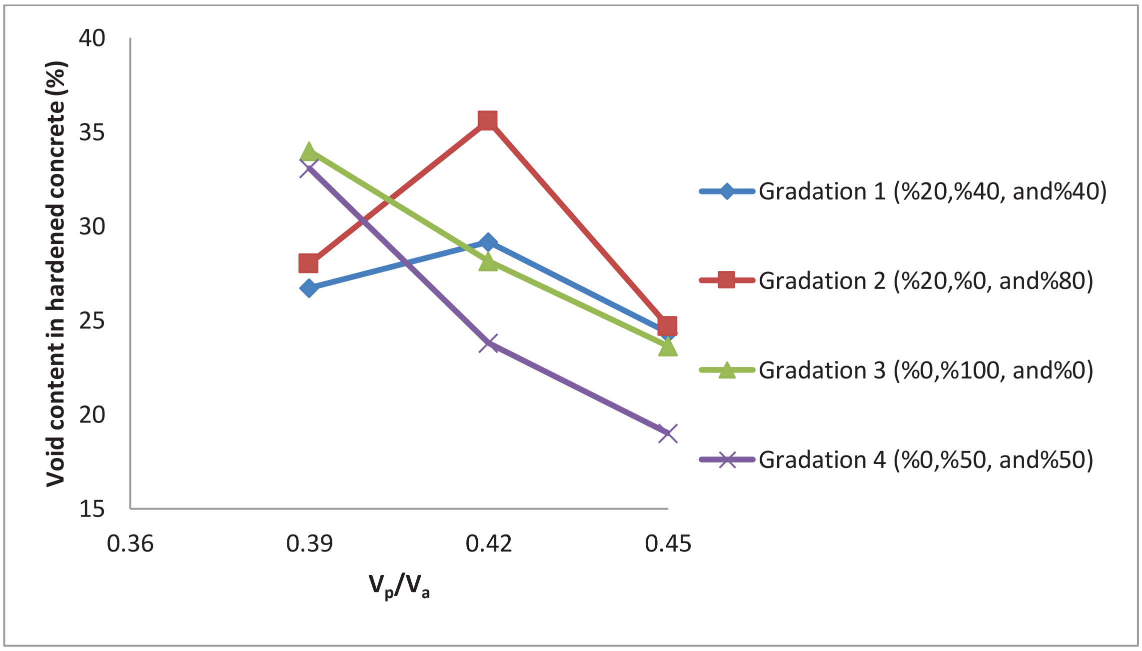

Figure 4.8 The void content in the hardened pervious concrete at different V_p/V_a

On the other hand, for gradation 1 and 2 that are both of include 4-8 mm aggregate, the void content firstly increased with increasing V_p/V_a then decreased

(Figure 4.8). The reason of that may be, when it consists of 4-8 mm, firstly, cement paste coated aggregate surface, if still increase the V_p/V_a, the cement paste may fill the aggregate voids. The main logic behind this thought as mentioned in Chapter 1, a small aggregate could have thin paste thickness.

Just like the unit weight of the fresh pervious concrete, it was found that for V_p/V_a = 0.45, the density of the hardened concrete was highest and Figure 4.9 showed that unit weight of the aggregate increased with increasing the density of hardened pervious concrete. It was found that for V_p/V_a = 0.45, the unit weights of the fresh pervious concrete were highest at each aggregate gradation. For the same aggregate gradation, the order of the unit weight of the fresh pervious concrete is the same for different V_p/V_a ratios.

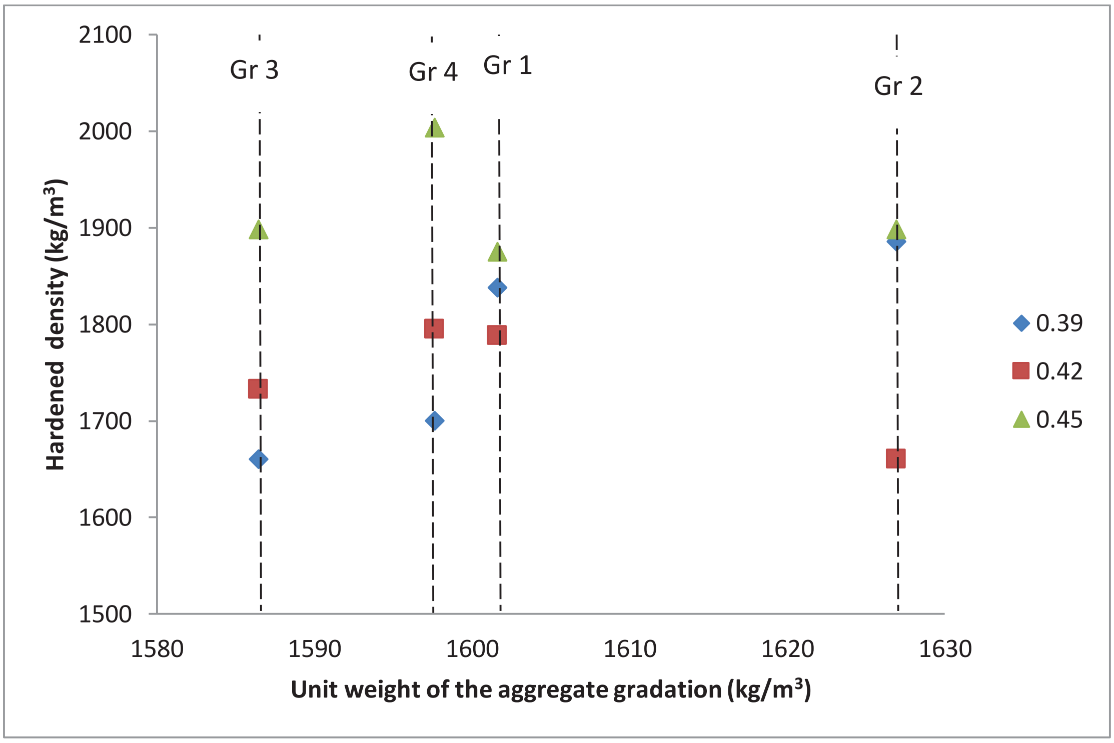

Figure 4.9 The relationship between unit weight of the hardened concrete and aggregate

4.1.2.2 Permeability

In this thesis, the permeability rate was measured in accordance with ASTM C 1701. The results show that except gradation 4, the permeability rate showed the same behavior with varying V_p/V_a. Among the different aggregate gradations, gradation 1 showed the best performance for permeability rate (Figure 4.10) and in general, the permeability firstly increased with increasing V_p/V_a ratios, then decreased. As seen in Figure 4.10, the permeability rate was decreased at a range of 0.42 to 0.45 V_p/V_a. the decrease was due to clogging of the pores resulting from higher paste content in the concrete.

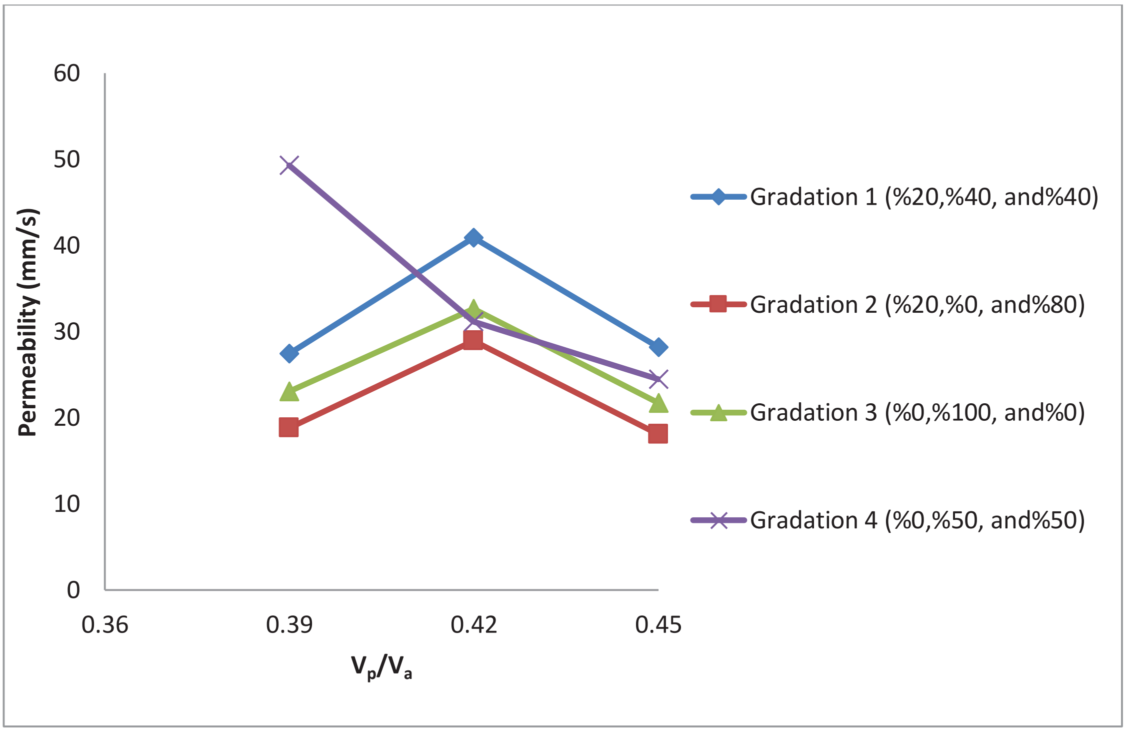

Figure 4.10 The permeability rate at different V_p/V_a

Some researchers describe the porosity as a percentage in the volume of voids according to the total volume of pervious concrete and porosity classified at two categories, which are effective porosity and inactive porosity [1]. The effective porosity is part of void space that allows the fluid flow during permeability process, on the other hand, inactive porosity is defined that isolated from or closed off neighbor void spaces that is not allow to transmit fluid. In this study, there was no direct relation between permeability and the void content in the unit weight of the aggregate [1]. This case may occur when pervious concrete compact very highly and an increase in the amount of cement paste per unit aggregate resulted with coating more paste on the aggregate surface up to a critical point within the pervious concrete structure, but after that critical point it may start to fill the voids in aggregate. Therefore, it may reduce permeability with decreasing the volume of pores and cause clogging of the pervious concrete (Figure 4.11).

Figure 4.11 The clogging of the pervious concrete due to the excess paste

4.1.2.3 Abrasion Resistance

In this study, abrasion resistance was calculated according to ASTM C 1747 M-13. The abrasion can be defined as the loss of mass under certain conditions with respect to the initial state of the concrete. The increasing abrasion values mean that the mass loss of pervious concrete increases. According to the results seen in Figure 4.12, at gradation 2, and 3, the mass loss reached 100%. In addition, except gradation 4, the mass loss of the pervious concrete showed the same behavior for all V_p/V_a ratios. The lowest values of mass loss were obtained when $V_p/V_a = 0.45$ and the highest values of mass loss generally were obtained when $V_p/V_a = 0.42$.

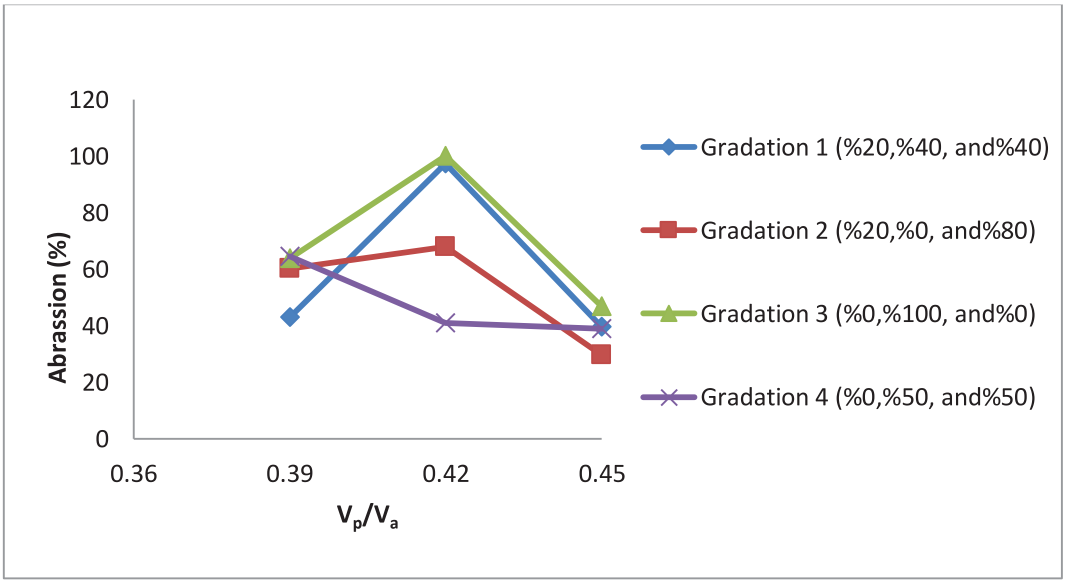

Figure 4.12 The mass loss at different V_p/V_a

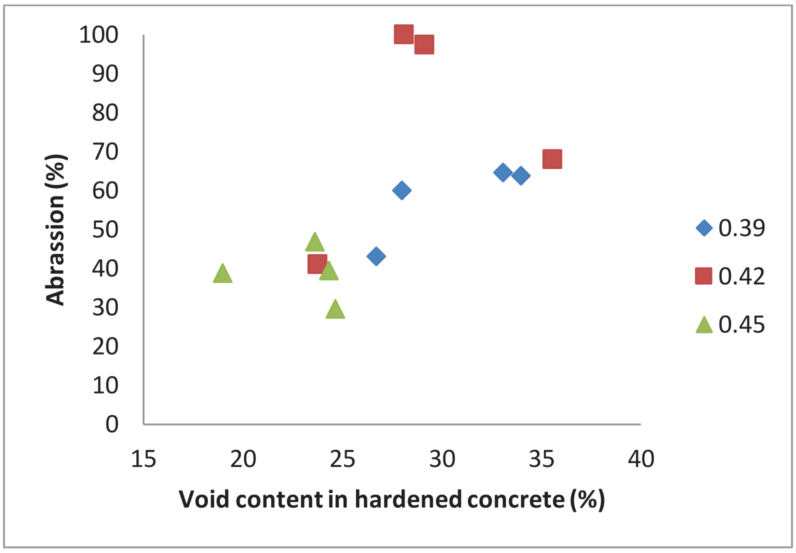

Figure 4.13 The relationship between abrasion and void content in hardened concrete

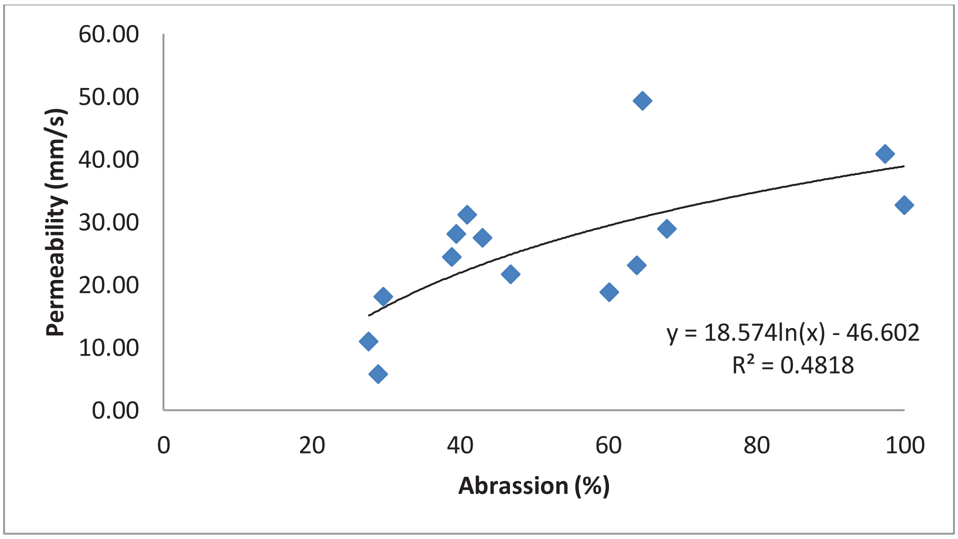

Figure 4.14 The relationship between permeability rate and abrasion values

There is a logarithmic relationship between mass loss and permeability (Figure 4.14). The increasing permeability is related with structure that is more porous and less strength that can cause higher mass loss.

4.1.2.4 Compressive and Flexural Strength

The compressive strength of the pervious concrete was tested at 7 days and 28 days. According to the results, all gradations showed the same behavior at different V_p/V_a ratios for both 7 and 28 days (Figure 4.16, 4.17, 4.18, 4.19 and 4.20).

Figure 4.15 The beam sample after the flexural strength test

While the compressive strength was similar for V_p/V_a ratios of 0.39 and 0.42, the strength was relatively higher for V_p/V_a = 0.45 (Figure 4.19). The grading did not affect the results as much as V_p/V_a 7-day strengths were between approximately 6 and 15 MPa (Figure 4.17). At the end of 28 days strength varied between 8 and 22 MPa. The highest strength belonged to the mixture with V_p/V_a = 0.45, Gr 1 and superplasticizer content is % 0.9 (by the weight of cement).

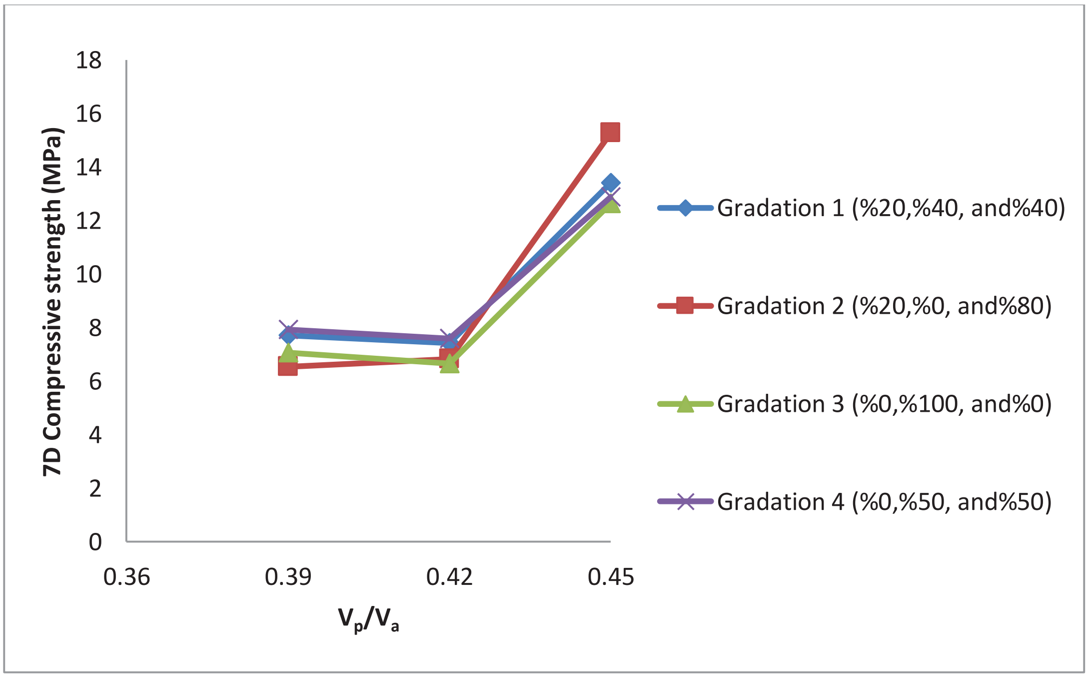

Figure 4.16 The compressive strength at different V_p/V_a

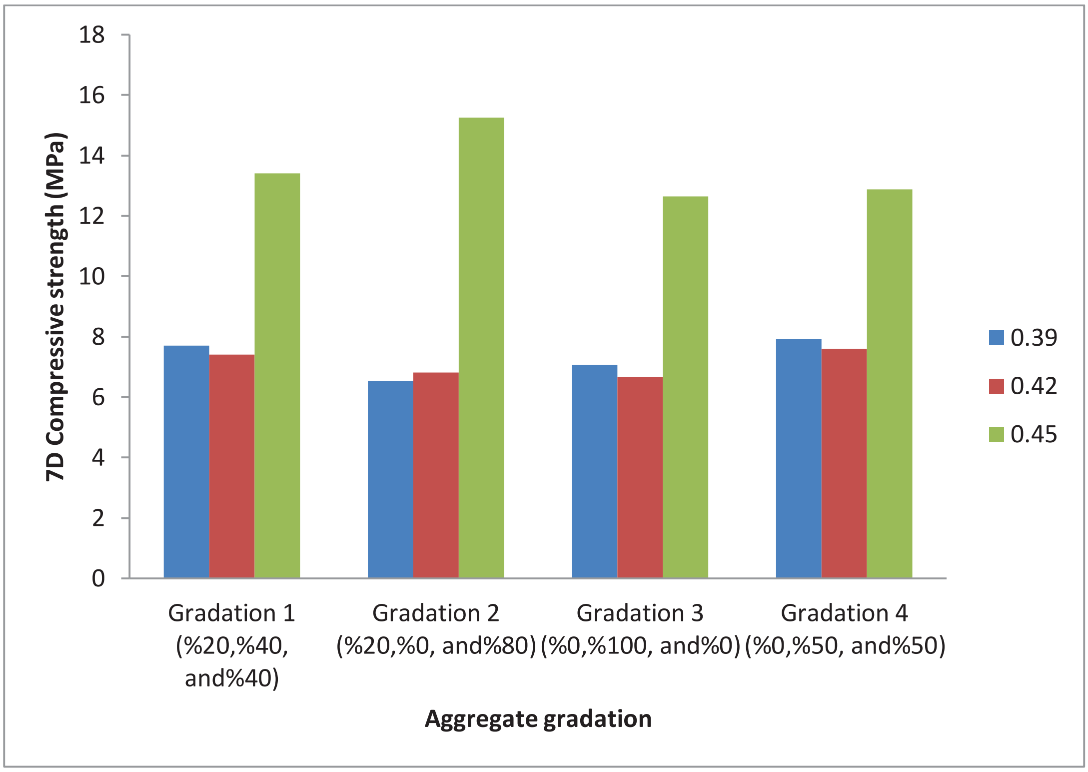

Figure 4.17 The compressive strength at different aggregate gradations

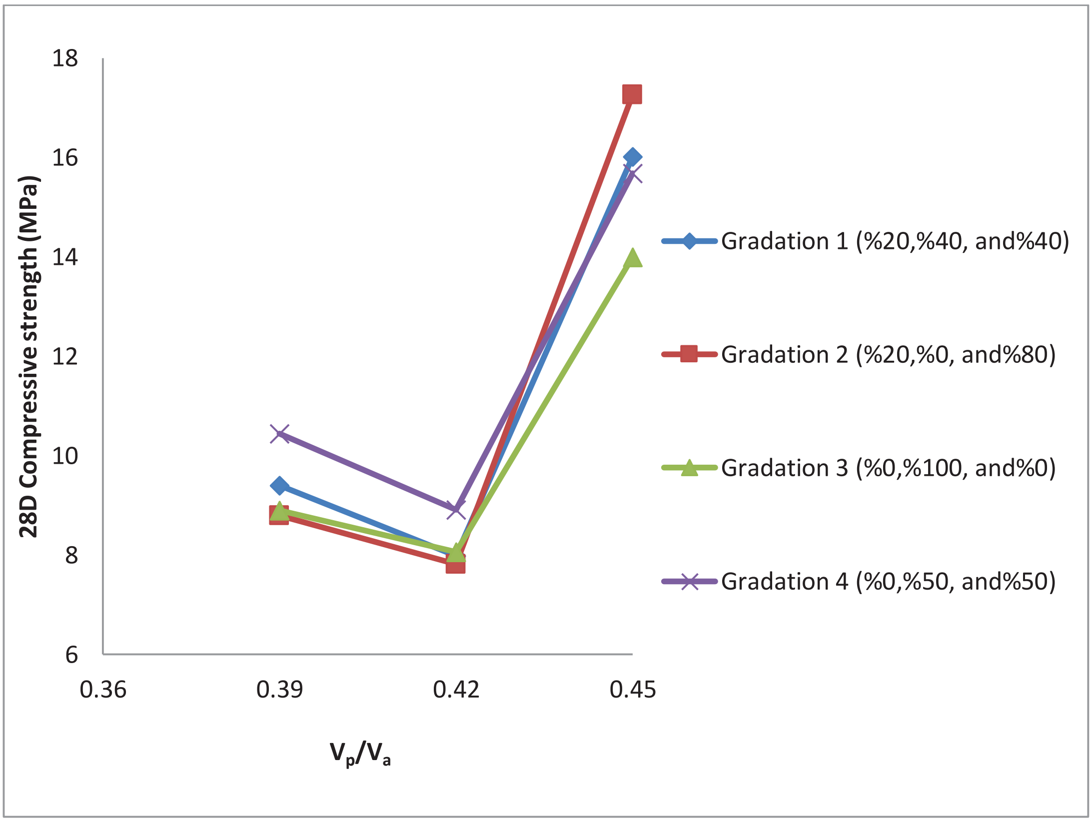

Figure 4.18 The compressive strength at different V_p/V_a

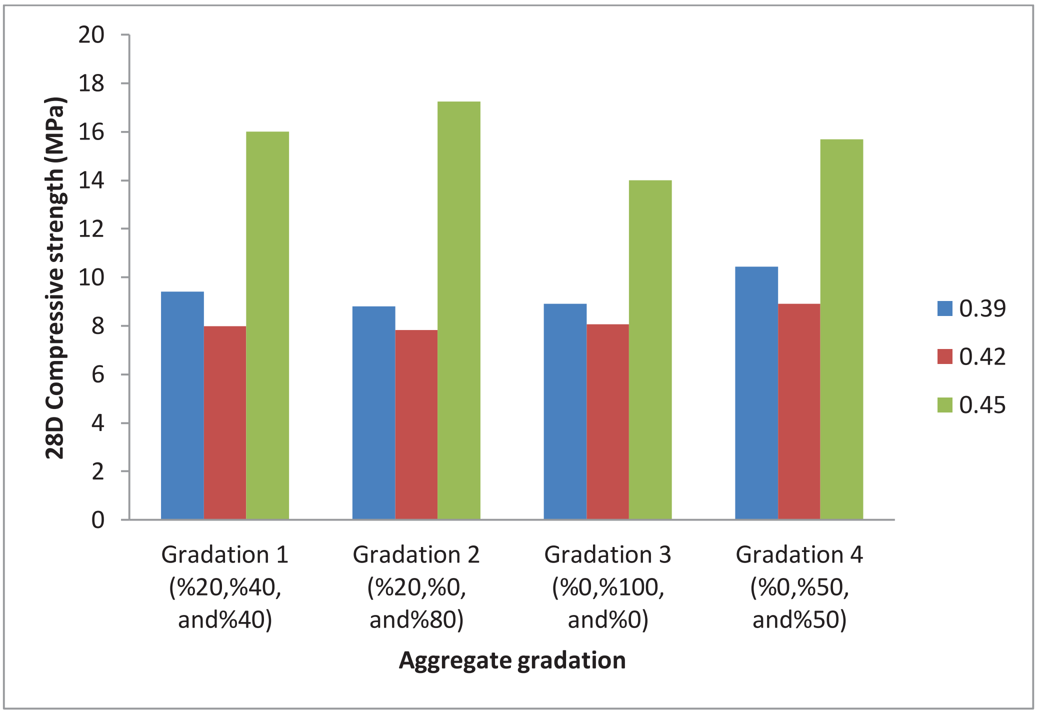

Figure 4.19 The compressive strength at different aggregate gradations

The relationship between flexural strength and paste volume to aggregate volume ratio showed the same behavior as the relationship between compressive strength at 28 days and V_p/V_a ratio (Figure 4.18 and Figure 4.20). The flexural strength was ranged between 1.92-5.11 MPa (Figure 4.21).

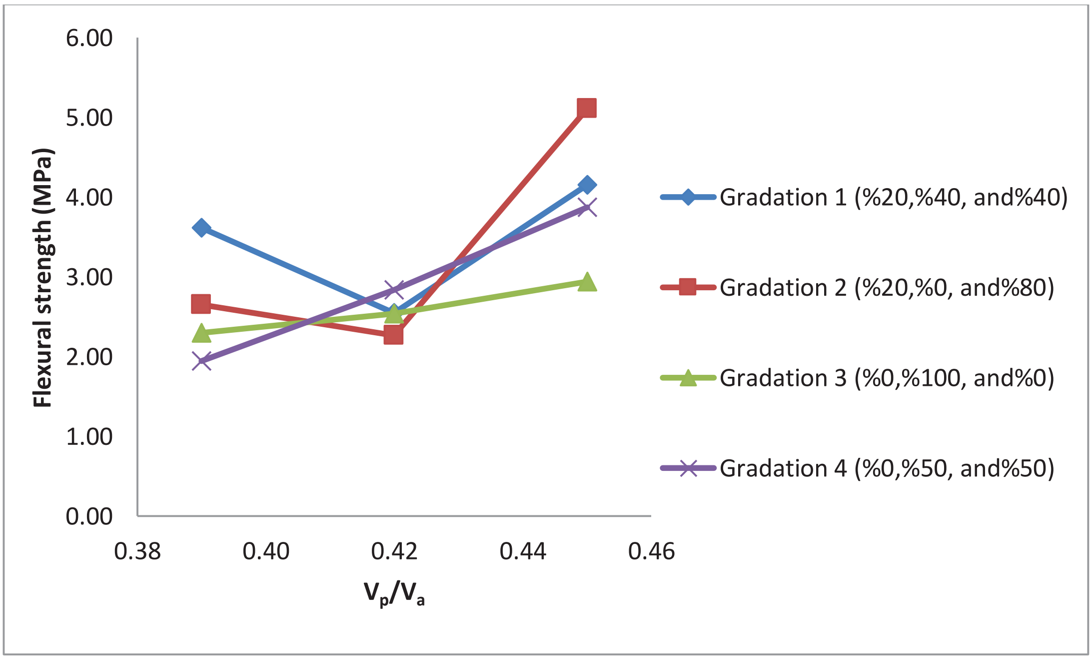

Figure 4.20 The flexural strength at different V_p/V_a ratios

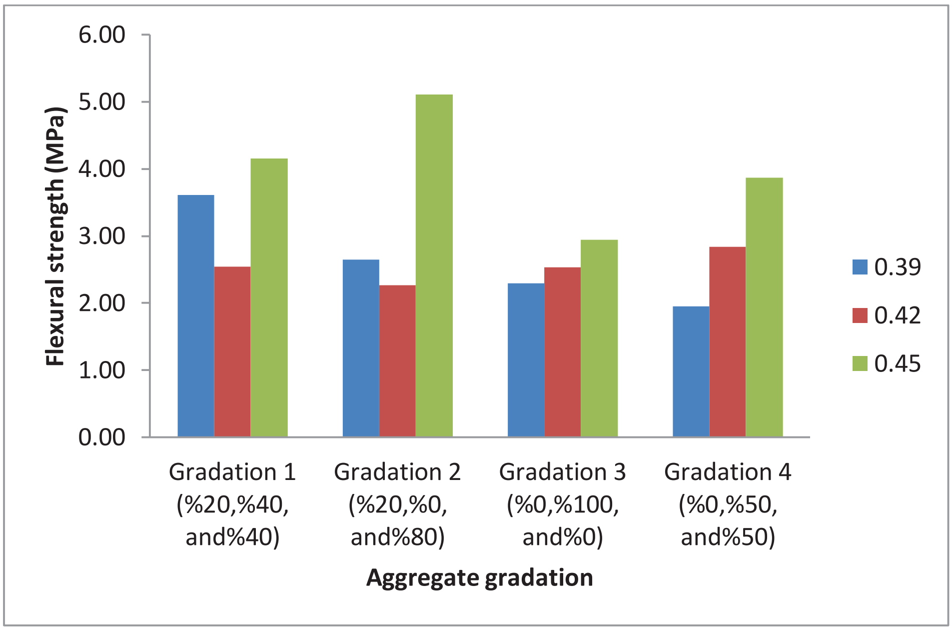

Figure 4.21 The flexural strength at different V_p/V_a ratio

As expected, there is a linear relationship between the unit weight of the fresh pervious concrete and compressive strength (Figure 4.22). There is also a linear relationship between the unit weight void of the fresh pervious concrete and compressive strength (Figure 4.23). When the unit weight of the fresh pervious concrete increases, the compressive strength increased. On the other hand, compressive strength decreased with increasing porosity of fresh pervious concrete.

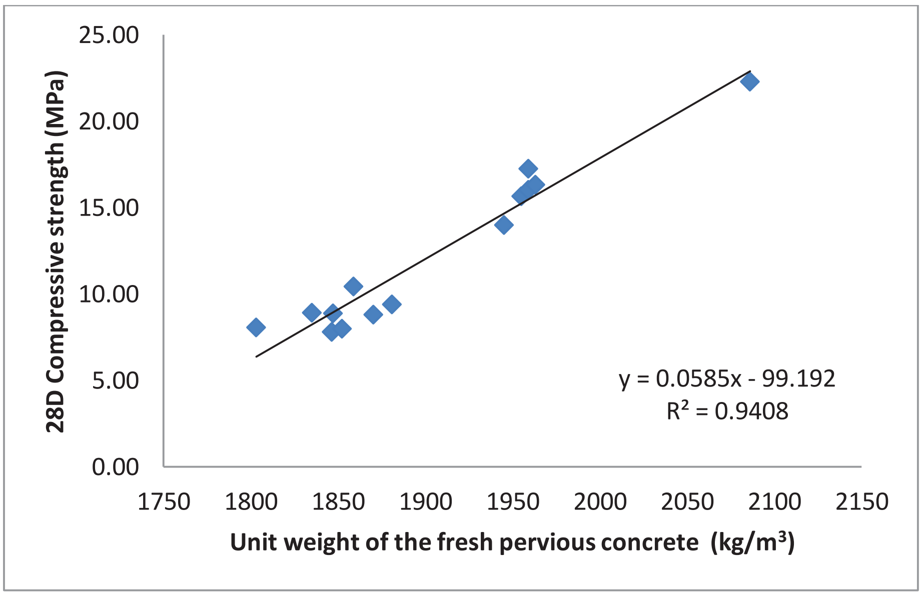

Figure 4.22 The relationship between the unit weight of the fresh pervious concrete and compressive strength

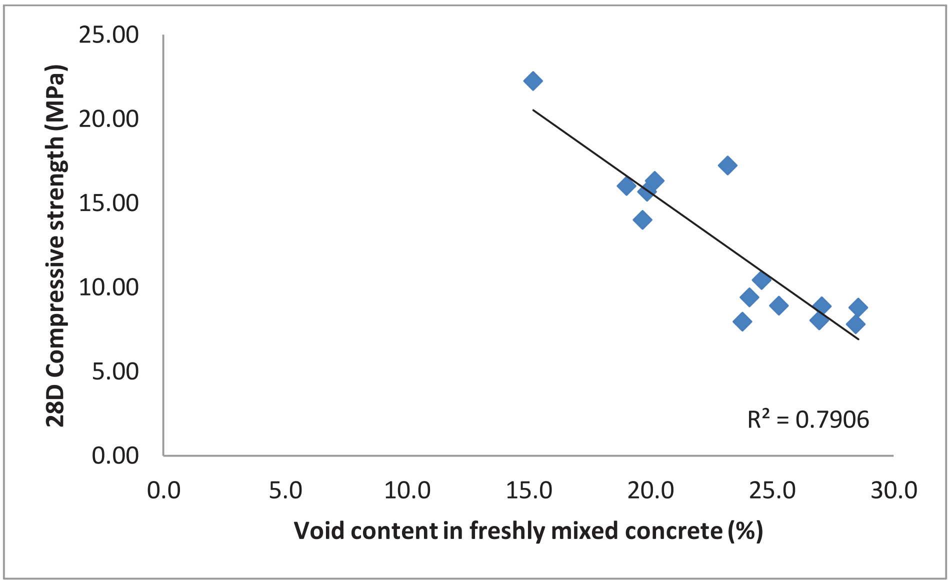

Figure 4.23 The relationship between void content in freshly mixed pervious concrete and compressive strength

Finally, as seen in Figure 4.24, there was a logarithmic relationship between permeability rate and compressive strength. The increase in the permeability rate resulted in decreasing compressive strength. In addition, when V_p/V_a was equal to 0.45, it has less permeable but high compressive strength values, on the other hand, V_p/V_a was equal to 0.42 and 0.45 the compressive strength value was less, but permeability was high (Figure 4.24 and Figure 4.25).

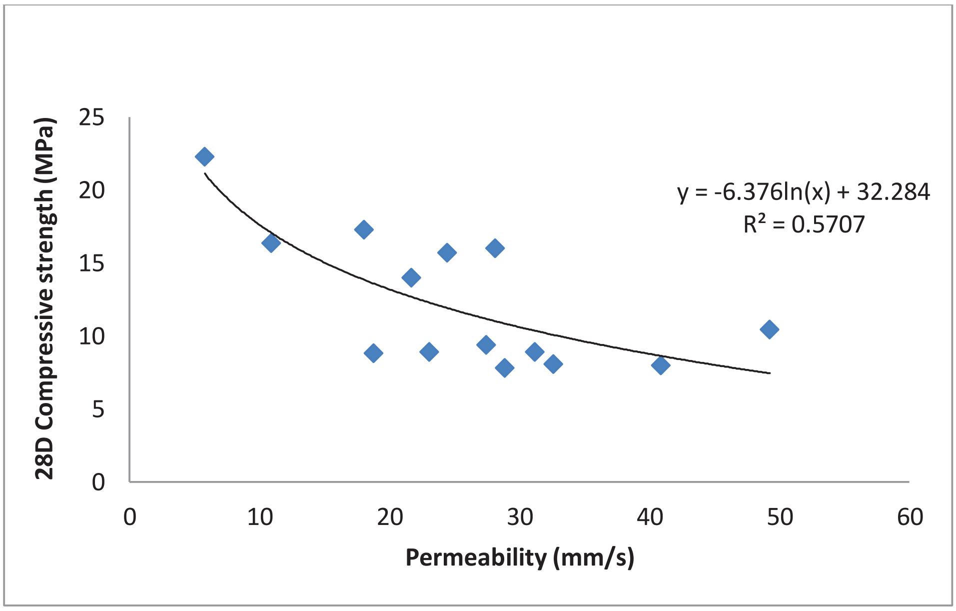

Figure 4.24 The relationship between permeability and compressive strength for all mixtures

In addition, it can be concluded that there was an inverse relationship between permeability and compressive strength. The reason for that can be explained with, for high permeability, it should be more pores structures, but porosity decreased the compressive strength.

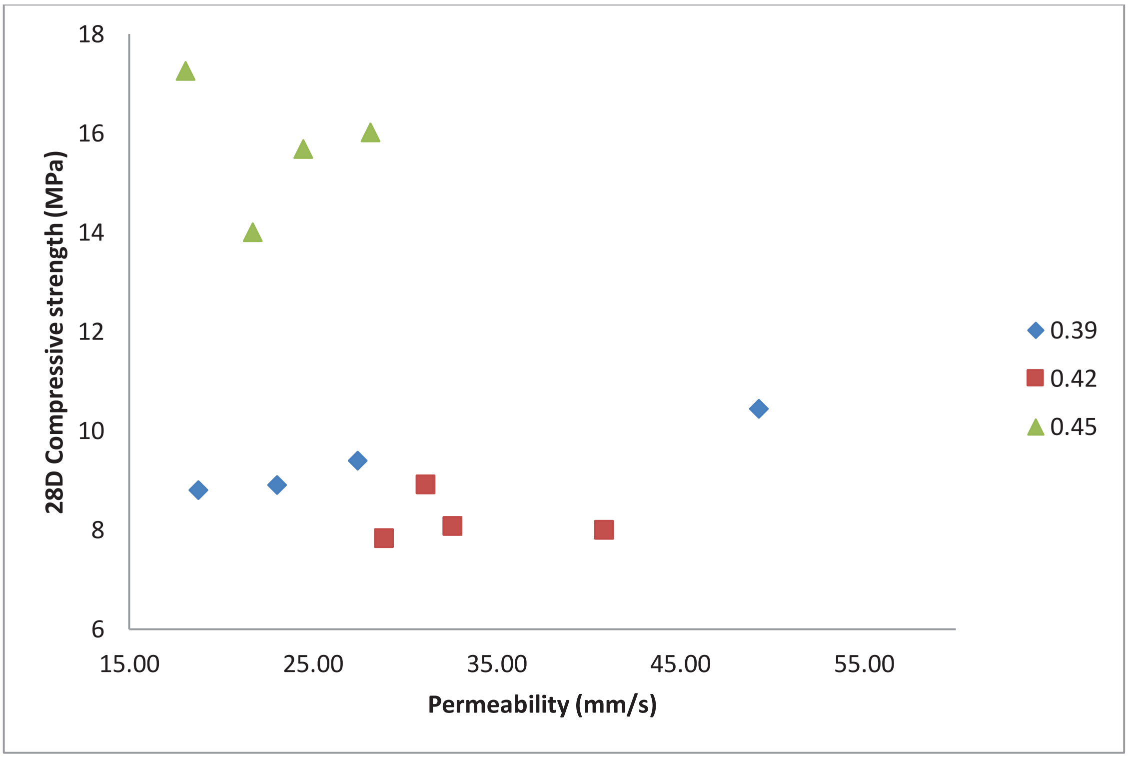

Figure 4.25 The relationship between permeability and compressive strength at SP content is equal to 0.5% (by the weight of cement)

4.2 Effects of the Different Superplasticizer Contents on the Performance of Pervious Concrete

In this study, to understand the effect of the superplasticizer on the pervious concrete, the different amount of super plasticizers was prepared. As seen in Figure 4.26, the Bingham model was set. According to results, when superplasticizer content is equal to 0.5% wt. by the weight of the cement, the highest yield stress was at that point. Moreover, when increasing the superplasticizer contents; yield stress was deceased as plastic viscosity.

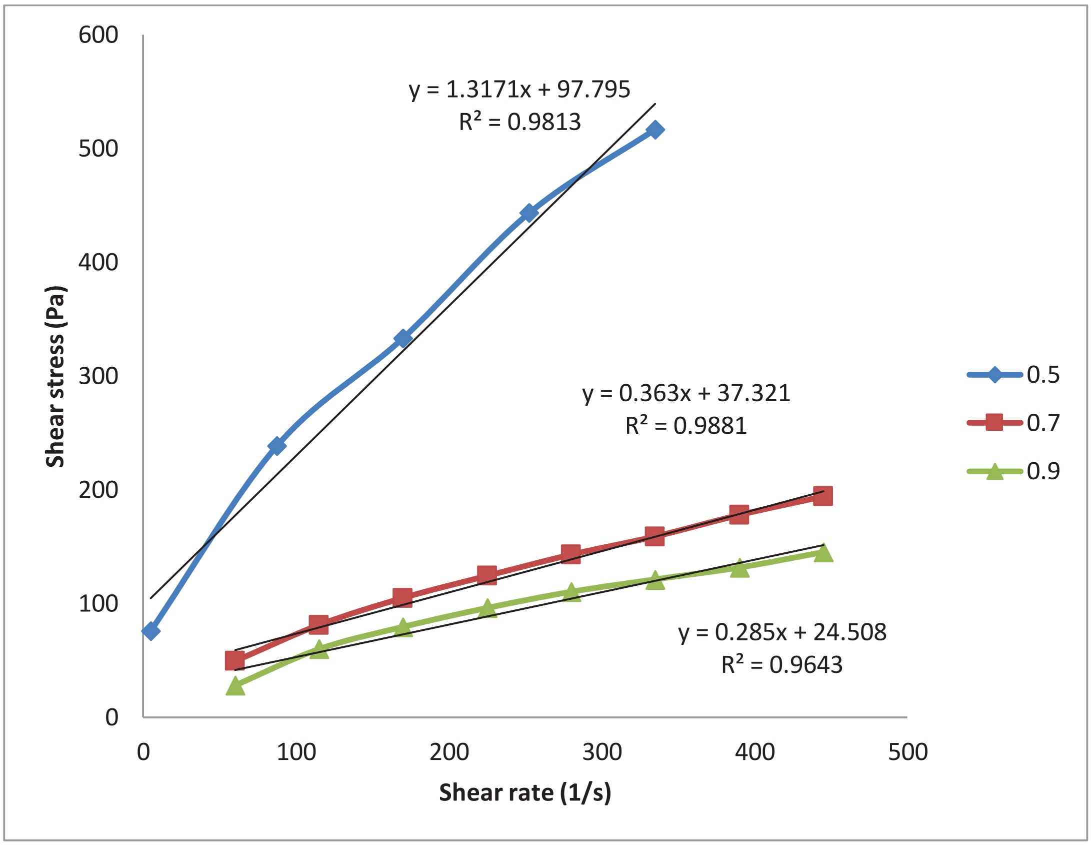

Figure 4.26 Bingham model for different superplasticizer content

In this study, many different amounts of superplasticizer were prepared to show effects of superplasticizer on pervious concrete (Table 4.4 and Table 4.5) and rheological measurement results showed that permeability rate ranged between 18.1-49.3 mm/s where the usage of superplasticizer content was 0.5% (by weight of the cement).

Table 4.4 Results of fresh pervious concrete at different superplasticizer contents

V_p/V_a	Superplasticizer content (%)	Grading type	Slump Value (cm)	Fresh Density (kg/m^3)	Fresh Density Void (%)
0.45	0.5	Gr 1	16.5	1959	19.0
0.45	0.7	Gr 1	20.5	1963	20.2
0.45	0.9	Gr 1	21.5	2086	15.2

Table 4.5 Results of hardened pervious concrete at different superplasticizer contents

V_p/V_a	Superplasticizer content (%)	Gradation Type	Beam σ (MPa)	Bond σ (MPa)	7D σ (MPa)	28D σ (MPa)	Permeability rate (cm/s)	Hardened Density (kg/m^3)	Hardened Density void (%)	Mass Loss (%)
0.45	0.5	Gr 1	4.15	13.3	13.41	16.02	2.81	1875	24	40
0.45	0.7	Gr 1	4.89	15.94	16.33	16.33	1.09	1936	23	28
0.45	0.9	Gr 1	4.47	12.84	15.88	22.28	0.58	1914	23	29

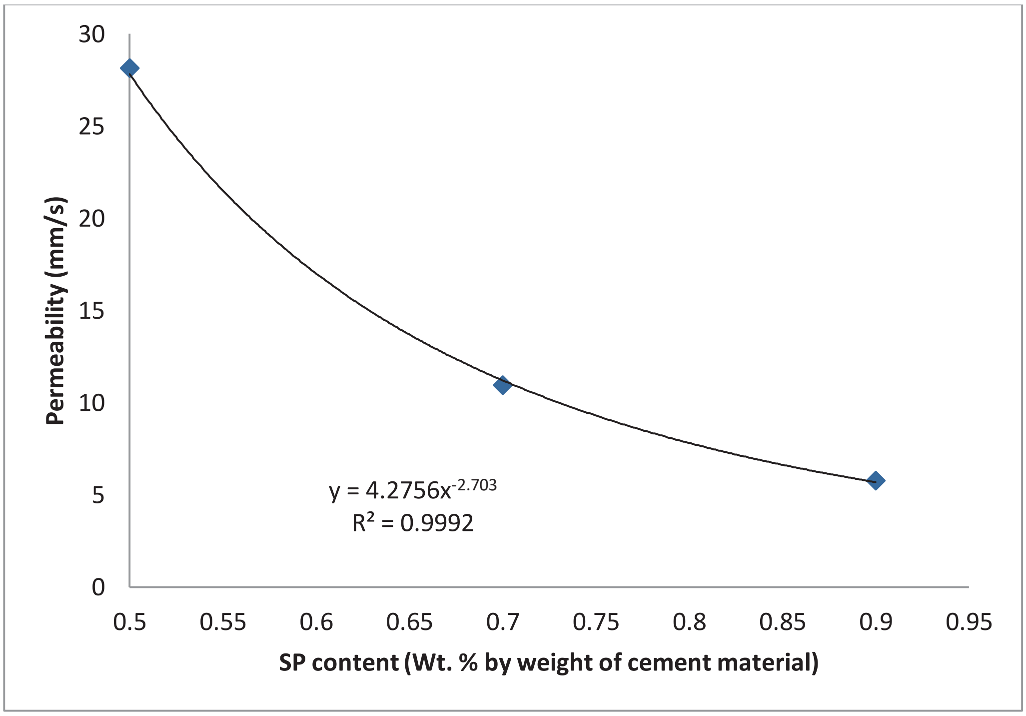

Figure 4.27 The effects of the superplasticizer content on the permeability rate

When amount of superplasticizer increased, the permeability rate reduced at 5.8-0.9 mm/s (Figure 4.27). Because increasing superplasticizer content cause to easily movement of cement paste and this situation may cause to cement paste drain into pores, filled the voids or accumulated at the bottom of the pervious concrete pavement.

A high superplasticizer content can result in the paste flowing through the voids and accumulate into void structure. A low amount of superplasticizer dosage can result in reduced adhesion between aggregate particles and placement problems. Therefore, there is a linear relationship between compressive strength and superplasticizer content.

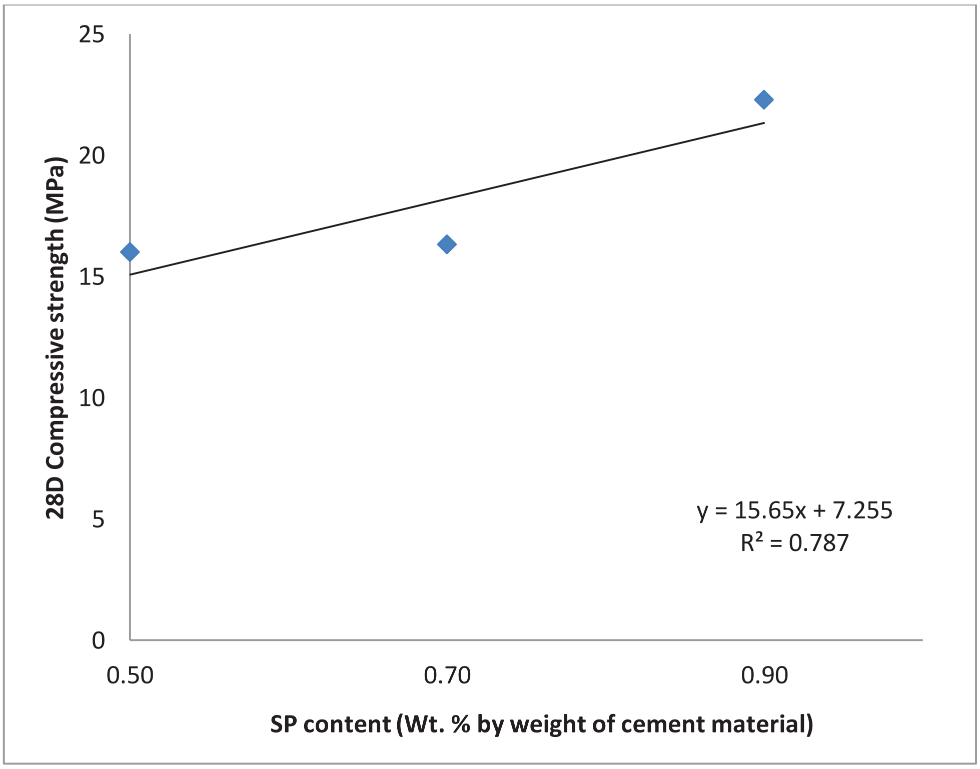

Figure 4.28 The effects of the superplasticizer content on the compressive strength

The compressive strength results show that when the amount of the usage of superplasticizer increased, compressive strength and flexural strength increased (Figure 4.28). Because when superplasticizer content increases, it can accumulate into void structure and it cause to closing of void structure. Also, as its dosage increase, the adhesion of cement paste on to aggregate surface increase, so it can cause increment of compressive strength.

4.3 Determination of Aggregate Properties and Paste Thickness

The properties of aggregate particles can affect paste thickness and performance of concrete. Therefore, in this study, shape properties of aggregate, surface area of aggregate by using different approaches and paste thickness were calculated.

4.3.1 Shape Properties of Aggregate

The shape of aggregate particles can affect properties of concrete in its fresh and hardened states. Therefore, it needs to be able to define the shape of aggregate particles [32]. It is generally accepted that the shape properties of fine aggregates and micro fines affect overall concrete properties more significantly in many cases due to their high surface area. The shape properties of coarse aggregate are determined relatively more easily and there is no fine aggregate in this study. The volume and weight of the one coarse aggregate can be easily measured. Volume (V_{true}) can be determined by using weighing in water (Archimedes' method) for coarse aggregate particles when its specific gravity is known. However, the surface area of one coarse aggregate particle is difficult to measure physically.

The dimensions of an aggregate and its position on the concrete can also affect the performance of the concrete [32]. For example, if the aggregate has a spheroid shape, the workability of concrete becomes easier and concrete has a more permeable structure, however, for the spheroid shape, the cement paste on the aggregate surface has less grip [32]. This situation is the opposite when the aggregate, has an angular shape. In other words, when angular aggregate is used in concrete, the workability and permeability are less than the spheroid aggregate. In this study, the aggregate shape properties are listed in Table 4.6.

Table 4.6 Aggregate shape properties

Aggregate shape properties					
Aggregate groups	**Sphericity**	**Shape Factor**	**Aspect Ratio**	**Elongation ratio**	**Flatness ratio**
4-8 mm	0.730	0.620	1.363	0.755	0.722
8-12.5 mm	0.692	0.492	1.315	0.802	0.570
12.5-16 mm	0.640	0.463	1.485	0.690	0.554

The flakiness index is expressed as a percentage of the flatness of the aggregate, which calculated as the percentage of the sample to the amount of aggregate passing through the grid sieve. In this study, the flakiness index was found to be 9.70%. (Table 4.7).

Table 4.7 Flakiness index results

Mass of the sample (M_o)(g)	2869	**The mass of deactivating sample (g)(under 4mm)**	253.5	
Sieve analysis by using normal sieve according to TS EN 933-3		Sieve analysis by using grid sieve according to TS 9582 EN 933-3		
Particle size fraction (d_i/D_i)	d_i/D_i Mass of the particle size fraction R_i (g)	Grid sieve opening ($D_i/2$)	The mass of the passing in the grid sieve (g)	F_i ((m_i/R_i)*100)
12.5/16	266.5	8	35.5	13.32
10/12.5	435.5	6.3	44	10.10
8/10	872.5	5	97	11.12
6.3/8	469.5	4	36.5	7.77
5/6.3	444	3.15	34.5	7.77
4/5	124.5	2.5	6	4.82
$M_1 = \sum R_i$ **:** 2612.5 g		$M_2 = \sum m_i$: 253.5 g		
$\mathbf{FI} = \frac{\mathbf{M_2}}{\mathbf{M_1}} \times \mathbf{100}$: 9.70				

Another important aggregate property that can affect the performance of pervious concrete is the crushing strength of the aggregate because when concrete is under the load, aggregates carry the load. In this study, the crushing strengths of different aggregate gradation groups were determined and they were as given in Table 4.8. The crushing strength of the aggregate results were changed between 0.70 MPa and 5.35 MPa.

Table 4.8 Results of the crushing strength for aggregate

Gradation of aggregate	Length (cm)	Width (cm)	Thickness (cm)	Thickness between two parallel plates (cm)	Maximum load P (KN)	Crushing strength value σ (KN/ cm^2)
4-8 mm	0.90	0.90	0.40	0.40	0.62	3.45
4-8 mm	1.25	0.80	0.40	0.40	0.30	1.67
4-8 mm	0.50	0.40	0.40	0.40	0.70	3.90
4-8 mm	0.90	0.60	0.50	0.50	0.40	1.43
4-8 mm	0.90	0.60	0.50	0.50	0.20	0.71
8-12.5 mm	1.10	1.00	0.40	0.40	0.93	5.20
8-12.5 mm	1.20	1.00	0.80	0.80	0.89	1.24
8-12.5 mm	1.00	0.95	0.30	0.30	0.54	5.35
8-12.5 mm	1.20	0.60	0.50	0.50	0.73	2.60
8-12.5 mm	1.10	0.90	0.45	0.50	0.72	3.17
12.5-16 mm	1.60	1.15	0.6	0.65	0.8	1.98
12.5-16 mm	1.30	1.10	0.75	0.75	1.27	2.00
12.5-16 mm	1.95	1.40	0.75	0.80	1.18	1.87
12.5-16 mm	2.05	1.30	0.82	0.80	1.21	1.61
12.5-16 mm	2.35	1.25	0.50	0.60	0.95	3.39
Crushing strength value σ	P: Maximum load before the failure of aggregate X: Thickness between two parallel plate $\sigma = \frac{2.8 * P}{\pi * X^2}$					

4.3.2 Surface Area of Aggregate

There are different techniques to determine actual surface area of aggregate like Surface Erosion-Dilation Techniques, Fractal Behavior Technique, and Hough Transform for analysis of angularity, and Intensity Histogram Method and Fast Fourier

Transform Method for analysis of texture, VDG-40 Video grader, Georgia Tech Digital Imaging System; Wip Frag and Wip Shape System, Retsch Technology (GMBH) and Illinois Image Analyser (University of Illinois at Urbana Champaign) [32].

Many researchers used digital techniques to estimate particle shape properties [27, 29, 64, 65]. Because it can be used to investigate particle shape at different scales and obtain different shape properties that, make possible to quantify their distinct effects on the properties of concrete. Also, it is quick method, can eliminate human errors and perform sophisticated measurements such as determination of perimeter, equivalent areas, shortest and longest dimensions, particle count, area fraction, size distribution, etc. the working principle of a digital imaging system is based on pixel analysis and the results are derived from two-dimensional images [32]. For example, to determine the porosity of concrete, computed tomography machine, which is based on image processing through image analysis, can be used. Image analysis can be used to estimate aggregate properties such as surface area, volume, flakiness roughness, circularity, etc. The most important advantage of CT is that the determined value can be considered the true value, but this idea may be limited by the scan resolution that means when aggregate shape becomes larger the obtained results are more accurate size-to-pixel size ratios and the using of CT devices are expensive and the process takes a long time when compared by using software programs [32]. Therefore, imaging technology has been started to use to quantify aggregate shape characteristics and their relationship to the performance of concrete. There are also important drawbacks as well as the advantages that using of the imaging system. One of the disadvantage is that dimensions measured in two-dimensions do not directly correlate or show the actual dimensions of the particles.

In this study, the surface area of the aggregates was calculated by different approaches as summarized below.

Approach 1 by dividing the paste volume to the paste thickness determined from AutoCAD measurements on the cut-section images (See Section 3.3.2.1), approach 2 by an empirical formula based on L (Longest dimension), I (Intermediate dimension), and S (Smallest dimension) of the aggregate, approach 3 by assuming that the aggregates have a spherical shape, and approach 4 by image analysis (ReCap Method).

In approach 1, the total surface area of aggregates was determined from Equation 4.1.

$$\textbf{Total Surface Area of Aggregate} = \frac{\textbf{Paste Volume}}{\textbf{Paste thickness with measured AutoCAD}}$$

(4.1)

In approach all, firstly the number of aggregates from each size group in the concrete was calculated according to Equation 4.2. Then, the surface area of one particle was calculated by dividing the total surface area to the number of particles.

$$\textbf{Number of aggregate} = \frac{\textbf{Mass of the aggregate at diffenrent aggregate gradation}}{\textbf{Mass of one aggregate at each aggregate groups}}.$$

(4.2)

In approach 2, an empirical equation (based on the assumption that the particle has a prismatic shape with dimensions L,I, and S) given in Equation 4.3 was developed in approach 2. The connection factor "k" in Equation 4.3 was determined by Solver Add-on in Excel software. This procedure was made for all of the 3 aggregate size groups. The surface area and connection factor for each group is given in Table 4.9.

$$\textbf{Surface area of 1 particle} = (\mathbf{L} * \mathbf{I} + \mathbf{L} * \mathbf{S} + \mathbf{I} * \mathbf{S}) * \mathbf{2} * \mathbf{k}$$

(4.3)

Table 4.9 Surface area of an aggregate and coefficient factor at different aggregate groups for approach 2

Aggregate groups	**Longest (L) (cm)**	**Intermediate (I) (cm)**	**Shortest (S) (cm)**	**Coefficient Factor (k)**	**Surface Area (cm^2)**
4-8 mm	0.890	0.660	0.440	2.67	2.40
8-12.5 mm	1.120	0.890	0.490	6.18	3.86
12.5-16 mm	1.850	1.240	0.684	5.24	8.82

In approach 3, the aggregate particles were assumed to have spherical shape. The average diameter of the spheres was assumed as the mid-size of an aggregate size group. For example, the average diameter of 4-8 mm size group was taken 6 mm. Then, the volume of 1 sphere was calculated. In this approach, again the number of particles were determined but this time it was calculated by dividing the volume of aggregates to the volume of a sphere for a given size group. Then the surface area of 1 particle was calculated by dividing the total surface area found in approach 1 to the number of particles. Afterwards, the model given in Equation 4.4 was established. The surface area and k_2 constant are given in Table 4.10.

$$\textbf{Surface area of 1 particle} = 4 * \pi * r^2 * k_2 \tag{4.4}$$

Table 4.10 Surface area of an aggregate and coefficient factor at different aggregate groups for approach 3

Aggregate groups	**Coefficient Factor (k_2)**	**Surface Area of 1 particle (cm^2)**
4-8 mm	5.68	1.13
8-12.5 mm	7.42	3.30
12.5-16 mm	7.34	6.38

Approach 4 is based on pixels in image analysis by using Autodesk ReCap Photo software program. Totally, five aggregate were analyzed in the software program and their averages was taken in order to represent a single value. A same process was done for each aggregate group. Then, the program gave the surface area of aggregate and their results were listed at Table 4.11.

Table 4.11 Surface area of an aggregate and coefficient factor at different aggregate groups for approach 4

Aggregate groups	**Coefficient Factor (k_3)**	**Surface Area of 1 particle (cm^2)**
4-8 mm	2.47	1.08
8-12.5 mm	8.84	2.7
12.5-16 mm	5.77	9.27

Paste thickness

The previous studies concluded that for determining average asphalt layer film thickness which affect the performance of concrete, SA_{true} is an important factor for determination. As the volume of the interfacial transition zone, permeability, strength, and elasticity are influenced by particle size distribution (PSD) and angularity, surface texture, hence the surface area of coarse and fine aggregates. Large surface area causes small film thickness.

Table 4.12 Results of paste thickness for a different hypothesis

V_p/V_a	Aggregate gradation	Paste thickness calculated by AutoCAD (mm)	Paste thickness calculated by Approach 2 (mm)	Paste thickness calculated by Approach 3 (mm)	Paste thickness calculated by Approach 4 (mm)
0.39	Gr 1	2.44	2.44	2.45	2.64
0.39	Gr 2	2.52	2.52	2.50	2.51
0.39	Gr 3	2.23	2.36	2.34	2.40
0.39	Gr 4	2.40	2.45	2.41	2.30
0.42	Gr 1	2.61	2.63	2.65	2.80
0.42	Gr 2	2.69	2.71	2.69	2.70
0.42	Gr 3	2.60	2.55	2.52	2.61
0.42	Gr 4	2.61	2.64	2.60	2.49
0.45	Gr 1	3.05	2.80	2.83	3.05
0.45	Gr 2	2.88	2.88	2.88	2.90
0.45	Gr 3	2.70	2.70	2.70	2.79
0.45	Gr 4	3.15	2.81	2.79	3.10

Paste thickness is a function of the surface area of the aggregate and the volume of paste used in pervious concrete. Therefore, to determine the cementitious paste thickness of each sample, firstly the surface area of aggregate has to be known. Since the surface area was determined by different approaches, the paste thickness calculations ended up several values as shown Table 4.12.

According to paste thickness results, when V_p/V_a ratio was increased, the paste thickness increased for all approaches. Generally, the gradation 3 showed the largest surface area and the least paste thickness and gradation 2 showed the smallest surface areas and the highest paste thickness (Figure 4.29 and Table 4.12). Results expressed that among different aggregate gradations, Gr 3 (which only 8-12.5 mm aggregate class) has the largest surface area (Figure 4.30).

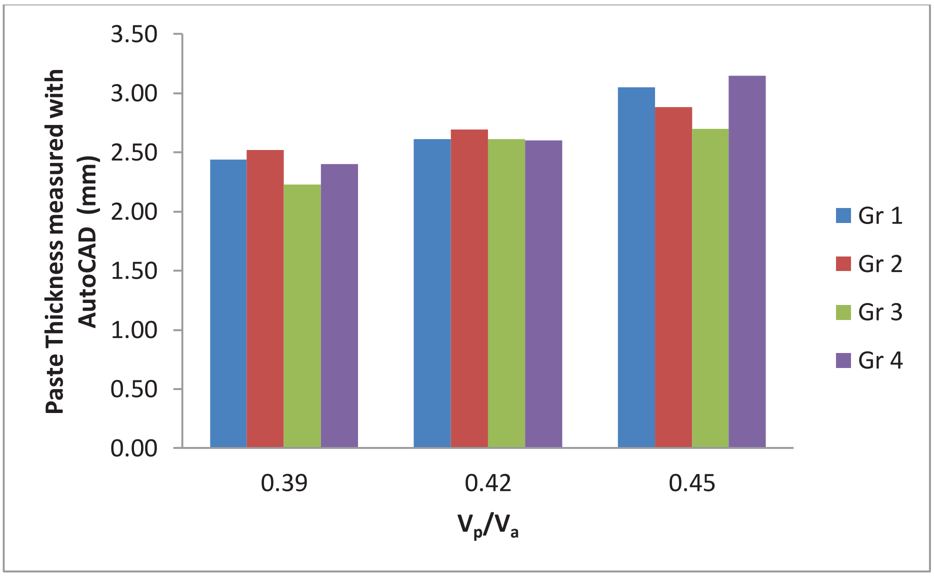

Figure 4.29 Paste thicknesses at different V_p/V_a ratios

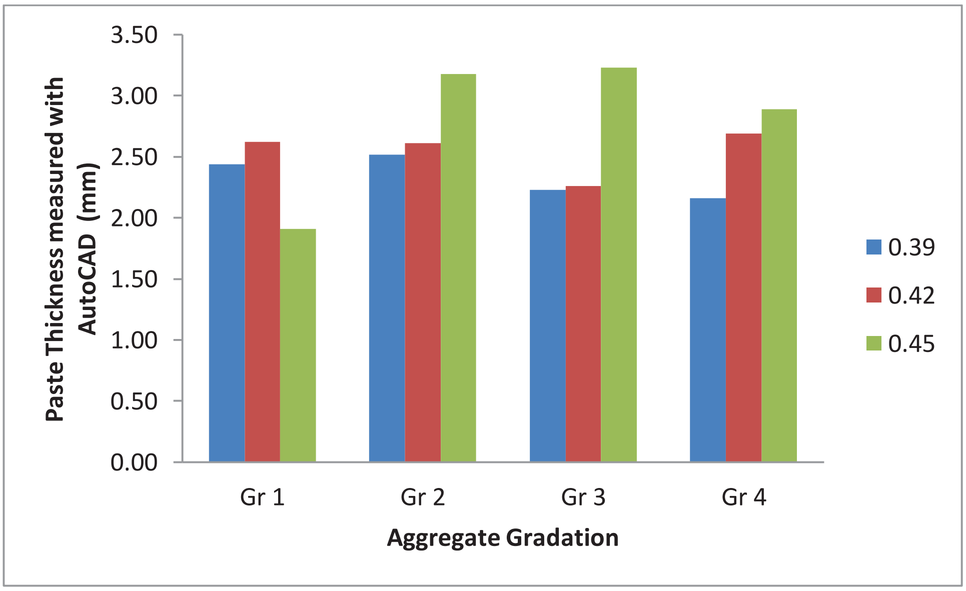

Figure 4.30 Paste thickness at different aggregate gradations

To sum up, small aggregates have high paste adhesion (hold more paste per mass of aggregate) than large-size aggregates, but due to their smaller surface area, the paste thickness on the aggregate surface is thinner than a larger particle.

Figures 4.31, 4.32, and 4.33 compare to the paste thickness values determined by different methods. As seen, all of the methods yielded R^2 values dose to 0.84, which indicates successful correlations.

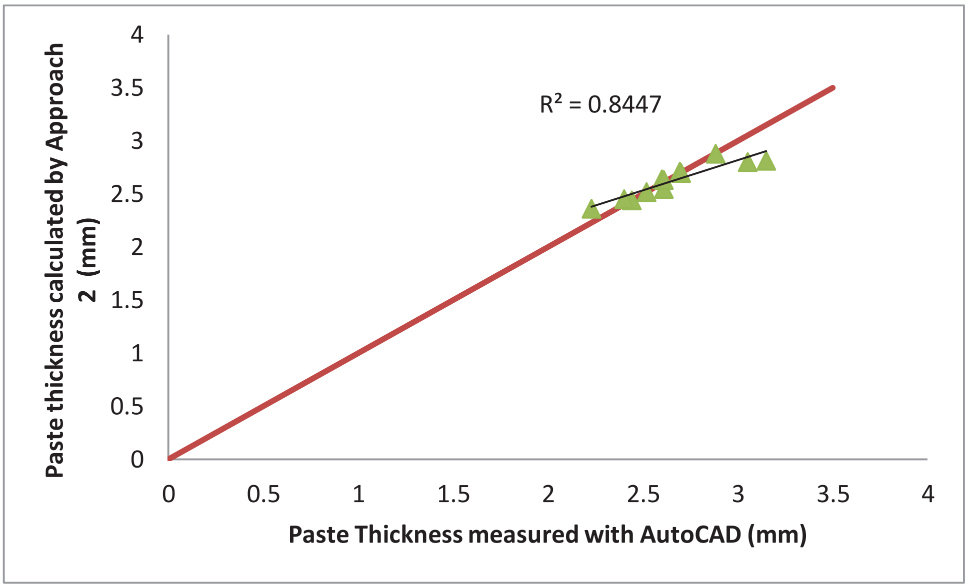

Figure 4.31 Relationship between paste thickness calculated by Approach 2 and paste thickness measured with AutoCAD

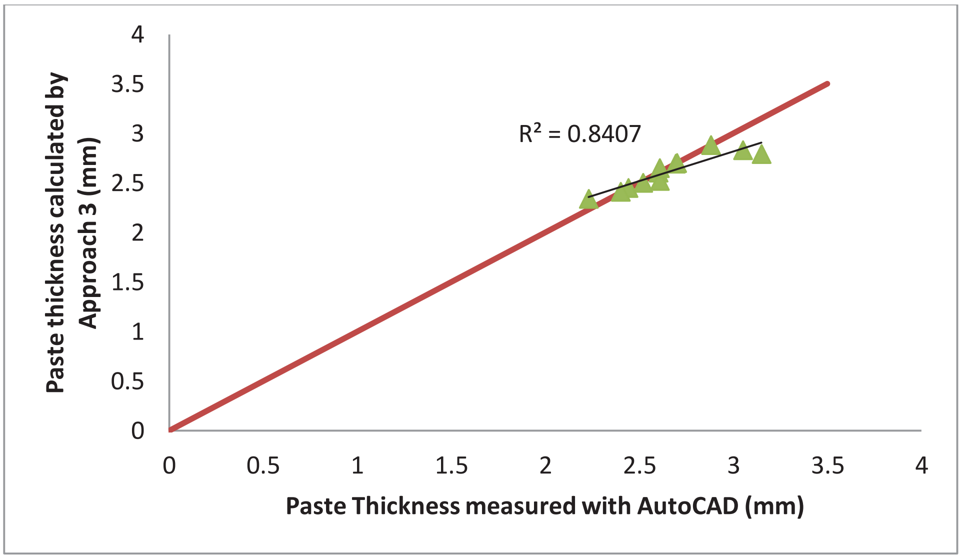

Figure 4.32 Relationship between paste thickness calculated by Approach 3 and paste thickness measured with AutoCAD

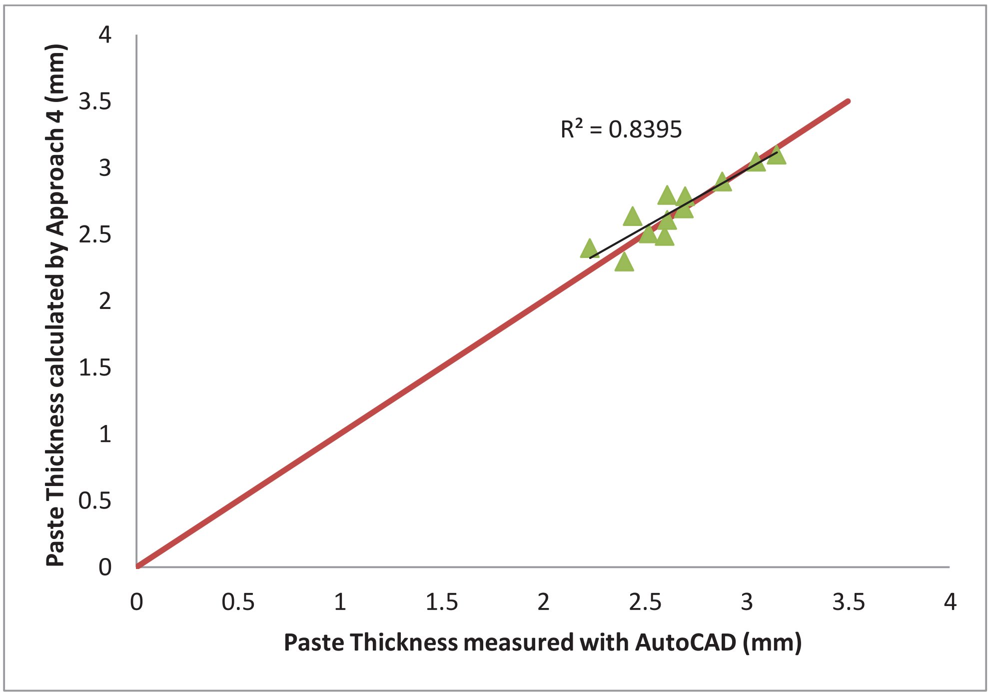

Figure 4.33 Relationship between paste thickness calculated by Approach 4 and paste thickness measured with AutoCAD

In addition to a comparison of paste thickness calculated by using the surface area of aggregate obtained from ReCap Photo program with paste thickness calculated by empirical formula showed similar paste thickness and R^2 value is 0.71 (Figure 4.34).

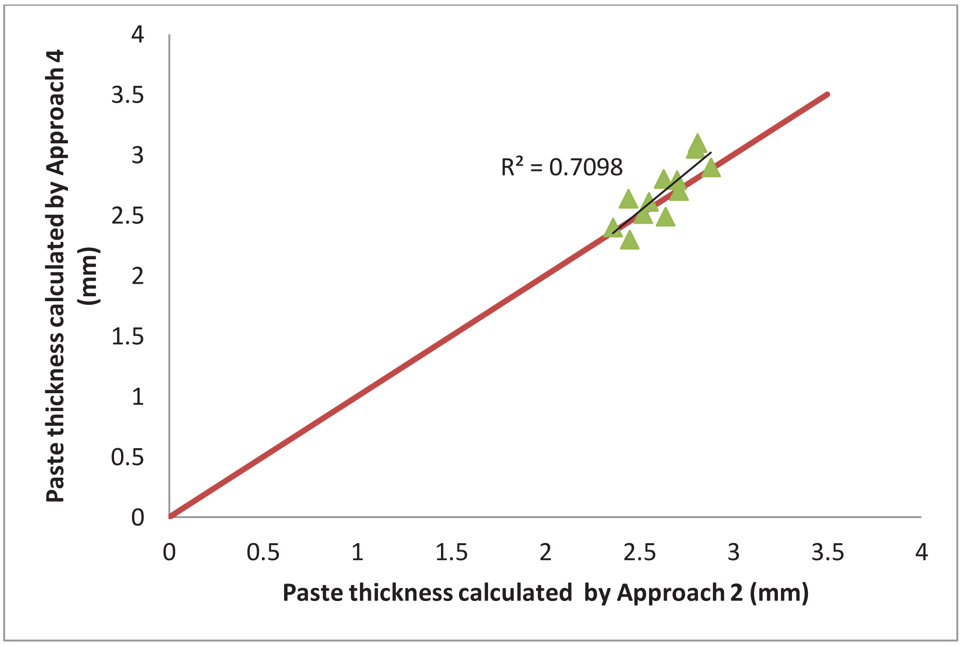

Figure 4.34 Relationship between paste thickness calculated by Approach 4 and paste thickness calculated by Approach 2

4.4 Relationship between Paste Thickness and Performance of Concrete

Structure of pervious concrete consists of coarse aggregate surrounded by a thin layer of portland cement paste and interrelated or closed pore. In this section, correlations between paste thickness and important properties of pervious concrete such as hardened density and it's void content, permeability, compressive and tensile strength were investigated. The paste thickness values discussed in this section were those obtained from AutoCAD measurements since they were the most reliable values.

4.4.1 Compressive Strength

A positive relation between paste thickness and compressive strength can be expected according to literature. As can be seen in Figure 4.35, an increase paste thickness, increased compressive strength of pervious. This situation was expected because paste thickness increase, aggregate/paste interlocking, bonding of aggregate structure, resulting in higher compressive strength.

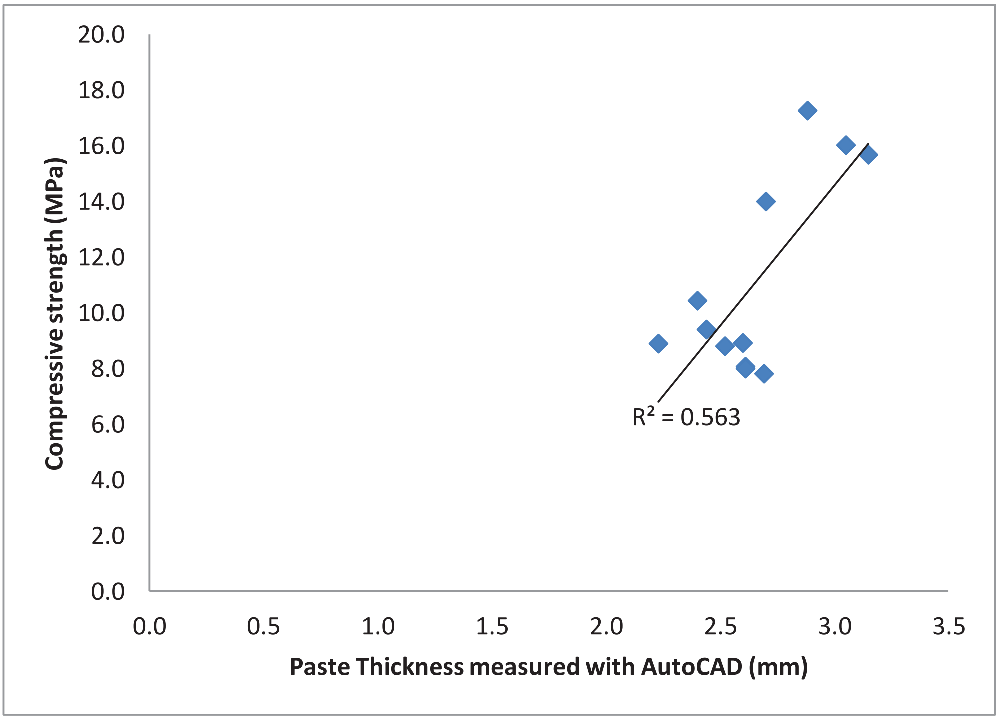

Figure 4.35 Relationship between compressive strength of pervious concrete and paste thickness measured with AutoCAD

4.4.2 Permeability

Generally, permeability rate is related with void percentage in pervious concrete, which means when the concrete has a higher porosity, the expectation is higher permeability. But this expectation may not be always true because the permeability is a function of the aggregate gradation, void surface area, void size, and distribution.

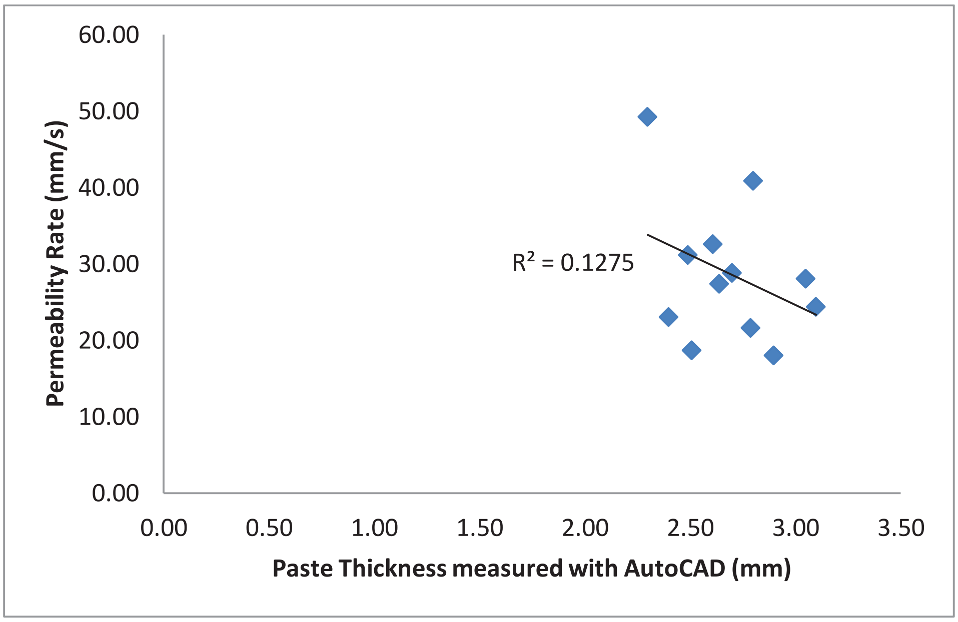

Figure 4.36 Relationship between permeability rate of pervious concrete and paste thickness measured with AutoCAD

According to paste thickness and surface area of aggregate results, the surface area of aggregate increase the paste thickness becomes a thinner around the aggregate surface. Therefore, it resulted in a higher permeability rate as seen in Figure 4.36. However, this has a negative effect on compressive and tensile strength of pervious concrete.

4.4.3 Hardened Density and Void Content

There is a linear relationship between the density of hardened pervious concrete and paste thickness. When paste thickness increases, hardened density increases (Figure 4.37).

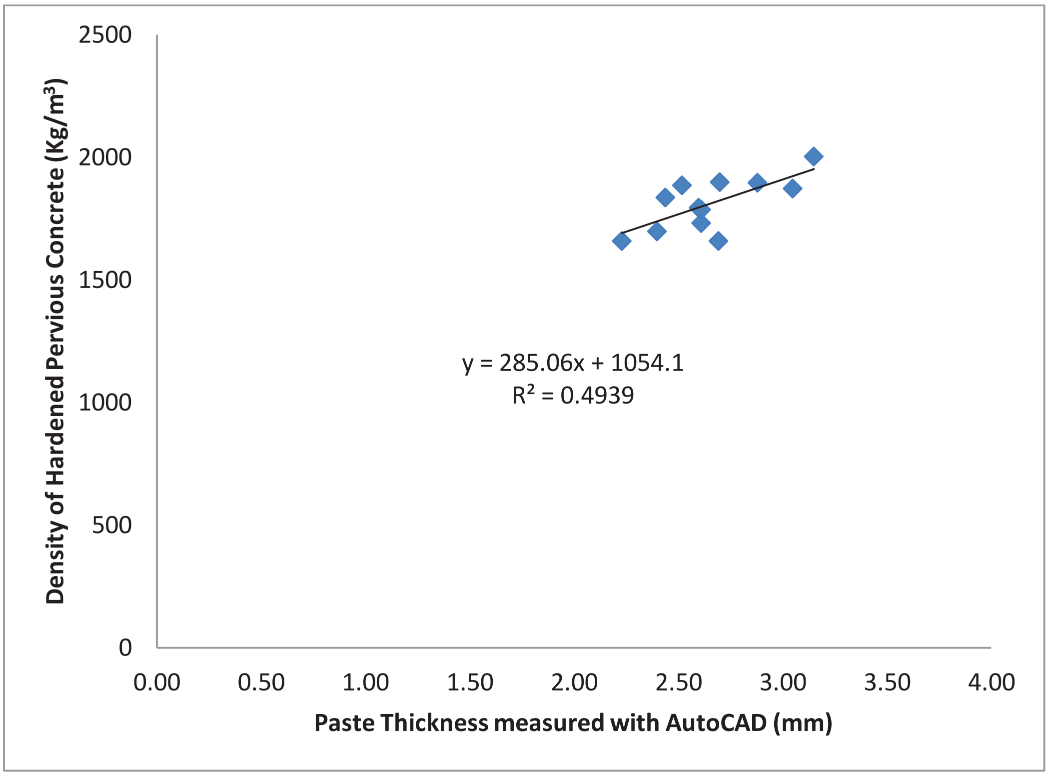

Figure 4.37 Relationship between the hardened density of pervious concrete and paste thickness measured with AutoCAD

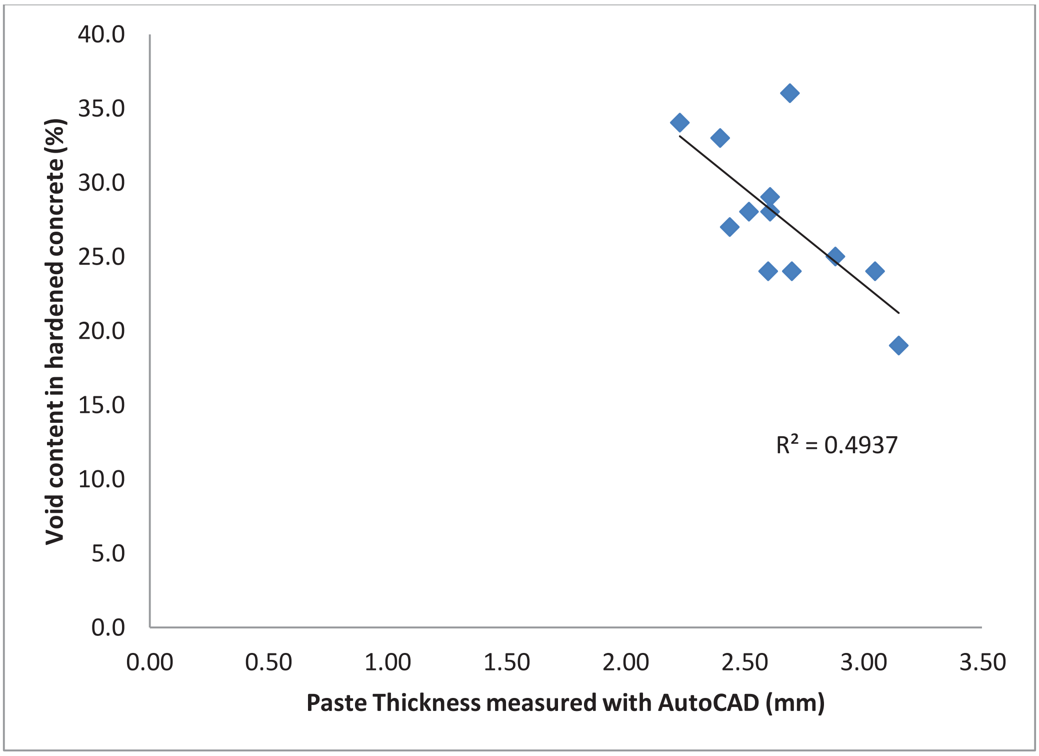

Figure 4.38 Relationship void content in pervious concrete and paste thickness measured with AutoCAD

There is also a linear but negative relationship between void content in hardened pervious concrete and paste thickness. The amount of materials in pervious concrete affects the thickness of the cement paste, the placement of the concrete and compaction technique influences paste thickness. Some studies concluded that the cement content and compaction level plays a role in the porosity of the samples. Uncompacted samples result in a lower paste thickness as well as a correspondingly higher porosity.

4.4.4 Superplasticizer Contents

Superplasticizer dosage has to be carefully determined in order to obtain adequate film-forming property and sufficient fluidity. Increase of SP dosage above the optimum dose will result in a reduction of paste thickness. In this study, paste thickness increased with increasing superplasticizer content at a specific point, after the optimum point, paste thickness decreased with increasing superplasticizer content.

CHAPTER 5

CONCLUSION

This study is on pervious concrete that has several advantages for the ecology. Therefore, many tests were performed to obtain an optimum mixture for pervious concrete. The performance of pervious concrete depends on its permeability rate, compressive strength, flexural strength, void content, and density. In this experimental study, firstly, the performance of pervious concrete was tested at different V_p/V_a and aggregate gradation to understand their effects on pervious concrete. According to the results, slump value did not affect significantly with V_p/V_a and aggregate gradation. Unit weight of the fresh pervious concrete reached at highest value when aggregate gradation is Gr 1, On the other hand, the highest void content in fresh pervious concrete was obtained at Gr 2. Also, it was found that the unit weight of the fresh density of pervious concrete depends on the unit weight of the aggregate gradation. For all mixtures, the highest performance in terms of unit weight of the fresh pervious concrete, density of hardened concrete, compressive strength and flexural strength was at $V_p/V_a =$ 0.45. However, the lowest performance obtained at $V_p/V_a = 0.45$ for the permeability rate and void content. The reason is that excess cement paste may cause clogging of the pores in pervious concrete and, it resulted in a reduction of permeability rate. The compressive strength of the pervious concrete increased only 2 MPa, when V_p/V_a ratio increased the 0.39 to 0.42, but the increment was significant when V_p/V_a ratio was 0.45. The compressive strength of pervious concrete reached 22.28 MPa when V_p/V_a ratio was 0.45 and Gr 2.

In second part of the study, for calculating paste thickness, four different approaches have been implemented on pervious concrete that takes into account the effect of the amount of cement paste and aggregate gradations in a mixture. These approaches based on obtaining nearly similar results of real aggregate surface area and these approaches are cheap and basic compared to other techniques in the literature. According to results, the size of the aggregate, V_p/V_a ratio, and aggregate gradation has an effect on the cementitious paste thickness, higher V_p/V_a ratio resulted in thicker paste surrounding the aggregate. When aggregate gets smaller, the cement paste thickness becomes higher. In this study, there is also a set a relation between paste thickness and properties of pervious concrete to understand the behavior of pervious concrete. According to the results, the permeability of the pervious concrete samples decreased with an increase in cementitious paste thickness. The thicker paste thickness resulted in smaller void space and the 28-day compressive strength and flexural strength increased with an increase in cementitious paste thickness up to a point.

CHAPTER 6

SUGGESTION

In this study shows that surface area of aggregate is so important to define paste thickness, therefore computed tomography system could be used to reach real surface area of aggregate and using of this surface area can be used to obtain real paste thickness that it could be compared with paste thickness by using AutoCAD measurements. Finally, the permeability rate of pervious concrete is so important, therefore permeability test can be performed in the field in the long term to understand the clogging with the time and this set up can be measured by using different permeability tests for comparing to each other such as falling head test, constant head test, etc.

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APPENDIX A

MIXTURE PROPORTIONS OF PERVIOUS CONCRETE

Table A.1 The mixture proportions for each mixture design in kg/m^3

Water	Cement	V_p/V_a Ratio	Agg. Grading type	4-8 mm	8-12.5 mm	12.5-16 mm	Aggregate	Pigment	SP
108.90	330.0	0.39	Gr 1	292.66	585.32	585.32	1463.29	8.25	1.65
108.90	330.0	0.39	Gr 2	292.66	0.00	1170.63	1463.29	8.25	1.65
108.90	330.0	0.39	Gr 3	0.00	1463.29	0.00	1463.29	8.25	1.65
108.90	330.0	0.39	Gr 4	0.00	731.65	731.65	1463.29	8.25	1.65
108.90	330.0	0.42	Gr 1	271.75	543.51	543.51	1358.77	8.25	1.65
108.90	330.0	0.42	Gr 2	271.75	0.00	1087.02	1358.77	8.25	1.65
108.90	330.0	0.42	Gr 3	0.00	1358.77	0.00	1358.77	8.25	1.65
108.90	330.0	0.42	Gr 1	0.00	679.39	679.39	1358.77	8.25	1.65
108.90	330.0	0.45	Gr 1	253.64	507.27	507.27	1268.18	8.25	1.65
108.90	330.0	0.45	Gr 2	253.64	0.00	1014.54	1268.18	8.25	1.65
108.90	330.0	0.45	Gr 3	0.00	1268.18	0.00	1268.18	8.25	1.65
108.90	330.0	0.45	Gr 4	0.00	634.09	634.09	1268.18	8.25	1.65
108.90	330.0	0.45	Gr 1	253.64	507.27	507.27	1268.18	8.25	2.31
108.90	330.0	0.45	Gr 1	253.64	507.27	507.27	1268.18	8.25	2.97

APPENDIX B

CALCULATION OF SURFACE AREA OF AGGREGATE

Table B.1. Calculation of surface area of aggregate

A	B	C	D	E	F	G	H	
Sieve	**Passing among two sieves %**	**Amount passing among two sieves, kg**	**Mass of 1 aggregate particle, kg**	**Number of particles in group i: n_i [C/D]**	**The surface area of 1 aggregate particle in group i,m^2**	**The surface area in group i: s_i, m^2 [E*F]**	**AutoCAD measurements**	
4-8	20	10.16	0.00044	23091	0.000678	15.64696	**Volume of paste, m^3**	0.215
8-12.5	40	20.29	0.00156	13007	0.002448	31.84244	**Paste thickness, m**	0.00305
12.5-16	40	20.29	0.00318	6381	0.004619	29.47312	**Total surface area of agg. particles, m^2**	0.215/0.00305
					Total surface area of agg.	76.96252		