Engineered water repellency for resilient and sustainable pavement systems

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Abstract

Moisture-related distresses are a significant contributor to pavement damage, especially considering the high-impact loads that pavements endure and the resulting variations in strain, stress, deformation, and strength reduction due to moisture changes. This leads to recurring maintenance expenses and activities that generate significant CO_2 emissions. Engineering of water repellency in pavement soils can help maintain more uniform moisture conditions, leading to reduced speculation of performance, and material and construction cost savings. Additionally, this technique can reduce emissions associated with road pavement damage. This study explores the effect of grain size on water repellency to improve performance. Soils, collected from different locations in the United States as well as glass beads were treated with a commercially available organosilane. Various tests were performed to assess the level of water repellency imparted to the soils and their performance. The results revealed that the water-repellency treatment was effective, with contact angles ranging from 119.5° to 148.5°. The contact angle decreased with increasing grain size, while the surface roughness increased the contact angle. Water drop penetration test results showed no recorded penetration even after 2 hours (7200s), regardless of grain size. Breakthrough pressure values ranged from 0.1kPa to 2kPa, decreasing with increasing grain size. This study shows that water-repellent soils can help achieve a sustainable low-carbon future by reducing road pavement damage caused by moisture-related distress. It is however important to consider the effect of grain size and porosity on the performance of water-repellent soils before use in pavement construction.

Keywords:

Pavements, Engineered Water Repellency, Carbon Emissions, Soils, Hydrophobicity, Maintenance, Breakthrough Pressure

1.0 Introduction

Frost heaving and thaw weakening in cold regions can cause significant damage to construction and transportation infrastructure, including pavements and granular roadways, resulting in substantial economic costs and safety hazards (Wasif Naqvi et al., 2022). Heaving is predominantly attributed to the continual water migration from the vadose zone to the expanding ice lenses, which results in significant uplift pressures on the surrounding soil and can cause extensive damage to infrastructure (Sadiq et al., 2023). The United States faces particularly high costs associated with road infrastructure damage caused by frost heaving and thaw weakening. According to The Road Information Program (TRIP), the cost of rebuilding the thousands of miles of pavement that sustain damage each winter is estimated to exceed $2 billion (FHWA, 1999). However, high demand for road maintenance work has significant environmental implications, with resource consumption and associated greenhouse gas emissions presenting critical sustainability challenges (Wu, Xia, and Zhao, 2014). Asphalt production, in particular, has a significant environmental impact due to the high resource consumption and associated greenhouse gas emissions. For instance, producing one tonne of plain asphalt and polymer-modified asphalt results in CO2 emissions of 226 kg and 296 kg, respectively, illustrating the environmental impact of asphalt production and highlighting the need for sustainable solutions in road construction and maintenance (Blomberg et al., 2011). To assess the environmental impact of road construction, Espinoza et al. (2019) conducted a comprehensive life cycle assessment (LCA) study, which revealed that the production of the hot mix asphalt (HMA) layer in pavement has a carbon footprint of 65.8 kg of CO2 emissions per kilometer of road. These findings emphasize the importance of pursuing sustainable road construction and maintenance solutions to mitigate the significant carbon footprint of road construction and promote a more environmentally responsible approach to infrastructure development.

Soil water repellency offers a promising solution for increasing the lifespan of pavements in cold climates, while also reducing carbon emissions associated with pavement rehabilitation. By applying water-repellent substances to the soil, the migration of water towards the freezing front can be reduced, thereby minimizing the freeze-thaw impacts on pavements and improving the durability of subgrade soil. This, in turn, increases the lifespan of pavements and reduces the need for frequent maintenance and rehabilitation work, which can contribute significantly to carbon emissions (J. ho Choi 2019). Maintenance and rehabilitation works are responsible for a significant proportion of global CO_2 emissions, with 30 to 40% attributed to the building industry (United Nations Environment Programme 2022). Therefore, increasing the lifespan of pavements and reducing the frequency of maintenance and rehabilitation work can help to reduce the industry's carbon footprint. The longer an energy-efficient building or infrastructure stands, the lower its carbon footprint. The need for Maintenance or Rehabilitation (M&R), which accounts for 5 to 6% of total CO2 emission for a structure, can be further reduced with soil moisture control. From a geotechnical prescriptive, bearing capacity failure or the need for road maintenance is closely linked to moisture changes which indirectly induces increased carbon emission. This reduces the economic costs of frequent repairs and rehabilitation work and also helps reduce fuel consumption significantly throughout a pavement life cycle (France-Mensah and O’brien 2019)

Soil water repellency presents a potential solution to increase pavement service life and reduce carbon emissions from the rehabilitation work of pavements in cold climates. Treatment of soil with water-repellent substances can decrease water migration toward the frost front, potentially reducing the freeze-thaw impacts on pavements and increasing pavement life by improving the durability of the subgrade soil. Soil water repellency can significantly help reduce the building industries' 30 to 40% contribution to global CO_2 emission (J. ho Choi 2019; United Nations Environment Programme 2022). The longer an energy-efficient building or infrastructure stands, the lower its carbon footprint. The need for Maintenance or Rehabilitation (M&R), which accounts for 5 to 6% of total CO_2 emission for a structure, can be further reduced with soil moisture control. From a geotechnical prescriptive, bearing capacity failure or the need for road maintenance is closely linked to moisture changes which indirectly induces increased carbon emission. This reduces the economic costs of frequent repairs and rehabilitation work and also helps reduce fuel consumption significantly throughout a pavement life cycle (France-Mensah and O'brien 2019)

Soil water repellency, also known as soil hydrophobicity, refers to the phenomenon where certain organic compounds coat soil particles, causing them to repel water. This results in a decreased affinity to water, impeding wetting for durations ranging from seconds to hours (Doerr, Shakesby, and Walsh 2000). Naturally occurring water repellency in some organic soils has been discussed in the fields of agriculture and soil science for a long time (Bonanomi et al. 2016; Capriel et al. 1995; Dymov, Milanovskii, and Kholodov 2015). It has also been found to negatively affect plant growth, reduce infiltration capacity, accelerate soil erosion, and cause preferential flow in soils in the field of soil science (Dekker et al. 2009; Imeson et al. 1992; Ritsema et al. 1993; 1997; Shakesby et al. 1993). However, recent studies have demonstrated the benefits of water repellency in civil engineering applications, such as improving the freeze-thaw durability of pavements, leachate barriers, surface protection, slope protection, and coal combustion residual management (Mahedi et al. 2020; Bardet, Jesmani, and Jabbari 2015; DeBano 1981; Dumenu et al. 2017; Feyyisa, Daniels, and Pando 2017; Oluyemi-Ayibiowu and Uduebor 2019).Water repellency offers an effective solution for preventing frost-heaving-related damage in foundations, concrete slabs, and basement walls by limiting water migration, with the potential to reduce both energy consumption and CO_2 emissions. By reducing the need for frequent maintenance and new construction, soil water repellency can lower the demand for raw materials and energy-intensive production processes, ultimately contributing to a more sustainable construction with a significantly lower carbon footprint. In addition, adjusting the water repellency of soil can create an impermeable or semi-permeable seepage barrier, suitable for various engineering applications (Daniels 2020; Daniels and Hourani 2009; Lin et al. 2019; Uduebor, Daniels, Mohammad, et al. 2022).

Soil water repellency can be achieved by treating the soil with natural or synthetic water-repellent substances. Natural water repellency has been observed in soils exposed to wildfires and the presence of organic materials. On the other hand, synthetic substances like wax coatings, Tung Oil, Paraffin Oils, and Silanes have been used to engineer water repellency in soils (Bardet, Jesmani, and Jabbari 2014; Chan and Lourenço 2016; Ng and Lourenço 2016). Silanes and siloxanes, in particular, are very effective in making soils hydrophobic, with studies showing that adding 2.5% or less by mass can induce water repellency (Brooks et al. 2022; Y. Choi et al. 2016; Uduebor, Daniels, Naqvi, et al. 2022).

An accurate assessment of the effectiveness of various treatment methods for inducing soil water repellency is essential. Various methods are available for measuring water repellency in soil, including the Contact Angle (CA) test, the Capillary Rise Method (CRM), the intrinsic sorptivity test, the molarity of an ethanol droplet test (MED), and the Water Drop Penetration Time Test (WDPT) (Hallett, Baumgartl, and Young 2001; Bachmann, Ellies, and Hartge 2000; Bachmann et al. 2003; Schulte, Culligan, and Germaine 2007; King 1981; Dekker et al. 2009). Among these methods, the CA test using the sessile drop method with a Goniometer and the WDPT are commonly used due to their simplicity and versatility (Bachmann, Ellies, and Hartge 2000; Diehl and Schaumann 2007; Feyyisa, Daniels, and Pando 2017; Keatts et al. 2018; Lee et al. 2015; Letey, Carrillo, and Pang 2000; Liu et al. 2012). The contact angle measurement is based on Young's equation (Equation 1), which describes the equilibrium of a water drop on a solid surface with three interfacial tensions, solid-air, solid-liquid, and liquid-air.

$$cos\theta = \frac{\gamma_{sa} - \gamma_{al}}{\gamma_{la}} \quad \text{- Equation 1}$$

Where γ_{sa} is the tension force between solid and air, γ_{al} is that between air and liquid and γ_{la} is the tension between liquid and air (figure 1).

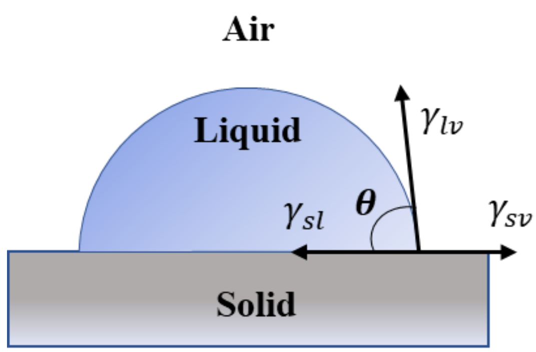

Fig 1: Schematic of Water Drop Showing Solid Liquid Air Interface

A CA value greater than 90° indicates low wettability or water repellency, while a CA value less than 90° indicates high wettability (Goebel et al. 2011). Among the various methods available for determining the contact angle, the Sessile Drop Method (SDM) is preferred due to its ability to directly measure the contact angle at the solid-liquid-vapor interface, providing a reliable estimate of soil wettability. All of the contact angle measurement methods have their flaws and drawbacks including multiple and varying CA values, swelling of the soil sample when immersed, and irregularity of the tested soil surface aside from user error (Y. Saulick, Lourenço, and Baudet 2017). Advancements have been made to ensure repeatability, including testing uniform-grained samples (Y. Choi et al. 2016), employing semi-automated techniques (Y. Saulick, Lourenço, and Baudet 2017), and automating the test procedure using defined drop volumes, height, and plane thickness. Despite these advancements, most studies have carried out tests only on uniform soil grains or materials, which do not represent the real composition of the soil, as it is made up of different particle sizes. Saulick et al. (2016) reported that finer materials exhibit a greater contact angle than coarse granular materials. The SDM procedure only tests the fine-grained portion of the soil that is usually left on the double-sided tape after sample preparation and does not necessarily represent the bulk mass. This can provide an erroneous value of the contact angle, particularly for soils where the fines are little and do not affect the overall soil characteristics. Therefore, there is a need to estimate the contact angle of the bulk soil mass based on the values of the individual grains of the soil sample.

In this study, an experimental program was carried out to understand the relationship between grain size and the water-repellent properties and behavior of soils.

2.0 Materials and Methods

2.1 Materials

Sand and fine-size glass beads and four naturally occurring frost-susceptible soils were chosen, including loess from Iowa (IA-PC), as well as silt from New Hampshire (NH-HS), North Carolina (NC-BO), and Alaska (AK-FB). Glass beads (GB) made of silica oxide (soda lime, type

S) in various grain sizes were obtained from Carl Stuart Ltd. in Dublin, Ireland. The glass beads were proportioned to model an average grain size of all four soils and provide an idealized particle size distribution. The natural soils were selected even though they are non-homogenous and prone to large variations because they provide real results that can be expected and compared to field conditions and predictions. The soils were oven-dried and sieved through the #4 Sieve. This was done to remove gravelly soil fractions and prevent variations in the sample specimens. Contact angle measurements are difficult to obtain from gravel-sized particles and the large pore space between them makes it unlikely that making the particles water-repellent will result in any meaningful hindrance to the flow of water through them.

Fig 2: Soils and Glass Beads Utilized in this Study; AK-FB, IA-PC, NC-BO, NH-HS, and GB

2.1.1 Water Repellent Chemical

Commercially available IE6683 from Dow Corning was utilized for the treatment of the soil samples. It is a water-based silane-siloxane emulsion blend with 40% active ingredients (alkoxysilane and polydimethylsiloxane) by weight. It has been used in previous research carried out by (Brooks et al. 2022; Feyyisa, Daniels, and Pando 2017; Keatts et al. 2018; Uduebor, Daniels, Mohammad, et al. 2022). Silanes provide a very stable -Si-O- bond to the surface of soil particles by the reaction of a silicon hydride (-Si-H) with water to yield a reactive silanol (-Si-OH).

Alkoxysilanes have the added benefit of coupling organic polymers to inorganic materials providing increased adhesion of the water-repellent molecule and improved surface modification (Arkles et al. 1992) Siloxanes have the added benefit of an extra silicon atom. This significantly improves its resistance to oxidation, and UV exposure and prevents any biodegradation (Ley et al., 2015)

2.1.2 Characterization

Table 1 presents a summary of the index properties of the soils utilized in this study. Specific gravity was carried out according to ASTM D 854 and ranged from 2.65 to 2.80. The particle size distribution was determined in accordance with (ASTM D7928 and showed between 38 to 98% passing through the #200 sieve. The soils were majorly Silty Sand, Silts, or Lean Clays. Atterberg limits tests; plastic limit (PL) and liquid limit (LL), were performed in accordance with ASTM D4318. Soils had a liquid limit ranging from 33% to 42%. All the soils were non-plastic (NP) except the Pottawatomie County (Iowa) Soil which had a plastic limit of 23%.

Table 1. Summary of Soil Index Properties and Classifications

Soil Property	**SOIL**			
	AK-FB	**IA-PC**	**NC-BO**	**NH-HS**
Specific Gravity, Gs	2.67	2.74	2.67	2.68
% Passing #4 Sieve (4.75 mm)	97.6	100	95.32	79.8
% Passing #10 Sieve (2mm)	96.0	99.8	91.84	74.18
% Passing #40 Sieve (0.425 mm)	93.4	99.6	86.88	52.69
% Passing #200 Sieve (0.075 mm)	84.5	98.4	38.88	42.41

Silt content (%) (75µm–2µm)	75.65	86.67	34.31	37.52
Clay content (%) (< 2µm)	8.87	11.69	4.57	4.88
USCS Classification	ML	CL	SM/SC	ML
AASHTO Classification	A-5	A-6	A-4	A-4
Frost Susceptibility Classification	F4	F3	F3	F4

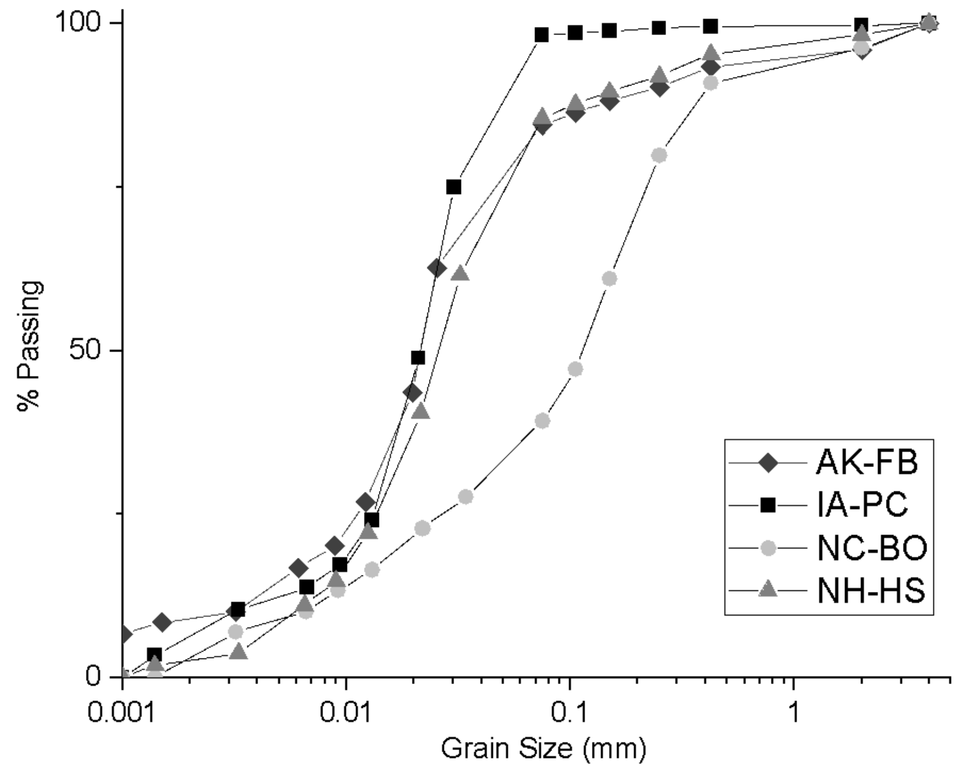

Fig 2: Grain Size Distribution of Soils

2.2 Methods

2.2.1 Treatment

A uniform dosage concentration ratio of 1:10 (OS: Soil, batched by weight) was selected for surface modification of the soil sample because it has been proven to induce sufficient water repellency in soils (Brooks et al. 2022; Uduebor, Daniels, Mohammad, et al. 2022). The OS was first dissolved with deionized water (~1µs/cm) and mixed with the soil to achieve a liquid-to-solid (L/S) of 2, ensuring complete saturation of the soil. This means for a 200g sample of soil, 20g of OS was mixed with water to make up 400mL utilized to treat the soil. The mixing was done in a 1000mL HDPE bottle mounted on a rotary tumbler to react for 24 hours. Studies carried out (Uduebor et al., 2022) have shown there is sufficient treatment even after 0.25 hours. At the end of the reaction time, the mixture was allowed to settle and then decanted. Excess OS within the mixture was washed out by adding DI water and agitating the bottle repeatedly and decanting after settling until the OS concentration was negligible. The resulting residue from the washing and decanting was split into two portions, one for air drying and the other for oven drying. The air-dried sample was placed in a fume cupboard in the laboratory with temperature and humidity at a relatively stable value of 22-24^{o}C and 40-45% respectively. Oven drying was done using a small lab oven at 60^{o}C. Samples were dried till there was no further weight loss. Oven-dried samples were stored in a desiccator to cool down before testing.

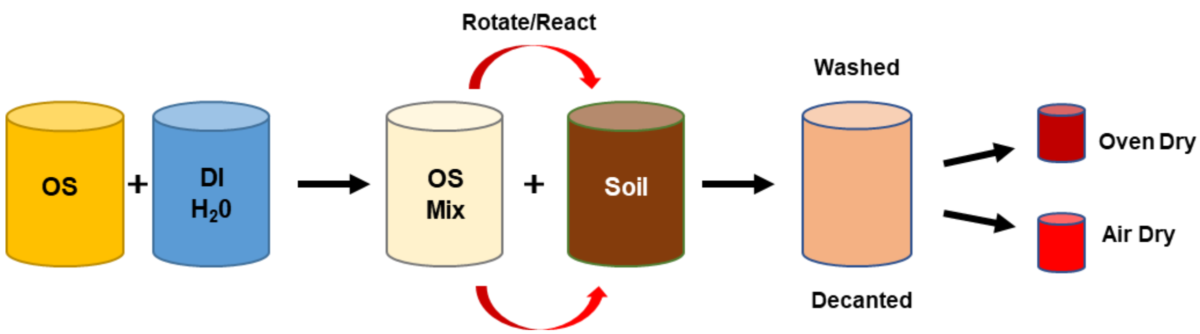

Fig 3: Schematic Showing Treatment Procedure

2.2.2 Contact Angle Test

Assessment of the water repellency of treated samples was carried out using the Sessile Drop Method (SDM) using a static measurement. Air and oven-dried samples were placed in a mortar and any agglomerations were broken up with the aid of a rubber end pestle. Where required, the soil sample was passed through sieves to provide a uniform range and test surface. A double-sided adhesive tape was affixed to a glass slide and the treated soil was placed on the other end with the aid of a spatula. A slight weight of about 100g was placed on the soil for about 2 minutes after which the excess loose material unattached to the tape was removed by flipping it and lightly tapping the sides of the glass slide. This process was repeated until there was full coverage of a monolayer of treated material over the surface of the adhesive tape.

The glass slide was placed on a goniometer and a water droplet was tittered to the surface of the soil using a Flow-Trac II, set with a predetermined flow rate of 0.0095l/s. Contact angle measurements were taken by capturing the water-soil-air interface for 10s with images taken at 1s intervals which were analyzed using the drop image analysis software, ASDA. To ensure consistency of results, the drop size was advanced as described in (Feyyisa, Daniels, and Pando 2017), until the contact radius reached equilibrium resulting in a constant angle measurement. Duplicate specimens were tested for each sample to evaluate variability in the results obtained.

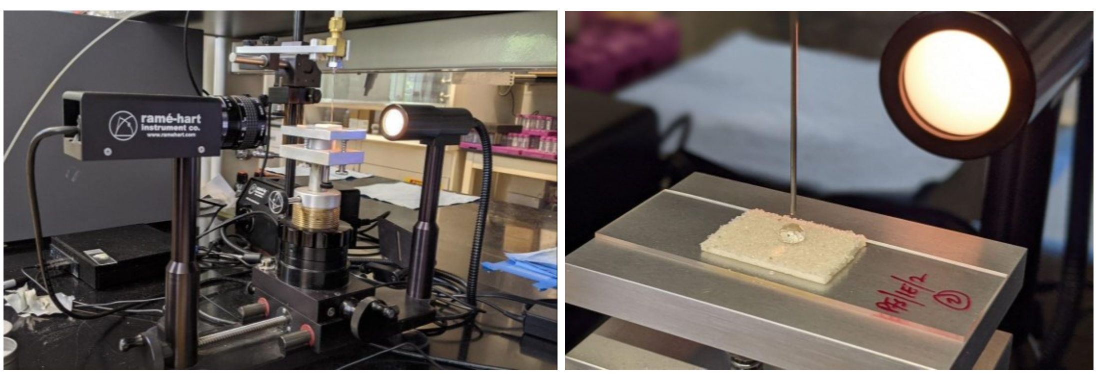

Fig 4: (a) Goniometer for Measuring Contact Angle (b) Water Drop on Test Sample

For aspects of the tests where sieving was required, the soils were passed through a set of sieves (#10, #16, #20, #40, #60, #80, #100, #160, #200) and the mass retained on each sieve, stored separately for testing. Studies have asserted that fairly uniform soil grains for the test make for a better, repeatable test. (Choi et al., 2016).

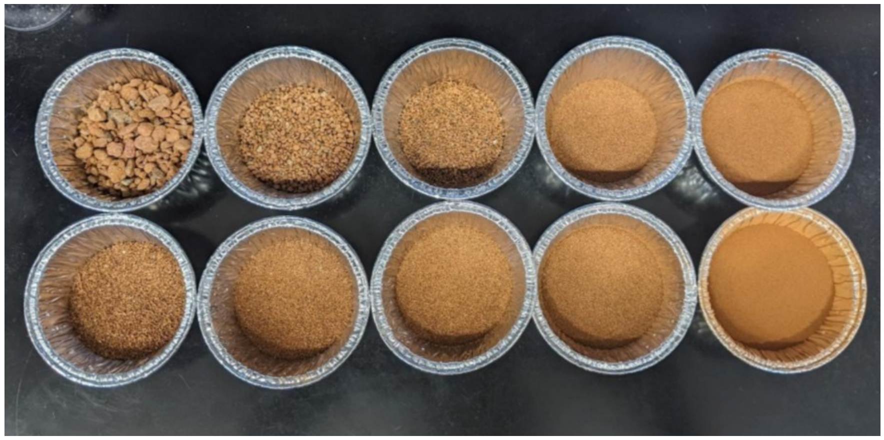

Fig 5: Sieved Soil Sample (NC-BO) Showing different grain sizes

2.2.3 Water Drop Penetration Test

The water drop penetration time (WDPT) method measures the degree of soil water repellency by evaluating the infiltration rate of water droplets into the soil (Letey, Carrillo, and Pang 2000). The Water Drop Penetration Time (WDPT) test involves placing water drops on the surface of an exposed surface of the soil with subsequent measurement of the time taken to infiltrate into the soil. Usually, an average is taken over some drops (typically three) and the mean is utilized in determining the degree of water repellency based on a given classification (King 1981; Liu et al. 2012). In this study, about 20g samples of the air-dried soil material were measured into a can and three drops of deionized water (50 ± 1 μL) were measured on the surface of the soil with a pipette. The time taken to complete the penetration of the water droplet was recorded with a timecode stamp to determine the time interval

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2.2.4 Breakthrough Head Tests

Breakthrough head tests were carried out to determine the water-repellent performance of a range of grain sizes. The samples were first dried in a desiccator until there was no further change in the mass of the samples. 100g of treated samples were compacted within a rigid walled tube lined with a rubber membrane for support, and placed on a porous stone upon the base of the triaxial cell. O-rings were placed with an O-ring expander to seal the membrane to the base and the top cap. The cell was set up and filled with distilled water and a confining pressure was applied while the valve to the top cap remains open to allow the outflow of excess air from the sample within the membrane. An initial "flushing" pressure (0.5kPa) is applied through the base of the setup using a FLOWTRAC II (Geocomp) to ensure there is no air trapped between the porous stones and the sample. A "back pressure of 0.1kPa was applied to the sample using the FLOWTRAC II and kept constant for 5 minutes and the volume of water flowing into the specimen was measured. The pressure was incrementally increased at 0.1 kPa intervals till 1kPa and at 1kPa intervals till the breakthrough volume was reached. A breakthrough volume of 0.1cc (cm^3) was utilized for this test. The test is ended after breakthrough has occurred within the sample.

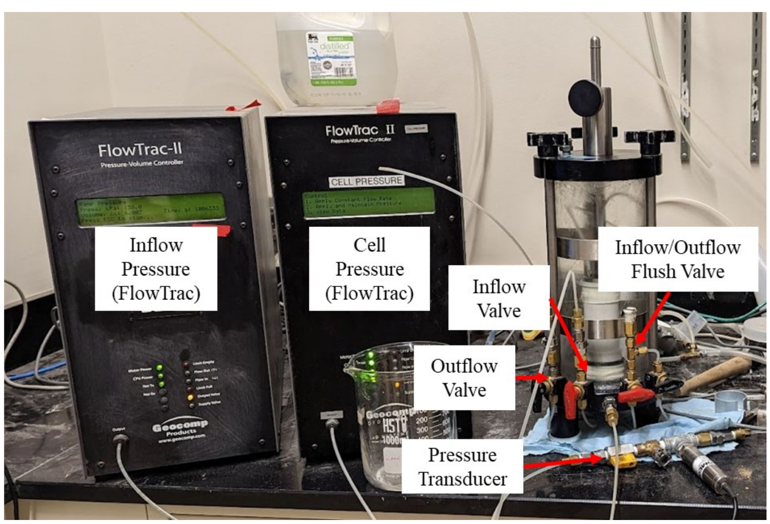

Fig 6: Setup for Breakthrough Test

3.0 Results and Discussion

3.1 Contact Angle Test

3.1.1 Contact Angle Using Bulk Mass.

Results from Contact Angle tests carried out using the bulk soil mass are given in Fig xx below. Water repellency treatment was effective with contact angles ranging from 119.5° to 148.5°. Based on the classification from (Goebel et al. 2011; McHale, Newton, and Shirtcliffe 2005), the soils can be considered hydrophobic (>90°) and close to superhydrophobicity (150°). Treated NC-BO soil can be classified as superhydrophobic. There was a slight increase in the CA values of the oven-dried soil. This can be attributed to the hygroscopic nature of the fine-grained portion of the soil. Oven-dried CA values represent the maximum possible CA of the treated soil sample for that dosage concentration while air-dried CA values are more representative of obtainable values after sufficient drying in the field (Uduebor, Daniels, Naqvi, et al. 2022). It must also be noted that values obtained from the contact angle tests are not the maximum CA possible for the treated soil. Johnson & Dettre, 1964 analyzed water-repellent treated heterogeneous surfaces and reported that a fairly constant contact angle was obtainable after over 40% of the total surface area has been made non-wettable. Therefore, increasing OS concentration will impact the performance of the treated material and not necessarily its contact angle as more surfaces of the material will be made non-wettable.

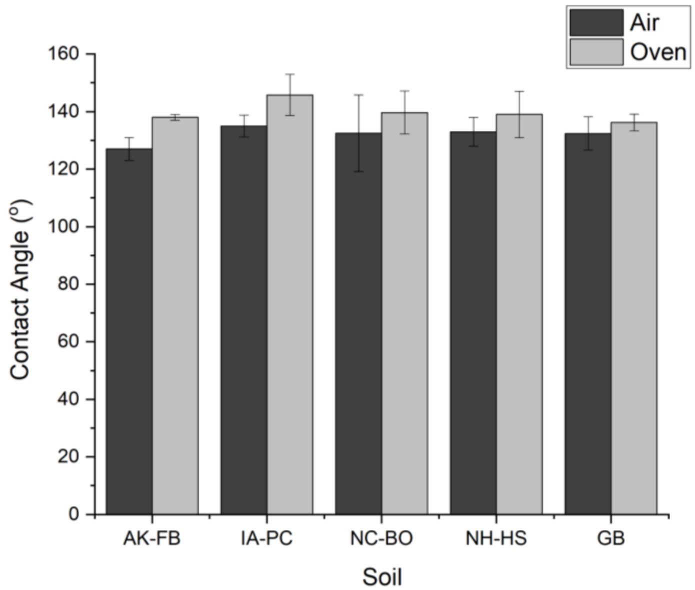

Fig 6: Contact Angle for different soils treated with organosilane (1:10, OS: Soil)

3.1.2 Contact Angle with Grain Size

Results of contact angle measurements of sieved grain sizes indicate a reduction in CA values with increasing grain size Figs 6a-e. This is due to a decrease in the treated total surface area. Finer-grained soils have a larger specific surface area than coarse-grained particles. Also, as grain sizes get coarser or rougher the contact angle also increases. This is noticeable in all soil particles except glass beads which have a uniform spherical shape and no rough edges. This marked increase in surface roughness has also been observed in previous studies carried out by (Yunesh Saulick, Lourenço, and Baudet 2016). This marked increase is noticeable around ~1mm. It is therefore important to note that no singular grain size is sufficient to characterize the CA of the bulk mass. Hence it is imperative to have a good knowledge of the grain size distribution of the soil mass and the relative effect of the major and minor constituents and their properties on the CA of the bulk mass. For example, soil with less than 5% fines if mounted for the CA test could give higher contact angle values from the fines that may not be representative of the CA of the bulk mass.

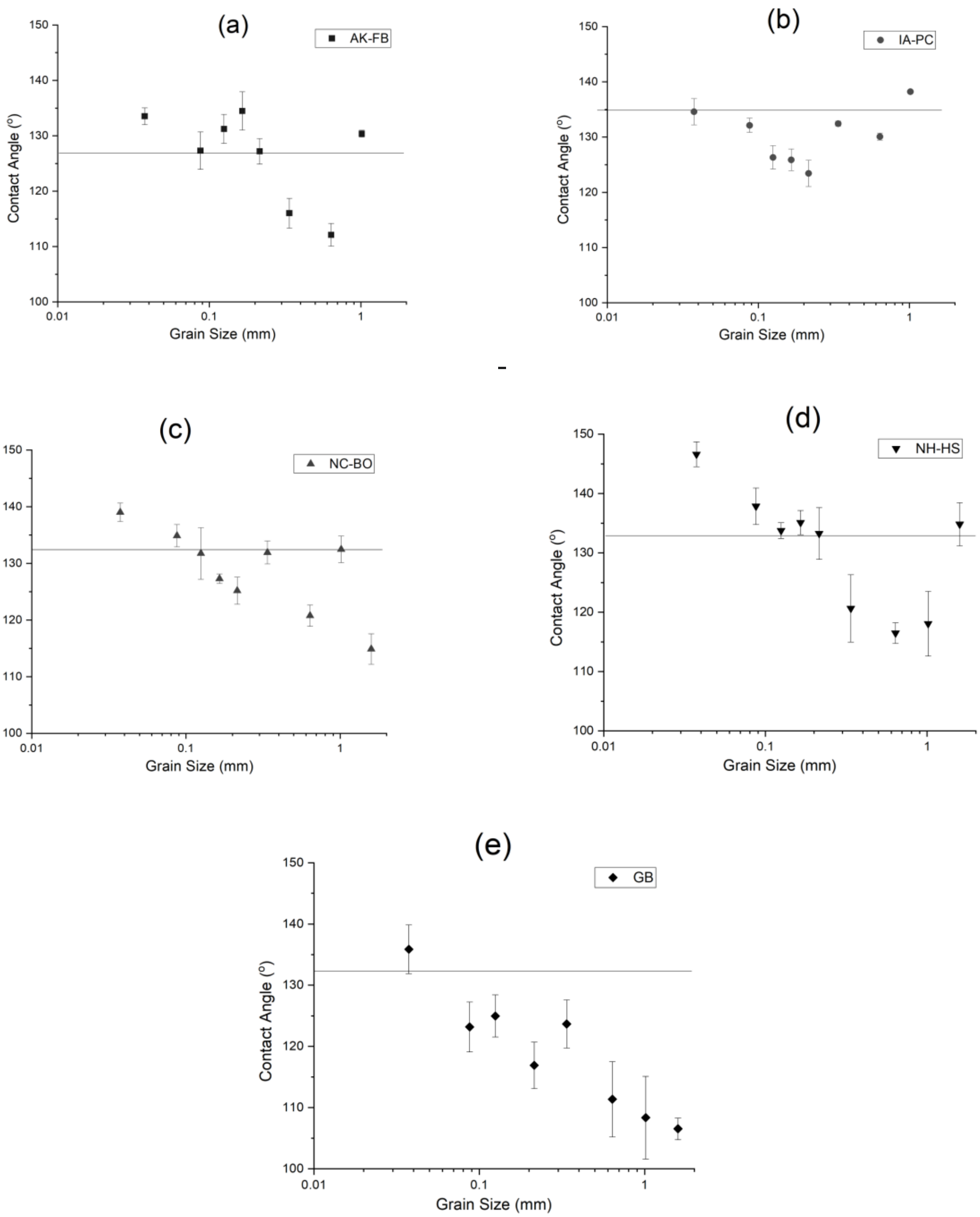

Fig 7: Contact Angles with Respect to Average Grain Size for Treated Soil Samples (lines show the Contact Angle of Bulk Mass)

3.1.3 Normalized Contact Angle with grain size

A normalized graph plot of the CA results is given in Fig x below. The maximum obtained CA is given a value of 1 and the other values are expressed as a fraction of the maximum value. It can be observed minimum CA values obtained are within 0.8 - 0.9 of the maximum value. This could form a standardized factor of safety for expressing CA values obtained using fine grains from the bulk mass only. Results obtained using bulk mass can be multiplied by 0.8 to give a range of values or utilized as a safe value for calculations.

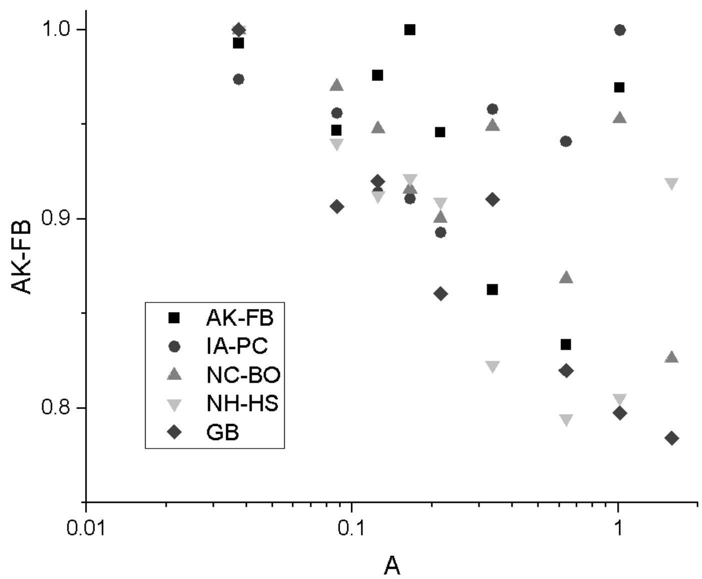

Fig 8: Normalized Contact Angle Values with Respect to Grain Size

3.2 Water Drop Penetration Test

All untreated soil samples had instantaneous penetration (<1s), except AKFB (~128s) and GB (~2s). AKFB possesses some humic properties that give it a pseudo-water-repellency that disappears after mixing with water, while the water droplet lagged before infiltrating into the glass bead sample. All treated samples did not get any infiltration, regardless of grain size, and penetration was not recorded even after 2 hours (7200s). This indicates that the surface of each particle was sufficiently treated and water-repellent regardless of particle size.

3.3 Breakthrough Pressure Test

As versatile as the contact angle and water drop penetration test time are, they only provide an empirical estimation of what the performance of the treated soil as a barrier will be. In many cases, other factors like densification, fluid type, and viscosity play an important role in determining the performance of water-repellent soils. The breakthrough pressure tests result is shown in Fig 9 below. There is a noticeable decrease in the breakthrough pressure values with an increase in the grain size of the samples.

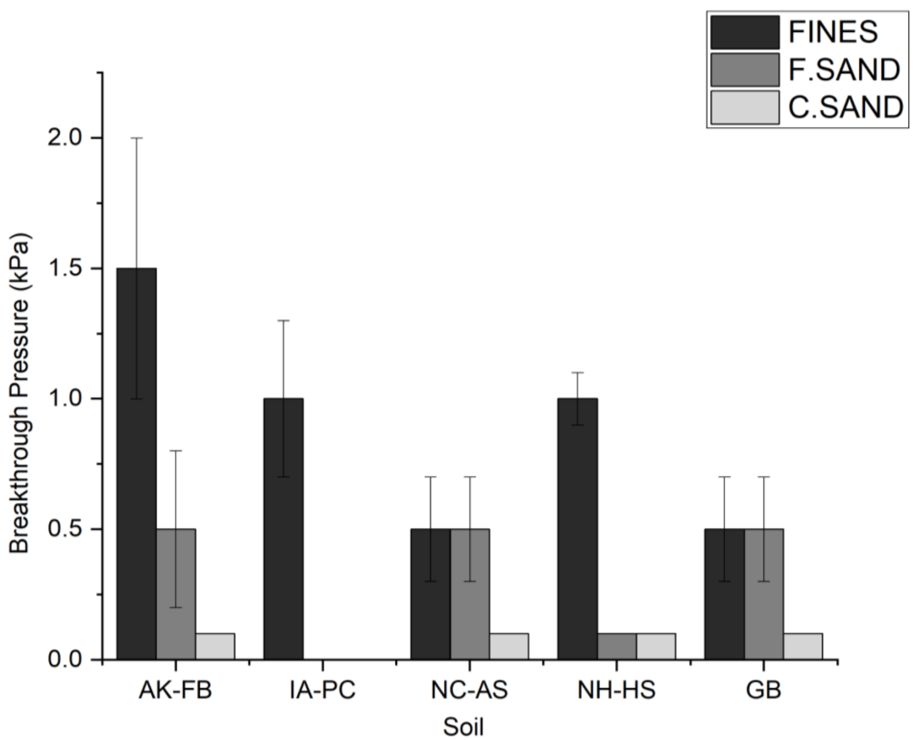

Fig 9: Breakthrough Test Results

This reveals the impact of pore size openings on the ability of treated water-repellent soil to sustain a hydrostatic head. While the particle surfaces themselves are water-repellent, as confirmed by the

WDPT tests, the pore spaces are open and their size ultimately determines the infiltration of water into the soil.

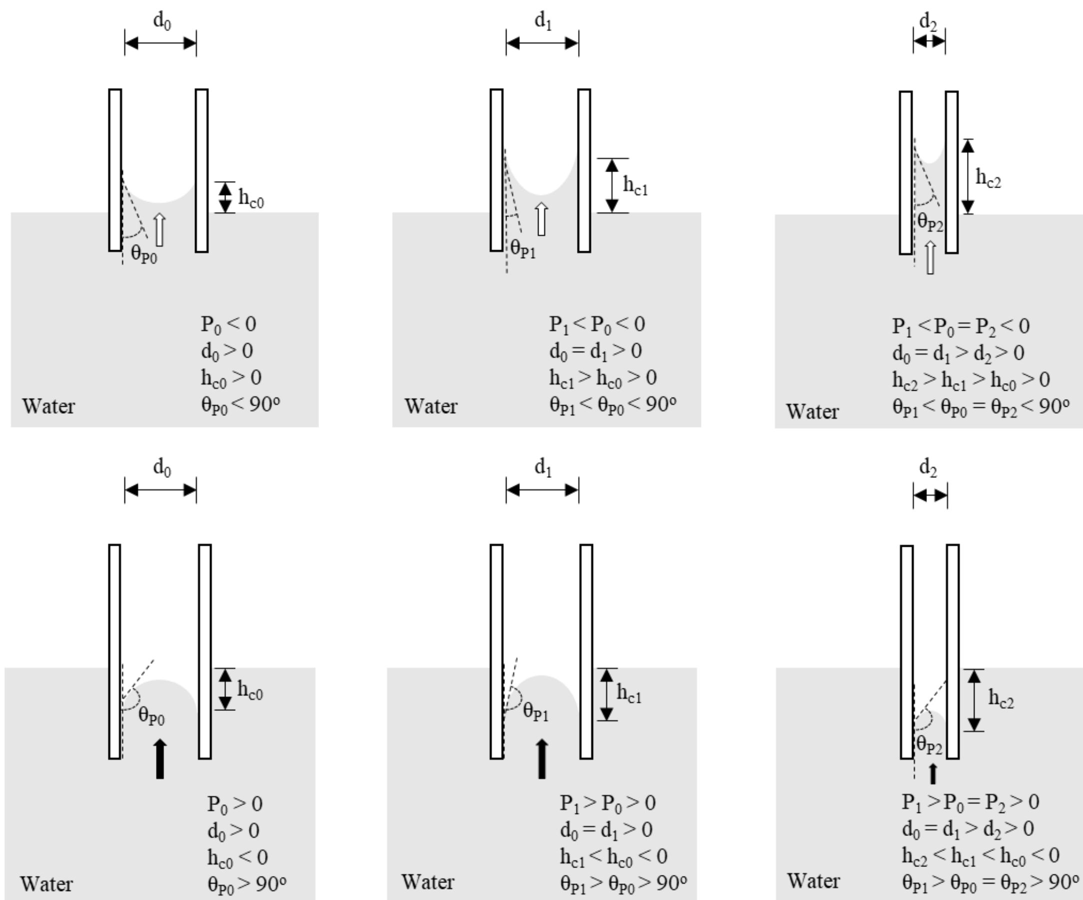

Fig 10: Idealized Sketch of The Difference in Capillary Rise in Hydrophilic and Hydrophobic Pore Spaces

Figure 10 shows an idealized sketch of the difference in the capillary rise in hydrophilic and hydrophobic pore spaces and the effect of changing pore diameter. For a hydrophilic pore, with a contact angle, $\theta_{P0} < 90^o$, the capillary rise within it can be increased by increasing the wettability (reducing the contact angle, $\theta_{P1} < \theta_{P0} < 90^o$) of the surface at a similar pore diameter ($d_1 = d_0 > 0$), or by decreasing the pore diameter, ($d_0 > d_2 > 0$), at the same degree of wettability ($\theta_{P0} = \theta_{P2} < 90^o$). Alternatively, for the hydrophobic pore, increasing the contact angle reduces the capillary rise (θ_{P1}

$> \theta_{P0} > 90^{o}$) at a similar pore diameter, and a corresponding decrease is achieved at the same degree of hydrophobicity by reducing the pore size. This reveals that at a uniform level of hydrophobicity of soil particles, the breakthrough pressure is dependent on the size of the pore space openings. Smaller openings will result in higher breakthrough pressure values and vice versa (Fig 11.)

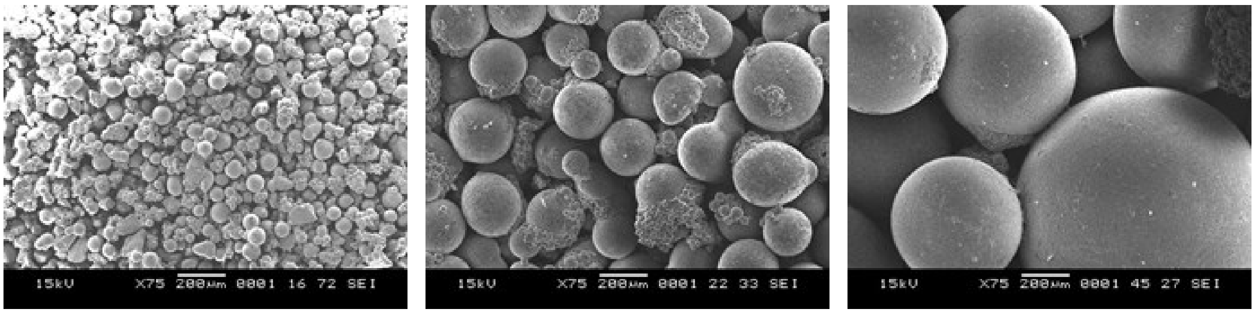

Fig. 11. SEM images (at x75 Magnification) of glass beads showing the various particle sizes and their pore space openings (a.) Fines (b.) Fine Sand, (c.) Coarse Sand

4.0 Conclusion

Moisture-related distresses account for a majority of pavement distresses, depending on the pavement type and environmental conditions. Particularly in cold regions where frost action exacerbates the damage done to civil engineering infrastructure. This damage results in perennial rehabilitation and maintenance activities that cost a lot and contribute majorly to global CO_2 emissions. There is a need for a sustainable solution to reduce maintenance costs and reduce emissions. Engineering Water Repellency in soils is a sustainable solution to mitigating moisture-related problems and frost damage, particularly in road pavements where moisture conditions can be kept uniform, allowing for better design, and long-term performance, saving construction and maintenance costs, and reducing global warming. This innovative technology requires the right knowledge and testing protocols to assess both its efficacy and performance, particularly in soils where treatment results vary for different soil grains and types within a soil mass due to mineralogy, size, and surface area. The conclusions from this study are summarized in the points below

1. Conventional tests like the Sessile Drop Method (Contact Angle) tests developed in soil science are more suited for uniform-sized material to obtain repeatable and reliable results. Engineering soil is a mixture of different grain-sized materials; hence it is important to consider the effect of the treatment of each grain size type in determining the overall contact angle for the soil. Test carried out indicates higher contact values are obtained for the finer-grained portion of the soils and gradually reduce with an increase in grain size (up to 20% decrease).

2. There is also a marked increase with an increase in surface roughness (noticeable after a certain grain size of ~1mm). Therefore, contact angle determination for civil engineering applications should be given either as a range of values or as the least observable measurement based on individual particle size or surface characteristics. Contact angle measurements should be determined for major soil constituents, particularly grain sizes greater than 10%, as they affect the overall contact angle of the bulk soil mass

3. While Contact Angle tests are simple and useful ways of determining the efficacy of water-repellent treatment, it does not give any behavioral or performance information useful to the engineer. Breakthrough Pressure tests provide a measure of the ability of the treated soil to sustain a hydrostatic head. Test results indicate that there is a higher breakthrough pressure for finer-grained soil compared to soils with larger grain sizes. This is due to the reduced pore space within them that limits the transport of moisture through the water-repellent soil.

4. There is a strong correlation between the pore size of the treated soil compared to the breakthrough pressure with an inverse relationship between them.

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