Study on Clogging and Permeability of Porous Concrete

By

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Preface

Concrete and steel are the two most commonly used structural materials. They sometimes complement one another, and sometimes compete with one another. As a result, the structures of a similar type and function can be built in either of these materials. However, even as we talk about the structures and facilities built from these materials, what should not be forgotten is the fact that it also leads to the destruction of natural environment, namely, greenery and water areas including the survival of endangered plants and animals that inhabit those areas not to mention the pollution and other detrimental effects that follow the developmental activities as mentioned above. But at the same time, it is not practical to do away with such developmental activities in lieu of the adverse effects that might follow. On the contrary, what is important is to keep moving forward with such inevitable activities and at the same time, find ways to minimize their negative impacts. And this is probably how the environmentally friendly porous concrete (POC) technology came into existence.

Porous concrete is basically different from the conventional concrete due to the fact that it possesses continuous voids which are intentionally created during its placement. These voids that it has, facilitates the movement of air and water, thereby, enabling it to perform many environmental friendly activities.

This research study focuses on the issues related to the clogging and permeability of porous concrete. Clogging is a phenomenon whereby the voids of the porous concrete get choked by the entrance of foreign materials into them. This defeats the very purpose of porous concrete which is the permeability of air and water through its voids.

The first chapter of the thesis includes the introduction of porous concrete, the background and the purpose of the research. In this chapter, porous concrete is extensively introduced. Furthermore, the background and purpose of the research are also discussed. Chapter 2 deals with the general description of porous concrete. The chapter focuses on the benefits and limitations of porous concrete, design and construction and applications of porous concrete. Chapter 3 deals with the other researches. It highlights the state of art of porous concrete especially those researches related to clogging and permeability. Chapter 4 is about my research study on, "Study of clogging and permeability of porous concrete." In my research study, basically three experiments related to clogging and permeability of POC have been carried out.

The first experiment is an effort to study the relationship between clogging and permeability of POC, using the single layered POC samples. Sand is used as the clogging material in the experiment and washing is applied at the end to see if the permeability is restorable after clogging. It is found out that clogging of the voids drastically reduces the permeability. Moreover, washing of the samples after the occurrence of clogging does not restore the permeability.

In the second experiment, along with the single layered samples double layered porous concrete samples are also applied to carry out the similar experiment as the first. Here it is observed that washing helps to restore the permeability of double layered POC to a great extent.

In the third experiment, smaller sized sand is used as clogging material to carry out the experiment as in the second one. The results are same as that of the second experiment showing the double layered samples giving very good permeability restoration after washing.

Chapter 5 is the concluding remarks of the research study. It also includes the future objectives and recommendations future research.

And finally, there are appendix and references.

Acknowledgements

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Chapter 1 Introduction

1.1 Background of the Research

(1)Clogging and permeability of POC

Porous concrete (POC) is a concept which consists of aggregate, binder and voids for its composition. It might sound a bit strange to relate voids with the concrete, however, porous concrete being a special kind of concrete, has continuous voids in it. These voids enable POC to allow the air and water to permeate through it by virtue of which porous concrete can perform many environmental friendly activities. The study of porous concrete is something that is fascinating along with being interesting. It has many benefits and at the same time, some drawbacks. Clogging is one of the most prominent among the drawbacks of porous concrete [10]. It renders POC useless by choking its voids and reducing/stopping its permeability. Therefore, it was felt necessary to find out some ways to tackle with clogging. The purpose of this research is to study the clogging and permeability of porous concrete. The study includes three experiments involving single and double layered samples. The first experiment deals with only single layered samples while the second and third experiments involve both single and double layered samples. The procedure for the experiments is the same for all the three of them.

1.2 Introduction of Porous concrete

The water or hydrological cycle is powered by the sun and water changes state and is stored as it moves through it. Human intervention is reducing the time it takes for water to return to the oceans resulting in less moisture on land, salinity and aridity. The key to survival in the future will be learning from nature and mimicking her subtle ways.

Knowing how our urban and agricultural practices have interrupted the water cycle, an effort should also be made to understand how roads and parking lots have become our higher level drainage system and the many deficiencies in their current design and ultimately to offer porous pavement solution. Engineers have for years not understood the environmental consequences of our road and parking networks in relation to which there are urgent water shortage, hydrological and environment quality preservation issues. They are not only surfaces for our cars to run and stand, they perform many other functions including setting the drainage pattern for an area, carrying sewerage, water and electricity under them, influencing the climate and defining zones for wildlife. In other words, they are the arteries, veins and lymphatic system to our towns and cities.

Researchers, designers, and builders are always looking for new and improved ways to protect the environment during development in the most cost effective ways possible. One emerging technology is the use of pervious materials such as porous concrete as an alternative paving material for surfaces such as parking lots, residential streets, patios and other low traffic areas. The porous concrete pavement is used mainly due to its ability to reduce nonpoint source (NPS) runoff as compared with impervious pavements which block the subsurface from natural water infiltration and are associated with NPS runoff leading to negative environmental effects on the surroundings. Furthermore, the NPS runoff from these sites carries with it a large quantity of pollutants, chemicals, and hydrocarbons that impact the receiving water systems and the surrounding wildlife and plant life in their respective ecosystems.

Porous concrete (hereinafter referred as "POC") is different from conventional Portland cement concrete mainly (or reduced amount of fine aggregates), the reduced amount of water used in the mixture, and the narrow gradation of coarse aggregate. These different mixture proportions, along with careful compaction and minimal vibratory techniques used during placements, allow it to be placed with a higher percentage of voids. As asphalt becomes more expensive and in short supply, and as the need to manage stormwater runoff increases, designers must revisit old assumptions and take a fresh look at how pavements need to work in a sustainable environment, and how to design and specify for them. Porous pavements are a recent addition to the list of viable paving options. Porous concrete is a concrete that possesses continuous voids in it.

These continuous voids that are intentionally incorporated facilitate the movement of air and water through the porous concrete.

POC is also sometimes called "no fines" concrete (due to the absence of fines), an innovation in concrete paving that is quickly taking hold as a green alternative to both traditional asphalt and concrete paving in parking lots, pavements, patios, in sidewalks, etc. Over the next several years as people become more and more concerned with the environmental degradation due to the impact we are having on it, the more prevalent porous concrete will become for paving projects of all sizes. The materials involved in the construction of POC are basically Carefully controlled amounts of water and cementitious materials are used to create a paste that forms a thick coating around aggregate particles without flowing off during mixing and placing. Its unique porous quality is achieved by eliminating fine aggregates, such as sand, from the mix. The exclusive use of course aggregates such as gravel and crushed stone creates air voids throughout the concrete. The result is a very high permeability concrete that drains quickly. Water is coarse aggregates, Portland cement and water. The cement paste acts as the binder for the interlocking of the aggregates.

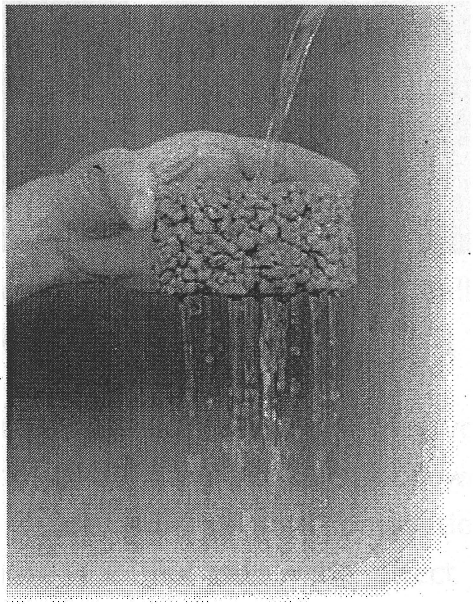


Figure 1.1 POC and its permeability [1]

therefore able to pass directly through the pavement and into the soil rather than collecting on or running off the surface. In this way, porous concrete can greatly reduce stormwater runoff and its associated problems. Due to the high void content, porous concrete is also lightweight, 1600 to 1900 kg/m^3 (100 to 120 lb/ft^3). After placement, porous concrete resembles popcorn. Using just enough paste to coat the particles maintains a system of inter-connected voids. The amount of paste around the aggregate to bind them varies with the change in intended void ratios of POC. Its low paste content and low fine aggregate content make the mixture harsh, with a very low slump. The compressive strength of porous concrete is limited since the void content is so high. However, compressive strengths of 3.5 to 27.5 MPa (500 psi to 4000 psi) are typical and sufficient for many applications [2]. The school of thought behind advocating this concrete is to have a system that would help in draining off the runoff water during a rainfall. Therefore, the phrase, "When it rains it drains" is very popularly used in the west to describe porous concrete. It is very important for the voids to be continuous in porous concrete. This particular requirement in turn, calls for good skills as well as careful execution during the construction of POC. Right from the design stage till the construction, utmost care should be exercised to assure the quality of the final product. The mix design should take care of the intended void ratio which should then be followed by proper mixing and compaction. Figure 1.2 illustrates the effect of quantity of water in the mix. It is visibly clear that the adequate quantity of water is an important factor in producing a good quality porous concrete. If insufficient amount of water results in the lack of strong aggregate bonding, excess amount adversely affects it as the flow value of the paste is too high to hold the aggregates together. It may be worth mentioning here that dripping is not tolerable in the construction of porous concrete as the binder drops to the bottom, thereby blocking the flow of the water into the ground along with the weakening of the bond.

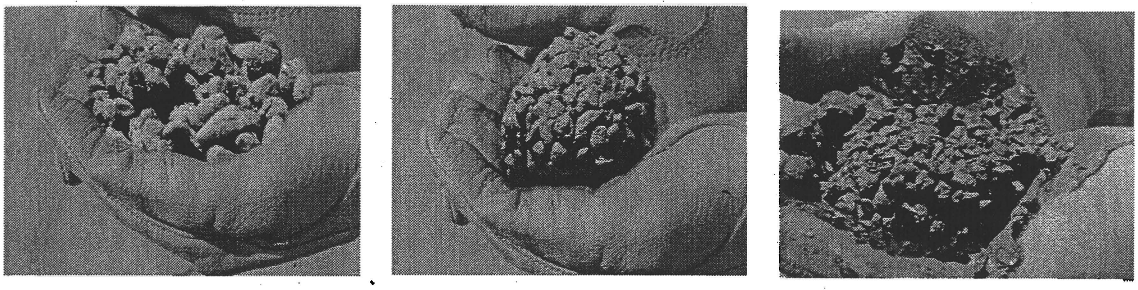


Figure 1.2 Samples of POC with different water contents formed into a ball: (a) too little water, (b) proper amount of water, (c) too much water [10]

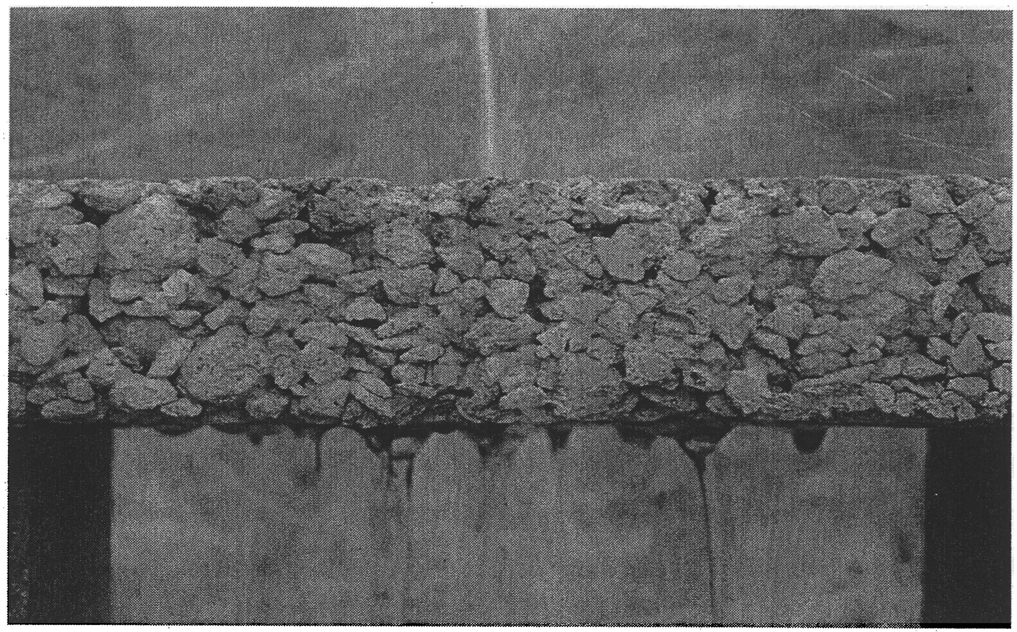


Figure 1.3 Magnified view of POC sample and its permeability[1]

1.3 Purpose of the research

(1) Clarification of clogging phenomenon of POC

As has been highlighted in the introduction of porous concrete, it is progressively gaining its importance as an environmentally-friendly technology. At a time, when the whole world is becoming more and more concerned about the deteriorating environment and ever so worsening global warming phenomenon, porous concrete is establishing itself as a tool to tackling such issues. Keeping in mind such ability of porous concrete, the research theme for this study was decided. Though POC has so many virtues that enable it to exhibit various environmentally-friendly performances, there are invariably some issues that act as impediments to its virtues. One of the major issues is the clogging phenomenon in porous concrete whereby, its continuous voids get blocked by the foreign materials entering them. This case regarding the clogging of POC was considered for my research due to the fact that it undermines the sole purpose of POC which is to allow the air and water to permeate through its voids. What follows the clogging is the inability of POC to allow the runoff water to permeate thereby, leading to the flooding of the area. In case of the areas where POC is applied, normally drainage provisions are done away with. Therefore, it gets worse when clogging occurs as flooding is the only possibility after that.

(2) Development of a remedial method for clogging

Going by the aforementioned issue related to clogging in porous concrete, it is easy to approve the fact that something needs to be done to it in order to be able to enjoy the long term service that POC is capable of providing. That is how and why the purpose of this research came into picture. The idea was to find ways to somehow prevent the clogging from happening in porous concrete so that its service could be derived for as long a time as possible. In keeping with the purpose or the expectation of the research, the concept of a double layered porous concrete was introduced for the first time to tackle the issue of clogging of POC. The basic philosophy behind this double layered POC is that the upper layer with smaller aggregate and lesser thickness should be able to restrict a lot of foreign materials on the surface itself or even if the enter into the voids, they should be able to enter through the bottom layer with bigger voids. This in principle can help maintain the K_T of the porous concrete system and prevent clogging.

CHAPTER 2 General Description

2.1 Benefits and limitations of porous concrete

(1) Benefits

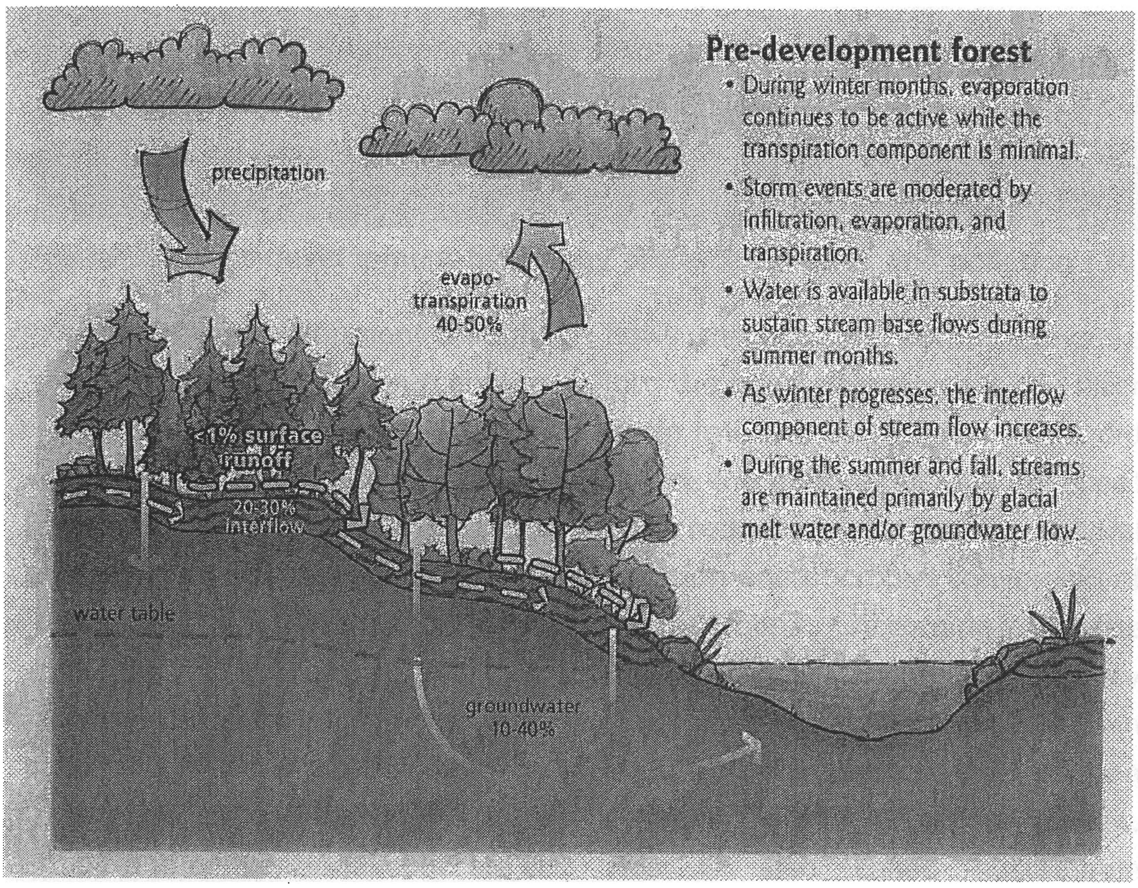
The world today is faced with so many grave challenges. Therefore, it is about time that every citizen of this world realized that he/she needs to contribute towards resolving these issues in whatever capacity possible. It is like, "If everyone does a little, no one has to do a lot." And the contribution has to be from all corners and disciplines so that a combined effort takes place to help resolve or reduce wide range of issues facing us today.

Porous concrete in the field of concrete technology is one such effort whereby; it makes noteworthy contributions towards improving the environment, which is one of the major concerns facing us today.

By virtue of being environmental friendly, porous concrete is one of the fastest growing technologies in the field of concrete construction. As emphasis on environmental protection and building green is continuing to increase, the demand for porous concrete will increase progressively as well [6].

Let's think about a conventional parking lot during a rain, the water usually runs to a drain and then to some form of storm water management system, frequently a "pond" somewhere on the property. When we have all our surroundings, parking areas, pavements, etc. done with normal concrete, there is this risk of the rivers, lakes and coastal waters getting polluted as the rainwater rushing across these surfaces picks up everything from oil and grease spills to deicing salts and chemical fertilizers. This can also cause erosion, flash floods during heavy downpour and the risk of water Table depletion is always there as the rainwater does not enter the ground due to the presence of conventional concrete everywhere. Also, with rain water unable to percolate into the soil beneath impervious pavements, plant roots are deprived of water and oxygen. This leads to the stunted growth and shortened lifespan of parking lot trees, a significant problem since trees are necessary for shading and air quality maintenance, as well as aesthetics. [2]

Such problems can be avoided with the application of porous concrete in the parking lots, pavements, patios, etc., since its void structure mimics that of grass, allowing equivalent amounts of water and oxygen to reach tree roots. Furthermore, in case of porous concrete pavements, the infiltration and sub-pavement collection of rainwater leads to aquifer recharge and increased groundwater, providing healthy conditions for tree growth. This means that in porous parking lots, paved space can be maximized without sacrificing the benefits provided by trees. As shown in Figure 2.1, before development of an area the surface runoff is less than 1% of the water that ends on ground as a result of rainfall or snow.



Pre-development forest

- During winter months, evaporation continues to be active while the transpiration component is minimal.
- Storm events are moderated by infiltration, evaporation, and transpiration.
- Water is available in substrata to sustain stream base flows during summer months.
- As winter progresses, the interflow component of stream flow increases.
- During the summer and fall, streams are maintained primarily by glacial melt water and/or groundwater flow.

Figure 2.1 Pre-development hydrology moderates rainfall [16]

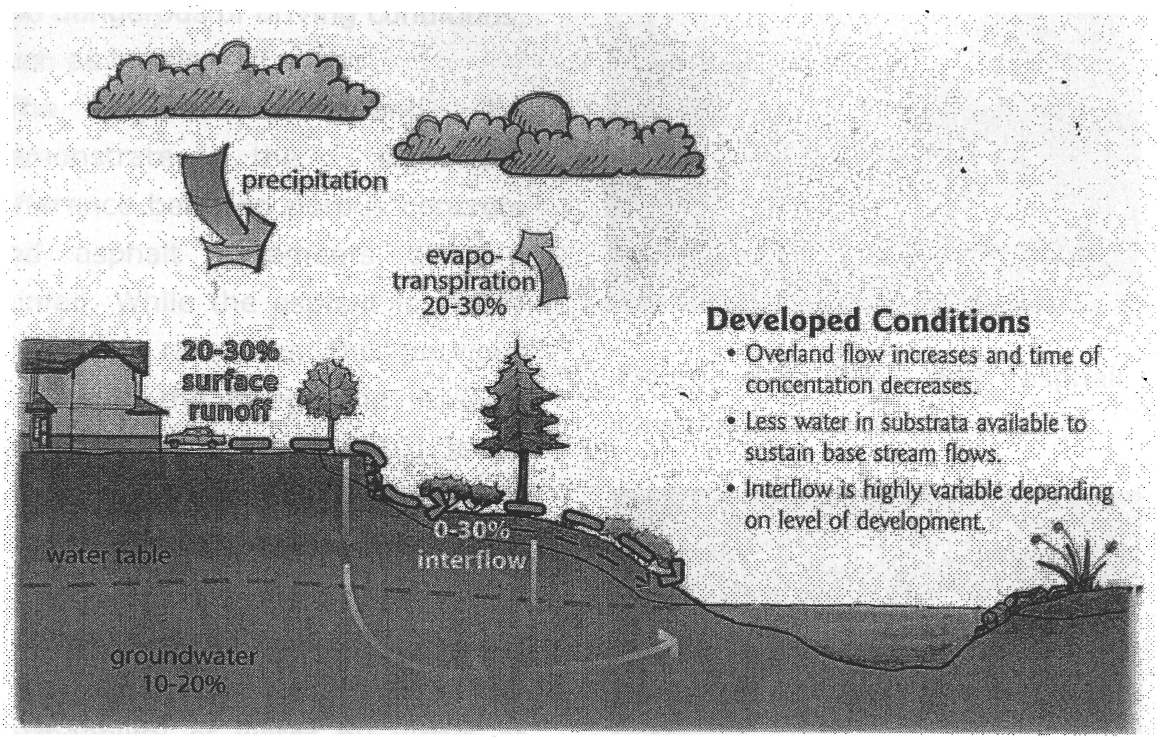


Figure 2.2 Post-development hydrology produces erosion and pollution [16]

However, after development though, shown in Figure 2.2, this percentage increases to about 20~30%. Thus, in connection with any development, there is a need to handle this resulting runoff that flows on different surfaces and address the problems it creates as a consequence. The use of porous concrete in the parking lots, pavements, patios, etc. in place of asphalt and conventional concrete is one of the ways to help reduce the runoff by allowing the water to permeate into the ground, thus recharging the ground water and replenishing the water table. Now let's think about a porous concrete parking lot during a rain. The water flows through the porous concrete into the base after which it can filter down into the earth - just like it did before the parking lot was installed! This reduces pollution by natural filtration and microbial conversion of hydrocarbons. According to the Environmental Protection Agency (EPA), porous concrete is an important element to consider when designing and/or installing paving. This is also called sustainable development. [16]

The exposed course aggregates of pervious concrete provide enhanced traction for vehicles and prevent driving hazards such as hydroplaning. The textured surface is especially beneficial during the most difficult and dangerous of driving conditions, such as in rain and snow.

The figures 2.3 and 2.4 demonstrate the significant difference between porous concrete and asphalt pavements after a rainfall. While the asphalt is visibly slick with rainwater, the pervious surface in the foreground remains unaltered by the weather [10]. It can be safely said that this distinct difference in the amount of moisture present on the surfaces of the two pavements is merely due to the fact that porous concrete facilitates the permeability of water by virtue of which the dryness can be maintained even during rainfall and snowfall [10].

Figure 2.3 POC and asphalt pavements after a rainfall [10]

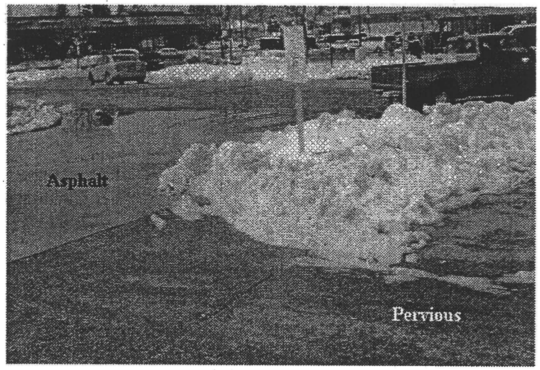


Figure 2.4 POC and asphalt pavements after a snowfall [10]

(a)Water-permeating/draining/ retaining performance

Porous concrete has many other applications. They are mentioned as follows:[7]

The water-permeating, draining, and retaining performances of the porous concrete have been utilized as building exteriors, plant bedding, permeable rainwater retention facilities, such as permeable trenches, permeable gullies and permeable gutters are few other applications in addition to the aforementioned performances. Particularly for road pavements, POC has been used for more than 5,000,000 m^2 of exterior pavement, sidewalks, and exhibition squares since 1985, most of which are of permeable full-depth types. Water-draining composite types have been used for middle and heavy traffic roads. For tollgates on heavy traffic expressways, the porous concrete having high rutting resistance, abrasion resistance and oil resistance as well as drainage function is bonded and unified with continuous reinforced concrete slabs into composite pavement to withstand the repeated stopping and starting motions of cars. For the purpose of ponding of rainwater and recharging into the ground, the porous concrete is applied for permeable trenches, and gutters.

(b)Water purifying performance

Pollution of urban rivers, lakes, and wetlands and enclosed coastal waters near large cities has been serious in recent years due to runoffs containing wastewater from homes and plants, posing problems of environmental disruption. Water purification by the porous concrete is a sort of inter-gravel contact oxidation, in which the biota formed on the internal surfaces of continuous voids provides an additional bio-purification function. It is therefore anticipated that the porous concrete applied to revetment and coastal areas would contribute to water purification by the biota consisting of various organisms including microbes. For example, waterway purification using the porous concrete blocks with embedded aerators, which are expected to adsorb nitrogen and phosphorus as well. Other examples include facilities for bio-purification by inter-gravel contact oxidation and those constructed as biotopes with a function of water purification where a wide variety of living organisms gather.

(c)Noise-absorbing performance

Porous materials can be used as noise-absorbing products. Active attempts have been made in recent years to develop precast concrete acoustic panels using the porous concrete, to impart not only a noise-insulating effect but also noise-absorbing one to concrete products. Practical application of the porous concrete to noise barriers, the backside of elevated roads and inside walls of tunnels is under way. The open structure of the porous pavement causes a difference in arrival time between direct and reflected sound waves as shown in Figure 2.5. This difference causes the noise level to have a lower intensity causing porous pavements to absorb sound (Olek *et al.* 2003), which has drawn the interests of many researchers to create quiet pavements (Kajio *et al.* 1998; and Olek *et al.* 2003). Kajio *et al.* (1998) compared the noise levels produced from porous concrete and dense asphalt pavements containing two different sizes of aggregate (i.e., 1/4-inch and ½-inch) at different vehicle speeds and showed that for both sizes of aggregate the noise was reduced using porous concrete compared to asphalt.

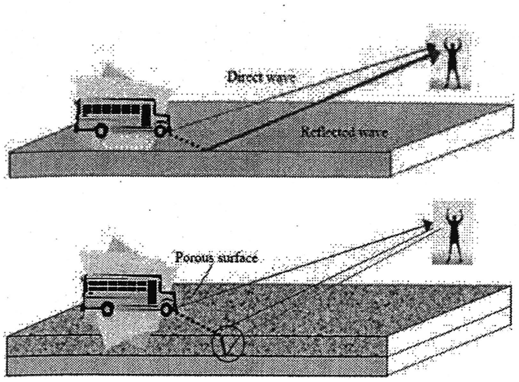


Figure 2.5 Reflection of sound waves resulting from moving vehicles
(a) Wave reflection from a dense surface
(b) Wave reflection from a porous surface (Olek *et*)

(d)Thermal performance

Thermal performance of the porous concrete refers to its performance to mitigate or improve the environment in terms of thermal conditions. Investigation into thermal performance of the porous concrete has just commenced. Field experience is still limited, with a limited number of application instances which includes road pavements and rooftop gardens.

(e)Moisture-conditioning/adsor-bing performance

The moisture-conditioning performance of the porous concrete is said to depend on the moisture-absorbing properties of aggregate, void content, the conditions of internal void surfaces, and the properties of the binder. Excellent moisture-conditioning performance can therefore be achieved for buildings requiring such properties by properly selecting the aggregate, binder and mixture proportions to be used. Due to its large surface area, the porous concrete can be made to possess a gas-adsorbing performance by selecting materials to adsorb Sox and NOx for the aggregate and binder (e.g., zeolite), with which hazardous gases can be fixed and made innocuous further by applying a photocatlyst, such as titanium oxide, to the porous concrete surfaces.

(f) Plant-growing performance

Examples of applications of the porous concrete in this field are revetment works, for the growth of plants and grasses, greening of the slope, etc.

For growing plants on the porous concrete, it is necessary to provide space for growing roots, ensure effective water retention, reduce the amount of alkali leaching and retain fertilizer components. Regarding space for roots, the recommended continuous void contents are as follows: not less than 25% for immediate plant growth, not less than 21% for later growth and not less than 18% for viable growth.

Applicable aggregate sizes, which determine the void size are crushed stone in the range of 5-13mm, 13-20mm, 20-30mm, 5-20mm, 15-20mm and 15-25mm.

For ensuring an effective amount of water retention, it is desirable to fill a water-retaining material in the voids to compensate for the low effective amount of water retention of the porous concrete or to cover the top surfaces with soil. Since porous concrete does not content nutrients necessary for the growth of plants, solid or liquid fertilizers is required to be supplied to the bedding.

(g)Insect/animal accommodating performance

Voids in the porous concrete may serve as habitats for larvae of waterside land insects, water bugs and benthic organisms in plain water. In order to achieve vegetation on river revetments made of the porous concrete, the void content should be not less than 18%, and the void diameter should be 1-2mm (crushed stone No.6: 5-13mm) or 3-4mm (crushed stone No.5: 13-20mm). Organisms of a size that fit such voids can inhabit the spaces. The viod diameter is a critical factor. Larvae of mole crickets (approximately 1cm long and 3mm thick) were reportedly found to grow in the porous concrete revetment with a void cement of 22% and void diameter of 3-4mm (crushed stone No.5: 13-20mm).

(h) Marine organisms

The high coarseness of the porous concrete makes it easy for seaweed and shellfish to cling to its surfaces. Though no particular recommendations are available for the void content and its size for these surface inhabitants, it is generally considered adequate to select a void content of not less than 18% using crushed stone No.6 (5-13mm), preferably No.5 (13-20mm) or greater, for the aggregate.

(i) Microbes

In enclosed waters such as gulfs, lakes and wetlands,, water quality deterioration by algal blooms of phytoplanktons, such as "red tide", has been posing a serious problem in recent years. This phenomenon is primarily attributed to increase in levels of biological nutrients entering such waters. The porous concrete made using crushed stone provides a range of surface coarseness depending on the aggregate diameter. When such surfaces are kept in contact with turbid water, not only aerobic but also anaerobic bacteria are reported to inhabit in the biofilms on the external surfaces of the porous concrete. It follows that microscopic anaerobic conditions can exist on such biofilms adhering to the minute irregularities of the surfaces. It is therefore desirable to select aggregate for the porous concrete to provide a hbitat for both aerobic and anaerobic bacteria by making the surface and internal environments more anaerobic, in order to accelerate the denitrifying effect [7].

The heat island effect is a phenomenon which has accompanied and increased with urbanization, and it refers to the fact that man-made structures tend to attract and retain heat at a higher rate than is normal in nature. This results in an increase in ground-level ozone production by as much as 30%.

Porous Concrete And The Heat Island Effect [1]

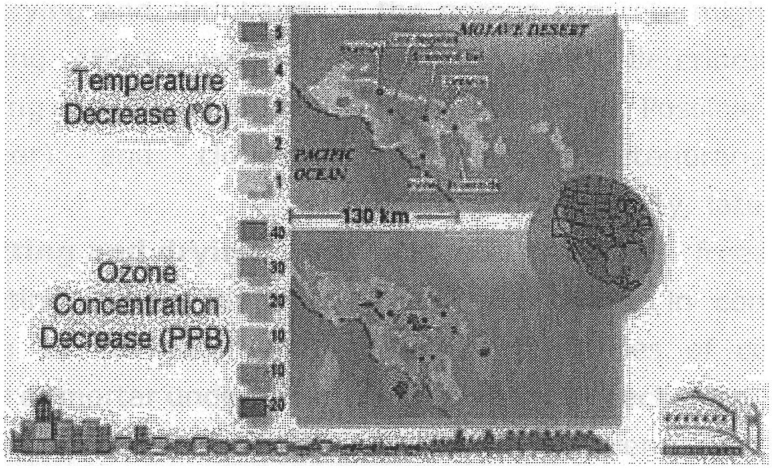


Figure 2.6 Pictorial illustration of heat island effect [1]

Choice of building material is key in reversing the heat island effect for structures which are dense dark-colored attract sunlight and retain it for long periods of time. All the concrete, including porous concrete, has a light color that resists heat absorption. The open pore structure of porous concrete allows air to circulate within, resulting in even lower heat retainment. Furthermore, since trees are able to coexist with porous pavement, they can easily be incorporated into urban settings. Trees provide shade and release oxygen, both of which contribute significantly to the lowering of temperatures. By incorporating these strategies and reducing the heat island effect, air conditioning costs can be lowered by as much as 12%, the intensity of air pollution lessened, and heat-related health problems prevented

(2) Limitations [7]

The advantages of the porous concrete notwithstanding, it is faced with a few challenges as well. Potential areas of concern are: effect of cyclic wetting and drying, freezing and thawing, drying and shrinkage, repeated loading effect, wearing, abrasion, raveling of surface (caused by tire sheer) and clogging phenomenon.

(a) Cyclic wetting and drying

Under alternating dry and wet conditions due to rainwater and moisture, paste or mortar undergoes expansion and contraction, which produces differences between the coefficients of drying shrinkage and thermal expansion of the matrix and the aggregate, causing concern about microscopic cracking. Various tests methods have conventionally been attempted to measure the resistance to this action, but the results are known to widely vary depending on the test method. It is generally reported that the use of fine aggregate and the use of small-diameter coarse aggregate improve the resistance to cyclic wetting and drying, that not only void content but also void size strongly affects the resistance, and that inclusion of short fibers may improve the resistance.

(b) Freezing and thawing

Being a structure having continuous voids, the porous concrete readily allows permeation of water including rainwater, resulting in freezing and thawing action internally and externally. This causes concern that the porous concrete might be more vulnerable to deterioration than normal concrete. Possible effects on this kind of deterioration include thermal conductivity, latent heat of concrete during freezing and thawing of water in concrete and thermal properties of concrete. A deterioration mechanism resulting from the difference between the coefficients of linear expansions of ice and paste is assumed for this phenomenon. Though a number of test methods and parameters have been proposed for evaluating the resistance to freezing and thawing, the results widely vary depending on the test method. It is therefore important to select a test method suitable for the specific use. In general, smaller diameters of coarse aggregates tend to lead to lower resistance to freezing and thawing. Methods of improving resistance to freezing and thawing of the porous concrete include the use of air-entraining admixture, densification of microstructures by the addition of silica fume and other additions, improvement of bond at aggregate-paste interfaces, and improvement of ductility by the addition of fibers.

(c) Carbonation

Major causes of carbonation of the porous concrete include CO2 permeation and reductions in the pH value due to leaching out calcium from concrete surfaces. Since the porous concrete has mostly been used for unreinforced concrete having no steel reinforcement such as steel bars, few examples of study or deterioration are currently available regarding carbonation.

(d) Abrasion

As the thin binder layer covering coarse aggregate is directly subjected to physical actions, significant abrasion is of concern. Abrasion by tires and tire chains of vehicles is expected for road pavement, whereas abrasion by water flow including gravel and sand is expected for revetments. The abrasion loss of porous concrete by erosion is lower than that of normal concrete, and the greater the coarse aggregate, the lower the abrasion loss. When comparing the porous concretes made using the same coarse aggregate, the higher compressive strength gives the higher abrasion resistance. In regard to the resistance to aggregate loss (by the Cantabro method, mass loss ratio), the losses increase as the void content increases, and decreases as the maximum aggregate size decreases.

(e) Repeated loading (Fatigue)

There are some reports focusing on the resistance of the porous concrete to repeated loading in road pavement. Whereas test results of the compressive fatigue properties of the porous concrete scatter more widely than of normal concrete, underwater resistance to fatigue of the porous concrete is known to be higher than that of normal concrete in the range of low upper limit stresses. Though the flexural fatigue properties of the porous concrete is lower in water than in air, it is pointed out that its fatigue life is comparable to that of a normal concrete.

(f) Sulfate Resistance

Aggressive chemicals in soils or water, such as acids and sulfates, are a concern to conventional concrete and porous concrete alike, and the mechanisms for attack are similar. However, the open structure of porous concrete may make it more susceptible to attack over a larger area. Porous concretes can be used in areas of high-sulfate soils and groundwaters if isolated from them. Placing the pervious concrete over a 6-inch (150-mm) layer of 1-inch (25-mm) maximum top size aggregate provides a pavement base, stormwater storage, and isolation for the porous concrete. Unless these precautions are taken in aggressive environments, recommendations from ACI 201 on water-to-cement ratio and material types/proportions should be followed strictly.

(g) Effect of plants

Possible effects of plants on the porous concrete include failure due to the growth pressure of roots and erosion by organic acids secreted from roots, but no such failure or erosion has so far been reported. The absence of defect incidents due to root growth is presumably attributed to the fact that there have been only a limited number of examples of planting arbors on the porous concrete, with the age being 5 years at the longest, and that the compressive strength of the porous concrete is significantly higher than soil hardness, while its tensile strength exceeds the pressure of growing roots. The absence of defects due to organic acids secreted from tree roots is considered to be due to the fact that organic acids are mostly weak acid with weak erosive action on concrete compared with inorganic acids and that chemical resistance of the porous concrete is high owing to the low water-cement ratio between 20 and 30%.

(h) Alkali-aggregate reaction

No reports have been available on defects induced by alkali-aggregate-reaction or investigation into the reaction in regard to the porous concrete. In light of the mechanism of concrete expansion due to alkali-aggregate reaction, it is considered probable that the expansion resulting from alkali-aggregate reaction in the porous concrete is absorbed by air voids, which account for more than 10% of the concrete volume, ending up with no expansion pressure or damage. On the other hand, it is also possible that cracking or bond failure can occur in the microscopic range, i.e., at the boundaries between coarse aggregate and paste or mortar, leading to damage including strength losses. This is another subject for future.

2.2 Materials used for the Construction of POC [10]

Pervious concrete uses the same materials as conventional concrete, with the exceptions that the fine aggregate typically is eliminated entirely, and the size distribution (grading) of the coarse aggregate is kept narrow, allowing for relatively little particle packing. This provides the useful hardened properties, but also results in a mix that requires different considerations in mixing, placing, compaction, and curing. The mixture proportions are somewhat less forgiving than conventional concrete mixtures. Tight controls on batching of all of the ingredients are necessary to provide the desired results.

(a) Cementitious materials

As in traditional concreting, portland cements may be used in porous concrete. In addition, supplementary cementitious materials (SCMs) such as fly ash, pozzolans, and ground-granulated blast furnace slag may be used. Testing materials beforehand through trial batching is strongly recommended so that properties that can be important to performance (setting time, rate of strength development, porosity, and permeability, among others) can be determined.

(b) Aggregate

Fine aggregate content is limited in pervious concrete, and coarse aggregate is kept to a narrow gradation. Commonly-used gradations of coarse aggregate used for porous concrete in Japan include aggregate grades G5 (13-20mm), G6 (5-13mm), G7 (2.5-5mm) and G8 (1.25-2.5mm). In the West, gradations include ASTM C 33 No. 67 (¾ in. to No. 4), No. 8 (⅜ in. to No. 16), and No. 89 (⅜ in. to No. 50) sieves [in metric units: No. 67 (19.0 to 4.75 mm), No. 8 (9.5 to 2.36 mm), and No. 89 (9.5 to 1.18 mm)] [8]. A narrow grading is the important characteristic. Larger aggregates provide a rougher surface. Recent uses for porous concrete have focused on parking lots, low-traffic pavements, patios and pedestrian walkways. For these applications, the smallest-sized aggregate feasible is used for aesthetic reasons. Coarse aggregate size G6 (5-13mm) is normally used for parking lot and pedestrian applications.

Generally, A/C ratios are in the range of 4.0 to 4.5 by mass. These A/C ratios lead to aggregate contents of between about 2200 lb/yd^3 and 3000 lb/yd^3 (1300 kg/m^3 to 1800 kg/m^3). Higher A/C ratios have been used in laboratory studies, but significant reductions in strength result.

Both rounded aggregate (gravel) and angular aggregate (crushed stone) have been used to produce porous concrete. Typically, higher strengths are achieved with rounded aggregates, although angular aggregates are generally suitable. Aggregate for pavements should conform to ASTM D 448, while ASTM C 33 covers aggregates for use in general concrete construction. As in conventional concrete, porous concrete requires aggregates to be close to a saturated, surface-dry condition, or close monitoring of the moisture condition of aggregates should allow for accounting for the free moisture on aggregates. It should be noted that control of water is important in porous concrete mixtures. Water absorbed from the mixture by aggregates that are too dry can lead to dry mixtures that do not place or compact well. However, extra water in aggregates contributes to the mixing water and increases the water-to-cement ratio of the concrete.

(c) Water

Water-to-cement ratios between 0.27 and 0.30 are used routinely with proper inclusion of chemical admixtures, and those as high as 0.34 to 0.40 have been used successfully. The relation between strength and water-to-cement ratio is not clear for porous concrete, because unlike conventional concrete, the total paste content is less than the voids content between the aggregates. Therefore, making the paste stronger may not always lead to increased overall strength. Water content should be tightly controlled. The correct water content has been described as giving the mixture a sheen, without flowing off of the aggregate. A handful of porous concrete formed into a ball will not crumble or lose its void structure as the paste flows into the spaces between the aggregates. See Figure 2.7.

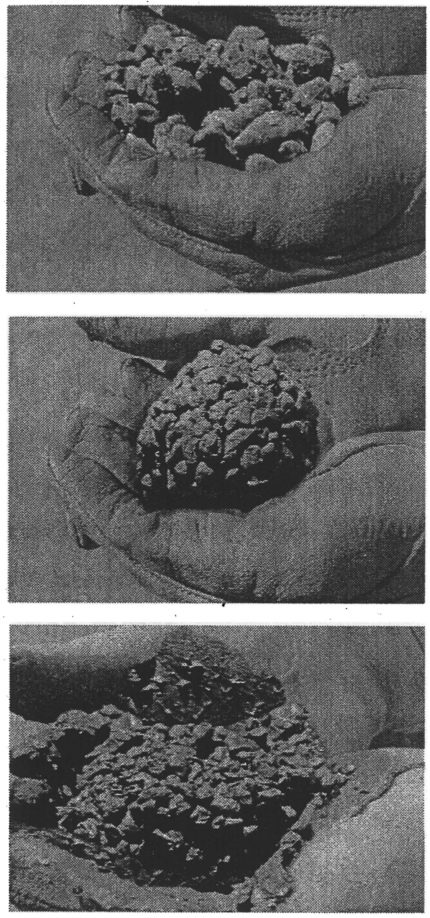


Figure 2.7 Samples of porous concrete with different water contents, formed into a ball: (a) too little water, (b) proper amount of water, and (c) too much water. [10]

Water quality is discussed in ACI 301. As a general rule, water that is drinkable is suitable for use in concrete. Recycled water from concrete production operations may be used as well, if it meets provisions of ASTM C 94 or AASHTO M 157. If there is a question as to the suitability of a water source, trial batching with job materials is recommended.

(d) Admixtures

Chemical admixtures are used in porous concrete to obtain special properties, as in conventional concrete. Because of the rapid setting time associated with porous concrete, retarders or hydration-stabilizing admixtures are commonly used. Use of chemical admixtures should closely follow manufacturer's recommendations. Air-entraining admixtures can reduce freeze-thaw damage in porous concrete, and are used where freeze-thaw is a concern. ASTM C 494 governs chemical admixtures, and ASTM C 260 governs air-entraining admixtures. Proprietary admixture products that facilitate placement and protection of porous pavements are also used.

2.3 Mix Proportioning of Porous Concrete

The following sample calculation of mix proportion for porous concrete will explain the method involved:

Fixed conditions:

W/C ratio = 30%, void ratio (v_r)=18%, Unit volume ratio = 53.3%

For a volume of $1m^3$ porous concrete:

For grade G7 aggregate:

Amount of Aggregate:

$g = r_g .\ u_g\ .\ f_c$ .... (2.1)

where: g = Amount of aggregate, ρ_g = density of aggregate, u_g = unit volume ratio(%) and fc= correction factor.

Density of aggregate=2.73($g/\ cm^3$) = 2730$kg/\ m^3$

Unit volume ratio =53.3(%)

Correction factor = 0.95-0.98

Amount of aggregate = 2730X0.533=1455.09($kg/\ m^3$)

Amount of cement paste:

Volume of cement paste (v_C) in $1m^3$ of concrete

$v_C = 1\ m^3 - u_g - v_r$ .... (2.2)

=1 - 53.3% - 18%

= 1-0.533-0.18=0.287 m^3

$v_C = \{C/\ \rho_C + W/\ \rho_W\}$ ....(2.3)

where: C=weight of cement, ρ_C=density, W=weight of water, and ρ_W= density

W/C = 30%=0.30

Or, W = 0.3C .... (2.4)

Replacing the value of w from (2.4) in (2.3), we get:

Taking density of cement as 3.15$g/\ m^3$=3150kg/m^3

Volume = C/3150 + 0.3C/1000 = 1.945C/3150

Or, 0.287 = 1.945C/3150

Or, C= 464.81$kg/\ m^3$

W=0.3C=0.3X464.81=139.44kg m^3

Therefore, for 1 m^3 of G7 porous concrete, the quantities of water, cement and aggregate are as follow:

Water = 139.44k/m^3

Cement = 464.81kg/m^3

Aggregate = 1455.09kg/m^3

Note: Unit volume ratios of G5 = 58.14, G6= 56%, G8 = 54.3%.

2.4 Construction method of T.N. Base pavement (A typical method)

(As Proposed by Dr Nakagawa, and assisted by Sunil Pradhan and other fellow researchers of Hatanaka laboratory, division of Architecture, faculty of Engineering, Mie University)

The following figures demonstrate the one of the methods followed in laying porous concrete or T.N. Base pavement in Japan. The T.N. base pavement is has two layers. The under layer is the normal POC pavement with high void ratio. The upper layer has a thin (about 1cm) layer of natural aggregates bond together using epoxy resin. The captions below the figures and the step-wise explanation of the method, present the overall laying procedure. In this method, the sub-base of stones and aggregates are not provided. In place of the sub-base, drainage system is provided underneath for the drainage of permeated water from the porous pavements during a heavy rainfall when the underlying soil is not able to absorb all of them. This will prevent the overflow of the runoff during the heavy rainfall. This drainage system will ensure that there is no flooding on the surface of the POC pavement.

(1) Laying of the lower layer

First the lower layer is cast and allowed to harden before placing the upper thin layer (about 1cm).

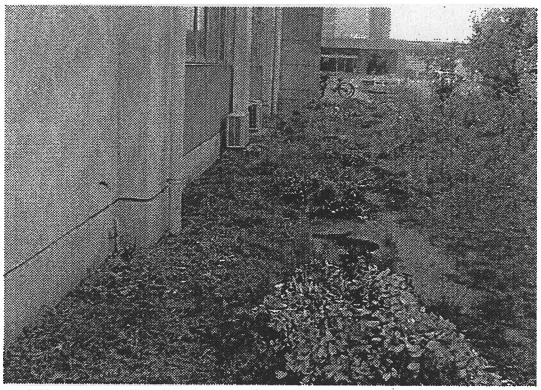


Figure 2.9 Site before T.N. Base pavement is constructed

Figure 2.10 Clearing of the site for placing of T.N. Base pavement

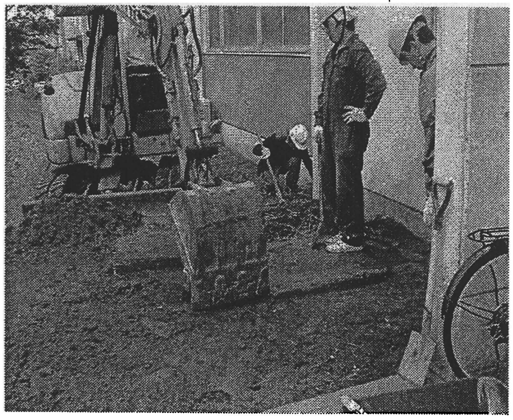


Figure 2.11 Cutting and leveling of the site

Step 1: Clearing of the grasses, plants and weeds needs to be carried out first before proceeding ahead with the ground preparation.

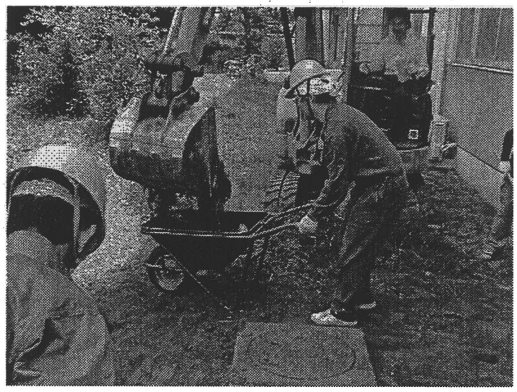


Figure 2.12 Clearing the debris from the site

Figure 2.13 Leveling of the site with the hand

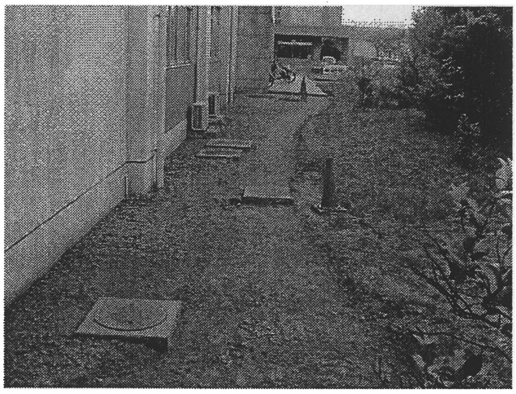


Figure 2.14 The look of the site after clearing and leveling

Step 2: After the clearing work, cutting, filling and leveling should be carried out to prepare the ground for placing of POC.

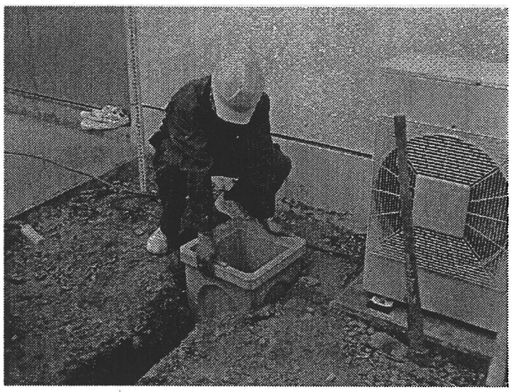


Figure 2.15 Fixing of the chamber for the collection of water

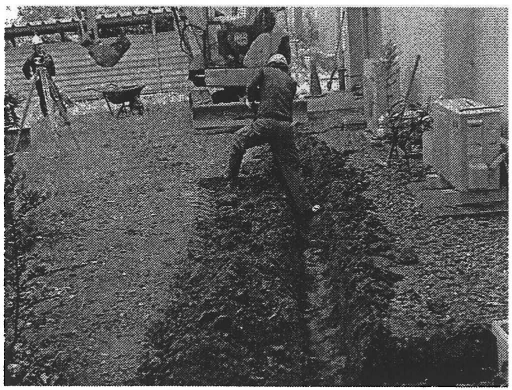


Figure 2.16 Drain for placing of drainage pipes

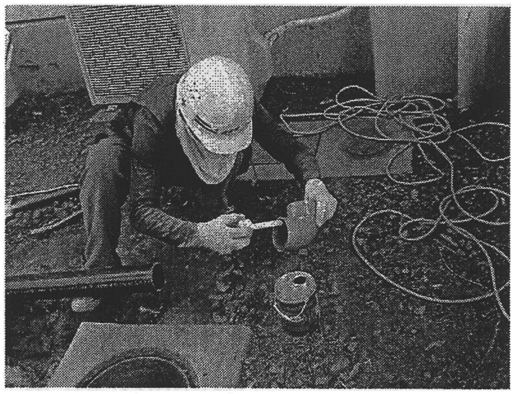


Figure 2.17 The connections of drainage pipes

Step 3: Proper drainage system has to be laid before the laying of POC.

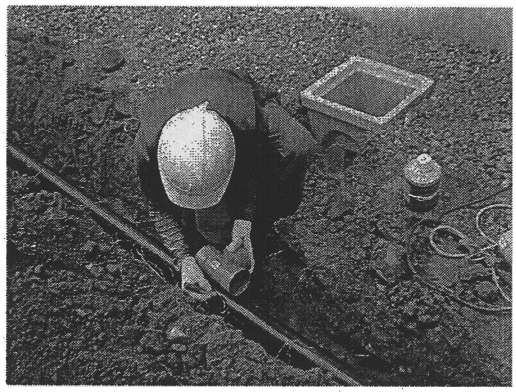


Figure 2.18 Laying of pipes for the drainage

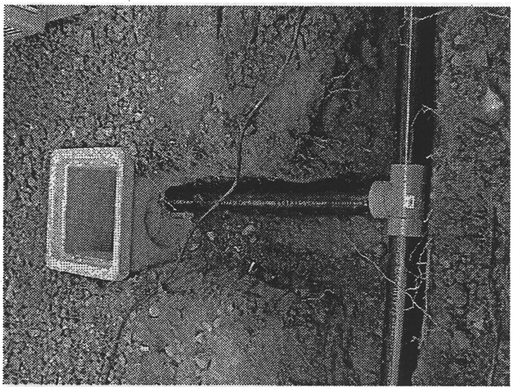


Figure 2.19 Drainage pipes laid and connected to the chamber

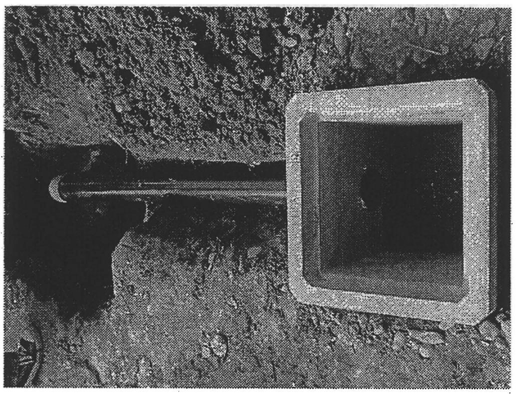


Figure 2.20 View of how drainage pipe is connected to the chamber

Step 4: The drainage system comes handy during heavy rainfall.

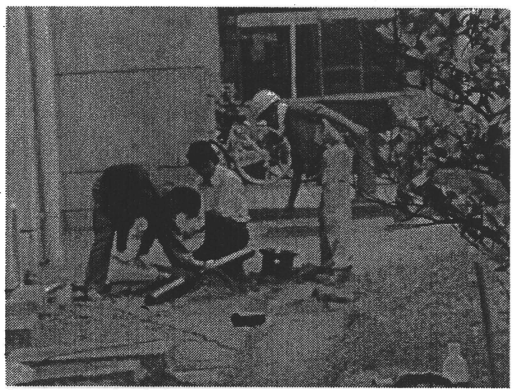


Figure 2.21 Base with appropriate slopes for proper drainage

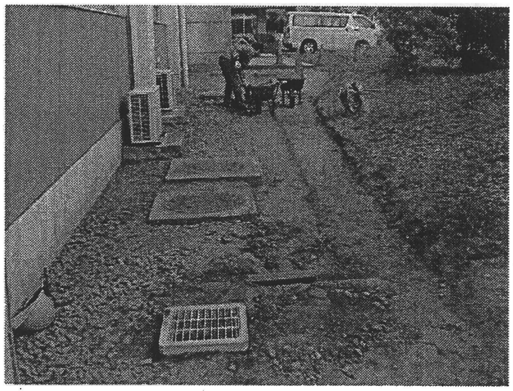


Figure 2.22 Leveling back after drainage pipes have been laid

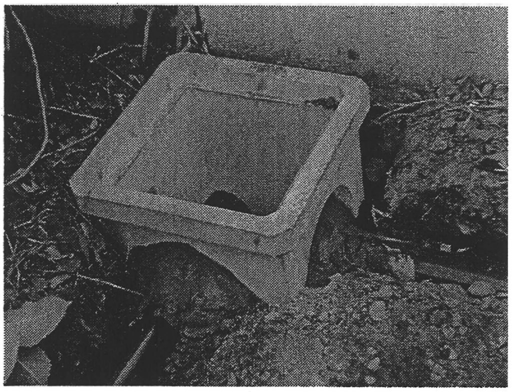


Figure 2.23 Sealing of the gap between the pipe and the hole of the chamber

Step 5: Proper care should be exercised to seal the joints and openings of the drainage system.

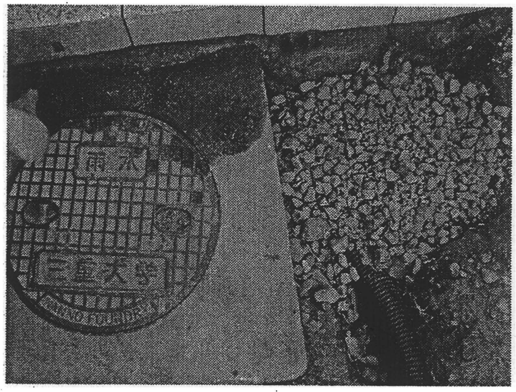


Figure 2.24 Aggregate at the Joint before filling helps to avoid choke

Figure 2.25 Laying of boundary walls for the placing of POC

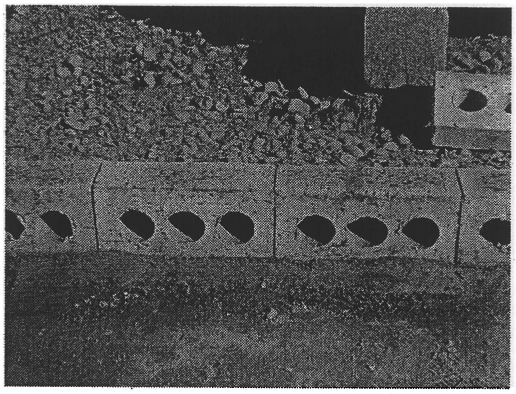


Figure 2.26 Boundary line bricks with holes in them

Step 6: The boundary walls are necessary for the POC pavement.

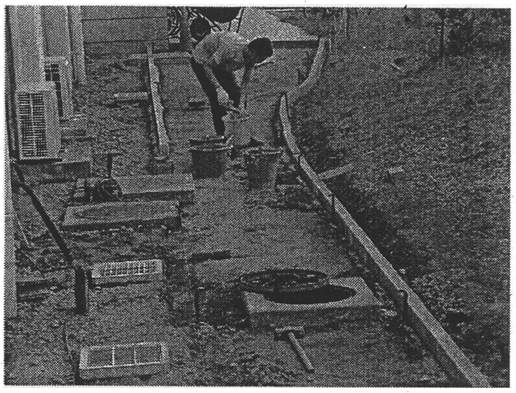


Figure 2.27 Laying of boundary walls in progress

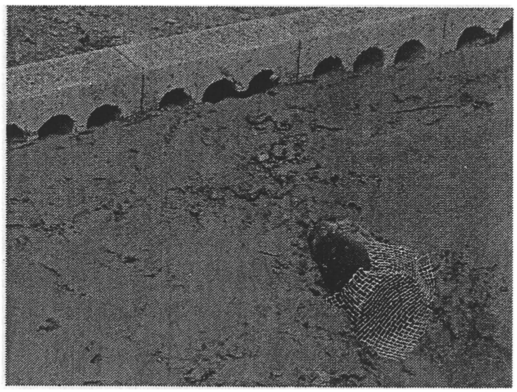


Figure 2.28 Cover the opening of the pipe with a net

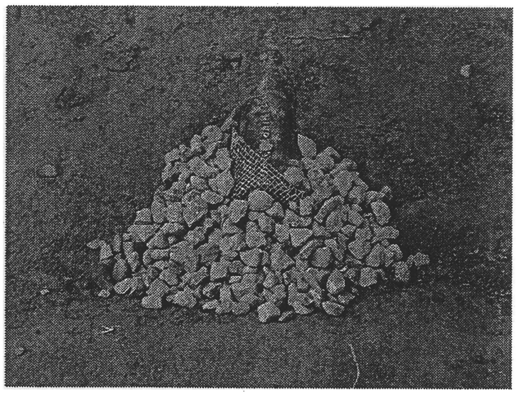


Figure 2.29 Covering the opening with aggregate avoids choking

Step 7: It is important to provide good protection to drainage pipes to avoid their chocking.

Figure 2.30 Fresh concrete from a concrete mixing plant

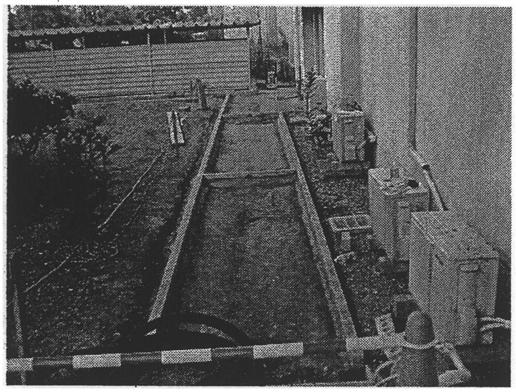


Figure 2.31 Provide construction joints to avoid shrinkage cracks

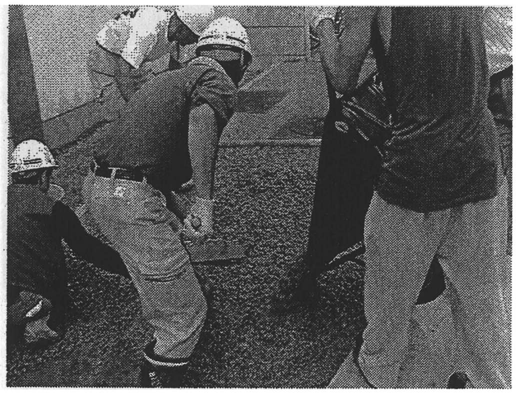


Figure 2.32 Placing of POC

Step 8: Construction joints are required at certain intervals to avoid shrinkage cracks.

Figure 2.33 Placing and laying of POC

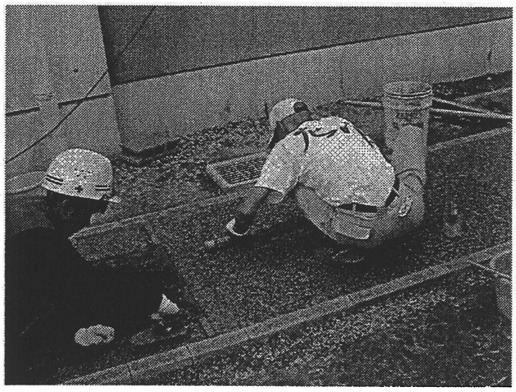


Figure 2.34 Leveling and compaction of POC

Figure 2.35 Placing in progress

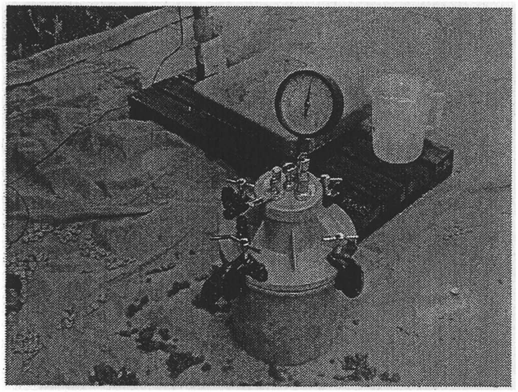


Figure 2.40 In-situ measurement of void ratio of POC mix

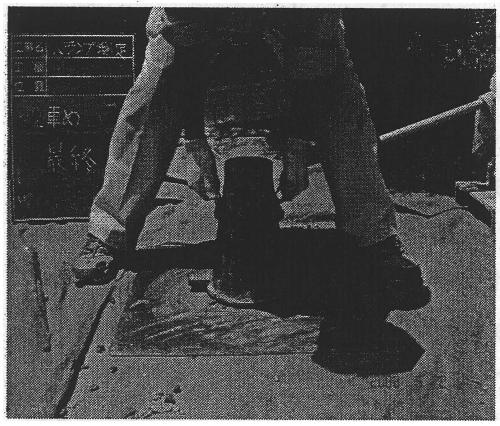


Figure2. 41 In-situ slump test of porous concrete mix

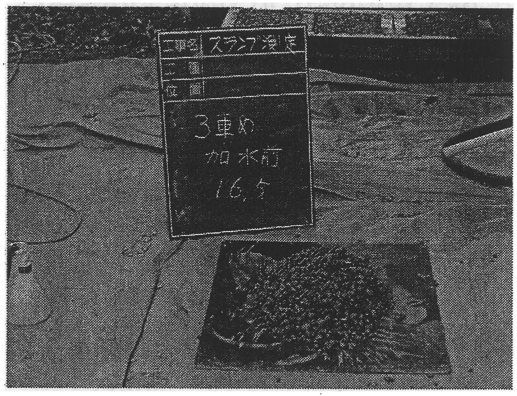


Figure 2.42 Slump value of 16.5 cm is found (Not carried out usually)

Step 11: Samples for different kind of tests like compressive strength, measurement of void ratio, permeability etc. are cast.

The in-situ measurement of void ratio is done finding the amount of water and air entering the mix by the use of aerometer.

(2) Laying of the upper layer

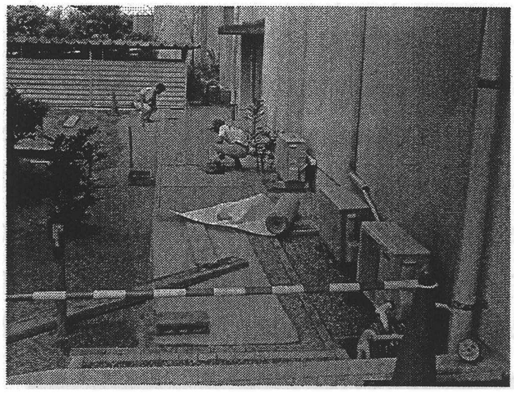


Figure 2.43 Laying of the upper layer of the T.N. base

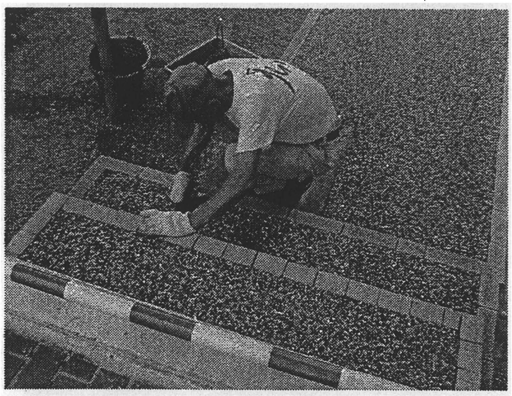


Figure 2.44 The upper layer is about 1 cm

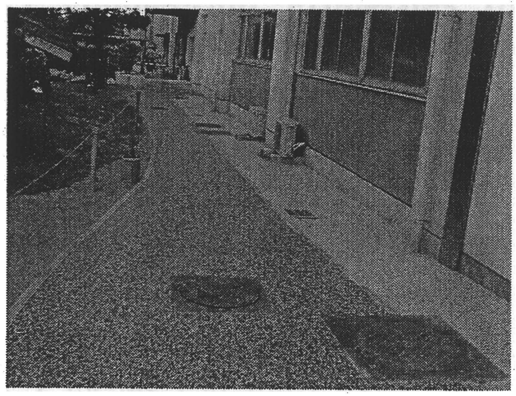


Figure 2.45 The finished T.N. Base pavement

1. Step 12: The upper layer of the T.N. Base is a thin layer of about 1 cm in thickness. Mostly colored natural aggregates of size about (5-6) mm are used for this layer. Recently, a new approach to paint the upper layer to give it the desired color had been developed. Therefore, colors of the natural aggregates can be either be chosen to blend with the surrounding of the place for beautification or painting can be applied to provide the desired look. The POC under layer has to be completely dry before placing of the upper layer of the T.N. Base.

   Materials for upper layer:

   a) Hardener: Reddish brown in color
   b) Resin: Transparent liquid
   c) Natural aggregate: Round shaped (about 6mm)
   d) Fine sand: 1.5mm (to counteract slipping during rain)

   Mixing method:

   -Firstly put natural aggregate (50kg) and fine sand (1.25kg) in the mixture and dry mix for about 30 seconds.

-Weigh the hardener (1.4kg) and resin (1.75kg) and mix them with an electric revolving mixture for about 30 seconds (till yellowish color with some kind of foam appears)

-Then slowly add the epoxy resin to the dry mix of natural aggregate and fine sand for about 1 minute while mixing them simultaneously.

This upper layer mix should be placed within 40 minutes after mixing. If not, placing becomes very difficult due to hardening of the mix.

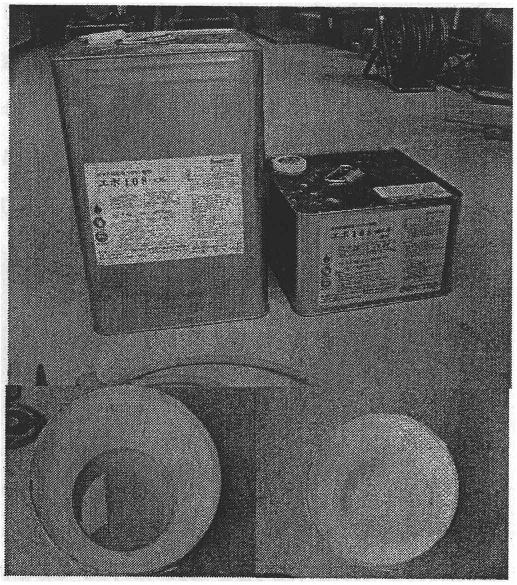


Figure 2.46 Hardener and resin used for T.N. Base upper layer

2.5 Engineering Properties of POC [10]

(1)Fresh Properties

The plastic porous concrete mixture is stiff compared to traditional concrete. Slumps, when measured, are generally less than ¾ inches (20 mm), although slumps as high as 2 inches (50 mm) have been used. When placed and compacted, the aggregates are tightly adhered to one another and exhibit the characteristic open matrix. For quality control and quality assurance, unit weight or bulk density is the preferred measurement because some fresh concrete properties, such as slump, are not meaningful for porous concrete. Conventional cast-cylinder strength tests are also of little value, because the field consolidation of porous concrete is difficult to reproduce in cylindrical test specimens, and strengths are heavily dependent on the void content. Unit weights of POC mixtures are approximately 70% of traditional concrete mixtures. Concrete working time is typically reduced for porous concrete mixtures. Usually, one hour between mixing and placing is all that is recommended.

(2)Hardened Properties

(a)Density and Porosity

The density of porous concrete depends on the properties and proportions of the materials used, and on the compaction procedures used in placement. In-place densities on the order of 100 lb/ft^3 to 125 lb/ft^3 (1600 kg/m^3 to 2000 kg/m^3) are common, which is in the upper range of lightweight concretes. A pavement 125 mm thick with 20% voids will be able to store 25 mm of a sustained rainstorm in its voids, which covers the vast majority of rainfall events. When placed on a 150-mm thick layer of open-graded gravel or crushed rock subbase, the storage capacity increases to as much as 75 mm of precipitation drainage system is provided in place of the sub-grade, for the drainage of water in case of heavy downpour and runoff water from the surrounding areas. However, in Japan, underground

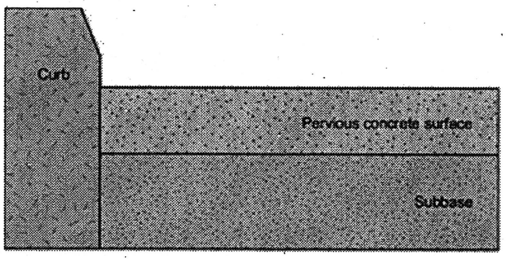


Figure 2.8 Typical cross section of porous concrete pavement. On level subgrades, stormwater storage is provided in the porous concrete surface layer. [10]

(b) Permeability

The flow rate through porous concrete depends on the materials and placing operations. It also depends on the void ratio of the porous concrete. (Typical flow rates for water through porous concrete are 0.2 cm/s to 0.54 cm/s, with rates of up to 1.2 cm/s). Even higher rates have been measured in the laboratory.

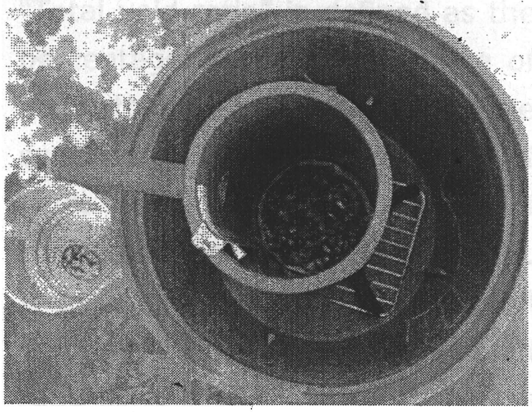


Figure 2.48 The top view of the apparatus with sample inside

(i) Method of measurement

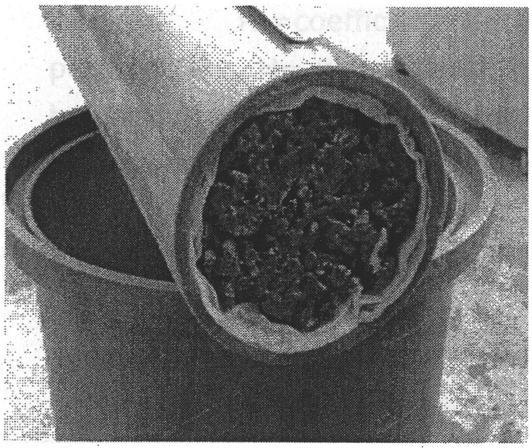


Figure 2.46 The sample being fixed for K_T

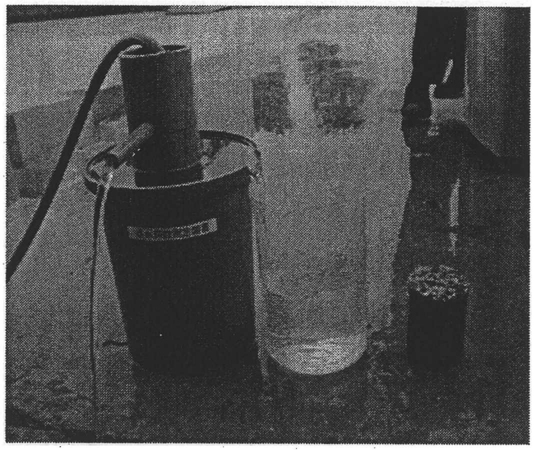


Figure 2.49 Permeability measurement

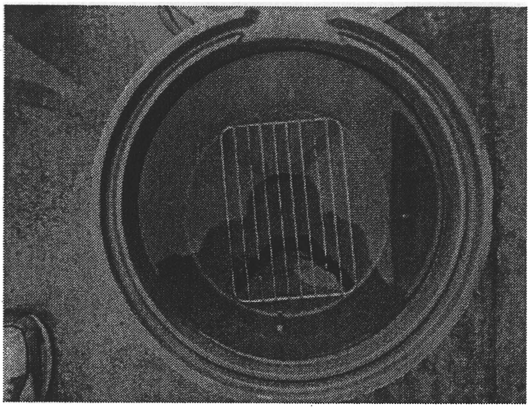


Figure 2.47 The base of the apparatus

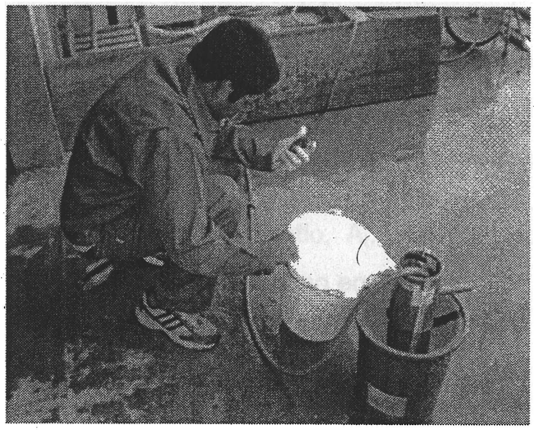


Figure 2.50 Permeability measurement in progress

Figure 2.51 The collected water is measured for calculation of K_T

(ii) Calculation of coefficient of permeability (K_T)

$$K_T=(H/h)*Q/A(t_2-t_1)$$

Where, K_T=coefficient of permeability, H= water head, h= height of the sample, Q=volume of water permeated from the sample, A= surface area of the sample, t_2=final time, t_1= initial time.

$Q= 602.13g$

$H= 6.2cm$

$h= 5.3cm$

$A= 67.89$

$t =15$ sec

$K_T= (6.2/5.3)X602.13/67.89X15$

$= 0.69cm/s$

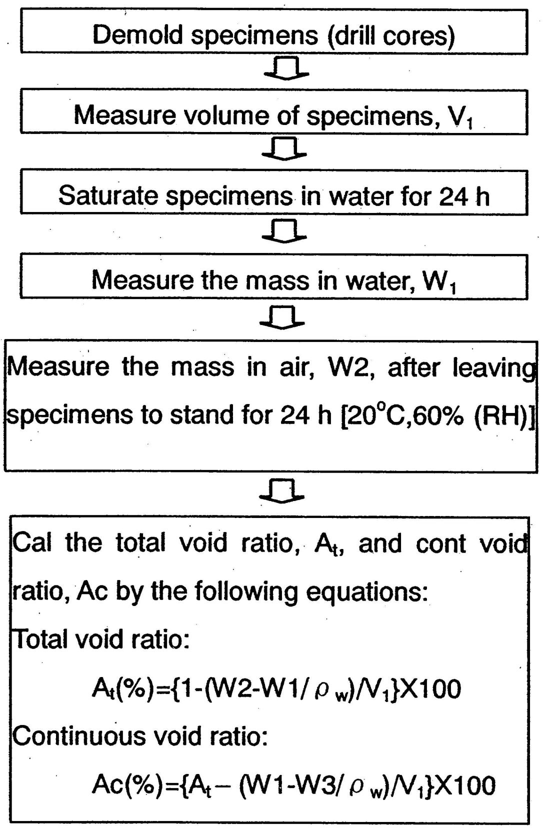
(c) Void ratio [7]

Definitions

"Continuous void ratio" is defined as the percentage of the volume of continuous voids to the total volume of the specimen. "Continuous voids" are defined as the voids that are continuous to the external surfaces and can be easily saturated with water and drained. "Total void ratio" is defined as the percentage of the total volume of voids to the total volume of the specimen. The total volume of voids is calculated as the sum of continuous voids and closed voids. It should be noted that the total void ratio is defined as the void ratio calculated by using the mass of a specimen in the air after draining it and leaving it to stand for 24 hours.

Measurement of mass in the air and determination of void ratio

The following flow chart shows the method of calculating the total void ratio and continuous void ratio.



Cal the total void ratio, A_t, and cont void ratio, Ac by the following equations:

Total void ratio:

$$A_t(\%)=\{1-(W2-W1/\rho_w)/V_1\}X100$$

Continuous void ratio:

$$Ac(\%)=\{A_t-(W1-W3/\rho_w)/V_1\}X100$$

(d) Compressive Strength

Porous concrete mixtures can develop compressive strengths in the range of 500 to 4000 psi (3.5 MPa to 28 MPa), which is suitable for a wide range of applications. Typical values are about 2500 psi (17 MPa). As with any concrete, the properties and combinations of specific materials, as well as placement techniques and environmental conditions, will dictate the actual in-place strength. Drilled cores are the best measure of in-place strengths, as compaction differences make cast cylinders less representative of field concrete.

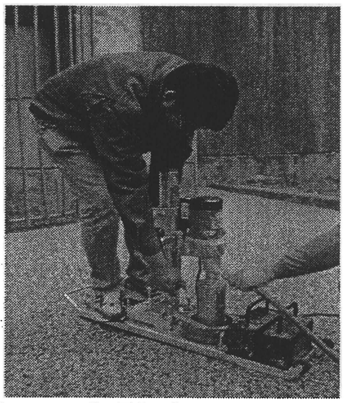


Figure 2.52 Core cutting

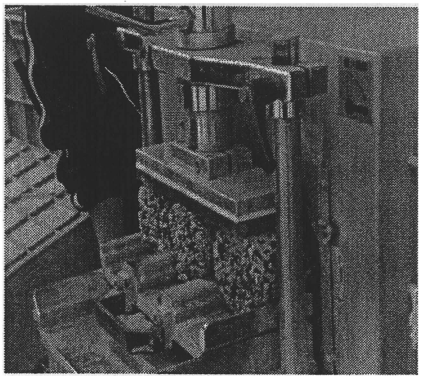


Figure 2.53 Grinding of surface

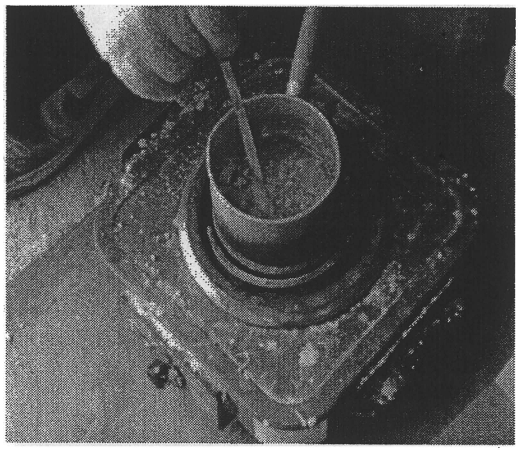


Figure 2.54 sulphur for capping

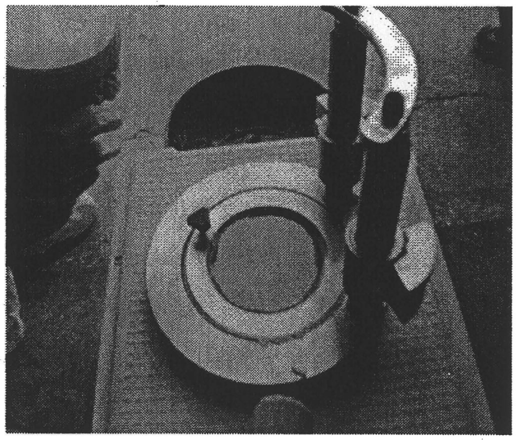


Figure2.55 Melted sulphur placed in the mould for capping

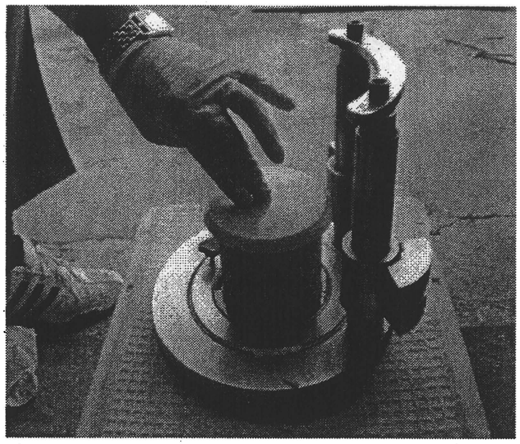


Figure 2.56 Capping in progress

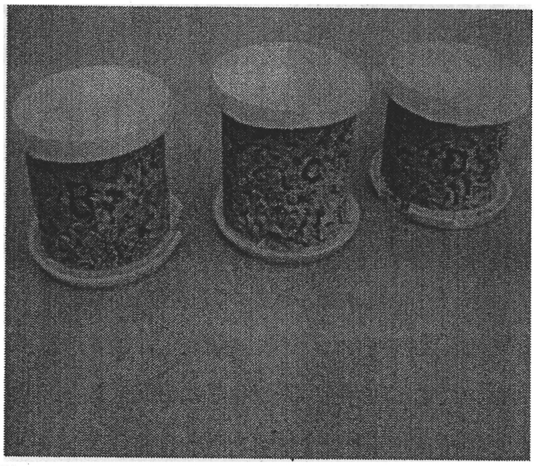


Figure 2.57 samples for Carrying out compressive strength test.

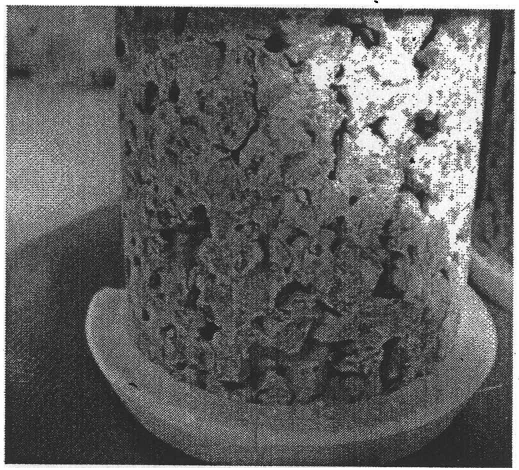


Figure 2.60 The pattern of failure after compressive strength test

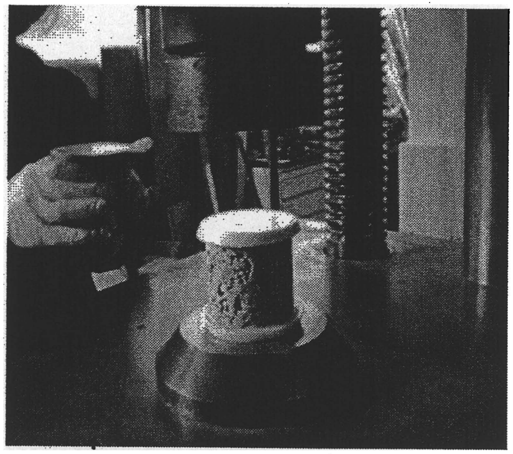


Figure 2.58 Compressive test in progress

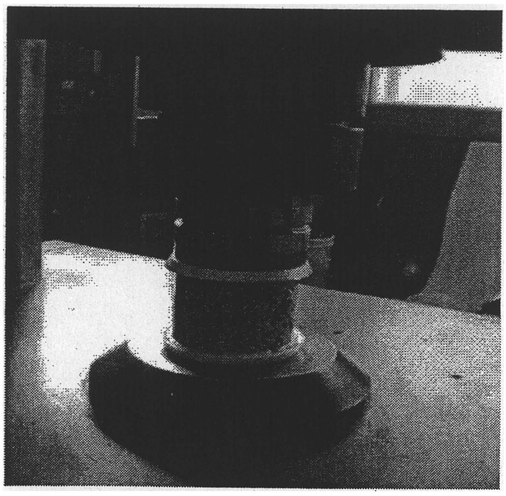


Figure 2.59 Compressive strength test in progress

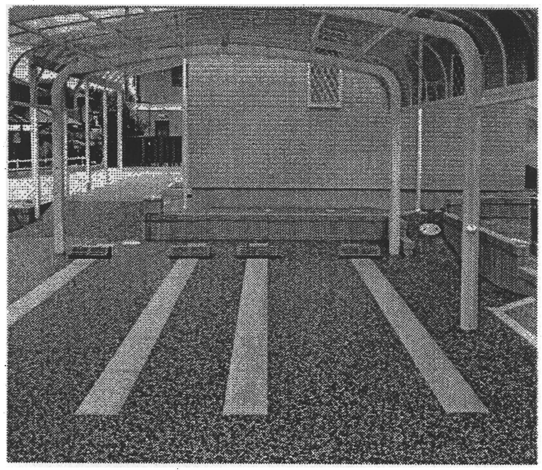
(e) Flexural Strength

Flexural strength in porous concretes generally ranges between about 150 psi (1 MPa) and 550 psi (3.8 MPa). Many factors influence the flexural strength, particularly degree of compaction, porosity, and the aggregate-to-cement (A/C) ratio. However, the typical application constructed with porous concrete does not require the measurement of flexural strength for design.

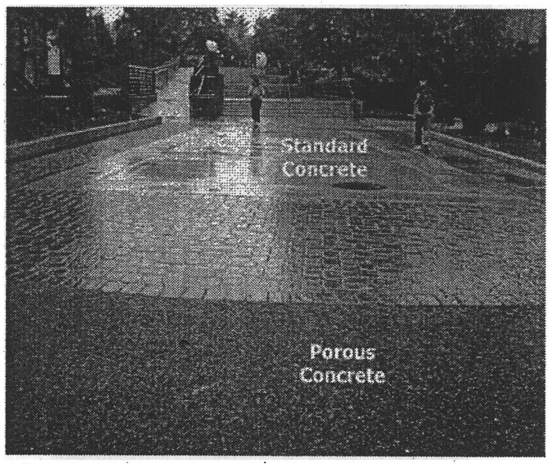
(f) Shrinkage

Drying shrinkage of porous concrete develops sooner, but is much less than conventional concrete. Specific values will depend on the mixtures and materials used, but values on the order of .002 have been reported, roughly half that of conventional concrete mixtures. The material's low paste and mortar content is a possible explanation. Roughly 50% to 80% of shrinkage occurs in the first 10 days, compared to 20% to 30% in the same period for conventional concrete. Even though the porous concrete has lower shrinkage and the surface texture, many of its pavements are made with control/construction joints to be at a safer side and avoid shrinkage cracks.

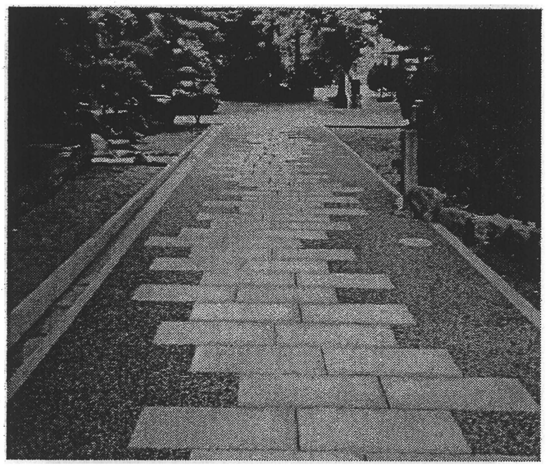
2.6 Applications of POC



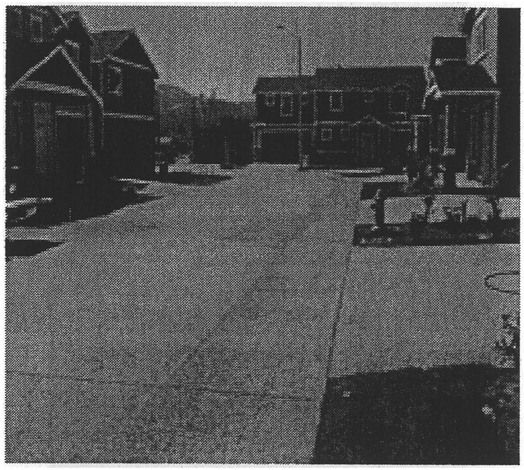
Car Parking



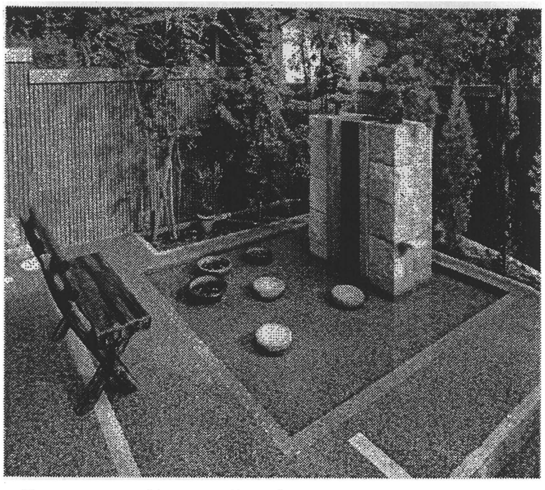
Pavement



Walkway



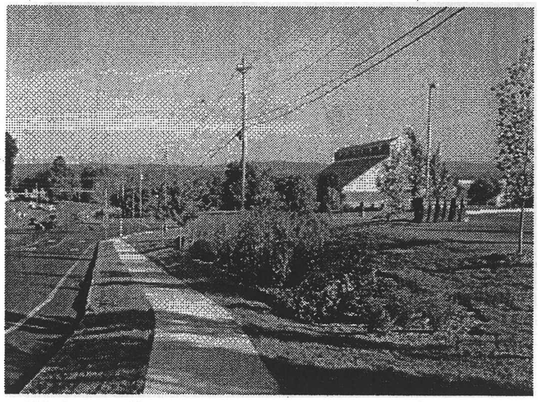
Roads and patios



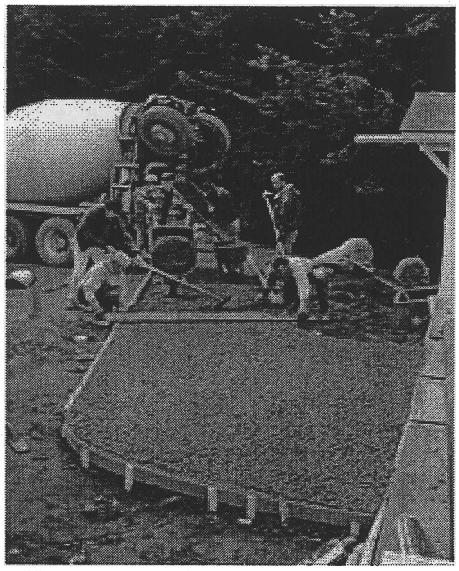
Surrounding of a house

Walkway and steps

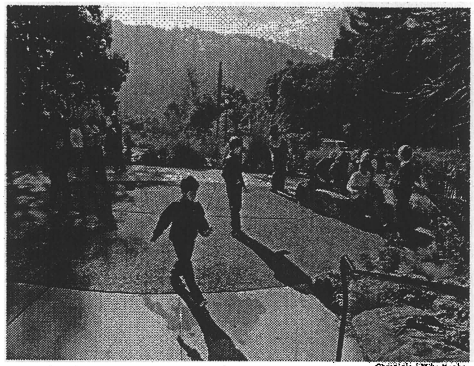
Small roads



Sidewalk

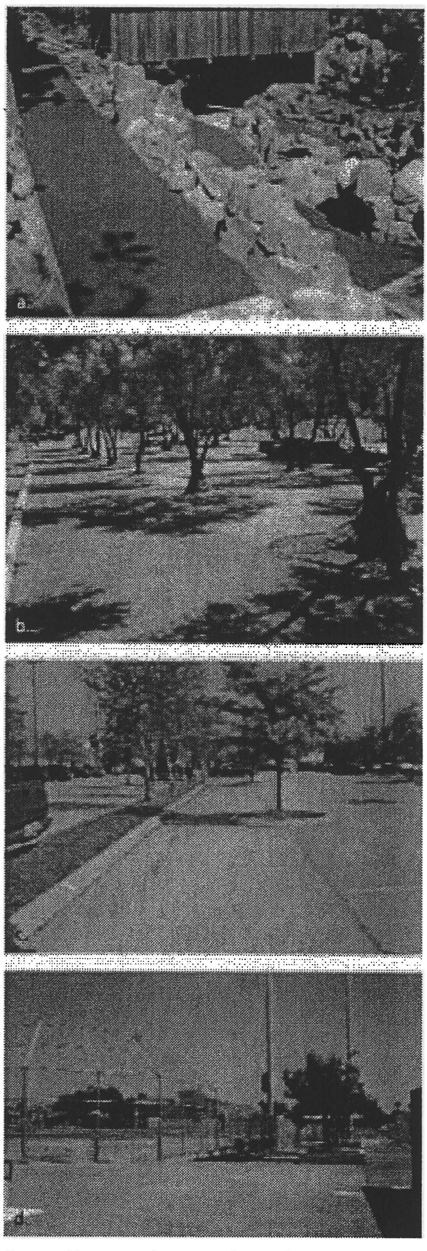


Narrow path

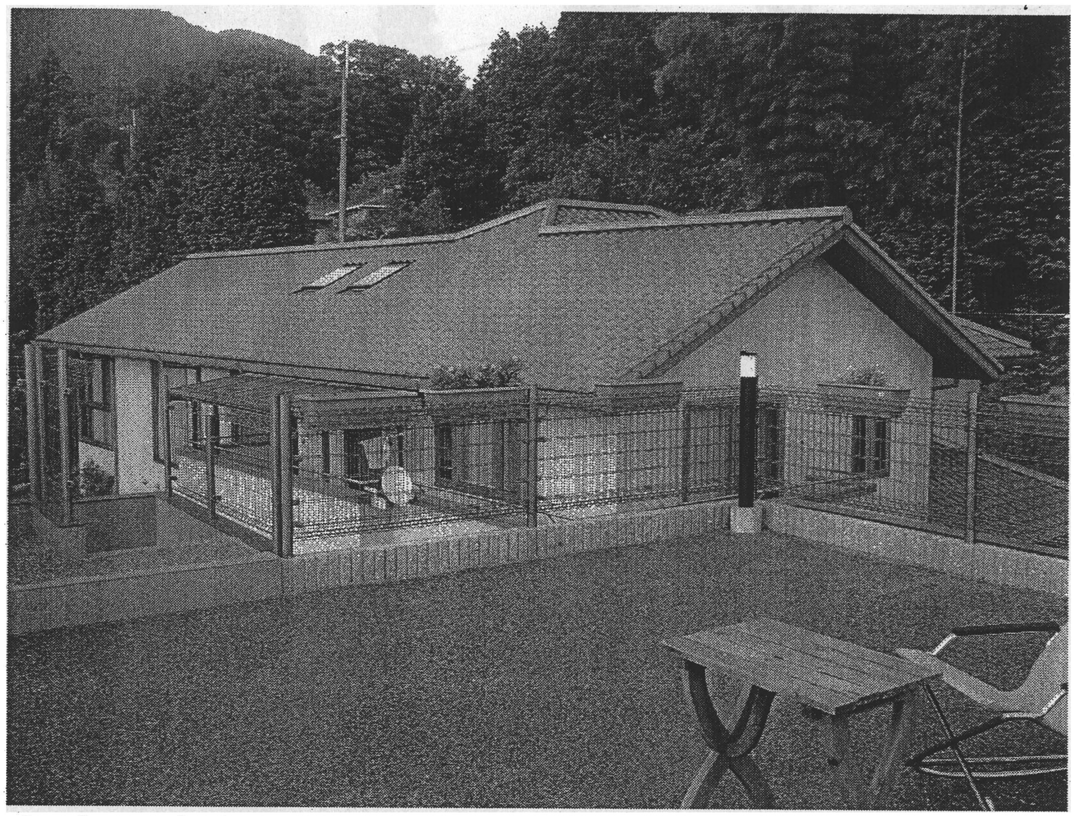


Chronicle / Mike Kepka

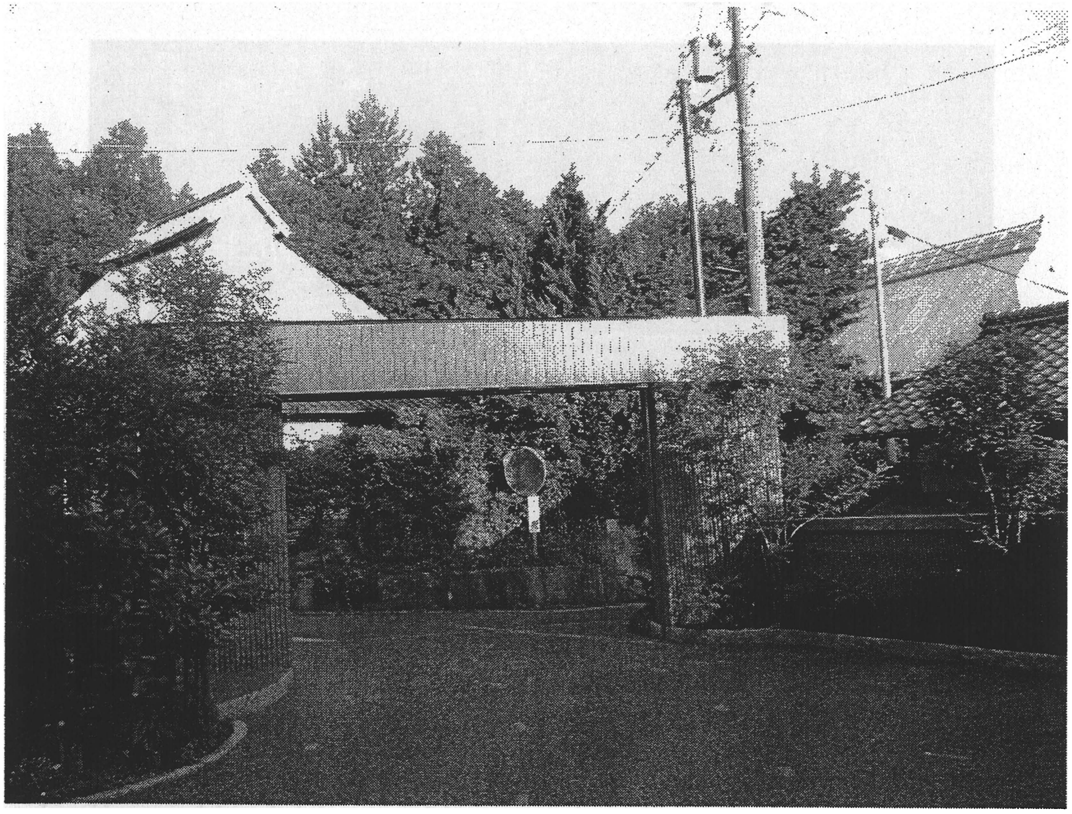
Parks



Small roads and sidewalks



Roof top of a house



Patio of a house

Pervious concrete parking [14]

Tree roots need air as well as water. Pervious concrete allows the passage of both. This pervious parking lot at Miller Park in Fair Oaks, Calif., is helping to preserve over 23 mature olive trees through natural irrigation. The lush tree canopy also shades the parking lot to provide natural cooling. [14]

Chapter 3 Other Researches on Porous Concrete

(State of art report)

3.1 Introduction

The study about other researches is important as it would give an insight on the type of research studies that have been done in the past and at the same time, would serve as an avenue to the future researches. A thorough study and the deep understanding of the other researches provide crucial hints for analyzing and deciding the needs for the future researches in the related field. Moreover, it is also beneficial in terms of acquiring knowledge to be equipped with various ideas and approaches which could be utilized while carrying out one's own research. By doing a thorough investigation of the other research studies, the horizon for the future research interest could be widened.

3.2 Clogging and Permeability Property

Clogging and permeability are easily the two most important fundamental properties of porous concrete.

Permeability is the ultimate purpose of applying a porous concrete. It is made possible by the continuous voids that are created intentionally into the aggregate binder matrix. Permeability increases with the increase in the void ratio. However, the increase in void ratio of porous concrete would mean the decrease in the compressive strength. The size of the voids can be changed as per the requirement simply by changing the size of the aggregate.

Clogging on the other hand is a phenomenon that is detrimental to the permeability of porous concrete. It occurs when the continuous voids of the POC get filled by the foreign materials due to which choking of the voids occur. Clogging reduces the permeability of the porous concrete and in the worst case, reduces it to the permeability equal to that of the foreign materials in the voids. If not prevented, it can render the porous concrete useless by reducing its permeability to lower than what would be required to drain the runoff water from a rainfall(passive runoff) and the nearby area(active runoff).

(1) Permeability predictions for sand-clogged Portland cement pervious concrete pavement systems [11]

Outline of the research

In this research, a theoretical relation was developed between the effective permeability of a sand-clogged pervious concrete block, the permeability of sand, and the porosity of the unclogged block. When the pervious concrete pores get clogged with sand the system permeability will be reduced by this to a fraction of the permeability of the sand, where this fraction can be represented by the porosity of the pervious concrete surface as

$$k_{eff}=(P_{top}/100)k_{sand}. \qquad (3.1)$$

where, k_{eff} = theoretical effective permeability of sand-clogged or covered pervious concrete block systems (cm/s). P_{top} = average porosity of the top quarter of the block as determined by an equation developed from laboratory analyses of other blocks taken from the same slab and given in percent. k_{sand} = permeability of sand (cm/s). The connecting pore system of pervious concrete is made up of irregular-sized voids caused by the cement matrix layers around the aggregate in pervious concrete, where the smaller diameters can effectively prevent sand from entering into many of the interior voids. The porosity that is assumed appropriate for the calculations in the experiment is that of the top section of the block:

$$P_{top}=1.07P-7. \qquad (3.2)$$

The infiltration rate is equals the volumetric rainfall rate minus the volumetric runoff rate:

k_{clog} = (Rainfall rate – Runoff rate)/Area of the block (3.3)

where k_{clog} = experimental permeability of sand-clogged pervious concrete block system (cm/s).

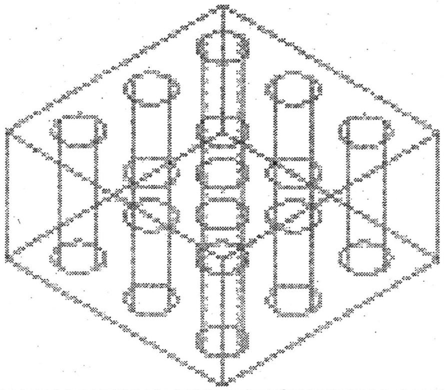


Fig. 3.1 Block section of pervious concrete representing approx. 20% porosity

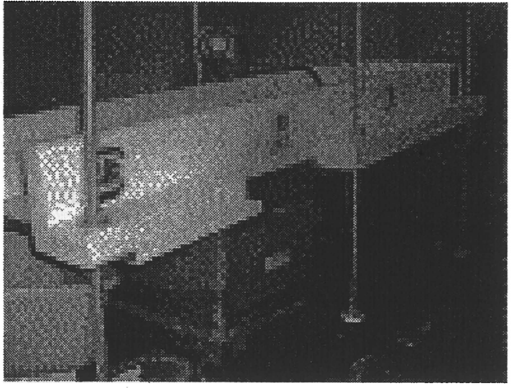


Fig. 3.2 Photo of experimental flume

Result and discussion

Experimental trials representing two different slopes (2% and 10%), different rainfall rates, and three different sand coverage depths (1.3, 2.5 and 5cm) were performed on the same pervious concrete block with a sand subbase.

The average k_{clog} for surface slopes of 2% (0.0044 cm/s) is nearly identical to the theoretically predicted value (0.0044 cm/s) for this system. There was very little variation regardless of sand cover or rainfall intensity. The average value for the simulations representing a 10% slope was 0.0037 cm/s. With an increase in slope, there will be a horizontal component to the flow which will discharge horizontally and add to the runoff.

Conclusion

The pervious concrete system clogged with the same sand as used in the sub-base resulted in negligible runoff for both the 2% and 10% sloped surfaces with simulations of typical rainfall intensities of up to 100 year frequencies.

Relation with my research: This research is also about the permeability of a sand clogged POC block and the unclogged block as that of my research. The difference here is that this study considers two slopes (2% and 10%) of the block, different simulated rainfall rates and three different sand coverage depths. It also takes into account the permeability of sand causing clogging of the block and finds out that the effective system permeability of a system clogged with fine sand of 0.02cm/s permeability is about 0.004cm/s which is similar to the rainfall intensity of a 30 min duration in southeastern United states. In case of my research, the emphasis is laid purely on the effect of clogging on permeability and its recovery. The permeability of sand is not considered. However, the comparative study of change in permeability with the addition of sand and after washing it, is made. Furthermore, double layer has been introduced in my research as a measure to tackle clogging problem.

(2) Infiltration and Clogging with Pervious Concrete Pavement

J. Patrick Coughlin[1,2] and David C. Mays[1] [12]

Outline of the research: The aim of this research is to find out how the infiltration rate of porous concrete sample is affected by clogging due to addition of sand and clay on it. It includes the measurement of steady state infiltration rates into porous concrete and the associated head loss. Furthermore, it also includes the measurement of clogging with up to 29kg/m^2 of sand and up to 0.45kg/m^2 of clay.

The unique aspect of this study is that it measures the flow through the porous concrete, base course, and underlying soil and not just the pavement. It also focuses on limiting case of saturation along with measuring the clogging.

Condition of the research:

A pervious concrete sample 30 cm square and 13 cm thick was mounted on 15 cm of Colorado Department of Transport (CDOT) base course and 15 cm of 0.6-0.3 mm sand, representing the underlying soil, enclosed in an acrylic box. A constant depth of 5 cm of tap water was maintained above the pervious concrete. Flow was measured with a graduated cylinder, and head loss was measured with piezometers (Figures 67 and 68).

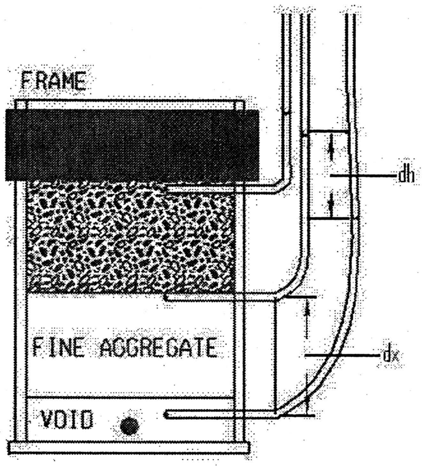


Figure 3.3 Schematic of apparatus

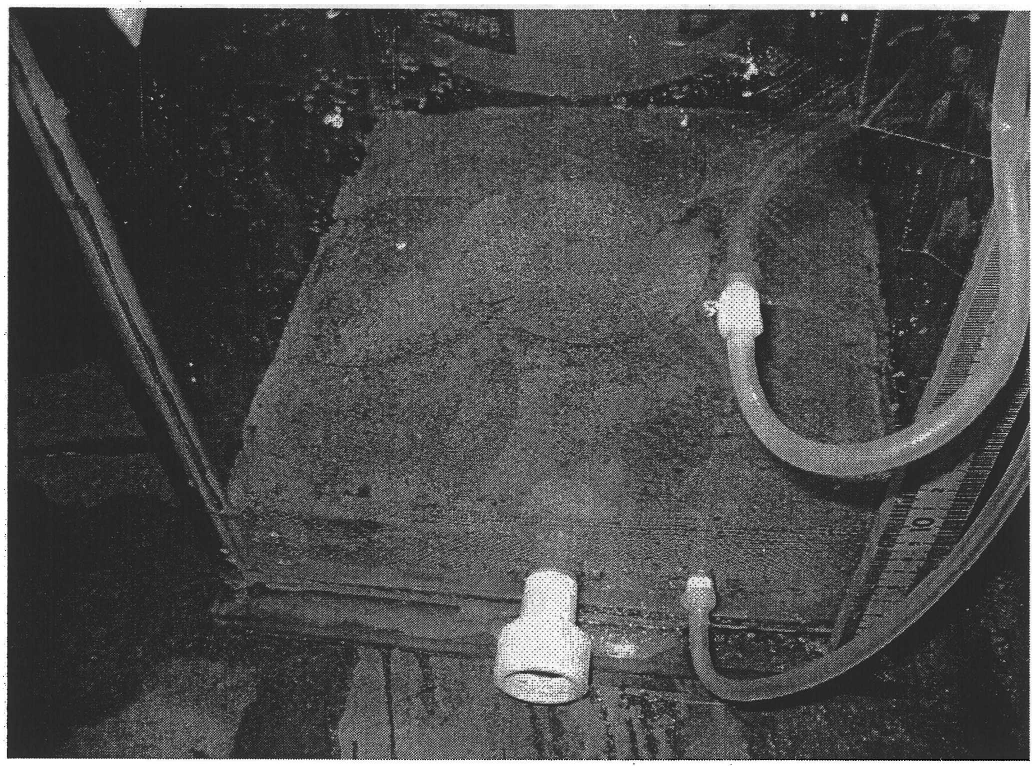


Figure 3.4 Acrylic box, showing the #100 mesh, above the drainage gallery, that supports the sand layer. The lower piezometer measures head at the bottom of the sand layer. The higher piezometer measures head at the base course-sand interface. Head is measured on the ruler shown at right (Coughlin, 2007)

Result and discussion Infiltration decreased when clogging materials were added (Figure 3.5). But, even with 29 kg/m2 of sand and 0.45 kg/m2 of clay, infiltration still averaged 15 cm/hr, well above the 100-year 1-hour rainfall for Denver of 6.6 cm/hr (UDFCD, 2004). There was no measurable head loss in the pervious concrete for as-built conditions. When sand was added, head loss in the top layer increased. Even still, a large fraction of the total head loss was dissipated in the underlying sand layer. Had this layer been soil, rather than sand, it likely would have been the flow-limiting layer in all cases.

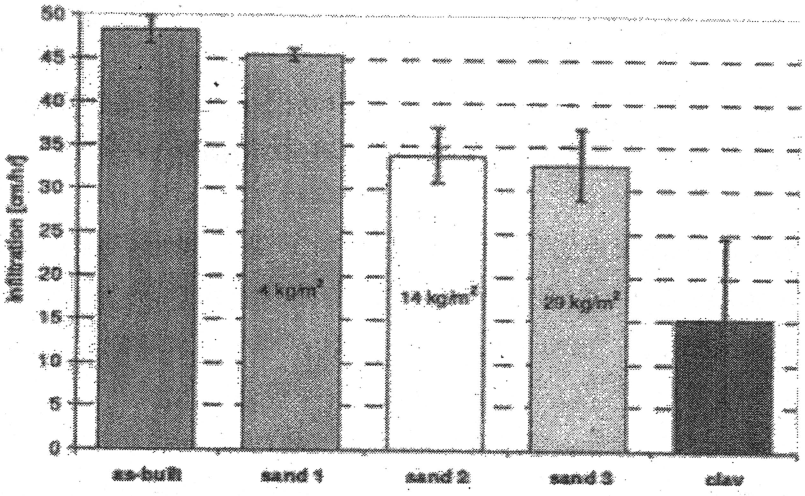


Figure 3.5 Infiltration rates. Error bars are one standard deviation, based on three replicates.

CONCLUSIONS

1. Infiltration rates are large, even when the pavement is clogged.
2. Infiltration is limited by underlying strata.
3. The effectiveness of pervious concrete as a stormwater BMP will be limited by the capacity of the underlying soils (or underlying engineered drainage system).

Relation with my research:

Few important details are found missing in this paper. There is no mention of the vital properties of the sample such as size of the aggregate used, void ratio as well as the size of the sand and clay used for clogging. However, it can be seen from figure 3.5 that there is this similar decreasing trend in the permeability following the addition of sand and clay, as it is in my research. And as expected, it can be observed that the addition of clay does the more harm to the permeability of the sample. The conclusions suggest that the infiltration rates are large even when the pavement is clogged or that it is limited by the underlying strata. When it comes to clogging and permeability, I strongly feel that a lot depends on size of aggregates used for preparing the sample and also the sizes of the sand used as clogging material for the experimental purpose.

In my research, it has been found out that addition of sand clearly hampers the permeability of the POC samples, both single and double layered. However, washing helps to recover the permeability of double layered samples to the tune of 65-70% in case of G6 aggregate bottom layer and G8 aggregate upper layer.

(3) Hydrologic Properties of Pervious Concrete

J. D. Luck, S. R. Workman, S. F. Higgins, M.S. Coyne [8]

Outline of the Research

The main objective of this project was to conduct research on the potential application of pervious concrete in agricultural settings, specifically for use in animal feed lots, manure storage pads, animal manure and bedding compost facilities, or floor system in animal buildings. Laboratory tests were conducted on samples of pervious concrete formed from two rock sources (river gravel and limestone) for coarse aggregate and different size fractions to determine hydrologic relationships.

Results and discussions

The aggregates used for making the samples were #8 river gravel, #9 limestone, #57 river gravel and #57 limestone. The mean reduction in permeability is the minimum in case of #8 aggregate, which has the minimum size (D_{50} of 6.9mm). This is due to the fact that the pores created were smaller because of which less compost penetrated into the specimens (table 3.1). Overall the porous concrete was effective in separating liquid and solids. Less than 8% of the compost was retained in the matrix even after 2000 mL of water was applied.

Table 3.1 Results of t-tests for effects of aggregate type on specimen permeability.[a]

Aggregate	Mean Initial permeability (L/s/m2)	Mean Compost retained (%)	Mean Permeability After Compost (L/s/m2)	Mean Reduction in Permeability (%)	Siginificant Difference in Permeability
#8 River gravel	14.0 a	2.8 a	11.1 a	22.2 a	Yes
#9 Limestone	13.1 a	7.2 b	7.8 a,b	48.0 b	Yes
#57 River gravel	11.3 a,b	6.1b	6.1 b,c	46.2 b	Yes
#57 Limestone	7.2 b	5.7 b	3.3c	52.8 b	Yes

[a] Mean values followed by the same letter are not significantly different ($p >= 0.05$).

Conclusion

The test results suggest that pervious concrete would be effective at providing solid/liquid separation in agricultural settings. Negligible amounts of compost were collected in the effluent from the pervious concrete specimens, and less than 8% of the added compost was retained in the surface voids.

The material collected in the surface voids reduced the permeability by 22% to 53%, but the resulting permeability exceeded typical rainfall events.

Relation with my research: This study also states that the mean reduction in permeability is the minimum in case of #8 aggregate, which has the minimum size (D_{50} of 6.9mm) among the aggregates used as the pores created were smaller because of which less compost penetrated into the specimens. I have used similar concept of smaller voids allowing lesser foreign materials to penetrate, in introducing the double layered POC with the upper layer having smaller voids to reduce clogging of internal voids as much as possible.

(4) EFFECTS OF PERVIOUS CONCRETE ON POTENTIAL ENVIRONMENTAL IMPACTS FROM ANIMAL PRODUCTION FACILITIES [13]

Joe David Luck and Dr. Stephen R. Workman

Outline of the research

Pervious concrete could reduce pollution when used for animal feeding pads, manure storage pads, or floor systems in animal buildings. The objective of this study was to provide more information concerning the use of pervious concrete in agricultural settings. Tests were conducted on replicated pervious concrete specimens to determine various hydrologic properties, solid material retention capacity, and the effluent nutrient reduction capacity of the material.

Results and discussions

The pervious concrete exhibited the potential to provide environmental benefits by reducing nutrients from compost effluent and significantly fecal coliform concentrations after only one week of rainfall simulations.

Conclusion

Overall, the pervious concrete exhibited potential for mitigating adverse impacts on the natural environment. Beyond the runoff reduction properties, which is beneficial in terms of reducing nutrients and pathogens in runoff, it has the potential to reduce pathogens and nutrients by acting as a type of bio-filter (a biologically active barrier where microorganisms break down contaminants thereby improving water quality). The liquid retention properties of pervious concrete may also provide environmental benefits.

Relation with my research: In this research, though the purpose of the study is for the agricultural settings, the basic finding revolves around the filtration aspect of porous concrete as it is in my research where a double layered POC is introduced with the aim to filter the foreign materials at the top itself so that clogging can be prevented.

(5) Virtual Pervious Concrete: Microstructure, Percolation and Permeability [9]

Dale P. Bentz

This paper presents various virtual pervious concrete micro-structural models and compares their percolation characteristics and computed transport properties to those of real world pervious concrete. The goal is to develop 3D micro-structural model to represent pervious concrete and to compute its percolation and transport properties for comparison against available experimental data. It captures the percolation and transport properties of the real in-place material and allows an extension to computational-based durability studies of the POC relevant to freezing-and-thawing resistance and clogging.

In this paper, a successful development of a virtual POC based on a correlation filter 3D reconstruction algorithm has been demonstrated. When full 3D tomography data sets are available from the actual POC, the presented percolation and transport property computation codes may be conveniently used to compute percolation, conductivity and permeability of the real materials.

Result and discussion

The results demonstrated that virtual pervious concrete based on the correlation filter reconstruction algorithm produces a simulated void microstructure whose percolation characteristics are quite close to those of various pervious concrete. Such a model could be used to predict the permeability, or conductivity of pervious concrete a priori. Clogging potential can be examined using virtual pervious concrete. Computationally, an algorithm similar to a mercury intrusion experiment can be used to examine the accessibility of the 3D porosity as a function of entryway pore size. By equating this entryway pore size to the size of the particles causing the clogging, the clogging potential of various pervious concretes might be assessed. An example of this is provided in Fig. 3.6. For both, the infiltration of particles 1 mm in diameter or greater could lead to considerable clogging, as indicated by the low intrusion volumes. For smaller particles (for e.g., 0.333mm), the 14% porosity should be more susceptible to clogging than 27% one. The clogging results for the virtual pervious concrete based on the hybrid HCSS model indicates a much larger critical pore size, consistent with this model's higher permeability values in comparison with the reconstructed and real pervious concrete.

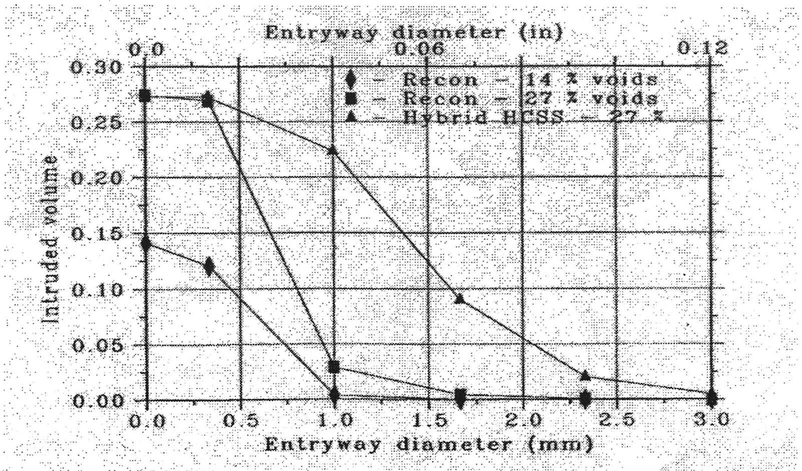


Fig. 3.6 Intruded volume versus entryway pore diameter

Conclusion

The virtual pervious concrete contains a 3D void structure that exhibits percolation characteristics and computed transport properties in good agreement with those of real world, based on available literature data. Finally, potential extensions of the virtual pervious concrete to exploring durability issues such as freezing-and-thawing resistance and clogging have been introduced.

Relation with my research: Although this research is regarding the 3D modeling of porous concrete, it emphasizes on the important aspect as capturing the percolation and transport properties of the real in-place material and allowing an extension to computational-based durability studies of the POC relevant to freezing-and-thawing resistance and clogging. That way, the concept can be utilized in my research studies as it helps to compute percolation and transport properties for comparison against available data. It may also provide crucial hint for my future research for the development of some kind of formula for the double layered POC relating the thickness of two layers and the permeability.

3.6 Hydraulic Performance of Pervious Concrete Pavements

Manoj Chopra[a], Martin Wanielista[a], Joshua Spence[a], Craig Ballock[a] and Matt Offenberg[b]

Outline of the research

This paper focuses on the hydraulic operations of a pervious concrete system including infiltration rates, storage capacity and clogging potential. Pervious concrete allows water to infiltrate at very high rates, typically 100 to 200 inches an hour, whereas the underlying soils will infiltrate water at much lower rate, usually by 1 to 2 orders of magnitude. Therefore, it is important to consider the effects of the entire system (pavement and soil) when predicting the infiltration capacity of pervious concrete pavements.

The study consists of detailed analyses of several pervious concrete parking lots that have been in operation for 5 or more years. Field analyses include testing for system infiltration rates, estimation of surface clogging of pavement and subgrade/subsoil investigations. In addition, a field test method for infiltration rates is developed treating the pavement as a system consisting of the pervious concrete and the sub-base soil.

Result and discussion

Several pervious concrete sites were tested to measure infiltration rates using the embedded single-ring infiltrometer test. These sites ranged from 6 to 18 service years. They are functional parking lots that are currently in operation and are in various conditions in terms of maintenance, clogging and raveling. Asummary of the results obtained from the field tests are in table 3.1 below.

Table 3.1: Results for infiltration rates at different field sites

Test Location	Avg. Concrete rate [in/hr](range)	Avg. soil rate [in/hr]	Limiting Factor
Site 1-Area 1	25.7 (19-32.4)	34.5	Concrete
Site 1-Area 2	3.6 (2.8-4.5)	14.8	Concrete
Site 2	5.9 (5.3-6.6)	5.4	Soil
Site 3	14.4 (2.1-22.5)	21.8	Concrete
Site 4-Area 1	2.1 (0.7-4.5)	15.6	Concrete
Site 4-Area 2	2.9 (0.9-4.9)	15.6	Concrete
Site 5	3.7 (1.7-5.4)	8.8	Concrete

The following observations are made:

1. The pervious concrete and subsoil system displays infiltration rates of nearly the same magnitude as the subsoil in locations where its infiltration rate is higher than that of the subsoil.
2. A significant number of the pervious concrete cores were found to have very low or no infiltrations rates and are primarily cases of its improper construction and placement where the voids of the concrete are not present.
3. The field test may also be applied to soils with lower infiltration rates as seen in the case of site 2.

Relation with my research: This paper deals with system infiltration rates and estimation of surface clogging of pavement. Therefore, it has similarity with my research about clogging and permeability. The difference is that it considers the effects of the entire system (pavement and soil) for predicting the infiltration capacity of pervious concrete pavements.

3.7 VERTICAL POROSITY DISTRIBUTIONS IN PERVIOUS CONCRETE

PAVEMENT [14]

Liv M. Haselbach (ACI Member), Robert M. Freeman

Outline of the research

This research shows that there is a vertical distribution of porosity in slabs placed with certain placement techniques. The vertical variation of porosity can affect the strength distributions within the material, the permeability of the system and its potential for clogging. It is shown that these slabs have a fairly linear vertical porosity distribution with the lowest porosities in the top quarter, average porosities in the center half, and the higher porosities near the bottom. These regional porosities may be important for determining characteristics of pervious concrete slabs such as the potential locations for clogging. The presence of reduced porosity near the top can be a benefit for environmental reasons as clogging may tend to accumulate near the surface from solids in runoff and surface debris and this clogged area may be readily accessible for removal through periodic maintenance such as vacuuming. It is important to know the vertical porosity distribution to understand how infiltrating water may carry sediments through the media and lodge in bottleneck areas prone to clogging due to different porosity levels.

Results and discussion:

There were a total of twenty-one 76mm and four 102mm cores tested for porosity according to the standard porosity test. After the initial porosity tests were carried out, all the cores were then sliced into the three vertical core regions-the top quarter, the middle half, and the bottom quarter-and subsequently tested for porosity. The weighted (by volume) average porosity P_w was also calculated for each core. The results show that there is clearly a relationship and pattern between porosity and depth within the pervious concrete samples. The data for both sized cores (small and large) show an average regional increase in porosity with depth within the slab.

Conclusion

It is seen that the pervious concrete slabs cast with a typical placement process have a fairly linear vertical porosity distribution with the lowest porosities in the top quarter, average porosities in the center half, and the higher porosities near the bottom. The results were statistically significant for the top and bottom regions where the variations from the average were the most extreme and the differences were greater than the expected error in the measuring techniques. The regional porosities may be important for determining characteristics of pervious concrete slabs such as the potential locations for clogging. This knowledge can be further used for research into, and design and specification of, improvements such as recommended maintenance procedures. The presence of reduced porosity near the top can be a benefit for environmental reasons as clogging may tend to accumulate near the surface from solids in runoff and surface debris and this clogged area may be readily accessible for removal through periodic maintenance such as vacuuming.

Relation with my research: This research focuses on the clogging of POC and says that having lower porosity near the surface will produce a positive environmental effect as clogging may tend to accumulate near the surface from solids in runoff and surface debris and this clogged area may be readily accessible for removal through periodic maintenance such as vacuuming. In my research also, the emphasis is on clogging and in trying to prevent clogging of the voids of POC. The difference is that in this research, it is still the single layer porous concrete with porosity increasing from top towards the bottom whereas, in my research, a double layered POC has been introduced with the thinner upper layer having smaller voids (made of smaller aggregates than the bottom layer). The smaller sized voids help in stopping most of the foreign materials on the surface itself. This in turn helps in preventing the clogging of the voids of porous concrete and makes it easier to restore the permeability by water pressure washing or vacuuming.

Chapter 4 MY RESEARCH EXPERIMENTS
(Study on clogging and permeability of porous concrete)

4.1 ABSTRACT

Porous concrete (POC) possesses continuous voids that are created intentionally to facilitate the permeability of air and water through it. However, clogging of its voids is a matter of serious concern in POC. This research study includes three experimental studies related to clogging and permeability of porous concrete. A double layered porous concrete samples are introduced in this study for the first time in this field. Out of the three experiments, the first experiment is on single layered POC samples (G6 and G7 aggregate grade) followed by two more experiments on single and double layered POC samples {G6, G7, G8 aggregate grade single layered samples and (G6+G7) and (G6+G8) double layered samples}. Silica sand is used as clogging material for all the three experiments. S6 grade silica sand is used in the first and second experiments while S7 grade (which is smaller) is used in the third one. After the occurrence of clogging, washing is applied as a remedial measure to find out whether or not permeability can be restored with the help of washing. The effect of washing is found to be different for the single and double layered samples. It was observed that the double layered samples showed impressive restoration of the permeability than the single layered samples.

4.2 INTRODUCTION

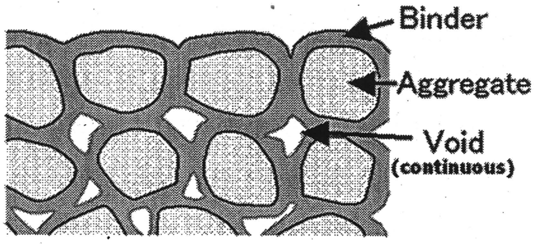


Fig 4.1Schematic diagram of POC

Porous concrete (POC) is a concept that is quite different from the conventional concrete. Unlike conventional concrete, porous concrete possesses intentionally created continuous voids that facilitate the permeability of water and air through its whole system. Fig. 4.1 shows the schematic diagram of porous concrete. The school of thought behind advocating this concrete is to have a system that would help in draining off the runoff water during a rainfall. Therefore, the phrase, "When it rains it drains" is often used in the west to describe porous concrete. It is very important for the voids to be continuous in porous concrete. This particular requirement in turn, calls for being very skillful as well as careful in the construction of POC. Progressively, the ability of POC to exhibit various environment-friendly performances is being realized. Given the fact that the world is faced with a grave concern regarding environmental degradation and global warming today, POC could play a very special role in its own small way in contributing towards reducing the environmental loads. To mention a few of them, POC can be used to avoid creation of imbalance in natural ecosystem by the prevention of pollution of rivers, lakes and coastal waters, erosion, flash floods, water Table depletion as rainwater rushing across pavement surfaces picks up everything from oil and grease spills to deicing salts and chemical fertilizers [1]. It can co-exist with micro-organisms; it can be used as a media for thermal and moisture-conditioning, plants and grasses can be grown on it to enhance the look as well as impart greening effect to areas like river protection works and barren slopes; it can also be utilized as noise barrier walls in railways and expressways. In Japan, POC is used for pavements, parking areas, the surroundings of a house (patios), walkways, etc.

The advantage of POC notwithstanding, POC is faced with a few problems as well. Potential areas of concern are: effect of cyclic wetting and drying, freezing and thawing, shrinkage cracks, repeated loading effect, abrasion, wearing and clogging phenomenon [2]. Clogging is detrimental to the very purpose of porous concrete which is to allow the permeability of water through its voids. Once the voids are clogged, it becomes close to impossible to restore the original permeability. Quite often, the permeability drops to zero rendering the porous concrete useless. The reason behind advocating the POC needs to be protected so that this amazing finding can be utilized for as long as intended. And in order to achieve that, one of the issues that requires to be tackled without any doubt is the clogging phenomenon. This will ensure the longevity in the use of porous concrete.

4.3 EXPERIMENTAL METHOD

This research study comprises of results from three experiments that havebeen carried out.

4.3.1 First Experiment (Effect of clogging on permeability of POC)

Table 1 represents factors and testing levels of the first experiment.

This experiment was carried out on single layered POC samples of size (50x150x40mm) and aggregate grades G6 (5-13mm) and G7 (2.5-5mm) with void ratios of 15%, 23% and 30% for G6 aggregates and 23% in case of G7 aggregates. Both the longitudinal faces of the samples have cut and ground surface to make them smooth and uniform throughout. This ensures that the samples fit in the apparatus perfectly well and prevent the water from entering through the area other than the top surface of the sample and comes out from the bottom surface. It is important to ensure that the flows only from the top surface of the sample. An indigenous apparatus as shown in Figure 4.2 was prepared to carry out the experiment.

Table 1 Factors and testing levels (1^{st} exp.: single layered POC) [3]

Factor	Testing Levels
Void ratio(%)	15, 23, 30
Size of Aggregate	$G6^{*1}$, $G7^{*2}$
Added sand (g)	0, 60, 120
[Vs/S.A^{*3} (cm^3/cm^2)]	[0, 0.4, 0.8]

Note: *1 Aggregate Grade G6 (5-13)mm, *2 Grade G7 (2.5-5)mm
*3 Vs: added sand volume, S.A: top surface area (150x40)mm

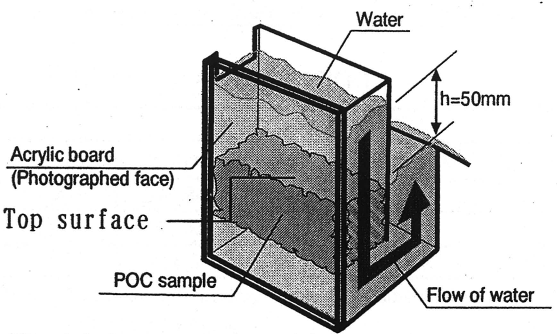


Fig.4.2 Apparatus used for the experiment

During the experiment, a water head of 50mm as shown in Figure 4.2 is maintained throughout. In order to calculate the coefficient of permeability (K_T), water permeating through the sample is collected at the outlet for 10 seconds and weighed every time. In the beginning, normal tap water is allowed to pass through the samples in order to measure the actual permeability of the sample. Then 60g each of grade S6 silica sand are added successively, again weighing the water collected for 10 seconds after each addition. This is carried out for three samples each of all the categories to take the average permeability. That way, the permeability of the samples first with just the normal tap water passing, second after the addition of 60g of silica sand followed by the addition of 60g more can be respectively measured. Washing is applied to the clogged samples after addition of each 60g sand, to study the behavior of permeability by washing, following the clogging phenomenon. Particle size distribution of the silica sand grades S6 and S7 used as clogging material during the experiment is as demonstrated in the Figure 4.3. S6 grade sand was used first and second experiments while S7 grade sand was used for the third experiment.

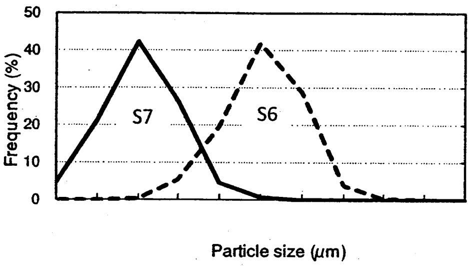


Fig.4.3 Particle size distribution
Of Grades S6 and S7 silica sand

4.3.2 Second Experiment (Double layered POC)

Table 2 displays the factors and levels and Table 3 shows the experimental conditions for the second experiment respectively. The mix proportion is shown in Table 4.

Table 2 Factors and testing levels (2nd exp.: double layered

Factors	Testing levels
Size of Aggregate	G6*1, G7*2, G8*3
Combination of layers	(G6+G7), (G6+G8)
Added sand (g)	0, 60, 120
[Vs/S.A*4 (cm^3/cm^2)]	[0, 0.4, 0.8]
Thickness of top layer (mm)	4,8,12

Note:*1 G6 (5-13)mm, *2 G7 (2.5-5)mm, *3 G8 (1.25-2.5)mm
*4 Vs: added sand volume, S.A: top surface area (150x40)mm

Table 3 Experimental conditions (2nd exp.: double layered POC)

W/C ratio (%)	30%
Void ratio of upper layers (%)	18%
Void ratio of under layer (%)	23%
Under layer (50mm)	G6
Size of single/under layer	(50x150x40)mm

Table 4 Mix proportion

	Unit weight (g/L)			
Sample	water	cement	Aggregate	SP*1
G6*2	544.84	1816.13	8163.79	1.63
G7*3	167.33	557.55	1746.11	0.50
G8*4	161.5	538.57	1778.87	0.48

Note: *1 SP: Superplasticizer, *2 G6 (5-13)mm, *3 G7 (2.5-5)mm, *4 G8 (1.25-2.5)mm

The procedure followed for the experiment is the same as in the first experiment. The only difference here is the introduction of double layered samples. Here, single layered POC samples of grades G6, G7 and G8 along with double layered samples of (G6+G7) and (G6+G8) were cast for carrying out the experiment. Figure 4.4 and Figure 4.5 represent the single and double layered samples. In case of double layered samples, the under layer is made of grade G6 aggregate with void ratio of 23% and the upper layers are of G7 and G8 aggregates with the same void ratio of 18%. The double layered samples have three different thicknesses for the upper layer i.e. 4mm, 8mm and 12mm. As for the under layer, its size is maintained the same as that of the single layered samples used in the first experiment (i.e. 50x150x40mm). This helps in making comparisons between the single and double layered samples as the sizes of the under layer and the single layer remain constant. The idea is to compare the permeability of the single layers and the change in permeability with the addition of an extra layer on the top of the single layer. It is also intended to find out what kind of effect does the change in the thicknesses of the samples of the same aggregate grades have in the change in the permeability. For instance, by measuring the permeability of grade G6, G7 and G8 single layers and the permeability of (G6+G7) and (G6+G8) double layers with the sizes of the single layers and under layers remaining the same and that of the upper layers of grade G7 and G8 aggregates changing as 4mm, 8mm and 12mm. In this way, it can be seen as to how the permeability changes with the change in the thicknesses of the upper layers against the constant thickness (40mm) of the single layer of the same grade aggregate. The comparison in permeability is made with just the normal tap water passing through the samples before the addition of the sand. After the sand is added as a clogging material, the intention is to find out the restoration of permeability by water pressure washing.

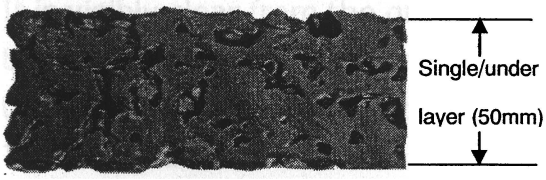


Fig.4.4 Single layer specimen
(Size of agg. G6, void ratio: 23%)

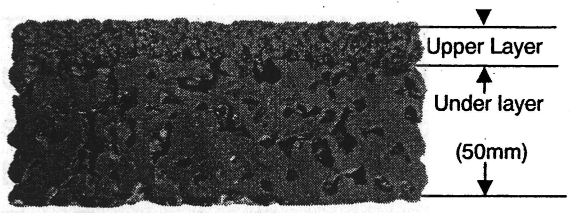


Fig.4.5 Double layer specimen
{upper layer = 8mm, (G6+G8)}

4.3.3 Third Experiment (Double layered POC)

The experimental method of the third experiment is the similar to that of the second experiment. The only difference is the change in the size of the silica sand used as a clogging material which is S7 as opposed to S6 in the second experiment. S7 grade sand is smaller than the S6 grade sand. The particle size distribution of both the S6 and S7 grades sand is shown in Figure 4.3. The aim here is to study the clogging pattern and the permeability restoration results, with the change in size of the sand used as clogging material. It is important to try it out with different sizes of the sand simply because of the fact that the sizes of the foreign materials entering the voids of a porous concrete installation vary in the real scenario. There may be very small sized particle entering the voids or there may be larger ones entering them or for that matter, different sized foreign materials entering the voids together. Therefore, the third experiment is carried out with a smaller size of the silica sand as a clogging material compared to the one (S6) used in the first and the second experiments.

4.4 RESULTS AND DISCUSSIONS

4.4.1 First Experiment (Effect of clogging on permeability of POC)

This experiment was conducted on single layered porous concrete samples of G6 and G7 grade aggregates. G6 grade aggregate samples used for the experiment are of three types with void ratios 15%, 23% and 30%. G7 grade aggregate sample considered for the experiment is with void ratio of 23%. The size of the samples used is 50X150X40mm.

(1) Permeability (K_T) of POC before the addition of sand

Figure 4.7 illustrates the relationship between the void ratio and the permeability (K_T) of the porous concrete. The x-axis represents the void ratio (%) and the y-axis represents the permeability (cm/s). It is visibly clear from the graph that the permeability (K_T) increases with the ascending value of void ratio. This is because of the fact that the void ratio and permeability are directly proportional to each other. The increase in void ratio means that there are more voids available in the sample which in turn facilitate the better permeability in the sample.

The Figure also illustrates that the permeability increases with the increase in the size of the aggregate used. It is obvious from the Figure where it can be observed that the permeability for grade G6 aggregate sample with 23% void ratio is higher than that of grade G7 aggregate sample with same void ratio.

(2) Permeability (K_T) of POC after the addition of sand

Figure 4.8 demonstrates as to how the presence of sand in permeating water affects the coefficient of permeability (K_T) of porous concrete samples with different void ratios and different aggregate grades. Figure 4.8 (a) illustrates how addition of sand affects the permeability of G6 grade aggregate samples with void ratios 15%, 23% and 30%. The x-axis represents the quantity of sand added and the y-axis represents the permeability. Figure 4.8 (b) shows how the addition of sand affects the permeability of grade G6 and G7 aggregate samples with 23% void ratio. The x-axis represents the quantity of sand added and the y-axis represents the permeability. It can be seen that the permeability in all the cases decreases with the increase in the amount of sand added. This goes to show that coefficient of permeability is bound to decline with time in the actual scenario as well since the amount of foreign materials entering or depositing on the porous concrete installation increases progressively. This finding helps in making the users consider about the solutions to such a problem of clogging with time in porous concrete. Clogging renders the porous concrete useless by making it incapable of allowing the air and water to permeate.

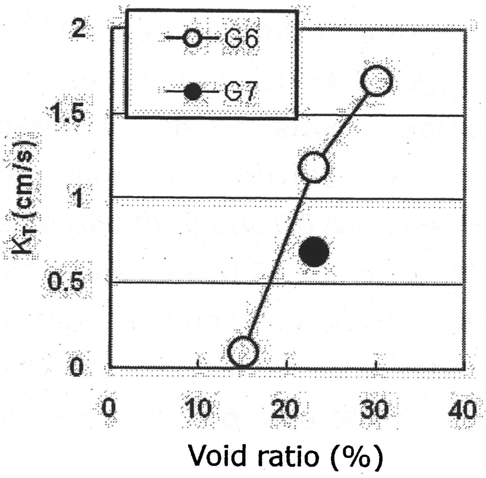
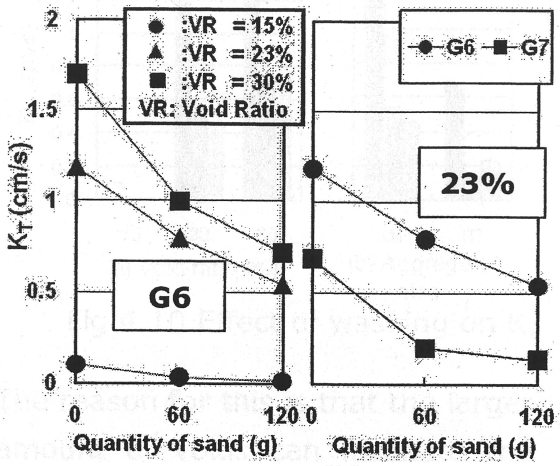
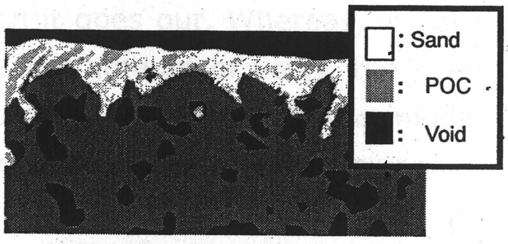


Fig.4.7 Relationship between K_T and void ratio

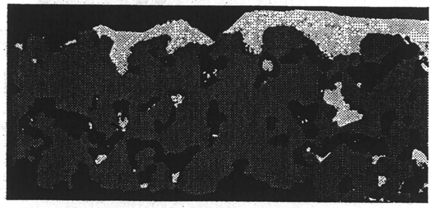


(a) Void ratio (b) Agg. size

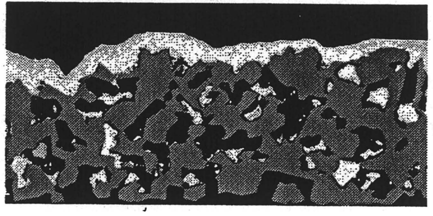
Fig.4.8 Effect of addition of sand on K_T



(a) Void ratio = 15%



(b) Void ratio = 23%



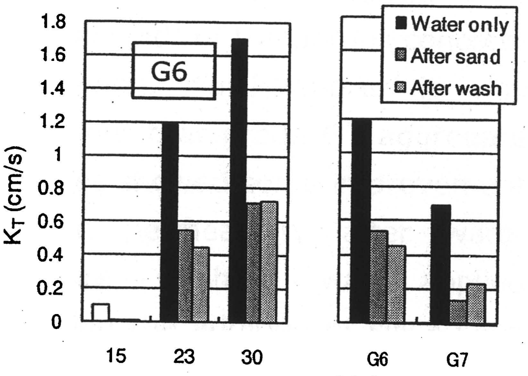
(c) Void ratio = 30%

Fig.4.9 State of sand inside voids of POC (Agg.size:G6)

Figure 4.9 displays the extent to which sand enters the grade G6 aggregate porous concrete samples with different void ratios (i.e. 15%, 23% and 30% respectively). The Figure brings to light the fact that greater the value of the void ratio, greater is the quantity of sand entering the void. Looking at the Figure 4.9(a) where the void ratio is 15%, it can be observed that the quantity of sand that has entered the voids is the minimum and most of the sand prevails on the surface of the sample as compared to that with void ratio 30% in Figure 4.9(c), where the sand has moved till the bottom most part of the sample. After the occurrence of clogging phenomenon, an attempt was made to see how effective would washing prove to be in restoring the coefficient of permeability of the clogged porous concrete samples. For washing the silica sand that had entered the voids or deposited on the top of the sample, water pressure was applied from the top portion of the sample.

(3) Effect of washing on K_T

As illustrated in Figure 4.10 (a), it is observed that after washing procedure is carried out, K_T decreased for grade G6 samples with void ratios 15 and 23 %, but a slight increase though very insignificant, could be noticed in case of the samples with void ratio of 30%.



(a) void ratio (%) (b) Aggregate size

Fig.4.10 Effect of washing on K_T

The reason for this is that the larger amount of voids can facilitate the easier movement of sand from top till the bottom of the sample after which it goes out. Whereas, in case of lesser amount of voids, the sand gets stuck somewhere in the middle even when water pressure is applied during washing. In other words, the voids get clogged due to the inability of the sand entering into them, to further move till the bottom of the samples.

A comparative study as shown in Figure 4.10 (b) was also made between samples of grades G6 and G7 aggregates with the same void ratio of 23%. In this case, it was noticed that washing helps to improve the coefficient of permeability of grade G7 aggregates as lesser amount of sand passes through to enter the voids of the sample as their sizes are smaller when compared to the void sizes of grade G6 aggregate samples. That way, it becomes comparatively easier to recover the permeability by washing away the sand deposited on the surface of the sample. It may be noted here that it is better for a porous concrete installation if the foreign particles get deposited on their surface than entering into the internal voids. This is because of the fact that it is easier to wash off the foreign materials or debris deposited on the surface than after they are inside. Therefore, an indication of the higher grade aggregate (smaller size) being a better option porous concrete installation when it comes to preventing clogging or permeability restoration, can be derived from the aforementioned discussion.

An observation of washing becoming effective with the increasing value of void ratio or decreasing size of the aggregate is made through this experiment. It is an important finding and sets a base for the design of the second experiment.

4.4.2 Second Experiment (Double layered POC)

This experiment is a follow up experiment of the first experiment. In the first experiment, it was realized that it would not be easy to restore the permeability after the foreign materials entered the internal voids of the porous concrete installation. Furthermore, it was found out that grade G7 aggregate samples showed some improvement in the permeability after water pressure · washing was applied following the addition of silica sand as clogging material while grade G6 aggregate samples did not. Triggered by this finding, a concept of double layered porous concrete has been introduced in the second experiment. The double layered sample has an under layer which is made of grade G6 aggregate with 23% void ratio and an upper layer made of grade G7 aggregate and grade G8 aggregate with 18% void ratio. So the double layered samples are (G6+G7) and (G6+G8). The under layer of G6 aggregate has a fixed size of 50X150X40 (same as single layered samples in first experiment) while the upper layers have three different thicknesses as 4mm, 8mm and 12mm. Single layered samples of grades G6, G7 and G8 aggregates are also considered for studying the differences in all of them. This would facilitate in making a comprehensive discussion on the overall mechanism of the samples in consideration thereby, making it possible to derive safe conclusions.

(1) Permeability (K_T) of different samples on normal condition

Figure 9 represents the coefficient of permeability (K_T) of all the samples when only the normal tap water is allowed to pass through them in the beginning. It can be seen here that though the coefficient of permeability of single layered grade G7 and G8 aggregate samples are low when their heights are 50mm, it can be observed that be increased by the reduction of their thicknesses as seen in the double (G6+G7) and

(G6+G8) potion of the graph. It is made obvious by the Figure where permeability in the double layered samples with lesser thicknesses (4mm, 8mm, 12mm) of grade G7 and G8 aggregates in the upper layer, are visibly greater than in their single layered samples. Furthermore, the Figure gives a clear picture of the coefficient of permeability (K_T) reducing with the increasing thicknesses of the upper layers as 4mm, 8mm and 12mm in case of the double layered samples. It can be seen that double layered samples (G6+G7) and (G6+G8) with 4mm upper layer have the maximum permeability and that with 12mm upper layer have the minimum permeability. It is also visible in the graph that the permeability increases with the decreasing grade of the aggregate (G6 single layered sample has the maximum K_T).

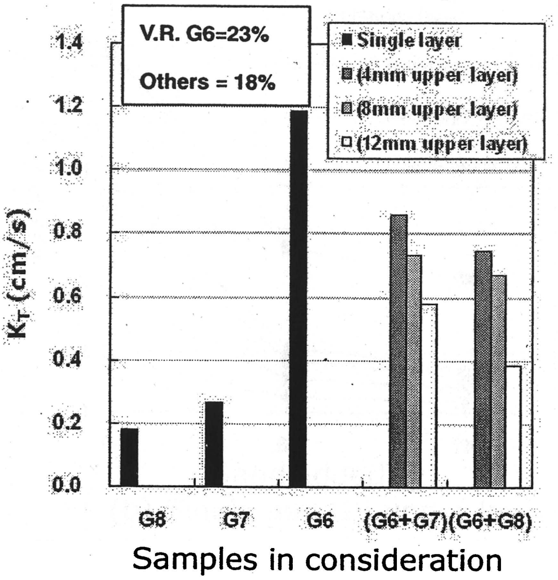
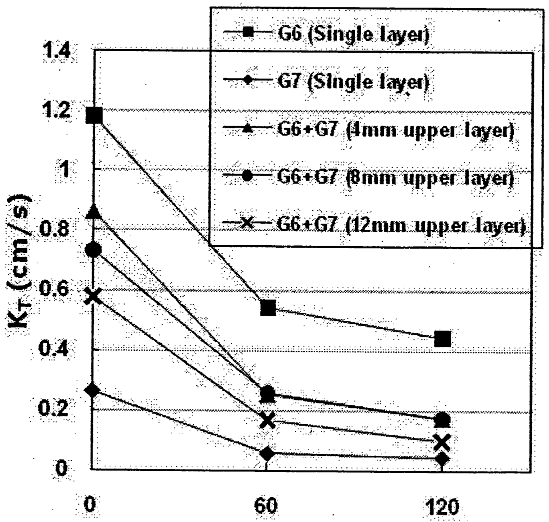


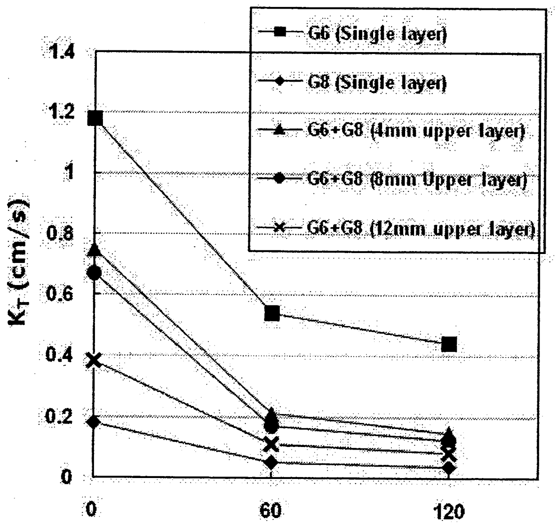
Fig.4.11K_T under normal condition

(2) Effect of addition of sand on the permeability (K_T)

Figure 4.12 illustrates the reduction in the coefficient of permeability (K_T) of the samples by the addition of 60g each of silica sand in two batches, respectively. Figure 4.12(a) shows the effect on grade G6 and G7 aggregate single layered samples along with double layered samples of (G6+G7) with three different thicknesses (4mm, 8mm, 12mm). Figure 4.12(b) shows the effect on G6, G8 and G6+G8 samples. The upper layers of G7 and G8 grade aggregates are 4mm, 8mm and 12mm thick. It is distinctly visible in the Figures that in all the cases, the permeability (K_T) reduces progressively. The trend is almost the same even if the values differ. It may be worth noting that the drop in permeability is sharp with the addition of the first 60g of the silica sand. The second addition of 60g more sand does not tend to bring down the permeability as sharply. It is rather close to horizontal which means that there is not so much difference in the drop from the addition of first batch of 60g sand to the next batch of 60g sand. An interesting observation can be made from both the Figures where the permeability of the double layered samples lie between that of the single layered samples of grades G6, G7 and G8 aggregates regardless of the presence of the sand on them. These results could possibly help us in predicting the permeability of double layered samples with further experimental studies.



(a) For single and G7 upper layers

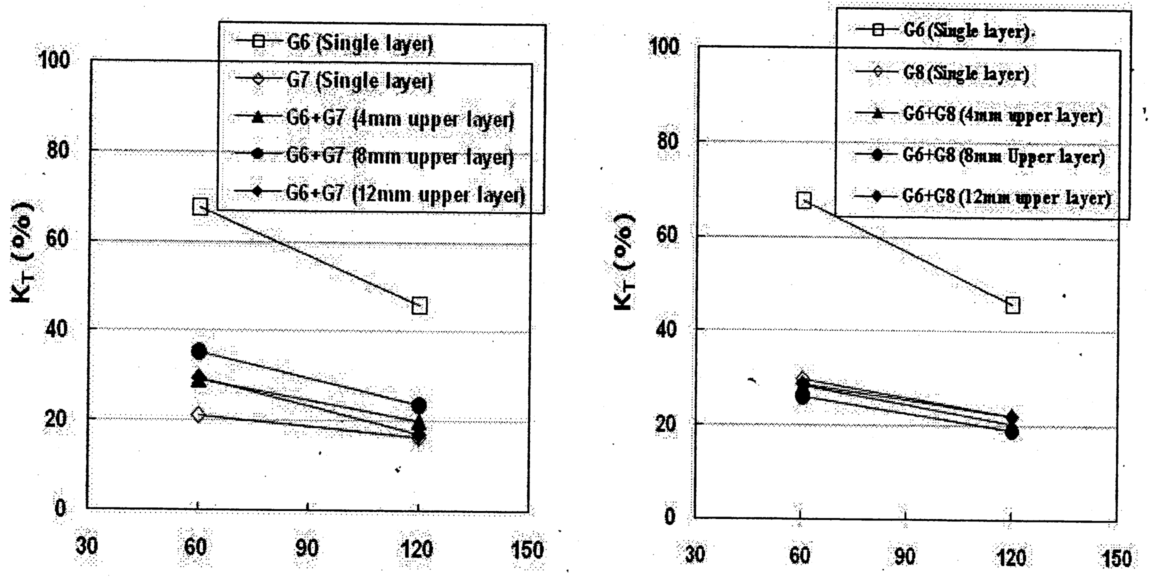


(b) Single and G8 upper layers

Fig.4.12 Effect of addition of sand on K_T

(3) Reduction of K_T by the addition of sand

Figure 4.13 portrays the percentage reduction of the permeability (K_T) after the addition of the silica sand as a clogging material. It can be observed from the figures that apart from grade G6 aggregate samples, the values in case of the other samples are very close to each other. This goes to show that the values of the permeability are almost dictated by the properties of the upper layer (viz. the void ratio, thickness) and the under layers have hardly any influence on them. This tendency is more obvious in case of G8 samples as shown in Figure 4.13(b). It may also be noted that the thickness of the upper layer is not playing a very significant role in this case as much as it does when only normal tap water is passed in the beginning, where distinct differences in the permeability is observed. In that case, it was observed that the 4mm upper layer gives the maximum permeability while the 12mm one gives the minimum.



(a) For single and G7 upper layers

(b) Single and G8 upper layers

Fig.4.13 Percentage reduction of K_T by addition of sand

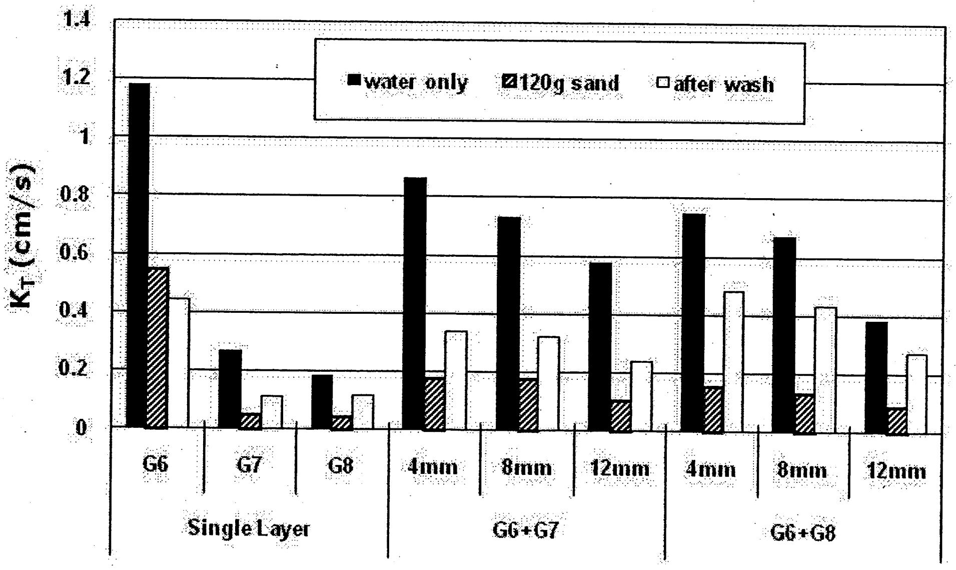


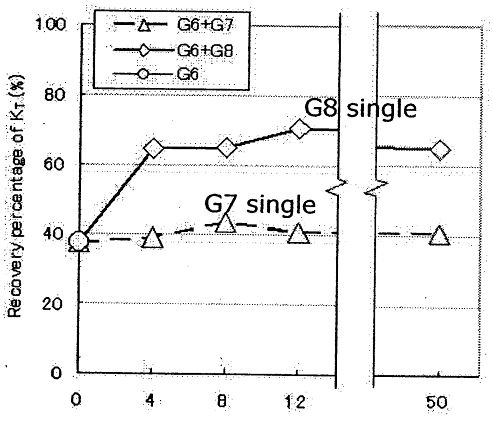
Fig.4.14 Effect of washing on K_T

(4) Effect of washing on K_T

Figure 4.14 demonstrates the effect of washing on the permeability (K_T) of all the single and double layered samples in consideration. From the Figure, a fairly good idea of the trend followed by the permeability (K_T) of different samples with the changing conditions can be derived. It can be seen that washing results in a significant improvement in the permeability of all the samples except for the grade G6 aggregate single layered samples. Grade G8 aggregate single layered and (G6+G8) aggregate double layered samples show noteworthy as well as consistent recovery of the permeability on washing. Noticeable restoration is also visible in case of grade G7 aggregate single layered and (G6+G7) aggregate double layered samples. This is because of the fact that with the smaller sizes of the aggregate, the amount of sand entering into the voids is lesser, as the voids formed by the smaller sized aggregates are smaller than that formed by the bigger sized aggregates. That will in turn contribute to the stopping more of the added sand (used as clogging material) on the surface of the sample than in case of samples made of larger sized aggregates. Moreover, majority of the sand entering from the smaller sized voids of grade G8 aggregate upper layer should be able to pass through the bigger sized voids of G6 aggregate layer underneath. This makes it possible to restore the permeability to a greater extent as the sand deposited on the surface of the samples can be either washed away with the water pressure or pushed through into the under layer of grade G6 aggregate, from where it can be expected to be navigated to the bottom of the sample and ultimately outside. On the other hand, by way of possessing bigger sized voids than the samples involving grade G8 aggregates, comparatively more amount of sand can be expected to enter through the voids of grade G7 aggregate single layered samples and (G6+G7) aggregate double layered samples. Consequently, the probability of under layer getting clogged becomes expectedly more. Therefore, the difference in the restoration of the permeability of the samples involving grades G7 and G8 aggregates.

(5) Recovery of K_T on washing

Figure 4.15 represents the recovery percentage of the permeability of the double layered porous concrete. This Figure supplements Figure 4.14 by giving clearer image of how the permeability (K_T) changes after the washing is applied for the samples in consideration following the occurrence of clogging. A visibly clear gap in the recovery percentages of the permeability exists between grades G7 and G8 aggregates double and single layered samples. As already mentioned in the earlier section, grade G8 aggregate samples display a much better permeability restoration tendency than the grade G7 aggregate samples. This is due to the fact that by virtue of having smaller voids than in grade G7 aggregate samples, grade G8 aggregate samples can stop comparatively more amount of added sand on its surface. Furthermore, the portion of added sand that passes through the smaller voids of grade G8 aggregate samples than the grade G7 aggregate samples, have a higher probability of passing through the bigger voids of the under layer of grade G6 aggregate which is the same for both the cases. This flow mechanism is the basic of the philosophy involved in the double layered porous concrete samples.



Thickness of samples (mm)

Fig.4.15 Recovery of K_T on washing

4.4.3 Third Experiment (Effect of particle size of sand as a clogging material, on the clogging, permeability and restoration)

The procedure involved in this experiment is the same as the previous two experiments. The only difference in this experiment is that the size of the silica sand which is used as a clogging material, is changed from S6 grade to S7 grade and is smaller. This is to investigate how the change in size of the clogging material would affect the overall performance of the samples similar to those involved in the second experiment as discussed in the previous section. In this experiment, the samples in consideration are the single layered samples of grades G6, G7 and G8 aggregates including 4mm thick upper layer double layered samples of (G6+G7) and (G6+G8).

(1) Effect of addition of sand on K_T

Figure 4.16 shows a very distinct difference in the drop of permeability of grade G6 aggregate single layered samples and (G6+G7) double layered samples. As can be seen from the Figure, the permeability does not drop as drastically when the added sand is smaller in size (S7) as compared to when it is bigger (S6). This is because the smaller sized sand can pass through the voids of the grade G6 aggregate samples as the size is much smaller than the size of the voids possessed by G6 aggregate samples. When there is a thin layer of grade G7 aggregate on the top of a grade G6 aggregate under layer, the sand entering in can pass through with more ease than the bigger sized S6 sand could. On the contrary, it can be seen that there is almost no difference in the drop in case of grade G8 aggregate sample. This means that when the voids are smaller, the change in the size of the sand added as a clogging material does not have so much influence. Since the size of the voids are smaller, they get clogged when the S7 sand enter the voids as not all of them can pass through.

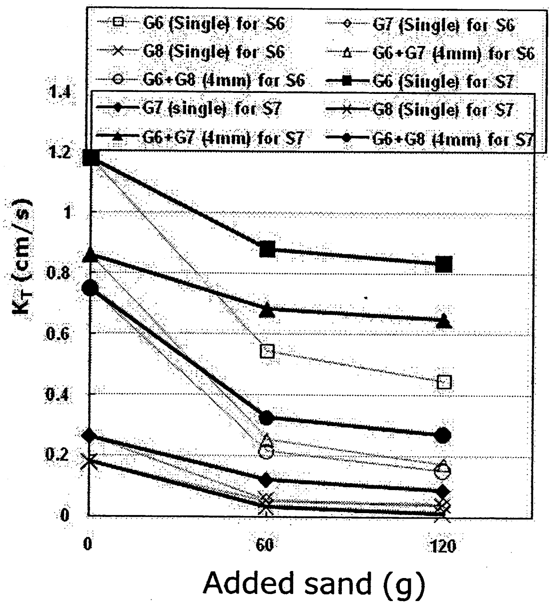


Fig.4.16 Effect of addition of sand on K_T

(2) Reduction of K_T by the addition of sand

It can be noticed from Figure 4.17 that there is a clear difference in the permeability pattern between the grade G6 aggregate samples and (G6+G7) double layered samples on the addition of sand S6 (bigger size) and S7 (smaller size) as the clogging material. In both the cases, the increase in the amount of sand added does not make any difference when it is smaller sized S7 silica sand. However, the permeability drops with the increase in the addition of larger sized S6 sand as shown in the figure. Furthermore, it can also be observed that unlike in other samples, the permeability of grade G8 aggregate samples drops with the use of smaller sized S7 sand.

The aforementioned observations are due to the difference in the size of the voids and the sand particles as has been mentioned in the previous section.

(3) Recovery of K_T on washing

However, the mechanism is slightly different in case of the thin layer (4mm) of grade G8 aggregate as the upper layer of grade G6 aggregate under layer. The sand on the top can be washed off while that getting stuck in the voids of the thin layer can be pushed through with the water pressure during water pressure washing. And once the sand gets into the under layer of grade G6 aggregate, the prevailing bigger voids in that region can facilitate the movement of sand till the bottom. Hence the restoration of the permeability after washing is substantially high in case of (G6+G8) samples as illustrated in the Figure 4.18. It has also been observed in the Figure that the permeability restorations are very impressive in case of grades G6 and G7 aggregate single layered samples as well as (G6+G7) double layered samples. A comprehensive detail of the actual permeability of the samples, their reductions after the addition of silica sand as a clogging material and the restoration of permeability after washing is illustrated in Figure 4.18.

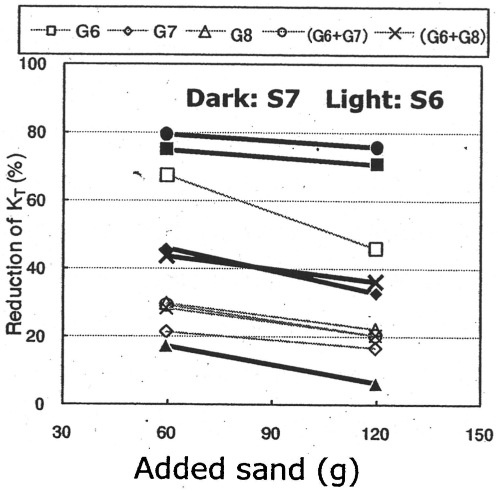


Fig.4.17 Percentage reduction of K_T by addition of sand

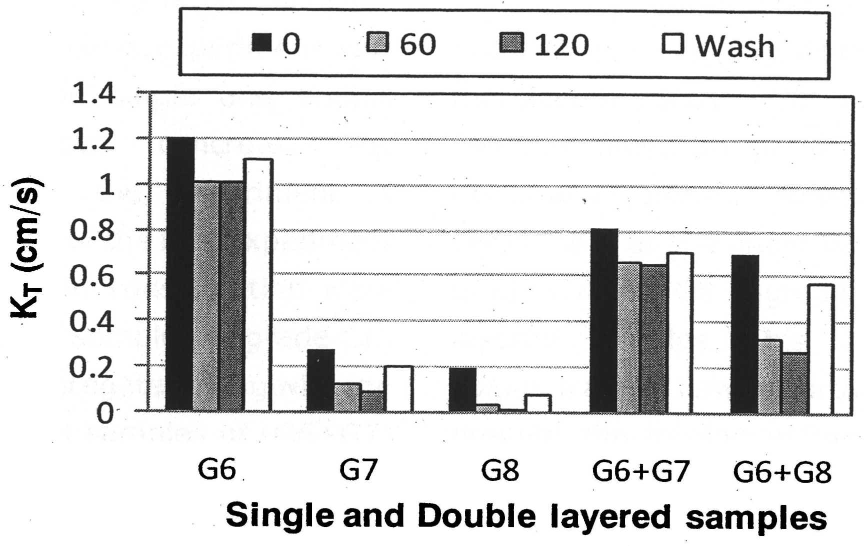


Fig.4.18 Effect of washing on K_T

4.5 Summary

This research study includes three experimental studies on clogging and permeability of porous concrete.

(1) The first experiment was carried out to find the effect of clogging on the coefficient of permeability (K_T) of single layered

porous concrete samples. The samples in consideration were of grade G6 aggregate (void ratios 15%, 23% and 30%) and grade G7 aggregate (void ratio 23%). Grade S6 silica sand was used as a clogging material for the experiment. Finally, water pressure washing was applied to study its effectiveness as a remedial measure to clogging. From the experiment, it was observed and realized that clogging has an inverse impact on the permeability of porous concrete. Washing was found to be unsuccessful in the permeability restoration efforts following clogging in case of grade G6 aggregate samples even though slight improvement could be observed in case of grade G7 aggregate samples.

(2) The second experiment was carried out on single and double layered porous concrete. The procedure of the experiment is similar to that of the first experiment. The samples in consideration were single layered samples of grade G6, G7 and G8 aggregates along with the double layered samples of (G6+G7) and (G6+G8). The upper layers of the double layered samples are 4mm, 8mm and 12mm while the under layer is the same as the single layered samples (50X150X40mm). Double layered samples were introduced for the first time in this experiment. From the experiment, it was found out that single layered samples of grade G8 aggregates and double layered (G6+G8) samples provided very impressive restoration of coefficient of permeability on washing.

Furthermore, it could be noticed that grade G7 aggregate single layer samples and (G6+G7) double layer samples performed fairly well in the permeability restoration efforts. However, the performance of grade G8 and (G6+G8) samples stood out with much higher recovery percentage of up to 70% of the actual permeability of the samples with just the normal tap water flowing, before the addition of silica sand or for that matter before the occurrence of clogging. As previously mentioned, grade G6 aggregate samples failed to perform in the restoration efforts. However, they served well as the under layer of the grade G7 and G8 aggregate double layered samples. This speaks in volumes about how important it is to prevent the foreign materials from entering the voids of the porous concrete at the first place. That way, it justifies the philosophy of the double layered porous concrete that was advocated for this experiment.

(3) The procedure followed in the third experiment is also similar to

that of the first and the second experiments. The samples considered for the experiment were grade G6, G7 and G8 single layered samples along with double layered samples of (G6+G7) and (G6+G8). The thickness of the upper layers here is 4mm while that of the under layer is the same as that of the single layered samples in the first and the second experiments (50X150X40mm). The difference is that it was carried out by changing the size of the silica sand used as a clogging material, from grade S6 to grade S7, which is smaller. In this experiment, it was observed that the restoration performance of grade G6 aggregate single layered samples and (G6+G7) double layered samples were very good and went up to 90% of the actual permeability. Though grade G8 aggregate single layered samples did not perform well, (G6+G8) double layered samples showed good restoration capability.

Going by the results of the aforementioned three experiments, it can be inferred that double layered porous concrete with smaller sizes of the voids on the upper layer and comparatively bigger ones underneath can be seriously considered as a new approach to resolve the issue of clogging in porous concrete.

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(4) Permeability Predictions for Sand-Clogged Portland Cement Pervious

Liv M. Haselbach, Srinivas Valavala, Felipe Montes, sand clogging, ranges from 0.20 to 1 cm/s (Montes and Haselbach, 2006).

(5) Infiltration and Clogging with Pervious Concrete Pavement

J.Patrick Coughlin[1,2] and David C.Mays[1] ,[1]University of Colorado Denver, Department of Civil Engineering, Denver, CO 80217-3364 [2]now at Parsons, 1700 Broadway, Suite 900, Denver, CO 80290 AGU/ASCE Hydrology Days, Fort Collins, CO, 26-28 March 2008

Chapter 5 CONCLUSION AND FUTURE OBJECTIVES

5.1 Conclusion

Porous concrete as an environmental friendly technology has a wide range of virtues and applications as a result of which it is progressively gaining popularity throughout the world. It has been an amazing finding in the field of concrete technology especially because of the fact that the earth is experiencing very grave issues of environmental degradation and global warming. Anything that has the potential to support the cause to deal with the environmental degradation and global warming issues would be welcomed with open arms. And porous concrete is definitely something that can be counted on as one of the important tools to do the needful in this case. Based on its water and air permeating ability, there are many applications of porous concrete which are listed as below:

1. Water-permeating/draining/retaining performance
2. Water purifying performance
3. Noise-absorbing performance (noise barrier railway, expressway)
4. Thermal performance (to mitigate or improve the environment in terms of thermal conditions)
5. Moisture-conditioning/absorbing performance
6. Plant-growing performance (stabilizing and greening of barren slopes, revetments, river protection works)
7. Insect/animal accommodating performance (to serve as a habitat for larvae of waterside land insects, water bugs and benthic organisms in plain water)
8. Habitat for marine organisms (seaweed and shellfish)
9. Habitat for microbes (aerobic and anaerobic bacteria)
10. Low-volume pavements
11. Residential roads, patios, alleys and driveways
12. Sidewalks and pathways
13. Parking areas
14. Low water crossings
15. Tennis courts
16. Swimming pool decks
17. Pavement edge drains
18. Foundations / floors for greenhouses, fish hatcheries, aquatic amusement centers, and zoos

The applications as mentioned above give us a fair idea of the versatility of porous concrete as an environmental-friendly material. Porous concrete is different from the conventional concrete by way of possessing continuous voids that are intentionally created. It is made possible by eluding the use of fine aggregate in the mix because of which it is also sometimes called "no-fines concrete." Installation of porous concrete calls for enriched skill and experience as it is important to maintain the continuity of the voids for permeability as well as to finish it well with adequate compaction. Therefore, right from the design to the placing, compaction and finishing, expertise is of great importance.

The various applications of porous concrete notwithstanding, it also has its own share of drawbacks. They are as listed below:

1. Effects of plain water and seawater
2. Cyclic wetting and drying
3. Freezing and thawing
4. Effects of clogging on permeability
5. Carbonation
6. Abrasion
7. Repeated loading (fatigue)
8. Effects of plants
9. Alkali-aggregate reaction

Considering all the issues related to porous concrete from installation to applications and drawbacks, the theme of my research was chosen as, "clogging and permeability of porous concrete."

The research includes three experimental studies.

(1) The first experiment was carried out to investigate the effect of clogging on the coefficient of permeability (K_T) of single layered porous concrete samples. S6 grade silica sand was used as a clogging material for the experiment while washing was applied to see if it helped to restore the permeability after clogging occurred. Through the experiment, it was observed and realized that clogging has an inverse impact on the permeability of porous concrete. And after applying washing, it was observed that it did not prove to be successful in the permeability restoration efforts though G7 grade aggregate samples showed some signs of improvement in the permeability. However, it was not significant and in case of G6 grade aggregate samples, there was not even a slight improvement.

(2) The second one was carried out on single and double layered porous concrete samples. Double layered samples were introduced in this experiment. It was observed that out of the G6, G7 and G8 single layered samples and (G6+G7) and (G6+G8) double layered samples considered for experiments, G8 grade aggregates single layered and double layered (G6+G8) samples

provided very good restoration of coefficient of permeability on washing.

Furthermore, it was noticed that G7 aggregate single layer samples and (G6+G7) double layer samples also performed fairly well in the restoration efforts. However, the performance of G8 and (G6+G8) samples stood out with much higher recovery percentage of up to 70% of the actual permeability of the samples, prior to the occurrence of clogging.

(3) The third experiment was carried out by changing the size of the silica sand used as a clogging material, from S6 grade to grade S7, which is smaller. In this experiment, it was observed that the restoration performance of grade G6 aggregate single layered samples and (G6+G7) double layered samples were very good and went up to 90% of the actual permeability. Though grade G8 single layered samples did not perform well, (G6+G8) double layered samples showed good restoration capability. Therefore, from the results of the aforementioned three experiments, it can be inferred that double layered porous concrete with smaller sizes of the voids on the upper layer and comparatively bigger ones underneath can be seriously considered as a new approach to resolve clogging problem in porous concrete.

5.2 Objectives for future research

The research topic that I had taken up for my master's degree program was on "Clogging and Permeability of porous concrete (POC)."

Three experiments involving the study of the relationship between clogging and permeability of POC on single and double layered POC samples were carried out. Double layered POC samples were applied in this study as a measure to tackle clogging issue.

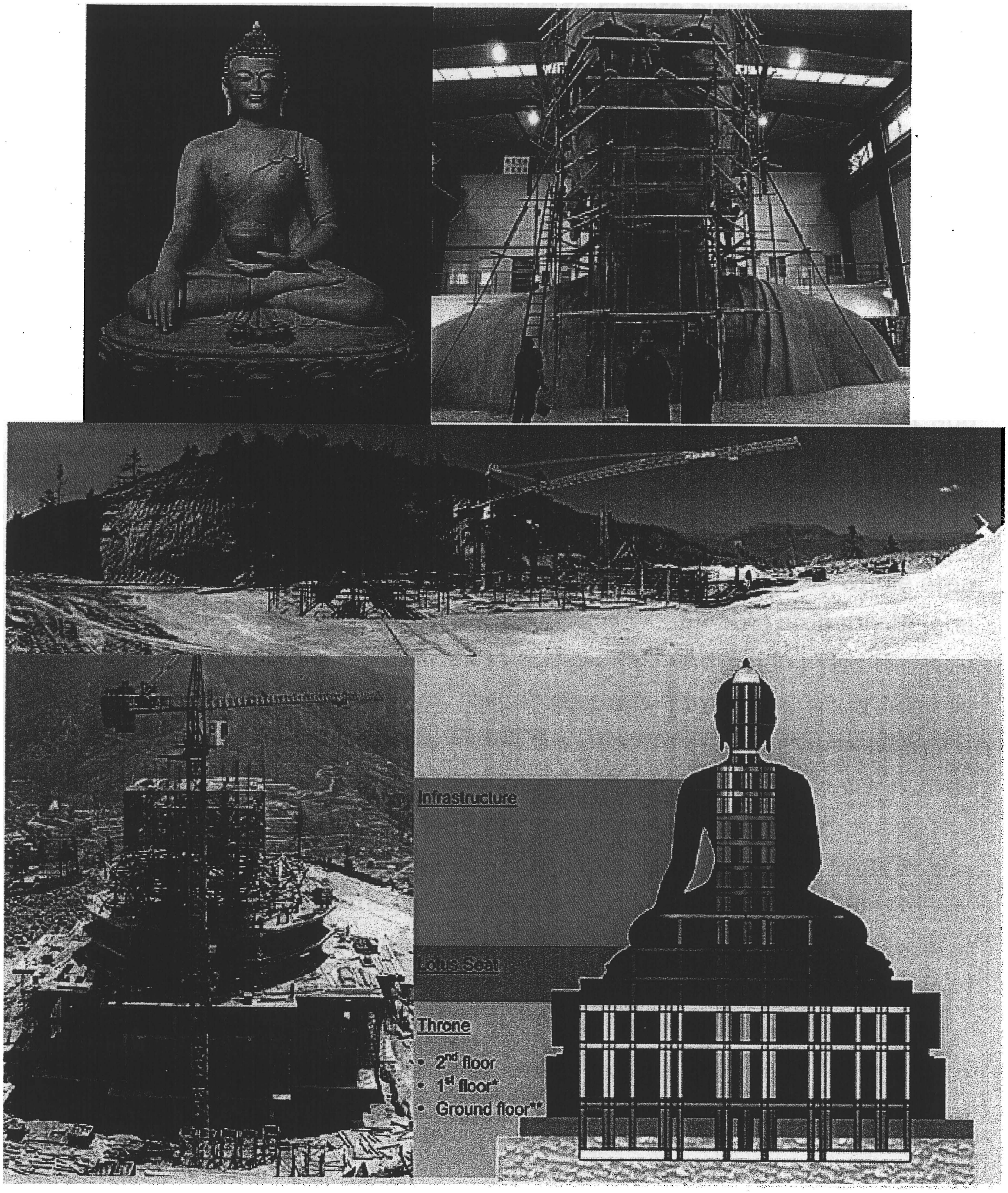
For the future studies, I intend to carry forward the study on clogging and permeability of POC in more depth and with more intensity. Since double layered POC is new in the field of clogging of POC, more experiments need to be carried out for clarifying various issues before transferring this fantastic concept to the real scenario. The points of main focus during my further studies will be as follows:

1) Study various combinations of thicknesses of the upper and bottom layers of double layered POC samples, using different sizes of the aggregates and different void ratios.

2) To subject samples of single and double layered POC samples to different site conditions for studying the pattern of clogging and its effect on the permeability, for certain time period.
3) To develop a formula relating different thicknesses of the two layers of double layered POC and the permeability.
4) To study other properties like durability in relation to the clogging phenomenon.
5) To develop a design concept for life cycle of POC using the information of clogging and by changing of void ratio based on the change in performance.

Appendix

(A Report on a project site in Bhutan that I visited for checking the prospect of using porous concrete in future).



The ongoing Buddha Project Site

Name of the Project: Buddha Dordenma Project.

Introduction

The 169ft tall Buddha Shakyamuni sits on a vajra throne because of which it is called Buddha Dordenma. It is supposed to radiate auspicious energy over the country and to all parts of the world, fulfilling the prophesy of bestowing blessings, universal peace and happiness to the whole world. Upon its completion, it will become a major pilgrimage center and a focal point for Buddhists all over the world to converge, practice, meditate and to do retreat. Inside this massive Buddha throne, 25,000 pieces of 12″ tall Buddha Dordenma statues will be installed and inside the lotus seat and Buddha's body, 100,000 pieces of 8″ tall Buddha Dordenma statues will be installed. Both these statues can be sponsored by anybody in his name for personal blessing and the blessing for the world peace and happiness.

This project site has a huge area surrounding it, for site development and landscaping. And by virtue of being noble as well as massive in size, it will definitely attract tourists from all parts of the world. That makes it important to make it aesthetic. Therefore, many parks and flower gardens, etc are scheduled to be developed. There will be pathways connecting the whole area for the people to be able to walk across and enjoy what would probably be one of the most strikingly beautiful areas in the capital. And having had the rare honor of meeting the founder of the project His Eminence Trizin Tsering Rinpoche during his visit to Japan, I took the opportunity to discuss with him about my research on porous concrete. Following the discussion, His Eminence kindly instructed me to look at the possibilities of applying the technology in the Dordenma Project. Consequently, I made a visit in the summer of 2008 to explore the possibilities and report about it to my Professor, Dr Shigemitsu Hatanaka. During my visit to the site, I found out that this was a place where porous concrete could be applied to enhance its beauty as well as make a beginning for itself in Bhutan. Therefore, if things work out and the opportunity prevails, I would like to apply porous concrete for the site development works in this project.

STUDY ON CLOGGING AND PERMEABILITY OF POROUS CONCRETE

(A 10 pages summary for the final defense of thesis)

Pradhan Sunil

ABSTRACT

Porous concrete (POC) possesses continuous voids that are created intentionally to facilitate the permeability of air and water through it. However, clogging of its voids is a matter of serious concern in POC. This research study includes three experimental studies related to clogging and permeability of porous concrete. Double layered porous concrete samples are applied in this study for the first time in the treatment of clogging phenomenon. The first experiment is on single layered POC samples (G6 and G7 aggregate grade) followed by two more experiments on single and double layered POC samples {G6, G7, G8 aggregate grade single layered samples and (G6+G7) and (G6+G8) double layered samples}.

1. INTRODUCTION

Porous concrete (POC) is a concept that is quite different from the conventional concrete. Unlike conventional concrete, porous concrete possesses intentionally created continuous voids that facilitate the permeability of water and air through its whole system. Fig. 1.1 shows the schematic diagram of porous concrete. Progressively, the ability of POC to exhibit various environment-friendly performances is being realized. To mention a few of them,

POC can be used to avoid creation of imbalance in natural ecosystem by the prevention of pollution of rivers, lakes and coastal waters, erosion, flash floods, water Table depletion as rainwater rushing across pavement surfaces picks up everything from oil and grease spills to deicing salts and chemical fertilizers it can be used as a media for thermal and moisture-conditioning, plants and grasses can be grown on it to enhance the look as well as impart greening effect to areas like river protection works and barren slopes; it can also be utilized as noise barrier walls in railways and expressways.

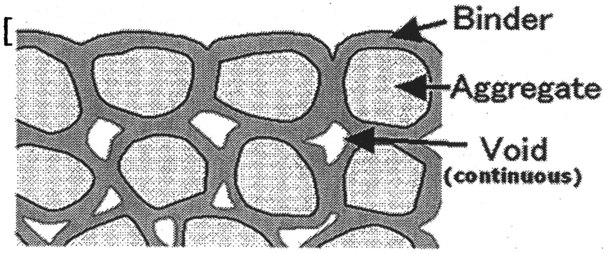


Fig 1.1 Schematic diagram of POC

The advantage of POC notwithstanding, POC is faced with a few problems as well. Potential areas of concern are: effect of cyclic wetting and drying, freezing and thawing, shrinkage cracks, repeated loading effect, abrasion, wearing and clogging phenomenon [2]. Clogging is detrimental to the very purpose of porous concrete which is to allow the permeability of water through its voids. Once the voids are clogged, it becomes close to impossible to restore the original permeability. Quite often, the permeability drops to zero rendering the porous concrete useless. The reason behind advocating the POC needs to be protected so that this amazing finding can be utilized for as long as intended. And in order to achieve that, one of the issues that requires to be tackled without any doubt is the clogging phenomenon. This will ensure the longevity in the use of porous concrete.

From the other research studies [4 to 9] pertaining to clogging and permeability of porous concrete, it is realized that clogging is a serious issues. However, none of them has provided any clue to deal with this issue. Therefore, in my research studies, an effort has been made to find out a solution for clogging issue by the application of a double layered porous concrete. The following findings from the other researches show that clogging has been an important part of their studies.

2. EXPERIMENTAL METHOD

In this paper, results from three experiments have been incorporated.

2.1 First Experiment (Effect of clogging on permeability of POC)

Table 1 represents factors and testing levels of the first experiment. This experiment is carried out on single layered POC samples of size (50x150x40mm) and aggregate grades G6 (5-13mm) and G7 (2.5-5mm) with void ratios of 15%, 23% and 30%.

An indigenous apparatus as shown in Figure 2.1 was prepared to carry out the experiment. During the experiment, a water head of 50mm as shown in Figure is maintained throughout. Water permeating through the sample is collected at the outlet for 10 seconds and weighed every time. Normal tap water is first allowed to pass through the samples. Then 60g each of grade S6 silica sand are added successively and collecting the water for 10 seconds after each addition. Finally, water pressure washing was applied to study the behavior of permeability after clogging occurred. Particle size distribution of the grade S6

Table 1 Factors and testing levels (1st exp.: single layered POC)

Factor	Testing Levels
Void ratio(%)	15, 23, 30
Size of Aggregate	G6*1, G7*2
Added sand (g)	0, 60, 120
[Vs/S.A*3 (cm^3/cm^2)]	[0, 0.4, 0.8]

Note: *1 Aggregate Grade G6 (5-13)mm, *2 Grade G7 (2.5-5)mm
*3 Vs: added sand volume, S.A: top surface area (150x40)mm

and S7 sand used as clogging material is as displayed in Figure 2.2

2.2 Second Experiment (Double layered POC)

Table 2 displays the factors and levels and Table 3 shows the experimental conditions. The mix proportion is shown in Table 4. The procedure for the experiment is the same as in the first experiment. Single layered POC samples of grade G7 and G8 along with double layered samples of (G6+G7) and (G6+G8) are used in the experiment. Figures 2.3 and 2.4 illustrate the single and double layered samples. The under layer is of G6 aggregate with void ratio of 23% and the upper layers are of G7 and G8 aggregates with the void ratio of 18%. The thicknesses considered for the double layered samples are 4mm, 8mm and 12mm.

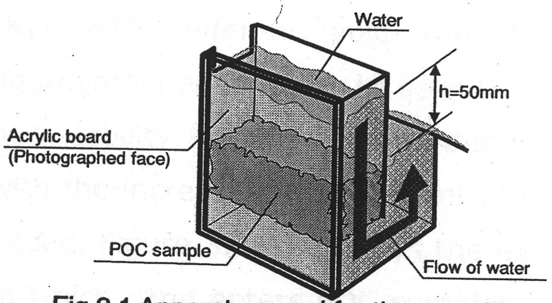


Fig.2.1 Apparatus used for the experiment

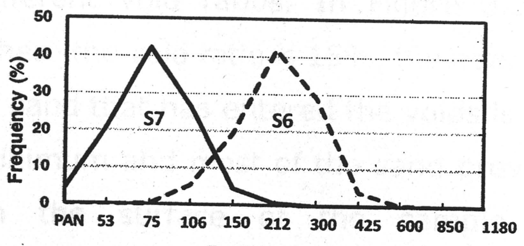


Fig.2.2 Particle size distribution Of Grades S6 and S7 silica sand

Fig.2.3 Single layer specimen (Size of agg. G6, void ratio: 23%)

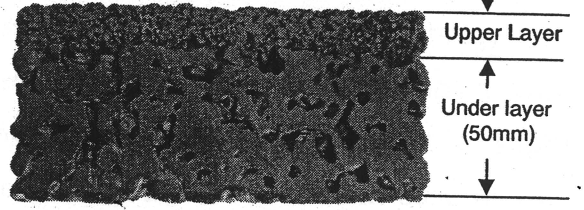


Fig 2.4 Double layered specimen (thickness of upper layer = 8mm, Agg. Size: G6 & G8)

Table 2 Factors and testing levels (2nd exp.: double layered POC)

Factors	Testing levels
Size of Aggregate	G6*1, G7*2, G8*3
Combination of layers	(G6+G7), (G6+G8)
Added sand (g) [Vs/S.A*4 (cm^3/cm^2)]	0, 60, 120 [0, 0.4, 0.8]
Thickness of top layer (mm)	4,8,12

Note:*1 G6 (5-13)mm, *2 G7 (2.5-5)mm, *3 G8 (1.25-2.5)mm
*4 Vs: added sand volume, S.A: top surface area (150x40)mm

Table 3 Experimental conditions (2nd exp.: double layered POC)

W/C ratio (%)	30%
Void ratio of upper layers (%)	18%
Void ratio of under layer (%)	23%
Under layer (50mm)	G6
Size of single/under layer	(50x150x40)mm

Table 4 Mix proportion

Sample	Unit weight (g/L)			
	water	cement	Aggregate	SP*1
G6*2	544.84	1816.13	8163.79	1.63
G7*3	167.33	557.55	1746.11	0.50
G8*4	161.5	538.57	1778.87	0.48

Note: *1 SP: Superplasticizer, *2 G6 (5-13)mm, *3 G7 (2.5-5)mm, *4 G8 (1.25-2.5)mm

2.3 Third Experiment (Double layered POC)

The experimental method is the same as that of second. The difference is the change in the size of the sand from S6 to S7. The particle size distribution is shown in Figure 2.2.

3 RESULTS AND DISCUSSIONS

3.1 First Experiment (Effect of clogging on permeability of POC)

This experiment was conducted on single layer POC of G6 and G7 aggregates.

(1) K_T of POC before the addition of sand

Figure 3.1 illustrates the relationship between the void ratio and the permeability (K_T). It is visibly clear that the K_T increases with the ascending value of void ratio. It is obvious from the Figure that the permeability for grade G6 sample with 23% void ratio is higher than that of grade G7 sample with same void ratio.

(2) K_T of POC after the addition of sand

Figure 3.2 demonstrates how the presence of sand in permeating water affects the coefficient of permeability (K_T) with different void ratios and aggregate grades. It can be seen that the permeability in all the cases decreases with the increase in the amount of sand added. Figure 3.3(a) displays the extent to which sand enters POC samples with different void ratios. In Figure 3.3(b) where the void ratio is 15%, the quantity of sand that has entered the voids is the minimum and most of the sand prevails on the surface of the sample as compared to that with void ratio 30% in Figure 3.3(c), where the sand has moved till the bottom most part of the sample. After the occurrence of clogging phenomenon, washing is tried in restoring the permeability of POC.

(3) Effect of washing on K_T

As illustrated in Figure 3.4(a), it was observed that after washing, K_T decreased for grade G6 samples with void ratios 15 and 23%, but a slight increase could be noticed in case of void ratio of 30%. A comparative study as shown in Figure 3.4(b) is also made between samples of grades G6 and G7 with the same void ratio of 23%. In this case, it is noticed that washing helps to improve the K_T of grade G7 aggregates as lesser amount of sand enter the voids of the sample.

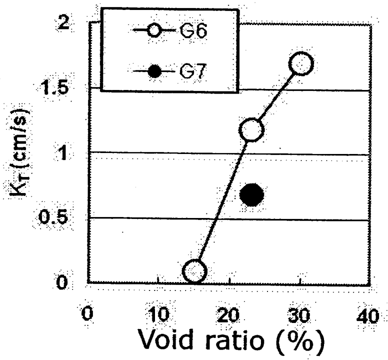
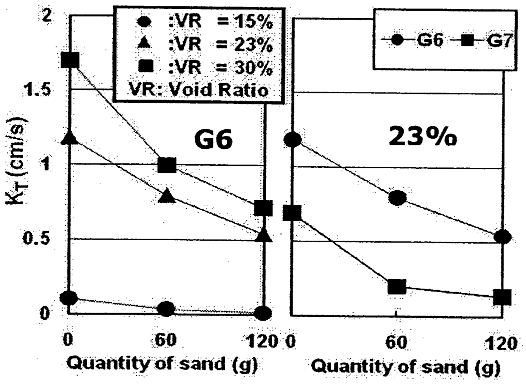


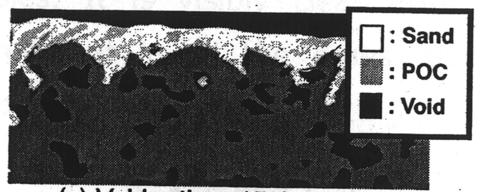
Fig.3.1 Relationship between K_T and void ratio



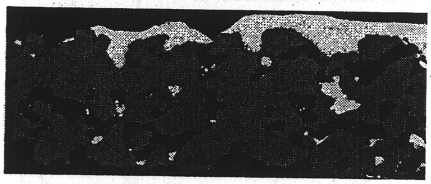
(a) Void ratio (b) Agg. size

Fig.3.2 Effect of addition of sand on K_T

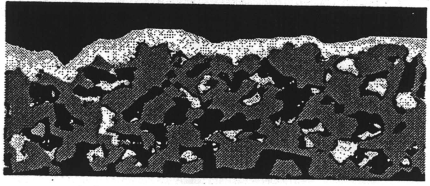
This makes it comparatively easier to recover the permeability by washing away the sand deposited on the surface of the sample.



(a) Void ratio = 15%



(b) Void ratio = 23%



(c) Void ratio = 30%

Fig.3.3 State of sand inside voids of POC

3.2 Second Experiment (Double layered POC)

This is a follow up experiment of the first experiment.

(1) K_T of different samples on normal condition

Figure 3.5 represents the coefficient of permeability (K_T) of all the samples when only the normal tap water is allowed to pass through them. It can be seen here that though the coefficient of permeability of single layered G7 and G8 samples are low when their height is 50mm, it can be increased by reducing their thicknesses. It is made obvious by the Figure where permeability in the double layered samples with lesser thicknesses of G7 and G8 aggregates in the upper layer are visibly greater than their single layers. Furthermore, the Figure clearly shows the reducing of K_T with the increasing thicknesses of the upper layers.

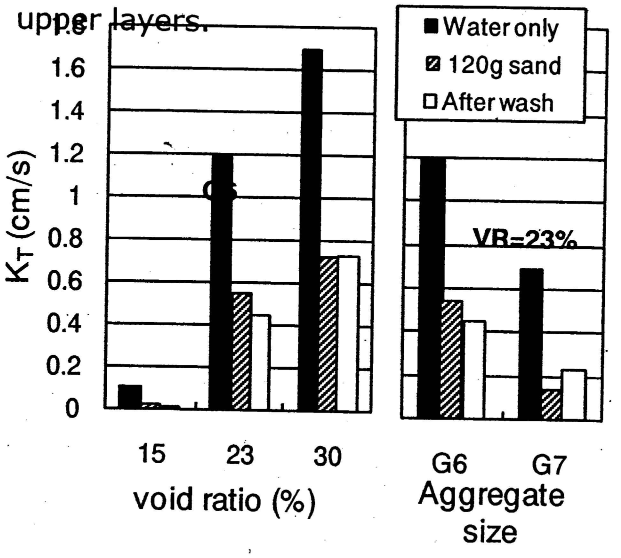


Fig.3.4 Effect of washing on K_T

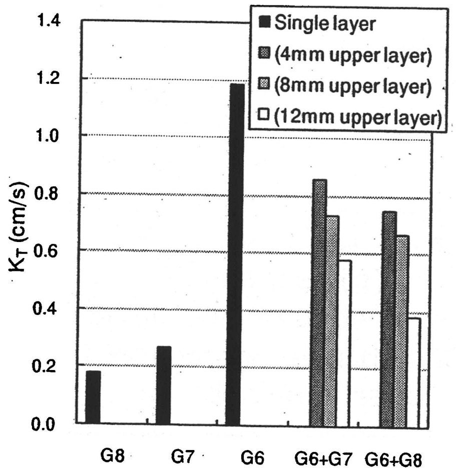
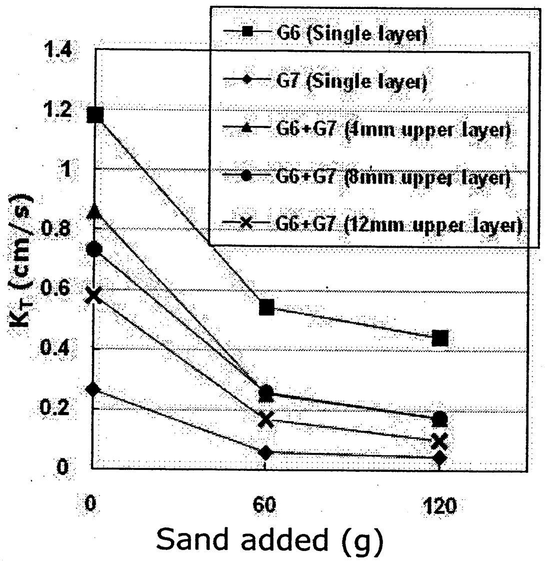


Fig.3.5K_T under normal condition

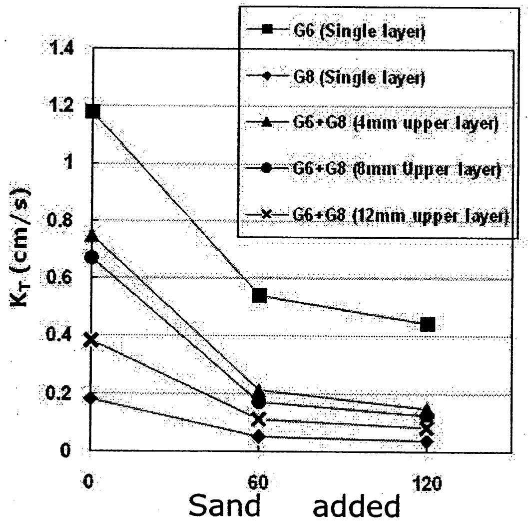
(2) Effect of addition of sand on K_T

Figure 3.6 illustrates the reduction in the K_T of the samples by the addition of 60g each of sand in two batches, respectively. Figure 3.6(a) shows the effect on G6 and

G7 single layered samples along with double layered samples of (G6+G7) with different thicknesses. Figure 3.6(b) shows the effect on G6, G8 and (G6+G8) samples. It is visibly clear from the Figures that in all the cases, the K_T reduces progressively.



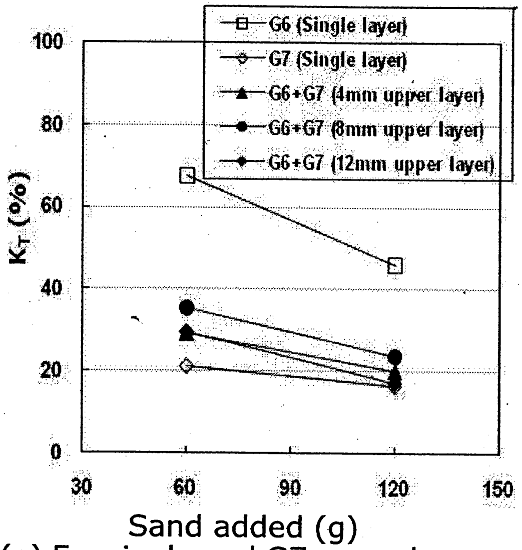
(a) For single and G7 upper layers



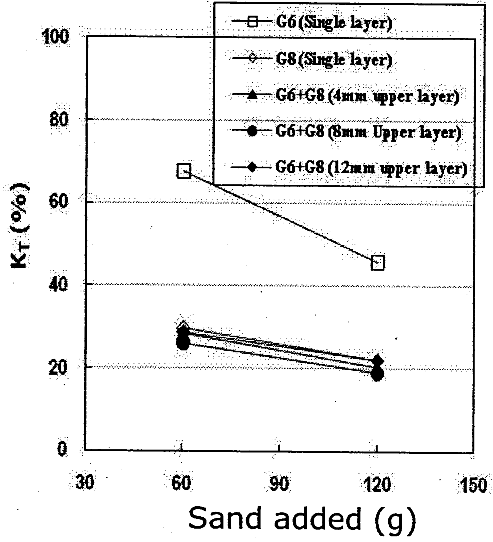
(b) Single and G8 upper layers

Fig.3.6 Effect of addition of sand on K_T

An interesting observation can be made from both the Figures where the K_T of the double layered samples lie between that of the single layered samples G6, G7 and G8, regardless of the presence of the sand on them.



(a) For single and G7 upper layers



(b) Single and G8 upper layers

Fig.3.7 Percentage reduction of K_T by addition of sand

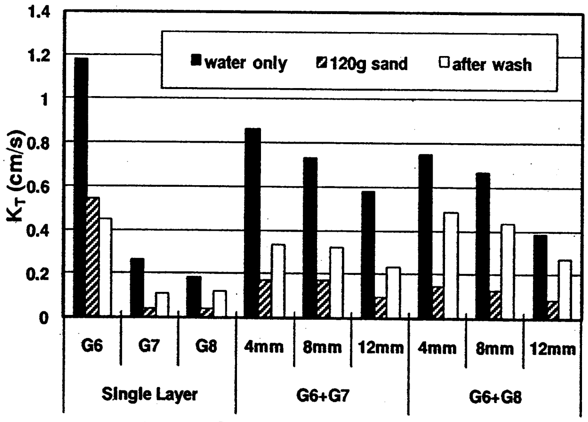


Fig.3.8 Effect of washing on K_T

(3) Reduction of K_T by addition of sand

Figure 3.7 portrays the percentage reduction of K_T after the addition of sand. It can be observed that apart from G6 samples, the other values are almost the same. This goes to show that the values of the permeability are almost dictated by the properties of the upper layer (viz. the void ratio, thickness) and the under layers have hardly any influence on them. This tendency is more obvious in case of G8 samples as shown in Figure 3.7(b).

(4) Effect of washing on K_T

Figure 3.8 demonstrates the effect of washing on the K_T of all the samples in consideration. A look at the Figure can give us a fairly good idea of the trend followed by the permeability (K_T) of different samples with the changing conditions. It can be seen that washing results in a significant improvement in K_T of all the samples except for the grade G6 single layer sample. G8 and (G6+G8) samples show noteworthy as well as consistent recovery of K_T on washing.

Noticeable restoration is also visible in case of G7 and (G6+G7) samples. This is because of the fact that with the smaller sizes of the aggregate, the amount of sand entering into the voids is lesser as the voids formed are smaller than that of bigger size aggregates.

Moreover, majority of the sand entering from the smaller voids of G8 aggregate upper layer should be able to pass through the bigger voids of G6 aggregate layer underneath. This makes it possible to restore the K_T to a greater extent as the sand deposited on the surface of the samples can be washed away with the water pressure. On the other hand, comparatively more amount of sand can enter through the voids of G7 and (G6+G7) samples because of which the probability of under layer getting clogged becomes more.

(5) Recovery of K_T on washing

Figure 3.9 represents the recovery percentage of coefficient of permeability of double layered POC. This Figure supplements Figure 12 by giving clearer image of how the K_T changes after the washing is applied for the samples in consideration. A visibly clear gap in the recovery percentages of the K_T exists between G7 and G8 aggregate double and single layer samples. As mentioned earlier also, G8 samples display a much better K_T restoration tendency than the G7 samples.

3.3 Third Experiment (Effect of particle size of sand on the clogging, permeability and restoration)

The procedure of the experiment is the same as the previous two experiments. The only difference in this experiment is that the size of the silica sand used as clogging material is changed from S6 grade to S7 grade, which is smaller. Here the samples in consideration are single layered samples of G6, G7, G8 and 4mm top double layered samples of (G6+G7) and (G6+G8). The main purpose of this experiment is to investigate how the change is size of the sand used for clogging would affect the restoration efforts of permeability along with the pattern of clogging phenomenon itself. This would in turn throw light on what kind of effect different sizes of foreign particles would have on the clogging and the permeability of a POC pavement along with the restoration of permeability.

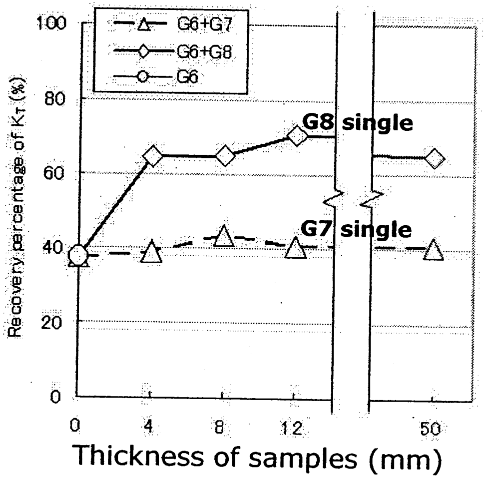


Fig.3.9 Recovery of K_T by washing

(1) Effect of addition of sand on K_T

Figure 3.10 shows a very distinct difference in the drop of permeability of G6 aggregate single layer samples and (G6+G7) double layer samples. As can be seen from the Figure, the permeability does not drop as drastically when the added sand is smaller in size (S7) as when it is bigger (S6). This is because the

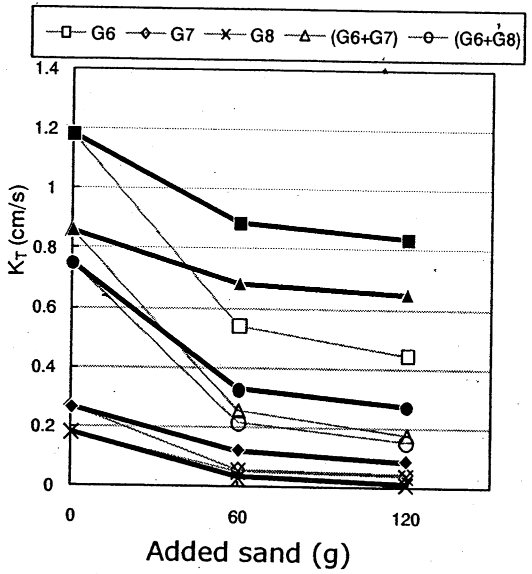


Fig.3.10 Effect of addition of sand on K_T

smaller sized sand can pass through the voids of the G6 aggregate samples as the size is much smaller than the size of the voids possessed by G6 aggregate samples. When there is a thin layer of G7 aggregate on the top of a G6 under layer, the sand entering in can pass through easily from the G6 under layer. On the contrary, it can be seen that there is almost no difference in the drop in case of G8 aggregate sample. This means that when the voids are small, the change in size of the sand added does not have so much influence. Since the size of the voids are smaller they get clogged when the S7 sand enter the voids as not all of them can pass through.

(2) Reduction of K_T by the addition of sand

It can be noticed from Figure 3.11 that there is a clear difference in the permeability pattern between the G6 aggregate samples and (G6+G7) double layer samples on addition of sand S6 (bigger size) and S7 (smaller size) sand. In both the cases, the increase in the amount of sand added does not make any difference when it is S7 silica sand. However, the permeability drops with the increase in the addition of S6 sand. However, the permeability of G8 aggregate samples drops when both S6 and S7 grade sand are used.

The aforementioned observations are due to the difference in size of the voids and the sand particles as has been mentioned in the previous section.

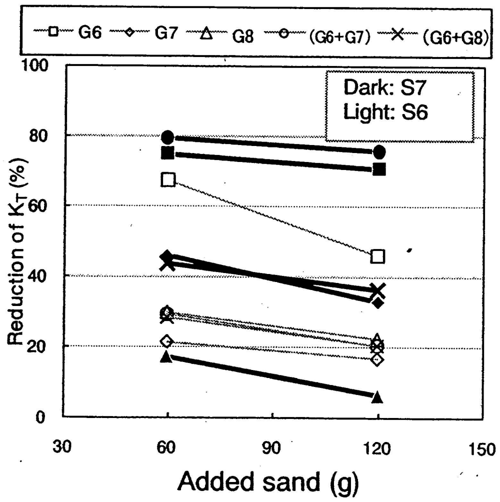


Fig.3.11 Percentage reduction of K_T by addition of sand

(3) Recovery of K_T on washing

However, the mechanism is a bit different in case of the thin layer of G8 aggregate on the top of G6 aggregate bottom layer. The sand on the top can be washed off while that getting stuck in the voids can be pushed through with the water pressure during washing. And once the sand gets into the G6 aggregate layer, the prevailing bigger voids in that region can facilitate the movement of sand till the bottom. Hence the restoration of the permeability after washing is substantially high in case of (G6+G8) samples as portrayed in Figure 3.12. The restorations are also very good in case of G6 and G7 single layered samples as well

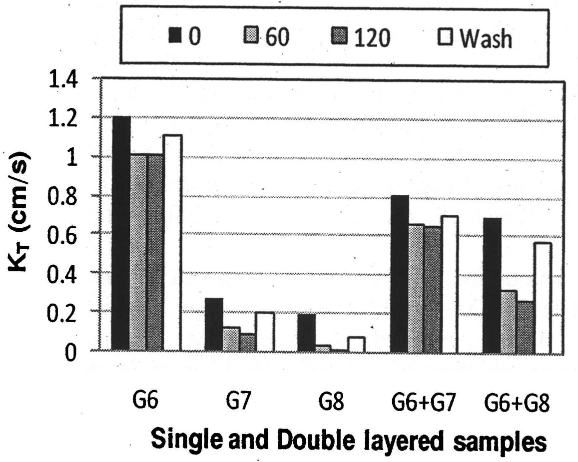


Fig.3.12 Effect of washing on K_T

4. CONCLUSIONS

This paper includes three experimental studies.

(1) The first experiment was carried out to find the effect of clogging on the coefficient of permeability (K_T) of single layered porous concrete. Here it was observed and realized that clogging has an inverse impact on the permeability of porous concrete. Washing was not

successful in the restoration efforts following clogging.

(2) The second one was carried out on single and double layered POC. In this experiment, it was observed that single layered samples of G8 grade aggregates and double layered (G6+G8) samples provided very good restoration of K_T on washing.

Furthermore, it was noticed that G7 aggregate single layer samples and (G6+G7) double layer samples performed fairly well in the restoration efforts. However, the performance of G8 and (G6+G8) samples stood out with much higher recovery percentage of up to 70% of the actual K_T of the samples before the occurrence of clogging.

(3) The third experiment was carried out by changing the size of the silica sand used for clogging, from S6 to S7 grade, which is smaller. In this experiment, it was observed that the restoration of grade G6 aggregate single layered samples and (G6+G7) double layered samples were very good and went up to 90% of the actual permeability. Though grade G8 single layered samples did not perform well, (G6+G8) double layered samples showed good restoration capability. Therefore, from the results of the aforementioned three experiments, it can be inferred that double layered POC with smaller sizes of the voids on the upper layer and comparatively bigger ones underneath can be seriously considered as a measure to tackle clogging issue in porous concrete.

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Achievements

1. Made presentation in the AIJ conference at Hiroshima, September 2008
2. Made presentation in the Tri University International seminar and symposium in China, October 2008
3. Made presentation in the JCI convention at Sapporo, July 2009
4. Will be making presentation in ConMat09 international conference on August 26, 2009
5. Received the award of distinction for my paper and presentation in Japan Concrete Institute Convention, Sapporo 2009.

- Technical Paper -

EFFECT OF CLOGGING ON PERMEABILITY OF SINGLE AND DOUBLE LAYERED POROUS CONCRETE

Sunil PRADHAN*1,Naoki MISHIMA*2 and Shigemitsu HATANAKA*3

ABSTRACT

One of the most prominent issues facing porous concrete is that of clogging where the continuous voids get choked. This paper is an effort made to first study the clogging and its effect on the coefficient of permeability of POC, followed by an additional experiment to find a solution for clogging by creating a double layered POC and further to investigate the effectiveness of the upper layer made of smaller sized aggregates with smaller value of void ratio, in recovering the permeability by washing after the voids get clogged by the added silica sand.

Keywords: porous concrete, permeability, clogging, double layer.

1. INTRODUCTION

Porous concrete (POC) is a technology in which concrete has intentionally created continuous voids inside. These particular continuous voids are designed to allow the water and air to permeate through them, which in turn will enable POC to exhibit various environmentally friendly activities. To highlight a few of them, POC can be used to avoid creation of imbalance in natural ecosystem by the prevention of pollution of rivers, lakes and coastal waters, erosion, flash floods, water table depletion as rainwater rushing across pavement surfaces picks up everything from oil and grease spills to deicing salts and chemical fertilizers [1]. It can co-exist with micro-organisms; it can be used as a media for thermal and moisture-conditioning, plants and grasses can be grown on it to enhance the look as well as impart greening effect to areas like river protection works and barren slopes; it can also be utilized as noise barrier walls in railways and expressways.

The advantages of POC notwithstanding, there are a few problems facing POC. Potential areas of concern are: effect of cyclic wetting and drying, freezing and thawing, shrinkage cracks, repeated loading effect, abrasion, wearing and clogging phenomenon [2].

In this paper, two experimental studies have been carried out. The First experiment was on single layered POC samples the purpose of which is to study the clogging phenomenon and its effect on the coefficient of permeability (K_T) [3]. The second experiment was carried out on single and double layered POC with the aim to study if the coefficient of permeability could be restored by washing, after the occurrence of clogging phenomenon. The results and discussion in the following sections of the paper will throw light on the outcome of the experiments.

Table 1 Factors and testing levels (1st exp.: single layered POC) [3]

Factors	Testing Levels
Void ratio(%)	15, 23, 30
Size of Agg.	G6*1, G7*2
Added sand (g) [Vs/S.A*3 (cm³/cm²)]	0, 60, 120 [0, 0.4, 0.8]

[Note]: *1 Agg.G6 (5-13mm), *2 Agg.G7 (2.5-5mm),
*3 Vs: added sand volume, S.A: surface area of the sample

Table 2 Factors and testing levels (2nd exp.: double layered POC)

Factors	Testing levels
Size of Agg.	G6*1, G7*2, G8*3
Under layer (50mm)	G6
Combination of layers	(G6+G7), (G6+G8)
Added sand (g) [Vs/S.A*3 (cm³/cm²)]	0, 60, 120 [0, 0.4, 0.8]
Thicknesses of upper layer (mm)	4,8,12

Note: *1 Agg.G6 (5-13)mm, *2 Agg.G7 (2.5-5)mm, *3 Agg.G8 (1.25-2.5)
*3 Vs: added sand volume, S.A: Surface area of the sample

Table 3 Experimental conditions (2nd exp.: double layered POC)

W/C ratio (%)	30%
Void ratio of upper layer (%)	18%
Void ratio of under layer (%)	23%
Size of single & under layer	50x150x40mm

Table 4 Mix proportion

	Unit weight (g/L)			
Sample	Water(g)	Cement(g)	Agg.(g)	sp(g)
G6*1	544.84	1816.13	8163.79	1.63
G7*2	167.33	557.55	1746.11	0.50
G8*3	161.5	538.57	1778.87	0.48

Note: *1 Agg.G6 (5-13)mm, *2 Agg.G7 (2.5-5)mm, *3 Agg.G8 (1.25-2.5

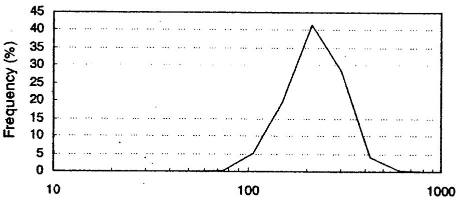

Fig.1 Particle size distribution of G6 silica sand

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2. Experimental Method

2.1 First Experiment (Single layered POC)

Table 1 shows factors and levels of the first experiment. This experiment was carried out on single layered POC samples of size (50x150x40mm) and aggregate grades G6 (5-13mm) and G7 (2.5-5mm) with void ratios of 15%, 23% and 30%. Single block of POC was first cast and later cut into required sizes of the samples. Both the longitudinal faces of the samples have cut and ground surface to make them smooth and uniform throughout. This ensures that the samples fit in the apparatus perfectly so that water enters only from the top surface of the sample and comes out from the bottom surface. An indigenous apparatus as shown in Fig.4 was prepared to carry out the experiment. During the experiment, a water head of 50mm as can be seen in figure was maintained. In order to calculate the coefficient of permeability (K_T), water permeating through the sample was collected at the outlet for 10 seconds and weighed every time. Normal tap water was first allowed to pass through the samples. Then 60g each of grade G6 silica sand were added successively, once again taking the weight of the water collected for 10 seconds after each addition. The procedure was repeated for all the four samples. Clogging patterns were observed and its impact on behavioral change in K_T was calculated using the data obtained from the experiment. The findings were then reproduced in the form of graphs for discussion.

2.2 Second Experiment (Double layered POC)

Table 2 displays the factors and levels and Table 3 shows the experimental conditions for the second experiment respectively. Table 4 shows the mix proportion for the three grade aggregate samples G6, G7 and G8. The procedure of the experiment was the same as in the first experiment. The only difference here was the introduction of double layered samples as opposed to only the single layered samples in the first experiment. Here, single layered POC samples of grade G7 and G8 along with double layered samples of G6+G7 and G6+G8 were prepared for carrying out the clogging versus permeability tests. Fig.2 and Fig.3 represent the double and single layered samples. The under layer is of G6 aggregate with void ratio of 23% and the upper layers are of G7 and G8 aggregates with the void ratio of 18%. In this case, the double layered samples had three different thicknesses for the upper layer i.e. 4mm, 8mm and 12mm. The under layer is maintained of the same size as the sample in the first experiment i.e. 50x150x40mm. The void ratio of the upper layer has been intentionally kept lower than that of the under layer to try and stop as much added sand as possible on the surface itself and to simultaneously ensure the easy movement of the sand from the under layer after it enters from the upper layer. This flow mechanism by virtue of the difference in void ratios and aggregate sizes in the two layers is expected to facilitate the movement of sand entering in from the upper layer, till the bottom of the sample.

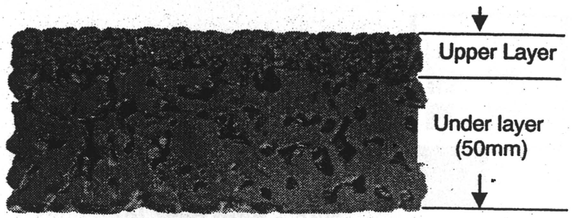


Fig.2 A double layered POC sample
Upper layer = 4,8 &12mm thick

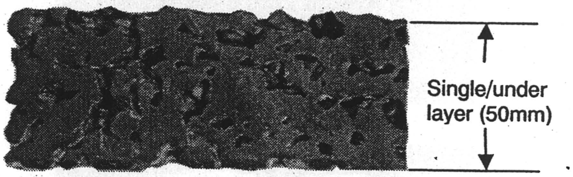


Fig.3 Single/under layer sample (G6)

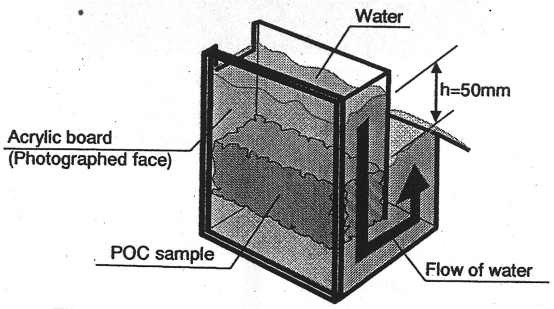


Fig.4 Apparatus used for the experiment [3]

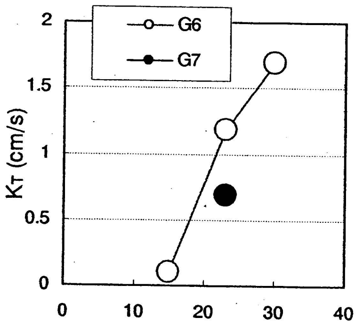
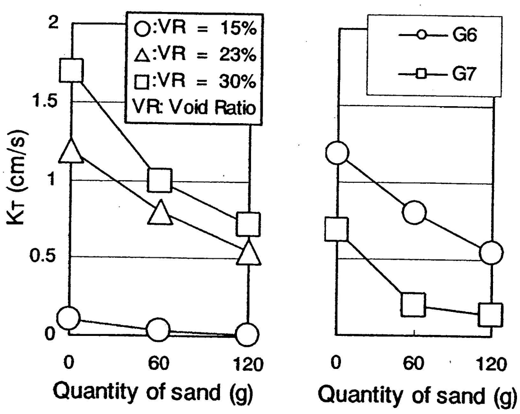


Fig.5 Relationship between K_T and void ratio [3]



(a) Void ratio (b) Agg. size

Fig.6 Effect of addition of sand on K_T [3]

3 Results and Discussion

3.1 First Experiment (Single layered POC)

This experiment demonstrated that the permeability of POC is inversely proportional to the clogging phenomenon. As the added silica sand entered the voids of POC, the clogging phenomenon occurred which eventually reduced the coefficient of permeability of the sample. Fig.1 shows particle size distribution of silica sand.

3.1.1 K_T of POC before the addition of sand

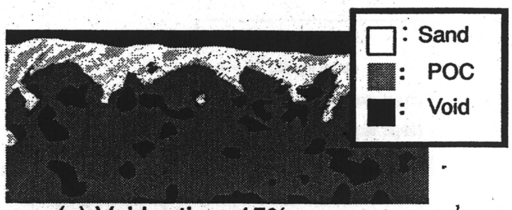
Fig. 5 illustrates the relationship between void ratio and K_T. It can be seen that the K_T increases with ascending void ratio. The figure also illustrates that K_T improves with the increase in size of the aggregate. It is clearly visible in the figure that the permeability for grade G6 sample with 23% void ratio is higher than that of grade G7 sample with same void ratio.

3.1.2 K_T of POC after the addition of sand

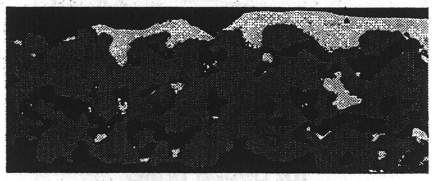
Fig.6 represents how the presence of sand in permeating water affects the coefficient of permeability (K_T) of POC with different void ratios and aggregate grades. It can be seen that permeability in all the cases decreases with the increase in amount of sand added. This goes to show that coefficient of permeability is bound to decline with time in the real situation also as the amount of foreign materials entering or depositing on the POC pavement increases progressively. Fig.7 displays the extent to which sand enters POC samples with different void ratios. The figure brings to light the fact that greater the value of the void ratio, greater is the quantity of sand entering the void. In Fig. 7(a) where the void ratio is 15%, the quantity of sand that has entered the voids is the minimum and most of the sand prevails on the surface of the sample as compared to that with void ratio 30% in Fig.7(c), where the sand has moved till the bottom most part of the sample. After the occurrence of clogging phenomenon, an attempt was made to see how effective would washing prove in restoring the coefficient of permeability of POC. For washing the silica sand that had entered the voids or deposited on the top of the sample, water pressure was applied from the top.

3.1.3 Effect of washing on K_T

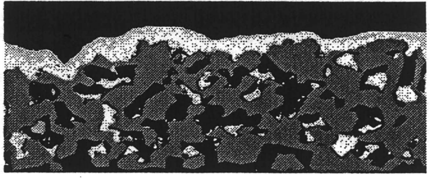
As illustrated in Fig.8(a), it was observed that after washing was carried out, K_T decreased for grade G6 samples with void ratios 15 and 23 %, but a slight increase though very insignificant, could be noticed in case of the samples with void ratio of 30%. The reason for this is that the larger amount of voids can facilitate the movement of sand from top till the bottom of the sample after which it goes out. Whereas, in case of lesser amount of voids, the sand gets stuck somewhere in the middle even when water pressure is applied during washing. In other words, the voids get clogged due to the inability of the sand entering in, to move till the bottom of the samples. A comparative study as shown in Fig.8 (b) was also made between samples of grades G6 and G7 with the same void ratio of 23%.



(a) Void ratio = 15%

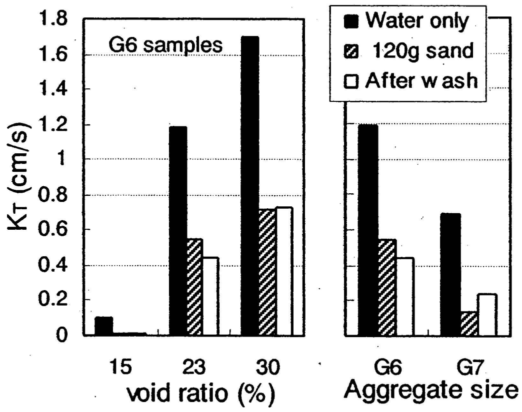


(b) Void ratio = 23%



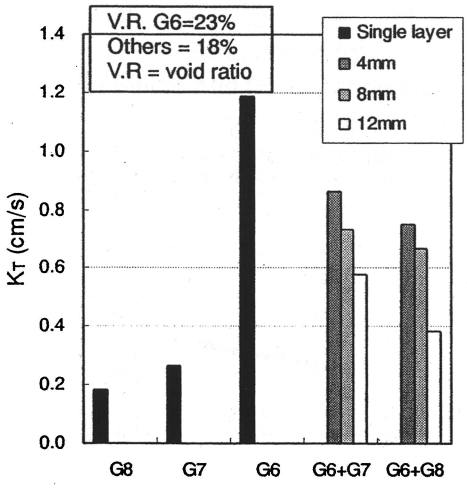
(c) Void ratio = 30%

Fig.7 State of sand inside voids of POC (Agg.size:G6)[3]



(a) Void ratio (b) Agg. size

Fig.8 Effect of washing on K_T [3]



Single and double layered samples

Fig.9 K_T under normal condition

In this case, it was noticed that washing helps to improve the coefficient of permeability of grade G7 aggregates as lesser amount of sand passes through to enter the voids of the sample. This makes it comparatively easier to recover the permeability by washing away the sand deposited on the surface of the sample.

An observation of washing becoming effective with the increasing value of void ratio or decreasing size of the aggregate was made through this experiment.

3.2 Second Experiment (Double layered POC)

As mentioned earlier, this experiment is a follow up experiment of the first experiment.

3.2.1 K_T of different samples on normal condition

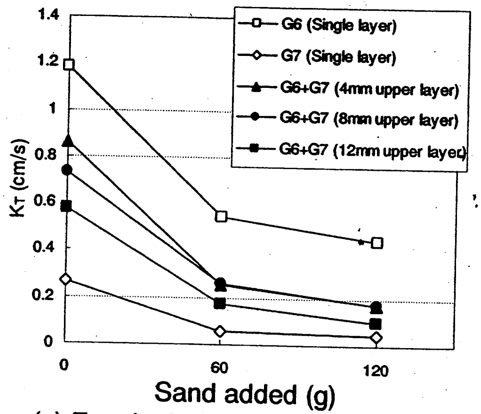
Fig.9 represents the coefficient of permeability (K_T) of all the samples when only the normal tap water is allowed to pass through them. It can be seen here that though the coefficient of permeability of single layered G7 and G8 samples are low when their height is 50mm, it can be increased by reducing their thicknesses. It is made obvious by the figure where permeability in the double layered samples with lesser thicknesses of G7 and G8 aggregates in the upper layer are visibly greater than their single layers.

3.2.2 Effect of addition of sand on K_T

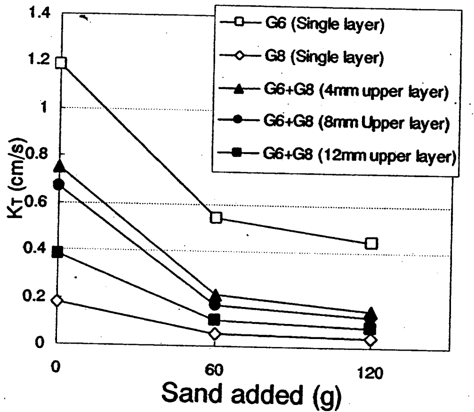
Fig.10 illustrates the reduction in the coefficient of permeability (K_T) of the samples by the addition of 60g each of silica sand in two batches, respectively. Fig.10 (a) shows the effect on G6 and G7 single layered samples along with double layered samples of G6+G7 with three different thicknesses. Fig.10 (b) shows the effect on G6, G8 and G6+G8 samples. The upper layers of G7 and G8 grade aggregates are 4mm, 8mm and 12mm thick. It is clearly visible in the figures that in all the cases, the K_T reduces progressively. The trend is almost the same even if the values differ. Though it may seem obvious in mentioning that the K_T decreases more with the increase in amount of the sand added, but it would be worthwhile as it provides an image of the real situation. This indicates that over the time, the permeability of a POC pavement is bound to decline as the deposits of foreign materials on the surface or in the voids increase inevitably with time. Therefore, it will be interesting to see what kind of impact washing has on the K_T of different samples in consideration. And should it work, it would provide a crucial breakthrough to the ever so bothersome clogging issue in single layered POC.

3.2.3 Reduction of K_T by the addition of sand

Fig.11 portrays the percentage reduction of K_T after the addition of sand. It can be observed that the decrease is the maximum in case of G8 and G6+G8 samples. It is because most of the sand gets deposited on the surface unlike G6 and G7 samples where comparatively more of them enter through the voids in the process facilitating the permeability to better extent.

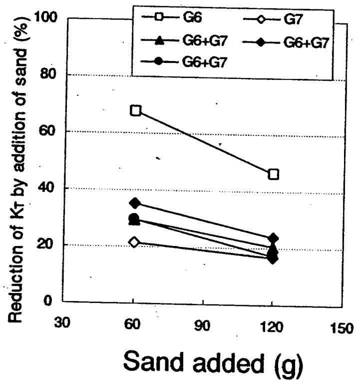


(a) For single and G7 upper layers

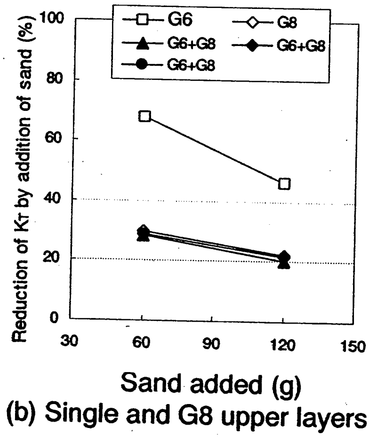


(b) Single and G8 upper layers

Fig.10 Effect of addition of sand on K_T



(a) Single and G7 upper layers



(b) Single and G8 upper layers

Fig.11 Percentage reduction of K_T by addition of sand

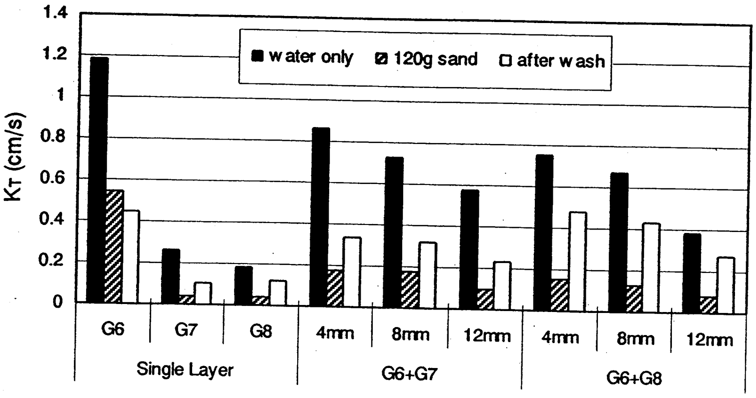


Fig.12 Effect of washing on K_T of single and double layered POC

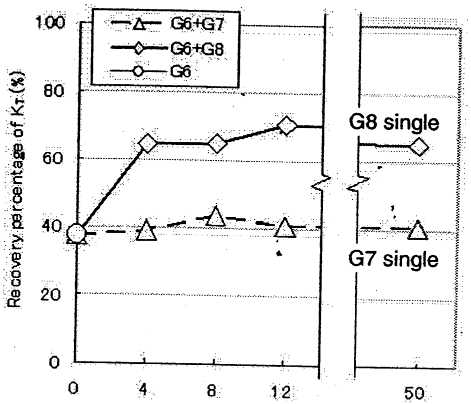


Fig.13 Recovery of K_T on washing

3.2.3 Effect of washing on K_T

Fig.12 demonstrates the effect of washing on the K_T of all the samples in consideration. A look at the figure can give us a fairly good idea of the trend followed by the K_T of different samples with the changing conditions. It can be seen that there is in fact a significant improvement in K_T for all the samples except for the grade G6 sample. G8 and G6+G8 samples' show noteworthy as well as consistent recovery of K_T on washing. Noticeable restoration is also visible in case of G7 and G6+G7 samples. This is because of the fact that with the smaller sizes of the aggregate, the amount of sand entering into the voids is lesser as the voids are smaller than that of bigger size aggregates even though the void ratios are the same. Moreover, majority of the sand entering from the smaller voids of G8 aggregate upper layer should be able to pass through the bigger voids of G6 aggregate layer underneath. And that is exactly what makes it possible to recover back the K_T to a greater extent as the sand deposited on the surface of the samples can be either washed away with the water pressure or pushed through the under layer. On the other hand, comparatively more amount of sand can enter through the voids of G7 and G6 +G7 samples because of which the probability of under layer getting clogged becomes more. This result is in keeping with the philosophy behind advocating the double layered POC which is to try and restrain the majority of the foreign materials from entering into the voids so that they can be washed away to restore and maintain the permeability. Further experiments with the combinations of different thicknesses and void ratios of the layers will have to be conducted to confirm the mechanism.

3.2.4 Recovery of K_T on washing

Fig.13 represents the recovery percentage of coefficient of permeability of double layered POC. This figure supplements Fig.12 by giving clearer image of how the K_T changes after the washing procedure is applied for the samples in consideration. A visibly clear gap in the recovery percentages of the K_T exists between G7 and G8 aggregate double and single layer samples. As mentioned earlier also, G8 samples display a much better restoration tendency than G7 samples.

4 Conclusion

This paper includes two experimental studies. The first experiment was carried out to find the effect of clogging on the coefficient of permeability (K_T) of single layered POC followed by a second one on double layered POC. The second experiment is an effort to see if clogging issue could be addressed with a double layered POC.

It can be inferred from the first experiment that clogging reduces the coefficient of permeability of POC. It reduces more with the increasing amount of added sand in water passing through it. Washing reduces the K_T of G6 aggregate sample with void ratio of 23%. A slight but insignificant increase in the G6 samples with 30% void ratio was noticed. Interestingly, better recovery in K_T could be noticed in case of G7 grade aggregate samples with 23% void ratio.

In the second experiment, it was observed that G8 and G6+G8 samples provided very good restoration of coefficient of permeability on washing. It was also noticed that G7 and G6+G7 samples performed fairly well in the restoration efforts. However, G8 samples stood out with much higher recovery percentage of up to 70% as opposed to G7 samples which was around 40%. This justifies the school of thought behind advocating the double layered POC that is to restrain the foreign materials from entering the voids of POC at the surface level by using smaller sized aggregates to create smaller voids. This way, maximum amount of the foreign materials can be stopped before they enter the voids. Therefore, clogging of voids can be prevented and the materials at the surface can be washed off to restore the permeability of porous concrete.

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