APPLICABILITY OF HYDROPHOBIC SAND TO COMBAT WATER SCARCITY AND POSSIBLE CHEMICAL RISK

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Abstract- Freshwater scarcity is known as a sever constraint in in the Middle East, especially in the Gulf Region. The cities in the Gulf Region including in the United Arab Emirates (UAE) depend mainly on seawater desalination due to existing arid climate and poor groundwater resources. Some cities in the UAE faced water demand escalation about 15% annually from 2004 to 2010 despite of seawater desalination direct cost of 1 dollar per meter cube. Thus, calling all measures of water conservation techniques to reducing indoor and outdoor water demands is inevitable. Hydrophobic sand (HS) can be a solution to reduce outdoor water consumption for landscaping and agricultural activities as it can reduce water seepage and increase the contact time between irrigation water and plants' roots. The HS is Normal Sand (NS) coated by a thin layer of hydrophobic organic silica compound called trimethylsilanol. However, concerns were raised about the leaching of harmful organic coating chemicals into the soil and groundwater. For some plants, requiring a certain range of permeability suggests a mixture of NS and HS. Assessing the potential risks of leaching additives including organic trimethylsilanol is one of the objectives of this research. The permeability of mixtures of HS with abundant NS was examined to assess validity and cost effectiveness of such technique when a certain permeability is required. Several leaching tests were conducted with monitoring the release of selected elements and nutrients. The soil classification were examined and constant head permeability tests were conducted for different configurations and mixtures of NS and HS layers. The leached elements and nutrients were within the allowable limits set by the typical standards and very small concentrations of organic silica were leached. This indicates that HS does probably not constitute an environmental hazard. Mixing different portions of NS and HS revealed unforeseen increase in the permeability and suggest invalidity of controlled sand mixture for a targeted permeability. Instead, a layer of NS should be placed over a bottom layer of HS to trap water for a relatively long period and improve roots' contact with irrigation water.

Keywords- Hydrophobic, Sustainable, Irrigation, Leaching, Permeability

I. INTRODUCTION

Water scarcity has always been a challenge ahead of urban development in the Middle East including in the UAE. The records shows that the UAE's the average daily sunshine hours is about 9.8 hours and average annual precipitation is 94 mm. Average monthly maximum day temperature is greater than 30 ˚C for 8 months of a year and monthly rainfall is from zero up to the maximum value of 25 mm in February. Dubai is categorized as Hyper-arid zone with sandy soil and minimal organic content (Arid Zone Forestry, 1989). Having top soil with high permeability of 0.0005 to 0.00065 cm/second is a key reason for typical soil's low moisture content in dry days (Kfoury et al., 2015). Such weather condition, soil properties and freshwater water scarcity has been seen as major challenges for the growth of UAE.

Dubai Electricity and Water (DEWA) authority provides 1.5 million cubic meters per day for about 3.6 million consumers (Dubai Statistic Center, 2013).The city does not rely on its very limited groundwater resources since groundwater pumping caused fast intrusion of seawater or deep saline aquifers into shallow freshwater aquifers in the past (Alsharhan et al., 2001). Seawater desalination is practiced as main practical water treatment technique to cope with increasing potable water demand in such growing city. Tremendous efforts has been made to improve the sustainability and feasibility of desalination techniques in the region and globally. Employing novel technologies reduced water desalination cost in half to the range of US$0.45 to $1.00 per cubic meter (Zhang and Babovic, 2012). Despite of such substantial enhancements, seawater desalination is not yet cost effective and environmental friendly since it is still highly energy intensive. To cope this financial and environmental burden, Dubai government has implemented all measures to reduce the potable water demand including outdoor water consumption for landscaping.

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). Dubai, which is one of the main cities in the United Arab Emirates, is also suffering from scarcity of water resources. This city is glowing with modernity and development; nevertheless, it is still fighting to supply water for different demanding sectors. Tourism industry contributes about 20% to 30% of Dubai's GDP. Dubai is steadily approaching ambitious target to host 20 million tourist by the year 2020 (Emirates NBD-Sector Economics, 2014). Studies show that man-made greenery plays a significant role in attracting tourists towards a city (Chaudhry P. and Tewari, 2010). due to the role of greeneries in attractiveness and well-being of the city, Dubai Municipality has planned to expand greeneries from 3.63% in 2005 to 8% in 2020 (How green was our city, 2016). Thus, instead of reducing greeneries and park areas,

reclamation of water for irrigation has been the main solution to tackle this challenge. Using water conservation techniques including xeriscaping, dripping irrigation and adjusting soil permeability are some practiced techniques to reduce irrigation water demand per unit area (DIME, 2014).

The main challenge is to optimize water demand without negative impact on greeneries' attractiveness and cultivation productivity. One of the most recent techniques for reducing irrigation water is adjusting permeability of soil using hydrophobic sand (HS) layers in the sandy areas like Dubai (Salem et al, 2010). HS is Normal Sand (NS) treated with organic chemical materials and turned into hydrophobic soil. Using HS sand is still under investigation in Dubai and is implemented in some limited areas. Given abundance of local materials and existence of local production companies, iIf it is approved to be safe for the environment and impermeable at practical conditions, it can be regarded as a feasible water conservation technique. Plants' roots in highly permeable sandy soil have considerably limited time to exploit irrigation water as water drains quickly into deeper layers. Such scenario might inevitably sweep soil nutrients into groundwater too. The HS 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 (Salem et al, 2010).

II. OBJECTIVES

The objective of this research is to assess the chemical risks that threaten groundwater quality and the environment when adding HS to normal Dubai top soil. The evaluation focuses on the examination and assessment of the HS's tendency to release chemical compounds received during the industrial preparation and coating processes. Leaching tests were carried out to determine both the extent and the rate of chemical release into the seeped irrigation water. Addition experiments were conducted to achieve the optimal soil permeability by mixing different quantities of the original NS and HS.

III. 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, the concentrations of nitrogen (N), phosphorus (P) and potassium (K) varies between 5-10 ppm, 1.5 ppm, 14-100 ppm (part per million), respectively (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 solid atoms or water molecules known as polar molecules. Thus they tend to be attracted to the NS grains which is the reason that NS is considered as a hydrophilic material and water spreads into the sand layer without forming drops or bead on top of NS surface (Healy & Brunner, 2007).

A hydrophobic surface has the characteristic of not adsorbing water since the repulsive force induced by sands surface on water is greater than the water adhesion tendency. When water is added over the hydrophobic surface, water drop is formed which minimizes the exposed surface area of the sand and reduces water infiltration in soil (Arkles, 2011). Using proper nanotechnology, a volatile liquid of an organ silicon compound, for example, trimethylchlorosilane [$(CH_3)_3SiCl$] is exposed to the pure silica particles in NS to form hydrophobicity. Trimethylchlorosilane is a colorless volatile liquid that fumes in moist air that reacts with the silica compounds (SiO_2) on the surface of NS and results a coating layer of hydrophobic methyl groups on NS grains. The trimethylsilane group [$(CH3)_3Si$…] replaces the hydrogen atom H, which is a part of hydroxyl compound in the NS (Fig.1). The result will be forming a silicone film (monolayer) of an organohalosilane called trimethylsilanol [$(CH_3)_3$(OH) Si-O] as a thin coating to the NS 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 HS 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 HS (Healy & Brunner, 2007).

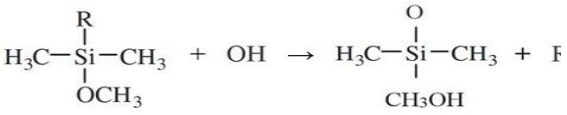

Fig 1: Anhydrous Deposition of Silane



Fig.2. Samples used for the constant head permeability test,

The HS was invented by adding melting wax to heated sand in India (Leonard, 1999). A group of scientists and researchers in Massachusetts, USA invented a procedure to develop a reaction between trimethylchlorosilane and the grains' surfaces of silicate materials, such as sand. Since then a considerable number of studies conducted to achieve the best usages of this treated sand (Healy & Brunner, 2007) including in plantation and farming in UAE. In UAE, the applicability of HS on the growth of palm trees and grass was evaluated recently. The results showed that the plants have 20 % denser roots and rise in harvest quantity by 33 %. The HS role to reduce rice farms' water demand was investigated (DIME, 2014). 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 researched conducted in UAE, it could save up to 75 % of water usage (Salem et al, 2013). It can be used around foundations, infrastructure and underground utilities to trapped away salinity and corrosive chemicals and in cold areas reduce damages due to freezing (Choo, 2014). The HS local producer claims its applicability to be used in sand bag for controlling flood and underneath landfills to reject leachate infiltration (DIME, 2014).

IV. MATERIALS AND METHODS

Sampling and permeability tests have been carried out for pure NS, pure HS and mixtures of NS and HS with different proportions and configurations in order to understand the extent of leaching and find suitable soil configuration. Soil samples have been selected from the UAE to suggest particular solutions for irrigation water conservation there. For this purpose, soil classification tests, permeability tests, leaching tests were conducted to understand the properties and behavior of NS and hydrophobic sands and any potential hazard risk associated to the release of hydrophobic chemicals. The leaching test was aiming to estimate rates of the release of organic silicon (i.e. trimethylsilanol) and other organic and inorganic chemical compounds in soil after using the HS and whether these rates are acceptable or not in the prospective of environmental sustainability.

Both HS and NS (called "NS–site") were carried from a local manufacturing company called "Desert Innovation Middle East LLC." in UAE. In addition, samples of typical NS which were obtained from a random place in Dubai and evaluated.

Soil classification: The soil particle distribution was conducted as it is the main characteristic for soil classification and is affecting soil hydraulic conductivity or permeability. 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). ASTM standard D422, "Standard Test Method for Particle-Size Analysis of Soils" was followed to characterize soil particle sizes that are larger than 75μm since the sand particles sizes are mainly greater than 75 μm (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. At this stage, the particle distribution size for the HS will be identified. Afterwards the coefficients of uniformity (Cu) and curvature (Cc) were calculated (Fratta et al, 2007).

Soil permeability: Permeability of soil is described by the coefficient of permeability (K) when water flows through saturated (Fratta et al, 2007). The coefficient of permeability (K) depends on the soil pores' average size. 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 possible fissures exist is formed in specimen (Craig, 1997). The range of (K) values for different types of soil is within 1 to 10^{-10} cm/s (Craig, 1997). The K value is expected to be in the ranges of 10^{-3} to 10^{-1}, 10^{-3} to 10^{-2} and 10^{-4} to 10^{-2} for fine sand, silty sand and clayey sand(Das, 2012). In order to reduce sand permeability, HS was added in different quantities and configurations to NS and different samples were tested. The permeability coefficient of the mixture is not estimated and requires experimental examination. Constant head permeability test for coarse and grained soil is used for the sand. The permeability tests were conducted as described in ASTM standards D2434 "Standard Test Method for Permeability of Granular Soils - Constant Head" (Fratta et al, 2007).

Permeability test's sets of 4 specimens for different mixtures including mixtures of 100%, 50%, 25% and 0% of HS mixed with natural sand from Dubai were examined. The test was conducted 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.2). The tests were run for both 35 cm and 101.5 cm water head. Different pressure heads were applied to check the consistency of k values at different pressure ranges. The second set of tests were conducted to study behavior of half a layer of HS when is placed under half layer of NS while all other parameters such as the height of the water head and the weight of sand were held fixed during the tests. Typical compaction for both layers were applied using a tamper. The last set of permeability and tested specimen contained a bottom layer of 50 % HS mixed with 50 % of NS and top layer of 50 % NS. This set was conducted to explore the possibility of constructing a semi-permeable layer under the NS both to reduce the cost of using HS and to assess if targeting a specific permeability is feasible.

Void ratio: Since the permeability coefficient (K) is a function of the void ratio (e), the void ratio of the sand samples should be also investigated. The void ratio is calculated from the specific gravity of soil (Das, 2012). In order to investigate the relationship between the weight and volume of soil, the specific weight ratio is considered as a fundamental parameter for this purpose. Thus, specific gravity (G_s), void ratio (e), dry density of soil (ρ_d) and porosity (n) were calculated according to the procedure ASTM D 854-00 (Standard Test for Specific Gravity of Soil Solids) (Craig, 1997). General range of G_s for sand is 2.63 to 2.67. 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). The porosity (n) is defined as the ratio of the volume of voids to the total volume of soil. The voids and soil pores transmit water, so larger pores and larger voids results in higher permeability (Terzaghi et al, 1996). Measuring and comparing void ratio for the NS sample and the HS sample is relevant to investigate whether transforming NS into hydrophobic will lead to change in void ratio and consequently change in permeability.

Leaching tests: The leaching tests were conducted to evaluate if the extent and the release rate of common nutrients and compounds from the hydrophobic sand. Three sand samples with 400 g mass of HS and NS from factory site (used as raw sand) and Dubai were examined. The NS was used as control samples. Four liters of deionized water was added to each sample and left for a specific period of time then water was decanted from each sample, filtered and tested for different chemical concentrations. The experiment was performed five 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 chemicals, 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 equipment used for measuring the concentrations of these materials is a direct read Photometer 9500 from YSI.

The next leaching tests aims to measure the release of trimethylsilanol extracted from samples and is considered as an organic silicon (Si) compounds' indicator. Alkane was used for extraction then measurement of the organic silicon compound from the leachate. Silicon compound including trimethylsilanol with partial hydrophobicity properties are used to coat the NS particles to produce hydrophobic sand. It is partitioned into organic phase such as hexane. Since 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 HS and both NS from factory and from random places in Dubai were considered as three sand samples. Three samples from each type of sand (totally nine samples) were tested for higher accuracy according to the recently adopted European standard ISO/TS 21268-1 (Gustafsson, 2014). The last steps of the test 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. The organic Si concentration in samples were analyzed by using ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometry, with a Thermal I CAP 6000 instrument). The results were registered and compared to investigate whether leaching of organic Si compounds has occurred.

V. RESULTS AND DISCUSSION

Soil classification test: The results of the sieve analysis for all samples were registered. The values of Coefficient of uniformity (C_u) and Coefficient of curvature (C_c) were calculated based on samples particle's size distribution shows uniformly-graded particles which means soil particles for HS 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. Gap graded and well graded soil have higher and lower permeability as compared to uniformly graded soil (Craig, 1997). Concluded from the above is that HS should have moderate permeability comparing with other types of soil.

Permeability tests: The first set of constant head permeability tests were executed. The area was measured accurately (A=31.15 cm^2) and the height of the cylinder (L=13.2 cm) and the constant head of water (h) was fixed at 101.50 cm for the inital 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 as reported in Table 1.

Table 1: Permeability coefficient (K) values,

Specimen type	Permeability coefficient at h = 101.50 Cm	Permeability coefficient at h = 35 Cm
100% of NS and 0% of Hydrophobic sand	$3.6 * 10^{-3}$	$2.34*10^{-3}$
50% of NS and 50% of Hydrophobic sand	$5.05 *10^{-3}$	$4.04*10^{-3}$
25% of NS and 75% of Hydrophobic sand	$6.93*10^{-3}$	$4.90*10^{-3}$
0% of NS and 100% of Hydrophobic sand	$7.75*10^{-3}$	$5.68*10^{-3}$

The permeability tests unexpectedly showed an increase in the permeability of sand when using the hydrophobic sand. To investigate if this is due to high pressure head of 105.5 m, the second set of constant head permeability tests for lowest possible water head of 36 cm was executed. The pore water pressure 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 decreased permeability. The permeability of the NS was still lower than the permeability of sand when mixed with HS or when using a specimen of pure hydrophobic sand. As shown in Figure 3, these two tests' permeability coefficients revealed that the permeability of HS has reduced as pressure head is reduced

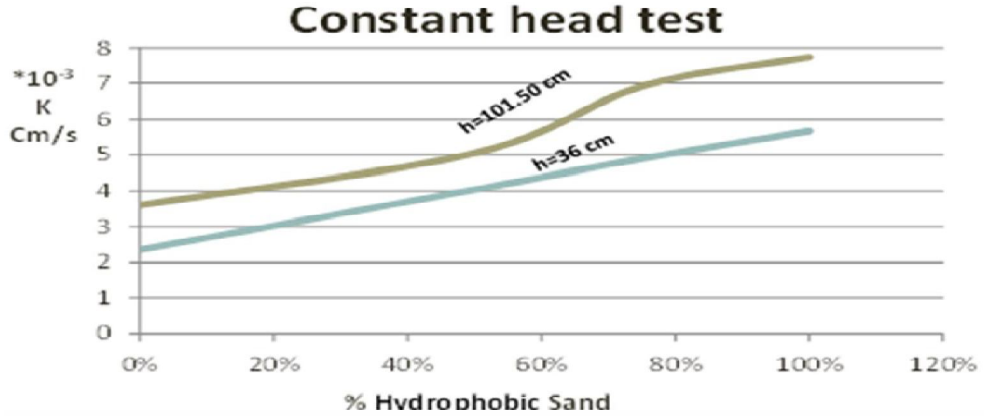

Fig. 3. Permeability Coefficient Curve for Mixtures ofHS and NS at different water head levels.

To investigate how mixing the HS with NS is the reason behind unexpected exceeded permeability in the mixture; another constant head permeability test was conducted by separating the NS and the hydrophobic sand. The half bottom of the specimen cylinder was filled with HS and the upper half was filled with NS when pressure head was fixed at 36cm where other parameters were held constant. The k value of $1.63*10^{-3}$ cm/s for a specimen of two separated layers of NS and HS shows a considerable decrease in permeability below all K values measured for single sand tests. Consequently, the impact of mixing NS with the HS at the bottom half of the test cylinder, where pure NS layer is set at the top half of the cylinder, was examined. This was planned to investigate if such cost effective arrangement still offers low permeability, lower than the permeability of pure NS. K value of $2.80 *10^{-3}$ cm/s for this arrangement, when equal amount of normal and HS are mixed for the bottom half, revealed that the mixture of these sands did not provide moderate permeability. It was deduced that the sand had its lowest permeability coefficient when the test specimen was composed of two equal separate layers of normal and HS layer which was placed at the bottom. Investigation of the performance of different heights of NS on the top of permeable sand is the objective of teams' further researches in future.

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 NS and HS specimens to become saturated were 80 s and 10 minutes, respectively. Also, it was noticed that saturation in HS was uneven or mosaic saturation and the wetting front proceeded in random areas in the specimen and formed in "finger" flow. After saturation, the volume rate of water through the HS was higher than its rate in NS. This might be due to the intention of the hydrophobic particles of sand to adhere to each other and form clumps to avoid contact with water. Consequently, it forms higher void ratio or great micro channels within the sand. Both of these cases facilitate water infiltration as a reason for higher k values for pure HS as compared to the K value for the NS. The finger flows might be due to channelling water through micro channels which causes partial saturation around channels and without wetting some other clumps of soil. In mixtures of normal and HS exposed to water pressure head, the extent of created void or number of micro channels might be greater as normal dry sand invites water through huge number of random fine paths in the soil the causing formation of more number of small clumps and consequently more frequent microchannel. The reduction of permeability of HS when placed in bottom half of the cylinder might be due to better compression of the bottom sand and more limited micro changeling in such a relatively confined zone.

The sequential permeability tests have demonstrated that the permeability ofHS 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 theHS when a layer of NS was placed in the upper part of the cylinder, on top of the hydrophobic sand.

The layer of NS has reduced the pressure caused by the column of water on the HS so water ran smoothly into the HS surface layer and pressure of water head

became lower than the air entry pressure as addressed in the literature (Dekker & Ritsema, 2000). This has reduced the water discharge and led to a lower permeability. When the HS became totally saturated, the existence of the NS layer on top has continued its impact on the water head pressure and reduced the water flow discharge. The research recommends avoiding mixtures of NS with HS in an agricultural field. Instead, a layer of HS should be placed under a layer of NS. The thickness of the NS layer is determined according to the depth of the plants' roots. Also, irrigation using drip-irrigation system is preferable to avoid ponding and excessive pressure when water is properly retained around the roots in the NS layer with slow flow toward the bottom hydrophobic sand.

Leaching tests: The results of the first set of leaching tests for measuring the concentrations of nutrients and several heavy metals including chlorine, iron, aluminium, copper, total nitrogen and phosphate were registered. The concentrations of the chemicals were below allowable concentration as per maximum allowable concentrations specified by EPA without significant difference between the responses from different sand samples.

The averages of concentrations of silicon (Si) in each type of sand were registered. The initial experiments show that the concentration of Si in the leachate from HS is 12.86 mg/l which is greater than 8.9 mg/l Si concentration from NS. Further examinations revealed that Si concentration did not represent the trimethylsilanol compound but some soluble harmless hydrophilic Si compound in water, most probably silicic acid or silicate. The results do not reject the possibility of the existence of organic trimethylsilanol in the leachate but its concentration was considerably low. It is important to note that although this study rules out significant existence 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, a separate layer of HS should be placed beneath the NS layer. The thicknesses of the layers depend basically on the type of the planted vegetation. Recommendations are provided to avoid mixing HS with NS as it would lead to increase of permeability. Leaching tests results showed that negligible concentrations of organic trimethylsilanol, used for coating the NS particles, leach into water. 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 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.

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