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Soil-to-Metal Friction, Soil Adhesion and Characterization of Nanosilica – Enhanced Coating Material for Cold-Rolled Steel

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ABSTRACT

A coating procedure that uses nanosilica as its precursor was developed and tested for its technical viability in reducing soil-to-metal friction and soil adhesion in cold rolled steels (CRS). This was in relation to the development of a nanosilica-based surface coating for the reduction of energy expenditure in tillage implements. CRS were dip–coated with sodium silicate hydrates to smoothen their surface. The nanosilica weight concentration (5%, 12.5% and 20%) and dipping time (5 min, 17.5 min and 30 min) in the silicate solution time varied among treatments. The coated CRS were oven dried, aged and dipped in a surface modifying agent (HMDS–Methanol Solution). Soil bin test using Maahas Clay showed that coating the CRS decreased soil-to-metal friction and adhesion coefficient by an average of 24.0% and 36.0%, respectively. Only the nanosilica concentration had a significant effect on soil-to-metal friction coefficient and adhesion coefficient. The optimum nanosilica weight concentration was at 5%. Surface characterization using Scanning Electron Microscope (SEM) showed that sodium silicate hydrates were deposited on the microscopic crevices. Hydration and deposition of the silicates created a thin film on of the CRS and increased the surface area-to-volume ratio of the silicas.

Keywords: soil-to-metal friction, soil adhesion, surface coating, nanosilica, nanotechnology

INTRODUCTION

Any mechanical manipulation of the soil that changes its structure is known as tillage. This definition encompasses a wide range of activities such as plowing the soil for agricultural purposes and leveling of land for civil works (Gill and Van Den Berg, 1968). However, in the field of agricultural engineering, tillage is often limited to the physical manipulation of the soil for crop production. It is done to improve the soil physical condition for seed germination and crop growth (Walters, 2016). Employing tillage operation, especially during land preparation also increases the available water that the crop can use.

Physical manipulation of the soil requires high power requirement. Consequently, tillage consumes most of the energy budget expended in the farm. In Malaysia, 48.6% or 1 747.33 MJ·ha-1of the operational energy requirement for lowland rice can be attributed to tillage. This accounts for the energy utilized in mechanizing the operation and includes direct and sequestered energy from machinery use (Bockari - Gevao *et al*., 2005). Tillage operation done in heavy clay soils can even consume 55 - 65% of the direct field energy consumption (Pelizzi *et al*., 1988 as cited by Stajnko *et al*., 2009).

Most of the energy expended in tillage comes from fossil fuel and as international prices of diesel fuel continuously rises, the cost of energy will also rise (Ghorbani *et al*., 2011 as cited by Lopez-Vazquez *et al*., 2019). Energy requirement has a positive correlation with the total production cost of the farm. Farms with high tillage power requirement need prime movers with high power rating. Consequently, such farms require higher capital outlay and operational and maintenance cost. This leads to low net farm income and high market price of most field crops.

Researches were conducted to decrease the energy requirement of tillage. Most of them focused on decreasing the force required to pull the tillage tool or implement through the soil (Walters, 2016). This force, which is commonly referred to as draft, is determined by the soil texture, soil moisture content, operating speed, cutting edge sharpness, and implement's over-all adjustment (Grisso *et al*., 1994 as cited by Okoko, *et al*., 2018). It is usually made up of frictional forces and interaction forces. These two forces usually occur between the soil and the material interface. (Gill and Van Den Berg, 1968).

A significant portion of tillage tool draft requirement can be associated with soil and metal interaction. In plowing alone, 42% to 62% of its draft requirement can be attributed to sliding friction between soil and metal (Vilde and Rucins, 2008). Reducing the total energy expenditure of field crop production may be significantly decrease by using appropriate measure to decrease soil-to-metal friction. One precautionary measure that reduces soil-metal sliding resistance is through surface coating. In the past, several coating materials, such as gypsum, enamel and TeflonTM, were used to lower the draft requirement of tillage implements. Enamel coating in moldboard plow can reduce specific draft by 23% (Salokhe and Gee - Clough, 1992). Adaptations of these coating were not successful because of either high cost of the coating material, complicated coating technique, poor performance or the material has low resistance to wear (Salokhe *et al*., 1992).

This study was conducted to develop and test a nanosilica-based surface coating for Cold Rolled Steel (CRS) that can eventually be used to reduce soil-to-metal friction and soil adhesion in tillage implements.

Silica (SiO_2) is used as raw material for polymer, ceramic and electronics materials and has wide range of technological application. It can be used thixotrophic agents, composite filler, thermal insulator and desiccant (Liou, 2004 as cited by Ignacio *et al*., 2014). Additionally, sodium silicate, from SiO_2, has been widely used for producing protective coating. It can form a durable waterproof coating that can withstand high temperature and can resist corrosion. Furthermore, it can be easily produced, cheap and non-toxic, making it suitable for different industrial application (Nazharova *et al*., 2018). These properties of silica, together with advances and development in nanotechnology, may provide innovative ways of reconstructing the surface properties of tillage implements.

REVIEW OF RELATED LITERATURE

A large proportion (42% - 62%) of the power requirement for tillage operation is used to overcome the sliding resistance as the soil moves through the surface of a soil-engaging unit of the tillage equipment (Vilde and Rucins, 2008). At low moisture content, the friction between the soil particles and the metal surface of the soil-engaging unit is due to pure sliding action. As the moisture content increases, friction increases because of adhesion. Moisture film between the soil particles and the metal expands and adhesive forces are created (Srivasta *et al*., 2006 as cited by Hasankhani – Ghavam *et al*., 2015). Between soil and other materials like metals, adhesive forces are exclusively due to moisture films. When a continuous film of water is between a saturated soil and a solid surface and reaches equilibrium, the moisture tension would be the same through the soil mass and the contact interface. The soil adhesion as a force per unit area caused by the water film is equal to the moisture tension; thus, the soil sticks. Moreover, soil adhesion increases as the proportion of clay particles increases. It is highest when the moisture content of the soil was between the plastic limit and liquid limit. (Lu - Quan *et al*., 2001). Further increasing the moisture content beyond the adhesion phase will reduce friction. This is at the phase where the moisture film acts as a lubricant on the interface of the soil and metal (Srivasta *et al*., 2006 as cited by Hasankhani – Ghavam *et al*., 2015.

One of the possible means of reducing the tillage requirement is to utilize surfaces with low frictional properties. This can be achieved by either using materials, like plastic and ceramic, that has low coefficient of friction or by coating the surface with low frictional properties such as enamel or TeflonTM (Salokhe *et al*., 1991). Similarly, the effect of moisture content on the coefficient of adhesion (Ca) differs from what material has an interface with the soil (Harsono, 2011).

Ceramic surface tends to produce a smaller soil adhesion component compared with Nylatron® and metal. Moreover, the behavior of coefficient of friction of the three materials as the soil moisture content increases is the same and in line with the results of previous study. At low moisture content, the soil adhesion for the three surfaces is low because of the low moisture tension and it increases as the moisture content increases. The coefficient of adhesion for the three surfaces is increasing from 25% to 55% moisture content. In this range, the ceramics offer the least adhesion. After the soil is saturated, there is enough moisture content in the soil moisture content at the surface to have a lubricating effect (Harsono, 2011).

Another means to lower the surface friction of the tillage equipment is by using various surface coating. Different coatings were used in the past like TeflonTM and ceramic; however, these materials were not successful because of either high cost of the coating material, complicated coating technique, low resistance to wear and tear, and inefficient in reducing the sliding resistance of the soil (Salokhe *et al*., 1991).

Lug surfaces of cage wheels were coated with TeflonTM tape, ceramic tile, and enamel. It was observed that three materials significantly reduce the soil adhesion (Salokhe et. al., 1991). Studies on float showed that enamel coating reduces the draft by 64%, 46% and 45% for clay, loam and sandy soils respectively (Canillas *et al*., 1982, as cited by Salokhe *et al*., 1991).

An enamel coated plate of moldboard plow shape was evaluated on different soil moisture content, depth of cut and operating speed. The specific draft requirement was reduced by 8 to 23%. Coating the moldboard plow showed the highest reduction of the draft requirement at 25 cm depth of cut, 32.8% moisture content and an operating speed of 5.8 kph (Salokhe *et al*., 1991).

An enamel-coated steel sheet disc-shaped plate was fabricated on an attempt to reduced draft in disc plows. The performance of the coated plate was evaluated at different moisture content, plowing speed and disc angle. The overall percent reduction in the specific draft of the disc was 4 to 21%. The reduction in the draft requirement for both tillage equipment can be attributed to the low adhesion of enamel coating to soil and low coefficient of friction between enamel and soil (Salokhe *et al*., 1991).

Nanotechnology development has provided innovative ways of constructing surface properties of solid materials at atomic, molecular and supramolecular level (Liu *et al*., 2006). Nanoparticles are organic or inorganic solid objects that have one dimension, usually the diameter, that measures 100 nanometers (nm) or less. Properties of many common materials change when it exists on its nanoparticle form. This is because nanoparticles have a greater surface area per weight than large particles. This causes nanoparticles to be more reactive to some other molecules. For example, metal nanoparticles have lower melting point, high specific surface areas, mechanical strength and specific magnetizations compared to bulk metals. These properties might prove attractive in various applications (Horikoshi and Serpone, 1993).

Nanoparticles in surface coating organize themselves to form a film and bond with the surface of the substrate. If the surface is smooth and not absorbent, the nanoparticle combines with the surface, repelling liquids along with other foreign materials. On the other hand, with porous surfaces, nanoparticles fill up the voids from the inside. In this manner, dirt and liquid are also easily expelled to the surface of the materials (Nanoman, 2015). They are often more efficient because they provide a nanoscopic surface layer that repels water (Felice, 2013).

Figure 1. Activated nanosilica derived from rice hull

MATERIALS AND METHODS

Experimental Design

Split-plot in Complete Randomized Design was used to determine the effect of nanosilica weight concentration (subplot) in the sodium silicate solution, dipping time (main plot) and their interaction to soil-to-metal friction coefficient and adhesion coefficient (Table 1). Each treatment was replicated thrice.

Preparation of Sodium Silicate Hydrate Solution

Aqueous sodium silicate (Na_2SiO_3) solutions were produced using activated nano SiO_2 (Figure 1) distilled water and NaOH, (AR) pellets. The nanosilica (Table 2) used were produced from rice hull by the UPLB Nanotechnology Laboratory. The sodium silicate solutions had a molar ratio of 3, with varying amounts of NaOH and nanosilica, depending on the desired SiO_2 weight concentration (Table 3).

Table 1. Graduated level of the two factors used in the study

INDEPENDENT VARIABLES	LEVELS			
Nanosilica weight concentration, (wt. %)	0.0	5.0	12.5	20.0
Dipping time (min)	-	5.0	17.5	30.0

Table 2. Hydrothermal nanolica characteristic used in the study

PROPERTY	DESCRIPTION
Particle size, nm[a]	10 ± 3 nm
Phase classification[b]	amorphous
Composition, %[c]	
Si	98.30 ± 1.18
Ca	0.41 ± 0.24
Fe	0.35 ± 0.03
Mn	0.15 ± 0.07
Cu	0.08 ± 0.00
Cr	0.03 ± 0.00
Zn	0.01 ± 0.00
Ba	0.084
K	1.217
Ti	0.038

[a]Particle size by Atmomic Force Mioroscopy
[b]Crystallographic Analysis by XRD
[c]Elemental Analysis by Energy Dispersive X-Ray Spectroscopy

Table 3. Quantity (g·L^{-1} of water) of NaOH and Nano SiO_2 needed at different SiO_2 weight concentration (wt. %) at three molar ratio (MR)

COM-POUND	NANOSILICA CONCENTRATION, (wt %)			
	0.0	5.0	12.5	20.0
NaOH	0.0	24.0	68.0	125.0
Nanosilica	0.0	54.0	152.5	281.0

Nano SiO_2 were initially activated inside a muffle furnace at 250°C for three hours. They were cooled at room temperature inside a desiccator. NaOH pellets were dissolved in 1.0 L of distilled water. Activated nanosilica were then added to the prepared aqueous NaOH solution. Stirring was done at 80°C to completely dissolve the nanosilica. Sodium silicate solutions (pH = 11.5) were then filtered using a Whatman filter paper no. 42 to remove any undissolved silica or precipitates. The solutions were then cooled to room temperature prior to dipping

Double Dip-Coating and Surface Characterization of CRS

Substrates were prepared by cutting several pieces of CRS. A threaded hole was drilled on the side of each substrate. Stainless metal rods with threaded end were prepared to serve as handles of the steel substrate during the coating process (Figure 2). The prepared CRS were sanded to even its surface and to remove rusts. The coating procedure developed by Setyawan *et al*., (2010) was adopted and modified in coating the metal substrates using nanosilica as a precursor. Substrates were cleaned using distilled water and ethanol. They were then dried inside an oven at 105°C for 15 minutes.

The cleaned CRS were dipped vertically into the prepared sodium silicate solution at different duration - 5 minutes, 17.5 minutes and 30 minutes. Control CRS samples were not dipped to the sodium silicate solution and represented nanosilica concentration at 0%. After dipping, the coated metals were immediately dried inside an oven at a temperature of 100°C for 20 minutes. These were then aged for at least 10 hours in room temperature

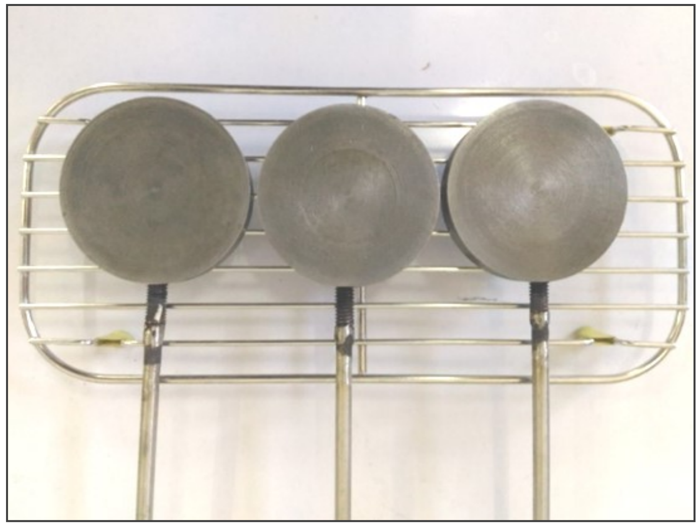

Figure 2. Cleaned and pre-treated metal substrates with stainless metal rod used in the study

to strengthen the adhesion of silica on the steel substrate. The nanosilica coated CRS were then dipped in methanol for one hour to allow exchange between pore water with methanol and to lower the coated sodium silicate pH below 10. After dipping, the CRS were oven dried at 105°C for two hours. At the same time, the surface modifying agent (SMA) was prepared by adding three parts HMDS to two parts Methanol (3:2). The aged substrates were then dipped on the SMA solution for seven hours. Afterwards, these were dried in an oven with a temperature of 100°C for two hours.

Soil Sample Preparation

Maahas clay from Agri-Park, College of Agriculture and Food Science, UPLB was used for the experiment. Soil samples were air dried for one week and then pulverized using a hammer mill with 4 mm sieve. Afterwards, soil samples were placed on a fabricated metal soil canister (Figure 3). Perforations were present on the metal canister to allow percolation and capillary action. Soils were layered gradually to the metal canister.

Each layer had an average depth of 2 cm. was compacted using a mallet from a height of 2.5 cm for two passes. Soil samples were then saturated by placing the metal canister on a basin with water. The

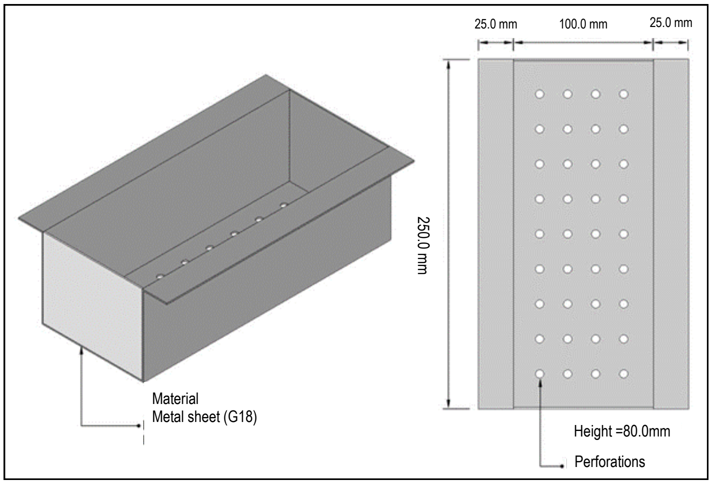

Figure 3. Fabricated metal soil canister

water level of the basin was maintained below the lip of the canister to prevent the soil from spilling from the canister. The soil canister was removed from the basin once the topmost soil was fully wetted and saturated Afterwards, the soil samples were left to drain for three days. This is to attain the moisture content of the soil at its field capacity. After draining the soils for three days, samples were taken for moisture content determination.

Soil-to-Metal Friction and Adhesion Coefficient Determination

A customized instrumentation set-up (Figure 4, Figure 5 and Figure 6) based from the study of Hazankhani-Ghavam *et al*., (2011) was fabricated to determine the soil-to-metal friction and adhesion coefficient between the metal substrates and the soil.

The soil bin was made up of lumber and had an effective length of 250 mm, the width of 100 mm and height of 80 mm. A 5-hp variable speed electric motor was used to control the movement and speed of the soil bin. A specialized chain and sprocket system were used as the transmission system between the soil bin and the power source.

One hundred grams of weight was placed on top of the steel substrate to serve as the normal load. The soil bin was then moved at a constant speed of 0.025 m s^{-1}. The shear (frictional) force on the metal-soil interface was measured by the load cell and was sent

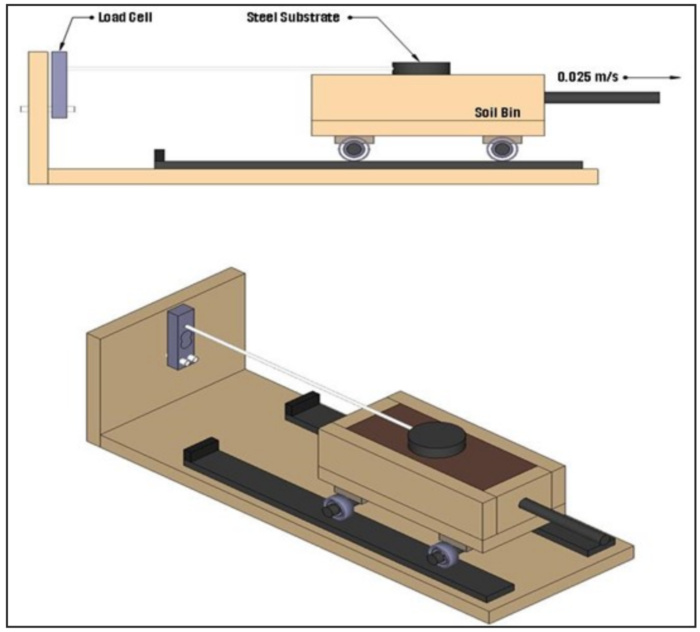

Figure 4. Schematic diagram of the fabricated soil bin test used in the study

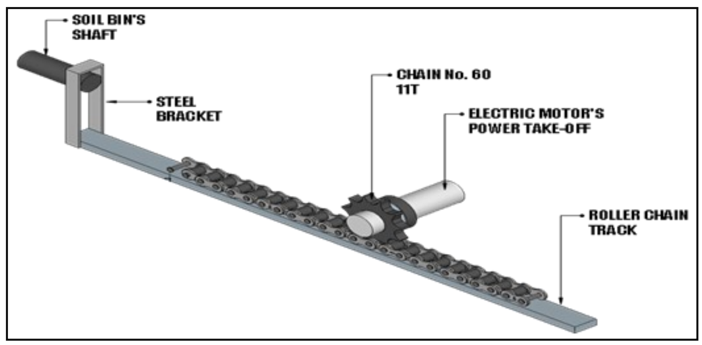

Figure 5. Transmission system of the fabricated soil bin

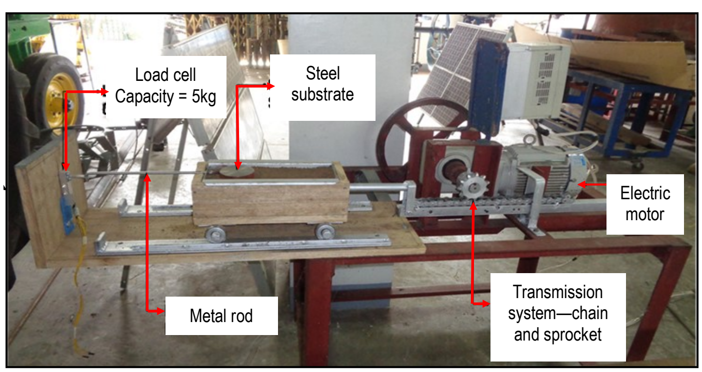

Figure 6. Actual soil bin used in the study

through the sensor amplifier and board to the laptop via Arduino. The same procedure was repeated with 200 grams and 500 grams normal load. Lint-free wipes were used to clean the substrates before every pass. A graph was generated by plotting the normal force and its corresponding shear force. The slope of the graph corresponded to the soil-to-metal friction coefficient while the intercept corresponded to the adhesion coefficient (KPa).

Statistical Analysis

Soil-to-metal friction coefficient, adhesion coefficient and the actual soil adhered to the CRS were subjected to one-way ANOVA in Split Plot in CRD. Means were compared using Tukey's HSD.

Surface Characterization of Coated CRS

Samples of both coated and uncoated CRS were characterized using Focused Ion Beam – Field Emission Scanning Electron Microscope (FIB – SEM) at the Advance Material Testing and Evaluation Laboratory (ADMATEL) – Industrial Technology Development Institute (ITDI) of the Department of Science and Technology (DOST).

RESULTS AND DISCUSSION

Soil-to-Metal Friction and Soil Adhesion Coefficient of Coated CRS

For each treatment, the soil bin test generated stress curves (Figure 7) using the Mohr-Coulomb Theory. These were established by plotting the shear stress (T_{max}) generated at 100 g (2.15 KPa), 200 g (4.30 KPa) and 500 g (10.75 KPa) normal stresses. The average soil-to-friction coefficient and adhesion coefficient component on each treatment were determined based on the slopes and y-intercepts of the generated stress curves, respectively.

ANOVA showed that only the weight concentration of the sodium silicate solution, had a significant effect on the soil-to-metal friction coefficient and adhesive coefficient (Table 4). Comparison of means using Tukey's HSD (Table 5 and Table 6) was used to evaluate the effect of the different nanosilica concentration varied significantly from each other. It was also used to determine the optimum combination of nanosilica concentration and dipping to be used for tillage implements. Increasing the nanosilica concentration from 5% to 20% has no significant effect on both soil-to-metal friction coefficient and soil adhesion. Hence, the optimum nanosilica concentration to be used for coating tillage implements can be limited to 5%.

Table 4. P-values from ANOVA of coated and un-coated CRS at Split Plot in CRD (α = 0.05)

SOURCES OF VARIATION	SOIL-TO-METAL FRICTION	ADHESION COEF-FICIENT
Nanosilica concentration	0.0012[a]	0.0139[a]
Dipping time	0.8468[ns]	0.1495[ns]
Interaction	0.2429[ns]	0.0906[ns]

[a]significant at α=0.05, [ns]not significant at α=0.05
cv (nanosilica concentration) = 14.68%,
cv (dipping time) = 12.88%

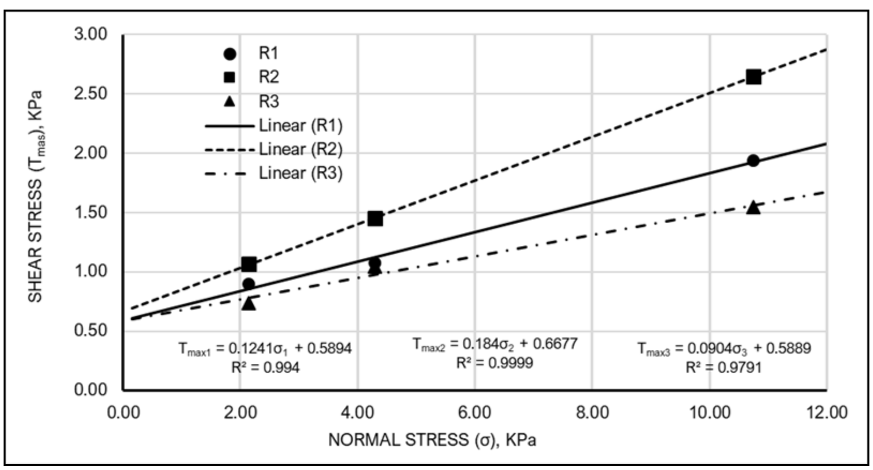

Figure 7. Sample generated stress curve from CRS coated with 5% nanosilica and dipping time of 30 min, soil moisture content at 45%.

Control or uncoated steel substrates produced the highest soil-to-metal friction coefficient and adhesion coefficient. It was consistent with the average soil-to-metal friction coefficient (0.194) and adhesion coefficient (1.25 KPa) of metal rake at 45% soil moisture content (Harsono, 2011). This also validated the accuracy of the fabricated soil bin in determining soil-to-metal friction and adhesion coefficient

Table 5. Average soil-to-metal friction coefficient of uncoated and coated CRS at different nanosilica concentration and dipping time, moisture content at 45%

DIPPING TIME, (min)	NANOSILICA CONCENTRATION, (wt %)			
	0.0	5.0	12.5	20.0
5.0	0.150	0.097	0.109	0.119
17.5	0.130	0.120	0.111	0.113
30.0	0.180	0.107	0.123	0.115
Average	0.152[a]	0.109[b]	0.108[b]	0.120[b]

Means with the same letter are not significantly different from each other at α=0.05

Coating CRS in sodium silicate solution with 5% wt. of nanosilica for five minutes had produced the lowest soil – to metal friction coefficient while coating CRS in sodium silicate solution with 5% wt. of nanosilica and was dipped for 17.5 minutes had produced the lowest soil adhesive components. Metal substrates from these two treatments were dipped on solutions with same nanosilica weight concentration of 5%. On the average, the coating procedure decreased soil-to -metal friction coefficient and adhesion coefficient by 24% and 36%, respectively.

Table 6. Average adhesion coefficient, in KPa, of uncoated and coated CRS at different nanosilica concentration and dipping time, moisture content at 45%

DIPPING TIME, (min)	NANOSILICA CONCENTRATION, (wt %)			
	0.0	5.0	12.5	20.0
5.0	1.290	0.704	0.860	0.610
17.5	1.018	0.603	0.790	0.634
30.0	0.904	0.614	0.548	0.731
Average	1.070[a]	0.641[b]	0.732[b]	0.660[b]

Means with the same letter are not significantly different from each other at α=0.05

It was previously mentioned that one of the factors that increase the soil-to-metal friction is soil adhesion. As moisture film develops in the surface of the metal substrate, soil adheres to it because water molecules on the surface of the steel and water molecules on the surface of the soil get attracted to each other thru cohesion. When there is a significant amount of soil that adheres to the metal surface, its morphology was altered, and soil-to-metal friction will increase and yield close to soil-to-soil friction. This is evident to amount of soil that adhered to the metal substrate during the soil bin test (Figure 8).

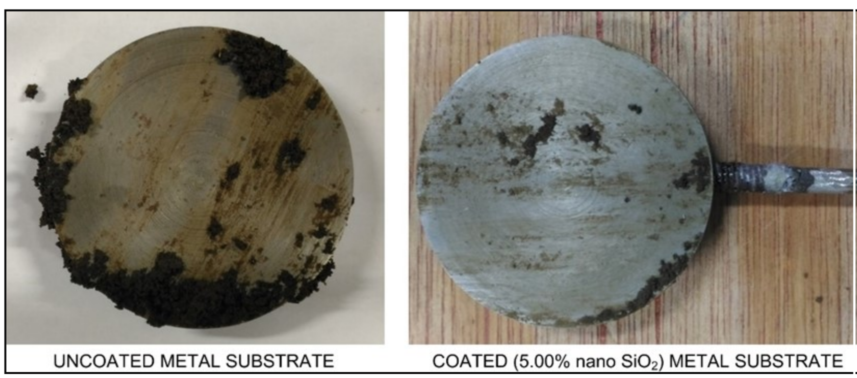

Figure 8. Uncoated and coated metal substrate after the soil bin test

Although the coating procedure had the ability to decrease the quantity of soil that stuck to the substrate, it did not decrease significantly the actual soil adhesion. Capillary action plays an important role in adhesion and the formation of water film in the produced tangential and normal force in the surface of tillage implements (Fisher and Baver,

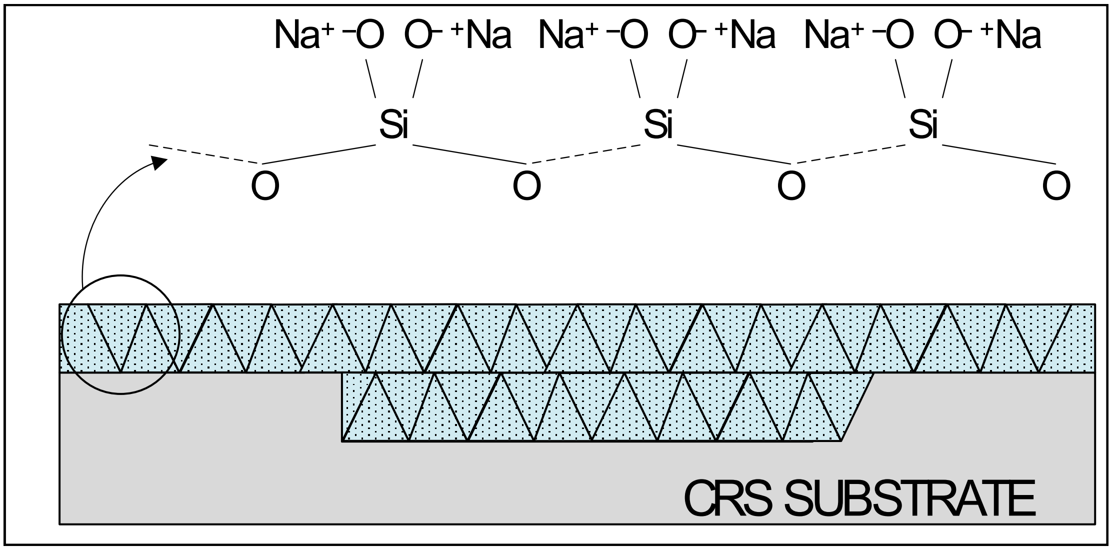

Figure 9. Sodium silicate hydrates deposition and film formation

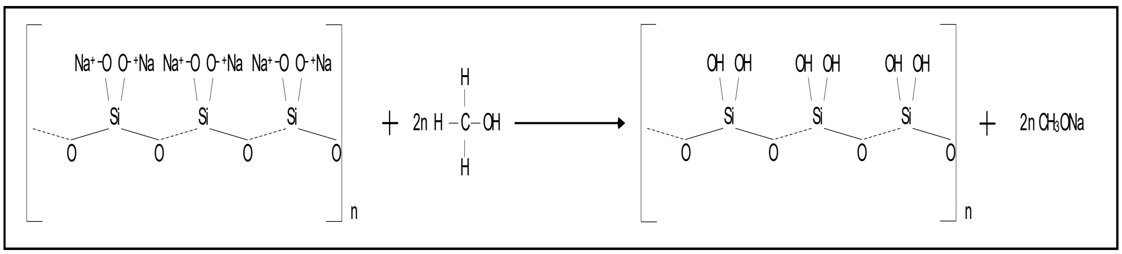

Figure 10. Silanol formation

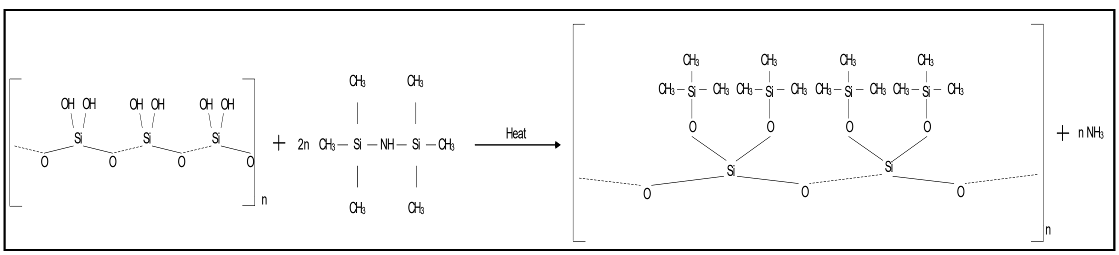

Figure 11. Surface modification using HMDS

1928 as cited by Khan *et al*., 2010). It was pinpointed that the sum of the capillary force from the moisture film (meniscus) produced by soil liquid in the surface of tillage implements and the potential chemical non- equilibrium between the moisture film and the free liquid in the soil contributed significantly to soil adhesion (Zhang, 1985 as cited by Khan *et al*., 2010).

This proved that the significant decrease in the adhesion coefficient was not enough to make the substrate hydro-phobic. Moisture film still developed on the surface of coated and uncoated substrate. Nonetheless, coating the metal substrate with the developed procedure has a significant effect on soil-to-metal friction coefficient. This may lead to a significant decrease in tillage draft because friction contributed a significant amount of energy expenditure. However, due to soil adhesion, the initial decrease in soil-to-metal friction may not be sustained because of soil adhesion

Surface Characterization of Coated and Uncoated CRS

Sodium silicate hydrates formed a hardened paste in the surface of the metal substrate. The crevices in the substrate served as an avenue where the hydrates can be accumulated and deposited (Figure 9). A layer of silica hydrates was also attached to even surface of the substrates.

Voids in the crevices were filled sodium silicate hydrate – a compound similar calcium silicate hydrates, the hardening paste present in concrete Due to the high surface area-to-volume ratio and concentration gradient, sodium silicates hydrates tended to fill the void in the crevices.

Drying the substrate at 100℃ hastened dehydration and the hardening of the coated paste. Further drying in the oven and dipping it in methanol (CH_3OH) left surface OH to the substrate (Figure 10). Coated substrates were dipped in the surface-modifying agent (HMDS solution). On a water free surface, the silicon on it bonds with the oxygen of the hydroxide. Trimethylsilane, $(H_3C)_3Si$, creates the hydrophobic layer in the substrate (Figure 11 and Figure 12). In the process, a free ammonia molecule was also produced. The deposition of the silica hydrates and surface modification of HMDS created a thin film that smoothens the surface of the cold rolled steel (Figure 13).

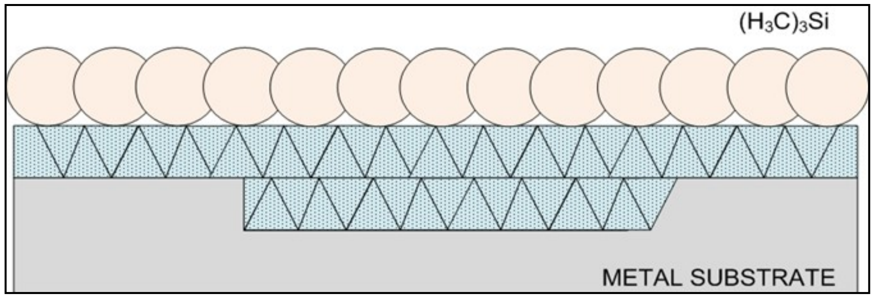

Figure 12. Schematic diagram of the formation of surface coating in the metal substrates

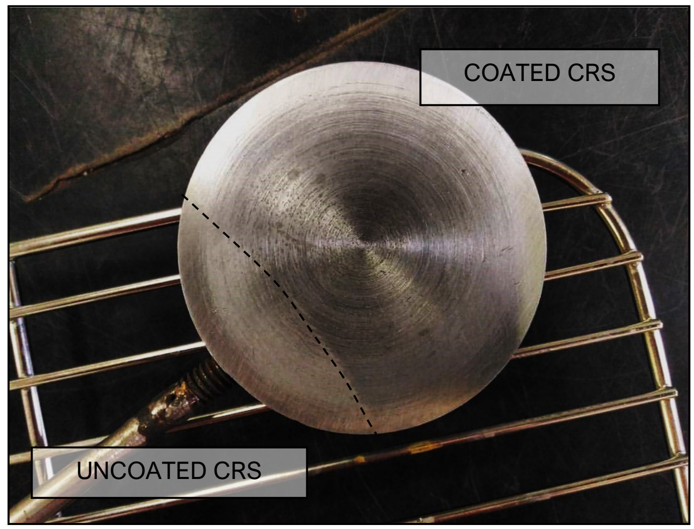

Figure 13. Thin film formation on CRS dipped on sodium silicate solution with nanosilica concentration at 5% wt.

FIB – FESEM was used to characterized and validate the coating that formed in the surface of the CRS. The surface morphology of coated and uncoated metal substrates (Figure 14, Figure 15 and Figure 16). The difference between the SEM image of the coated and uncoated metal substrates indicated the alteration brought by the developed coating procedure. It was also used to determine the relative size of silica present in the surface of the substrates.

Uncoated metal substrates had microscopic crevices that made its surface rough. These crevices served as an avenue wherein moisture can be deposited. During tillage operations, this had a significant effect because the accumulation of moisture film in the surface of the tillage implements causes soil adhesion. These microscopic crevices served as starting point for localized corrosion. Crevice corrosion occur when there were shielded surface wherein stagnant solution is present. The chemical environment between the exposed and the shielded surface accelerates the corrosion process (Rashid *et al*., 2007).

In the case of tillage implements, the moisture trapped within the crevices create a near-neutral solution wherein dissolved oxygen act as a cathode and the metal substrate as the anode. These reaction causes the rapid wear and tear of the implements. It also further alters the surface morphology of the surface and makes it rougher.

The reduction in soil-to-metal friction coefficient and adhesion coefficient of the metal substrate can be attributed to the alteration brought by sodium silicates hydrates on the surface. The coating made the surface smoother and decreased the sliding friction between the substrate and the soil. In addition, the coating sealed crevices where capillary action may take place. In effect, these contributed significantly to the adhesion coefficient of the substrate but no effect to the actual soil adhesion.

Lowering the surface area of the metal substrates and decreasing the microscopic crevices in the substrates significantly affects the performance of the substrate during the soil bin test. The length of time the metal substrates were dipped on the sodium silicate solution, the amount of silica deposited was dependent on the substrate concentration and on the

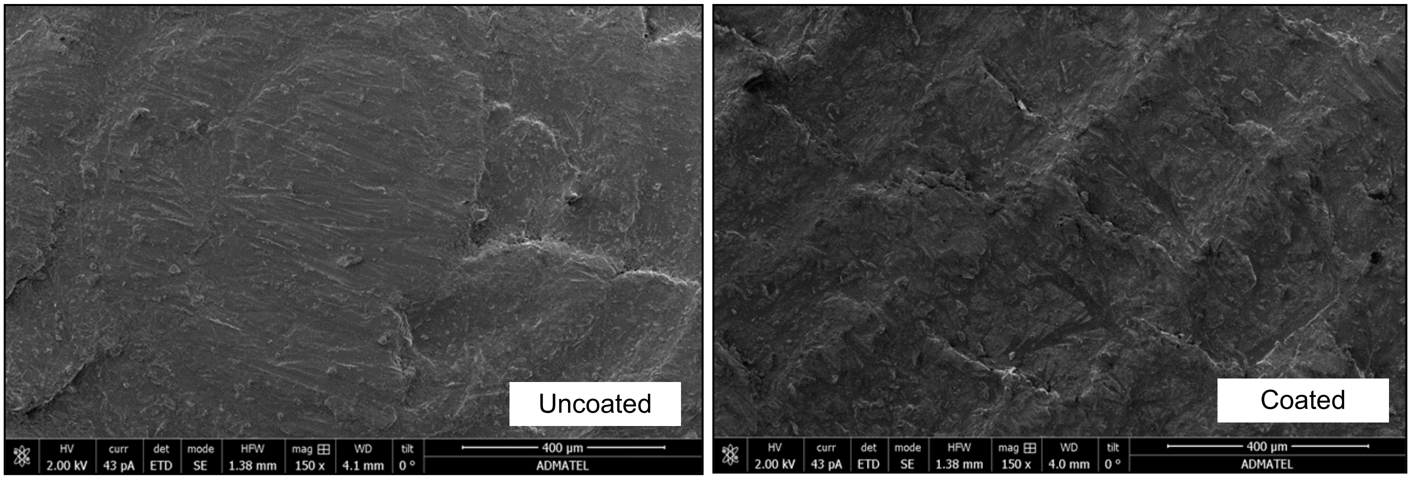

Figure 14. SEM images of uncoated and coated metal substrate (5.0% SiO_2) viewed at 150 x magnification

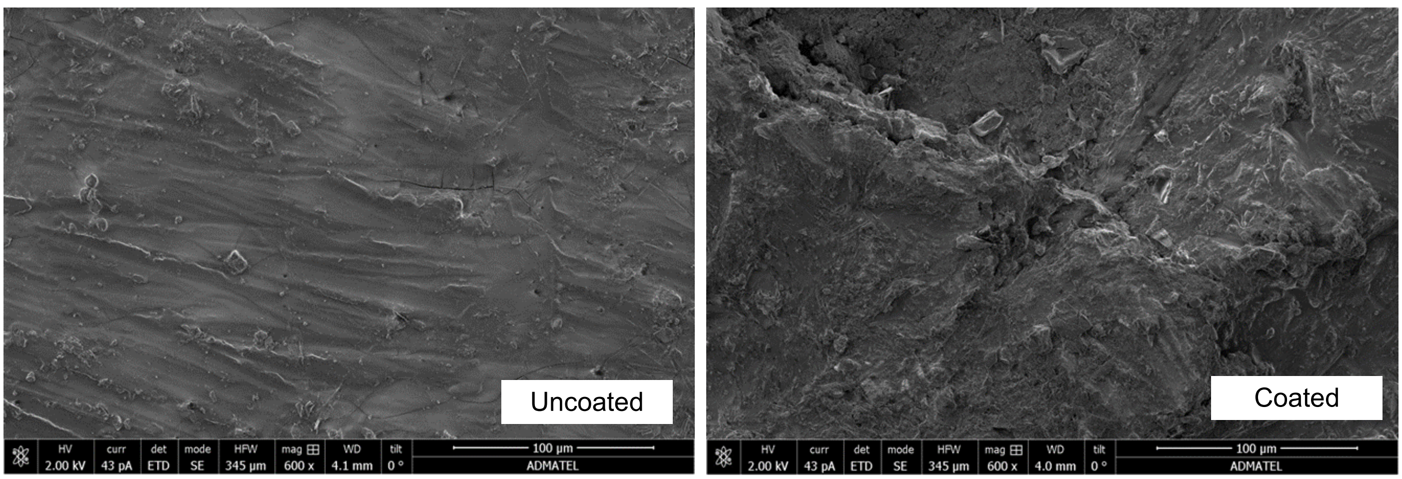

Figure 15. SEM images of uncoated and coated metal substrate (5.0% SiO_2) viewed at 600x magnification

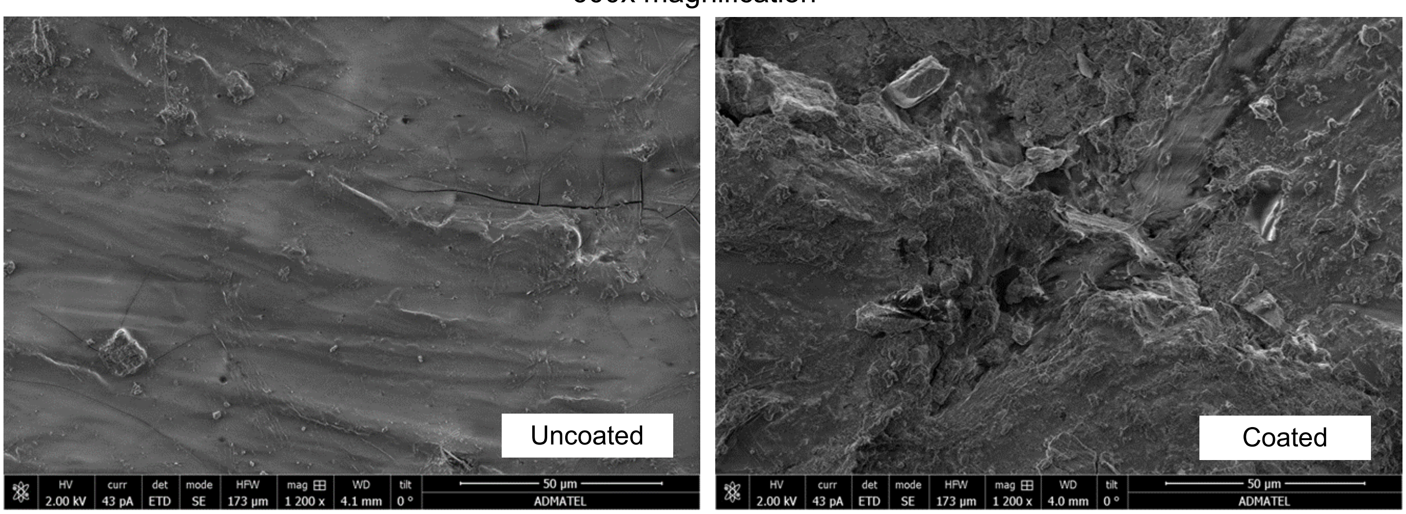

Figure 16. SEM images of uncoated and coated metal substrate (5.0% SiO_2) viewed at 1200x magnification

manner of dipping. Furthermore, the performance of the coated steel substrates was expected to become significantly better provided that the hydrophobic films were formed on the surface of the metal.

The SEM images of coated metal substrates showed the silica deposition and film formation in the substrate were not uniform throughout the surface of the substrates. Silica can be seen clearly in the crevices and flat surface of the steel substrates; however, the hydrophobic film on the substrate was not prominent and continuous. This explained the insignificant effect of the coating procedure for soil adhesion. The results also showed that the transformation of nanosilica to sodium silicate had caused the nanosilica to be attracted to larger NaOH molecules causing the silica to become larger and were no longer within the nanoscale.

CONCLUSION

The coating procedure decreased soil-to-metal friction coefficient and adhesion coefficient by an average of 24% and 36%, respectively. Of the two independent variables, only the nanosilica concentration of silica in the sodium silicate concentration had a significant effect on both the soil-to-metal friction and adhesion coefficient. The soil-to-metal friction and adhesion coefficient between metal substrates that were coated with different concentration of sodium silicate did not vary significantly. The optimum nanosilica weight concentration and dipping time that can be used for coating tillage implements was 5% and 5 min., respectively.

Assessing the surface morphology of uncoated and coated steel substrates showed that microscopic crevices were deposited with sodium silicate hydrates. This created a thin film that smoothens the surface. However, the second dipping of the substrate did not create a uniform hydrophobic film on the surface of the substrate. Due to the formation of the sodium silicate hydrates, the developed silica coating was no longer on the nanoscopic scale. Hydration and deposition had decreased the surface area-to-volume ratio of the silica particles.

The reduction in soil-to-metal friction coefficient and adhesion coefficient of the metal substrate can be attributed to the alteration brought by the sodium silicates hydrates on the surface. Lowering the surface area and decreasing the microscopic crevices in the substrates significantly affects the performance of the substrate during the soil bin test. With these findings, the use of nanosilica as coating for metal implements use for tillage has high potential. This would reduce the soil to metal friction during tillage operations which would result to lower draft and lower power requirement to work on the soil.

RECOMMENDATIONS

Future studies such as using dipping machines may improve the coating procedure. Using a constant withdrawal rate of the substrate in the sodium silicate solution may have a significant effect on the thickness and uniformity of the film produced. Abrasion test and life cycle analysis of the coating is also recommended for testing the coating's durability.

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