**KTH Land and Water
Resources Engineering**

Hydrophobic Sand To Combat Water Scarcity - Properties And Possible Chemical Risk

Sundus Alazawi

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SUMMARY IN SWEDISH

Under de senaste decennierna har bristen på vattenresurser i världen blivit alltmer allvarlig, men vissa delar av världen har drabbats mer än andra. Ett exempel på ett sådant område är Mellanöstern, särskilt i Gulfregionen. Detta examensarbete utgår från vattenbristen i Dubai, vilken är en av de större städerna i Förenade Arabemiraten. Dubai är känt för sin moderna livsstil, sin expansion och snabba tillväxt. Detta ställer stora krav på vattenresurserna. Stadens vattenförsörjning är huvudsakligen beroende av avsaltning av havsvatten, och till en mindre del på grundvatten. Dock har den låga årsnederbörden och saltinträngning från havet lett till att användningen av grundvatten minskat avsevärt. Eftersom kostnaderna för avsaltning av havsvatten är jämförelsevis höga, är det bråttom att finna nya lösningar för att lösa vattenresursbehovet. En tänkbar lösning för att minska de vattenmängder som används för jordbruk och bevattning av parker är att använda så kallad hydrofob sand.

Hydrofob sand är normal sand som behandlats med organiska kiselföreningar. Med användning av nanoteknik kan man låta den hydrofoba organiska föreningen trimetylsilanol bilda en tunn beläggning som täcker sandpartiklarna vilket gör att sanden blir hydrofob (dvs. vattenavstötande). Dock har det funnits farhågor om utlakning av skadliga organiska kemikalier, som används vid behandlingen, till mark- och grundvatten. Dessutom kan användningen av hydrofob sand i stora områden bli mycket kostnadskrävande.

Ett syfte med examensarbetet var därför att bedöma de kemiska risker som kan påverka miljön till följd av användningen av hyrdofob sand. För detta ändamål har flera laktester gjorts, dels med normal sand från Dubai och dels med hydrofob sand som ställs till mitt förfogande av ett företag som förväntas förse de lokala marknaderna med denna produkt. Ett antal utvalda element och näringsämnen testades. Dessutom extraherades vissa laktestprover med hjälp av en organisk fas för att bestämma koncentrationen av organiska kiselföreningar och alltså undersöka möjlig utlakning av organisk trimetylsilanol.

Ett annat mål med examensarbetet var att undersöka hur permeabiliteten av sand förändras vid blandning av hydrofob sand med normal sand. En sådan blandning skulle kunna minska mängden använd hydrofob sand och därmed minska kostnaderna utan att äventyra dess effektivitet. Permeabilitetstester genomfördes och olika kombinationer av normal sand och hydrofoba sandlager testades. Dessutom undersöktes hur olika procentsatser av hydrofob sand och normal sand påverkade resultatet. Tryckhöjden i permeabilitetstestet varierades också för att undersöka effekten av vattentrycket på den hydrofoba sandens permeabilitet. Dessutom undersöktes provernas specifika vikt samt jordartsklass.

Resultaten visar att koncentrationen av utlakade ämnen och näringsämnen var inom de tillåtna gränser som anges av EPA (det amerikanska Naturvårdsverket). Dock var vissa resultat mycket osäkra på grund av de låga koncentrationerna. Ett exempel var koncentrationen organiska kiselföreningar som befanns vara mycket låg. Detta kan förklaras genom att trimetylsilanol brutits ned eller omvandlats till andra föreningar, eller genom att föreningen bundits så starkt till jorden så att mycket låga koncentrationer återfinns i lakvattnet. De tester som gjorts tyder alltså på att den hydrofoba sanden inte orsakar miljöskadliga effekter i mark- och grundvatten. Dock analyserades inte koncentrationen av andra, kiselfria, organiska föreningar i detta arbete, och detta förblir en viss osäkerhet som behöver undersökas i framtida arbeten.

När det gäller permeabilitet har resultaten visat att blandning av normal sand med hydrofob sand ökar permeabiliteten jämfört med endast normal sand. På grund av den hydrofoba karaktären av hydrofob sand tenderar partiklarna att vidhäfta till varandra och bilda klumpar vilket ökar porstorleken. Det tog också längre tid att mätta den hydrofoba sanden jämfört med normal sand. Därför rekommenderades att man bör undvika att blanda hydrofob sand med normal sand. I stället bör ett lager av normal sand placeras över ett skikt av hydrofob sand. Vatten kommer då att finnas kvar i det

normala skiktet under en relativt lång period vilket ger tillräckligt med tid för växterna att utnyttja vattnet. Djupet av det hydrofoba skiktet bör dimensioneras utgående från vilken typ av vegetation som är aktuell.

SUMMARY

Shortage of water resources has caused a serious problem in the recent decades for the whole globe; however it has dramatically affected some parts of the world more than others. One of these parts is the Middle East, especially in the Gulf Region. The case study of this thesis lies in Dubai, one of the major cities in the UAE. This city is well known by its modernized life style, its urban expansion and its rapid growth. This modernity is accompanied by extreme demands for water resources. The city depends mainly on sea water desalination and occasionally on ground water wells. Limitations of rainfall averages and salt intrusion have considerably reduced the usage of ground water. As the cost of sea water desalination is comparatively high, the need for a replacing solution was urgent. One of the solutions was reducing water quantities consumed for agriculture and watering of parks by using hydrophobic sand.

Hydrophobic sand is normal sand treated by organic silica compounds. With the usage of nanotechnology, the hydrophobic organic compound of trimethylsilanol forms a thin coating that covers normal sand particles and causes sand hydrophobicity to water. However, concerns were raised about the leaching of harmful organic chemicals, used in the treatment procedure, into the soil and ground water. Also, using hydrophobic sand in large areas for agriculture purposes may require high costs.

The above mentioned concerns were the foundations for this thesis. Assessing the chemical risks that might affect the environment as a result of using the chemically treated sand was one of the objectives. For this purpose, several leaching tests were conducted.

A number of selected elements and nutrients were tested using samples of normal sand from Dubai and samples of hydrophobic sand obtained from the company that is expected to provide the local markets with this product. Also, leaching tests using an organic phase to extract the organic silica compounds were undertaken in order to examine the leaching of the organic trimethylsilanol.

The other objective was testing the permeability of sand when mixing hydrophobic sand with normal sand in order to reduce the quantity of the used hydrophobic sand and consequently reduce the costs without compromising its efficiency. Constant head permeability tests were implied and different configurations of normal sand and hydrophobic sand layers were tested. Also different percentages of hydrophobic sand and normal sand were mixed. The water head in the permeability test was also changed to investigate the effect of water pressure on the hydrophobic sand permeability. Additionally, the specific gravity and the soil classification were examined.

It was concluded from the lab results and the discussion part that the leached elements and nutrients were within the allowable limits set by the EPA; however some results were very low, which make them uncertain. As for the leaching of the organic silica compounds, very small concentrations were leached which is explained either by the decomposition of the trimethylsilanol or by it being combined to the sand particles or not being leached and extracted in harmful concentrations. The tests indicate that hydrophobic sand does probably not constitute an environmental hazard. However, additional investigations need to be undertaken to examine the probability of the existence of other silica- free organic compounds in the leachate.

As for the permeability tests, the results have shown that mixing normal sand and hydrophobic sand, at different mixing percentages, increased the permeability compared to the case with only normal sand was used. Because of the hydrophobic character of the hydrophobic sand, particles tend to adhere to each other and form clumps when saturated with water which increase the particle voids. Also it was noticed that the saturation period for the hydrophobic sand is considerably higher than the saturation period for normal sand. Accordingly, it was recommended to avoid mixing hydrophobic sand with normal sand, instead a layer of normal sand should be placed over a bottom layer of hydrophobic sand. Water will be trapped in

the normal layer for a relatively long period and consequently enough time will be provided for the plants to utilize water. The depth of the hydrophobic layer will be designed according to the type of the planted vegetation and its need for water.

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Sundus Alazawi

TABLE OF CONTENTS

Abstract

The city of Dubai, which lies in the Middle East is, as many other cities in the area, suffering from shortage of fresh water resources. This issue is handled by desalination of sea water, which is a rather expensive procedure. Recently, the city tends to promote using hydrophobic sand in order to reduce irrigation water quantity and watering durations. Economically, this procedure has fewer costs than water desalination but concerns were raised regarding whether the chemical compounds, used in the treatment process of normal sand, impose any contamination risks for soil and groundwater.

Due to the fact that normal sand has high permeability comparing to other types of soil, such as silt and clay, the rates of water seepage in normal sand is considerably high which results high water consumption in agriculture. One of the objectives of this thesis is to identify the most effective design for utilizing hydrophobic sand and normal sand layers to obtain the most suitable permeability rates for plantation purposes. Another objective is to discuss the probability of organic chemicals and heavy metals seepage when using the hydrophobic sand in soil; leaching tests were carried out to provide input to this discussion. The study showed that the hydrophobic sand has higher permeability than normal sand when it is saturated with water. However, it needs a considerably longer time in order to reach the saturation stage so recommendations were provided to use a separate layer of hydrophobic sand beneath the normal sand layer where vegetation is planted and avoid using sand mixtures.

Based on the leaching tests' results, it was also concluded that negligible concentrations of the organic silica compounds will be released into soil and ground water and the rates of heavy metals in leaching water were within the allowable limits. However, the possibility of the transformation of the organic compounds, used for normal sand treatment, into silica-free organic compounds was not discussed in this thesis. In other words, the usage of hydrophobic sand for agriculture purposes does not threaten the safety of neither soil nor groundwater concerning the leaching of the chemical compounds and metals that were tested in this study.

Introduction

Water scarcity has always represented an issue in most parts of the Middle East where the draught and high temperature form the main weather conditions throughout the year and lack of natural water resources has caused considerable shortage of water supplies. With the continuous climate change that is affecting the whole globe and scarcity of rainfall, the problem of water shortage will have a greater impact in the future and will also affect wider regions (Pimentel et al, 2004).

Dubai, which is one of the main cities in the United Arab Emirates, is also suffering from scarcity of water resources (Fig.1). The region, where Dubai lies, has a desert climate with neither rivers nor lakes and it rarely rains so depending on groundwater as a resource for water is out of question (Salem et al, 2010).

This city is glowing with modernity and high level of technology; nevertheless, it is still fighting to provide water for different purposes. Increasing of population and rapid urban development, massive number of construction projects all over the city, recreation areas and parks, developing of agricultural projects, all of that has increased the demands for water. The present technique used for providing water in Dubai is the desalination of sea water. This technique is relatively expensive but it

Fig.1. Emirates map, (Förenade Arbemiraten, 2015)

is considered as the main method for obtaining water in this desert atmospheric area. Consequently, limiting and controlling the usage of water is a main requirement in the city and the country as a whole. Also, researchers recommend cutting water consumption quantity to avoid severe water scarcity in Emirates in the future by a number of solutions, among that is increasing awareness about the necessity of rational consumption of water, minimize the usage of water in agriculture and farming, prevent polluting and overexploitation of groundwater and protect it from salt deterioration. Reclamation of water used for irrigation and using dripping irrigation technique are some common ways that are used in Dubai to control and reduce the quantity of irrigation water (DIME, 2014).

Since 85 % of water is consumed in irrigation (Salem et al, 2010), the present trend is to control and reduce it to the minimum quantity that maintains good cultivation. One of the most recent techniques for reducing water consumption in irrigation is using hydrophobic sand layers in the sandy areas, which represent the major nature of the region (Salem et al, 2010). This new trend is still under investigation in Dubai and is used in some limited areas. But if it is approved to be as safe for the environment as the production companies describe then using it will form an effective tool for decreasing water consumption. Normal sandy soil is known with its high rates of seepage for water. Plants' roots in sandy soil have considerably limited time to exploit irrigation water because of the high permeability of sand. Water tends to drain quickly into deeper layers, sweeping soil nutrients. Hydrophobic sand is normal sand treated with organic chemical materials which turn it into hydrophobic soil to water. Hydrophobic sand assists to preserve water for longer time; consequently the plants' roots will have relatively enough time to utilize water and the nutrients which exist in soil.

OBJECTIVES

The objective of this master thesis is to investigate and assess the chemical risks that threaten the environment when adding hydrophobic sand layers to normal sand. This will be achieved by studying and testing the quality of water in the soil where the hydrophobic sand is used in order to analyze the impacts of using organic chemical compounds in coating normal sand. Leaching tests are carried out to determine the

maximum release and the rate of release of these chemicals into the soil and consequently to the groundwater and whether they produce any type of pollution into the soil and groundwater.

Also implying experiments in order to achieve the optimal soil permeability by mixing different quantities of the original normal sand and hydrophobic sand and implying permeability tests until the most suitable permeability, for plants' irrigation purposes, is obtained.

BACKGROUND

Normal sand

The nature of soils in UAE is mostly of silty sand, the percentage of sand in the soil is about 85 %. The concentration of organic matter is very low, between 0.1 and 0.2 %. In general, the concentrations of main elements are rather low comparing with other types of soils. For example, nitrogen (N) concentration ranges between 5-10 ppm (part per million) while phosphorus (P) has concentration range of about 1.5 ppm and potassium (K) has also a low concentration that ranges between 14-100 ppm (Salem et al, 2013).

The concentrations of other compounds that are considered as minor elements are also low comparing to other types of soils in other areas around the world. For example, the concentration of calcium carbonate ranges between 20-40 % (Salem et al, 2013). The surface of the sand grains is bonded to hydrogen atoms by covalent bonds, which are polar bonds, where pairs of electrons are shared between the atoms. Since water molecules have also polar bonds and are considered polar molecules, thus they tend to be attracted to the normal sand grains. Consequently, normal sand is considered as a hydrophilic material and water spreads into the sand layer without forming drops or bead on top of normal sand surface (Healy & Brunner, 2007).

Hydrophobic sand

A hydrophobic surface has the characteristic of not adsorbing water or be wetted by water (Fig.2). In other words, if the forces accompanied with the interaction of surface with water are higher than the cohesive forces accompanied with the bulk liquid water, this will result spreading of water into the surface and no drops of water will be formed. If the cohesive forces accompanied with bulk water are higher than the forces accompanied with the interaction of water with the surfaces, then water drops over the surface will be formed and the surface will form a hydrophobic layer (Arkles, 2011).

The hydrophobic sand is obtained by coating normal sand with hydrophobic compounds. When hydrophobic sand surface is exposed to water, sand particles on the top layer will tend to adhere to each other as a result of hydrophobicity to water, (Arkles, 2011). This will cause minimizing the surface area of the sand which will reduce soil's water requirements. When the pure silica particles in normal sand are exposed to a volatile liquid of an organ silicon compound, for example, trimethylchlorosilane $[(CH_3)_3SiCl]$ while using nanotechnology, this additive, which is a colorless volatile liquid that fumes in moist air, will react with the silica compounds (SiO_2) in the normal sand, when it interacts with the surface of the sand, resulting a coating layer of hydrophobic methyl groups to the surface of normal sand grains. The trimethylsilane group $[(CH_3)_3Si…]$ will replace the hydrogen atom H, which is a part of hydroxyl compound in the normal sand (Fig.3). The result will be forming a silicone film (monolayer) of an organohalosilane

Fig.2. Hydrophobic sand (Global forum, 2015)

called trimethylsilanol [$(CH_3)_3$(OH) Si-O] as a thin coating to the normal sand grains, (Katz, 2005).

Some molecules are non- polar, others are polar. How different atoms share electrons is described by chemical polarity. These methyl groups, which are coating the sand grains, are non-polar compounds; they tend to act as a hydrophobic material to the polar molecules of water (Healy & Brunner, 2007).

This hydrophobicity will create a capillary breaking hydrophobic encapsulation which results a repellent material for water (Salem et al, 2010). When the hydrophobic sand is exposed to water, the surface area of the sand will minimize as a result of the particles' tendency to approach to each other. Because water molecules are unable to bond to the hydrophobic non- polar groups coating, this will leave a gap of air between the water molecules and sand particles and keep water as drops on the surface of the hydrophobic sand (Healy & Brunner, 2007).

History of hydrophobic sand

The earliest indication for the water proof sand was in a book titled "The boy mechanic book 2" which was published in 1915. It was mentioned in this book, which was written by a group of well-known mechanics, (Leonard, 1999) that the hydrophobic sand was invented for the first time in India and used by magicians. It was obtained by adding melting wax to heated sand. While the present combination, was invented by a group of scientists and researchers who are employed at Cabot Corporation in Massachusetts, USA. They invented a procedure to develop a reaction between trimethylchlorosilane [$(CH_3)_3SiCl$] and the grains' surfaces of silicate materials, such as sand. The invention was manufactured for the markets at the beginning of the eighties. Since then a considerable number of studies were implied to investigate the progress of the practical applications for the hydrophobic sand and experiments were executed to reach a conclusion about the best usages of this treated sand (Healy & Brunner, 2007).
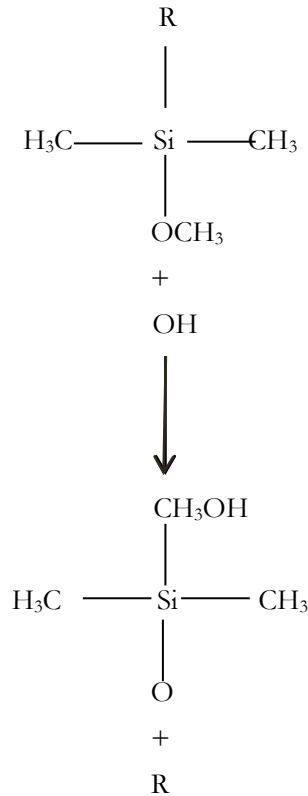
4

$$
\begin{array}{c}
R \\
| \\
H_3C \!-\!\!-\!\! Si \!-\!\! CH_3 \\
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+ \\
OH \\
\Downarrow \\
CH_3OH \\
| \\
H_3C \!-\!\! Si \!-\!\! CH_3 \\
| \\
O \\
+ \\
R
\end{array}
$$

Fig3. Anhydrous Deposition of Silane (Gelest, 2011)

Other studies were undertaken in UAE to study the effect of using hydrophobic sand for plantation and farming. For example, a two year study was conducted in UAE University about the impacts of using hydrophobic sand on the growth of palm trees and grass. The result of the study showed that the plants have 20 % denser roots and rise in harvest quantity by 33 %. These results have encouraged UAE University to measure the water quantity that is required for growing rice, which needs significant amounts of water. The results of these studies were published in the Water Resources Management Journal and in the Journal of Food Agriculture and Environment that are issued in UAE (DIME, 2014). Also, a study about water conservation and management with hydrophobic sand was conducted in Alain University in UAE (Salem et al, 2010). After the invention of the Nanotechnology, producing the hydrophobic sand has become one of its tremendous applications.

Hydrophobic sand applications

- Hydrophobic sand can be used in farms for agriculture purposes to reduce water seepage into the lower layers of soil and into the groundwater. Water quantity that flows through sand will be significantly less because of using hydrophobic sand which traps water allowing plants roots to obtain the ultimate benefit of water and reduce the irrigation duration and number of watering rounds per day. It could be used also in gardens and parks as a landscape tool for creating a natural looking stream when water flows over the hydrophobic sand. According to the studies held by the production company in UAE and studies conducted by UAE University, it could save up to 75 % of water usage (Salem et al, 2013).

- It can be used in foundations, infrastructure and underground utilities protection.

5

In the Middle East grounds, the existence of salt is very common and it is the main cause for the weakness in foundations because of steel bars oxidation and the existence of salt in the concrete mix through the drying procedure. Using the multi-grain hydrophobic sand instead of the mono- grained normal sand in constructions will from a rigid foundation when it is stressed and compressed while the normal sand is uncompressible and soft. Salt and water will be trapped away when using hydrophobic sand under foundations which will ensure more sustainability for structures. Also, using hydrophobic sand for underground utility protection, when extending pipes or around laid cables will prevent water from affecting them and will ensure longevity of the pipes net. It is widely used around the pipes and cables laid underground in the Arctic area. When reparation and maintenance work is needed for the cable net, which are buried to protect them from the severe cold and harsh weather, it would be easier to work when using hydrophobic sand as a cap for the electrical junction boxes. Because it doesn't freeze and icy water cannot drain through, it is always dry even during winter and this would facilitate maintenance and reparation work (Choo, 2014).

- For oil adsorption, as oil is a non- polar compound, it is attracted to the hydrophobic sand which is a non- polar material also and they both hydrophobic to the polar water molecules. When adding hydrophobic sand into oil contaminated water, oil will penetrate the sand and they will both form one unit and sink into the water where it could be easily collected. Coastal areas, which are polluted with floating petroleum spilled from oil tankers, could be easily cleansed by using hydrophobic sand to trap oil and create heavy clumps of sand and oil united together which are easily extracted from water. This was the main reason behind inventing the hydrophobic sand, cleaning polluted water, beaches and coasts (Healy & Brunner, 2007).

- For flood and coastal protection, using hydrophobic sand in bags will help to prevent the flood from advancing towards residential areas and will act as efficient barriers. Using normal sand is a traditional action against floods and is considered as a quick solution but after a short period of time, normal sand will be saturated with water and its efficiency in repelling water is reduced so water will continue flowing through the bags after a period of time. Hydrophobic sand property in constant repelling of water will assist for a longer duration of preventing floods from advancing (DIME, 2014).

- For parks and playgrounds, usually normal sand is used in playgrounds, golf courses and horse racing tracks but since normal sand could be easily wetted in the event of rains for example and gets muddy, it would be wiser to use hydrophobic sand which remains dray even in rainy seasons. Hydrophobic sand could be used as a surface layer for playgrounds and parks because it does not clump in wet seasons (DIME, 2014).

- Protecting ground water from contamination with pollutants of heavy metals and other pollutants when used as a layer beneath landfills. Contaminated water with wastes from landfills will seepage creating its bath towards the groundwater unless there is a layer of hydrophobic sand that prevents the contaminated water from reaching the groundwater (DIME, 2014).

MATERIALS AND METHODS

Sampling and permeability tests have been carried out for pure normal sand, pure hydrophobic sand and mixtures of normal sand and hydrophobic sand with different proportions and configurations in order to select the mixture with the most appropriate permeability for Dubai environment and climate and for most types of plantations. For this purpose, soil classification tests and permeability tests were conducted in the AUD (American University in Dubai) laboratories. Also, leaching tests were conducted there to measure common heavy metals concentrations in the leached water after different periods of time.

A second set of leaching tests were undertaken, in SLU and KTH laboratories, to examine the degree of pollution in water after adding the hydrophobic sand with its chemical coating of the organic hydrophobic agent, trimethylsilanol. The aim of this leaching test was to estimate the chemical risks resulted from using this technique. For this purpose, a test of two stages was conducted to determine the rates of the release of organic silicon (Si) compounds (i.e. trimethylsilanol) in soil after using the hydrophobic sand and whether these rates are acceptable or not in the prospective of environmental sustainability.

The materials that were used are samples of hydrophobic sand which were brought from a manufacturing company for this product in UAE that lies in Alain city, and is expected to provide the municipalities with their needs of the hydrophobic sand if it approves to be safe for the environment. This company is called "Desert Innovation Middle East LLC". Samples of typical normal sand which were obtained from a random place in Dubai, also samples of normal sand were extracted from the site, used by the manufacturing company, to produce the hydrophobic sand.

Soil classification

The soil particle distribution is considered one of the most significant characteristics of soils. The sizes of soil particles may vary from less than 0.1 μm diameter, such as clay particles, to approximately 20 cm diameter boulders (Craig, 1997). Also, the range of soil particles has essential implications; for example, interaction of water with soil is controlled by the size of the smallest soil particles and size distribution of particles. Moreover, the hydraulic conductivity or permeability of soil is determined by particle size of soil. In general, particle size is responsible for electrical conductivity, soil plasticity, chemical seepage, shear strength behavior and consolidation property of soils (Craig, 1997).

There are several different tests, used to determine soil classification, due to the broad rank of soil particles' sizes and related soil properties. The aim of these tests is to assess the range of particle sizes and to describe the interaction of water with soil particles. This information is related to soil classification systems to assist the researchers in describing the engineering parameters of different soil types (Fratta et al, 2007). Since one of this thesis' objectives is investigating the permeability of normal sand when combined with hydrophobic sand, soil classification laboratory test was conducted.

Soil sieve analysis test

There are two different tests used for characterizing the wide range of soil particle sizes. Hydrometer test which is used to characterize soil particle sizes that are smaller than 75 μm and the sieve analysis test used

7

to characterize soil particle sizes larger than 75 μm. These tests are described in details in ASTM standard D422, "Standard Test Method for Particle- Size Analysis of Soils" (Fratta et al, 2007).

The classification systems of soil (especially for sand) and the evaluations of engineering parameters of these types of soils were based on the results of these tests.

Since the sand particles sizes are greater than 75 μm, the sieve analysis test was undertaken to characterize and identify the sand particle sizes in the obtained samples for this case study.

The basic concept of this test is using a stack of standard metal sieve meshes to mechanically separate different ranges of soil particle sizes (Fig.4).

The square openings of the sieve retain particles that have diameter size larger than the opening. In order to interpret the results from this test, the size of the square opening that is equal to the particle diameter is assigned to the retained soil fraction (Fratta et al, 2007).

The sieve sizes that were used for testing the sand samples were: No. 4, 10, 20, 40, 60, 100, and 200.

These sieves were weighed one by one and their masses were recorded, a sensitive electrical balance was used for this purpose. A sample of 115 g hydrophobic sand, as recommended in the ASTM standard D422, was placed on the top of the sieve stock. The sieve stock was placed on sieve shaker for about 5 min to accelerate the separation of sand particles into different sizes and facilitate the procedure. Afterwards, the mass of each sieve with the retained sand was measured and recorded. The difference between the mass of the empty sieve and the mass of the sieve with the retained sand will result the mass of the retained sand and the mass of the sand that passed. From these records, the mass of the soil retained on the No. 200 sieve, which has the smallest diameter size and usually placed at the bottom of the sieve stack, will control the evaluation of particle size distribution. The sand particles that retained on sieve No. 200 were considerably fine so the "wet washing" technique was used, according to the ASTM standard D1140, "Standard Test Methods for Amount of Material in Soil Finer than the No. 200 (75 μm) Sieve". The soil retained by sieve No. 200 was washed on the sieve. The retained sand specimen was removed from the sieve, dried in the oven and the mass of the dried sand was recorded. The recorded mass is the mass of retained sand on sieve No. 200. For the evaluation of distribution of sand particle size, this mass record was used.

Using the results, the cumulative passing percentage was calculated to obtain the required information to build the grain size distribution curve.

By this stage, the particle distribution size for the hydrophobic sand will be identified to pave the way for the permeability tests. Afterwards the coefficients of uniformity (C_u) and curvature (C_c) were calculated using Eq. 1 and Eq. 2 (Fratta et al, 2007).

$$C_u = D_{60}/D_{10} \qquad \text{(Eq. 1)}$$

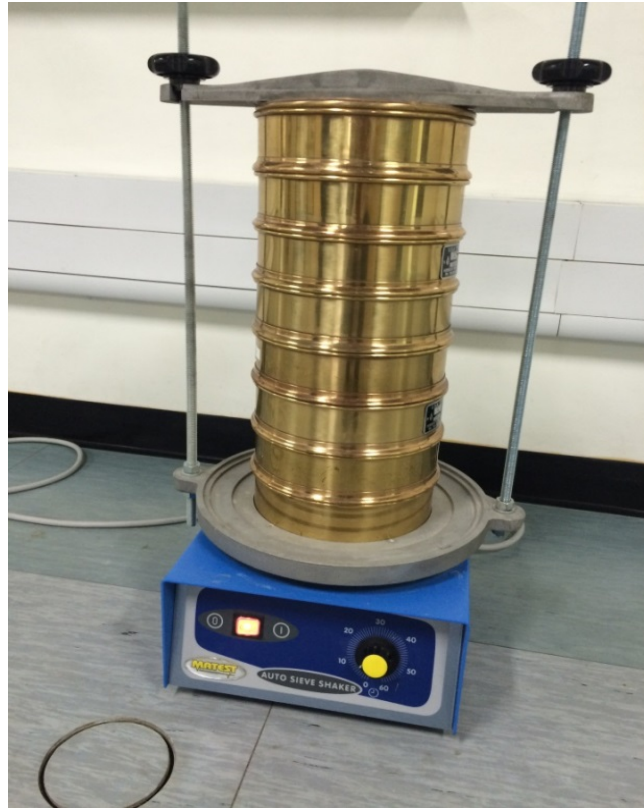$$C_c = (D_{30})^2 / D_{10}*D_{60} \quad \text{(Eq. 2)}$$

Fig.4. Sieve analysis test, (AUD, 2014).

Where, D_{xx} is the particle size that corresponds to xx percentage passing. The coefficient of uniformity and coefficient of curvature provide information about the uniformity of the hydrophobic sand independent of the average particle size (Fratta et al, 2007).

Soil permeability

According to Darcy's empirical law (Eq. 3), water flows through soil only when it is fully saturated (Craig, 1997). By use of permeability tests it is possible to assess and evaluate the interaction between the pore water and the soil structure. This soil property is also known by the hydraulic conductivity when the drained liquid is water. Permeability or hydraulic conductivity in the case of water is described by the coefficient of permeability (K) (Fratta et al, 2007).

The ease of water flow through soil is defined by the hydraulic conductivity while the dissipation of the pore water pressure, when the saturated soil is exposed to load, is characterized by the consolidation coefficient.

$q = Aki$ (Eq .3)

$V = q/AKi$ (Eq. 4)

Where,

q = Volume of water flowing per unit time (cm³/s)

A = Cross sectional area of soil corresponding to the flow q (cm²)

K = Coefficient of permeability.

i = Hydraulic gradient.

V = Discharge velocity (cm/s)

The coefficient of permeability (K) depends on the soil pores' average size. The pore size for any type of soil depends on soil structure, soil particles distribution and shape and degree of saturation. Generally,

when the soil particles are relatively small, the pores would be small and the coefficient of permeability would be low. (K) is a function of void ratio for a given soil. Also, permeability differs according to the soil stratification and when fissures exist, i.e. in desiccated clay soil (Craig, 1997).

Permeability of soils depends also on temperature upon which the viscosity of water depends. The lower the temperature is, the lower the coefficient of permeability would become.

However, the range of (K) values for different types of soil is within (1-10^{-10}) cm/s (Craig, 1997), Table 1.

Table 1. Typical values of hydraulic conductivity K for saturated soils (Geotechnical Engineering, 2011).

Soil type	Hydraulic conductivity, K (cm/s)
Clean gravel	1 to 100
Sand gravel mixtures	10^{-2} to 10
Fine sand	10^{-3} to 10^{-1}
Silty sand	10^{-3} to 10^{-2}
Clayey sand	10^{-4} to 10^{-2}
Silt	10^{-8} to 10^{-3}
Clay	10^{-10} to 10^{-6}

The permeability of sand is considerably higher than those of clay and silt (Table 1). The aim of this thesis is to reduce the permeability of sand to obtain the best harvesting in both quantity and quality, reduce the quantity of water used in irrigation and number of irrigation rounds. In order to reduce sand permeability, hydrophobic sand was added in different quantities and configurations to normal sand and different samples were tested. The permeability coefficient was calculated for each specimen using the constant head permeability test.

Constant head permeability test:

There are two setups for measuring and calculating the hydraulic conductivity of soils in permeability tests: falling-head and constant-head parameters. The permeability tests are described in ASTM standards D2434 "Standard Test Method for Permeability of Granular Soils (Constant Head)" and D5084 "Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter.

For the permeability tests in this thesis, the constant- head test was implied. During the duration of this type of permeability test, the total hydraulic head must remain constant. For a specified period of time, set by the experimenter, the volume of the drained water is measured. Constant head permeability test is recommended to be used for coarse and grained soil as sand while for finer soils, such as silt and clay, falling-head tests are recommended. Since the specimens in interest contain sand so the constant- head test was chosen for permeability measurements for this thesis.

Eq. 5 is used for calculating K in the constant head permeability as follows:

$K = V * L / A * t * h \rightarrow$ derived from Darcy's law

Since $q = V/t$ then:
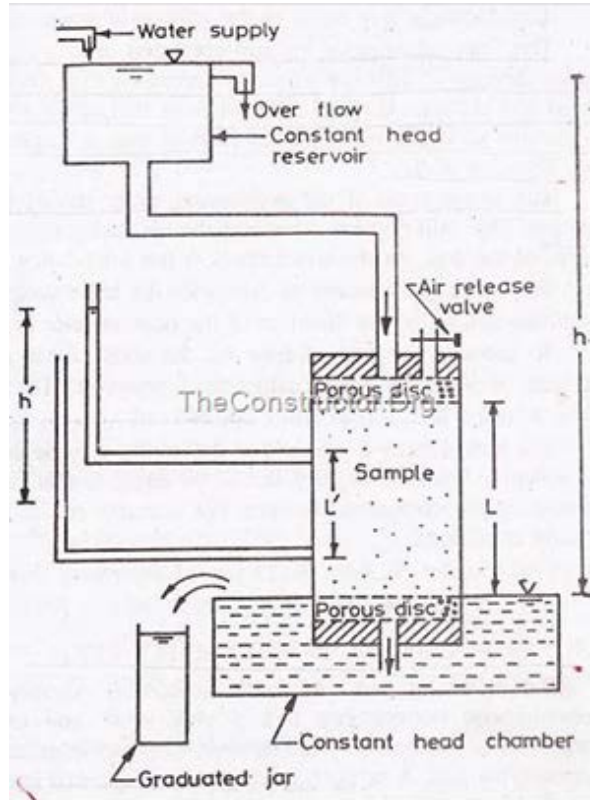
$K = q * L / A * h$ (Eq. 5)

Fig.5. Constant head permeability test (Civil Engineering Home, 2015)

where V is the volume of water flowing through the soil specimen that has the length L and a cross –sectional area A during time t, h is the constant water head, q is the discharge of water during a specific time (Fratta et al, 2007) (Fig.5).

Permeability tests - sets and specimens

Several sets of permeability tests were conducted. In each set, four different specimens were used as follows while keeping all the other parameters fixed for each set. Only the type of sand used in each specimen was different.

In the first set of tests, a specimen of pure natural sand from Dubai was used to calculate the hydraulic conductivity for normal sand and utilize the result for comparison with the results of calculating the hydraulic conductivity when mixing with the hydrophobic sand.

Afterwards, a specimen containing a mixture of 50 % of normal sand and 50 % of hydrophobic sand was used and the hydraulic conductivity (permeability coefficient K) was calculated. The same procedure was repeated using a mixture that contained 25 % of natural sand and 75 % of hydrophobic sand. At the end, 100 % of pure hydrophobic sand was used as a specimen for calculating the permeability coefficient.

After checking the results and comparing the values of (K) that have been obtained, further permeability tests were conducted.

A second set of permeability tests was implied using specimens of the same mixing percentages as the first set of tests but this time the water head was reduced to approximately one third of the water head used in the first set of the experiments. The reason behind that was to check whether the pressure caused by the water head on the soil specimen is responsible for the changes in the values of (K) or adding the hydrophobic sand is the main reason behind these changes. Also, the values of (K) that were obtained were checked and compared to each

Fig.6. Samples used for the constant head permeability test, (AUD, 2014).

other. Upon the result of comparison, a decision of conducting a third set of permeability tests was adopted.

The difference in the third set was using separated layers of sand in the cylinder and avoid mixing them. All other parameters such as the height of the water head and the weight of sand were held fixed during the tests. One specimen was used in this set. It was pointless to repeat the tests using either 100 % of normal sand or 100 % of hydrophobic sand because the parameters were held the same as in the last set of test

In the specimen, the bottom half of the cylinder's void was filled with hydrophobic sand and the upper half of the cylinder was filled with normal sand after suitable compaction for the bottom layer using a tamper.

Since the aim behind conducting the permeability tests in this study is to minimize the quantity of hydrophobic sand used in soil, in order to minimize the economic costs, at the same time obtaining the optimal soil permeability, a final permeability test was conducted.

In this final test, the tested specimen contained a bottom layer that formed 50 % of the cylinder void and included a mixture of 50 % of normal sand and 50 % of hydrophobic sand. While the upper layer, which formed the remaining void of the cylinder, consisted of pure normal sand.

The values of (K) for the preformed sets of permeability tests were organized in tables and diagrams to reach a conclusion about the most appropriate configuration for normal sand and hydrophobic sand layers.

In general, the procedure in the constant head permeability test is as follows (Craig, 1997):

The test was implied using a plastic soil specimen cylinder, used for placing the sample of soil in, two porous stones to be placed at the top and bottom of the cylinder, two rubber stoppers, one spring at the top of the cylinder, one constant head chamber, a large funnel and some plastic tubes (Fig.6).

At the beginning, the mass of the cylinder, the porous stones, the spring, and the two rubber stoppers was determined and registered. Dry sand was placed in the cylinder to the required height and was compacted several times by gently vibrating the cylinder with a pestle. Afterwards, the stones and plastic stoppers were placed at the bottom and top of the cylinder and the mass of the assembly was determined using the scale and was registered. The mass of the sand was then calculated by the

difference between the two records. Then, a plastic tube was fixed from the top to a large funnel and from the bottom; it was fixed to the sand specimen. The large funnel, in its turn, was fixed to a water inlet. The water flowed through the sand specimen to the constant head chamber. After a period of time which differs according to the type of soil used as a specimen, the soil specimen will become saturated and the water will start to flow from the bottom of the cylinder to the constant head chamber. That period of time was also measured using a stop watch and registered to compare the saturation time for the normal sand and the hydrophobic sand. After some time water will start to flow into another container through the outlet of the chamber of constant head. The supply of water was adjusted so that the water head level remains fixed during the test. The flowing water out of the constant head chamber was collected in a graduated container after a steady flow of water was established, that is once the water head (h) is constant. The time needed to collect the flowing water in the graduated container to a certain discharge (q) was registered using a stop watch also the discharge (q) was calculated. Using this information, the coefficient of permeability (K) was computed and registered. This test was repeated several times for the different types of sand, different mixing percentages, different configuration of sand layers and different levels of water head as described above.

Soil-specific gravity tests

Because of the fact that permeability coefficient (K) is a function of the void ratio (e), then the void ratio of the sand samples should be also investigated for this study. The void ratio is calculated from the specific gravity of soil (Das, 2012).

For soils, specific gravity is defined as the ratio of the weight of a specific volume of the soil to the weight of an equal volume of distilled water (Das, 2012). In order to investigate the relationship between the weight and volume of soil, the specific ratio is considered as a fundamental parameter for this purpose. Thus, specific gravity G_s, which is dimensionless, is defined as:

G_s = unit weight of soil solids only/ unit weight of water

$$G_s = W_s/V_s/\varrho_w = W_s/ V_s*\varrho_w \qquad \text{(Eq. 6)}$$

Where W_s = mass of soil solids (g)

V_s = volume of soil solids (cm^3)

P_w = density of water (g/cm^3)

General ranges of G_s for various soils were registered (Table 2).

Table 2. Ranges of specific gravity for soils (Fundamentals of Geotechnical Engineering, 2012).

Soil Type	Range of G_s
Sand	2.63 - 2.67
Silts	2.65 - 2.7
Clay and silty clay	2.67 – 2.9
Organic soil	Less than 2

The void ratio (e) is defined as the ratio of the volume of voids to the volume of solids in soil, the volume of voids includes the volume of water and the volume of air that fills the voids of soil (Das, 2012).

$$e = V_v / V_S \qquad \text{(Eq. 7)}$$

where e = void ratio

V_v = volume of voids (volume of water V_w + volume of air V_a)

V_s = volume of soil particles

The following equation (Eq.8) is driven from Eq. 6 and Eq. 7 and was used for calculating the void ratio for the samples in this thesis:

$$\varrho_d = G_s . \varrho_w / 1+e \qquad \text{(Eq. 8)}$$

where ϱ_d = The dry density of soil

G_s = Specific gravity of soil

e = Void ratio for soil

ϱ_w = density of water

The porosity (n) is defined as the ratio of the volume of voids to the total volume of soil (Terzaghi et al, 1996):

$$n = V_v / V \qquad \text{(Eq. 9)}$$

The relationship between the void ratio and porosity (n) is driven from Eq. 7 and Eq. 9 and is expressed by the following equation:

$$e = n / 1-n \qquad \text{(Eq. 10)}$$

The porosity and void ratio have direct impact on permeability. The voids and soil pores transmit water, so larger pores and larger voids results in higher permeability (Terzaghi et al, 1996).

Generally, high porosity results high permeability. Any variation in the volume of voids affects the permeability. For example, the procedure of compaction or consolidation which minimizes the total void ratio, minimizes permeability (Terzaghi et al, 1996). From the above, calculating and comparing void ratio for the normal sand sample and the hydrophobic sand sample is relevant to investigate whether transforming normal sand into hydrophobic will lead to change in void ratio and consequently change in permeability.

The specific gravity for a normal sand sample was tested in the AUD laboratory and also the specific gravity for a hydrophobic sand sample. Afterwards, the void ratio for these two samples was calculated and the results were compared.

The specific gravity was determined according to the procedure described below, which is applicable for soils structured of particles smaller than 4.75 mm in size, ASTM D 854-00 (Standard Test for Specific Gravity of Soil Solids) (Craig, 1997).

A flask was filled with 500 ml of distilled water then the mass of the flask and water was determined. Afterwards, approximately 100 g of dry normal sand from Dubai was added to the water (Fig.7). The next step was removing the air from the sand- soil mixture in order to release all the entrapped air, a vacuum pump was used for that purpose. Then, the
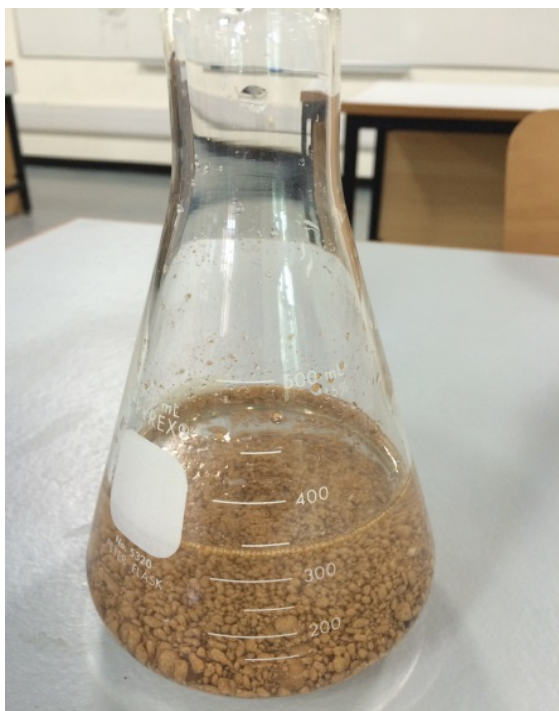
Fig.7. Specific gravity test (AUD, 2014).

combined mass of the flask with the sand- water mixture was determined. Afterwards, the mixture was poured into an evaporating dish which then was placed in an oven to dry the mixture into a constant weight. The last stage in this test was determining the mass of the dry soil in the evaporating dish which its mass, when empty, was already registered.

The same procedure was repeated using the hydrophobic sand sample. The void ratio was calculated and void ratios for both samples were compared.

Leaching tests

Two sets of leaching tests were conducted. The first set was conducted in the AUD laboratory in the Environmental Engineering department while the second set was carried out at two places; part of the tests was executed at the Swedish University of Agricultural Sciences (SLU) at the laboratory of the Department of Soil and Environment in Uppsala, and the other part was conducted at KTH, at the laboratory of the Division of Land and Water Resoruces Engineering in Stockholm. The leaching tests were conducted to determine whether a number of common nutrients and compounds are released from the soil samples and their release rates, after using the hydrophobic sand, which is formed by coating the normal sand particles with organic additives as mentioned previously.

For this purpose, three samples of sand were examined. Each sample weighed 400 g. The first sample was normal sand taken from Dubai, the second sample was hydrophobic sand and the third sample was normal sand from the site where sand is extracted and treated to become hydrophobic. The reason for testing the normal sand samples is to compare the concentration of the chemical materials before using the additive with their concentrations after using the organic additive by testing the hydrophobic sand sample. Four liters of distilled water were added to each sample and left for a specific period of time. Afterwards, water was decanted from each sample, filtered and tested.

The experiment was performed four times for each sample. Each time for a different duration of contact: after 10 minutes, 1 hour, 8 hours, 24 hours and 72 hours. The tested elements nutrients, in this set of leaching tests, were chloride –free (Cl), iron (Fe), aluminum (Al), copper (Cu), ammonia (NH_4), nitrogen (N) and phosphorous (PO_4). The device used for measuring the concentrations of these materials is a direct read Photometer 9500 from YSI (Fig.8).

The readings, which represent the concentrations of the above mentioned chemicals, were recorded and a comparison was implied.

The second set of leaching tests has the objective of analyzing and measuring the release of organic silicon (Si) compounds, represented by the trimethylsilanol, in the leaching test extracts for the selected samples. This set of leaching tests was executed partly at SLU and the remaining part was completed at KTH. The concept in this leaching test is to use an organic alkane for extraction of the organic (Si) compound from the leachate, and then to measure its concentration. The principle behind this concept is that the organic silicon compound such as trimethylsilanol , which is coating the normal sand particles for producing hydrophobic sand, is partly hydrophobic and should, accordingly, partition into an organic phase such as hexane. Hexane, which is an alkane of six carbon atoms with the chemical formula C_6H_{14}, was chosen for this purpose. However, because the hydrophobicity of trimethylsilanol is relatively low, the procedure of extracting the organic Si compound was carried out twice to ensure obtaining almost the whole quantity. Afterwards, the organic Si compound was removed from the water phase.

The samples, which were used for this set of leaching tests, were normal sand from a random place in Dubai, normal sand that was excavated from the site of the hydrophobic sand production plant and the hydrophobic sand samples. Three samples from each type of sand were tested for higher accuracy. The total tested samples for this set of tests were nine.

The first step in this leaching test was to add 60 ml of 0.001 M calcium chloride ($CaCl_2$), to 30 g of each sand sample in order to simulate the field conditions. The procedure is according to the recently adopted European standard ISO/TS 21268-1 (Gustafsson, 2014).

After mixing the contents of each sample properly, they were laid in a shaking machine for 24 hours to ensure sufficient mixing of the contents. Afterwards, the solutions were decanted into polypropylene centrifuge tubes, (in all tests, using glass tubes and containers was avoided because trimethylsilanol is known of its strong binding property to glass). The samples were then centrifuged at 2000 rpm for 20 min. After this step, a pipette was used to transfer the clear supernatant to clean plastic tubes to be used for the next step. The next step was to conduct the pH measurement by withdrawing 5 ml solution from each sample prepared by the previous step, to a scintillation bottle and then the pH measurement was registered by using a properly calibrated Radiometer combination electrode.

The next step is extracting the organic Si of the hydrophobic sand sample stored from the previous step in 5°C. 10 ml of the $CaCl_2$ extract was added to 20 ml hexane. The mixture was shaken for about one hour to ensure adequate mixing. After leaving the sample to settle for about 20 min, the hexane phase, which is lighter than the water phase, was visibly separated. Then, it was removed carefully from the sample. At this stage, the hydrophobic trimethylsilanol will partition into the organic

Fig.8. Photometer 9500, (AUD, 2014)

hydrophobic hexane. By extracting the hexane phase, the trimethylsilanol will be extracted too. The last step was repeated twice after adding another 20 ml hexane to the remaining water phase, to ensure extracting almost the whole concentration of the trimethylsilanol from the sample.

In order to calculate the organic Si concentration, which is assumed to be leached as a result of using the organic coating of trimethylsilanol, samples of normal sand from Dubai, normal sand from site, hydrophobic sand after the extracting stage and the extracted hydrophobic sand sample using hexane, were analyzed by using ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry, with a Thermal I CAP 6000 instrument) at the KTH laboratory. The results were registered and compared to investigate whether leaching of organic Si compounds has occurred. It is worth mentioning that immediately before analysis of the samples using the ICP-OES device, 30 % nitric acid (HNO_3) of suprapur quality had been added to a final concentration of 1 %.

RESULTS AND DISCUSSION

Soil classification test

The results of the sieve analysis, undertaken for hydrophobic sand sample, were registered (Table 3).

Table 3. Sieve analysis test results for hydrophobic sand, (AUD, 2014).

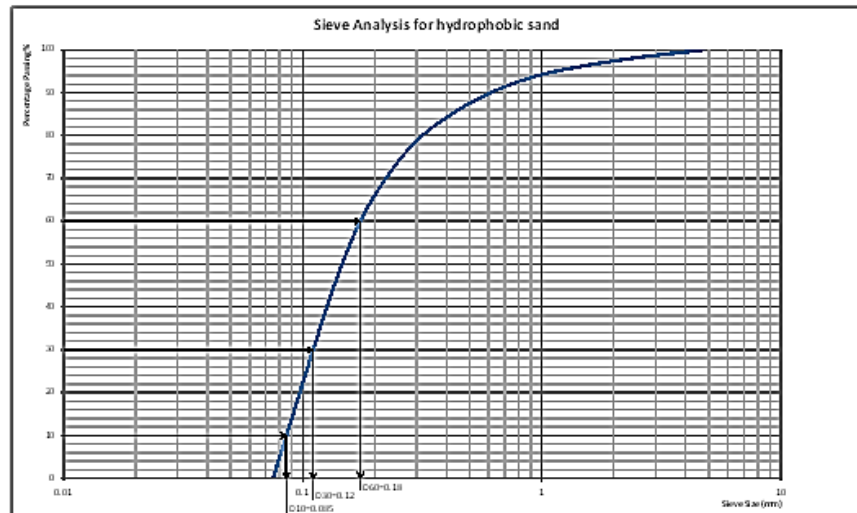| Sieve opening size (mm)	Accumulative percentage (%)
4.75	100
2.00	97.4
0.85	93.1
0.425	85.2
0.25	73.8
0.15	51.7
0.075	0

Fig.9 Soil particles size distribution for hydrophobic sand

Using the results in Table 3, Fig.9 was created.

The values of $D_{10,}$ D_{30} and D_{60}

$D_{10} = 0.085$

$D_{30} = 0.12$

$D_{60} = 0.18$

The values of C_u and C_c were calculated by using Eq. 1 and Eq. 2 respectively, the results were:

$C_u = 2.118$

$C_c = 0.941$

Afterwards, the calculated values of C_u and C_c were compared with the standard values of these coefficients (Table 4), which is a general table used for classifying the grading of soil particles for different types of soils (Craig, 1997). In order to specify the particles' gradation type for hydrophobic sand, a comparison between the obtained C_u and C_c from calculations and the standard classification coefficients' limitations As a result of comparing values of Cc and Cu, it was concluded that hydrophobic sand has uniformly - graded particles because the calculated C_c and C_u values lie within the range of uniformly graded soil in Table 4. Thus, soil particles for hydrophobic sand have nearly the same size. Particles grading, which describes the range of size distribution for soil particles, has an essential role in controlling the interaction of soils with water along with the size of the smallest particles. Uniformly graded soil has higher permeability than the well graded soil and lower permeability than the gap graded soil (Craig, 1997). Concluded from the above is that hydrophobic sand has moderate permeability comparing with other types of soil.

Table 4. Classification limits for different types of soils, (Soil mechanics, 1997).

Soil classification coefficients		Well graded soil	Gap graded soil	Uniformly graded
Coefficient of uniformity (C_u)		40.00	31.47	2.96
Coefficient of curvature (C_c)		0.16	0.08	1.40

Permeability tests

The first set of constant permeability tests were executed by; firstly using a specimen of 100 % normal sand from Dubai. The first step was registering the mass of the empty cylinder (M_c) with its accessories described previously in the constant head permeability test steps paragraph.

M_c = 2026 g

This value is constant and was used through all of the calculations related to the permeability test.

The total mass of the specimen with the normal sand (M_t) was measured and registered;

M_t= 2667. 60 g

The mass of the soil (M_s), which is in this case the normal sand, was calculated:

$M_s = Mt - M_c = 2667.6 - 2026 = 641.60$ g

In order to calculate the cross sectional area of the specimen cylinder, the diameter was measured accurately and registered and the cross sectional area was computed;

A = 31.15 cm², this value was also fixed for the whole calculations of the permeability tests.

The height of the cylinder (L) was registered equal to 13.20 cm which is constant for all the tests. The constant head of water (h) was fixed at 101.50 cm for this set of permeability tests. The collected discharged water mass was measured and the collecting time was registered. The test was repeated as described, in the permeability constant head test paragraph, in the Methods section. Then the permeability coefficient for every test was computed (Table 5). Against what is expected from using the hydrophobic sand, which is reducing the permeability of soil, the permeability tests showed an increase in the permeability of sand when using the hydrophobic sand.

To investigate whether the increase of permeability, when using hydrophobic sand, is resulted of the high pressure caused by the height of the water head, the second set of constant head permeability tests was designed and executed. This time the constant water head level (h) was reduced to the minimum available height in the test set. In this set, (h) was held equal to 36 cm which represents approximately one third of the previous height. The concept behind reducing water head level is lowering the water pressure on the specimens, the pore water pressure will consequently become lower and water seepage velocity will decrease as a result (Craig, 1997). According to Darcy's law, fluid discharge is proportional to permeability, so decreasing the discharge means

Table 5. Permeability coefficient (K) values (AUD, 2014).

Specimen type	Permeability coefficient at h = 101.50 Cm	Permeability coefficient at h = 36 Cm
100% of normal sand and 0% of Hydrophobic sand	$3.6 * 10^{-3}$	$2.34*10^{-3}$
50% of normal sand and 50% of Hydrophobic sand	$5.05 *10^{-3}$	$4.04*10^{-3}$
25% of normal sand and 75% of Hydrophobic sand	$6.93*10^{-3}$	$4.90*10^{-3}$
0% of normal sand and 100% of Hydrophobic sand	$7.75*10^{-3}$	$5.68*10^{-3}$

decreased permeability.

Same configuration of specimens as in the first set of tests was used. The coefficient of permeability (K) was calculated by using the new adopted low water head and fixing other parameters constant such as L, A and room temperature.

Using Eq. 5 (derived from Darcy's law) the coefficient of permeability was calculated.

Again, by studying the computed permeability coefficients for different specimens of sand while using low water head, the results were also against what is expected from using the hydrophobic sand which is obtaining relatively low permeability. The permeability of the normal sand was still lower than the permeability of sand when mixed with hydrophobic sand or when using a specimen of pure hydrophobic sand.

However, by comparing the permeability coefficients obtained from the first set of tests when the constant water head was relatively high with the permeability coefficients obtained from the second set of tests while using the lowest allowable water head in the test set, a considerable reduction of permeability coefficients was noticed in the second set when comparing with the results for the same sand type and mixing percentages, (Fig.10).

To investigate whether mixing the hydrophobic sand with normal sand is the reason behind the exceeded permeability in the mixture; another constant head permeability test was conducted by separating the normal sand and the hydrophobic sand. The half bottom of the specimen cylinder was filled with hydrophobic sand and the upper half was filled with normal sand. The constant head level was fixed at 36cm. All other parameters were held constant.

K = 1.63*10^{-3} is the calculated permeability coefficient for a specimen of two separated layers of normal and hydrophobic sand.

The value of the permeability coefficient in the previous test shows a considerable decrease in permeability when separating the two layers of sand. A comparison of the coefficients of K registered from the second set of permeability tests when the water head level was fixed at 36 cm.
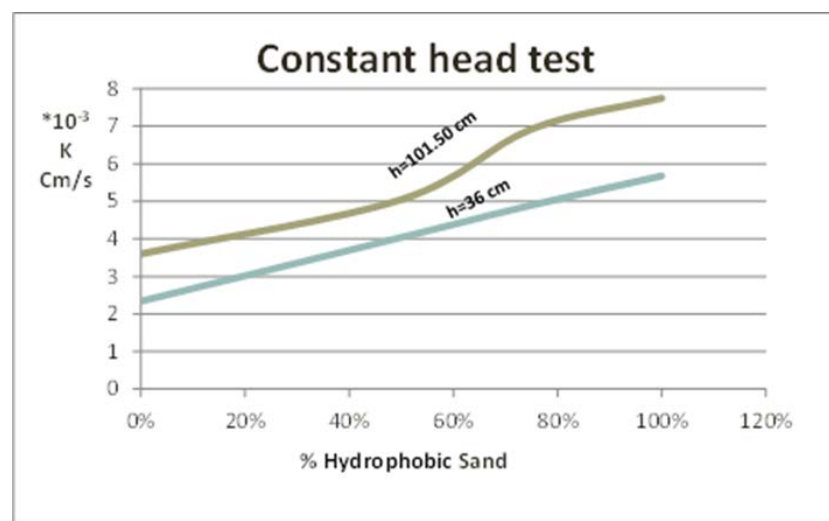

Fig.10. Permeability coefficient curves for mixtures of hydrophobic sand and normal sand at two different water head levels.

The result was that the lowest K was obtained when using two separate layers of hydrophobic sand at the bottom of the specimen and normal sand at the top.

The discussion, which was raised at this stage of permeability investigations, was whether it is still possible to mix normal sand with the hydrophobic sand at the bottom half of the test cylinder, keep pure normal sand layer at the top of the cylinder and still obtain low permeability, lower than the permeability of pure normal sand. The constant water head (h) was held at its minimum level in the set, which is 36 Cm. The value of (K) was computed:

K = 2.80 *10^{-3} is the permeability coefficient for a specimen composed of two separate equal layers of sand, bottom layer of mixed normal sand and hydrophobic sand and top layer of pure normal sand.

Comparing the different values of K for different specimens of sand at the same constant water head level of 36 cm and same parameters throughout the tests, sand had its lowest permeability coefficient when the test specimen was composed of two equal separate layers of normal
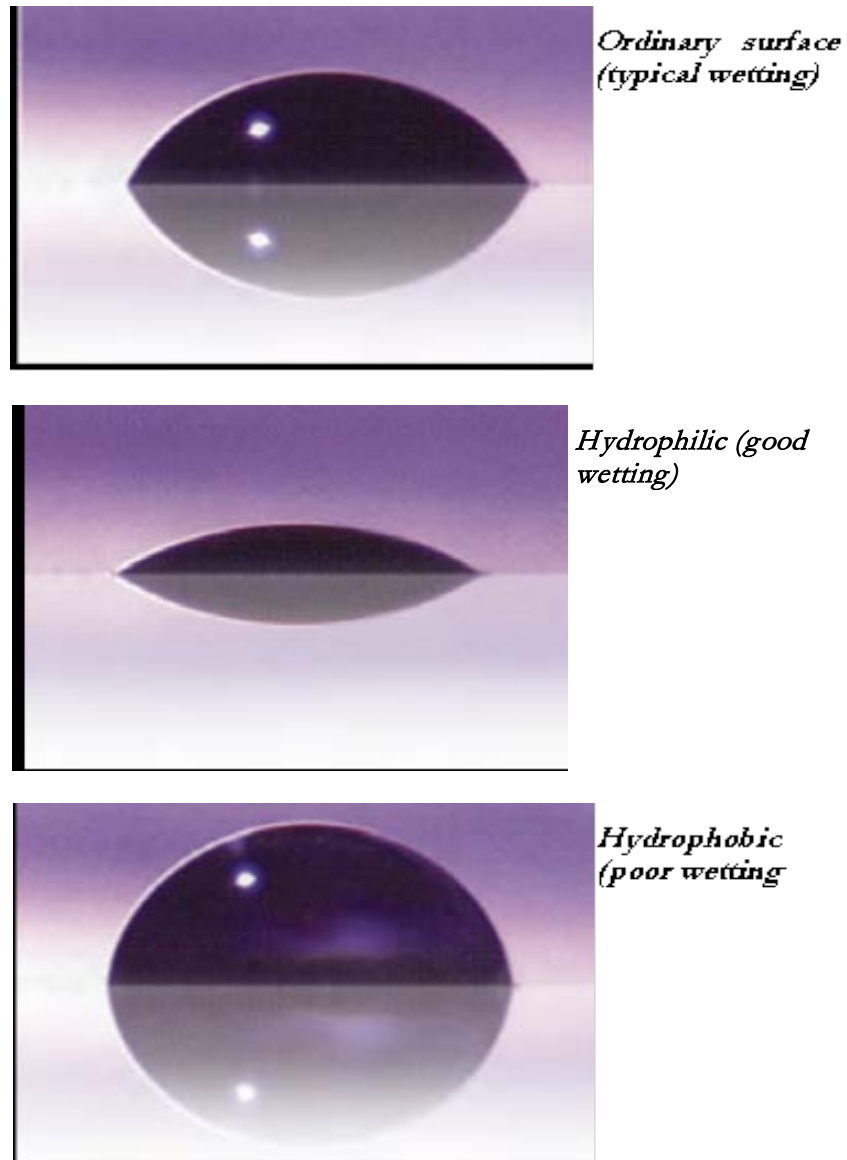

Fig.11. Water interaction with soil surfaces (Gelest, 2011).

21

and hydrophobic sand layer which was placed at the bottom.

It was mentioned previously that the tested specimens in the permeability tests should be thoroughly saturated before starting to collect the flowing water in the graduated container. The time period needed for pure normal sand specimen to become saturated was computed using a stop watch and it was equal to 80 s. The pure hydrophobic sand needed approximately 10 min, which is equal to 600 s, to become relatively saturated. Also, it was noticed that saturation in hydrophobic sand was uneven or mosaic saturation and the wetting front proceeded in random areas in the specimen and formed in "finger" flow.

The rate of water infiltration through the hydrophobic sand, after the saturation period, was higher than its rate in normal sand (Fig.11). When the specimen of hydrophobic sand became fully saturated, the hydrophobic particles of sand tend to adhere to each other and form clumps to avoid contact with water particles. This has led to increase in soil void ratio and porosity which in its turn led to increase in the water discharge rate and consequently increase in K value. This explains the higher K value for pure hydrophobic sand than the K value for the normal sand. Even when mixing the normal sand with hydrophobic sand, same behavior has occurred by the sand particles.

Water starts to infiltrate into soil when water head pressure exceeds the air entry pressure (Dekker & Ritsema, 2000). This means that the pressure imposed by the depth of the ponded water should become higher than air pressure in the voids of soil in order for the infiltration of water through soil takes place (Dekker & Ritsema, 2000), (Fig.11).

The sequential permeability tests have demonstrated that the permeability of hydrophobic sand becomes greater as the depth of ponded water increases, which is in agreement with the positive relationship between hydraulic conductivity in soil and water head depth. This explains the lower permeability for the hydrophobic sand when a layer of normal sand was placed in the upper part of the cylinder, on top of the hydrophobic sand.

The layer of normal sand has reduced the pressure caused by the column of water on the hydrophobic sand so water ran smoothly into the hydrophobic sand surface layer and pressure of water head became lower than the air entry pressure. This has reduced the water discharge and led to a lower permeability.

Water was trapped, for a relatively long period of time in the normal sand layer before the water head pressure exceeded the air pressure in the voids of the hydrophobic sand. Even when the hydrophobic sand became totally saturated, the existence of the normal sand layer on top has continued its impact on the water head pressure and reduced the water flow discharge.

Accordingly, recommendations from this thesis would be to avoid mixing normal sand with hydrophobic sand or placing 100 % of hydrophobic sand to use it as an agricultural field. Instead, a layer of hydrophobic sand should be placed under a layer of normal sand. The thickness of the normal sand layer is determined according to the height of the plants' roots.

Also, irrigation using drip-irrigation system is preferable to avoid high tense, on sand particles, produced by the pressure of water column when using for example the shower-irrigation system. During the periods of time, when water is trapped in the normal sand layer and before the hydrophobic sand becomes saturated, vegetation roots will utilize water

Table 6. Results of specific gravity tests for normal sand and hydrophobic sand.

Sand specimen	Specific gravity (Gs)	Void ratio (e)	Porosity (n)
Normal sand	2.728	0.748	0.428
Hydrophobic sand	2.11	0.352	0.260

considerably longer time than when hydrophobic sand layer is absent.

Specific gravity test

The results of the specific gravity tests, void ratio and porosity calculations for normal sand and hydrophobic sand were registered (Table 6).

As observed from the results above that the void ratio and porosity for the hydrophobic sand is less than the void ratio and porosity of normal sand which is inconsistent with the results of the permeability tests, recorded in the previous section.

The permeability test results show that the permeability coefficient for hydrophobic sand is higher than the normal sand permeability coefficient which is not in a reasonable agreement with the results of void ratio and porosity calculations for the two types of sand. One possible explanation for this disagreement is the adhering property of the saturated hydrophobic sand. The hydrophobic sand particles tend to adhere to each other when the sample is saturated which leads to increase in permeability while the specific gravity tests are implied for thoroughly dry sand samples.

Leaching tests

The results of the first set of leaching tests for measuring the concentrations of nutrients and several heavy metals were recorded and registered (Table 7-12, Fig.12-18). The values represent the average concentrations.

The acquired results from the first set of leaching test reveal that the rates of release for the measured materials and nutrients were high at the first period of time and gradually decreased afterwards. Also, the rates of leaching for these materials are substantially lower in the hydrophobic sand. The reason behind that could be the release of nutrients, which are stored in sand mainly through adsorption from storm water or nearby vegetation and foliage, occurs dominantly at the first minutes of the contact between sand and water. Accordingly, a considerable release of nutrients and materials should be expected at the first period of

Table 7. Chloride (Cl) concentrations, (AUD, 2014).

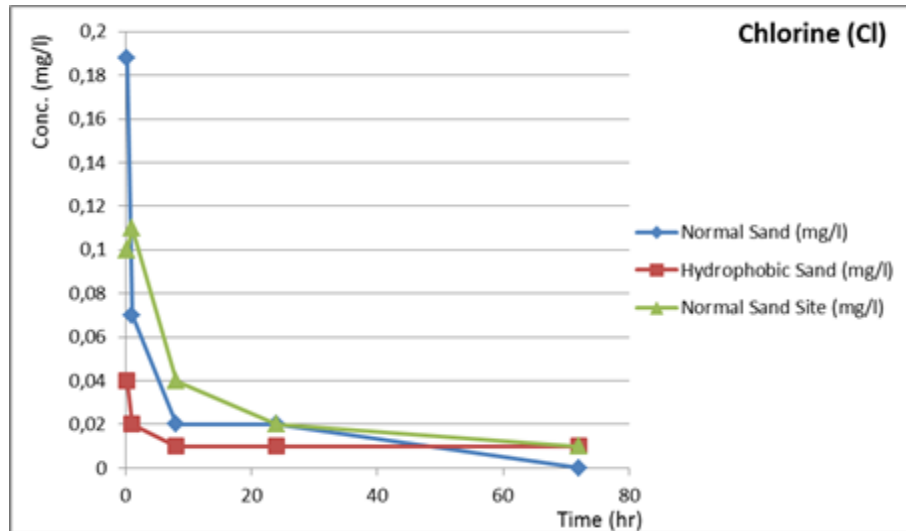| Period of time(hr)	Normal sand (mg/l)	Hydrophobic sand(mg/l)	Normal sand from site (mg/l)
0.167	1.88	0.04	0.10
1	0.07	0.02	0.11
8	0.02	0.01	0.04
24	0.02	0.01	0.02
72	0.00	0.01	0.01

Fig. 12: Concentrations of chloride for three samples of sand at different periods of time

communication with irrigation water. Nevertheless, it was observed that the hydrophobic sand sample released lower concentrations of materials comparing to the other sample. It can be concluded that the manufactured hydrophobic sand hasn't been exposed to storm water or from surrounding environment yet. The reduction of the measurable release by time could indicate that the elements and nutrients have accumulated in soil.

Also, the settlement of particles by time results the decrease in materials' concentrations after longer periods of time. What were observed at the beginning are the high concentrations of the suspended particles into the solution. Due to the settlement of the small particles and colloids which contain the analyzed elements, reduction of concentrations was registered by time in the leachate. Moreover, it was noticed that the concentrations of the tested elements were considerably lower in hydrophobic samples; this could be explained by the physical characteristic of the hydrophobic sand particles which tend to settle more rapidly than sand.
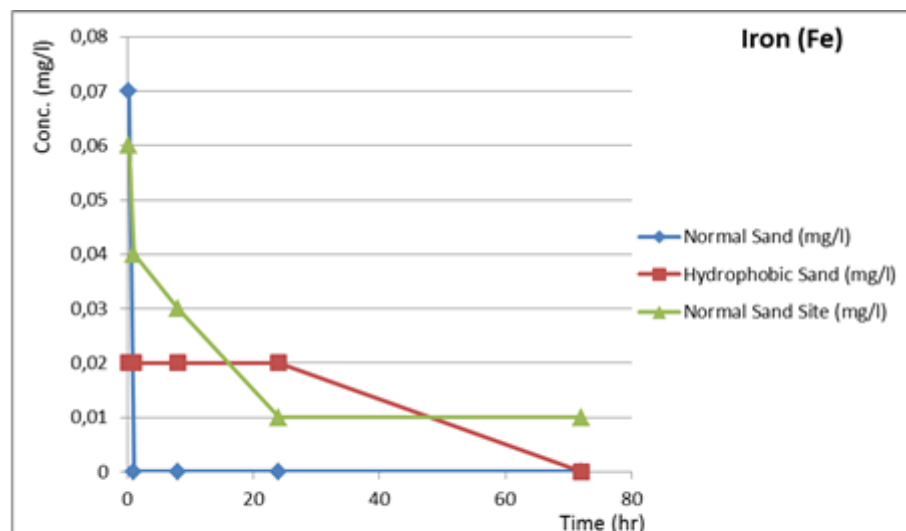

Fig. 13. Concentrations of iron for three samples of sand at different periods of time
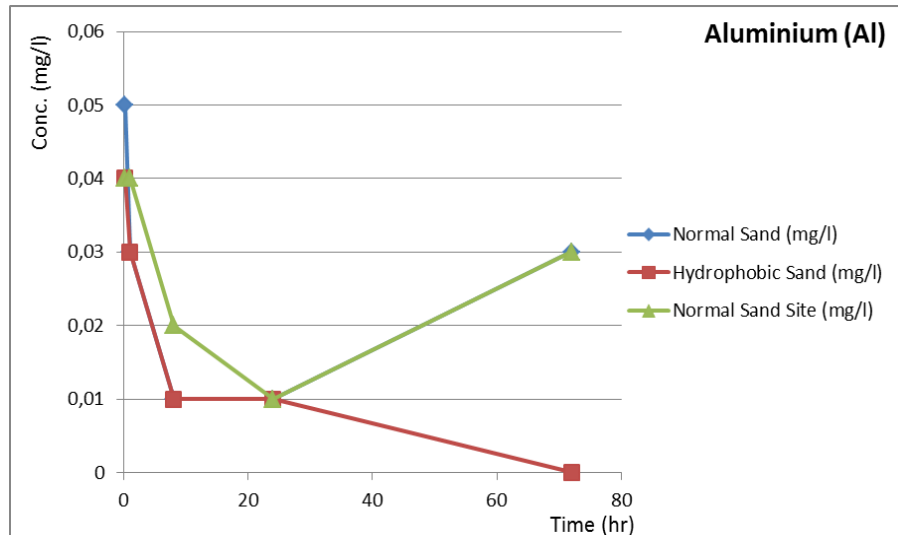
24

Fig.14. Concentrations of aluminium for three samples of sand at different periods of time.

Table 8. Iron (Fe) concentrations, (AUD, 2014).

Period of time(hr)	Normal sand (mg/l)	Hydrophobic sand(mg/l)	Normal sand from site (mg/l)
0.167	0.07	0.02	0.06
1	0.00	0.02	0.04
8	0.00	0.02	0.03
24	0.00	0.02	0.01
72	0.00	0.00	0.01

Table 9. Aluminum (Al) Concentrations (AUD, 2014).

Period of time(hr)	Normal sand (mg/l)	Hydrophobic sand(mg/l)	Normal sand from site (mg/l)
0.167	0.05	0.04	0.04
1	0.03	0.03	0.04
8	0.01	0.01	0.02
24	0.01	0.01	0.01
72	0.03	0.00	0.03

Table 10. Copper (Cu) Concentrations, (AUD, 2014).

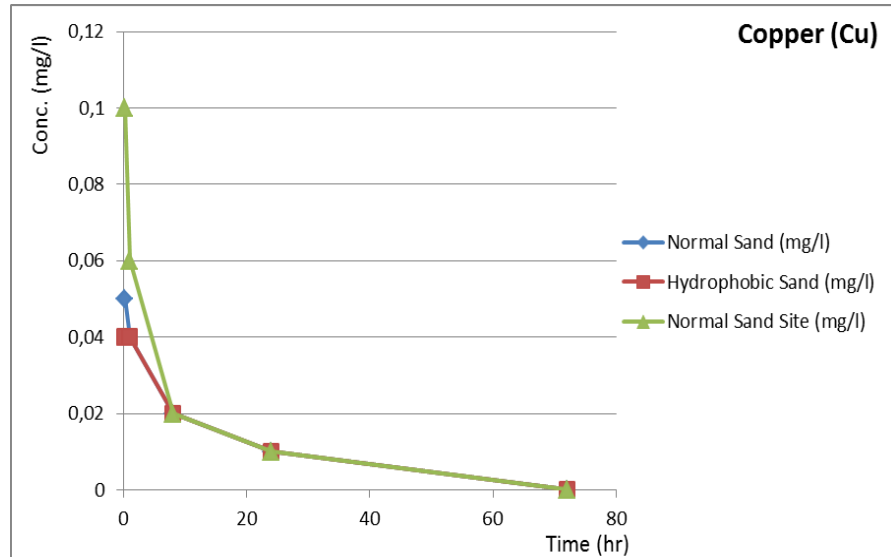| Period of time(hr)	Normal sand (mg/l)	Hydrophobic sand(mg/l)	Normal sand from site (mg/l)
0.167	0.05	0.04	0.10
1	0.04	0.04	0.06
8	0.02	0.02	0.02
24	0.01	0.01	0.01
72	0.00	0.00	0.00

Fig.15. Concentrations of copper for three samples of sand at different periods of time.

Table 11. Ammonium (NH4), Nitrogen (N) concentrations (AUD, 2014).

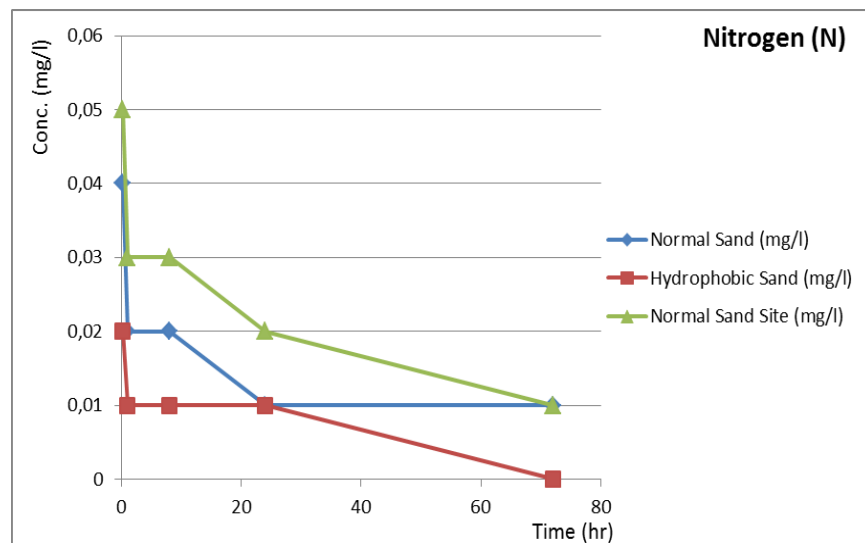| Period of time(hr)	Normal sand (mg/l)	Hydrophobic sand(mg/l)	Normal sand from site (mg/l)
0.167	0.052, 0.04	0.026, 0.02	0.065, 0.05
1	0.026, 0.02	0.013, 0.01	0.052, 0.03
8	0.026, 0.02	0.013, 0.01	0.039, 0.03
24	0.013, 0.01	0.013, 0.01	0.026, 0.02
72	0.013, 0.01	0.00, 0.00	0.013, 0.01

Fig.16. Concentrations of Nitrogen for three samples of sand at different periods of time.

26

Table 12. Phosphate (Po₄) concentrations (AUD, 2014).

Period of time(hr)	Normal sand (mg/l)	Hydrophobic sand(mg/l)	Normal sand from site (mg/l)
0.167	0.51	0.38	0. 62
1	0.32	0.12	0.16
8	0.12	0.11	0.14
24	0.12	0.11	0.10
72	0.11	0.11	0.10

It is worth mentioning that the obtained results provide insight into the rates of release of impurity rather than the precise concentrations in the runoff when 400 g of sand samples were exposed to 4 liters of distilled water. In order to estimate whether the obtained results fall within the standards of allowable concentrations of nutrients and elements in runoff, a comparison was performed between the results and the standards published by the Environmental Protection Agency (EPA). This agency has published recommended standards for the nutrients and elements in runoff in order to maintain high quality of disposed runoff and consequently the quality of groundwater, aquifers and aquatic life, (Table 13).

By performing a holistic comparing of the results with the above standards, it can be concluded that the nutrients and metals' release rates for the tested samples are located within the allowable standards during
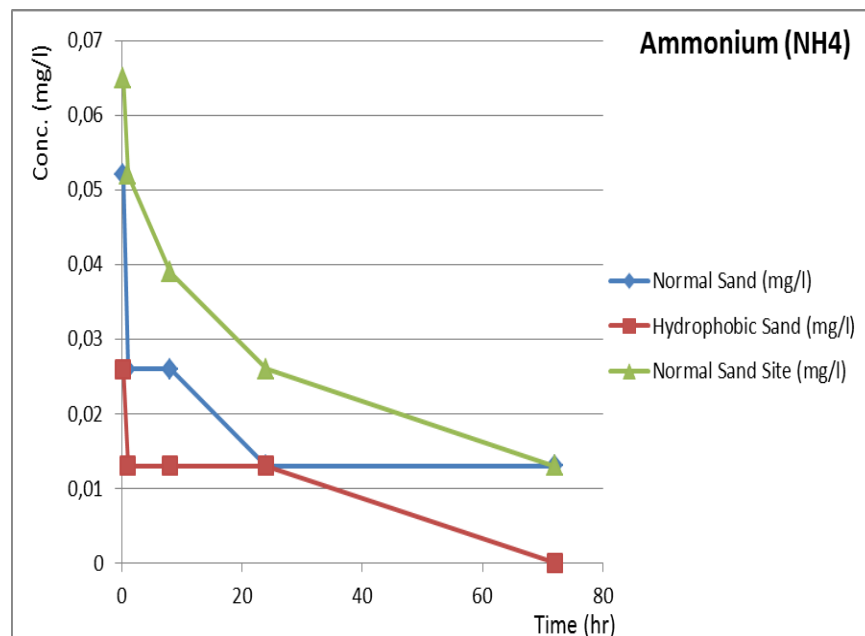

Fig.17. Concentrations of ammonium for three samples of sand at different periods of time.

Table 13. Maximum allowable concentrations of nutrient in water resources (EPA, 2015).

Nutrients	Runoff (mg/l)
Total Nitrogen	0.4 – 20
Total Phosphate	0.02- 4.3
Ammonia	0.5
Chlorine	-
Copper	0.01-0.4
Aluminum	0.2
Iron	0.2
Phosphate	-

the observation period of the tests. Nevertheless, it should be also mentioned that some obtained concentrations were lower than the limit of detection which make them very uncertain.

As for the second set of leaching tests, the results were as follows:

The pH measurements for the sand samples were recorded. Triple measurements of pH were implied for each type of sand because three samples from each specimen of sand were tested. The average of measurements for each type of sand was computed and registered (Table 14).

The measured pH values, for all sand samples, were within the allowable limitations of pH value for ground water which lies between 6.5 and 9.0 (EPA, 2015). Since all the pH values are over 7, this means that water becomes slightly alkaline but since values are within the allowable limits, there are no risks on ground water quality. It is easily observed that the pH value for the hydrophobic sand has increased slightly which is a reasonable consequence for adding the organic additive to the normal sand sand. The averages of concentrations of silicon (Si) in each type of sand were registered (Table 15).

Table 14. pH values of leached water from different types of sand samples (SLU, 2015).

Sand type	pH average
Normal sand	8.12
Normal sand (site)	8.15
Hydrophobic sand	8.41

Table 15. Si concentrations in sand samples.

Sand type	Si (mg/l)
Normal sand	10.03
Normal sand (site)	8.90
Hydrophobic sand	12.73
Hydrophobic sand (extracted)*	12.86

*this result is for extracts that had been subjected to hexane extraction.

As for the value of Si in sand, it is noticed that the hydrophobic sand had higher Si concentrations comparing to normal sand samples. However, extremely small Si concentration was extracted into hexane, as shown by the close correspondence between the extracts that had been extracted by hexane and the ones that had not (Table 15). This strongly suggests that the organic additive of trimethylsilanol led to increase in Si
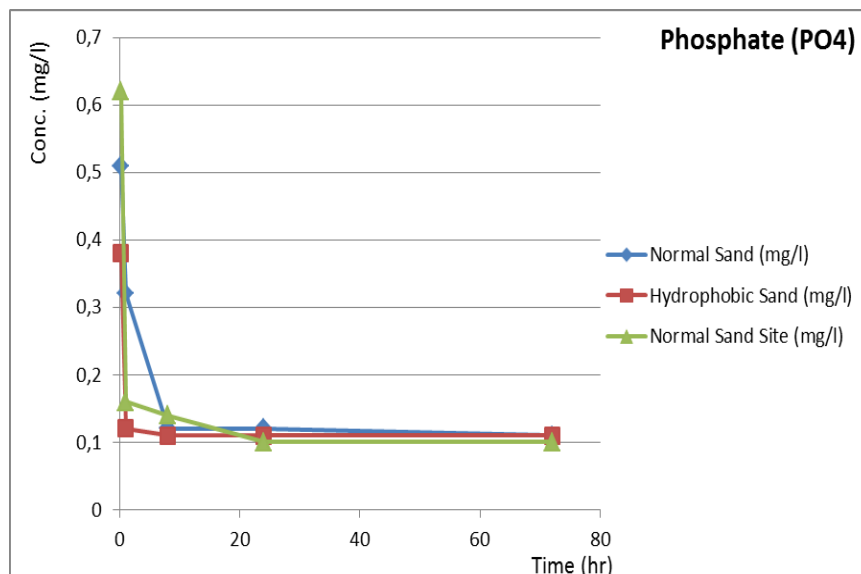
Fig.18 Concentrations of phosphate (Po₄) for three samples of sand at different periods of time.

concentration in the leachate. Nevertheless, the recorded increase in Si concentration did not represent the trimethylsilanol compound but some hydrophilic Si compound that is soluble in water; it is, most probably, silicic acid or silicate. A possible explanation for the existence of this silicic compound or silicate is the decomposition of the added trimethysilanol into silicate. In this case, the observed increase belongs to the inorganic silicon Si which is totally harmless. The possibility of the existence of organic trimethylsilanol in the leachate still remains but its concentration must be considerably low because internal standards test for the pure trimethysilanol compound was included in the analysis and the results showed very high intensities of Si, approximately 10 times higher than the equivalent concentration of the inorganic Si. Accordingly, if trimentylsilanol had been leached it would be instantly noticed and appeared in high concentrations.

It is important to note that although this study rules out an important role of dissolved organo-Si compounds, it can nevertheless not be excluded that other organic substances (possible transformation products of trimethylsilanol) could constitute a problem. Such organic compounds were not included in the analysis, however.

CONCLUSION

The results from this case study demonstrates that, in order to reduce sand permeability and consequently reduce irrigation water consumption and duration, a separate layer of hydrophobic sand should be placed beneath the normal sand layer. The thicknesses of the layers depend basically on the type of the planted vegetation. Recommendations are provided to avoid mixing hydrophobic sand with normal sand as it would lead to increase of permeability.

Leaching tests results showed that negligible concentrations of organic trimethylsilanol, used for coating the normal sand particles, leach into soil and groundwater. In other words, it is safe for the environment and will not lead to potential chemical risks concerning this particular Si organic compound. However, further investigations could be implied to

study the possibility of a serious seepage of other organic compounds after a rather long period of time, for example, after ten years or more. Also, studies could be undertaken to investigate whether the organic coating of trimethylsilanol will continue to preserve its hydrophobic characteristics after longer durations of time and its actual expiring date. Leaching tests for specific elements have shown low concentrations of seepage. Being so low in some registrations, uncertainty still exists.

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