Clogging of permeable pavements in semi-arid areas

Master of Science thesis
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December, 2010

Delft
University of
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Acknowledgement

This report has been written as the final result of my Master thesis in Water Resources Management at the Faculty of Civil Engineering and Geosciences of Delft University of Technology.

I would like to thank my supervisor Frans van de Ven for his guidance and comments .I benefited a lot from his knowledge and remarks during this research. This thesis would have been impossible without his advices.

I would like to show my gratitude to my committee members, Prof. Van de Giesen for his comments and support and especially Prof. Uijttewaal for his guidance, support and encouragements.

I am grateful to Arie M. den Toom, Sander de Vree, Hans Tas for their great assistance to do the tests and solving many problems that I had during the experiments in water lab. Also I would like to thank Frank Kalkman and Jaap van Duin for their help to prepare the test requirements.

I owe my deepest gratitude to Karel Karsen, John Stals and specially Inge Verhoeven for their support to solve my problems during my studying.

I would like to appreciate Mohammadreza Rajabalinejad, Naveed Alam and Atiq Tariq for their comments and clarifying the problems.

I would like to thank Floris Boogaard and Steven te Slaa for their guidance and cooperation.

And finally I am indebted to my family and friends for their support during my studying.

Delft, December 2010
Mahsa

Executive Summary:

Urban development and consequently covering more areas by the impervious surfaces, has led to the decrease in natural process of rainfall infiltration and as a result deduction in ground water recharge. This decrease in ground water recharge has caused number of environmental concerns such as the decrease in base flow in streams and drying up of drinking water supplies. In arid and semi arid areas with low annual rainfall and high evapotranspiration (P/ET<0.5) no excess water for run-off or ground water recharge would be available. Therefore capturing the rainfall for water supplies in such regions is more important. Due to these problems and by considering the role of permeable pavements in capturing water and replenishment of aquifers, using this kind of paving has been considered as a sustainable solution.

Although permeable pavements have been used as a sustainable way to reduce the impacts of urbanization on water quality and improving water management in urban areas but they also have some disadvantages. Clogging in these pavements is the main problem which causes the decrease in infiltration rate. Review of existing researches shows that most of the researches about clogging have been limited to western countries with almost the same climatic condition and the effect of climate on clogging has not been considered yet, especially in dry regions. Although in these areas capturing more rainfall to recharge ground water is really vital. Therefore the effect of climate on clogging of the permeable pavements should be investigated more to choose the proper pavement for dry climate and increasing the infiltration rate.

In order to investigate the effect of semi-arid climate on clogging of the permeable pavements, porous concrete was chosen in this research as the proper type to apply in these areas. As the fine dust in these areas is the main cause of clogging, the pavement behavior under this condition was evaluated by the lab experiment. During the lab experiment different sub-bases (sand and stone) were also examined to see the differences in clogging process under various conditions.

The results from this research shows that the wind suspended particles, as the main cause of clogging in semi-arid areas, can be washed through the pavement and cause a very slow clogging process. Comparison the results of different sub-bases shows the significant effect of the pores size in the sub-base on the clogging process. In case of higher porous sub-base, sediments can be migrated from the pavement to the sub-base easily. But in case of less porous sub-base the blocking of the interface and first layers of the sub-base can create more resistance through the flow migration. As the clogging in case of larger particles happens rapidly, therefore in order to design the pavement, average size of particles that can go through it should be taken into account.

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Glossary: [1]

Pavement	Any treatment or covering of the earth surface to bear traffic
Course	Layer in a pavement structure
Surface course	Pavement surface that receives the traffic load directly, and presents the pavement’s surface quality, appearance and resistance to abrasion
Base course	Base course or base is a layer below surface course to increase the pavement thickness
Sub-base	The layer of materials below the base course to extend the pavement thickness.
Sub-grade	The soil under the pavement structure that bears its load
Pavement structure	A combination of courses of material placed on a sub-grade to make a pavement
Filter layer	Any layer which is placed between two other layers, or between pavement layer and the sub-grade. The migration of particles from one layer to the other one will be prevented by filter layer.

1. Introduction

Nowadays by developing urbanization and covering more areas by impermeable pavements, roads and buildings, the natural process of rainfall infiltration has been diverted and decreased. Decreasing the infiltration rate causes deduction in recharging groundwater which has led to a number of environmental concerns in recent years, for instance decreasing the base flow in streams and drying up of small streams. Most of the public water suppliers rely on wells that tap groundwater. Consequently by decreasing ground water recharge, the drinking water supplies will dry up rapidly. In order to minimize the impacts of our lifestyle and surfacing of urban areas and also draining the surface runoff in a sustainable way, permeable paving has been introduced and used as a solution. In areas with suitable soils, permeable pavements allow storm water to enter the sub-soils, replicating the natural hydrological cycle by allowing for groundwater recharge and moderating the fluctuations of flows in water courses.

• Permeable pavements and recharging aquifers

Recharging groundwater can occur naturally by rain, snow melt or by surface water (rivers and lakes) or artificially which rainwater or reclaimed water is routed to the subsurface. Developing impermeable pavements in urban areas can impede this process. On the other hand using groundwater for irrigation purposes can lower groundwater table. For proper groundwater management the volume of recharged water should be equal or more than the amount of withdrawal. Due to these problems and by considering the role of permeable pavements in capturing water and replenishment of aquifers, using this kind of paving has been considered as a sustainable solution.

• Clogging as the main problem in permeable pavements

Although permeable pavements has been used as an effective way to reduce impacts of urbanization on water quality and improving urban water management but they are not free of problems. Clogging in these kinds of pavements is the main problem which leads to decrease infiltration rate and consequently costly maintenance works. [1],[2]

- **Significance of the research**

Applying permeable pavements as an alternative to traditional drainage systems should be extended, especially in dry regions in order to recharging groundwater. Under these conditions, capturing more rainfall and minimizing evaporation is the main purpose. Reviewing existing researches shows that most of the experiments have been limited to western countries with almost the same climatic condition and the effect of climate on clogging has not been considered yet, especially in dry regions.

More research about the effect of climate on the clogging should be done which leads to: choosing the proper pavement for dry climate, capturing more rainfall and increasing infiltration rate, reducing maintenance cost due to clogging.

1.1. Developing urbanization and its effect on recharging ground water

At the beginning of the 21st century, 50% of the world population lived in big or mega cities. Due to the urban development and consequent changes in the environment and hydrologic patterns water resources are affected. These changes in the environment can be categorized as follow:

- "Micro-climate changes, including increase in precipitation intensity because of the "heat island" effect;
- Blocking of soil surfaces by impervious layers;
- Release of water intentionally or inadvertently to local recharge or run-off with time distribution different from the natural pattern
- Release of pollutants."[3]

Also by increasing the impermeable surfaces in the urban areas, infiltration and evaporation reduce and surface run-off increases.

Four basic reasons which increase the surface runoff in cities can be summarized as below:

- "Building activities disturb the natural infiltration capacity by dewatering and compaction of the infiltration pathways,
- The introduction of impervious surfaces increase the run-off speed and reduce evaporation,
- The introduction of an improved drainage system, which is constant over the seasons, increases or decreases groundwater recharge,
- Run-off from impervious surfaces begins immediately after storm events as compared with run-off in open areas, thus, changing the time distribution of run-off."[3]

In humid conditions, ground water recharge is affected more by the infiltration capacity rather than the water availability. Therefore urban run-off can change the locality of recharge but usually affects the overall balance of the aquifers marginally.

In semi-arid areas, due to the high evaporation the surface runoff usually is a minor factor in water balance and the competition between evapotranspiration losses from the soil layer and the percolation rate. Therefore the prevention of the natural infiltration by the impervious surfaces will reduce the recharge of the underlying aquifers and decrease in ground water level. Application of the proper infiltration techniques can compensate the losses of groundwater recharge. [3]

1.2. Semi-arid climate definition

Semi-arid or steppe regions are characterized by low annual rainfall, about 250-500 mm and the ratio of rainfall/evapotranspiration less than a half(P/ET<0.5). Without the uneven distribution of precipitation the year around and the occasional heavy rainfall during the wet season, no excess water for either run-off or groundwater recharge would be available. Therefore capturing this stormwater is of the utmost importance for the water supply of such regions. [3]

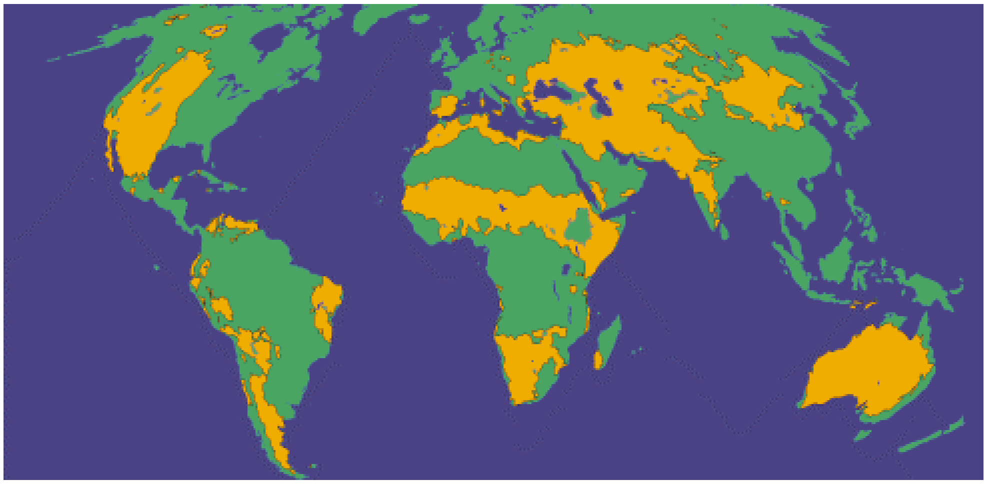

Figure (1.1) Semi-arid areas in yellow

1.3. Research questions

As it was explained in the introduction part, the effect of climate on clogging of the porous pavements has not been investigated. Especially in dry regions where the application of these kinds of pavements is vital to increase the rainfall infiltration, clogging can be more problematic. Considering these matters led to the following research questions:

1. How can climatic condition in semi arid areas affect infiltration thorough the porous pavements?
2. Clogging process under influence of fine mineral dust

1.4. Research method

In order to answer the research questions two main steps were done:

1. Literature study:
    - Different types of porous pavements, as a conventional method to increase the infiltration, were assessed to find the proper type for semi- arid regions.
    -Through literature study different factors that influence the urban runoff and infiltration rate in urban areas were reviewed.
    - Previous researches about the clogging process of porous pavements were reviewed to find the factors that influence the clogging.
    - Factors that influence the clogging under climatic conditions in semi-arid areas were studied.
2. Lab experiment
    - As this research was done for semi-arid climatic condition, and as the clogging is a long term process, it was not practical to assess the behavior of the pavements under real conditions, for instance by measuring the infiltration rate through the available pavements. Therefore, to evaluate the behavior of the pavement under specific climatic condition, lab experiments were done to simulate the clogging process in those regions under the influence of fine dust.

1.5. Reader guide

This report starts with explanation about different types and properties of porous pavements in chapter2.
Chapter 3 contains the review of different factors that influence the infiltration process, urban runoff generation and also characteristic of porous mediums.
In chapter 4 clogging process, factors that have effect on it and also ways to reduce it will be discussed.
Lab experiment to model the clogging process is described in chapter 5.
Chapter 6 contains the result and analysis part, and the final conclusion and recommendation is presented in chapter 7.

2. Porous pavement

Porous pavement is a permeable surface pavement which is designed to allow infiltration of storm water through the surface into the subsoil. Through this process runoff will be treated, but in contrast to an impervious surface of a normal pavement sheds rainfall and surface pollutants, and finally they will discharge directly into the nearest storm drains and then to the streams and lakes. Porous pavements usually appear the same as traditional asphalt or concrete without fine materials. Void spaces are combined and connected together and allow water infiltration. Low traffic or overflow parking areas are best places for using these kinds of pavements.

2.1. Physical properties of porous media

- **Porosity**

Porosity of a material is defined as the fraction of the volume of the voids over the total volume. The porosity is a dimensionless parameter between 0-1, or as a percentage between 0-100 percent. Equation (2.1) is used to define the porosity. [4]

$$n = \frac{Vv}{Vt} \tag{2.1}$$

Vv **:** The volume of the voids (m^3)

V_t**:** The total volume of the material (m^3)

Void ratio is another dimensionless parameter that is used and defined by equation (2.2):

$$e = \frac{Vv}{Vs} \tag{2.2}$$

Vs: Volume of mineral solids in a given volume of material (m^3)

As $V_t = Vs + Vv$ then void ratio and porosity are defined by below equations:

$$n = \frac{e}{1+e} \quad , \quad e = \frac{n}{1-n} \qquad (2.3)$$

In different geologic materials, porosity has different forms. In granular materials such as gravels, sands and silt, the pores between the mineral grains make an interconnected network (intergranular porosity). This network is the main portion of the total porosity (Figure 2.2)

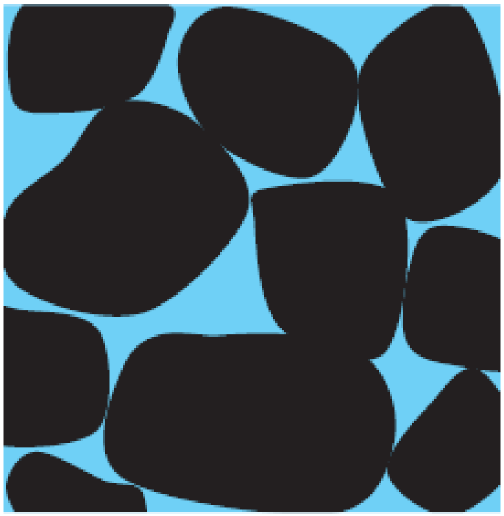

Figure (2.2) Intergranular matrix porosity in a well-sorted granular material 4

Fractures through the clayey deposits and rocks are another important component of the porosity. (Figure 2.3) In porous sandstones or in clays, the amount of matrix porosity is bigger than fracture porosity

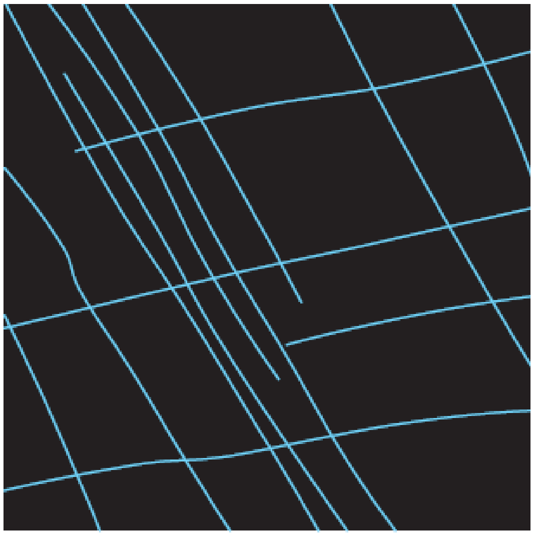

Figure (2.3) Fracture porosity in crystalline rocks[4]

- **Effective porosity:**

In a porous media some pores are dead-end or landlocked. Therefore they are not considered as a part of the pore network which conducts flow and their contribution to flow is negligible. So another useful concept called effective porosity is used in flow and transport analysis. Effective porosity (n_e) is defined by Equation (2.1) which *Vv* is the volume of voids that contribute to the flow. If the percentage of landlocked and dead-end pores is high then the effective porosity deviates significantly from the total porosity. [4]

- **Grain size**

The size of the mineral grains is a key characteristic of unconsolidated materials. Grain size distribution determines how much pore space is available to hold water, and how easily water is transmitted through the material. Table (2.1) shows the grain size range of different materials.4

Table (2.1) Grain size distribution[4]

Grain Size Range (mm)	
Material	**Grain Size Range (mm)**
clay	<0.002
silt	0.002-0.05
sand	0.05-2.0
Gravel	>2.0

- **Volumetric water content and bulk density**

The volumetric water content (θ) is the volume of water in a given volume of material and is defined by the equation (2.4) θ is dimensionless and can be reported as a decimal fraction or as a percent.[4]

$$\theta = \frac{V_w}{V_t} \tag{2.4}$$

V_t: volume of material (m^3)
V_w: volume of water (m^3)

In a saturated material, all the pores are filled with water and $\theta = n$, otherwise the pores contain some air and $\theta < n$

Dry bulk density is another parameter which is defined by the equation (2.5)[4]

$$\rho_b = m_s / V_t \tag{2.5}$$

$m_{s:}$ mass of the solids in sample (gr)
V_t: sample volume (cm^3)

The wet or total bulk density is defined like dry bulk density but includes the mass of both solids and water (equation.2.6)[4]

$$\rho_t = (m_s + m_w) / V_t \tag{2.6}$$

m_w: mass of water in the sample

2.2. Advantages of using porous pavements

• Reduce surface runoff

Comparing the performance of the traditional pavements and porous pavements could result in reduction in the peak flows in rivers and streams. This reduction is due to the decrease in overland flows which reaches the receiving waters. The reduction in surface run off also prevents over-load of combined sewer treatment plants. Pratt et al. (1989) found that the discharge rates from permeable pavements were significantly lower (30% of peak rainfall rate) and the time of concentration was greater (5 to 10 minutes, compared to 2 to 3 minutes for traditional pavements.[5]

• Reduce pollutants in run-off

Surface water quality is negatively impacted by urban development due to pollutant loads in stormwater runoff and increases in runoff peaks and volume. Before the storm, areas which are covered by impervious surfaces had been accumulating pollutants deposited from the atmosphere, dripped from vehicles, leached from metal gutters, and defecated by animals. When the first rain fell, the watershed's impervious pavements and roofs turned essentially all of the pollutants into surface runoff that flushed the pollutants into the stream. The water that dense pavements spoil and discard would, if it were conserved, be capable of supporting the future population growth of millions of people .One potential focus for nonpoint source pollution mitigation in residential developments is reduction of driveway runoff. A porous pavement infiltrates and treats rainwater where it falls. Its pore space stores water like a retention basin. The pores house a micro ecosystem that filters and biodegrades the pollutants that occurs generically on residential, commercial, and office pavements; the underlying soil ecosystem is a backup treatment system that assures high treatment level.[5,6,1]

- **Reduce thermal pollution**

Urban construction materials absorb and store solar heat. After heat absorption by the dense materials it will be conducted to the depth of the material and make a thermal storage battery. This heat will be re-emitted to the air which will increase air temperature. In porous materials due to the reduced thermal capacity, daytime heat will be conducted downward and will not be stored. Also lack of water permeability in dense pavements prevents rainwater infiltration and consequently plants growth will decrease. In addition heat and moisture exchange between soil and air will decrease so the temperature and humidity in large cities cannot be adjusted. This brings the phenomenon of urban heat island in built-up areas. The heat-island effect has a subtle influence on rainfall that could be considered either an advantage or a disadvantage. During summer thunderstorm conditions, city heat enhances convective rainfall downwind of city centers. Seasonal rainfall increases of 9 to 17 percent are possible.[1]

- **Noise reduction in cities**

Porous pavement can reduce traffic noise at the source by absorbing sound energy and also pressing the air around the tires into the voids. Noise reduction in case of high-frequency sounds, which are relatively loud, is more efficient. In wet conditions, due to the water splash, the noise intensity is higher. In this condition, puddled water will drain fast through the porous pavement. [1]

- **The promise of safe driving**

Small aggregates in the pavement material make friction and consequently resistance to skidding of vehicles on the pavement surfaces. This friction exists in both dense and porous pavements. In wet conditions, the puddled water on the dense pavement surface will reduce the contact of tires and pavement and consequently the surface friction will decrease as well.

At the beginning of the rainfall, the dropped lubricants from the vehicles will be combined with water and makes a slippery pavement surface. In porous pavement, water and oil will be drained through the pores, and prevents lubricant accumulation on the surface.

Drainage of Puddled water from the pavement surface and reduction in water splash will improve driving visibility and reduce accidents.[1]

- **Increase the infiltration rate and groundwater recharge**

The increase of groundwater recharge depends on the amount of rainwater and also the infiltration rate. In urban areas, impervious layers block the soil surface which reduces the infiltration. Also compaction of the percolation area by construction has negative effect on ground water recharge. In semi-arid areas, as the surface runoff is not significant, the recharge rate depends on the competition between the evapotranspiration from the soil layers and infiltration rate, consequently impervious surface reduces natural infiltration and ground water recharge.

Application of the porous pavements is a contributor to solve this problem. Porous pavements as an option to traditional dense asphalt and concrete allows stormwater infiltration into the soil and ground water recharge. Figure (2.4) shows the contrasting hydrological effect of dense and porous pavement. [1, 5 ,7]

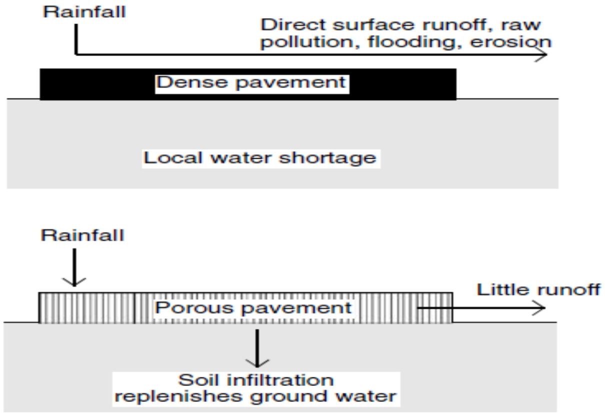

Figure (2.4) Contrasting hydrological effect of the dense and porous [1]

2.3. Problems of porous pavements

Clogging of the pores with fine materials is one of the major drawbacks of porous pavements which happen between 5 and 10 years after pavement construction. The fine materials include clay; silt or other materials derive from tire wear and pavers. After rainfall, the suspended sediment in runoff, will deposit on pavement surface which causes the clogging of the pores. After percolation of the fine particles into the base material and their settlement at the bottom of the recharge bed, the storage volume and percolation of the stored water into the ground water system will decrease. [8]

The damage of the pavement surface is another problem. It is caused by the use of incorrect sub-base materials. When water stores in the pavement, the traffic load is taken by the sub-base material. Due to the use of incorrect materials, small particles can flow in the road bed and cause structural problems such as abrasion. To avoid this problem, the sub-base materials should have sufficient bearing capacity.

During winter time, deicing salts and frost can damage the pavement. Areas with highly polluted runoff, low soil permeability, seasonal high ground water tables are not proper places to use porous pavements. [2 ,7]

2.4. Porous pavement components

Porous pavements like dense pavements are assembled from several types of components. Depends on the requirements of each pavement, they have a specific combination of components. [1]

- **Surface and base course**

As the surface course bears the traffic load and its abrasion effect, usually it is made of relatively expensive material to resist abrasion and also provide other requirements such as appearance and accessibility. On the other hand, a thick base course can be made of inexpensive materials and spread the traffic load on the pavement to the sub grade. Figure (2.5) shows the surface and base course in a pavement. [1]

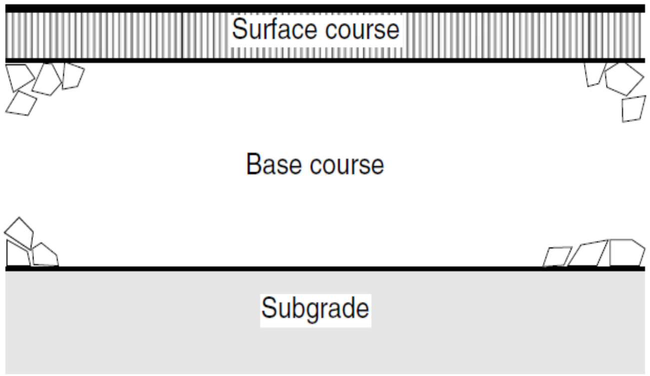

Figure (2.5) Section through a pavement with distinct surface and base courses

- **Overlay**

Application of an overlay over a dense pavement, and the consequent water drainage, will improve pavement's surface benefits. Figure (2.6) shows porous type of overlay over a dense-surfaced pavement. [1]

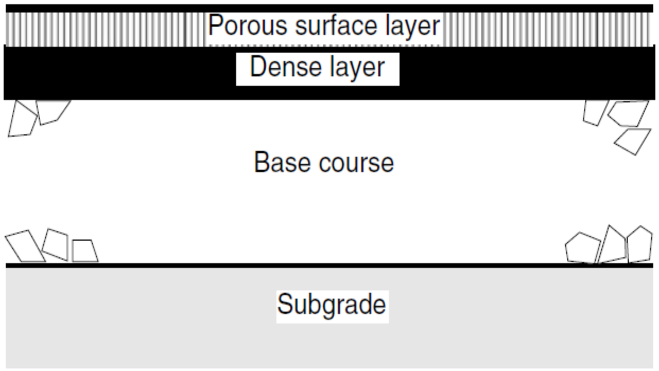

Figure (2.6) Pavement with a porous overlay

- **Reservoir**

A reservoir, which is also called a drainage layer or drainage blanket, is composed of pavement materials which store water and also they have a structural function. Water stores between the void spaces of the material. Water storage in the pavement can reduce the size of drainage system, flooding and erosion in downstream. In addition water infiltration from the reservoir into the sub-grade will increase groundwater level and stream base flow.[1]

- **Filter layers**

Filter layers are inserted between two layers to prevent particle migration from the layers. The segregation of pavement materials is needed to maintain the porosity of each layer. Filter layers can be inserted in the form of intermediate-size aggregate or geotextiles. Although geotextiles are permeable they prevent the movement of small particles, also they increase the tensile strength of the pavement. [1]

- **Liners**

In order to prevent the water infiltration from the pavement in to the sub grade, the bottom of the porous pavement can be lined by the manufactured impermeable fabrics or “geo-membranes”. For instance in areas where the sub grade soil will swell by the moisture, and also when the soil contains toxic chemicals, liner application can be practical. Liner turns the pavement structure into a water reservoir.[1]

2.5. Types of permeable pavements

- **Porous aggregate**

Aggregate is any mass of particulate material such as gravel, crushed stone, crushed recycled brick, or decomposed granite. Single-size aggregates can be practical in some applications such as:Porous concrete, porous asphalt, filling the joints of paving blocks and open cells, base course of the pavement, surface course in very low traffic areas such as residential driveways, lightly used pedestrian walkways.

Single- size particles can provide 30-40 percent porosity. As the deflections from heaving on the aggregate’s irregular surface are not noticeable, they are applicable in freezing or swelling soil. Also the low price is another advantage of them. Maintenance to level the surface and replace of the lost material is needed in this kind of pavement.[1]

- **Plastic geocells**

Plastic geocells are manufactured lattice-like products and are usually made from recycled materials. They hold aggregate or topsoil in their cells, and prevents displacement and compaction of the aggregates.

Combination of geocells and aggregate or turf can be used in areas with frequent traffic. In this case the geocell bears the compaction force or weight of the cars. Also due to their flexibility, they are proper to use in sites with swelling or freezing soil.[1]


Figure (2.7) Plastic geocell

• Porous turf

A turf surface is a “green” open space. It is also in effect a pavement that supports pedestrian or vehicular traffic. Excessive traffic should be avoided to keep the turf’s permeability. Also due to the irregular surface of turf, sub-grade deflections are not noticeable, so it is applicable in areas with swelling soil or frost heave. In order to reinforce of the turf in areas with heavy or frequent traffic load, geocells, grids or blocks can be used. As the maintenance of the turf must be done regularly and scheduled, it should be used in places with controllable and predictable traffic, such as in an office, church or in event parking. [1]

• Open-jointed paving blocks

Paving blocks are solid units of concrete, brick, or stone laid side by side to bear traffic loads. The blocks are molded in a way to produce open joints between adjacent units. The joints are filled with turf or aggregate which makes the pavement permeable. As the blocks are durable, they can be used in heavy traffic areas. Also their long lifetimes reduce the life-cycle costs. By using a thick base course in areas with deep frost, deformation on the pavement surface can be avoided. Also in areas with swelling soil, water infiltration through the soil can be prevented by lining. [1]

Figure (2.8) Open jointed block pavements

- ## Open-celled paving grids

Open-celled paving grids are units of concrete or brick, which are designed with open cells that can be filled with porous aggregate or turf. The surface appearance of the pavement is influenced by the type and maintaining condition of the filling aggregate or grass. Due to the good maintenance, grass will spread over the ribs and the pavement create a green open space and suitable for walking. On the other hand, filling the cells with aggregate or poor maintenance causes an irregular surface. The bearing capacity of these kinds of pavements is usually high. Areas with swelling soil are not proper place to use grid pavements. [1]

Figure (2.9) Open celled paving grids

- ## Porous asphalt

Porous asphalt is made of single-size aggregate bound together by bituminous asphalt binder. Although porous asphalt has a high permeability the binder can cause clogging. In case using a fluid binder or weak connection between aggregate and the binder, the binder from the pavement surface will drain downward and make a clogging layer inside the structure and particles at the surface will be unbound. [1]

- ## Porous concrete

Porous concrete is made of attached single-size aggregate by Portland cement. Aggregate is the main part of the concrete volume. Chemical properties of porous concrete are similar to the dense concrete. The existence of voids in the concrete structure due to the application of open-graded aggregate is the main difference. In porous concrete sufficient paste, which is created by controlled amounts of water and cementation materials, coats and binds the aggregate particles and create a highly permeable and well drained system .The porosity of the porous concrete is about 15%-25% and flow rate for water is about 480 in. /hr (0.34 cm/s, which is 5 gal/ft2/ min or 200 L /m2/min). For mitigating the effects of the urban heat island, porous concrete's light-colored surface has the theoretical advantage of low absorption of solar heat. The low traffic driveways, walkways, moderate traffic loads such as residential areas and parking lots are appropriate places to use porous concrete. As it is capable of cracking it is not practical to use in areas with swelling soil conditions.[1],[2]

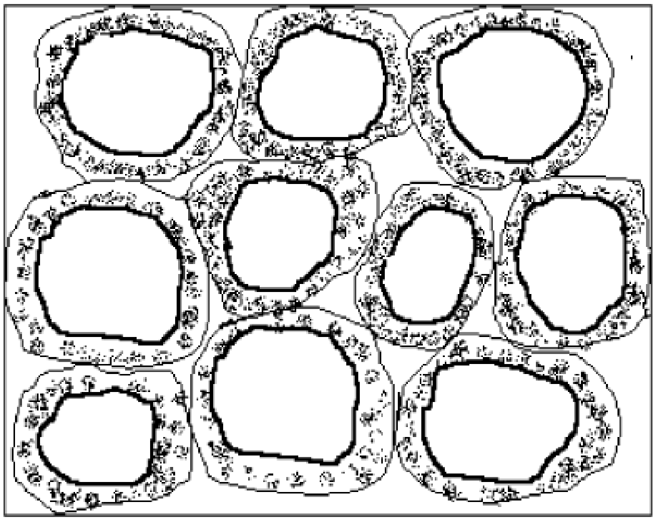

Figure (2.10) Schematic model of pervious concrete

- ## Soft paving materials

The category of "soft" paving materials includes any granular material from an organic or recycled source such as bark mulch, crushed shells, or rubber granules. Areas with light traffic are the best place to use them, such as pedestrian, walkways and lightly used parking stalls. Heavy traffic can displace the particles or compact them and make an impervious surface. Windy places or areas under concentrated surface runoff are not the proper place to use them as well. [1]

- **Decks**

Decks are bridge-like structures which can be suspended over the soil by the footings. They can be made from natural, manufactured or recycled materials. Application of the decks can prevent the compaction of the underlying soil. By installing the deck footing under the active soil zone, these kinds of pavements can be used in areas with freezing or swelling soil conditions. Decks can be the best pavement in steeply sloping areas and sites where the tree roots or ecosystem should be protected.[1]

Figure (2.11) A deck over a wetland

2.6. Porous concrete

In order to use the proper type of porous pavements in different regions there is not a conclusive subdivision. Two main factors that usually were considered to categorize the porous pavements are bearing capacity and also freezing or swelling soil conditions in the region. Under climatic condition, usually cold areas and also places where the swelling of the soil is probable have been considered[1]. Previous experiences in dry regions show that porous concrete is suitable to apply in these conditions.[9]

2.6.1. Engineering properties

- **Hardened properties**
  - **Density and porosity**

The density of the porous concrete depends on the properties and proportions of the material used and also on the compaction procedures used in place. The range of the in-situ density is about 1600 kg/m3 to 2000 kg/m3 which is in upper range of light weight concretes.[2]

Permeability

Permeability of the pervious concrete depends on the materials and placing operations. Typical flow rate of water for the porous concrete is 0.2 cm/s to 0.54 cm/s in place, and rates of higher than 1.2 cm/s have been measured in the laboratory. The decrease in infiltration rate will be slight if there is no significant external source of clogging matter.[2]

Compressive strength

The compressive strength of the pervious concrete is in the range of $34*10^5$ to $270*10^5$ (N/m^2) which is suitable for a wide range of application. The typical value is about $170*10^5$ (N/m^2). This strength and durability is adequate for moderate traffic loads. In comparison the dense concrete has the compressive strength around $240*10^5$ (N/m^2). Low mortar content and high porosity can decrease the strength of the concrete. [2]

Shrinkage

Shrinkage of the pervious concrete develops rapidly at the first 10 days of installation. About 50% to 80% of the shrinkage happens at this period. In compare of conventional concrete the shrinkage of porous concrete develops sooner but is less. The materials's low paste and mortar content could be the reason of this difference. Due to the lower shrinkage in porous concrete, control joints can be ignored in these kinds of pavements.[2]

Freeze-thaw resistance

The existence of the open pores in porous concrete makes it so sensitive to the freeze-thaw. In this case its resistance depends on the saturation level of the pores at the time of freezing. By increasing the water content of the voids, their resistance to the freeze- thaw will decrease. But usually in the field, due to the rapid drainage of the pavement, the water content of the pavement is not high and near to saturation point, so it can show better resistance. In order to improve freeze-thaw resistance some methods such as: entrained air, using a drainable rock base, such as thick sub-base like 25 mm crushed stone with the thickness of 150mm-300mm or even 450mm, liquid polymer and latex additives can be useful.[1,2]

Sulfate resistance

Chemicals, such as acids and sulfates, in soil and water threat the pervious and conventional concrete. In case of porous concrete due to its pores, it is more susceptible to danger. Pervious concrete can be used in high-sulfate soils and ground waters when they are isolated from them. This isolation can be provided by placing the pervious concrete over a 150mm layer of aggregate (25mm). Also this can provide a storm water storage and pavement base. [2]

Abrasion resistance

Abrasion of the aggregates can be a serious problem in pervious concrete due to its rough surface and open structures, especially in cold climate where snowplows are used to clear the pavement surface. At the beginning of porous pavements application, some surface aggregates which have a weak bound to the surface will be separated from the pavement structure. The rate of surface raveling will decrease gradually. The surface raveling of the aggregates can decrease by proper compaction and curing techniques. [1,2]

2.6.2. Mixture properties

• Materials

The porous concrete materials are the same like the conventional concrete, except that in porous concrete, the fine aggregate is eliminated to provide open voids. Addition of fine aggregate will decrease the void content and increase the strength of the porous concrete. Table (2.2) provides the typical ranges of materials proportions in pervious concrete.[2]

Table (2.2) Typical ranges of material proportions in Porous concrete

	Proportions	Proportions (Kg/m^3)
Cementitious materials		**270 to 415**
Aggregate		**1190 to 1480**
Water: cement ratio* (by mass)**	**0.27 to 0.34**	
Aggregate: cement ratio* (by mass)**	**4 to 4.5:1**	
Fine: coarse Aggregate Ratio**(by mass)**	**0 to 1:1**	

• Cementitious materials

Portland cement, which is the most costly component, and blended cement are used in pervious concrete like dense concrete. The amount of cement in porous concrete is more than dense concrete. Some supplementary cementitious materials such as fly ash and blast-furnace slag are also used in porous concrete which is a type of pozzolan. As fly ash is less expensive than Portland cement, by using large amounts, it can replace more than one quarter of the Portland cement in concrete. [1,2]

- **Aggregate**

Aggregate occupies most of the porous concrete's volume and is the principal load-bearing component. It must be open-graded in order to produce voids commonly used gradations of coarse aggregate include ASTM C (in metric units) No. 67 (4.75 to 19 mm), No. 8 (2.36 mm), or No. 89 (9.5 to 1.18 mm) because they are widely available from local suppliers. Single-sized aggregate up to 25 mm also has been used. [1,2]

- **Water**

Water to cementitious materials ratios are shown in table 2.2. In porous concrete, the total paste content is less than the voids content between the aggregates. So the relation between the strength and water to cementitious materials ratio is not clear. Therefore increase the strength of the paste may not always lead to the increase of overall strength. 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.[2]

2.6.3. Design

- **Basis for Design**

The thickness of the pervious concrete pavement is determined by two factors: the hydraulic properties, such as permeability and volume of voids, and the mechanical properties, like strength and stiffness.

Pavement thickness and materials should be selected properly to support the hydrological requirements and traffic loads. For this purpose separate analyses should be done and the larger thickness should be selected for design. [2]

- **Hydrological design consideration**

Three main factors that should be considered in design of a pervious concrete are amount of expected rainfall, pavement characteristics and underlying soil properties. The intensity of surface runoff that can be tolerated by a pervious concrete should be considered in design. Due to the infiltration and interception of the rainfall, amount of the runoff is less than the total rainfall. The soil properties and rate of infiltration to the soil, and also the nature and amount of the storm itself affect the amount of runoff. These factors will be discussed as follows.[2]

- **Rainfall**

A proper rainfall event must be used to design pervious concrete pavement. The standard rainfall event which is used for this purpose is rainfall with 2 years return period and 24 hours duration. [2]

Storage capacity

The storage capacity of the pervious concrete is designed for the specific rainfall. This rainfall depends on the local requirements. The total volume of the rainfall and also the infiltration rate of the soil should be considered. The storage capacity of the system includes the capacity of the pervious concrete pavement, capacity of the sub-base and amount of water which infiltrates into the underlying soil. The effective porosity of the pervious concrete which can be filled with rain in service is the theoretical storage capacity of it. Every 25mm pervious concrete with 15% effective porosity can hold 4mm of rain. The sub-base of the pavement system is another source of the storage. Compacted clean stone (#67 stone, for example) used as a sub-base has a design porosity of 40%; a conventional aggregate sub-base, with a higher fines content, will have a lower porosity (about 20%). [2]

Sub-base and sub-grade soils

"As a general rule, soils with a percolation rate of 12 mm/hr are suitable for sub-grade under pervious pavements. Clay soils and other impervious layers can decrease the infiltration rate and should be modified to allow percolation of precipitation. In some cases, the impermeable layers may need to be excavated and replaced. If the soils are impermeable, a greater thickness of porous sub-base must be placed above them. The actual depth must provide the additional retention volume required for each particular project site. Open-graded stone or gravel, open-graded Portland cement sub-base (ACPA 1994), and sand have provided suitable sub-grades to retain and store surface water runoff, reduce the effects of rapid storm runoffs, and reduce compressibility. For existing soils that are predominantly sandy and permeable, an open-graded sub-base generally is not required, unless it facilitates placing equipment. A sand and gravel sub-grade is suitable for pervious concrete placement. In very tight, poorly draining soils, lower infiltration rates can be used for design. But designs in soils with substantial silt and clay content—or a high water table—should be approached with some caution." [2]

Traffic loads

"The anticipated traffic carried by the pervious pavement can be characterized as equivalent 18,000-lb single axle loads (ESALs), average daily traffic (ADT), or average daily truck traffic (ADTT). Since truck traffic impacts pavements to a greater extent than cars, the estimate of trucks using the pervious pavement is critical to designing a long-life pavement."[2]

Inspection and maintenance

Construction inspection and testing

As mentioned before slump test and cylinder strength are not proper method to test the strength of the pervious concrete. In order to assess the quality of the porous concrete, a unit weight test can be used. The best values are in the range of 1600 kg/m^3 and 2000 kg/m^3. ASTM C 29[1]

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generally is preferred over ASTM C 138 because of the consistency of pervious concrete, although ASTM C 138[2] is used in some areas. [2]

○ Post-Construction inspection and testing

Seven days after construction, core samples can be taken and tested for unit weight (ASTM C 42[3]). A typical testing rate is three cores for each 75 m^3.Unit weights, in accordance with ASTM C 140[4], provide an acceptance measurement; typical requirements dictate that average unit weights are within 80 kg/m^3 of the design unit weight. [2]

• Maintenance

Prevention of clogging of the voids in pervious concrete is the major maintenance that should be done. Landscaping materials such as mulch, sand and topsoil should not be loaded on pervious concrete. To remove debris from the pavement surface and prevent decrease in infiltration rate frequently vacuuming, power blowing and pressure washing are necessary.[2]

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[1] This test method covers the determination of bulk density (“unit weight”) of aggregate in a compacted or loose condition, and calculated voids between particles in fine, coarse, or mixed aggregates based on the same determination. This test method is applicable to aggregates not exceeding 125 mm [5 in.] in nominal maximum size.

[2] This test method covers determination of the density of freshly mixed concrete and gives formulas for calculating the unit weight, yield or relative yield, cement content, and air content of the concrete. Yield is defined as the volume of concrete produced from a mixture of known quantities of the component materials.

[3] This test method covers obtaining, preparing, and testing cores drilled from concrete for length or compressive strength or splitting tensile strength determinations and beams sawed from concrete for flexural strength determinations.

[4] These test methods provide various testing procedures commonly used for evaluating characteristics of concrete masonry units and related concrete units. Methods are provided for sampling, measurement of dimensions, compressive strength, absorption, unit weight (density), moisture content, flexural load, and ballast weight·

3. Urban runoff

3.1. Rainfall

In order to analysis the rainfall characteristics four aspects as below should be identified:

- Depth: amount of generated rainfall (mm)
- Intensity: amount of generated rainfall per unit of time (mm/hr)
- Duration: The time between the beginning of the rainfall and its end (hr)
- Frequency: how often does a specific rainfall event occur(years)

In order to find the rainfall characteristics three main methods to describe rainfall characteristics are used:
1. Depth-duration-frequency curve:
Rainfall depth-duration-frequency (DDF) curves describe rainfall depth as a function of duration for given return periods
2. Design storm:
A storm which its magnitude, intensity and rate does not exceed the design load for a storm drainage system or a flood protection structure.
3. Rainfall series: Historical rainfall records with a specific measuring interval. [10]

3.2. Evapotranspiration

The most fundamental methods to estimate the evaporation are based on the energy balance. The energy balance at the earth surface can be written as:

$$Q^* = G+LE+H \qquad (3.1)$$
Q^*: net radiation ($W.m^{-2}$)
G: amount of heat absorbed by the earth's surface ($W.m^{-2}$)

LE: amount of heat used for evaporation (latent heat). L is the evaporation heat~2.5.10^6 [J.kg^{-1}], E is the vapor transport in (kg.m^{-2} s^{-1})
H: amount of tangible heat transferred to the atmosphere (W.m^{-2})
The equation is based on the energy balance at the surface; advection (horizontal air movement) has not been taken into account. In case of advection the magnitude of the terms H and LE change. At the transition from land to water surface and also from large paved areas to green areas advection should be taken into account. [11]

- **Penman Method**

Evaporation of the open water from net radiation, wind velocity, temperature and relative humidity can be calculated by the Penman method. This evaporation is indicated by E_0 as below:

$$E_0 = \frac{sR_{no} + \gamma E_a}{s + \gamma} \tag{3.2}$$

R_{no}: net radiation over open water
s: slope of saturation vapor pressure curve at mean dew point(mb °C^{-1})
E_a: f (u) (e_s-e_a) (e_s and e_a are saturated and actual vapor pressure) (mb)
γ: psychrometric constant

- **Evaporation from paved surfaces**

The energy balance of the urban hydrology can give an estimate about the evaporation from the paved terrain. The warm pavement can supply heat rapidly and this heat plays a significant role in the evaporation process. By considering this inflow of heat that is stored in the underground a modified version of the Penamn equation can be used as below:[11]

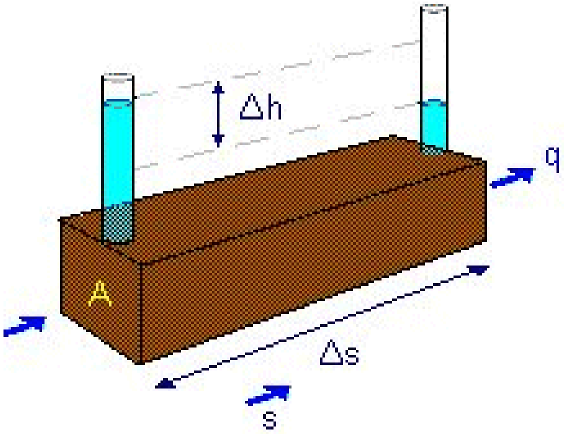
$$LE_0 = \frac{A(Q^* + H_s) + B(e_{zs} - e_z)}{1 + A} \tag{3.3}$$

A= constant
H_s= heat flow from the pavement to the surface
B= factor for the wind effects
e_{zs}= saturated vapour pressure at the elevation z
e_z= vapour pressure at the elevation z

3.3. Infiltration process

- **Darcy's law and Hydraulic conductivity**

The flow of a fluid through a porous medium is described by Darcy's law.
According to it, with a specific porous medium, the discharge depends on the cross sectional area to flow (A) and pressure drop over a given distance. Equation (3.4) shows this relation.



$$Q_s = -K_s(dh/ds) \tag{3.4}$$

Q_s: Discharge in s direction [L^3/T]
K_s: Hydraulic conductivity in s direction (or conductivity), which is a property of the medium and is a measure of the ease with which a medium transmits water. [L/T]
Therefore a material with higher *Ks* transmits water more easily than low *Ks* materials.
The dimensionless quantity *dh/ds* is known as hydraulic gradient and represents the rate of changes in head in the s direction.
As the head decreases in the direction of the flow so the minus sign is necessary.
Materials with small pores allow small migration of water in compare of materials with larger and less constricted pores. Water traveling through small, constricted pores must shear itself more in the process of traveling a given distance than water traveling through larger pores. More shearing in the water causes more resistance and slower flow.[4]

• Intrinsic permeability and conductivity of other fluids

The hydraulic conductivity is the permeability of the medium to the flow of the fresh water. The flow of other fluids is described by the intrinsic permeability (k). Intrinsic permeability (k) unlike hydraulic conductivity (K) does not depend on fluid properties and only depends on the medium. The two parameters are related as follows: [4]

$$k = \frac{K\mu}{\rho w g} \tag{3.5}$$

μ: dynamic viscosity (N s/m^2)
ρ_w: water density (kg/m^3)
g: gravitational acceleration(m/s^2)

Limits on the application of Darcy’s Law

Laminar and Turbulent Flow

When groundwater flow is small enough and the flow is laminar and not turbulent, Darcy’s Law can be applied. In laminar flow velocity and momentum are small and there is not eddies development.

Turbulent flow, like in the atmosphere or a flowing stream, is characterized by rapid variation of velocity and pressure and Darcy’s Law is not applicable in this case.

A measure to determine the laminar or turbulent behavior of a flow is the Reynolds number, Re, a dimensionless parameter which is defined as follows:[4]

$$\mathrm{R_e} = \frac{\rho v d}{\mu} \tag{3.6}$$

ρ : fluid density

v: fluid velocity

μ : dynamic viscosity of the fluid

d: characteristic length such as mean pore diameter or mean grain size

Experimental data shows that in the case of laminar flow in granular media $\mathrm{R_e}$ varies between 1 and 10.

In media with large pores and high flow velocity turbulent flows develop which is usually happens in coarse granular materials like rip-rap.

In laminar flows, specific discharge (discharge per cross-sectional area) is proportional to the hydraulic gradient with a constant ratio.[4]

$$\frac{q_x}{(dh/dx)} = -K \tag{3.7}$$

But in turbulent flows this ratio is not constant and by increasing the specific discharge this ratio will decrease, because more turbulence causes more frictional losses during flow.

Estimating average hydraulic conductivities

For flow analyses, it is often necessary to estimate average values of hydraulic conductivity based on a set of measured values.

One situation is the parallel layers of materials with different hydraulic conductivities.

The x axis is parallel to the layers with different hydraulic conductivities, and z axis is normal to the layers. The layered system can be presented as one homogenous layer with one value of hydraulic conductivity in horizontal and vertical direction as below:[4]

$$K_{xe} = \frac{\sum K_{xi} d_i}{\sum d_i} \tag{3.8}$$

$$K_{ze} = \frac{\sum d_i}{\sum (d_i / K_{zi})} \tag{3.9}$$

K_{xi}: the x-direction conductivity in the ith layer [L/T]
d_i: the thickness of the ith layer [L]
K_{zi}: the z-direction conductivity in the ith layer [L/T]

• Correlations of grain size to hydraulic conductivity

The saturated hydraulic conductivity depends on the size and distribution of pores in a material. The following empirical relation shows the correlation of the grain size and saturated hydraulic conductivity for sand:[4]

$$K = C(d_{10})^2 \tag{3.10}$$

K: hydraulic conductivity (cm/sec)
C: constant with units of (cm.sec)$^{-1}$, and varies from 40 to 150 for most sands. C is at the low end of this range for fine, widely graded sands and C is near the high end of the range for coarse, narrowly graded sands.
d_{10}: grain diameter in centimeters such that grains this size or smaller represent 10% of the sample mass.

The constant C is varying in 40 to 150 ranges for most sands. Fine and widely graded sands are close to the low end, and coarse and narrowly graded sands have the highest C value. Kozeny–Carmen equation (equation 3.11) shows the empirical correlation for granular materials:[4]

$$K = \left(\frac{p_w g}{\mu}\right)\left(\frac{n^3}{(1-n)^2}\right)\left(\frac{(d_{50})^2}{180}\right) \tag{3.11}$$

$p_w g$: the unit weight of water units
μ: viscosity of water
n: porosity
d_{50}: the median grain diameter.

For widely graded materials, the porosity term $n^3/(1-n)^2$ is significantly smaller, as the pore size in this kind of materials (poorly sorted) is smaller than in a well sorted material with the same d_{50}. The Kozeny–Carmen equation is dimensionally consistent, so it may be used with any consistent set of units.[4]

Another form of Carman-Kozeny equation to investigate the relationship between porosity and hydraulic conductivity of field placed pervious concrete can be mentioned as follows:[12]

$$K_s = \alpha[\frac{n^3}{(1-n)^2}] \tag{3.12}$$

The factor α is defined by:

$$\alpha = \frac{gC_0}{\nu M_s} \tag{3.13}$$

g: gravitational acceleration (cm s^{-2})
v : the kinematic viscosity of water (cm^{-2} s^{-1})
M_s: specific surface area of the material (cm^{-1})
C_0: empirical constant

Previous experiments show that α = 18 can be a good estimate to relate hydraulic conductivity and porosity of the porous concrete. [12]

3.4. Runoff generation

The difference between runoff and rainfall is caused by the losses.
The losses on the paved areas can be mentioned as follow:

- Moisturizing losses
- Depressions storage
- Infiltration losses
- Evaporation

Moisturizing loss is the amount of water absorbed to roof covers and pavements in such a way that it cannot run off any more. This water can be removed just by the evaporation.
Depression storage depends on the pavement surface. For a normal paved terrain usually the values of 0.5-1.5 mm are considered.
Infiltration in pavements usually is considered zero, although it should be taken into account in porously paved surfaces. [11]

4. Clogging

4.1. Clogging process

The decrease in infiltration rate of the soil due to the reduction in soil porosity and hydraulic conductivity is described as the clogging.

Studies over the past 20 years show that clogging of the porous pavements happens between 5 and 10 years after construction[8]. Due to the clogging and consequent reduction in infiltration rate, water discharge over the pavement surface and its advantage are lost. Also the clogging particles are usually polluted, so they should be retained at the surface and cannot reach to the soil or ground water.

The process of clogging begins with sand getting caught in the surface of permeable material. At this point there is no change in infiltration rates. Then, pores located between the grains of sand become obstructed by even finer elements which can no longer move about in the structure. These fine elements may be clay particles, or come from wear of the surface itself, or be tyre particles from passing cars. The filtering capacity decreases little by little until a relatively impermeable matrix is formed. The development of clogging is therefore characterized by an increase in the quantity of materials retained on the surface and not by migration to the interior of the permeable surface. [5]

4.2. Causes of clogging in semi-arid areas

• Wind erosion

Erosion is the process of weathering of the earth's surface, usually by the action of water or wind, and transport of solids (sediments, soil, rock and other particles) and their depositions in another place. The severity of erosion depends on the quantity of material supplied by detachment and the ability of the running water or wind to carry it.

Areas with little or no vegetation, often in arid climates, where there is not sufficient rainfall, are extremely vulnerable to wind erosion. Therefore as the focus of this research is on semi arid areas wind erosion will be discussed in this chapter as the main source of dust production.

Wind erosion happens when the forces applied to the soil by wind are greater than the resistance of the soil to these forces. The forces are the function of the environmental conditions, such as climate, soil, topography and land use. Climatic variables such as temperature and precipitation have effect on wind erosion. They affect vegetation growth. In addition the presence of soil moisture can reduce the soil erodibility by wind, because wet soil has greater cohesion than dry soil and cannot be detached easily.

Erosion of the sediments by wind (Aeolian processes) is affected by the air velocity and surface sediment grain size. Wind generates shear forces on the ground surface which is expressed in terms of a drag or shear velocity. The drag velocity of wind (u*) (ms^{-1}) at a particular height above the ground surface increases with wind speed. Equation (4.1) shows the shear velocity of wind. [13],[14]

$$u^* = \frac{u_z}{5.75 \log \frac{z}{z_0}} \tag{4.1}$$

u_z : Velocity at the height of measurement (z)

Z_0 : surface roughness length, approximately equal to d/30, and d is the mean particle diameter (m)

- **Dust particle size distribution**

Three process of wind erosion include saltation, suspension and creep along the soil surface. Saltation is the process where fine particles with the size between 70-500 micro meters are lifted from the surface and follow trajectories under the influence of the air resistance and gravity. 55 to 72 percent of particle movement during wind erosion events is in saltation phase.

Suspended particles are dislodged by saltating particles and represent 3 to 10 percent of eroding particles. Wind turbulence keeps particles suspended, resulting in the transport of suspended particles for long distances before being deposited, especially for fine, dust-sized particles. In general suspended dust particles have the diameter less than 70 micro meter.

In long term suspension, which lasts several days, suspended particles may travel thousands of kilometer from the source. These particles have the upper size limit about 20 micro meter.

In short term suspension, coarser dust particles (20 micro meter<d< 70 micro meter) travel a few meter to several kilometers. Particles remain in this phase from minutes to hours.

In creep phase, which accounts for 7 to 25 percent of the soil movement, Sand-sized particles or aggregates are set in motion by the impact of saltating particles, and tend to roll or creep along the surface.

Figure (4.1) shows these three phases. [15]

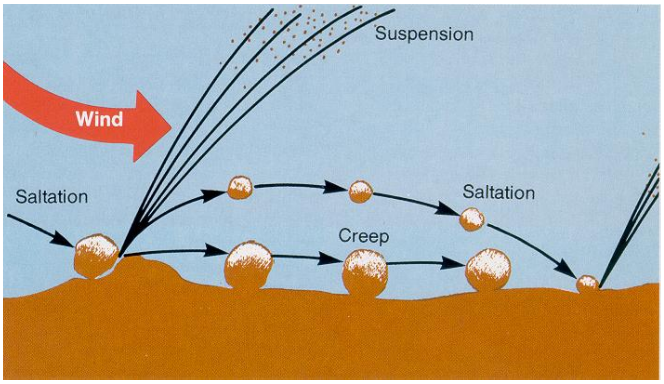


Figure (4.1) Three phase of wind erosion process

When the gravitational force is greater than the forces holding the particles in the air, the windborne sediments will deposit. This process occurs when there is decrease in wind velocity. This decrease can happen by physical barriers such as vegetation or ditches. Raindrops can also remove dust from the air.

4.3. Ways to reduce clogging of porous pavements

As it has been mentioned in chapter 2, porous pavements are very susceptible to clogging. Decrease in infiltration capacity due to the clogging in these kinds of pavements should be considered if they are demanded to use.
The best way to prevent rapid clogging in porous pavements is their application in proper location. Areas where sand and salt are applied to roadways should not be considered for porous pavements. Occasional sweeping or vacuuming of debris, pressure washing with clean water are some methods that could restore the infiltration rate of porous pavements. Besides these methods educational signs as a teaching tool for the public and as a reminder of maintenance should be used in places where porous pavements is installed.

5. Physical modeling of clogging

As it was explained in section 2.6 the porous concrete, which was used in this research, can be the proper type of porous pavement to apply in arid and semi-arid areas. For this experiment the porous concrete tiles were provided from the factory instead of designing in the lab. In this case it can be assumed that different used tiles have the same characteristics and the tests were done under the same conditions. Simple tests showed that the tiles are highly porous. Therefore just application of one tile could show the decrease in flow rate due to the clogging. So the experiment set up was designed for one tile.

Also according to section 4.2.2 suspended particles with diameter less than 20 micro meter, can travel thousand of kilometer and remain suspended for several days. As the clogging is not a rapid process this range of particle size can be considered as the clogging causes. So in order to simulate the dust particles Micro Silica (MS) was used which is available in different size distribution. Also previous researches show that it is the best alternative to reproduce the clogging effects in the laboratory experiments. [16]

5.1. Experimental setup description

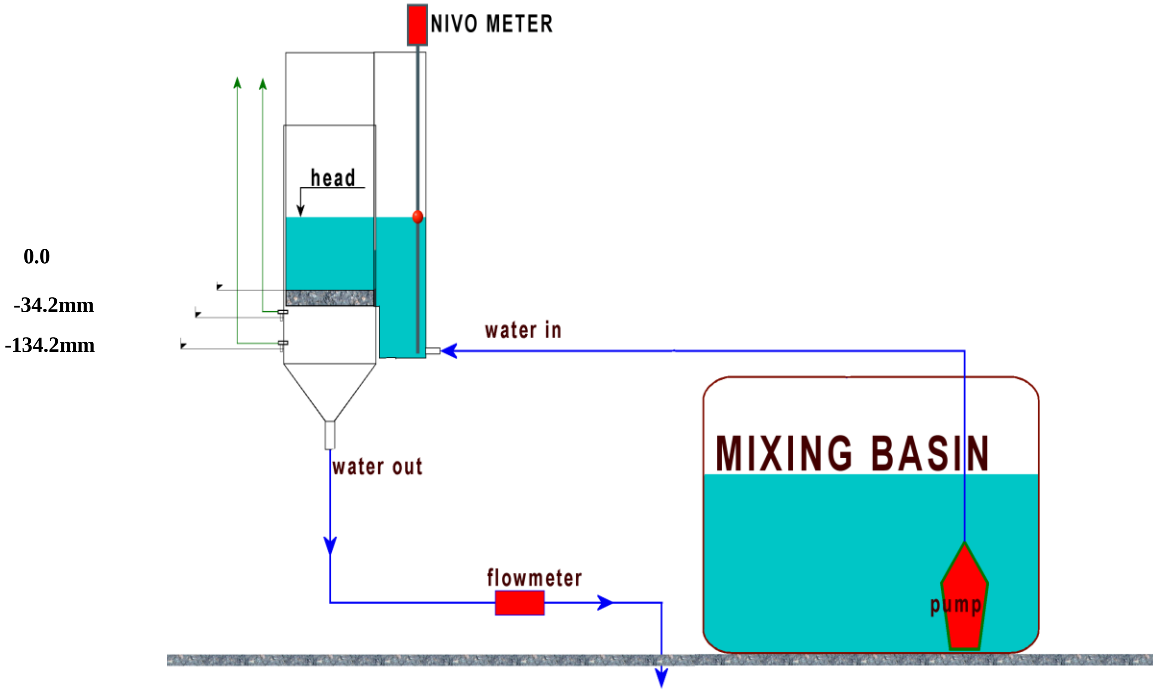


Figure (5.1) Scheme of the experimental setup

The test facility composed of the box to hold the tile, mixing basin, outflow collecting basin, sensors, pumps and flow meter. Figure 5.1 shows the scheme of the setup.
The main component of the experimental setup is composed of two wooden boxes. The smaller and interior box (Figure5.2, 5.3) with the dimensions of 0.32m*0.32m*0.9 m, holds consists of upper rectangular part with the dimensions of 0.36m*0.36m*1.2 m, and the lower pyramidal part. In order to test the effect of different sub-base material on the clogging process, a very fine steel mesh was set at 10 cm below the tile position in the outer box to carry the sub-base material (Figure5.5). As the mesh hole size is bigger than MS (M600) grains (Annex II), all the materials can pass through it and it does not disturb the clogging process. Annex III shows mesh specification (Mesh 150). Water level above the tile, water pressure under the tile and also under the sub-base are measured and recorded by sensors which are connected to the computer.

Figure (5.2) Interior box

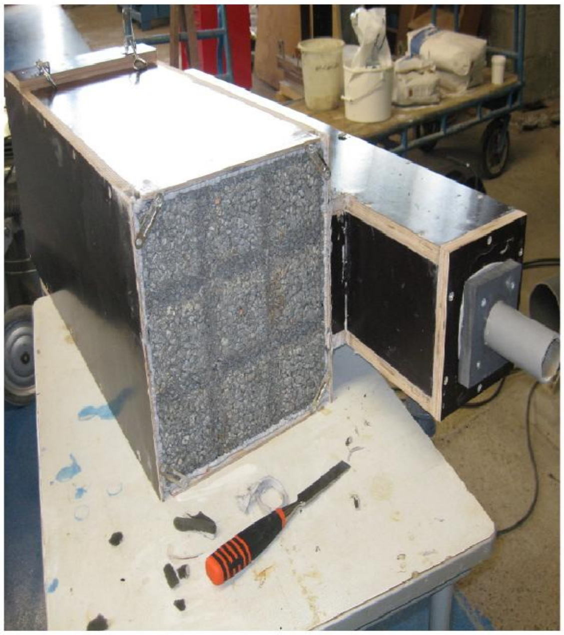


Figure (5.3) Tile inside the box

Figure (5.4) Outer box

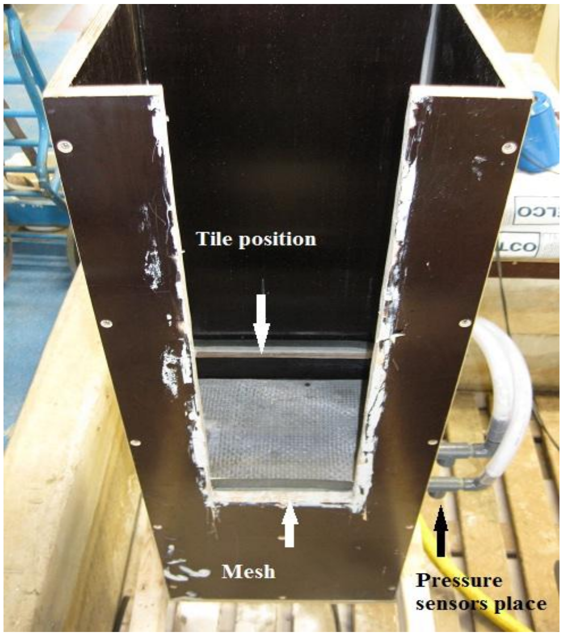


Figure (5.5) Tile, Mesh and Pressure sensors positions in outer box

Figure (5.6) shows the interior box inside the outer box. By designing the setup in this way it is possible to test the effect of various sub-bases and use a new tile for each test.

Figure (5.6) Setup after placing the interior box inside the outer one

The other part of the test facility is the mixing basin (Figure5.7). MS is mixed with water in the basin by the mixer with the speed of 7 rps. Then the mixed water is pumped above the tile. As the pump has a regulator it is possible to keep the head at a desired constant level.

The discharged water through the tile is measured with the digital flow meter. Two different flow-meters were used in this experiment for different cases.

In order to reuse the mixed water, the outflow is collected in another basin and pumped back to the mixing basin.

Figure (5.7) Mixing basin and mixer

Figure (5.8) shows all parts of the experimental setup.

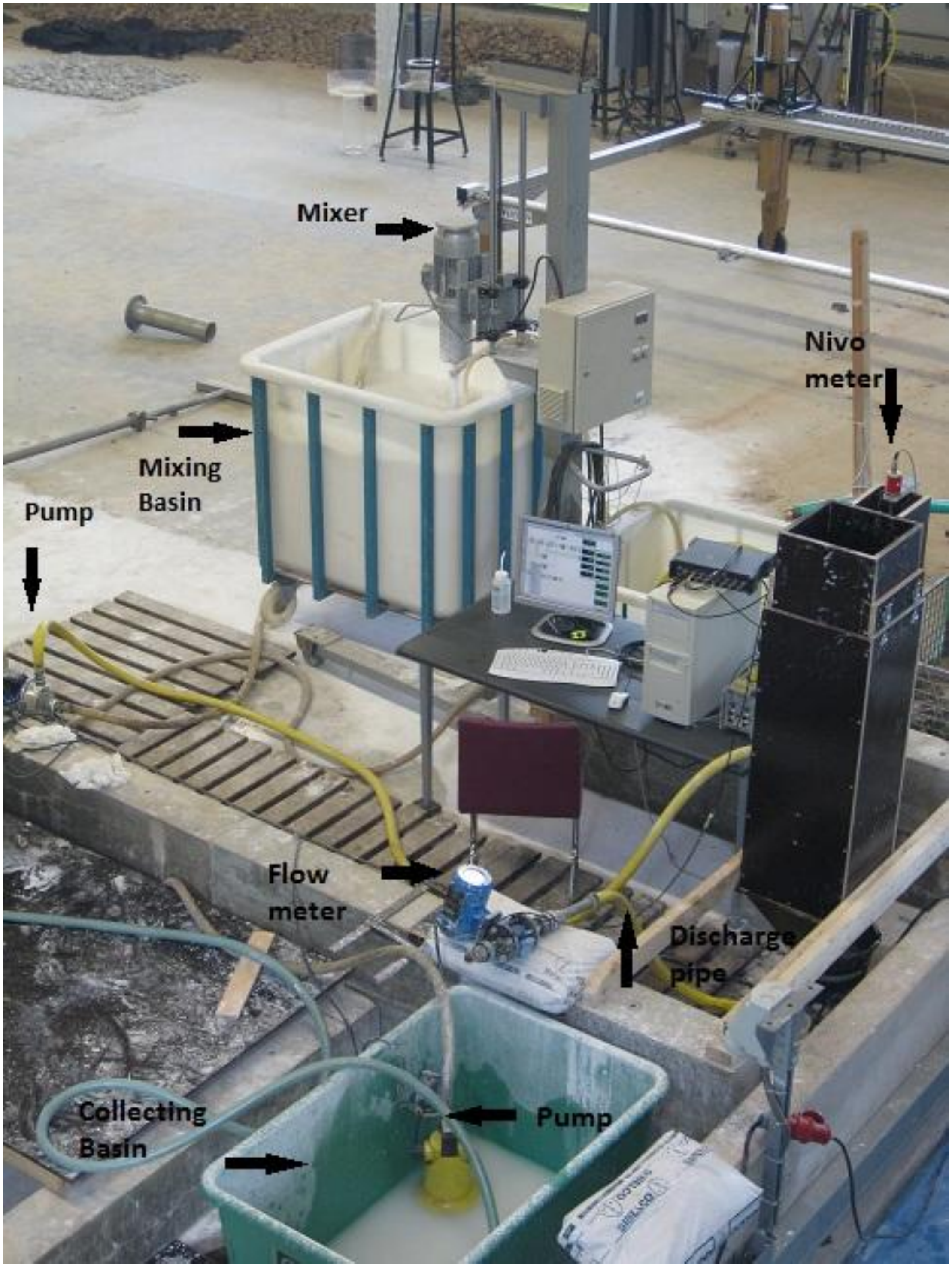


Figure (5.8) Experimental set up

5.2. Experiment description

Preparation of the tiles

The experiment was started by washing and drying the purchased tiles from the factory as follows:

- Washing the tiles

In order to remove any deposited sediments in the pores of the tiles, due to the replacement in the factory or probable erosion of the tile surface by putting them on each other during replacement, the tiles were washed by water pressure (30 bars) to clean all the tile pores.

- Drying the tiles with air pressure(8 bar)

After washing and in order to dry the tiles for some measurements, such as porosity, as the cement/water ratio and water content of the tiles after washing was not available, the proper temperature and time for drying by oven could not be estimated. So to prevent any damage and creating micro cracks into the tiles, drying was done by the air pressure and after that the tiles were left in normal room temperature for some days to dry completely. Comparison of the tile weight before and after washing showed that they got dry properly.

Measuring the porosity

As no information about the tile was provided by the factory, the next step of the experiment was measuring the porosity of the tiles. Totally 10 tiles were used for checking the behavior of the setup and also the tests, but 4 of them were weighted which results showed that it can be assumed all of them have the same characteristics.
According to the definition of the porosity, the ratio of the volume of the pores to the total volume of the material is called porosity. Due to the non-homogenous shape of the tile, measuring the bulk volume of the tile was difficult by common methods such as measuring the dimensions or immersion the tile into the water. Also cutting the tile in a homogenous shape was not practical, as a result of the large grains in the tile. So the gaps of the tile were filled in by clay, and by calculating the volumes of the used clay, the volume of the gaps in the tile were calculated.

Figure (5.9), filling the gaps of the tile with clay to measure the porosity

- Calculating the volume of the clay:

Weight of the used clay to filling the gaps: 0.354 kg

Measuring the density of the clay:
Dry weight of piece of clay: 0.091 kg
Weight of the clay in water: 0.033 kg
Water temperature: 19° C
Water density at 19° C: 998 kg/m^3
The decrease in the weight of the clay= the weight of the replaced water with the same volume of the clay
$(0.091-0.033) * g = \rho vg$
$0.058=998 * v$
$v= 5.81 * 10^{-5}\ m^3$
$\rho= m/v = 0.091/ 5.81 * 10^{-5}= 1566.26\ kg/ m^3$

Volume of the used clay for filling the gaps:

$\rho= m/v$, $m= 0.354$ kg, $\rho= 1566.26\ kg/ m^3$
$v= 2.26 * 10^{-4}\ m^3$

- Calculating the bulk volume of the tile:

Average thickness of the tile: 3.42 cm
The dimension of the edges: 8mm * 4mm
Bulk volume of the tile: $0.3*0.3*0.0342= 3.078*10^{-3}\ m^3$
Volume of the edges: $0.008*0.004*0.3*4= 3.84*10^{-5}\ m^3$
Volume of the gaps**:** $2.26 * 10^{-4}\ m^3$
Net volume of the tile:
$3.078*10^{-3} – (3.84*10^{-5} + 2.26 * 10^{-4}) = 2.81*10^{-3}\ m^3$

- Measuring the tile weight in water:

For measuring the weight in water, at first the tile was put in a bucket and then the air of the bucket was vacuumed, to be sure that all the pores are filled with water, then the tile was weighted. Table (5.1) shows the dry and wet weight of four tiles.

Table (5.1) Dry weight and wet weight of the tiles

Tile Number	Dry weight After Washing (kg)	Weight In Water (kg)
1	5.791	3.415
2	5.643	3.386
3	5.804	3.428
4	5.834	3.446

The below calculation was done for one tile to measure the porosity:

Dry weight:	5.643 kg
Weight in water:	3.386 kg
Decrease in the weight:	2.257 kg

- **Real volume:**

$2.257*g= 998* v*g$,
$v= 2.26*10^{-3}\ m^3$

- **Porosity:**

$n= Vv / V_t$, $Vv = 2.81*10^{-3} – 2.26*10^{-3} = 0.55* 10^{-3}$ m
$n= 0.55* 10^{-3}/ 2.81*10^{-3} = 19.57$ %

The measured porosity shows that the tile is highly porous; Figure (5.10) shows the flow through the tile.

Figure (5.10) Flow through the tile

- Amount of required sediment for clogging the tile:

For simulating the clogging process, the micro silica M600 was used, with almost 95% particles less than 20 μm, and density of 2650 kg/m^3. The required MS to clog one tile can be calculated as below:

Vv= $0.55 * 10^{-3}$ m^3
m= ρ * v, m= $2650* 0.55*10^{-3}$ = 1.45 kg

- **Estimating the flow through the tile:**

Before connecting the sensors and also flow meter to the model, the flow through the tile was estimated .At different heads, the water that passed the tile in 10 seconds was weighted and the maximum flow through the tile was calculated about 1 lit/ seconds.
Table (5.2) shows the result of this test.

Table (5.2) Flow estimation through the tile

Head (cm)	Initial weight (kg)	Final weight (kg)	Difference in Weight (kg)	Flow (lit/sec)
22	12.3	21.5	9.2	0.92
40	45.3	56.4	11.1	1.11

Calibration of the mixing basin

In order to find the volume and weight of water at different depth of the basin, the basin was calibrated .At first the empty basin was weighted, then after adding about 100kg water to it, the depth of water at a certain point was measured. Table (5.3) shows the result of this measurement.

Table (5.3) mixing basin calibration

Measuring state	Weight (kg)	Difference in weight (kg)	Water depth (cm)	Depth difference (cm)	Difference In Volume (lit)
Empty basin	132.2				
Filled basin (1)	232.2	100	9.3	9.3	100
Filled basin (2)	332.4	100.2	19	9.7	100.2
Filled basin (3)	432	99.6	27.5	8.5	99.6
Filled basin (4)	532	100	37	9.5	100
Average (1:4)		99.93		9.23	99.93

In order to estimate the change of volume with depth, the average of weight and depth was considered. According to the table (5.3) every 9.2 centimeter of water depth has the volume of about 100 lit.

Testing the pump capacity

At the beginning of the experiment the pump with regulator was not available. So the normal gravity pump was used for the first days of testing the model.

The pump capacity should be tested to find out whether it is practical for the experiment or not? By using the pump to discharge water, in one minute the water depth had 7 cm decrease. So the pump capacity can be estimated as follows:

100 lit (water) ~ 9.23 cm ⟹ 7cm ~75.84 lit ⟹
Pump capacity: 1.26 lit/sec

As the maximum flow that can pass through the pavement is about 1 lit/s, the pump capacity is enough for the tile, because it can provide 1 lit/s flow.

- **Test the clogging**

In order to test the clogging behavior of the tile two major steps were taken: assessment of the setup behavior with MS (M6.1) and test with MS (M600 and M6.1).

First of all to check whether fine grains like MS will be washed through the tile or not, another type of MS which is coarser than M600 was used (M6.1). For this case two different concentrations under the same head were tested.

Afterwards the main tests with MS (M600) were done. This step includes three parts: test with two different sub-base and tile without sub-base. For each part two different sediment concentrations were used. Test with the defined concentration was done continuously for three hours under three different heads.

These three steps will be explained in the next sections.

- **Preparation for the tests:**

Although every test was done in three hours, the preparation of each one took about two days, which was not only very time consuming but also very difficult to do. That includes taking out the used tile, washing the setup, replacement of a new tile, calibration the sensors and flow meter, emptying and washing the mixing basin in case of changing the type of MS.

Although the best condition to assess the clogging of the tile is application of a clean and new tile, but due to the time limitation the tile was changed only when sediment concentration and sub-base was different. Test the water head effect was done continuously with the same tile.

After each test and for changing the tile, all the connected pipes and sensors should be disconnected from the model. Then the glues which were used to close the open joints between two boxes had to be cut. For taking out the interior box the crane was used with the help of two persons. As the interior part was heavy and was partly stuck to the outer box, it was difficult to take it out and caused some damages to the setup. So usually before the next test, it was needed to repair the setup to prevent leakage from the broken parts. Figure (5.11) shows taking out the box by the crane.

Figure (5.11) Taking out the interior box by crane

After separating two boxes, and taking out the old tile from the interior box, both parts were washed completely. Especially the outer box was washed with water pressure to clean the mesh completely. Figure (5.12) and (5.13) shows two separate boxes after washing.

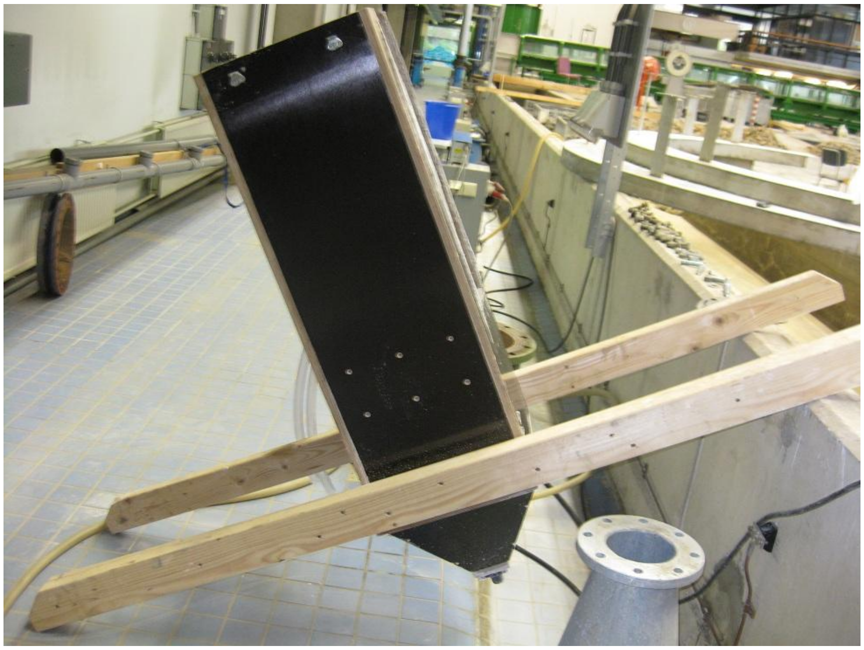


Figure (5.12) Outer box after washing

Figure (5.13) Interior box after washing

The next day, after the boxes dried, the tile could be placed. The edges of the tile were glued to the box to be sure that the measured flow is just through the pores. Figure (5.14) shows the new tile after replacement.

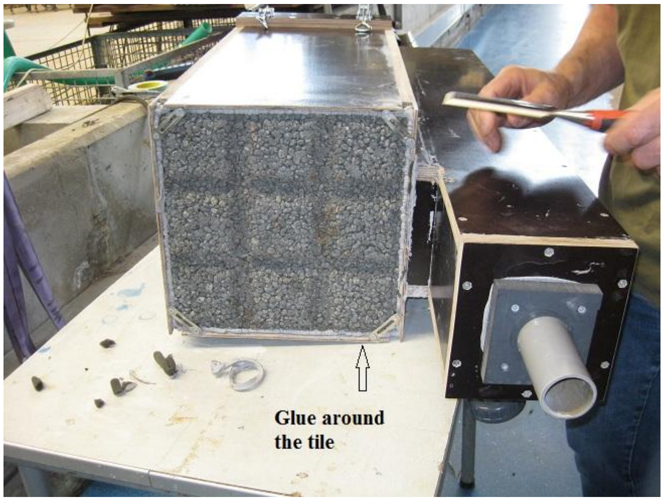


Figure (5.14) the new replaced tile

A few hours later, when the glue dried, the interior box was put inside the outer one, and all the open joints was glued, which took one day to dry. In the meantime, the discharge pipe was washed by water pressure or sometimes was changed completely. Because after stopping the test, the sediments were settled in the pipe and it got blocked.

Next day when the setup dried and ready for the test, at first the calibration of the flow meter and pressure sensors were checked and usually were changed again. The calibration of the sensors should be changed for different tests, such as sand sub-base or stone sub-base.

And sometimes even when the conditions of the tests were the same (same sub-base) the calibration of the pressure sensors should be done again which took a long time. In addition for testing various sub-bases, different flow meters were needed and calibrated. This phase of preparation took half a day or even sometimes two or three days, especially after disconnecting all devises for cleaning after construction in the lab. Moreover after a while one of the pressure sensors was broken down and replaced by a new one.

Before recording the data, as it was necessary to be sure that there is no air in the system, the water head was set on higher level and then gradually decreased to the lower level, or the system was filled by clean water from the bottom to the top, through the outflow point of the flow meter.

• Test with clean water

At the beginning of each test, the experiment was started with clean water to find the Discharge-Head equation for different heads. The graphs of the flux and calculated resistance for each test will be explained in the result section.

• Assessment of the setup behavior

As the MS (M600) is a very fine material, there were some possibilities that it would be washed through the tile. So at first it was decided to run the tests with another type of MS (M6.1) with 90% grains smaller than 95µm. Annex IV shows the grain size distribution. Therefore as this kind of material could be washed, then M600 with finer grains will definitely be washed as well.

For this purpose two different concentrations of M6.1 (0.013kg/lit and 0.039 kg/lit) were used and pumped above the tile for one hour under the head of 20 cm. As it was mentioned before, at the beginning of the experiment, the pump with regulator was not available. So keeping the constant head above the tile was done manually. For this case, another discharge pipe was located at the bottom of the interior box, and full of water should be bended and water level should be kept constant by reading the head from the computer. After some minutes from running the test, due to the rapid clogging of the tile, water level increased so fast. Also the full discharge pipe was very heavy to bend it easily and quickly. Although keeping the constant head above the tile was difficult but the fluctuations in water level was not more than one centimeter. Figure (5.15) shows the discharge pipe for regulation.

Figure (5.15) Water level regulation by the pipe

- **Test with M600**

As mentioned before, in order to assess different factors on the clogging rate, different concentrations, sub-base and heads were tested. For these tests pump with regulator was used. Figure (5.16) shows the matrix of these tests.

Sub-base	**MS(M600) Concentration**	**Individual test with one tile**		
		Head and Duration		
		150mm/ 1 hour	**300mm/ 1hour**	**600mm/ 1 hour**
Tile without sub-base	0.05 kg/lit			
	0.1 kg/lit			
Tile with sand sub-base	0.05 kg/lit			
	0.1 kg/lit			
Tile with stone sub-base	0.05 kg/lit			
	0.1 kg/lit			

Figure (5.16) The test matrix of porous concrete tile with M600

After testing the tile without any sub-base and in order to assess rate of clogging by different sub-bases, the 10 cm free space under the tile was filled in with sand and stone.

Figure (5.17) shows using sand as the sub-base. Annex V shows sand grain size distribution that was used as the sub-base.

Figure (5.17) Application of sand as the sub-base

Figure (5.18) shows the MS at the interface of the sub-base and the tile after the test.

Figure (5.18) Interface of the sand sub-base after test

As a result of application of large stones for test (2-5 inches), the void space in the sub-base does not have any significant effect on the clogging process. Therefore and also due to the time limitation the test with stone sub-base and concentration of 0.05 kg/lit was not done.
Figure (5.19) shows the interface of the stone and tile after the test.

Figure (5.19) Interface of the stone sub-base after test

• Repeated tests with sand sub-base:

Due to some technical problems that happened during the tests, the result of tests with sand sub-base was not acceptable. Therefore these two tests were repeated again. But after the repeat just the result of test with 0.05kg/lit was accepted. In Annex VI some explanation about reasons that led to wrong tests has been provided.

• Test with M6.1

In order to compare the effect of sediment grain size on clogging process, it was decided to do one test with M6.1 under the same condition with tests of M600. This test was done with sand sub-base and 0.05 kg/lit concentration. For this test, as the hole size of the former mesh was smaller than M6.1 grain size, which could disturb the clogging, the mesh was replaced. The applied mesh size is shown in Annex III (Mesh 50). But the results did not have a logical trend. Therefore they are not included in the result part. The flow in this test was so small from the beginning of the test due to the rapid clogging of the tile by larger particles than M600. Figure (5.20) shows the small flow through the tile.

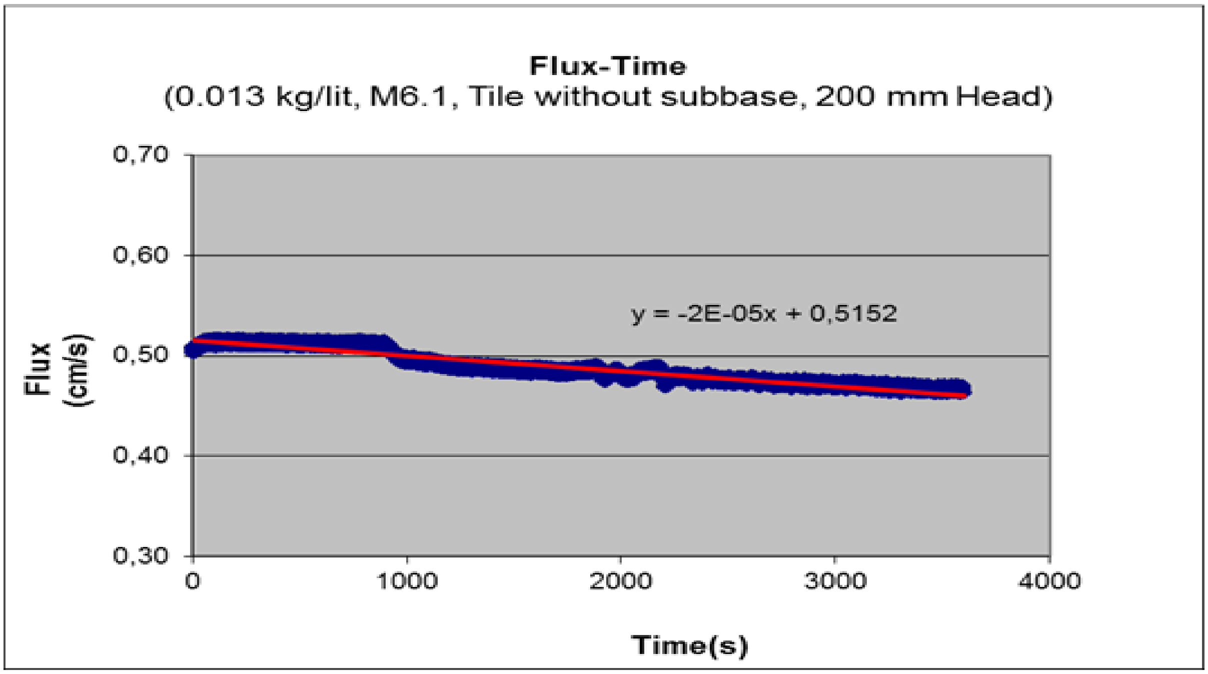
Figure (5.20) Small flow in test with M6.1, sand sub-base

6. Results and discussion

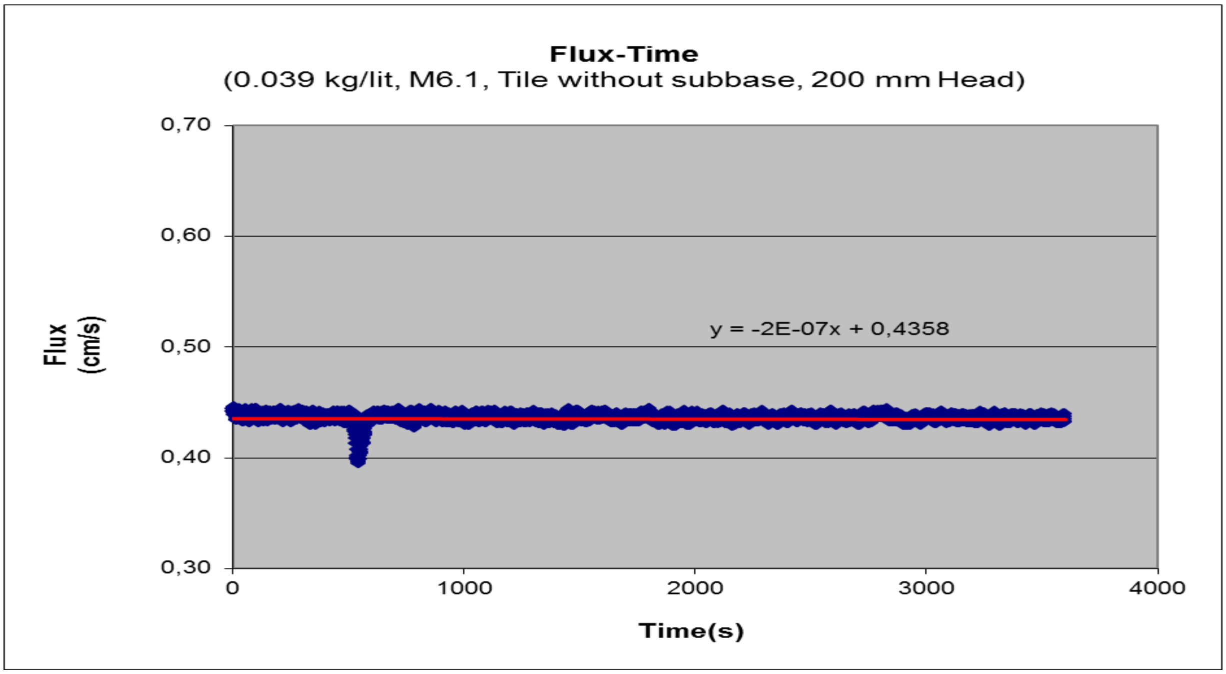
6.1. results:

6.1.1. Test the behavior of the system with M6.1

- ○ **Concentration of 0.013 kg/lit**



- ○ **Concentration of 0.039 kg/lit**



These two tests were done to see the behavior of the system. As it can be observed from the graphs the flow is reducing over the time, which shows that the sediments were not washed completely through the tile and the tile was clogged by MS.

Comparison of two graphs shows that in test with the higher concentration the intercept of the flux is lower than the test with lower concentration. This shows more and rapid clogging in case of higher concentration which leads to reduction in flux through the tile.

6.1.2. Test with M600 and without sub-base

- **Flux-Head drop, test with clean water:**

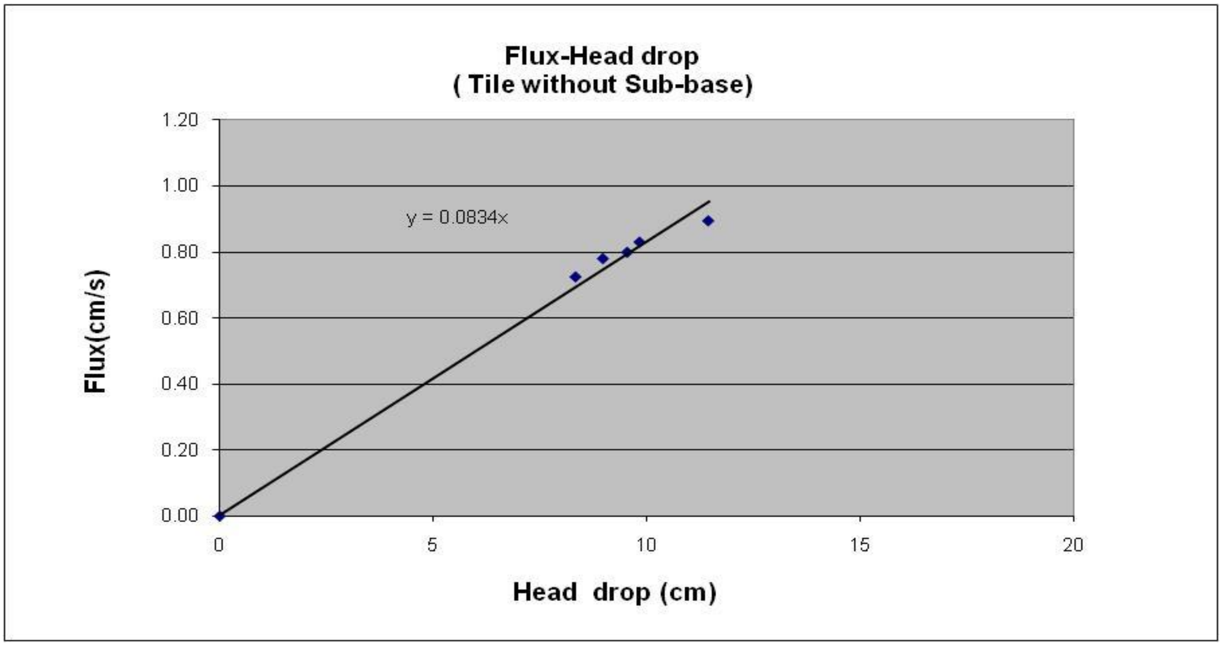


Figure (6.1), Flux-Head drop through the tile, Test with clean water

The graph shows the relation between flux and head drop through the tile. Results seem to follow a linear trend; only the maximum point is slightly diverted from the linear trend. Also the deviation is not so significant, and overall trend can be still considered as consistent. But higher deviations, under higher water levels, could be explained by changing flow regime from laminar to turbulent. While changing the flow to turbulent, the hydraulic conductivity will not be constant and Darcy's law is not valid anymore. Also by changing the flow regime from laminar to turbulent the pressure gradient will change proportional to the square of velocity. Higher velocity in turbulent flow causes more eddies and turbulence in the fluid and consequently more resistance for the flow to overcome and more decrease in the pressure.

- **Hydraulic conductivity of the tile**

As the porosity of the tile was calculated about 19.57% the hydraulic conductivity of the tile under laminar flow condition and in the direction of the flow can be calculated as below:
According to the equation (3.11)

$$K = \left(\frac{p_w g}{\mu}\right)\left(\frac{n^3}{(1-n)^2}\right)\left(\frac{(d_{50})^2}{180}\right)$$

Pw g : the unit weight of water = 9810 (N/m^3)
μ: viscosity of water = $1.002*10^{-3}$ ($N\ s/m^2$)
n: porosity : 19.57 %
d_{50}: the median grain diameter: $6.5*10^{-3}$ m
➔ $K=2.66*10^{-2}$ m/s

Also by applying the equation (3.12) hydraulic conductivity will be calculated as follows:

$$K_s = \alpha[\frac{n^3}{(1-n)^2}]$$

By considering α=18 :
K_s= 2.08*10^{-3} m/s

This is very lower in compare of 2.66*10^{-2} m/s.

- **Comparison the of calculated hydraulic conductivity with the experiment:**

As it was explained in chapter 3, in laminar flows specific discharge (discharge per cross-sectional area) is proportional to the hydraulic gradient with a constant ratio as below:

$$\frac{q_x}{(dh/dx)} = -K$$

q_x: specific discharge
dh: head drop
dx: tile thickness = 3.42cm

The slope of the graph (0.0834) shows the ratio of (q_x/dh), therefore the value of hydraulic conductivity will be 2.8*10^{-3} m/s.
Comparison of the three values of hydraulic conductivity shows that the calculated value from the equation (3.11) has a big difference with the other two (2.66*10^{-2} m/s vs 2.08*10^{-3} and 2.8*10^{-3} m/s). Over estimation of the grain size by the factory can be one reason for this difference. The tiles were used in the experiment were a commercial product and the grading has not been carried out very accurately.

- **Boundary for laminar and turbulent flow**

To find the boundary for the laminar flow, as it was mentioned in chapter 3, Reynolds number should be less than some values between 1 and 10.
As there is no data available about the pore size of the concrete tile, it is not possible to calculate the boundary for the flux that the flow through the tile has a laminar regime. But figure (6.1) shows that the flow through the tile is more close to the laminar under lower pressure drops.
In order to find the deviation of the flow from laminar to turbulent from the graph, at first it was assumed that the flow under lower water levels is laminar, producing a linear relation as shown in figure (6.1). However, if the flow would be turbulent we would expect a quadratic relation; that is why a quadratic function was fitted through the same data-set. The results are shown in figure (6.2). When forcing this function through (0, 0) and adding a fictive value for flux of 1 cm/s, the curve shows a good fit. This could be an indication that the change from laminar to turbulent flow occurs at a flux between 0.8 and 0.85 cm/s.

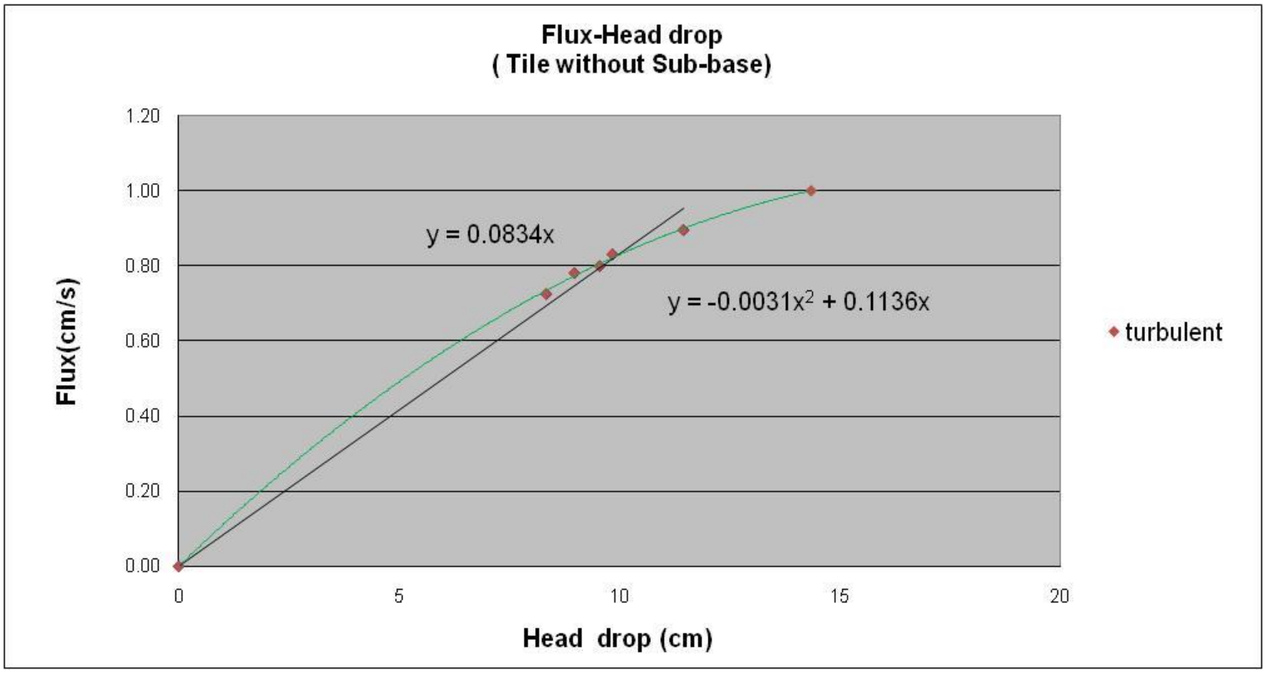
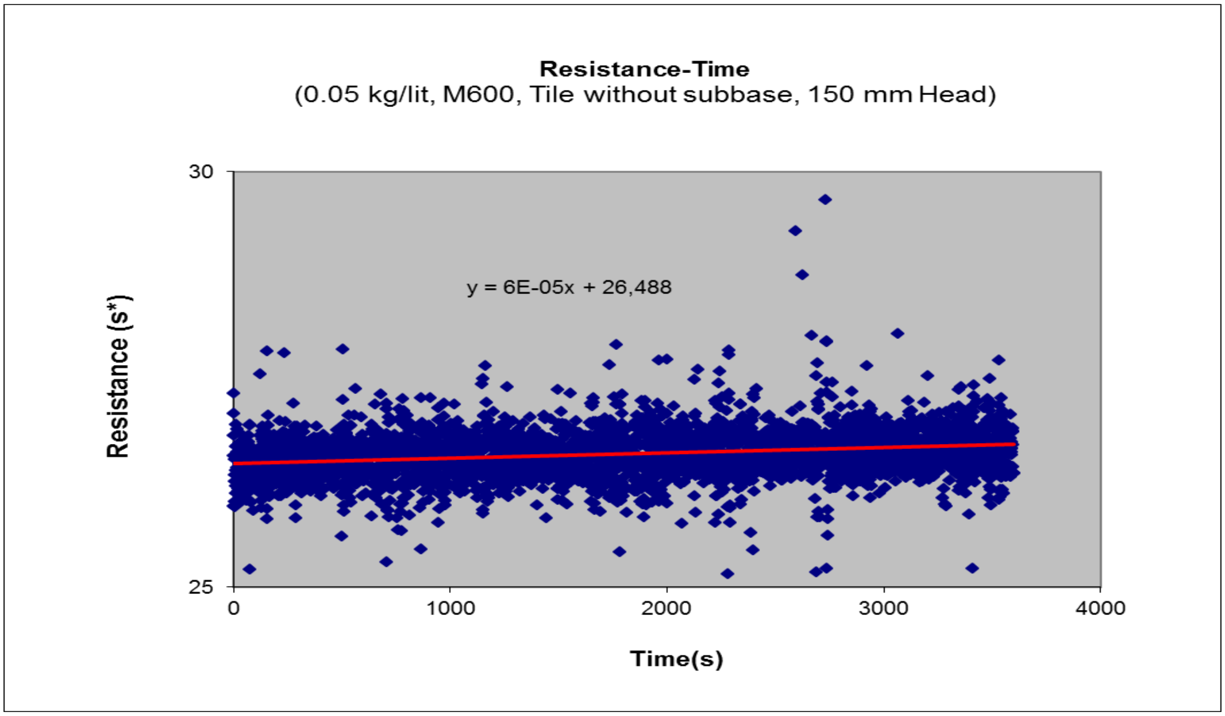
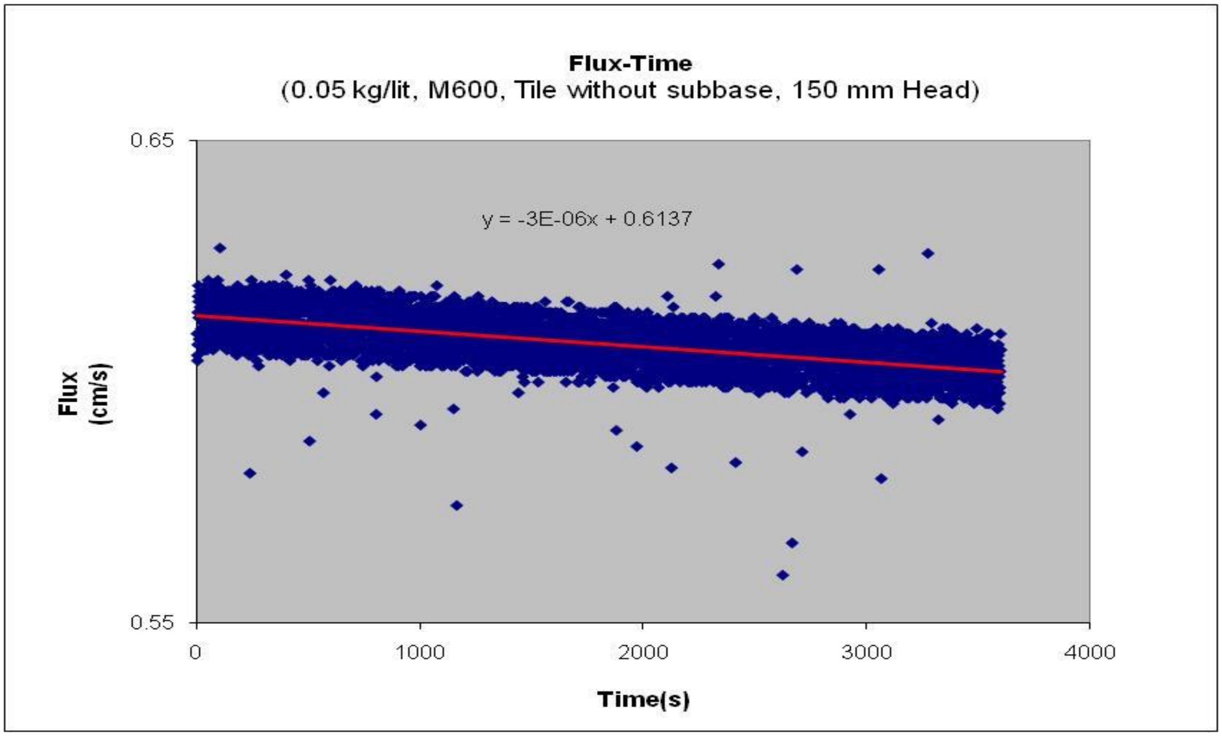


Figure (6.2), Flux-Head drop through the tile, Deviation from laminar to turbulent flow

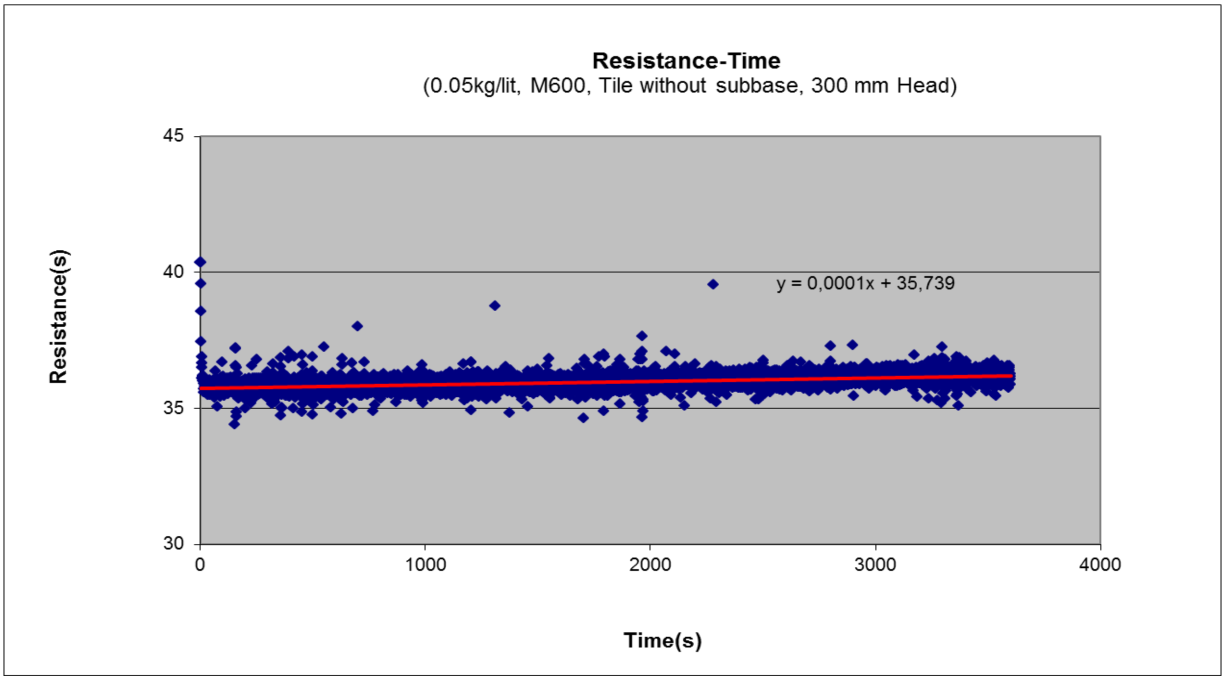
- **Concentration of 0.05 kg/lit**
    - **150 mm Head**

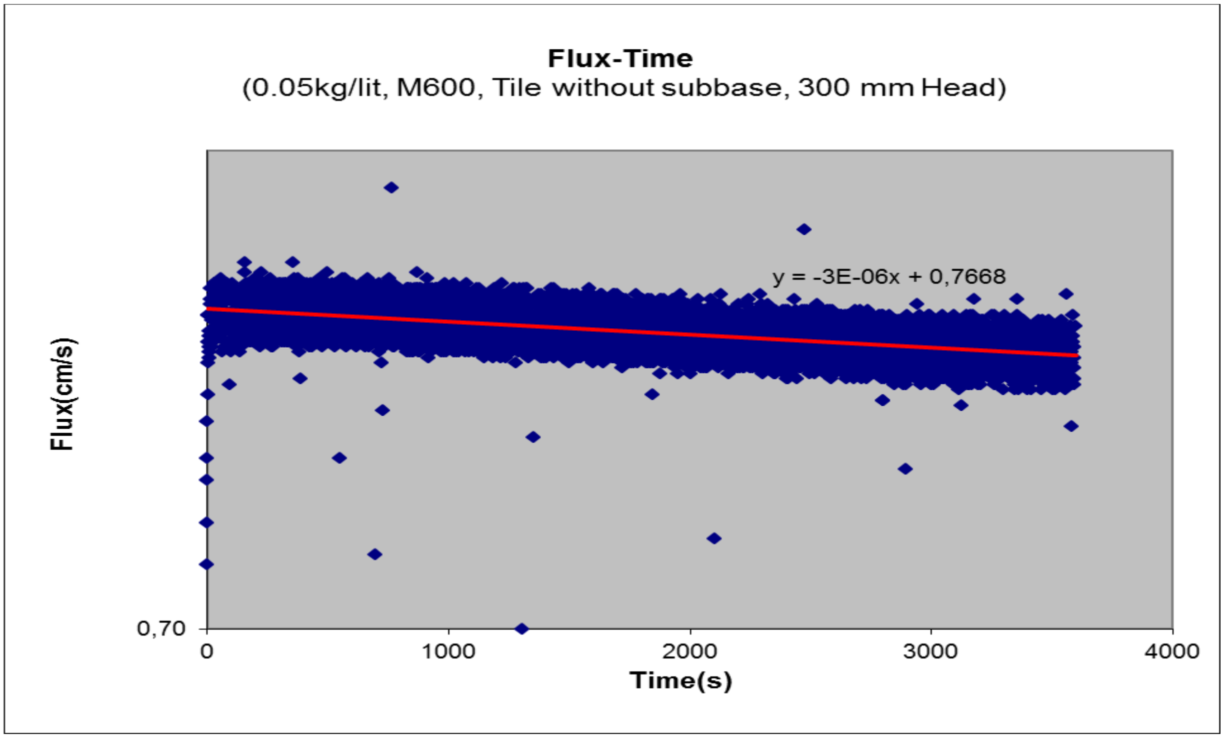




The graphs show the reduction in flux over the time and increase in resistance. Due to the clogging of the tile, less pores is available for flow which reduces conductivity and also makes more resistance through the flow.

- ### 300mm Head

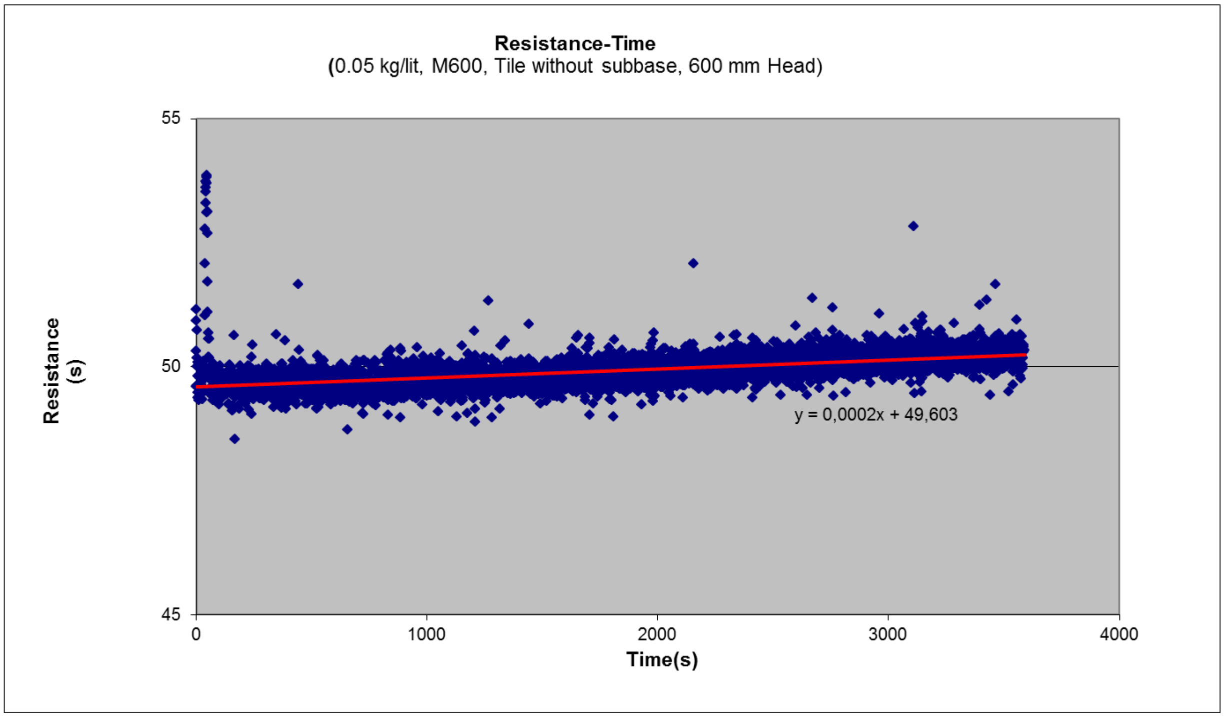

Resistance-Time
(0.05kg/lit, M600, Tile without subbase, 300 mm Head)
Resistance(s)
45
40
35
30
0
1000
2000
3000
4000
Time(s)
y = 0,0001x + 35,739


Flux-Time
(0.05kg/lit, M600, Tile without subbase, 300 mm Head)
Flux(cm/s)
0,70
0
1000
2000
3000
4000
Time(s)
y = -3E-06x + 0,7668

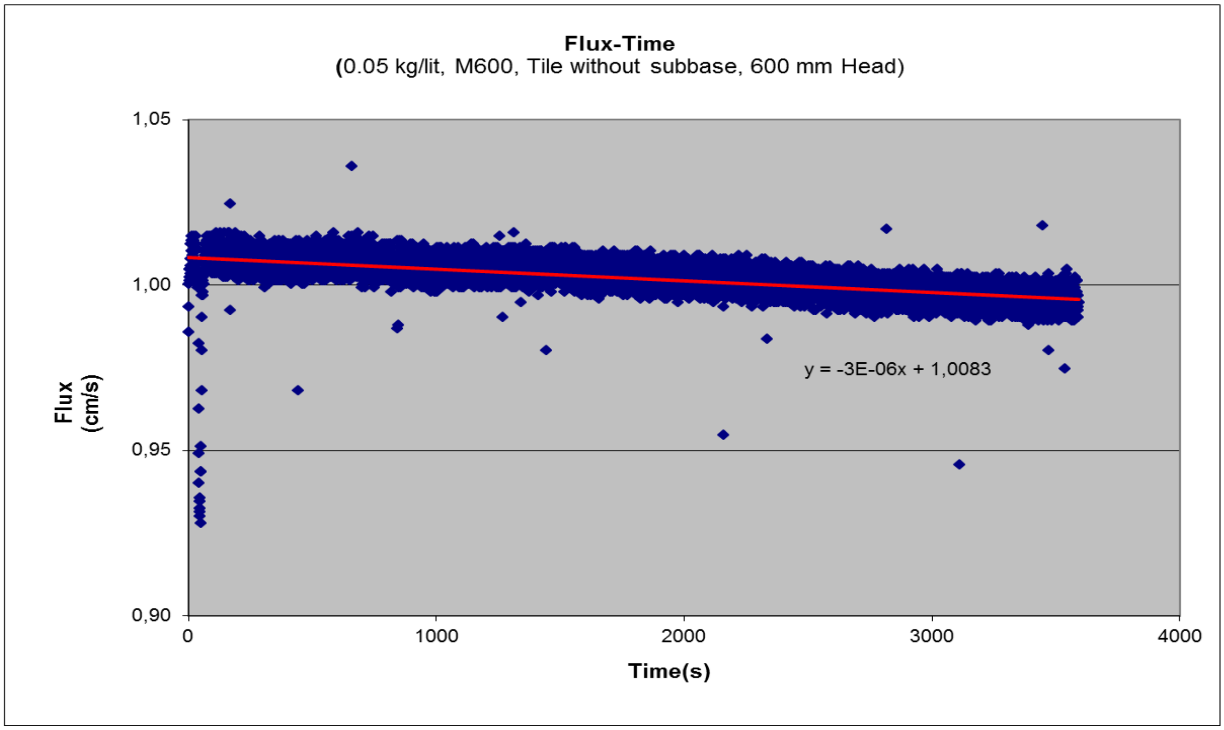
The graphs show the reduction in flow through the tile and increase in resistance over the time. Comparison with the head of 150mm shows the increase in the flux intercept due to the higher water pressure above the tile. But the rate of flux reduction over the time in both cases is the same.

Also increase in the water level led to the increase in the resistance intercept, although the flux under higher water level is higher, but the decrease in pressure in 300mm water level is higher than 150mm, which shows by increase in the water level the velocity through the tile has increased which causes more resistance for the flow to overcome and consequently more pressure drop.

○ 600 mm Head



Resistance-Time
(0.05 kg/lit, M600, Tile without subbase, 600 mm Head)
Resistance (s)
55
50
45
0
1000
2000
3000
4000
Time(s)
y = 0,0002x + 49,603



Flux-Time
(0.05 kg/lit, M600, Tile without subbase, 600 mm Head)
Flux (cm/s)
1,05
1,00
0,95
0,90
0
1000
2000
3000
4000
Time(s)
y = -3E-06x + 1,0083

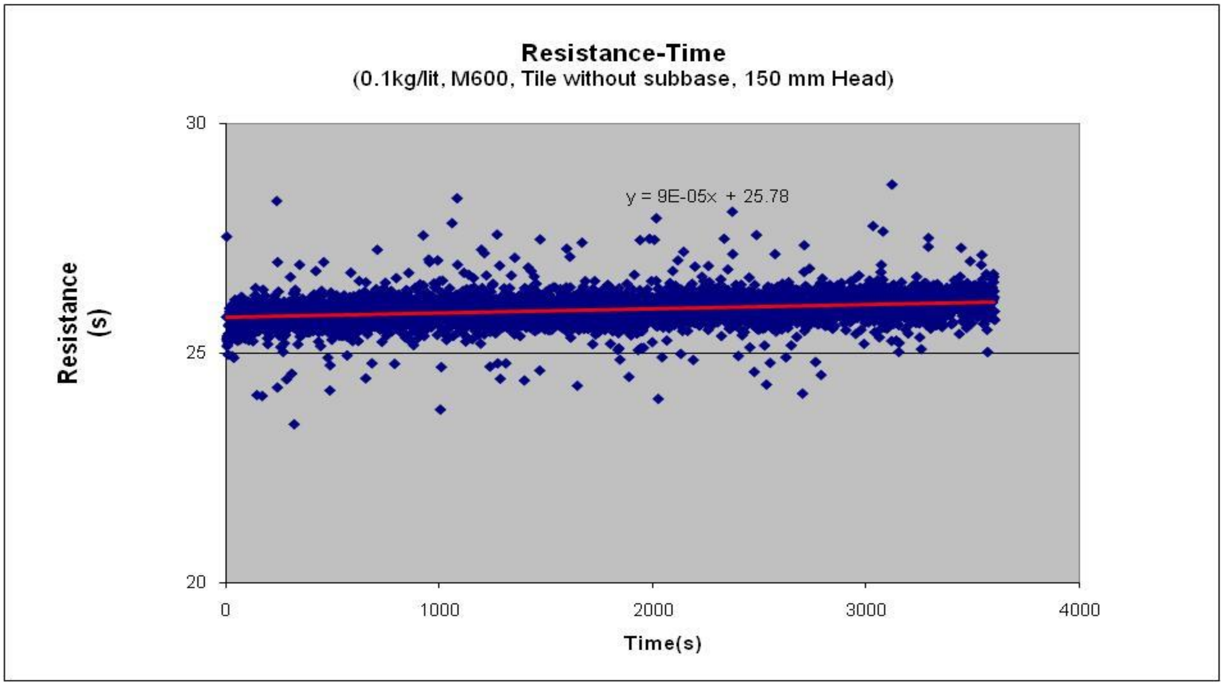
As it is clear from all graphs, under all water levels the flow through the tile is decreasing and the resistance is increasing by time.

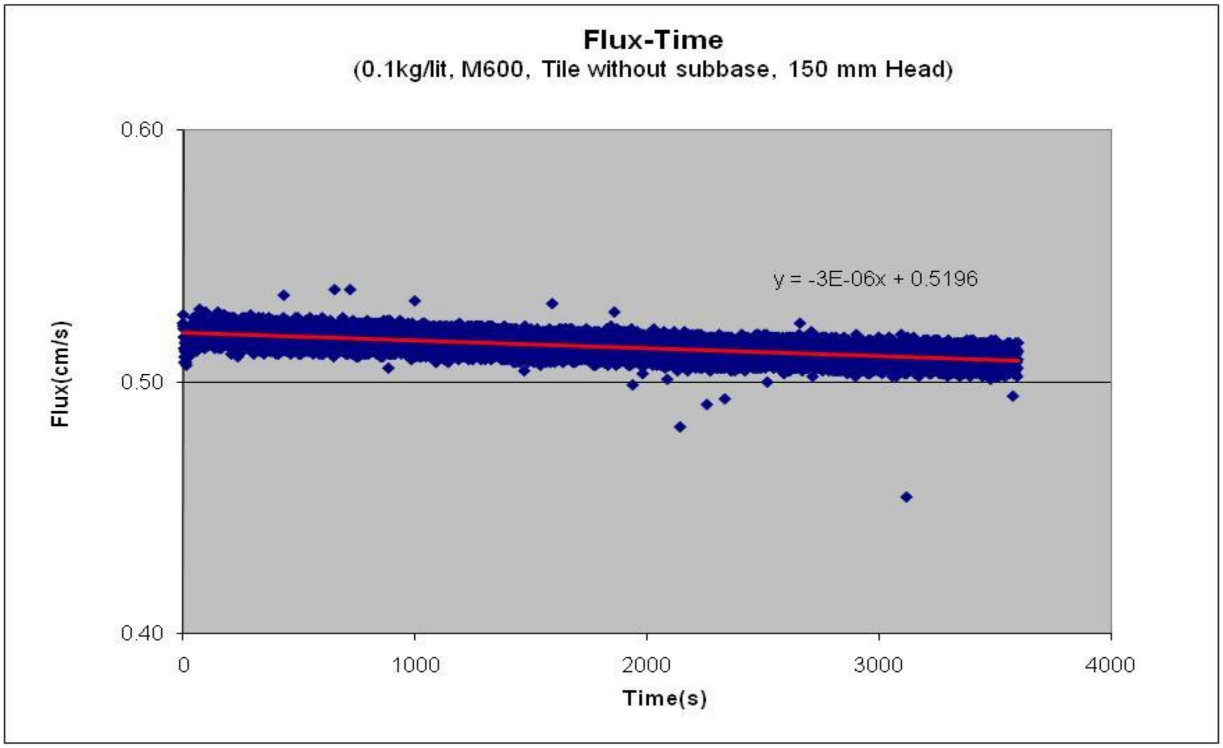
Under higher water level and higher pressure the flow is also higher and the rate of decrease in flow is the same under different heads.

Under higher water levels, the resistance is also higher and the rate of increase in resistance is also higher over the time.

Although in higher water levels the flow is increasing but the resistance is also increasing. This shows that under higher water level the magnitude of pressure drop is higher than increase in flow. By increasing the head, the flow velocity will increase as well which causes more eddies and turbulence in the fluid, and consequently more resistance for the flow to overcome. Also clogging in the tile is another reason for this pressure drop. This will lead to the higher pressure drop than increase in the flow and consequently more resistance in higher water levels.

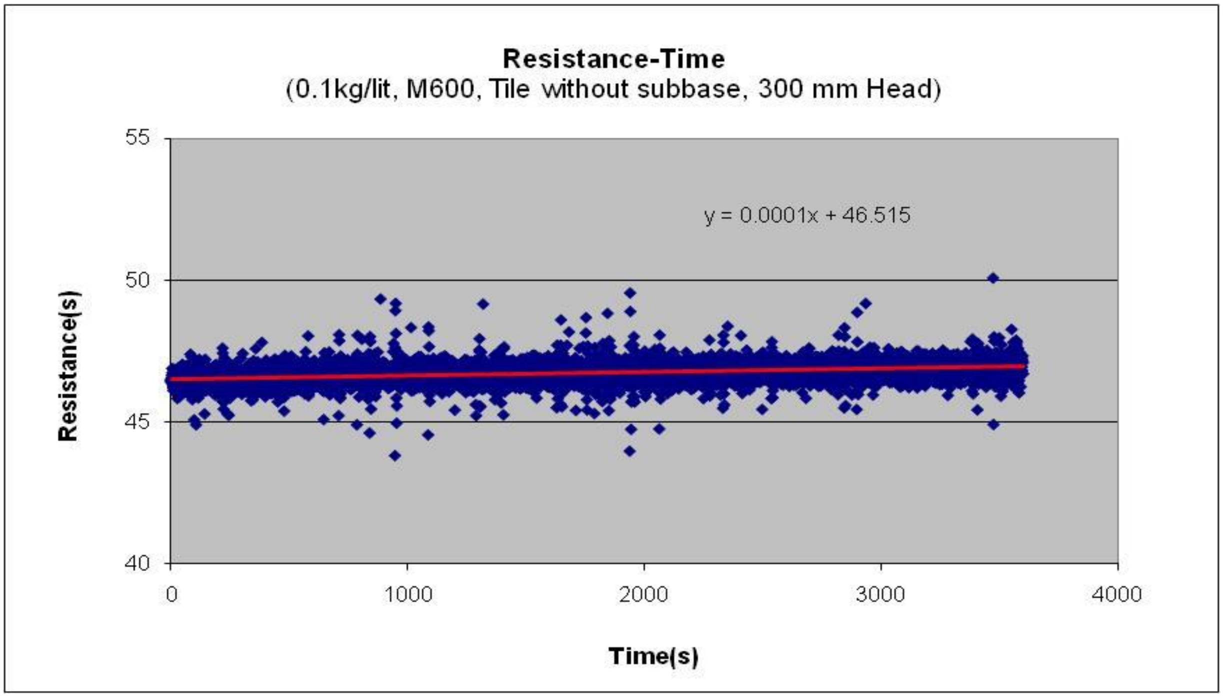
- **Concentration of 0.1 kg/lit**
    - **150 mm Head**

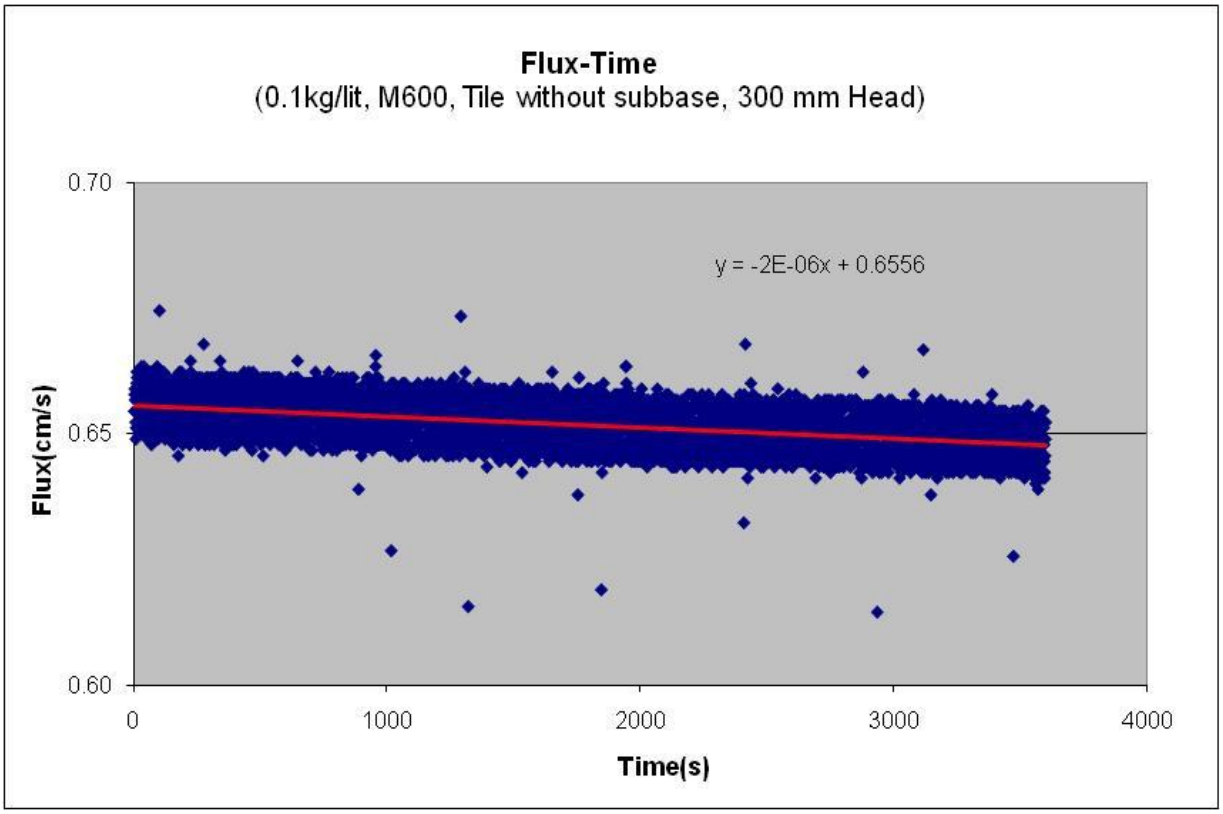




Like the test with the concentration of 0.05 kg/lit, the graphs show the reduction in flux and increase in the resistance over the time. By increase the clogging and reduction in conductivity the resistance will increase over the time.

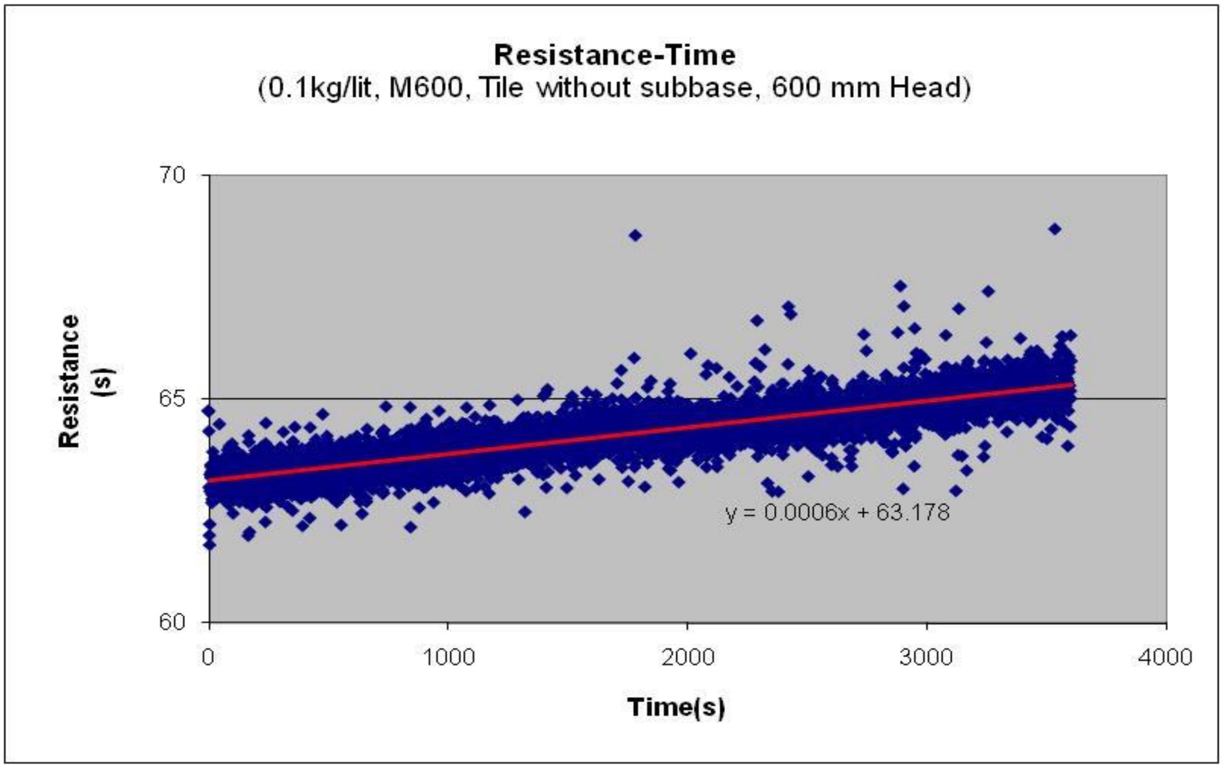
- ○ **300 mm Head**

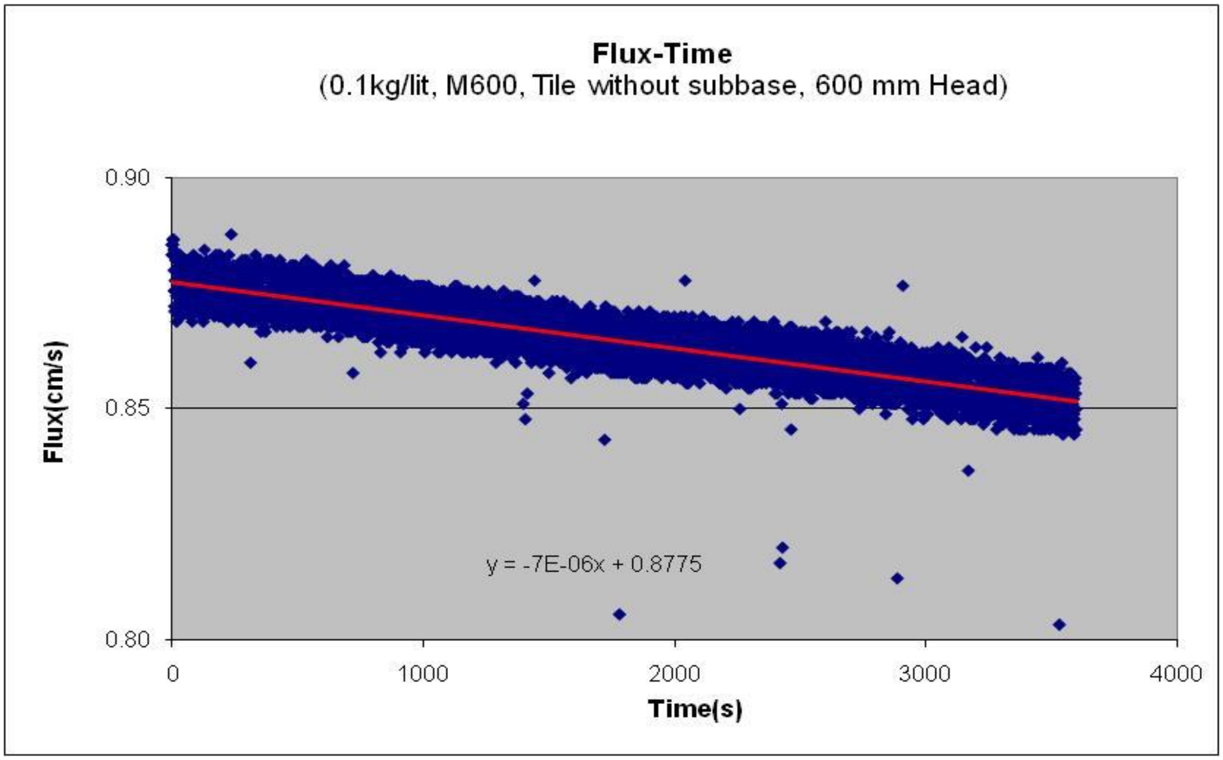

Resistance-Time
(0.1kg/lit, M600, Tile without subbase, 300 mm Head)
y = 0.0001x + 46.515
Resistance(s)
55
50
45
40
0
1000
2000
3000
4000
Time(s)


Flux-Time
(0.1kg/lit, M600, Tile without subbase, 300 mm Head)
y = -2E-06x + 0.6556
Flux(cm/s)
0.70
0.65
0.60
0
1000
2000
3000
4000
Time(s)

The graphs show the reduction in flow through the tile and increase in resistance over the time under 300mm water level.
In compare of 150mm water level the flux intercept is higher due to the higher water pressure above the tile. But the rate of flux reduction over the time is lower.
Also increase in the water level led to the increase in the resistance intercept, although the flux under higher water level is higher, but the decrease in pressure in 300mm water level is higher than 150mm, which shows by increase in the water level the velocity through the tile has increased which cause more resistance for the flow to overcome and consequently more pressure drop.

- **600 mm Head**


Resistance-Time
(0.1kg/lit, M600, Tile without subbase, 600 mm Head)
Resistance
(s)
70
65
60
0
1000
2000
3000
4000
Time(s)
y = 0.0006x + 63.178


Flux-Time
(0.1kg/lit, M600, Tile without subbase, 600 mm Head)
Flux(cm/s)
0.90
0.85
0.80
0
1000
2000
3000
4000
Time(s)
y = -7E-06x + 0.8775

In this test like the previous one, under all water levels, the resistance is increasing and the flow is decreasing over the time.

Under higher water levels, the resistance is also higher and increase in resistance in higher water levels is higher.

The flow under higher pressure is also higher, and the rate of decrease in flow does not have a consistent change by changing the water level. Increasing the water level from 150mm to 300mm caused the less reduction in flow over the time, but increasing the head from 300mm to 600mm caused higher reduction in flow over the time.

Higher pressure drop in higher water levels, which causes more resistance, can be explained by the same reason like the previous test.

6.1.3. Test with M600 and sand sub-base

- **Flux-Head difference of the test with clean water:**

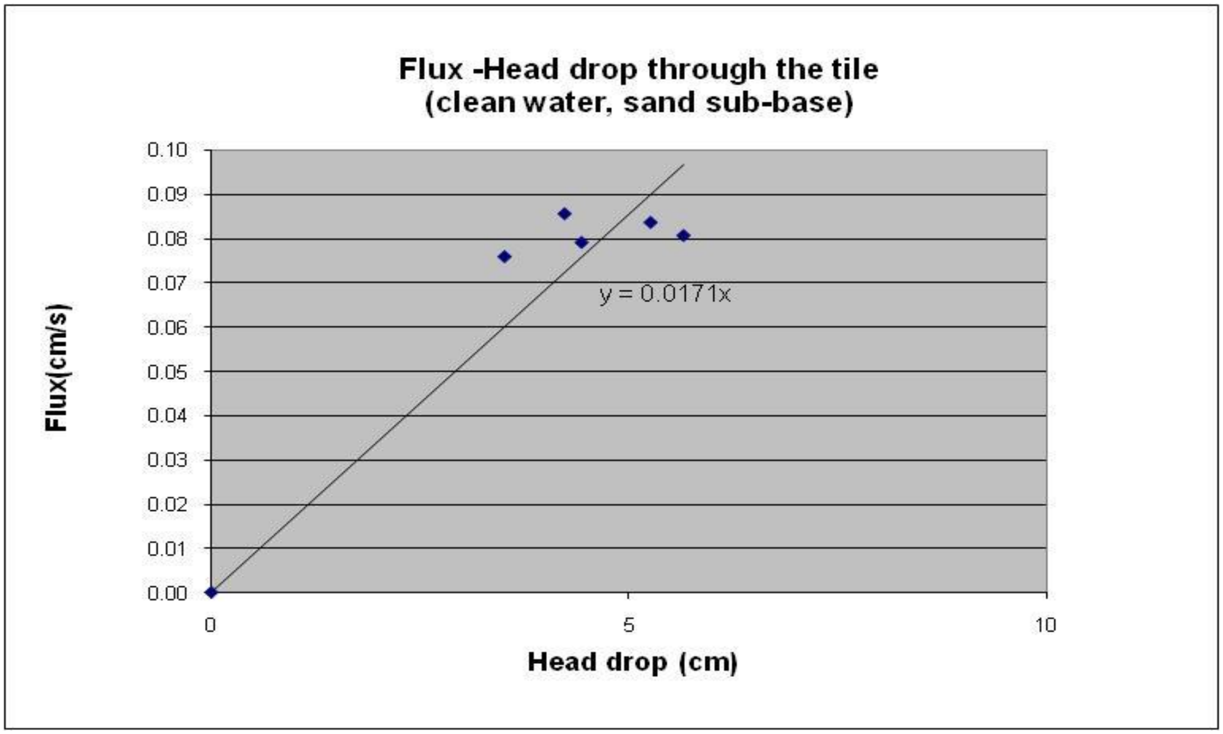


Figure (6.3), Flux- Head drop through the tile with sand sub-base, test with clean water

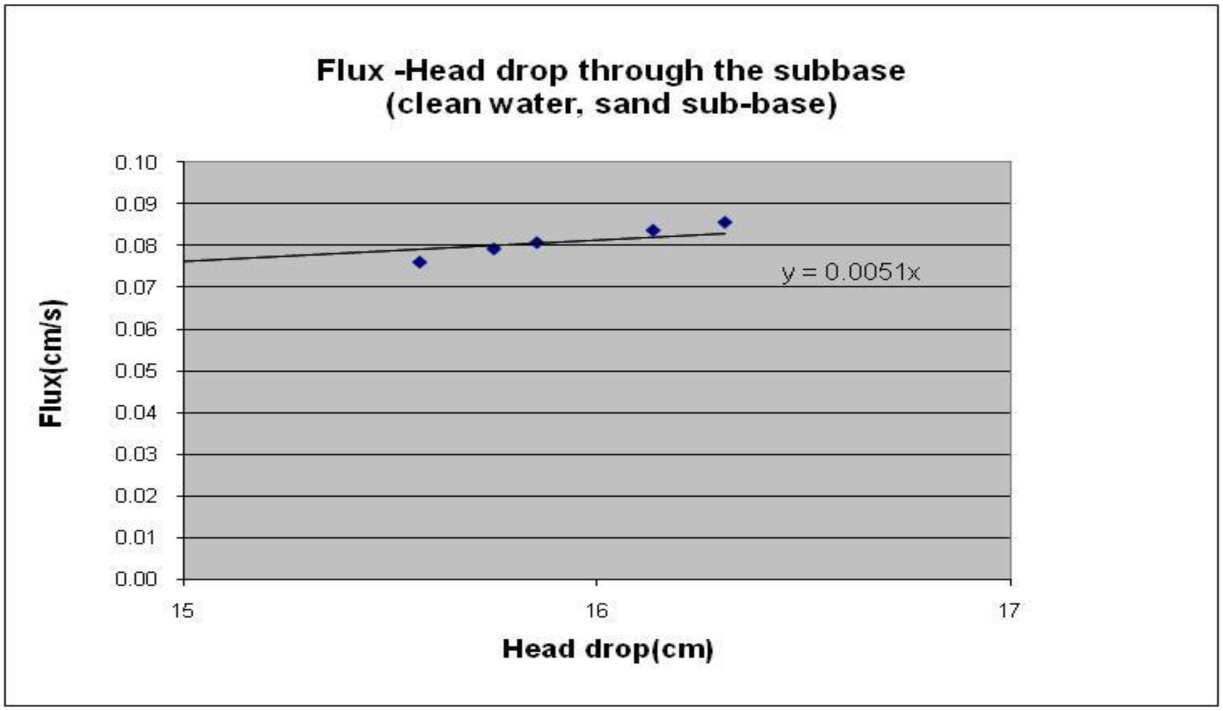


Figure (6.4), Flux- Head drop through the sand sub-base, test with clean water

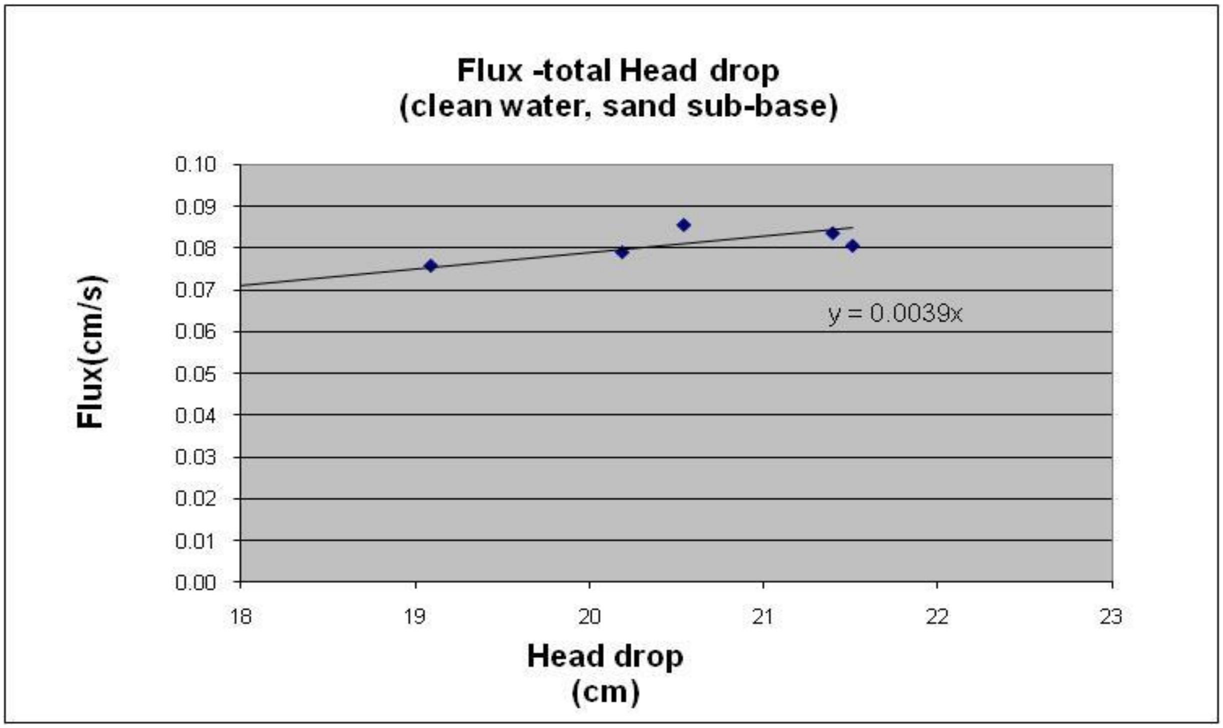


Figure (6.5), Flux- Total head drop, test with sand sub-base and clean water

Comparing this graph with figure (6.1) shows the significant reduction in discharge, which shows the resistance of the subbas through the flow. Also comparison of figure (6.5) with figure (6.3) and (6.4) shows that the head drop is mainly through the sub-base rather than the tile.

- **Boundary for laminar and turbulent flow**

As it is clear from the graph the flow-head drop through the sand sub-base (figure (6.4)) is linear, which shows the laminar flow through the sand sub-base. As the pores in the sand sub-base are small the flow velocity through it is low and pressure gradient and flux through the sand sub-base has a linear relation. But the flow through the tile for higher water levels and higher head drops does not have a linear trend and is more close to the turbulent flow.

- **Hydraulic conductivity of the sand sub-base**

In order to compare the conductivity through the sand sub-base with the tile, the conductivity of the sand can be calculated from equation (3.10) as follows:

$$K = C(d_{10})^2$$

K: hydraulic conductivity in cm/sec,

C: constant with units of $(\text{cm}\cdot\text{sec})^{-1}$,

d_{10}: grain diameter in centimeters: 0.2mm =0.02 cm

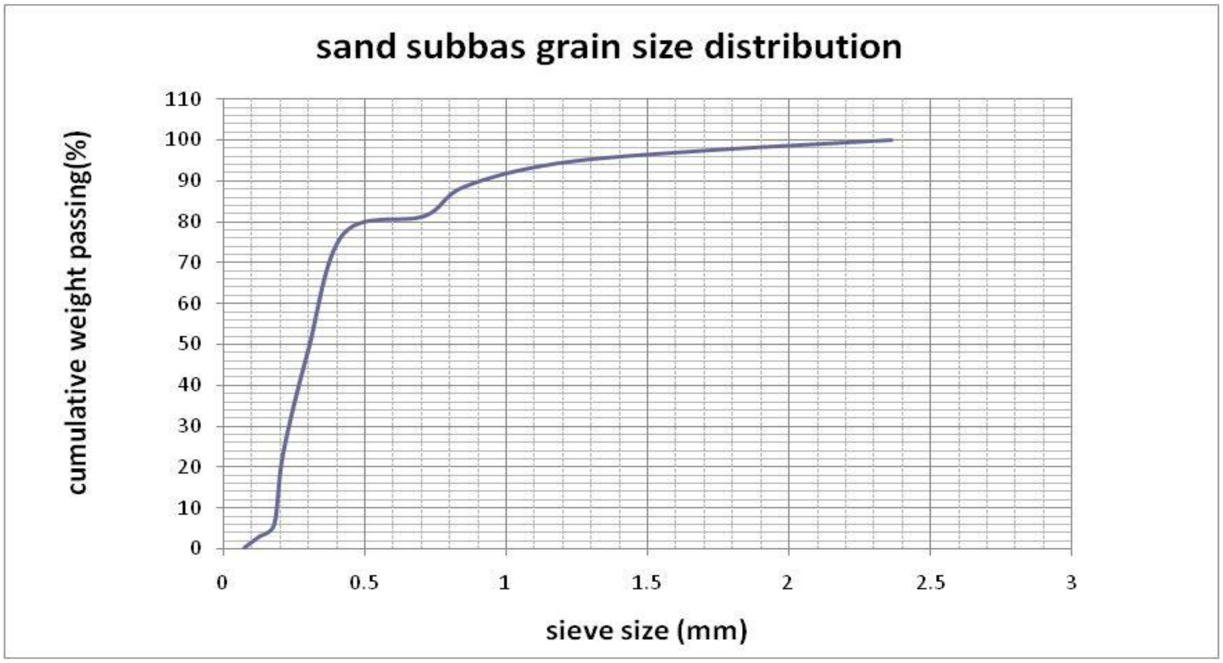


Figure (6.6), sand sub-base grain size distribution

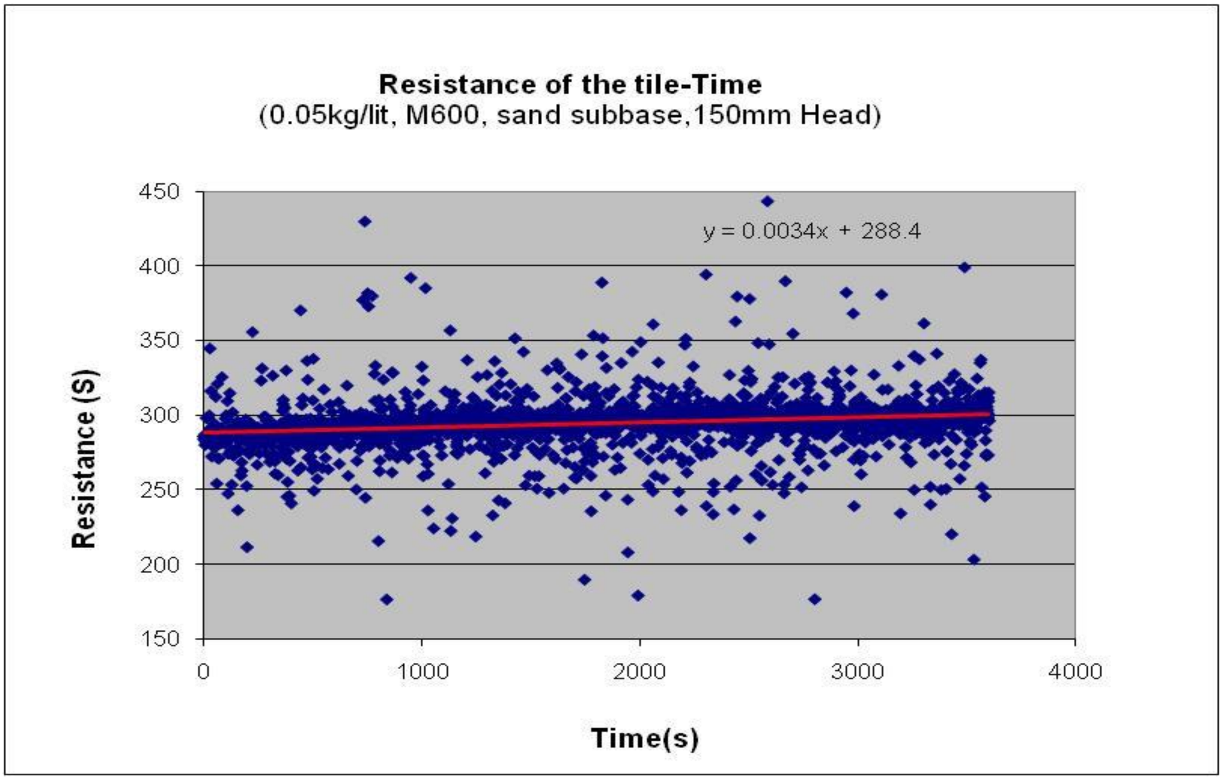
As the sub base can be categorized as the medium sand (different sand types in Annex VII) the value for C is selected as 100 $(cm.sec)^{-1}$

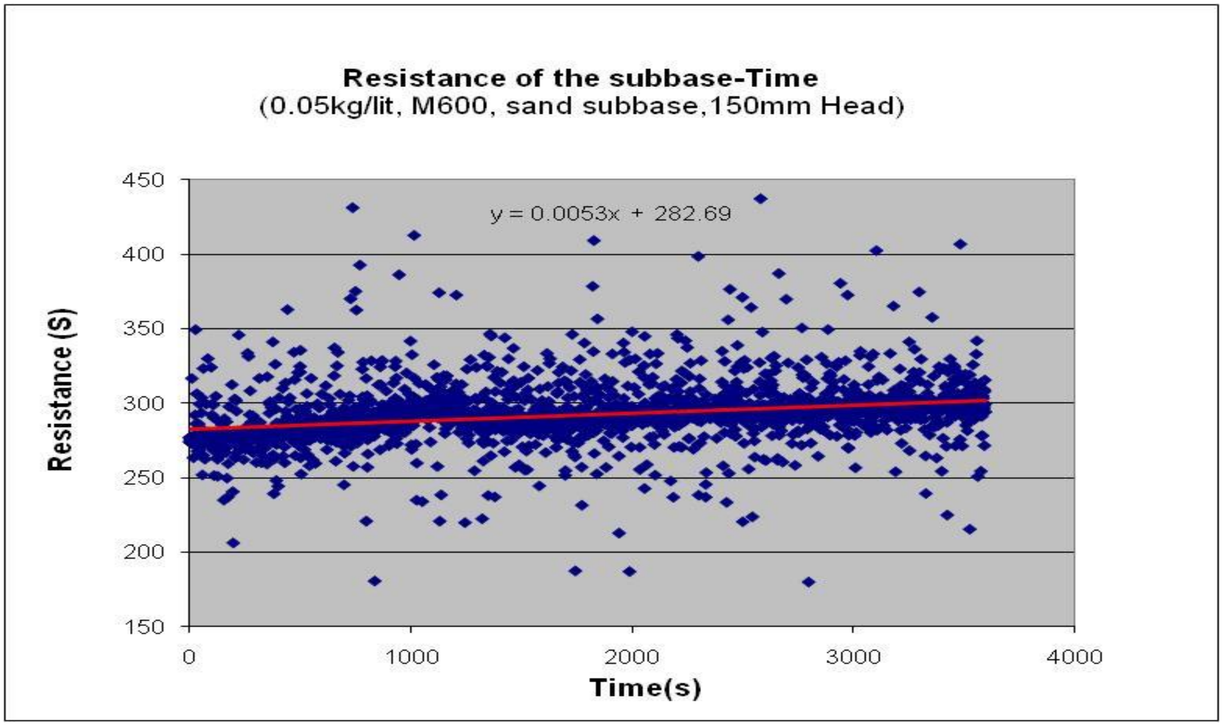
$$K = C(d_{10})^2,$$

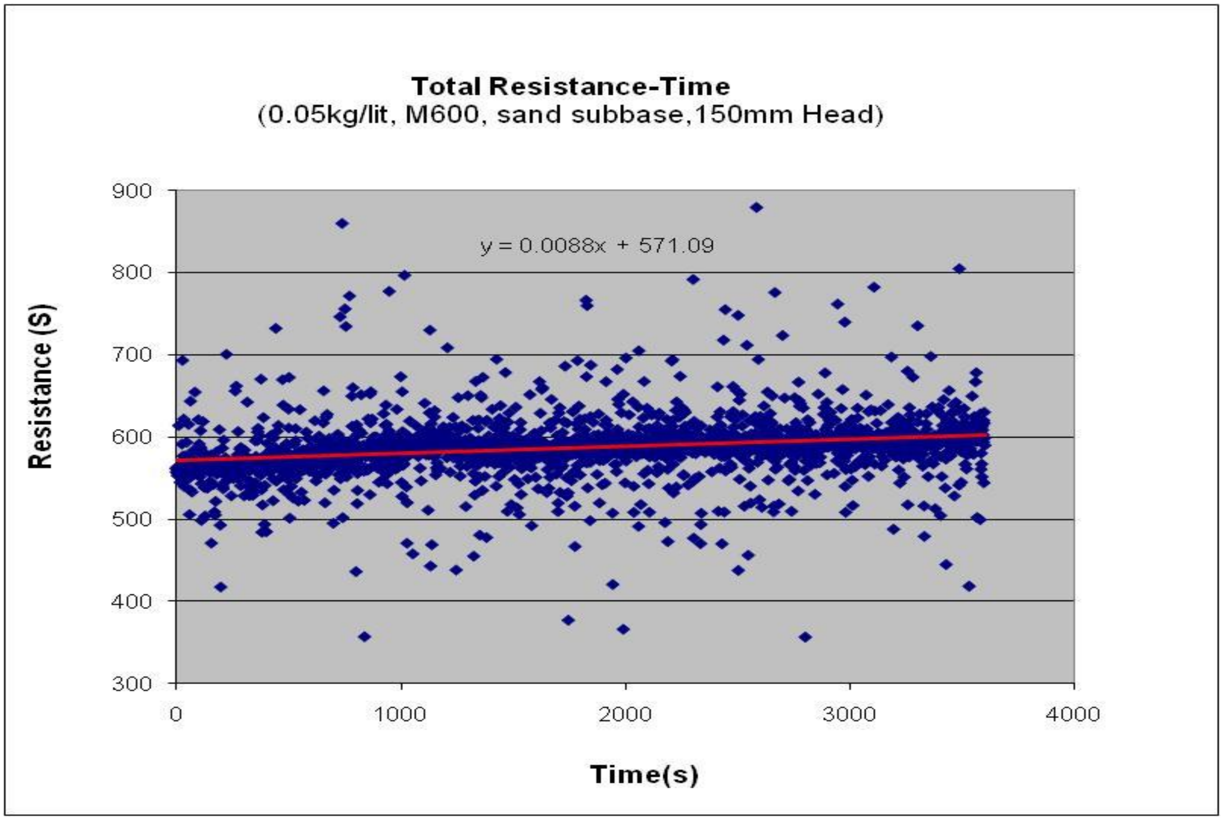
K=0.04 cm/s

Comparing the hydraulic conductivity of the sand sub-base with the tile (2.66 cm/s), shows the significant reduction in conductivity in sand. It shows the tile transmits water easily than sand. In case of sand, as the water should travel through small and constricted pores, it should shear itself more and in process of travelling, water movement is greatly reduced by surface tension. This causes more resistance through the flow and significant reduction in flow in case of sand sub-base.

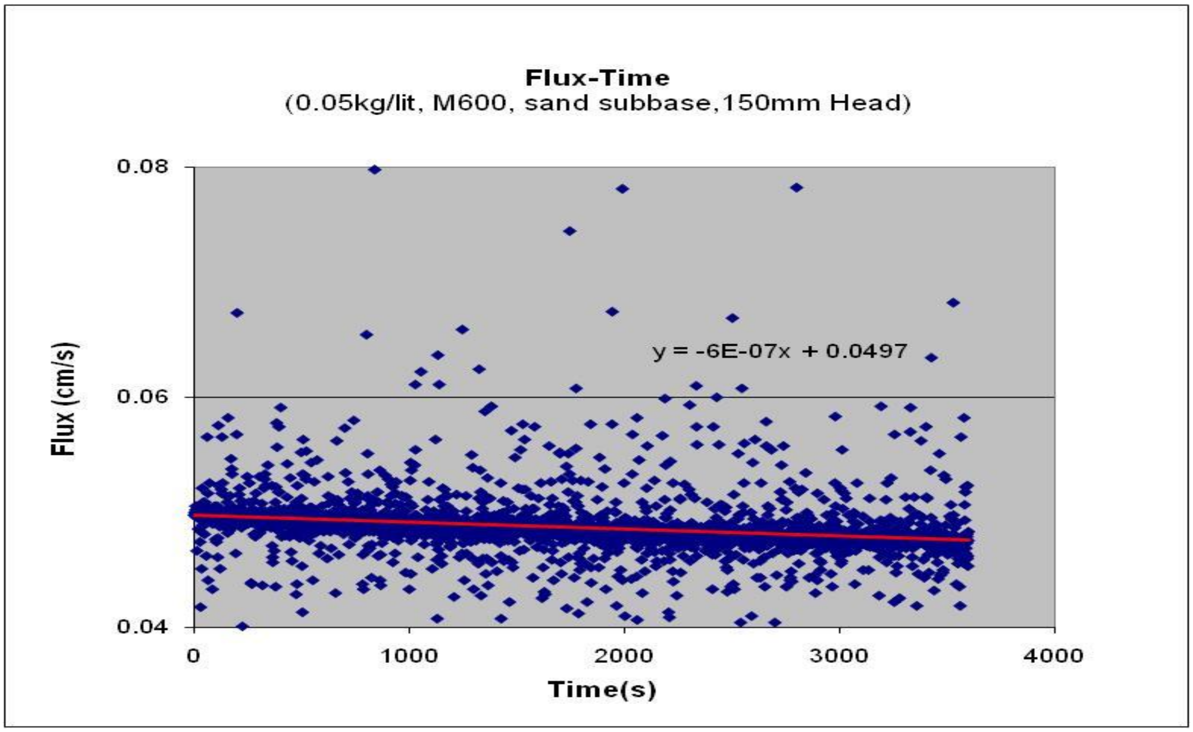
- **Concentration of 0.05 kg/lit**
  - **150mm Head**





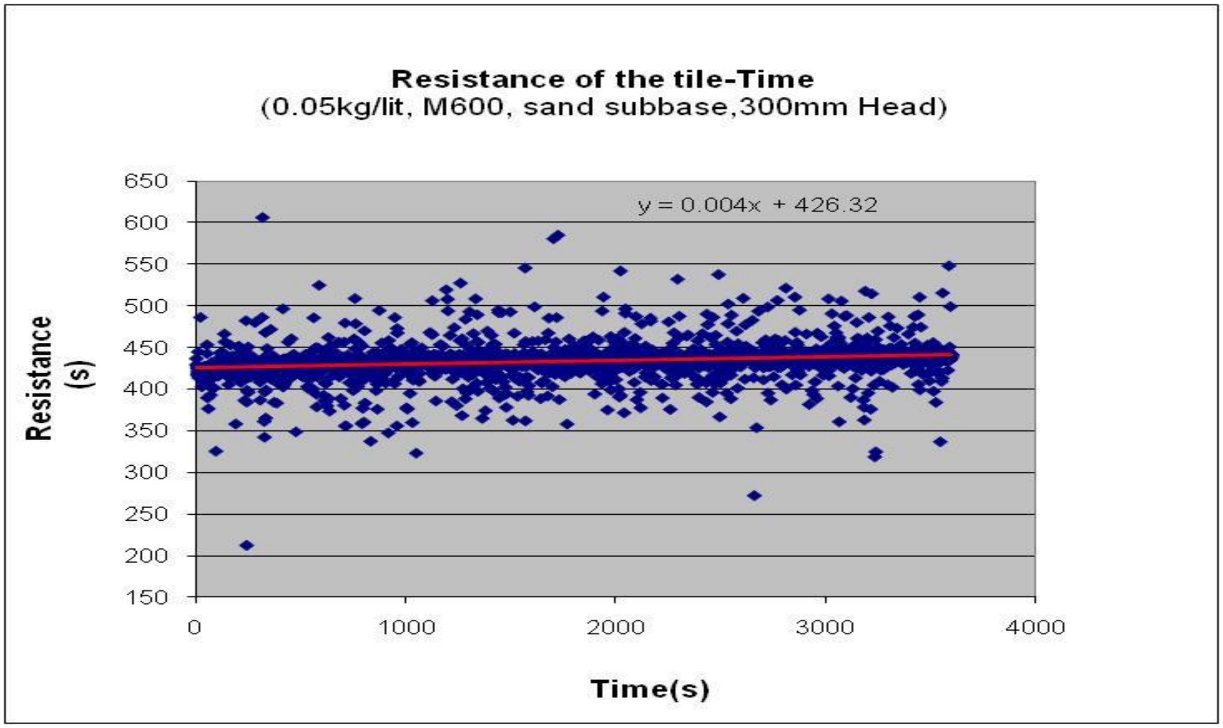


In all graphs, the resistance is increasing over the time. The initial resistance of the tile and sand sub-base are close to each other and with a small difference the tile resistance is higher than sub-base resistance, although in case of pure water the resistance in the sub-base was higher.
The rate of increase in the resistance in sub-base is faster than the tile.

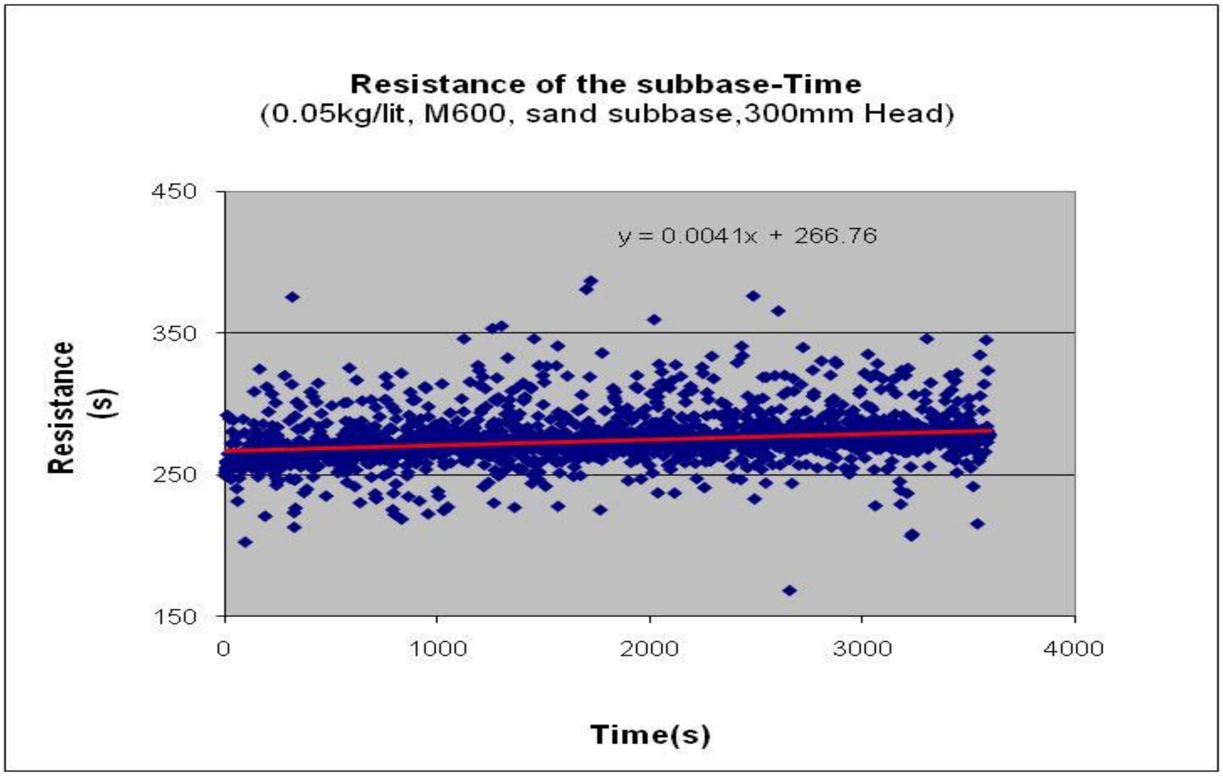


The graph shows the reduction in flow over the time, and in compare of test without sub-base and stone sub-base, the intercept is lower which shows the resistance of the sand sub-base through the flow.

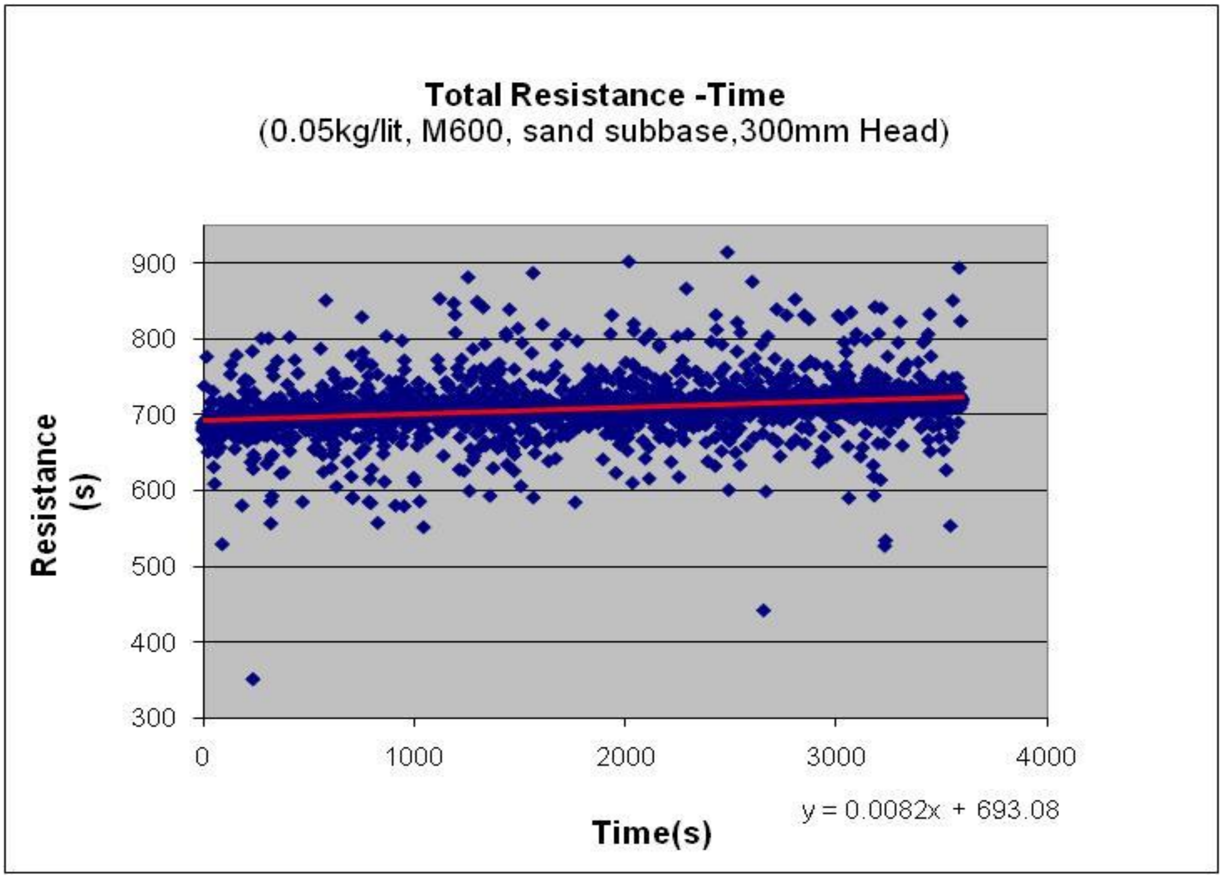
- **300mm Head**



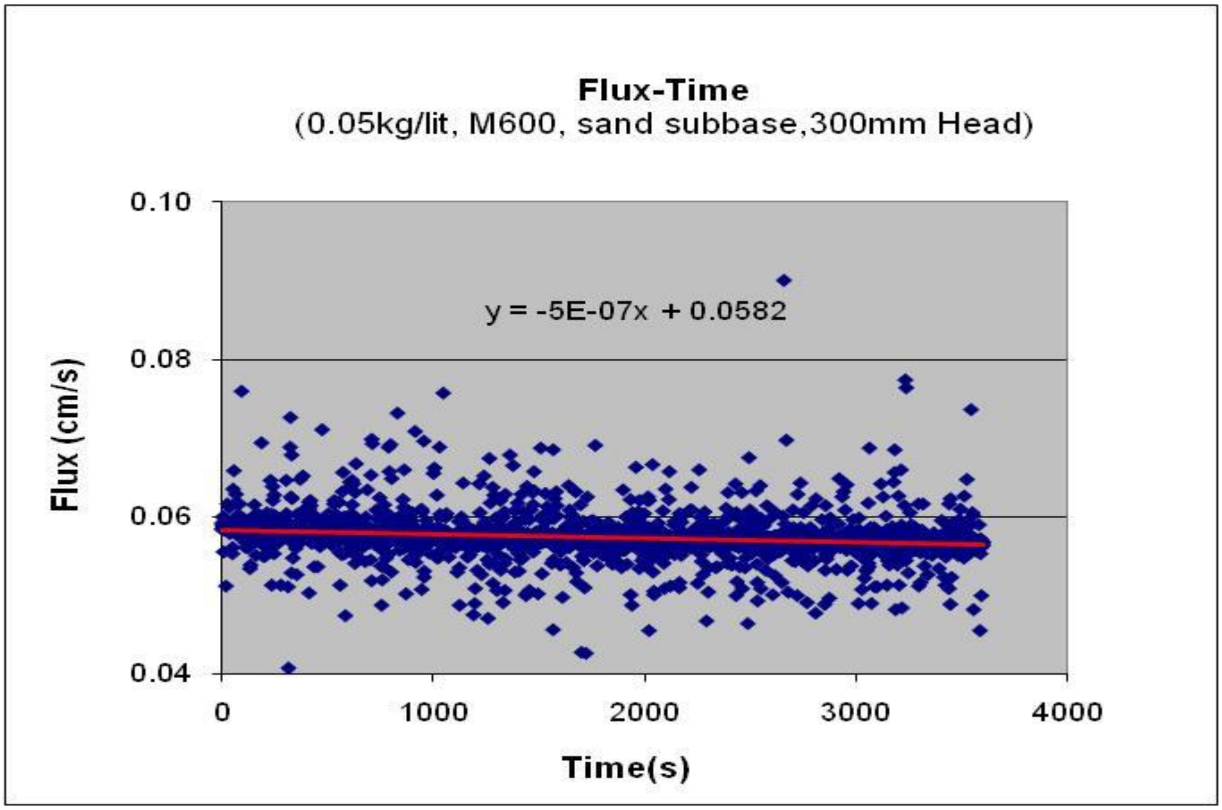
Resistance of the tile-Time
(0.05kg/lit, M600, sand subbase,300mm Head)
y = 0.004x + 426.32
Resistance (s)
650
600
550
500
450
400
350
300
250
200
150
0
1000
2000
3000
4000
Time(s)



Resistance of the subbase-Time
(0.05kg/lit, M600, sand subbase,300mm Head)
y = 0.0041x + 266.76
Resistance (s)
450
350
250
150
0
1000
2000
3000
4000
Time(s)

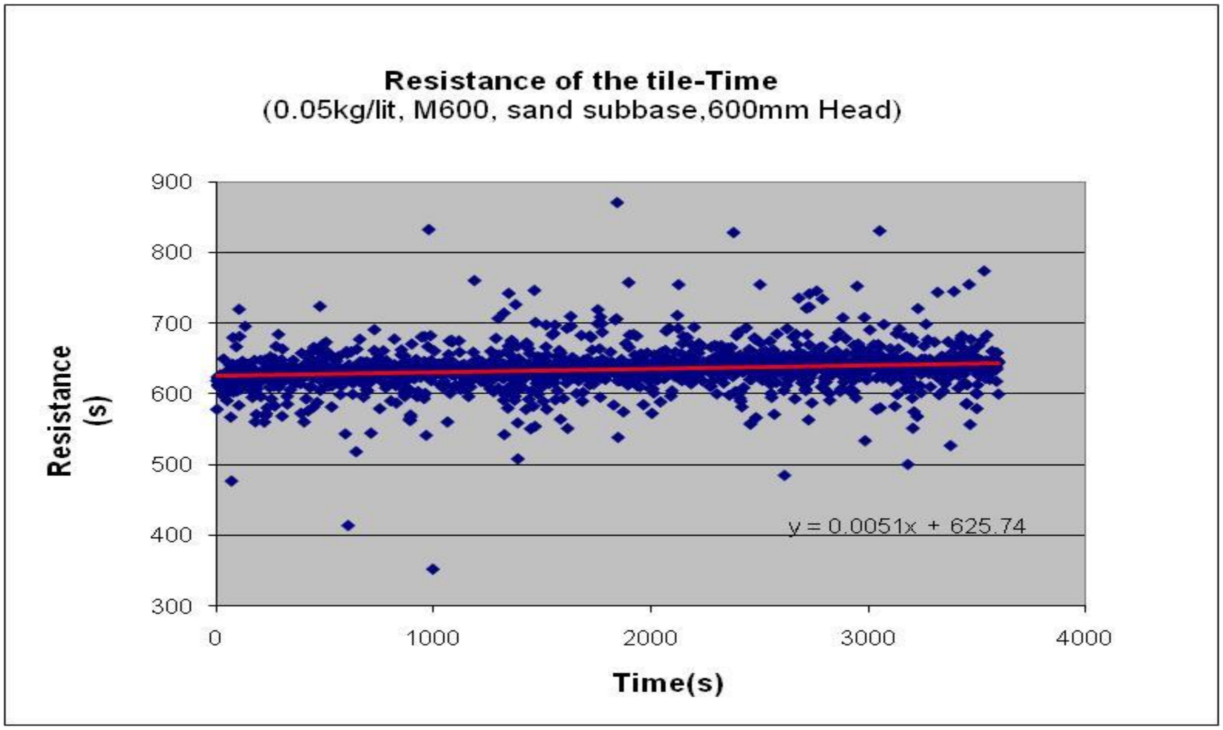


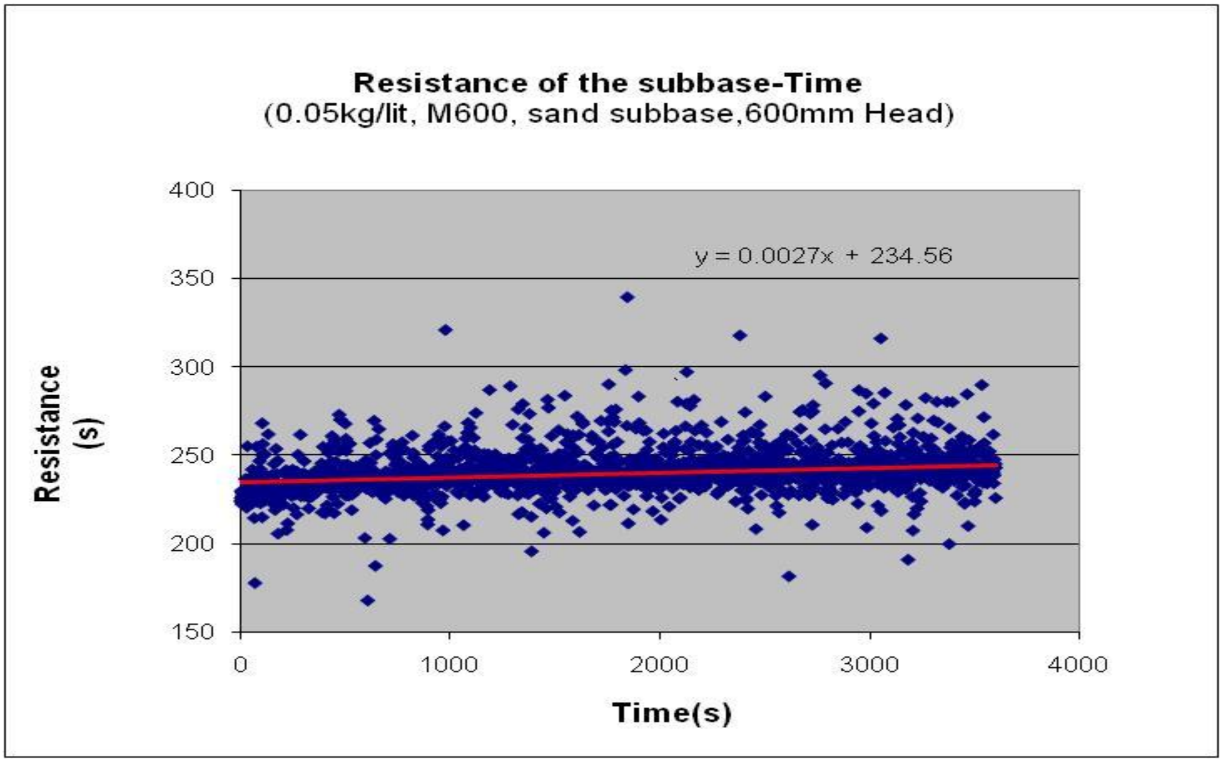
In case of 300mm water level, again the resistance is increasing over the time. In this case the tile resistance is more than 1.5 times higher than sub-base resistance.

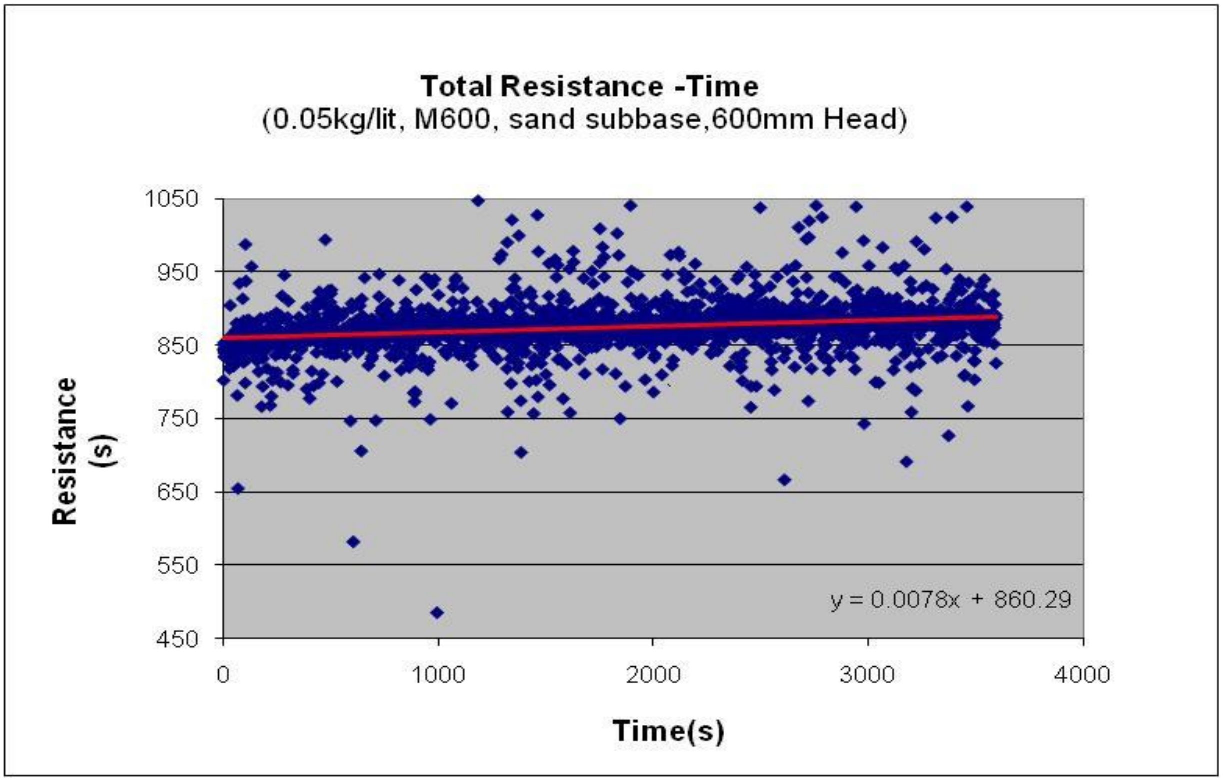


The graph shows the reduction in flux under 300 mm water level. In compare of 150mm water level the intercept is higher, but the rate of clogging over the time is lower.

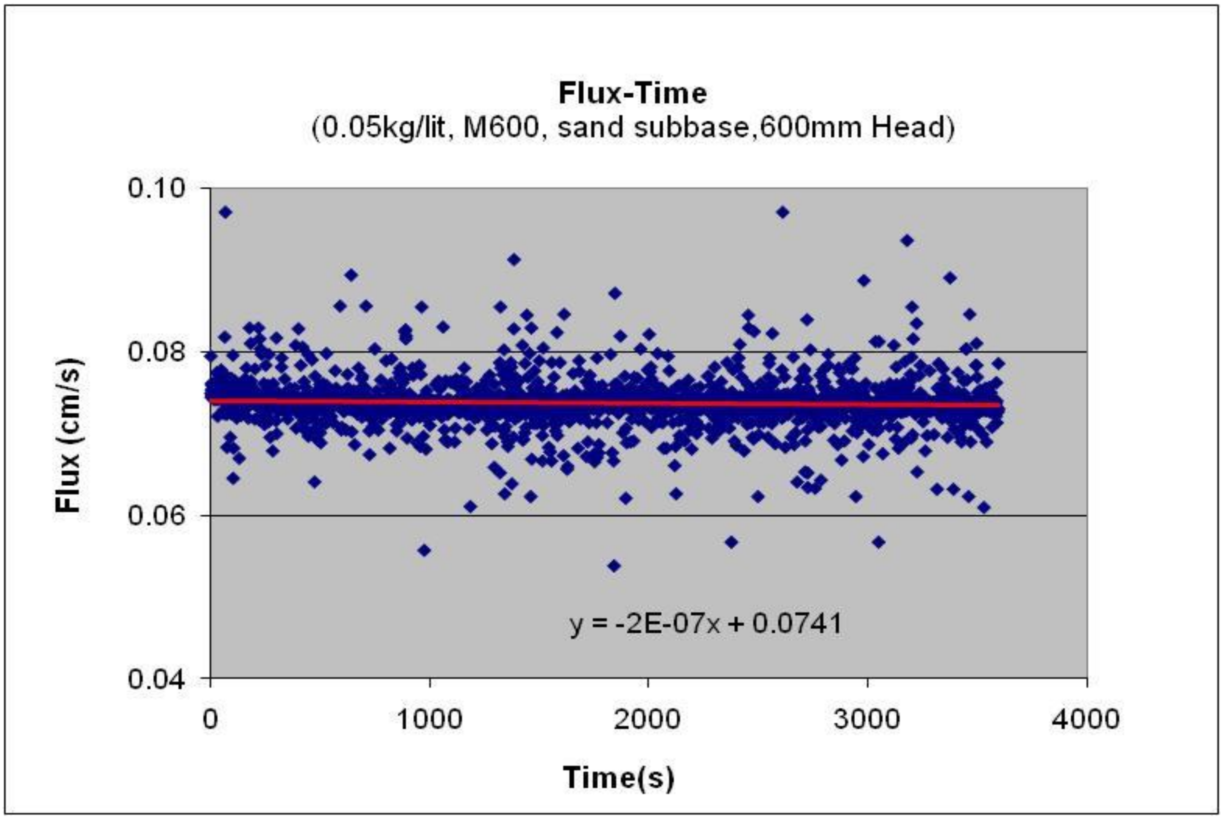
- **600mm Head**


Resistance of the tile-Time
(0.05kg/lit, M600, sand subbase,600mm Head)
Resistance (s)
900
800
700
600
500
400
300
0
1000
2000
3000
4000
Time(s)
y = 0.0051x + 625.74


Resistance of the subbase-Time
(0.05kg/lit, M600, sand subbase,600mm Head)
Resistance (s)
400
350
300
250
200
150
0
1000
2000
3000
4000
Time(s)
y = 0.0027x + 234.56



In case of 600mm water level, the tile resistance is getting higher, and the difference between tile resistance and sub-base resistance is higher than two previous cases. (More than 2.5 times higher) The slope of increase in the resistance in the tile is also faster than the sub-base (almost 2 times faster)



By increasing the water level above the tile, the intercept of the flux is also higher in compare of 150 and 300 mm water level.

6.1.4. Test with M600 and stone sub-base

- **Flux-Head drop, test with clean water**

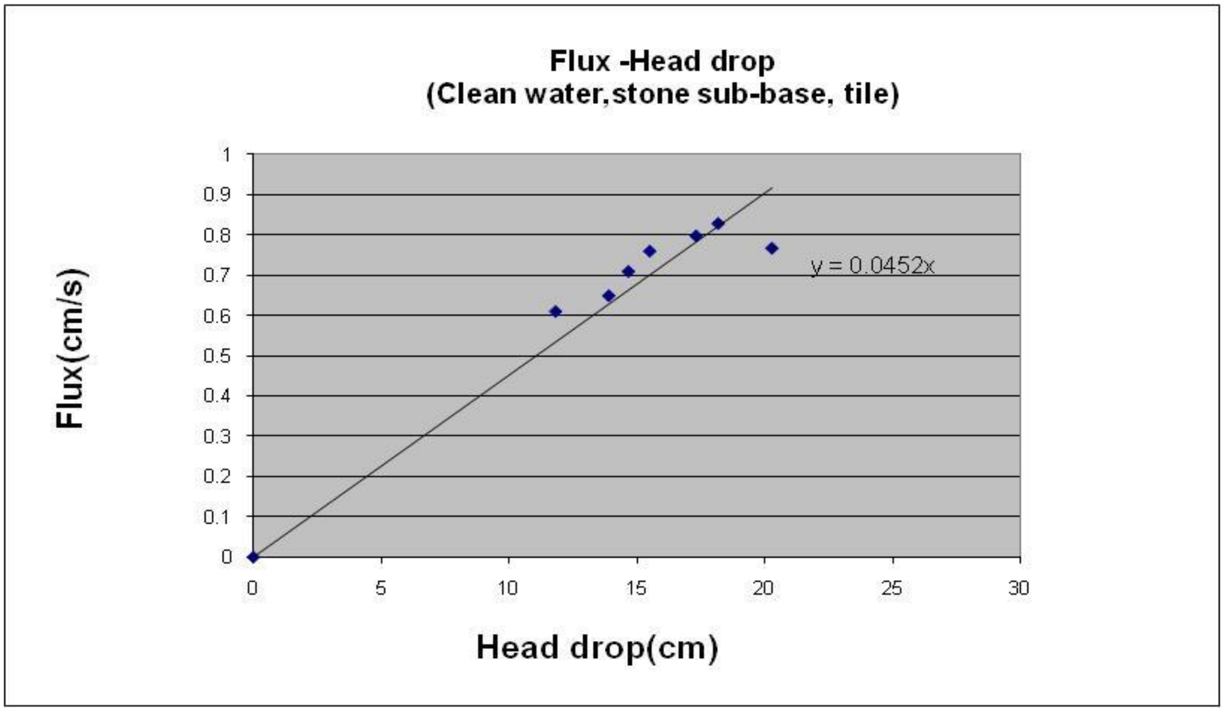


Figure (6.7), Flux-Head drop through the tile, Test with stone sub-base and clean water

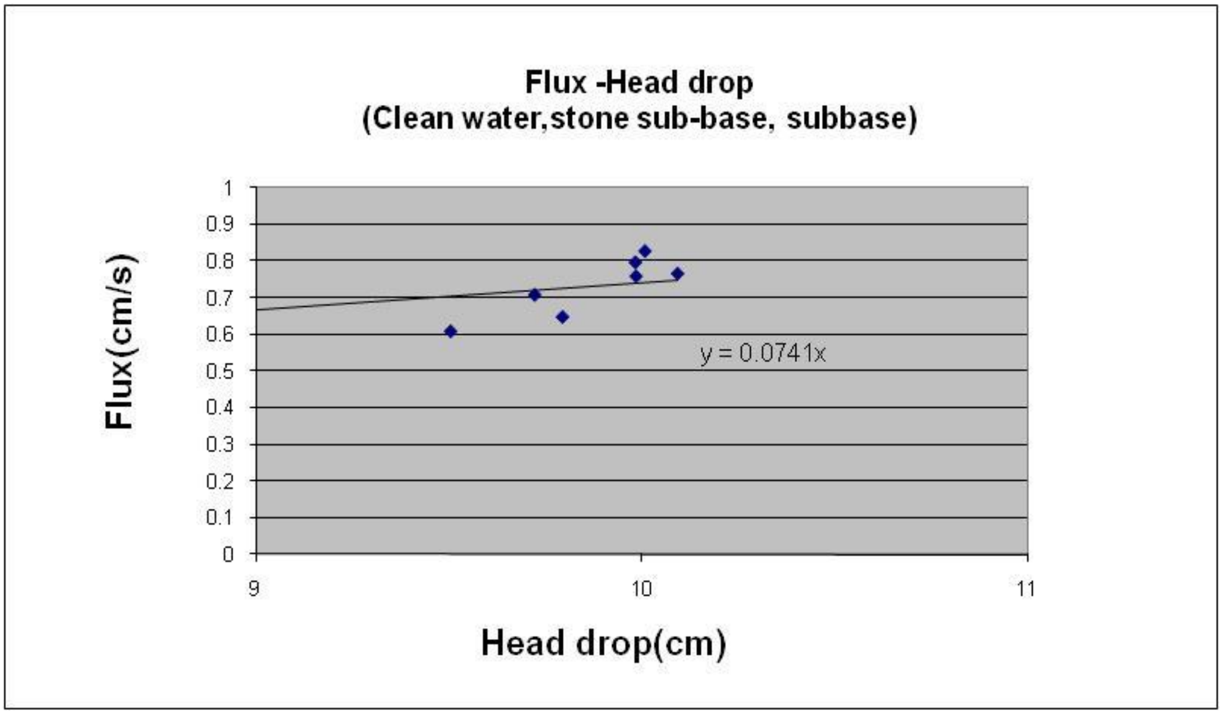


Figure (6.8), Flux-Head drop through the sub-base, Test with stone sub-base and clean water

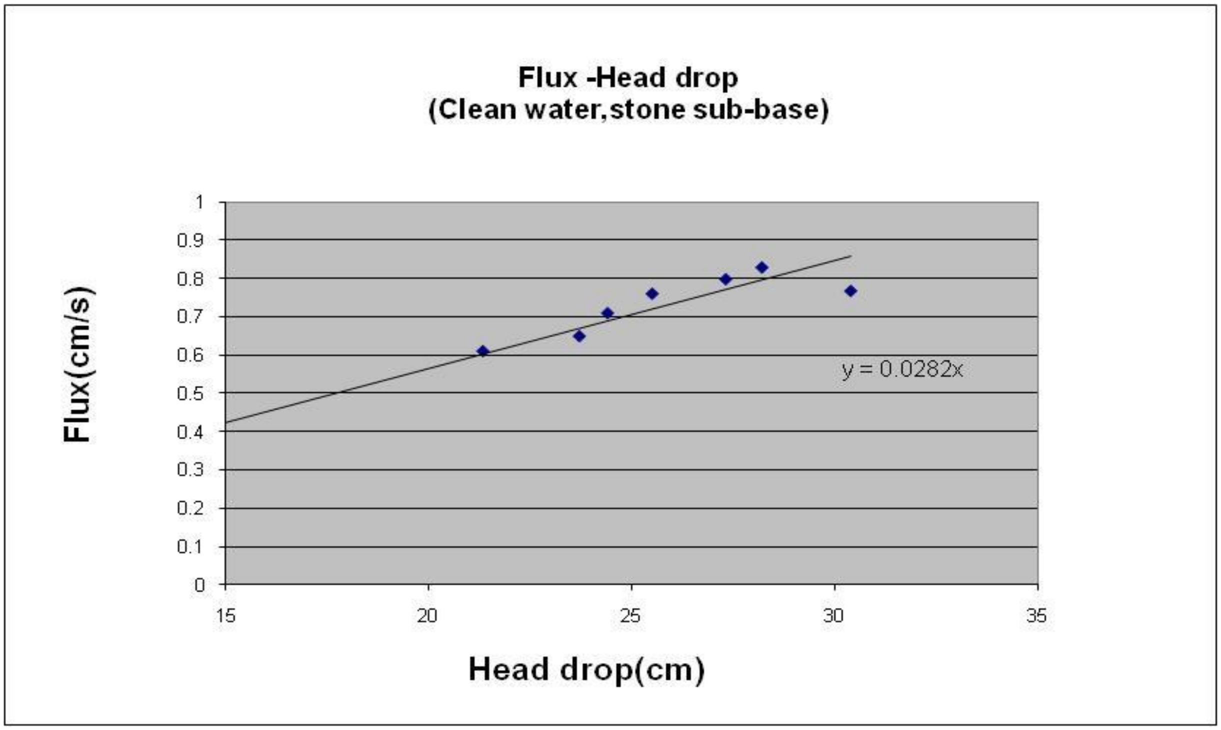


Figure (6.9), Flux-Head drop, Test with stone sub-base and clean water

The graphs show the relation between flux and head drop through the tile and stone sub-base. Results are following a linear trend; only the maximum point is slightly diverted from the linear trend. Also the deviation is not so significant. But higher deviations, due to the higher water levels could be explained by changing flow regime from laminar to turbulent as it was explained in case of tile without sub-base (figure (6.1)). While changing the flow to turbulent, the hydraulic conductivity will not be constant and Darcy's law is not valid anymore.
Comparison of the test with fresh water through the tile without sub-base (figure (6.1)) figure (6.9) shows that the discharge in both cases under different heads is almost the same, which shows the negligible resistance of the stone sub-base through the flow.

- **Deviation from laminar to turbulent flow:**

The flux-head drop trend in case of stone sub-base is linear, although the stone sub-base is more porous than the tile and may have a non-linear trend. But in our case by adding the stone sub-base the total resistance is higher than having no sub-base. Therefore the flux is lower.
Also in case of stone sub-base, comparison of the flux-head drop graph in tile with sub-base (figure (6.7)) shows that the trend line in tile graph has more non-linear trend than the sub-base. As the porosity of the tile is lower than the stone sub-base, therefore the velocity in tile is higher (with the same flux in both materials) and there is more chance for having turbulent flow.
Also measurement of pressure sensors in case of tile are more independent to medium as compare to stone sub-base, so the flux- head drop in case of tile, produces more smooth graphs and it is easier to find deviation, even with a few points, but in case of stone sub-base the pressure gauges below the tile and below the sub-base are influenced/ dependent by the behavior of both mediums, so the resultant graphs in such case are not really smooth, so more points are required to detect any deviation from laminar to turbulent flow.

- **Comparison of the flow through the tile in all cases:**

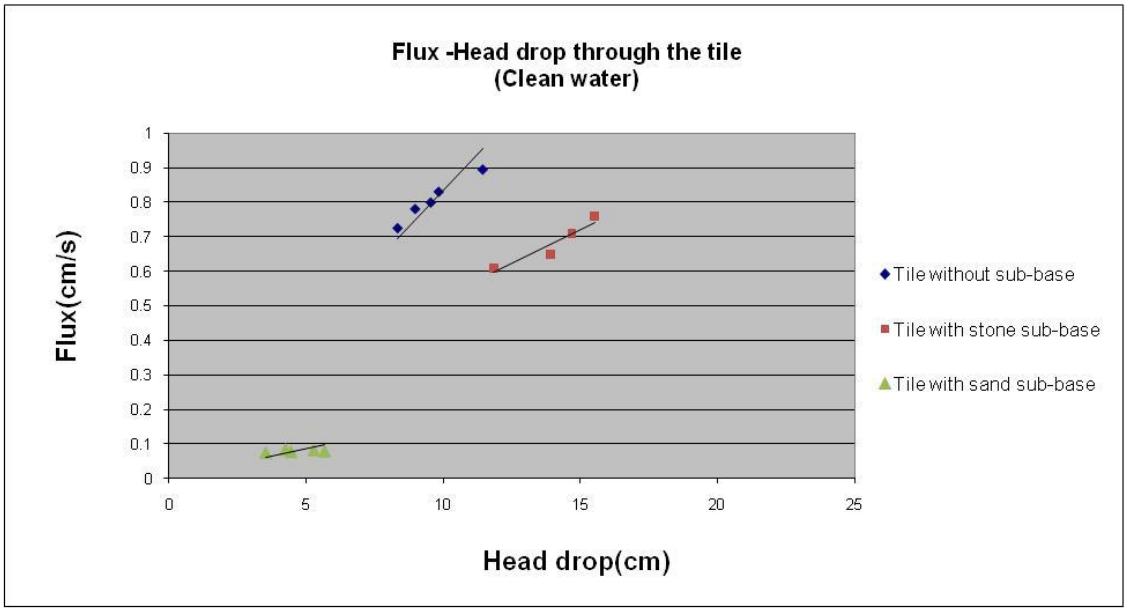
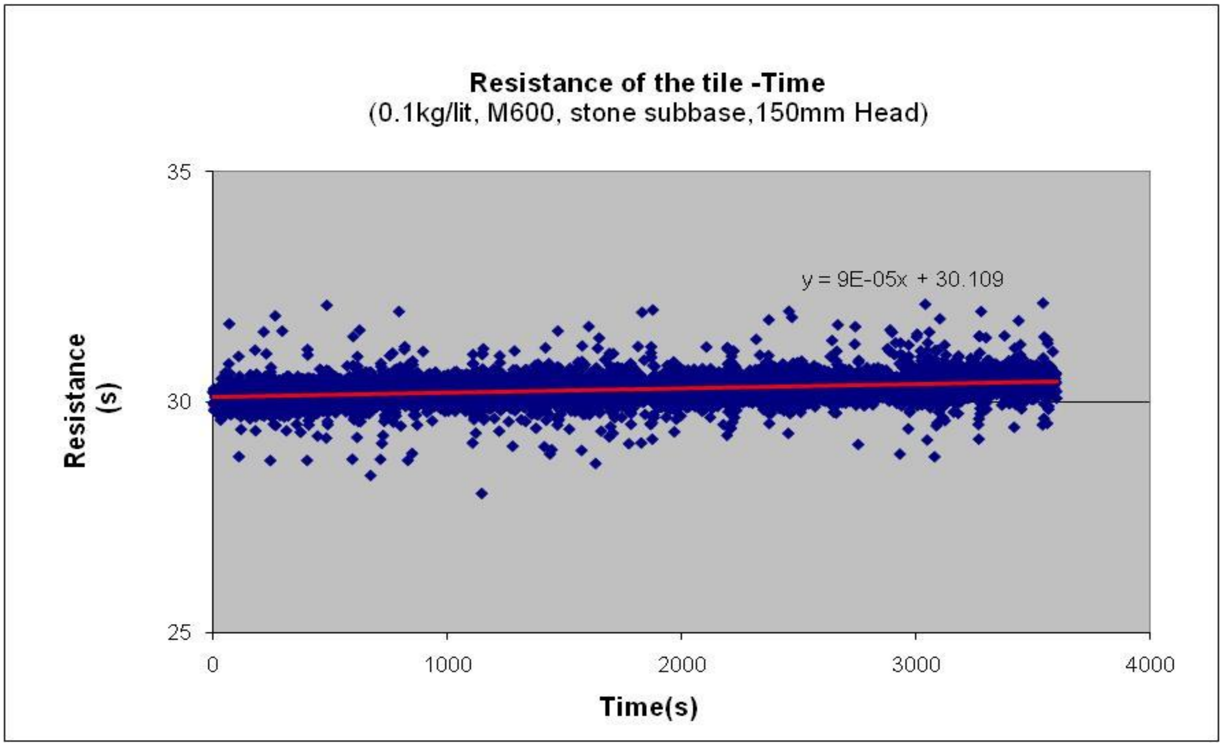
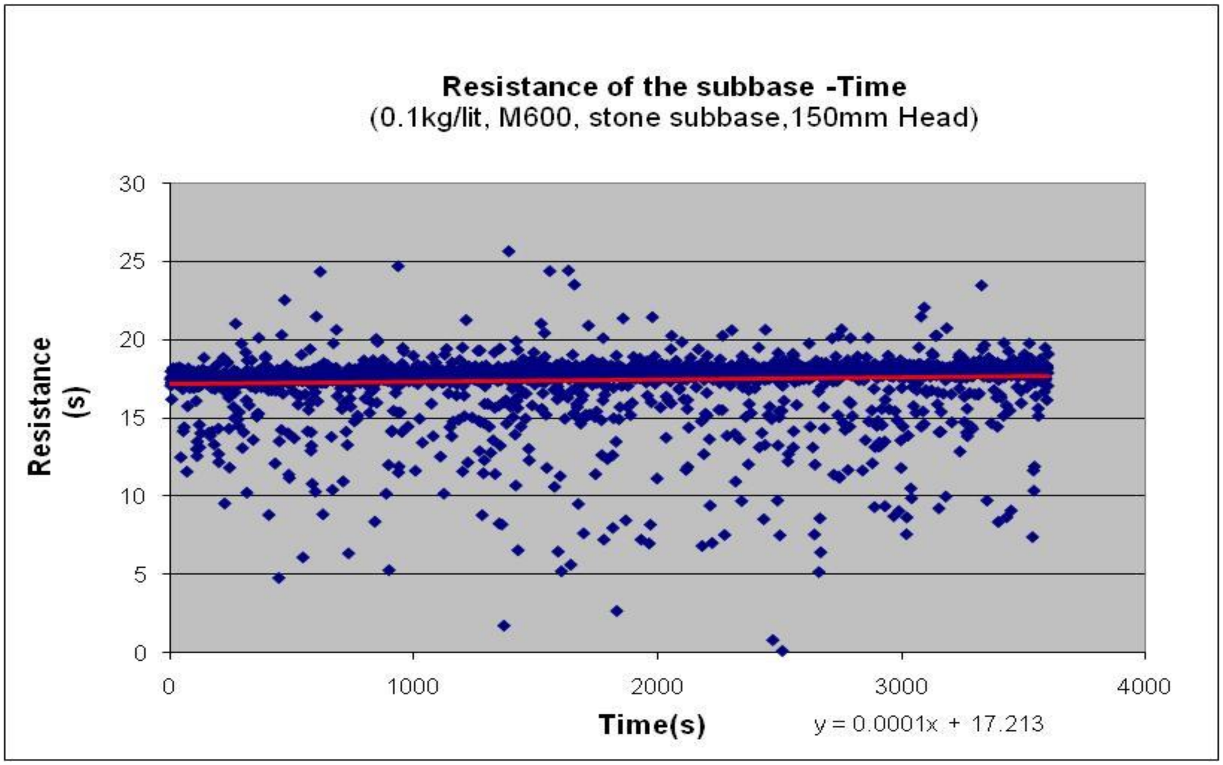


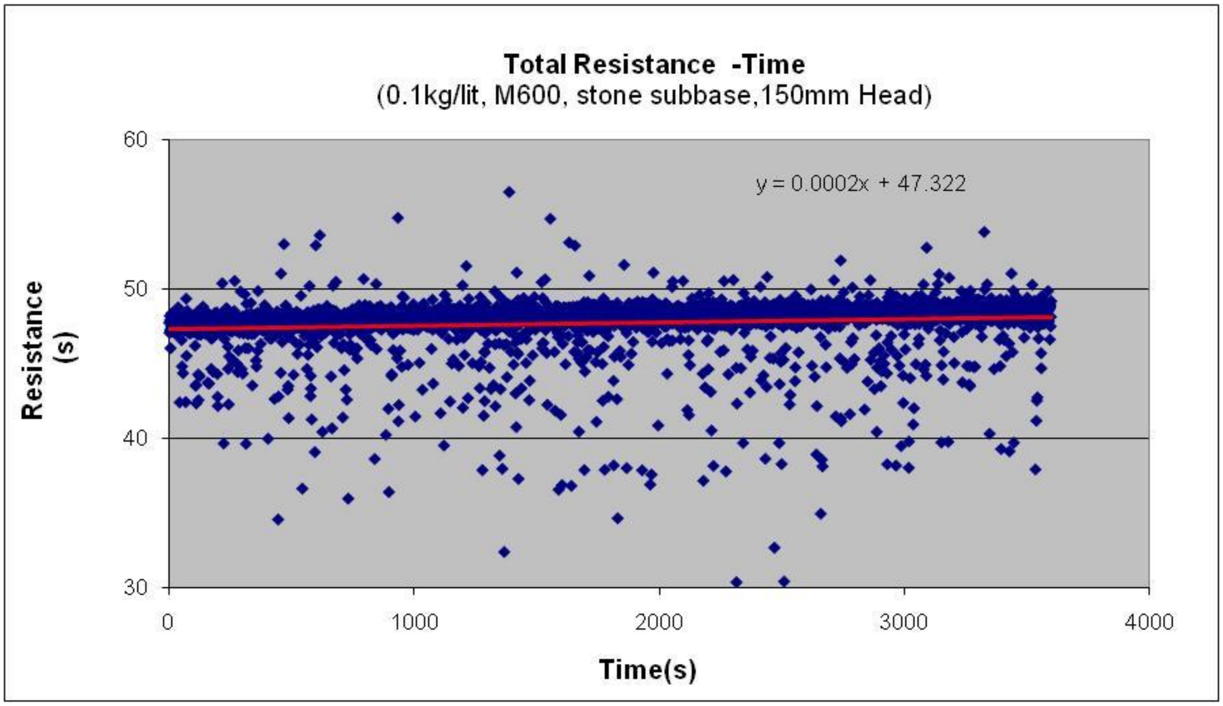
Figure (6.10), Comparison of the flow through the tile in all cases

The graph shows the flux- head drop through the tile, for all cases with pure water.
As it was explained before the flux through the tile in test with stone sub-base and tile without sub-base (figures (6.1) and (6.7)) are close to each other which shows the small resistance of the stone sub-base due to its high permeability. But in case of sand sub-base, less permeable sub-base causes more resistance through the flow and significant reduction in flow through the tile.
As the graphs show the head drop through the tile, it would be expected that the head drop in all cases have the same changes under the same water levels. Also in case of sand sub-base, the head drop through the tile is different from other cases. These deviations from the expected behavior can be explained by the presence of a very thin layer of sub-base just above the pressure sensor which is located under the tile. Therefore the hydraulic conductivity of tile obtained from the graph is slightly low in case of gravel and sand sub-base. Also different tile characteristics and some errors in measurements can create this unexpected trend.
As it can be concluded from the graphs the flux-head drop in tile has a linear trend. As it was explained before, it shows the laminar flow through the porous concrete tile. Slightly deviations from linear trend could be because of the error in the measurements. Also previous experiments and researches[12] about the flow regime in porous concretes show that the flow regime in pervious concrete for typical applications is laminar, and under higher water levels and higher porosities it can deviate to turbulent regime.[12]

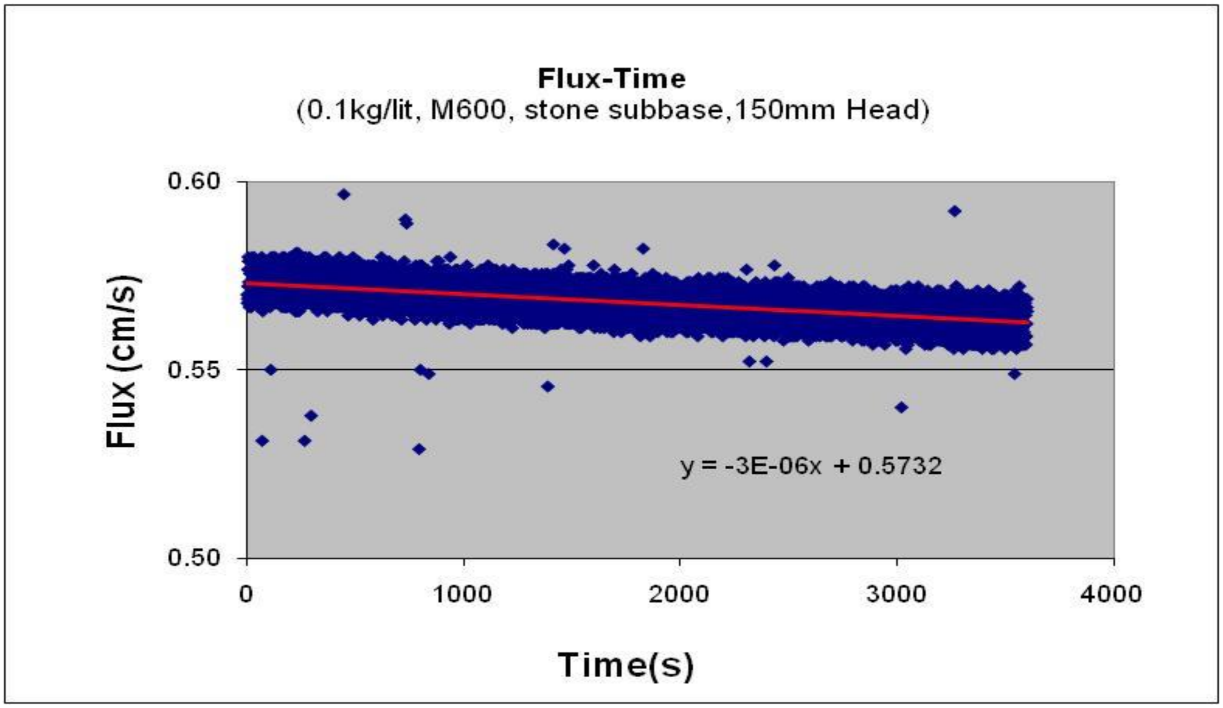
- **Concentration of 0.1 kg/lit**
    - **150mm Head**





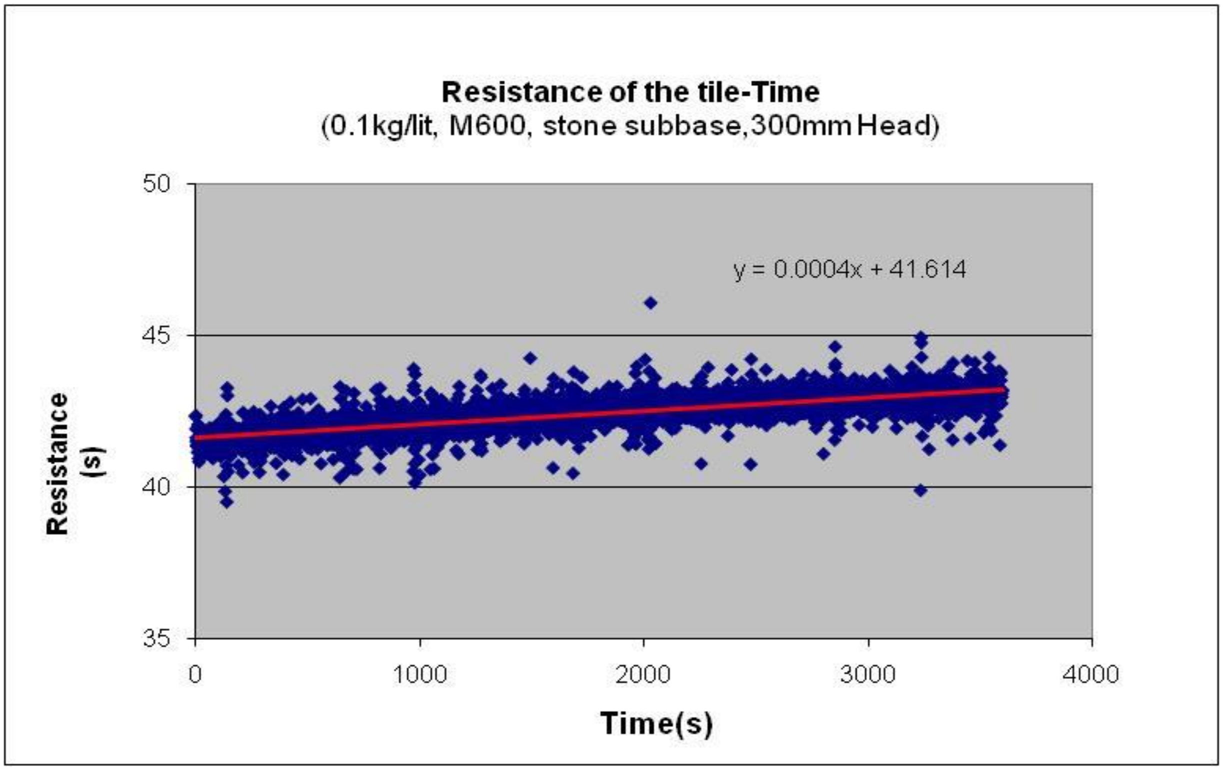


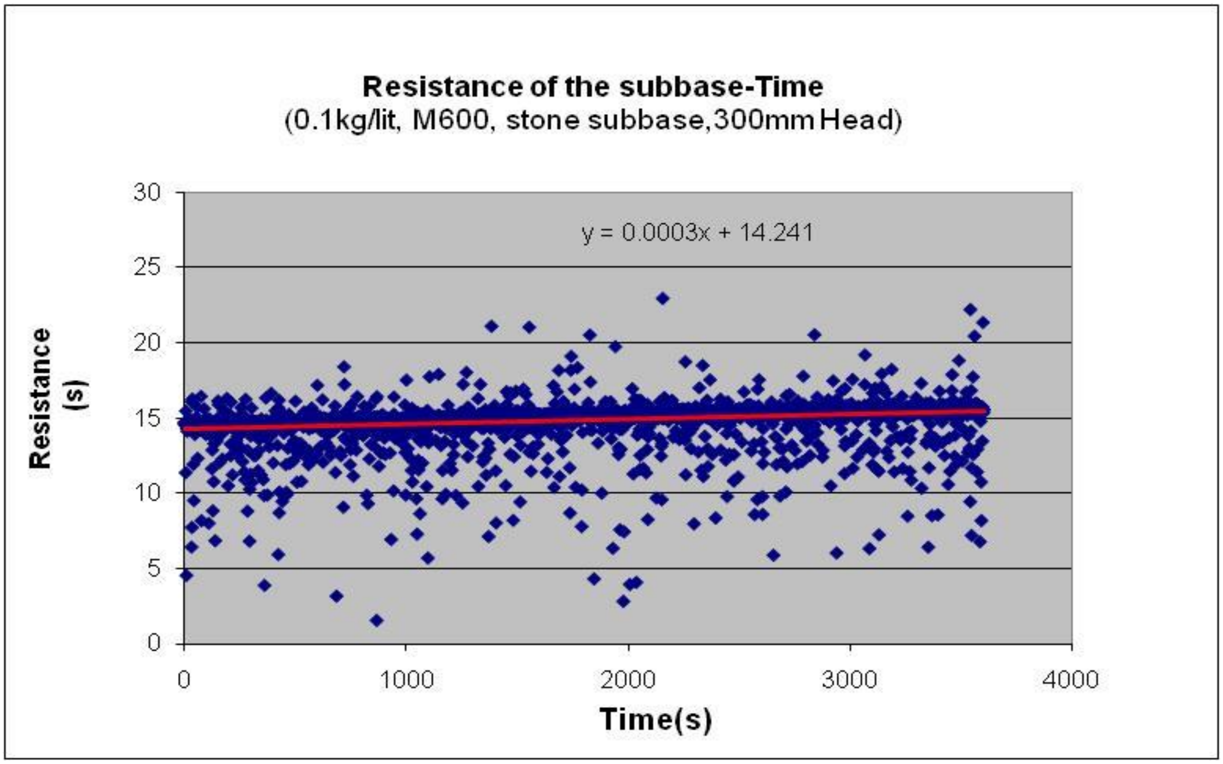
The graphs show the increase in the resistance over the time. Comparison of the graphs show that the resistance in the system is mainly through the tile rather than the stone sub-base and the initial resistance through the tile is almost two times higher than the resistance in the sub-base.
The rate of increase in the resistance over the time in the sub-base is higher than the tile.

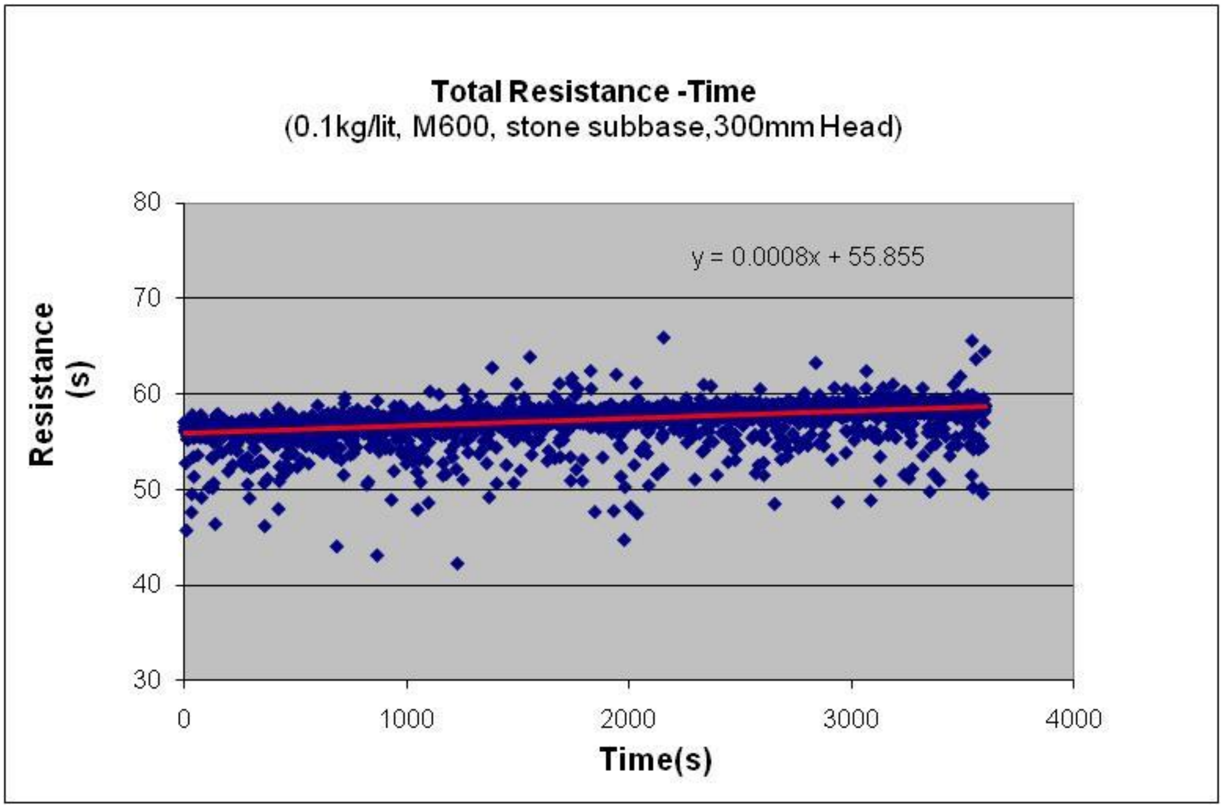


The graph shows the reduction in flow over the time due to the clogging. The intercept of the flux is close to the flux intercept in test without sub-base and is so higher than the test with sand sub-base. As it was explained before high porosity of the stone sub-base led to this behavior of the system.

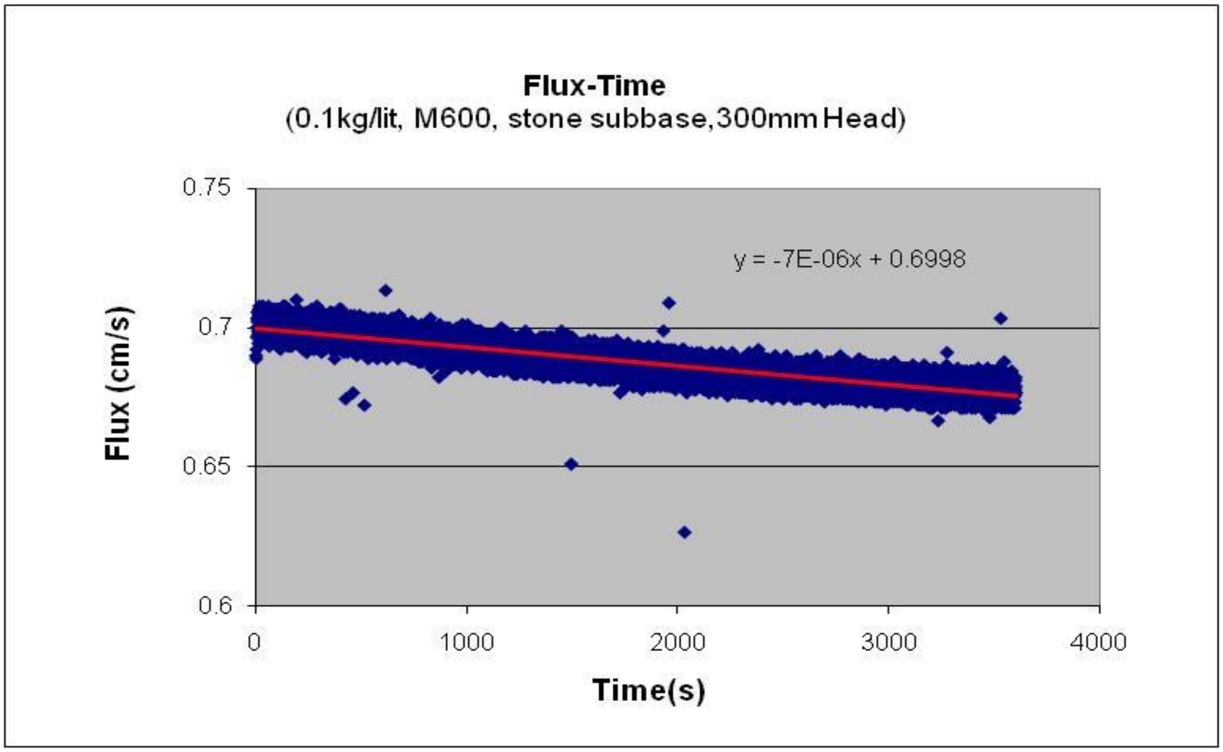
- **300mm Head**


Resistance of the tile-Time
(0.1kg/lit, M600, stone subbase,300mm Head)
y = 0.0004x + 41.614
Resistance (s)
Time(s)
50
45
40
35
0
1000
2000
3000
4000


Resistance of the subbase-Time
(0.1kg/lit, M600, stone subbase,300mm Head)
y = 0.0003x + 14.241
Resistance (s)
Time(s)
30
25
20
15
10
5
0
0
1000
2000
3000
4000

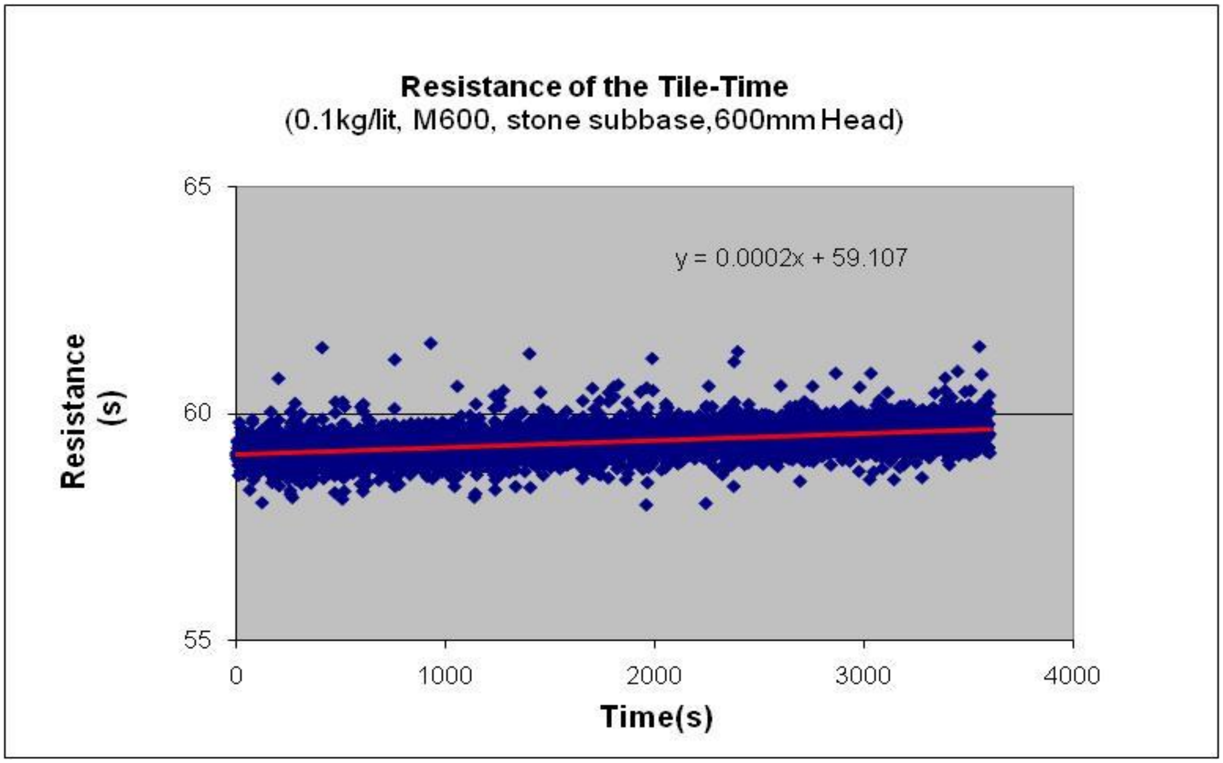


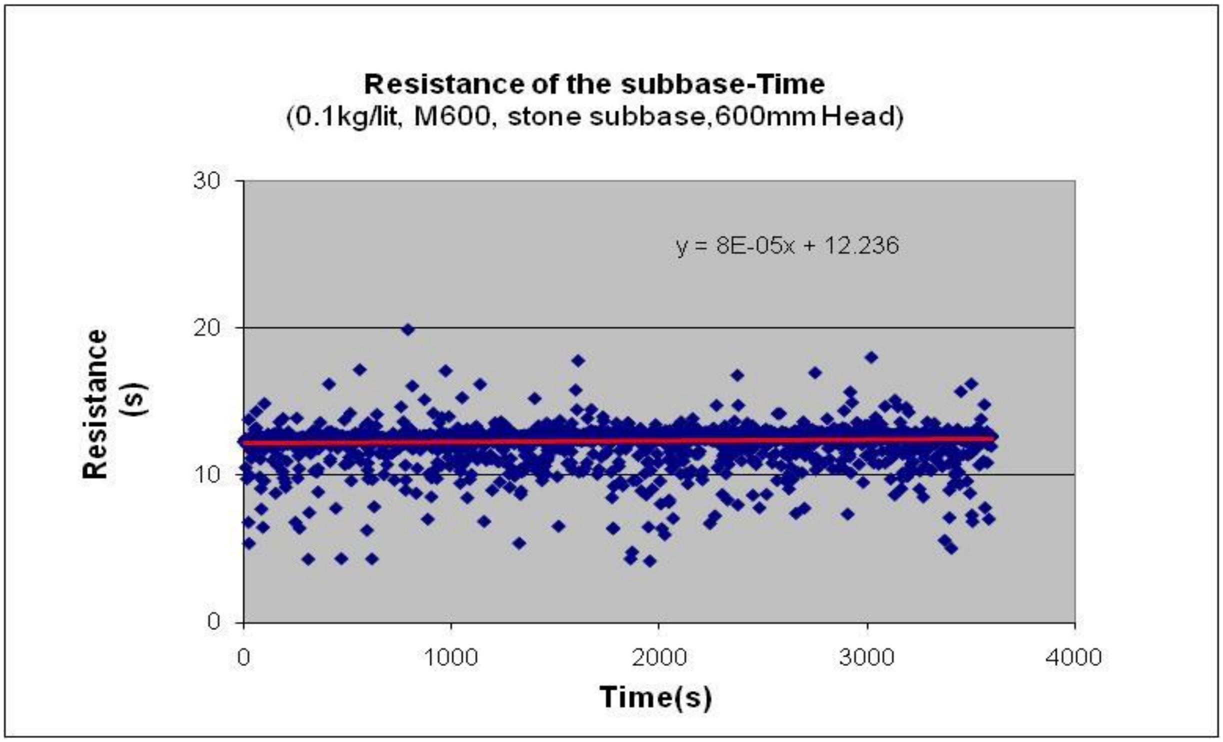
Like in the case of 150mm water level, the resistance is mainly through the tile rather than the sub-base. And the rate of increase in the resistance in tile is higher than the sub-base.

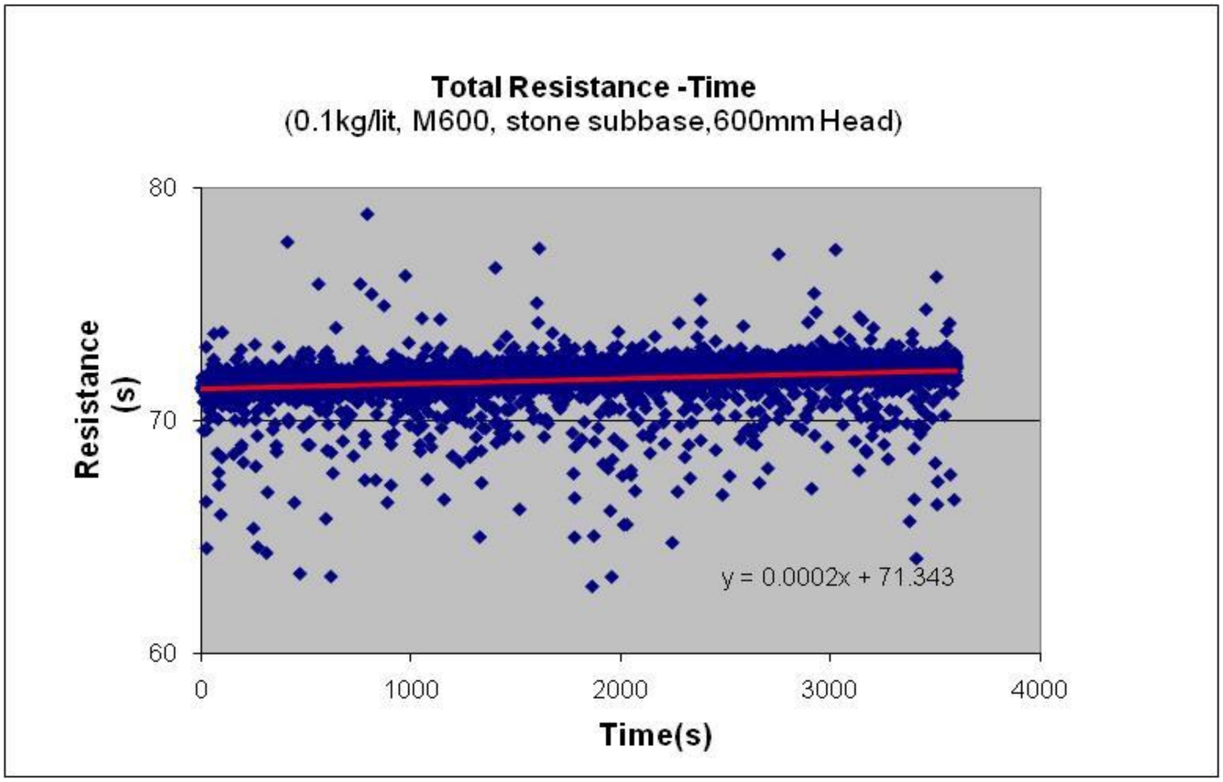


The graph shows the decrease in flow over the time. The intercept of the flux is close to the flux intercept in test without sub-base and is so higher than the test with sand sub-base

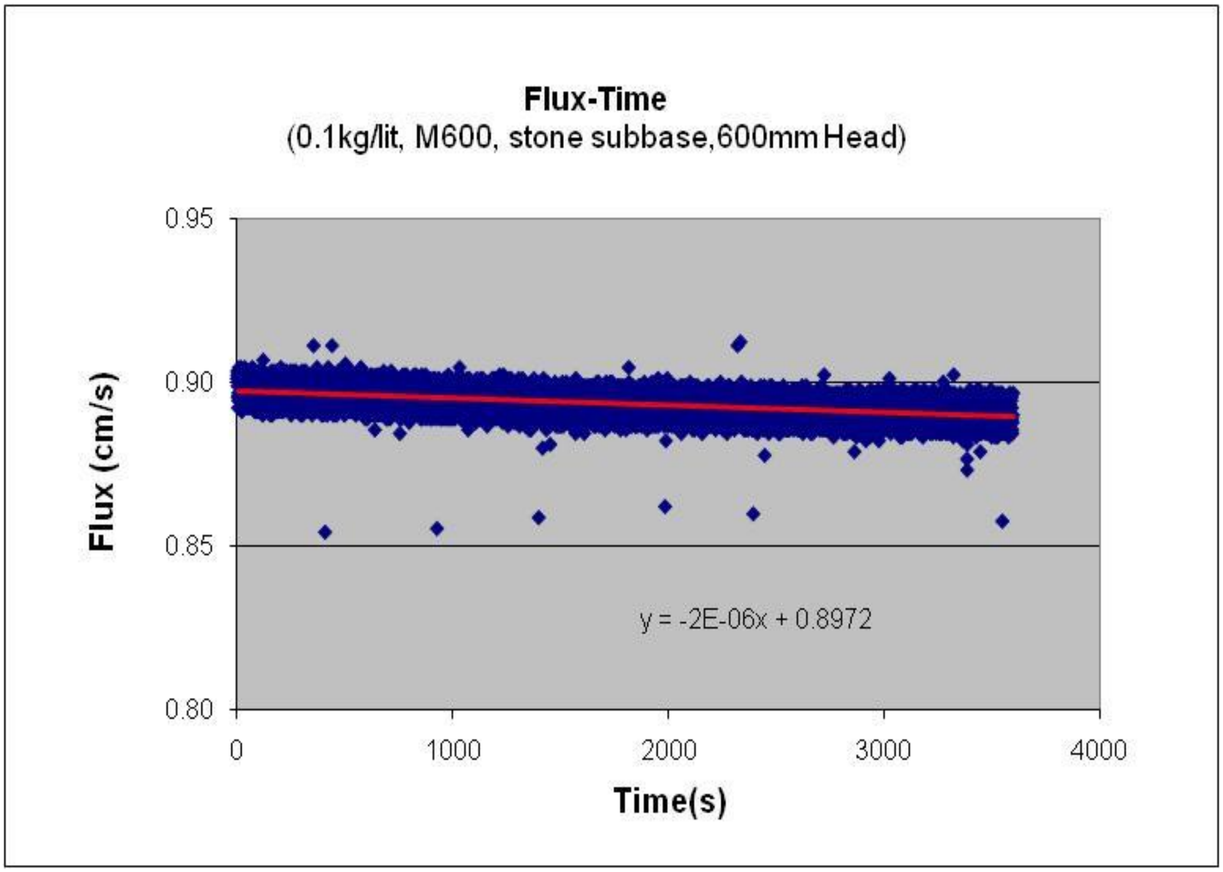
- **600mm Head**


Resistance of the Tile-Time
(0.1kg/lit, M600, stone subbase,600mm Head)
y = 0.0002x + 59.107
Resistance
(s)
65
60
55
0
1000
2000
3000
4000
Time(s)


Resistance of the subbase-Time
(0.1kg/lit, M600, stone subbase,600mm Head)
y = 8E-05x + 12.236
Resistance
(s)
30
20
10
0
0
1000
2000
3000
4000
Time(s)



Like the previous cases, the tile resistance is higher than the sub-base resistance, and the rate of this increase in the tile is faster than sub-base.



The graph shows the flux under 600mm water level. Like all the other tests, increasing the water level led to the higher flux.

6.2. Analysis:

6.2.1. Analyzing the flux equations:

- **Test without sub-base**

Table (6.1) Intercept of flux equation in test without sub-base

Sub-base	MS Concentration	Intercept of the flux equation(cm/s)		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base (M600)	0.05 kg/lit	0.6137	0.7668	1.0083
	0.1 kg/lit	0.5196	0.6556	0.8775

Comparing the intercept of the different heads shows that by increasing the head the flux will also increase.

Also increasing the concentration under the same heads shows less flux through the tile, this is because of more clogging in higher concentration.

Increasing the head in lower concentration (0.050kg/lit) has more effect to increase the flux rather than higher concentration (0.1 kg/lit), which shows in higher concentration due to the more clogging, increasing the head cannot increase the flux so much.

Table (6.2) Slope of the flux equation in test without sub-base

Sub-base	MS Concentration	Slope of the flux equation		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base (M600)	0.05 kg/lit	-3E-6	-3E-6	-3E-6
	0.1 kg/lit	-3E-6	-2E-6	-7E-6

In all tests the slope of the decrease in flux is so low over the time, which shows a very slow clogging over the time.

In case of 0.05 kg/lit concentration, the change in head did not change the slope of the flux reduction.

In case of 0.1 kg/lit concentration, by increasing the head from 150mm to 300mm the slope became lower. By changing the head from 300mm to 600mm the slope of reduction in flux is higher.

Under the same water level, the reduction in flux over the time does not have the same change. Under 150mm water level, there is no change in the slope, under 300mm water level, the reduction in lower concentration is faster, and under 600mm water level, the reduction in lower concentration is slower.

- **Test with sand sub-base**

Table (6.3) Intercept of the flux equation in test with sand sub-base

Sub-base	MS Concentration	Intercept of the flux equation(cm/s)		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with sand sub-base M600	0.05 kg/lit	0.0497	0.0582	0.0741

Increasing the water level could increase the flux, and the increase in flux by changing the water level from 300mm to 600mm is more than changing the water level from 150mm to 300mm,

Table (6.4) Slope of the flux equation in test with sand sub-base

Sub-base	MS Concentration	slope of the flux equation		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with sand sub-base M600	0.05 kg/lit	-6E-7	-5E-7	-2E-7

By increasing the head the rate of reduction in flux is decreasing over the time, and changing the water level from 300mm to 600mm could decrease this slope more than the other case.

- **Test with stone sub-base**

Table (6.5) Intercept of the flux equation in test with stone sub base

Sub-base	MS Concentration	Intercept of the flux equation(cm/s)		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with stone sub-base M600	0.1 kg/lit	0.5732	0.6998	0.8972

Increasing the head in test with stone sub-base also increased the flux, and the flux under different heads is almost like the result of tile without sub-base and 0.1 kg/lit concentration, which shows that the stone sub-base does not have any significant resistance through the flow.

Table (6.6) Slope of the flux equation in test with stone sub-base

Sub-base	MS Concentration	slope of the flux equation		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with stone sub-base M600	0.1 kg/lit	-3E-6	-7E-6	-2E-6

Increasing the head, did not change the slope of the flux reduction consistently. And the slope is also like the test of the tile without sub-base.
By increasing the head from 150mm to 300mm, the flux reduces with higher slope over the time, but by increasing the head from 300mm to 600mm the slope of flux reduction is slower over the time.

6.2.2. Analyzing the resistance equations:

- **Test without sub-base**

Table (6.7) Intercept of the resistance equation in test without sub-base

Sub-base	MS Concentration	Intercept of the Resistance equation(s)		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base (M600)	0.05 kg/lit	26.488	33.739	49.603
	0.1 kg/lit	25.78	46.515	63.178

In tests without sub-base, by increasing the head the resistance is also increased. This increase in resistance is due to the pressure drop in the system. As by increasing the head, flow is higher, therefore the pressure drop should be larger than increase in flow which causes higher resistance in higher water levels. The pressure drop is due to the clogging and also the turbulent flow in the tile. In the case of higher water level, the velocity and turbulence in the tile becomes higher which cause more resistance in the flow and consequently higher decrease in pressure.

In the concentration of 0.1 kg/lit, increasing the head from 150mm to 300mm has more effect on the increase in resistance. But changing the water level from 300mm to 600mm the increase in resistance in both cases are almost the same.

Under the 150mm water level, and different concentrations, the resistance in lower concentration is slightly higher than in case of 0.1 kg/lit concentration, which can be because of different tile properties.

Under 300mm water level, the resistance in higher concentration is higher which is logical (due to the more clogging and less flow)

Under 600mm water level, the resistance will increase by increasing the concentration.

In general it can be concluded that the higher concentration will increase the resistance.

Table (6.8) Slope of the resistance equation in test without sub-base

Sub-base	MS Concentration	Slope of the Resistance equation		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base (M600)	0.05 kg/lit	6E-5	0.0001	0.0002
	0.1 kg/lit	9E-5	0.0001	0.0006

By changing the water level the slope of increase in resistance is also increasing.

By changing the head from 150 to 300mm, the change in the slope in lower concentration is higher.

By changing the water level from 300 to 600mm, the increase in resistance in higher concentration is more.
Under the same water level, in higher concentration the slope is higher or the same.
In case of 150mm, it is 1.5 times higher and in case of 600mm its 3 times higher. (More increase in resistance over the time in higher concentration and higher water level)

- **Test with sand sub-base**

Table (6.9) Intercept of the resistance equation in test with sand sub-base

Sub-base	MS Concentration	Resistance	Intercept of the resistance equation(s)		
			Head and Duration		
			150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with sand sub-base M600	0.05 kg/lit	Tile	289.69	428.49	625.74
		Sand sub-base	281.46	265.33	234.56
		Total	571.15	693.82	860.29

The total resistance in all cases is more near to the tile resistance, by increasing the head the resistance of the sub-base is decreasing a little, although the resistance of the tile is increasing almost with the same rate(about 1.5 times higher in each case)
By increasing the head the difference between tile and sub-base is getting higher, although at the begging they were almost the same.

Table (6.10) Slope of the resistance equation in test with sand sub-base

Sub-base	MS Concentration	Resistance	slope of the resistance equation		
			Head and Duration		
			150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with sand sub-base M600	0.05 kg/lit	Tile	0.0035	0.004	0.0051
		Sand sub-base	0.0053	0.0041	0.0027
		Total	0.0087	0.0081	0.0078

In case of tile, the increase in resistance over the time in higher water levels is higher,
In case of sub-base and total resistance this slope is decreasing over the time.
Under the same water level, at 150mm water level, the slope in sub-base is higher and in case of 600mm the slope is tile is higher, and under 300mm water level they have the same change.

- **Test with stone sub-base**

Table (6.11) Intercept of the resistance equation in test with stone sub base

Sub-base	MS Concentration	Resistance	Intercept of the resistance equation(s)		
			Head and Duration		
			150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with stone sub-base M600	0.1 kg/lit	Tile	30.109	41.614	59.107
		Stone sub-base	17.213	14.241	12.236
		Total	47.322	55.855	71.343

The resistance is mainly through the tile rather than the stone sub-base.
By increasing the head the resistance in tile is getting higher although the resistance in stone sub-base is decreasing.
Increasing the head from 300mm to 600mm could increase the tile resistance more rather than the first change in water level.

Table (6.12) Slope of the resistance equation in test with stone sub-base

Sub-base	MS Concentration	Resistance	Slope of the resistance equation		
			Head and Duration		
			150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Test with stone sub-base M600	0.1 kg/lit	Tile	9E-5	0.0004	0.0002
		Stone sub-base	0.0001	0.0003	8E-5
		Total	0.0002	0.0008	0.0002

Increasing the head does not have a consistent change in the slope of the resistance.
By changing the head from 150 to 300mm, the slope is increasing, and this increase in the tile is more than the sub-base,
But changing the head from 300mm to 600mm the slope reduces, and this reduction in the sub-base is higher than the tile.

6.3. Discussion:

• Flux:

Table (6.13) Intercept of the flux equation in all tests

Sub-base	MS Concentration	Intercept of the flux equation(cm/s)		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base	0.05 kg/lit	0.6137	0.7668	1.0083
	0.1 kg/lit	0.5196	0.6556	0.8775
Tile With stone sub-base	0.1 kg/lit	0.5732	0.6998	0.8972
Tile With sand sub-base	0.05 kg/lit	0.0497	0.0582	0.0741

Comparison of flux intercepts in different tests shows that in all tests under higher water level and higher pressure, the flux is increasing.

In case of two tests without sub-base, higher concentration caused more clogging and consequently by filling the pores, conductivity and flux is decreasing more in compare of lower concentration.

Test with stone sub-base has almost the same result like test without sub-base, which shows that large pores size in the sub-base have less resistance through the flow.

In test with sand sub-base, the flux has significantly decreased in compare of other cases. This shows the high resistance of micro pores in the sub-base through the flow in compare of the larger pores in tile or in stone sub-base. Less available pores for flow reduce the conductivity and make more resistance through the flow travelling.

Table (6.14) Slope of the flux equation in all tests

Sub-base	MS Concentration	Slope of the flux equation		
		Head and Duration		
		150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base	0.05 kg/lit	-3E-6	-3E-6	-3E-6
	0.1 kg/lit	-3E-6	-2E-6	-7E-6
Tile with stone sub-base	0.1 kg/lit	-3E-6	-7E-6	-2E-6
Tile with sand sub-base	0.05 kg/lit	-6E-7	-5E-7	-2E-7

The table shows the slope of the flux equation in different cases.
In case of tile with 0.05kg/lit, the slope is constant over the time. In test of 0.1 kg/lit, the slope does not have a consistent trend by changing the water level. From 150 to 300 mm water level, the slope is decreasing and from 300 to 600mm the slope is increasing.
In test of stone sub-base, again slope does not have a consistent trend over the time. At first by increasing the water level the flux is reducing with a higher slope over the time and then from 300mm to 600mm the slope of reduction is decreasing.
In case of sand sub-base increasing the water level led to lower reduction in flux.

- ## Resistance:

Table (6.15) Intercept of the resistance equation in all tests

Sub-base	MS Concentration	Resistance	Intercept of the resistance equation(s)		
			Head and Duration		
			150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base (M600)	0.05 kg/lit	Tile	26.488	33.739	49.603
	0.1 kg/lit	Tile	25.78	46.515	63.178
Test with stone sub-base M600	0.1 kg/lit	Tile	30.109	41.614	59.107
		Stone sub-base	17.213	14.241	12.236
		Total	47.322	55.855	71.343
Test with sand sub-base M600	0.05 kg/lit	Tile	289.69	428.49	625.74
		Sand sub-base	281.46	265.33	234.56
		Total	571.15	693.82	860.29

The intercept of the resistance of all tests is presented in table (6.13).
As it is obvious, by increasing the concentration in tests with tile without sub-base, the resistance is increasing. Due to the higher concentration clogging will occur faster therefore by filling the pores with MS less pores is available for flow, as a result the resistance through the flow is higher and conductivity will decrease.
Comparison of the stone sub-base test with test without sub-base shows almost the same resistance for the tile in both cases. The resistance of the sub-base is lower than the tile, which shows higher conductivity of the sub-base due to the larger pores size and higher porosity. Also the total resistance is close to the tile resistance with smaller pores and less conductivity in compare of the sub-base. As the pores in the sub-base are large, clogging is not considerable in the sub-base. Therefore the resistance in the sub-base does not have any significant change. And by increasing the head and consequently increase in flux through the sub-base, the resistance through the sub-base is decreasing which shows less pressure drop over the large pores of the stone sub-base.
In case of sand sub-base, the resistance of the tile is highly increased in compare of the first two tests without sub-base. Also as it was shown in test with clean water, the resistance was mainly through the sand sub-base. But in test with MS, the resistance is mainly through the tile. As it was

shown in figure (5.18) the interface of the tile and sand was covered by the Microsilica, which means the Microsilica was washed through the tile and accumulated on the sand sub-base. In addition as the pressure sensor which measures the pressure under the tile, is not exactly under the tile (figure 5.1, Schematic view of the setup) and was placed under first layers of the sand sub-base, this big reduction in pressure can be explained by clogging of the first layers of the sand and covering the interface by Microsilica.

Table (6.16) Slope of the resistance equation in all tests

Sub-base	MS Concentration	Resistance	Slope of the resistance equation		
			Head and Duration		
			150mm/ 1hour	300mm/ 1hour	600mm/ 1hour
Tile without sub-base (M600)	0.05 kg/lit	Tile	6E-5	0.0001	0.0002
	0.1 kg/lit	Tile	9E-5	0.0001	0.0006
Test with stone sub-base M600	0.1 kg/lit	Tile	9E-5	0.0004	0.0002
		Sand sub-base	0.0001	0.0003	8E-5
		Total	0.0002	0.0008	0.0002
Test with sand sub-base M600	0.05 kg/lit	Tile	0.0035	0.004	0.0051
		Sand sub-base	0.0053	0.0041	0.0027
		Total	0.0087	0.0081	0.0078

Table (6.14) shows the slope of the resistance equations in different tests.
Comparing different cases does not show any consistent trend in increase of resistance over the time.
In case of tile without sub-base increasing the water level led to increase in the resistance slope.
But on other cases increasing the water level led to both decrease and increase in the slope.

7. Conclusion and recommendations:

7.1. Conclusions:

In order to assess the effect of dust storms in semi-arid areas on clogging of porous pavements, and also increase the infiltration through them four main steps, which were explained in section 1.4, were done. The conclusions of these steps can be summarized as follows:

Proper type of permeable pavements to use in semi arid areas:

- Available types of permeable pavements can be divided to: porous aggregate, plastic geocells, porous turf, open jointed paving blocks, open celled paving grids, porous asphalt, porous concrete, soft paving materials and decks.
- To select the proper type of porous pavements in different regions there is not a conclusive subdivision. Two main factors that are mostly considered to categorize them are bearing capacity of the pavement and also freezing or swelling soil conditions in the region.
- Considering the bearing capacity of this kind of pavements is the main factor to categorize them in order to apply them in different places with different traffic loads.
- Under climatic condition, usually cold areas and also places where the swelling of the soil is probable have been considered. Porous aggregates, plastic geo-cells, porous turf, open-jointed paving blocks and also decks are recommended to use in these areas. Previous experiences in dry regions show that porous concrete is also suitable to apply in these conditions.

Factors that influence the urban runoff and infiltration rate:

- In semi-arid areas, in order to increase the infiltration rates, the capturing capacity of the infiltration facility should be taken into account. This can be obtained by proper design of the pavement and also prevent the clogging in the facility.

- Infiltration of the flow through the porous medium depends on its physical properties. This conductivity is mainly defined by the average grain size of the medium and its porosity.
- Due to the clogging, fewer pores will be available for the flow migration. Therefore more resistance will be through flow travelling, and conductivity which is the ease of water travelling will decrease.

Clogging process and factors that influence the clogging:

- Filling the pores of the porous pavement with sand is the beginning of the clogging process.
- Obstruction of the pores between sand grains by finer elements is the next step of the clogging process.
- The best way to prevent rapid clogging in porous pavements is their application in proper place. It is not recommended to use them on polluted areas. Also maintenance such as vacuuming of debris and pressure washing could restore the infiltration rate in porous pavements.
- In addition this study showed that large pore size in porous pavement allows fine sediments to be washed through it to the sub-base of the pavements.

Conclusions from **factors in semi-arid areas that influence the clogging:**

- In semi-arid regions the percentage of the covered areas by vegetation is low. Therefore such are highly vulnerable to wind erosion, and erosion can be considered as the main source of dust production in these areas.
- Wind suspended particles have small diameter typically smaller than 20micrometer and can travel thousands of kilometers from the source and be suspended for several days.
- As clogging happens in long term and is not a fast process, the wind suspended particles smaller than 20 micro meters can be considered as the size of sand particles that cause clogging.

Conclusions from **Lab testing of the clogging process**:

- Results of the tests without sub-base show that the clogging process was very slow .Fine particles were washed through the tile into the sub-base.
- In case of stone sub-base the results are close to the result of tests without sub-base, which shows that stone sub-base with large pores does not have significant effect on clogging process and clogging in this case is mainly through the tile.
- In case of test with sand sub-base and with pure water, due to the very fine pores in the sub-base, the flow was significantly reduced in comparison with the other tests, which shows the significant resistance of the sub-base through the flow.
- In test with sediment loaded water and sand sub-base, the interface of the tile and sub-base was covered by the MS, which shows that sediments were washed through the tile and by covering the interface, the flow path was blocked. The low concentration of Microsilica in sand sub-base (Annex VIII) also confirms it.

- Comparing the results of different sub-bases shows the significant effect of the pores size in the sub-base on the clogging progress, beside the porosity of the pavement. In case of sand sub-base, due to the small pores in the sub-base, migration of the sediment grains through the sub-base cannot be done easily which results to the blocking of the first layers of the sub-base and more resistance through the flow.
- Due to the clogging in different tests, the decrease in infiltration rate over the time does not have any consistent trend.
- Observation from the tests with larger particles (M6.1) shows the rapid clogging in tile (without sub-base) and also in case of sand sub-base. Especially in case of sand sub-base the flow from the beginning of the experiment was very small. Therefore in order to design the pavement, average size of particles that can go through it should be taken into account.
- As it was concluded from literature studies, semi-arid areas can be regarded as not proper place for the application of the porous pavements, due to the high wind erosion and dust production. But as the result of this research showed that by using a porous sub-base, at least as porous as the pavement, the infiltration capacity can significantly be increased and the clogging risk is reduced.

7.2. Recommendations

- A porous sub-base can highly increase the infiltration rate through the system. But in practice placement of the pavement over a highly porous material (like gravel in this research) potentially leads to reduction in its bearing capacity. Therefore more studies on the proper porous sub-base are needed.
- As semi-arid areas are mainly in developing countries, due to the lack of financial sources, education and management, the maintenance of porous pavements might not be done regularly. This will lead to the decrease of the working life of the pavement. Therefore these matters should be taken into account to select the proper type of pavement in different places.
- Effect of other factors such as the erosion of the pavement under climatic condition on clogging process can be done in future studies.
- Not only the porosity of porous pavement is important but also the pore diameters, as these are relevant to the clogging by fine particles. Information on pore diameter should be included in the product information.

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Annexes

Annex I:

Porous concrete pavement construction:

- **Construction**
    - **Sub grade and Sub base Preparation**

One of the preparations that should be done before the placement of the pervious concrete is the compaction of the sub grade. The proper compaction should be done to reach to the minimum density of 90 % to 95 % of theoretical density. When the sub grade is compacted less than 95%, more thickness of the sub-base or the pavement can compensate the soft sub grade. However the soil permeability will decrease by increasing the density. Before placement of the pavement the sub-grade must be moist enough. It should be done to prevent removing water by the lower part of the pavement too soon. In case of conventional concrete pavement, especially when the rate of evaporation is high, this practice is highly recommended. This is more important in previous concrete placement, because the pores in the pavement cause more and rapid evaporation and drying of the pavement, which decrease the strength and durability of the pavement.[2]

- **Batching and mixing**

In pervious concrete in order to provide the adequate strength and permeability, the water content is limited to a narrow range. But also to prevent the flowing off the aggregates a tighter control is needed as well. More water content in pervious concrete has more drastic impact than in conventional concrete.” The water content must be sufficient to allow the cement paste to coat the aggregate particles, but it is strictly limited by the danger of the overly wet paste draining through the material’s pores. Drainage would leave aggregate particles in the upper part of the slab without adequate binding, and an accumulation of excess paste would clog the voids at the bottom. A proper mixture of pervious concrete before delivery at the job site should be done. Sometimes at the site a slight change is necessary to achieve proper consistency. A unit weight test of the mix can show the proper mixture proportions. Typical unit weights are in the range of 1600 kg/m^3 and 2000 kg/m^3, and on-site measured values are typically 5% of the design unit weight.[2]

- **Transportation**

Due to the low water content of the pervious concrete, its discharge from the transit mixer is slower than conventional concrete. In this case transit mixers with large discharge openings can provide faster unloading time. The mixture should be discharged within one hour after initial mixing. Application of the retarding chemical admixtures or hydration-stabilizing admixtures can extend the discharge time to 1 ½ or more.[2]

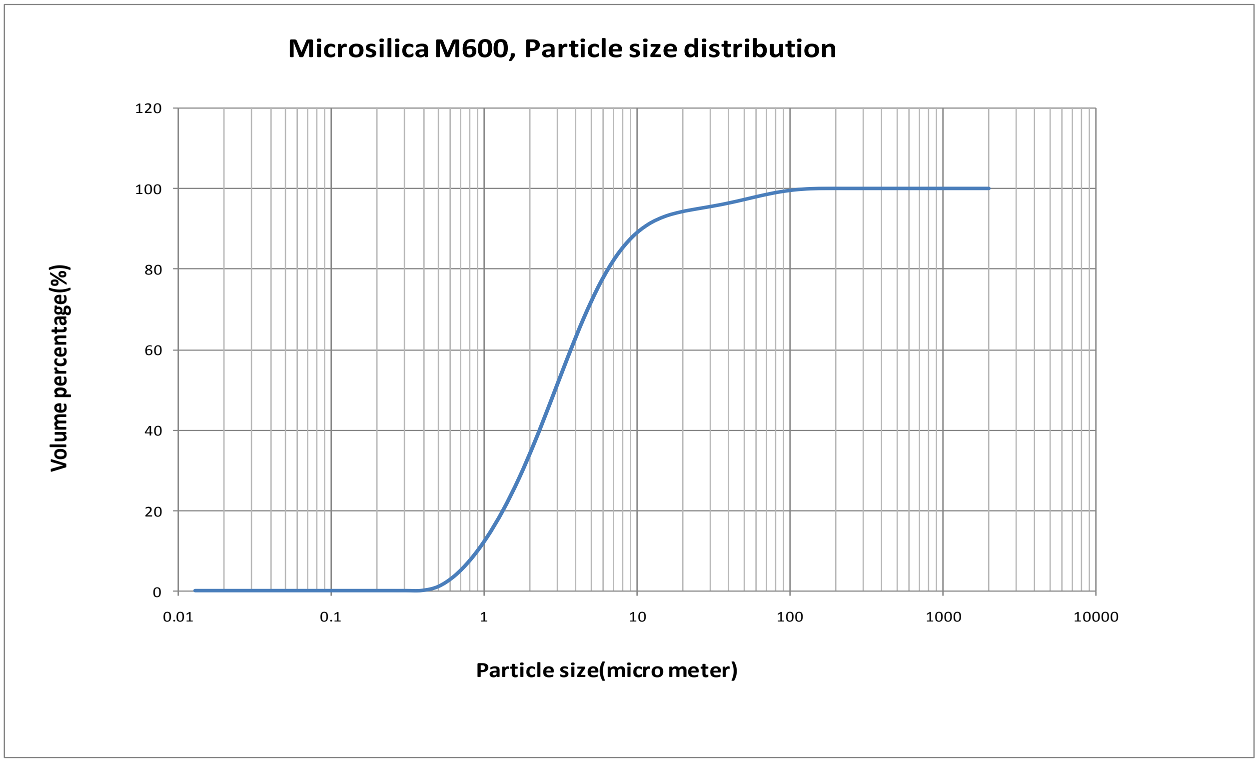
- **Placement**

The placement of porous concrete is different from dense concrete. After placement the concrete, compaction should be done by rolling it to its finished elevation. By rolling the contact of surface aggregate particles will increase. Compaction should be controlled to preserve void space. A vibratory screed that is used for dense concrete is not proper for porous concrete, as it smears the cement across the pores which seal the surface. Also other common finishing operations such as floating and brooming should not be done in porous concrete, as they also seal the surface pores. As the moisture content in porous concrete is low, it sets quickly, and also the evaporatin rate through the open pores is high. Therefore to preserve the moisture in the mixture to complete the hydrating reaction, it is necessary to work quickly after concrete placement. In order to prevent drying, after rolling the concrete surface should be covered by plastic sheeting which should be remained for a number of days.[2]

Annex II:

M600, Grain size distribution,

(Measured in the lab)



Annex III

Mesh Specification:

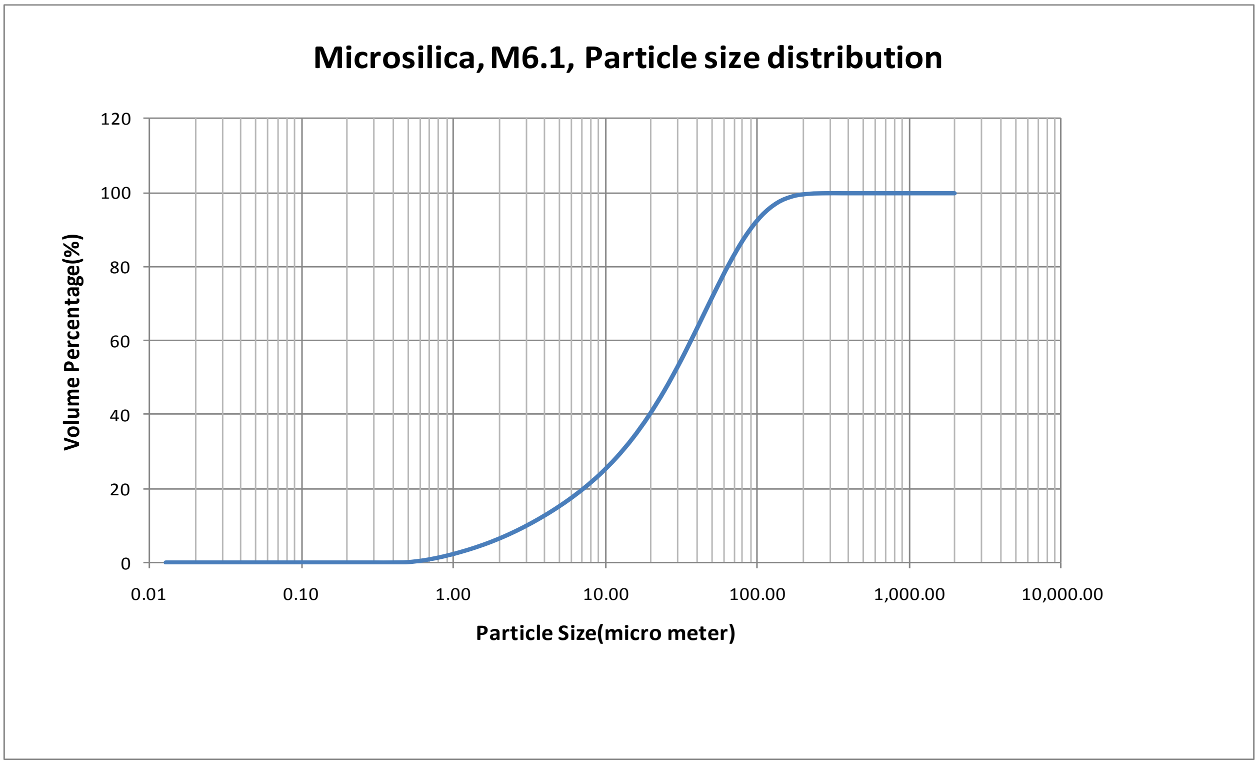
Standard woven mesh specification AISI-316

Mesh number	Wire Diameter (mm)	Opening (mm)	Width (mm)	Opening (mm)	Width (mm)	Open area (%)	Binding	weight (kg/m^2)
2,0	2,0	1,200	1,200	11,500	1000	82	plain	1,45
2,0	2,0	1,600	1,600	11,100	1000	76	plain	2,59
3,0	3,0	1,600	1,600	6,867	1000	66	plain	3,88
4,0	4,0	1,200	1,200	5,150	1000	66	plain	2,91
4,0	4,0	1,600	1,600	4,750	1000	56	plain	5,17
5,0	5,0	1,000	1,000	4,080	1000	65	plain	2,53
6,0	6,0	0,900	0,900	3,333	1000	62	plain	2,45
7,0	7,0	0,800	0,800	2,829	1000	61	plain	2,26
8,0	8,0	0,700	0,700	2,475	1000	61	plain	1,98
10,0	10,0	0,600	0,600	1,940	1000	58	plain	1,82
10,0	10,0	1,000	1,000	1,540	1200	37	plain	5,05
12,0	12,0	0,500	0,500	1,617	1000	58	plain	1,52
13,0	13,0	0,450	0,450	1,504	1220	59	plain	1,33
14,0	14,0	0,400	0,400	1,414	1000	61	plain	1,13
16,0	16,0	0,370	0,370	1,218	1000	59	plain	1,11
16,0	16,0	0,450	0,450	1,138	1000	51	plain	1,64
18,0	18,0	0,280	0,280	1,131	1000	64	plain	0,71
18,0	18,0	0,350	0,350	1,061	1000	57	plain	1,11
18,0	18,0	0,400	0,400	1,011	1200	51	plain	1,45
20,0	20,0	0,340	0,340	0,930	1000	54	plain	1,17
20,0	20,0	0,400	0,400	0,870	1220	47	plain	1,62
25,0	25,0	0,300	0,300	0,716	1000	50	plain	1,14
30,0	30,0	0,260	0,260	0,587	1000	48	plain	1,02
36,0	36,0	0,240	0,240	0,466	1000	44	plain	1,05
40,0	40,0	0,220	0,220	0,415	1000	43	plain	0,98
45,0	45,0	0,200	0,200	0,364	1000	42	plain	0,91
50,0	50,0	0,200	0,200	0,308	1000	37	plain	1,01
60,0	60,0	0,160	0,160	0,263	1000	39	plain	0,78
60,0	60,0	0,190	0,190	0,233	1000	30	plain	1,09
60,0	60,0	0,190	0,190	0,233	1220	30	plain	1,09
70,0	70,0	0,150	0,150	0,213	1000	34	plain	0,80
75,0	75,0	0,140	0,140	0,199	1000	34	plain	0,74
80,0	80,0	0,130	0,130	0,188	1220	35	plain	0,68
80,0	80,0	0,140	0,140	0,178	1525	31	plain	0,79
80,0	80,0	0,170	0,180	0,148	1380	22	plain	1,17
90,0	90,0	0,112	0,112	0,170	1000	36	plain	0,57
100,0	100,0	0,112	0,112	0,142	1220	31	plain	0,63
100,0	100,0	0,112	0,112	0,142	1525	31	plain	0,63
120,0	120,0	0,080	0,080	0,132	1220	39	plain	0,39
120,0	120,0	0,090	0,090	0,122	1525	33	plain	0,49
130,0	130,0	0,080	0,080	0,115	1220	35	plain	0,42
140,0	140,0	0,080	0,080	0,101	1000	31	plain	0,45
145,0	145,0	0,060	0,060	0,115	1220	43	plain	0,26
150,0	150,0	0,065	0,065	0,104	1220	38	plain	0,32
150,0	150,0	0,065	0,065	0,104	1525	38	plain	0,32
165,0	165,0	0,050	0,050	0,104	1220	46	plain	0,21

Annex IV:

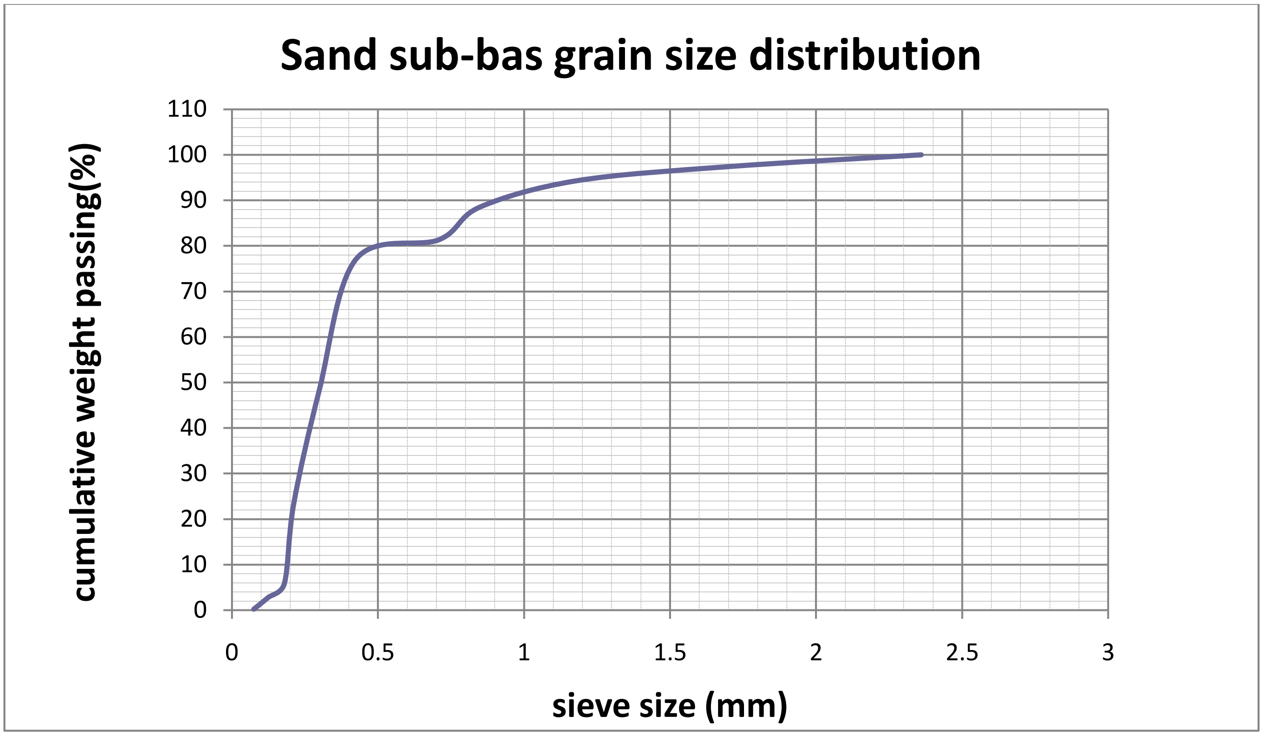
M6.1 Grain size distribution:

(Measured in the lab)



Annex V:

Sand sub-base Grain size distribution:



Annex VI :

Explanation of wrong results

As it was explained in the report, the results of some tests were not acceptable. For instance:

- The flow was increasing during the test which is not correct, as the clogging will decrease the flow or at least the flow should remain constant during the test.
- The measured pressures did not have a logical trend. For instance the pressure was decreasing and after a while increasing.
- Calculated resistance had a decreasing trend, but it is clear that by increasing the clogging the resistance should increase as well.

One reason for these errors in the results can be the existence of air in the system. Filling the interior box with higher water level and gradually decreasing the level to lower ones at the beginning of the test, also filling the system from the discharge pipe first by fresh water can deaerate system.
The existence of air in the pump (with regulator) can be another cause. Placing the inlet pipe of the pump at the bottom of the mixing basin and keep it fixed there could solve this problem.

Annex VII :

Sand classification

ASTM Particle Size Definition:

Definition	ASTM Metric Size (mm)	ASTM U.S. Size(inch)
Fine Gravel	4.76 to 10.0	4 to 3/4"
Coarse Sand	2.0 to 4.76	10 to 4
Medium Sand	0.42 to 2.00	40 to 10
Fine Sand	0.074 to 0.42	200 to 40
Silt and Clay	<0.074	< 200

Annex VIII :
Concentration of M600 in sand sub-base

- After the test a sample of sand sub-base was taken from the cross-section. The sample was wet and included Microslica. The sample was mixed by water to wash it, and after each time the used water was collected. This was repeated until reaching to clean water from the sand to be sure that all Microsilica was washed from the sand. Then collected water (which includes Microsilica) was left for couple of days to settle all Microsilica particles in the vessel. After that the deposited layer at the bottom of vessel was dried in oven and weighted. The clean sand sample was dried in the oven as well.
  The measured weight of sand is as follows:

Density of the applied sand:	2.68 gr/cm^3
Weight of the dry sand sample (dried by oven):	390.5 gr
The volume of dry sand:	390.5/2.68=145.7 cm^3

In order to find the pores volume of the sand, the sample was filled with water up to the surface of the sample. Then it was weighted again and the difference shows the weight of water :

Clean water content:	81 gr
The volume of the water shows the volume of the voids in sand:	81 cm^3
Total weight of the vessel contained water and Microsilica:	514 gr
Vessel weight: 490 gr ➔ weight of Microsilica:	514-490= 24 gr
Microsilica concentration :	24/(24+390.5) *100= 5.8%