# Influence of water and sand content on adhesion of clayey soils

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**Abstract**

Clogging occurs during mechanical tunneling with a Tunnel Boring Machine (TBM) because of adhesion of clayey soils to the cutter head and conveyor system. The present study examined the effects of water and sand contents on clogging in Montmorillonite clayey soil. Testing was carried out using an adhesion test device on 28 samples with different water and sand contents to determine adhesion stress and degree of clogging. The results indicate that the consistency index ($I_c$) of the samples decreases as the sand and water content increases. The results for variation of adhesion stress versus water content at different sand contents formed similar bell-shaped curves. In all graphs, an increase in sand content decreased adhesion stress. Adhesion stress increased until the water content increased to 138%, at which point it began to decrease. The results show that adhesion of the soil to the surface of the metal piston did not occur in samples having a sand content of >40% and in samples with >133% water content having a sand content of <40%, $I_c$>0.5 adhesion occurred.

**Keywords***: Adhesion, Clayey Soil, Clogging, TBM, Tunnel Boring Machine.*

## Introduction

During mechanized tunneling through clayey soil, the soil sticks to the machine cutter head and extruded through the screw conveyor and in the passages conveying the soil. Clogging occurs as a result of the adhesion force in the clayey soil at different levels and can be removed using contrivances. If the problem persists, it can cause sticking in the TBM and stoppage of the entire project (Thewes & Burger, 2005). The Anrewarp and Second Heinenoord Tunnels in Holland (Kooistra, 1998) and the Abbey Sewer Tunnel in Leicester (Atkinson *et al*., 2003) are examples of projects that have experienced clogging. The problem caused by clogging in mechanized tunneling requires a reliable system of assessment and measurement of adhesion. There is no unified method for assessing adhesion; researchers have suggested and applied different methods. Sass and Barbaum (2009) suggested a unified and standard method that could be helpful in tunneling projects. Owing to the importance of this phenomenon, Fernandez *et al*. (2008) emphasized the pursuit of solidity studies to determine the adhesion potential of soils and argillaceous rocks. Thewes (1999) classified soils based on plasticity and consistency indices into three groups having high, middle and low clogging potential. Geodata (1995) proposed a similar classification of soils based on the plasticity index versus the natural water content and the plastic limit. Sass and Barbaum (2009) suggested the use of an adhesion test device to calculate maximum tension stress in cohesive soils.

The present research examined the effect of water and cohesionlesss and content on adhesion stress in Montmorillonite clayey soil. An adhesion testing device was used to investigate the effect of water and sand contents on adhesion.

## Testing Procedure

*Sample preparation*

Testing was carried out on samples containing processed montmorillonite dominant bentonite clay and fine sand. The liquid limit (LL) and plastic limit (PL) of the clay were determined to be LL=397.5% and PL=46%, respectively, for sand grain sizes of 0.15 to 0.25 mm.

Testing was performed at normal laboratory temperatures. Coarse-grained soil was sieved with a shaker to produce sand of the desired size to combine with bentonite. The bentonite samples containing 0, 10, 20, 30, 40, 50 and 60% sand were prepared and classified into seven groups (A, B, C, D, E, F and G, respectively) based on their sand content.

The desired wetness of the samples was produced using distilled water. Each group was then classified into four subgroups. All samples were mixed in a mixer for 15 min and then placed in an adhesion testing device. Table 1 shows the physical properties of the samples.

Table 1. Physical properties of tested samples

| Sample No. | M% | S% | μ% | PL% | LL% | PI | $I_c$ |
|---|---|---|---|---|---|---|---|
| A1 | 100 | 0 | 80 | 46.2 | 397.51 | 351.31 | 0.9 |
| A2 | 100 | 0 | 133 | 46.2 | 397.51 | 351.31 | 0.8 |
| A3 | 100 | 0 | 186 | 46.2 | 397.51 | 351.31 | 0.6 |
| A4 | 100 | 0 | 239 | 46.2 | 397.51 | 351.31 | 0.5 |
| B1 | 90 | 10 | 80 | 41.91 | 334.3 | 292.39 | 0.87 |
| B2 | 90 | 10 | 133 | 41.91 | 334.3 | 292.39 | 0.69 |
| B3 | 90 | 10 | 186 | 41.91 | 334.3 | 292.39 | 0.51 |
| B4 | 90 | 10 | 239 | 41.91 | 334.3 | 292.39 | 0.33 |
| C1 | 80 | 20 | 80 | 36.86 | 300.2 | 263.34 | 0.84 |
| C2 | 80 | 20 | 133 | 36.86 | 300.2 | 263.34 | 0.64 |
| C3 | 80 | 20 | 186 | 36.86 | 300.2 | 263.34 | 0.43 |
| C4 | 80 | 20 | 239 | 36.86 | 300.2 | 263.34 | 0.23 |
| D1 | 70 | 30 | 80 | 30.22 | 247.58 | 217.36 | 0.77 |
| D2 | 70 | 30 | 133 | 30.22 | 247.58 | 217.36 | 0.53 |
| D3 | 70 | 30 | 186 | 30.22 | 247.58 | 217.36 | 0.28 |
| D4 | 70 | 30 | 239 | 30.22 | 247.58 | 217.36 | 0.04 |
| E1 | 60 | 40 | 80 | 26.2 | 214.16 | 187.96 | 0.71 |
| E2 | 60 | 40 | 133 | 26.2 | 214.16 | 187.96 | 0.43 |
| E3 | 60 | 40 | 186 | 26.2 | 214.16 | 187.96 | 0.15 |
| E4 | 60 | 40 | 239 | 26.2 | 214.16 | 187.96 | -0.13 |
| F1 | 50 | 50 | 80 | 22.46 | 164.45 | 141.99 | 0.6 |
| F2 | 50 | 50 | 133 | 22.46 | 164.45 | 141.99 | 0.22 |
| F3 | 50 | 50 | 186 | 22.46 | 164.45 | 141.99 | -0.15 |
| F4 | 50 | 50 | 239 | 22.46 | 164.45 | 141.99 | -0.53 |
| G1 | 40 | 60 | 80 | 19.88 | 93.02 | 73.14 | 0.19 |
| G2 | 40 | 60 | 133 | 19.88 | 93.02 | 73.14 | -0.55 |
| G3 | 40 | 60 | 186 | 19.88 | 93.02 | 73.14 | -1.27 |
| G4 | 40 | 60 | 239 | 19.88 | 93.02 | 73.14 | -2 |

(M% percentage of montmorillonite, S% percentage of sand, ω% water content, PL% Plastic Limit, LL% Liquid Limit, PI Plasticity index, $I_c$ Consistency Index)

*Test method*

Figure 1 shows the adhesion testing device used. The prepared samples were molded in a sample container. The mixture was added to the cylinder in a series of thin layers to avoid entrapment of air. Testing was performed quickly after preparation of the samples to control for rapid changes in wetness that occurs on the surface of the samples.

Figure 1. Pull-out adhesion testing device

The sample container was attached to the holding surface using pins. The holding surface was then moved upward to establish contact between the soil and piston surface. The stress required for this was7kPa, the maximum pressure that could be placed on the sample by piston without piercing it. The piston rested on the sample for 1 min and then the holding surface was moved downward at a speed of 0.5 mm/s as suggested by Thewes and Burger (2004). The tension required to detach the soil from the piston was recorded using a data logger attached to the machine. Figure 2 shows a sample of the output from the testing device.

All similar samples profiles were delineated and the level of tension stress required for detachment of the piston from the soil was measured. Table 2 shows these values for the test samples while Figure 3 shows the testing procedure.

Detachment of the piston from the samples (Table 1) was observed to occur in two forms. One form was where portions of sample soil adhered to the detached piston; this was defined as adhesion.

The second form was the absence of soil adhering to the piston; this was defined as non-occurrence of adhesion. These two states are shown in Figure 4.

Table 2. Tension required detaching piston from soil, minimum and average tension stress for the number of performed tests on each sample with statistical variants that show the suitable nature of the number of performed tests in each sample to reach an acceptable research result

| **Sample No.** | **N** | **Tension stress (kPa)** | | | **S** | **% $C_v$** | **$t_\beta$** | **P** | **adhesion of clay soil to the surface metal** |
|---|---|---|---|---|---|---|---|---|---|
| | | **Ave.** | **Max.** | **Min.** | | | | | |
| A1 | 10 | 9.3 | 10.1 | 8.8 | 0.63 | 7 | 0.83 | 1.12 | No |
| A2 | 10 | 18 | 20 | 17 | 1.07 | 6 | 0.83 | 1.03 | Yes |
| A3 | 10 | 14.4 | 15.2 | 13.4 | 0.61 | 4 | 0.83 | 1.02 | Yes |
| A4 | 10 | 10.6 | 10.8 | 10.3 | 0.2 | 2 | 0.83 | 1.03 | Yes |
| B1 | 10 | 8.25 | 8.88 | 7.73 | 0.32 | 3.9 | 0.83 | 1.02 | No |
| B2 | 10 | 17 | 19.44 | 15.1 | 1.41 | 8.3 | 0.83 | 1.05 | Yes |
| B3 | 10 | 13.04 | 13.23 | 12.81 | 0.149 | 1.1 | 0.83 | 1.01 | Yes |
| B4 | 10 | 9.4 | 9.83 | 9.1 | 0.22 | 2.3 | 0.83 | 1.01 | No |
| C1 | 10 | 5.81 | 6.01 | 5.43 | 0.16 | 2.7 | 0.83 | 1.01 | No |
| C2 | 10 | 16.4 | 17.99 | 15.14 | 0.93 | 5.7 | 0.83 | 1.03 | Yes |
| C3 | 10 | 12.21 | 12.62 | 11.71 | 0.31 | 2.5 | 0.83 | 1.01 | No |
| C4 | 10 | 8.54 | 9.01 | 8.1 | 0.30 | 3.5 | 0.83 | 1.02 | No |
| D1 | 10 | 3.48 | 4.39 | 3.08 | 0.36 | 10.2 | 0.83 | 1.06 | No |
| D2 | 10 | 15 | 17.36 | 13.9 | 1.13 | 7.5 | 0.83 | 1.04 | Yes |
| D3 | 10 | 10.81 | 11.05 | 10.51 | 0.17 | 1.6 | 0.83 | 1.01 | No |
| D4 | 10 | 8.1 | 8.64 | 7.66 | 0.35 | 4.3 | 0.83 | 1.02 | No |
| E1 | 10 | 1.76 | 2.16 | 1.51 | 0.21 | 11.97 | 0.83 | 1.07 | No |
| E2 | 10 | 12.51 | 13.24 | 11.73 | 0.51 | 4.1 | 0.83 | 1.02 | No |
| E3 | 10 | 10.23 | 10.46 | 9.82 | 0.21 | 2 | 0.83 | 1.01 | No |
| E4 | 10 | 7.05 | 7.39 | 6.23 | 0.34 | 4.9 | 0.83 | 1.03 | No |
| F1 | 10 | 1.42 | 1.81 | 1.05 | 0.26 | 18.08 | 0.83 | 1.11 | No |
| F2 | 10 | 9.97 | 10.26 | 9.32 | 0.31 | 3.07 | 0.83 | 1.02 | No |
| F3 | 10 | 8.05 | 8.08 | 7.98 | 0.03 | 0.34 | 0.83 | 1.00 | No |
| F4 | 10 | 6.18 | 6.34 | 5.87 | 0.17 | 2.68 | 0.83 | 1.01 | No |
| G1 | 10 | 0.94 | 1.11 | 0.81 | 0.10 | 10.96 | 0.83 | 1.06 | No |
| G2 | 10 | 7.6 | 7.95 | 7.12 | 0.27 | 3.51 | 0.83 | 1.02 | No |
| G3 | 10 | 5.61 | 5.71 | 5.44 | 0.09 | 1.62 | 0.83 | 1.01 | No |
| G4 | 10 | 4.3 | 4.56 | 4.01 | 0.18 | 4.13 | 0.83 | 1.02 | No |

S variance, $t_\beta$ coefficient of certitude, $C_v$ coefficient of variation, N number of examines and P accuracy index

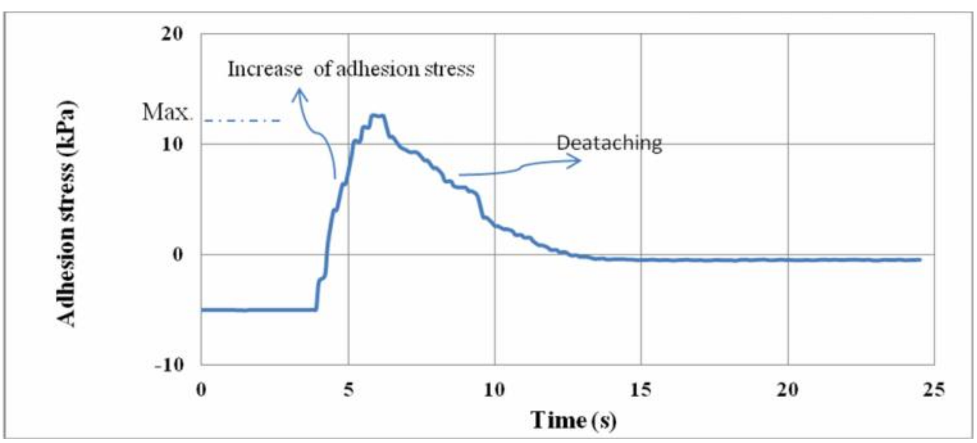


Figure 2. Sample of testing output

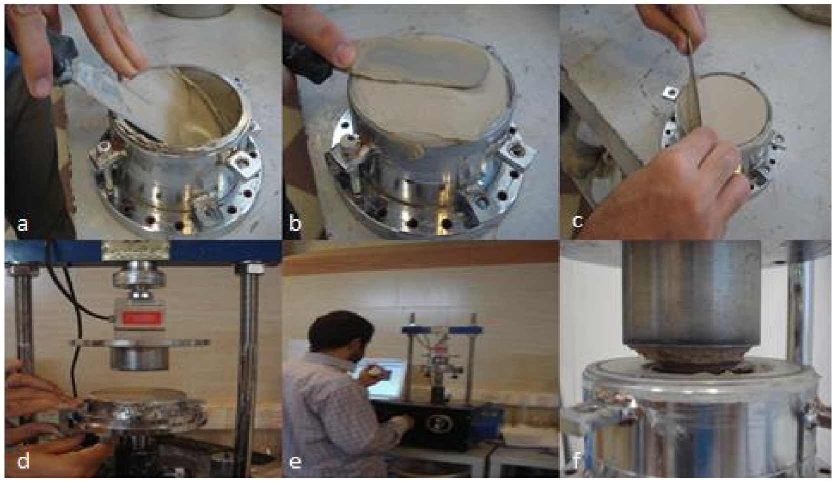


Figure 3. Testing procedure; a and b) remolding the sample in cylinder at thin layers, c) tabulating the surface of sample, d) emplacing the cylinder and stabilizing it, e) attaching of sample to the surface of piston and applying pressure on the sample in the distinct time, f) detaching the sample and cylinder and recording the data with data logger

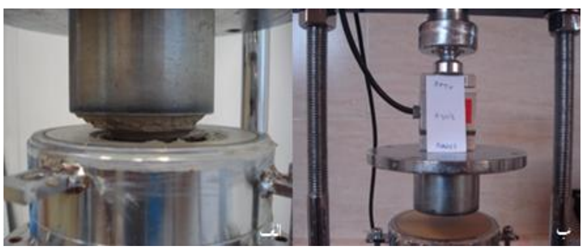

Figure 4. Results of testing: a) adhesion; b) non-occurrence of adhesion

*Determination of required number of tests*

To obtain an acceptable and accurate result, it was necessary to repeat and compare the tests and results, respectively. Two methods were used in this project;the first method as suggested by Duncan (2000) is based on calculation of the coefficient of variation ($C_v$). In the present tests, $C_v$ varied from 1.1 to 18.0%. This is an acceptable value in comparison with the acceptable range for shear strength of undrained clay soils which is 13 to 40%. The second method is application of the precision index introduced by Gill *et al*. (2005) where the precision index (P) is calculated as shown in Equation (1):

$$p = \frac{M+t\beta\frac{S}{\sqrt{n-1}}}{M-t\beta\frac{S}{\sqrt{n-1}}} \qquad (1)$$

where $M$ is the average of the data, $S$ is the standard deviation, $n$ is the number of samples, $t_\beta$ is the confidence coefficient obtained from the student t-test distribution, and$\beta$ is determined by the confidence level (95%).

Gill *et al*. (2005) suggested $P \leq 1.35$ as acceptable for civil projects and $P \leq 1.2$ for research projects. Table 2 indicates that for 10 tests, Pvaried from 1 to 1.12. This indicates that 10 test repetitions on one sample yields acceptable results.

## Interpretation of Results

*Consistency index versus coarse grain content*

The consistency index ($I_c$) was used to explain the natural consistency of clayey soils. $I_c$ is defined as shown inEquation (2) as:

$$I_c = LL\text{-}\omega n/PI \qquad (2)$$

Figure 5 shows the profile of changes in $I_c$ versus sand content at different water contents. These profiles are delineated based on the information in Table 1. As seen in Figure 5, as the sand content increased, $I_c$ decreased. This regressive trend was similar for samples with different water contents and showed two different gradients. For samples composed of <50% sand, the regressive gradient was milder than for samples with >50% sand composition. The gradient for samples with lower water contents was less than for those with higher water contents.

*Consistency index versus water content*

Figure 6 shows the changes in $I_c$ versus water content for different sand contents. These profiles are based on data from Table 1. At a specific sand content, $I_c$ decreased as the water content increased. Samples A, B, C, D, E and F contain 0 to 40% sand and show a reductive trend for $I_c$ that is constant with the decrease in water content. Sample G has a sand content of >50% sand and shows a higher gradient for the regressive trend in $I_c$ with an increase in water content.

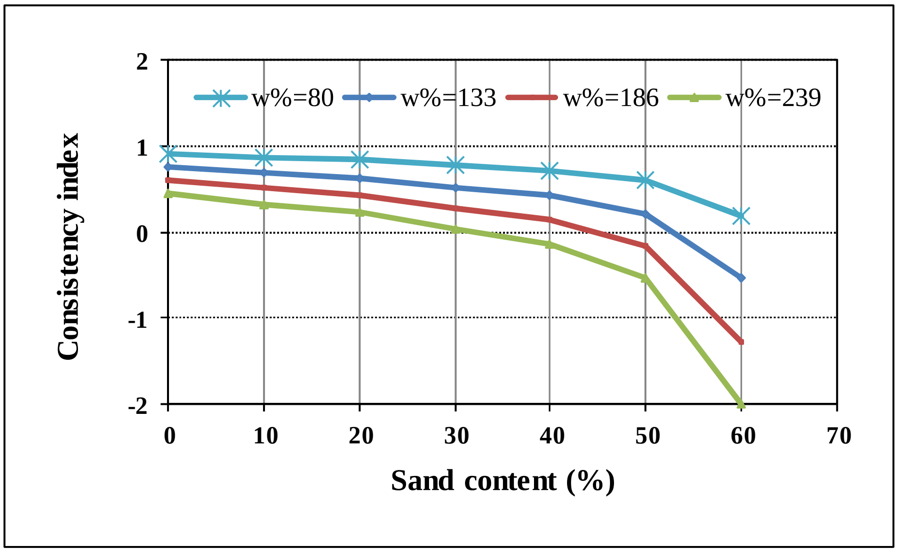


Figure 5. $I_c$ versus sand content at different water contents; consistency index decreases with increase in the sand content and for >50% sand contents, the decreased gradient is higher

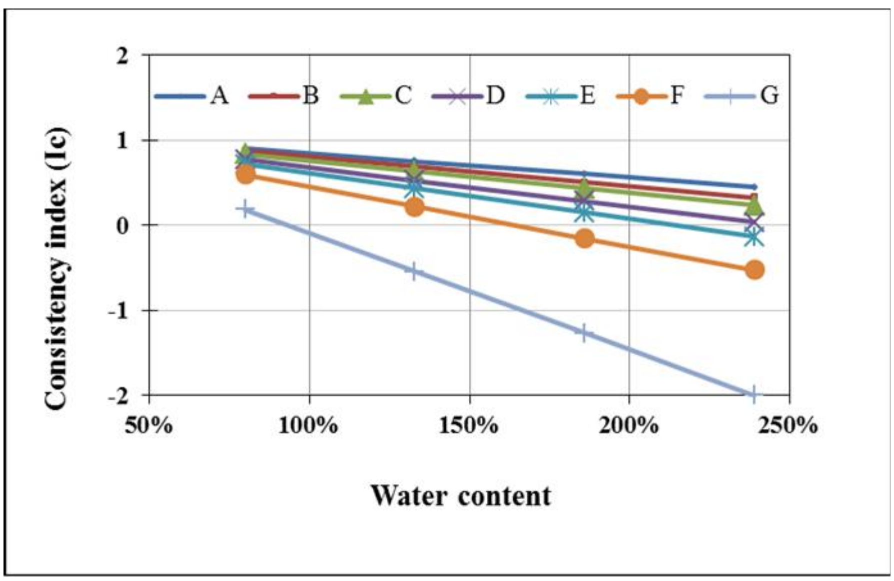


Figure 6. $I_c$ versus water content for different sand contents, with an increase in water content the consistency index decreases in all samples

*Effect of sand content on adhesion of clayey soils*

Figure 7 is based on the data from Table 2 and shows the variation in adhesive stress at different sand and water contents. It is clear that for a specific water content, an increase in sand content decreased adhesive stress. The regressive trend in adhesive stress at different water contents was the same and produces approximately the same gradient. This indicates that an increase in sand content and decrease in water content decreased the adhesive stress for the range of water content values values and soil types examined.

*Effect of water content on adhesive stress of clayey soil*

Figure 8 shows the change in water content versus adhesive stress at different sand contents based on the data from Table 2. For all samples, adhesive stress increased as water content increased up to 138%. This water content is about twice as much as the plastic limit of a sample of pure montmorillonite. At higher and lower water contents, adhesive stress decreased.

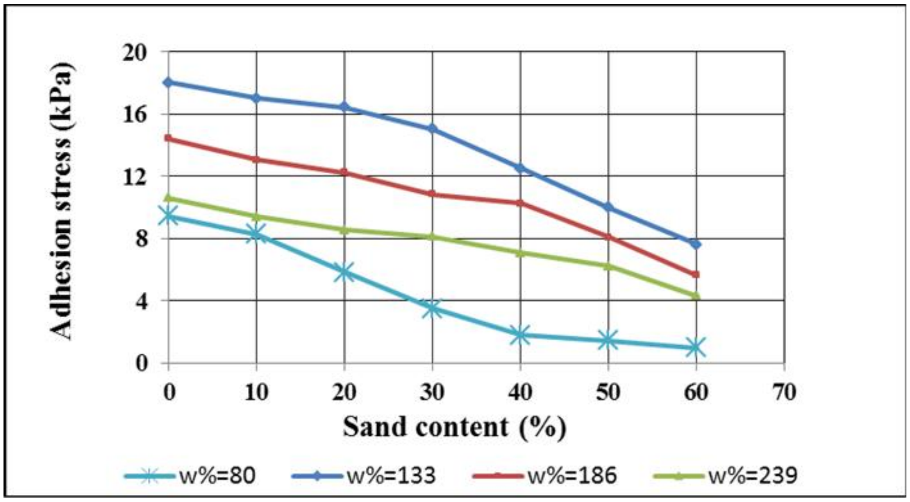


Figure 7. Variation in adhesive stress at different sand and water contents, with an increase in the percentage of sand and water content, adhesion stress decreases

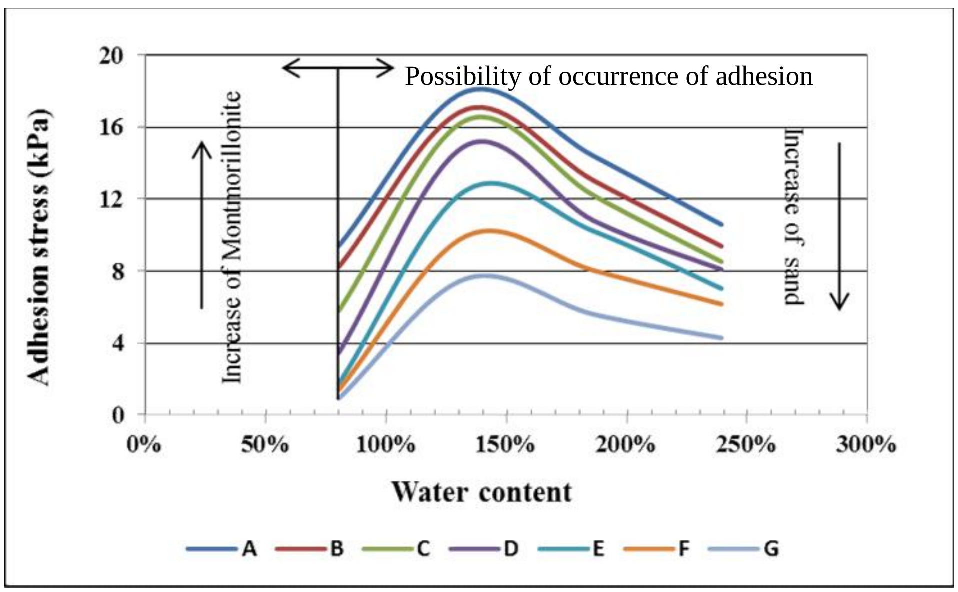


Figure 8. Water content versus adhesive stress at different sand contents, with an increase in percentage of sand, adhesion stress decreases, in addition with an increase in water content to 138%, adhesion stress increases and then decreases

*Occurrence or non-occurrence of adhesion*

Table 2 shows the values for adhesion of soil to the metal surface. Figure 9 shows soil adhesion to the metal surface at different water and sand contents for samples A and B.

Figures 10 and 11 are based on the data from Table 2. Figure 10 shows that with thevariation in water and sand contents, the zone in which soil adhered to the surface of the metal is separate from the zone in which soil did not adhere. For sand content of >40% (E, F, G), no adhesion was reported at the various water content values. However, samples with <40% sand content (A, B, C, D) experienced both occurrence and non-occurrence of adhesion. As the sand content decreased and the water content increased, adhesion adhesion tended to increase.

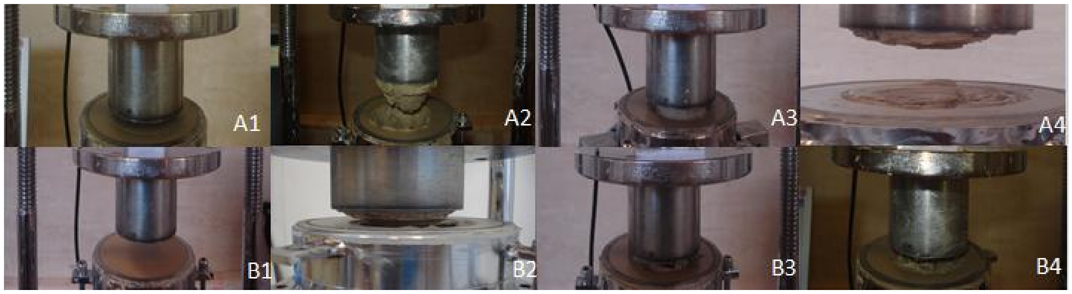


Figure 9. Adhesion stress variation of clayey soils to the metal surface for samples A1, A2, A3, A4, B1, B2, B3 and B4 respectively

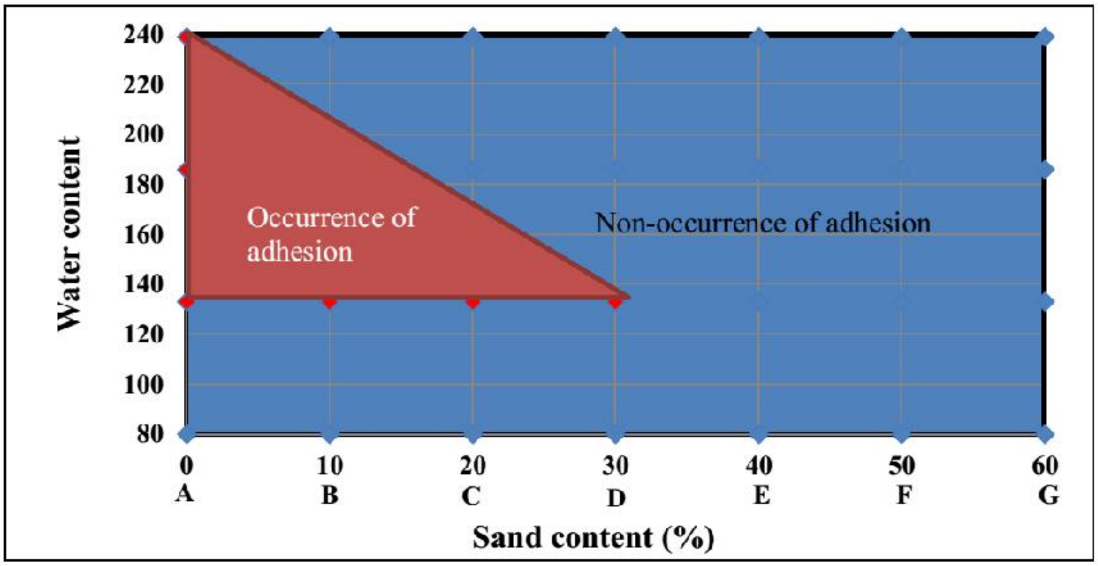


Figure 10. Soil adherence zones by water and sand content

Figure 11 shows the points at which adhesion of soil to metal occurred along with those at which adhesion did not occur by water content and $I_c$. As shown, adhesion occurred in samples having an $I_c$> 0.5 and water content of>133%.

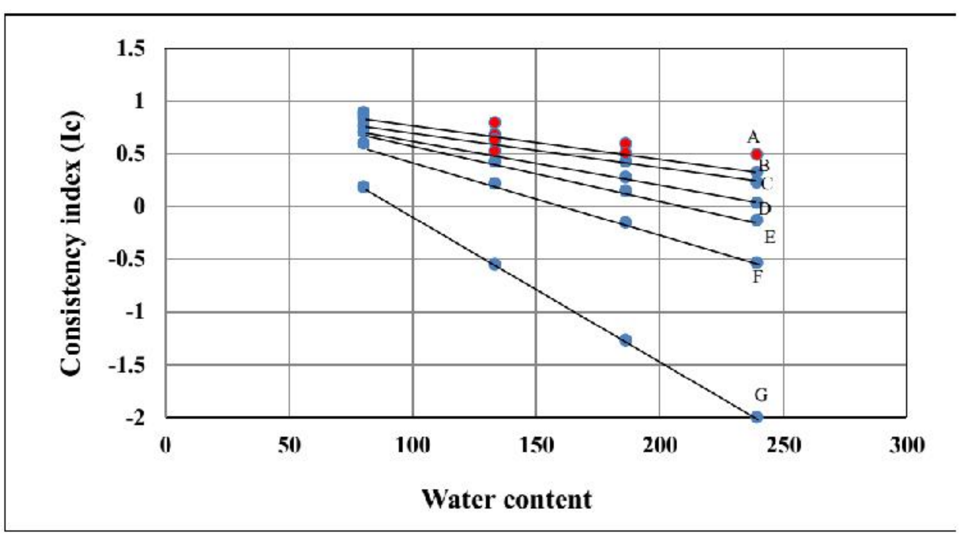


Figure 11. Adhesion of soil to metal by water content and Ic

## Conclusion

This study determined the effect of water and fine sand contents on the consistency index, adhesion stress and occurrence of adhesion of montmorillonite clayey soil to the metal surface of a pull-out adhesion test device. The results showed that an increase in sand and/or water content decreased $I_c$ and that the reduction trend is a function of the sand content. The curve for changes in water content versus adhesion stress of clayey soils was bell-shaped for all samples.

At a specific sand content, an increase in water content increased adhesive stress up to a maximum level, after which it began to decrease. This trend was the same for all samples; maximum adhesion was measured at 138% water content which is about about twice that of the plastic limit of pure montmorillonite.

Observations show that in samples with >40% sand content, adhesion does not occur. In samples with >80% water content, adhesion also does not occur. In samples with <40% sand, as the water content increased, adhesion of soil to the metal surface increased. In samples with >133% water content where $I_c$>0.5, adhesion occurred between the soil and the surface of the piston.

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