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ON THE NORMALIZED RELATIVE ROUGHNESS FOR SOIL-FIBER REINFORCED POLYMER INTERFACE SHEAR BEHAVIOUR

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ABSTRACT: Several studies in the literature have investigated the shear behaviour of soil-steel interface. Furthermore, a normalized relative roughness parameter, R_n, has been used successfully to describe the shear behaviour of the sand-steel interface. On the other hand, few studies are available in the literature regarding the interface shear behaviour of fiber reinforced polymer (FRP). The aim of this study is to investigate the shear behaviour of soil-FRP interface and examine the validity of R_n for the FRP case. Experimental program using a modified direct shear test apparatus was conducted for this purpose. The testing materials in this study include two different types of FRP, and five different-size glass beads in terms of the mean particle size, D_{50}. The experimental results show that the interface shear behaviour of FRP is different than steel. The observed difference could be explained in terms of the expected contribution of the interface ploughing resistance in the FRP case compared to the steel where its interface shear behaviour is mainly controlled by the interface sliding resistance.

Keywords: Roughness, interface, shear, FRP, steel.

INTRODUCTION

During the last two decades fiber reinforced polymer (FRP) materials have attracted more attention in the civil engineering field due to their high strength and durability in harsh environments. In geotechnical engineering, FRP-tube confined concrete piles were used to overcome the low durability of conventional concrete piles in waterfront and aggressive environments. The FRP-tube plays two roles; strengthening the concrete by the confinement effect, and protecting the concrete from the aggressive environment (Iskander and Hassan 2001). As soil-FRP interface shear behaviour controls the pile's shaft resistance, an attention should be paid to understand this behaviour.

In fact, there is a vast literature about the interface shear behaviour of inextensible continuum surfaces and in particular steel (Potyondy 1961; Coyle and Sulaiman 1967; Brumund and Leonards 1973; Heerema 1979; Yoshimi and Kishida 1981; Poulos, 1989; Tsubakihara et al. 1993; Tabuncanon et al., 1995; Paikowsky et al., 1995; Uesugi and Kishida 1986; Uesugi et al. 1989; Evgin and Fakharian 1996). One of the major achievements in this field was introduced by Uesugi and Kishida (1986) who conducted a comprehensive experimental study to investigate the shear behaviour of sand-steel interface and proposed a normalized roughness parameter, $R_n=R_{max}/D_{50}$, where R_{max} is the absolute vertical distance between the highest and lowest valley along the surface profile over a sample length equal to D_{50} as shown in Fig.1. In fact, R_n is able to express successfully the influence of the steel surface roughness, and the particle size of the granular material on the interface friction coefficient, $\mu=\tan(\delta)$ where δ is the interface friction angle. Below a certain critical R_n, Uesugi and Kishida (1986) show existing of a unique linear relation between μ and R_n where μ increases as R_n increases. However, beyond this critical value of R_n, the value of μ becomes constant and equal to the internal soil shear resistance.

On the other hand, few studies are available in the literature regarding the interface behaviour of FRP materials (Frost and Han 1999; Pando et al. 2002; Sakr et al. 2005; Dove et al. 2006). Furthermore, none of these studies has discussed the validity of R_n for FRPs. As FRP surfaces usually have lower hardness than steel, ploughing resistance could play a role in the interface shear behaviour of FRP. The concept of R_n is valid for the steel case where its interface shear behaviour is mainly controlled by the interface sliding resistance. The effect of ploughing mechanism on the validity of R_n concept is not known yet. Therefore, further research work is required to answer this question. The aim of this study is directed to investigate experimentally the validity of R_n concept for FRP materials at different hardness levels.

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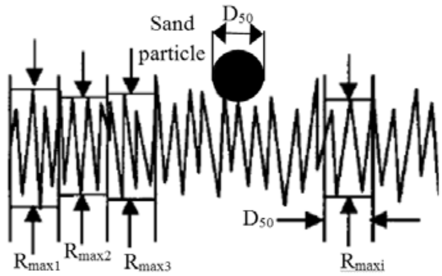
TESTING MATERIALS AND EXPERIMENTAL PROGRAM

Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP) were used as testing counterface continuum materials in this study. The ability of these materials to resist scratching or abrasion can be inferred from its surface hardness value, HV (ASTM E384). The hardness value of GFRP and CFRP is 65 and 49, respectively. A stylus profilometer was used to determine R_{max} of GFRP and CFRP. Five different-size glass beads in terms of their mean particle size, D_{50}, were used in this study as listed in Table 1.

Two different interface shear testing paths in R_{max}-D_{50} plane were used in this study to investigate the FRP interface shear behaviour in R_n-μ_p plane as shown in Fig. 2. Path 1 involves shearing the FRP testing specimen along different granular materials in terms of D_{50} and determining the corresponding μ_p values. Therefore, R_n increases as D_{50} decreases. Path 2 involves shearing a certain size of the glass beads along several counterface surfaces having the same FRP type but different surface roughness levels, R_{max}. The surface roughness can be changed by machining/polishing process (Paikowsky et al. 1995). According to Uesugi and Kishida (1986) the results of both testing paths should give a unique linear R_n-μ_p relation.

The experimental program in this study includes conducting interface shear tests according to path 1, and 2 for GFRP. However, only interface shear tests according to paths 1 were conducted for CFRP. For testing the GFRP according to path 2, the GFRP sheet was machined/polished to produce rough/smooth surface roughness compared to the surface roughness of the GFRP sheet as received from the manufacturer. Therefore, each size of glass beads could be sheared along these three different GFRP materials in terms of the surface roughness. The glass beads GB2, GB3, and GB5 were used for this test.

A modified direct shear apparatus, as shown in Fig.3, was used in this study. The top part of shear box comprises a square box (60 mm x 60 mm) and height of 24 mm. The bottom part of the shear box comprises a sheet of the counterface continuum material glued to a rigid plywood base which is longer than the top part of shear box so the shear area remains constant during a test. To minimize the friction between the sand and the soil box, the inside of the walls was coated with a thin film of grease. Furthermore, the thickness of the shear box wall at the interface with the plate was decreased to be 1 mm and it was also coated by a thin film of grease. The testing glass beads were prepared at 85% relative density using the air pluviation technique. The tests were



$$\bar{R}_{max} = (R_{max1} + R_{max2} + R_{max3} + \cdots + R_{maxn})$$

$$R_n = \frac{\bar{R}_{max}}{D_{50}}$$

Fig. 1 Normalized relative roughness, R_n

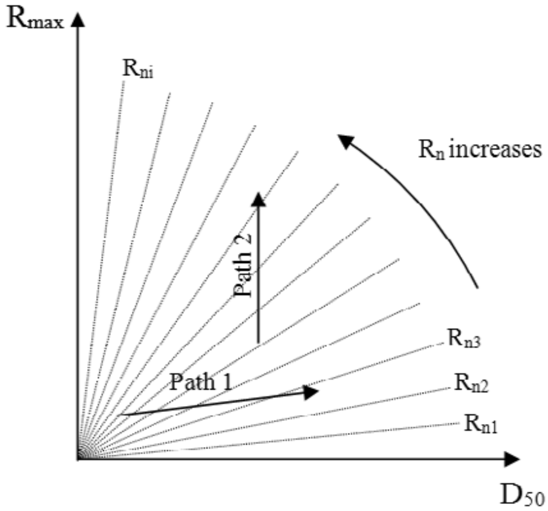


Fig. 2 Different interface shear testing paths

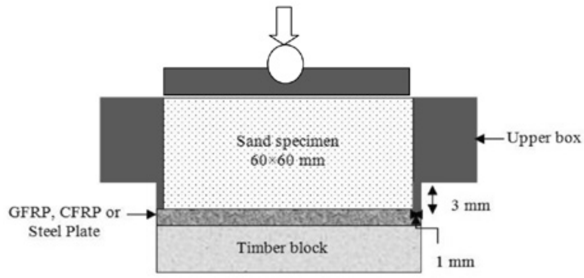


Fig. 3 Modified shear box (cross section normal to the shearing direction)

TEST RESULTS AND DISCUSSION

The interface shear test results of the conducted experimental program (paths 1, 2) in this study are plotted in R_n-μ_p plane, as shown in Fig.4, where μ_p is the peak interface shear coefficient. The test results of path 1 in Fig.4a show the effect of HV on the R_n-μ_p relation as higher μ_p values were obtained for GFRP (HV=65) compared to CFRP (HV=49). In general, a bilinear R_n-μ_p relation was observed for both FRP materials. The value of μ_p increases linearly as R_n increases then tends to level off at low μ_p compared to the internal friction coefficient of the testing granular materials (0.45 to 0.7) as shown in Fig.4a. Therefore, the observed behaviour for FRP materials is different than the reported sand-steel interface behaviour by Uesugi and Kishida (1986).

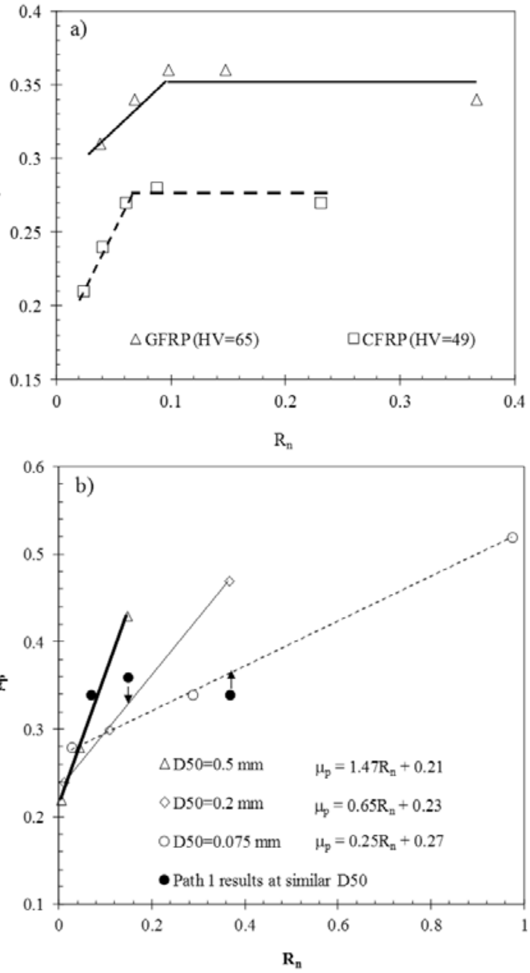


Fig 4. Interface shear test results: a) Path 1, b) Path 2 for GFRP

Table 1. Diameter of the testing glass beads

Rounded Glass beads	D_{50} (mm)
GB1	1
GB2	0.5
GB3	0.3
GB4	0.2
GB5	0.075

The difference in the interface shear behaviour between the steel (HV= 130) and FRPs is also observed by comparing the test results of path 2 for GFRP (this study), and steel (Uesugi and Kishida 1986) as shown in

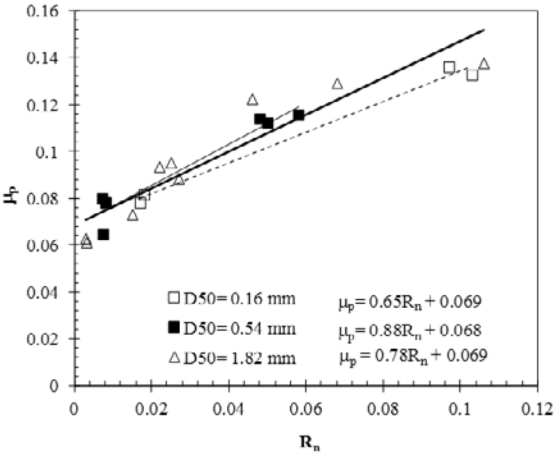


Fig. 5 Roundness modified interface shear testing results of Seto Sand along mild steel (Uesugi and Kishida 1986)

Figs.4b and 5, respectively. The test results in Fig.4b indicate that, for GFRP, the R_n-μ_p relations depend on D_{50} where $\partial\mu_p/\partial R_n$ decreases as D_{50} decreases. However, this is not the case for the shear results of Seto sand-mild steel interface by Uesugi and Kishida (1986) as shown in Fig.5. The GFRP test results of path 1 at D_{50} values similar to what have been used in path 2 tests were also plotted in Fig.4b. Considering the inevitable scatter in the laboratory test results, it is believed that each test result of path 1 is almost located on the corresponding R_n-μ_p relation of path 2 results in terms of D_{50}. Therefore, the relative roughness parameter, R_n, introduced by Uesugi and Kishida (1986) is not valid to normalize the effect of D_{50} and R_{max} on the interface shear behaviour of FRP materials.

CONCEPTUAL UNDERSTANDING OF R_n-μ_P RELATION

The observed test results behaviour of FRPs in Fig. 4 can be schematically conceptualized as shown in Fig. 6a where a series of R_n-μ_p relations for different D_{50} values, according to path 2, are plotted as dotted lines having, for the sake of simplicity, a similar μ_p value at R_n=0. Under path 1, as D_{50} decreases (R_n increases), μ_p gradually changes and pass through the different R_n-μ_p relations as shown in Fig.6a. In other words, R_n-μ_p relation obtained from path 1 is composed of an infinite number of small segments of R_n-μ_p relations obtained from path 2. However, as R_n-μ_p relation can be considered as D_{50} independent for the mild steel, as shown in Fig.5, a linear relation can be approximately obtained from path 1 as shown in Fig.6b. Consequently, the results of paths 1 and 2 for the mild steel should produce a unique linear R_n-μ_p relation (Uesugi and Kishida 1986). Therefore, for path 1 the evolution of R_n-μ_p relation is controlled by the rate of $\partial\mu_p/\partial R_n$ change with respect to D_{50}.

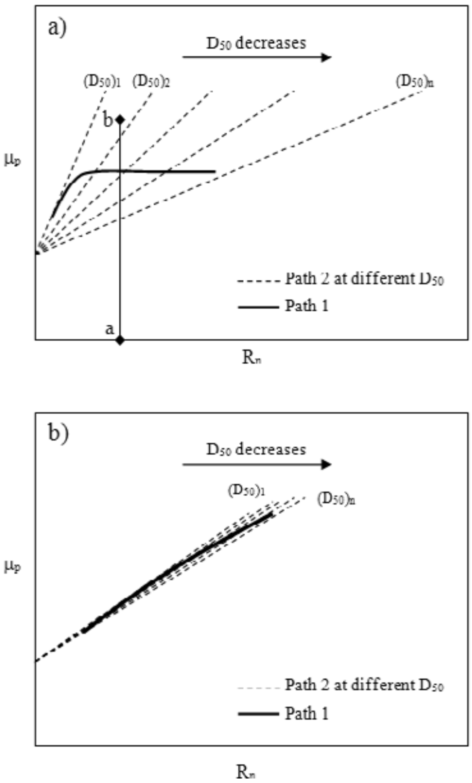


Fig. 6 Schematic conceptual explanation for the interface test results: a) low HV, b) High HV

Based on the above interpretation, the rate of $\partial\mu_p/\partial R_n$ change with respect to D_{50} for GFRP and CFRP can be back-calculated using the test results of path 1 (Fig.4a) as shown in Fig.7. The dotted lines in Fig.7 are representing the R_n-μ_p linear relations at different D_{50} values where μ_p value at R_n=0 was approximately determined using the line passing through the two points of the smallest R_n values. Fig.8 shows the evolution of $\partial\mu_p/\partial R_n$ as D_{50} changes for GFRP, and CFRP. For comparison purpose, the rate of $\partial\mu_p/\partial R_n$ change with respect to D_{50} for the mild steel case by Uesugi and Kishida (1986) as shown in Fig.5 was also included in Fig.8. However, considering the inevitable scatter in the inevitable scatter in the laboratory test results, it can be concluded that $\partial\mu_p/\partial R_n$ is D_{50} independent for the mild steel as shown in Fig.8.

The results in Fig.8 suggest that the rate of $\partial\mu_p/\partial R_n$ changes with respect to D_{50} depends on the hardness, HV, of the counterface material. It decreases as HV increases and becomes almost zero at HV≈130 (mild steel). This

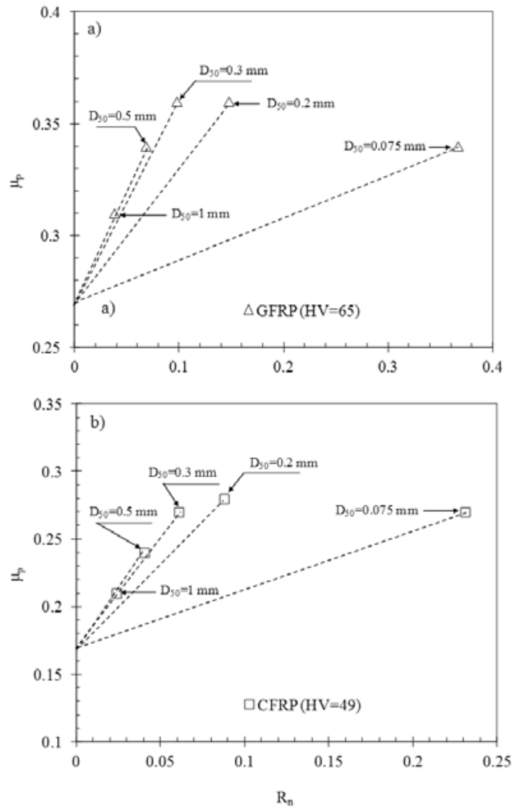


Fig. 7 Determination of $\partial\mu_p/\partial R_n$ at different D_{50} values using the test results of path 1

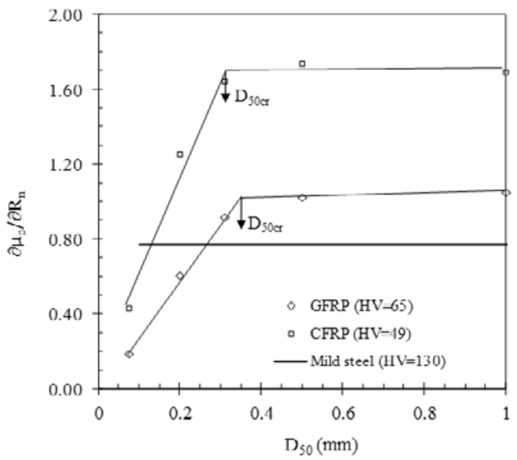


Fig. 8 Evolution of $\partial\mu_p/\partial R_n$ as D_{50} changes

behaviour could be related to the mobilized ploughing interface shear resistance that also decreases as HV increases (O'Rourke et al. 1990; Frost et al. 2002). However, the mobilized ploughing interface shear resistance is also a function of D_{50}. As D_{50} increases (R_n decreases), the number and area of particles contacting the conterface surface decreases causing the actual contact stress per particle to increase. In fact, as contact stress per particle increases, the possibility of damaging the counterface surface by micro-cracking and ploughing processes increases. Consequently, it is believed that the mobilized ploughing interface shear resistance increases as D_{50} increases (Dove and Forst 1999). Therefore, the increase of μ_p at constant R_n as D_{50} increases, as shown in Fig.6a, line ab, can be interpreted in terms of the expected increase in the mobilized ploughing interface shear resistance as D_{50} increases. However, as the GFRP and CFRP results in Fig.8 show the existing of a critical D_{50} value, D_{50cr}, where beyond this value the rate of $\partial\mu_p/\partial R_n$ change with respect to D_{50} becomes almost insignificant, it is believed that the mobilized ploughing interface shear resistance becomes D_{50} independent beyond this critical D_{50} value.

CONCLUSIONS

The results of the conducted experimental program in this study show that the interface shear behaviour between FRPs could be different than steel-granular interface behaviour. In fact, the FRP test results indicated that R_n-μ_p relation depends on D_{50}. However, the R_n-μ_p relation for steel surfaces is D_{50} independent. This behaviour could be explained in terms of the difference in the surface hardness between steel and FRP materials that controls the contribution of the interface ploughing resistance.

REFERENCES

ASTM E384-11e1 (2011). Standard Test Method for Knoop and Vickers Hardness of Materials.

Brumund, W.F. and Leonards, G.A. (1973). Experimental study of static and dynamic friction between sand and typical construction materials. J. Testing and Evaluation, JTEVA, l(2): 162- 165.

Coyle, H.A. and Sulaiman, I.H. (1967). Skin friction for steel piles in sand. J. Soil Mech. Found. Div., ASCE, 93(6): 261-277.

Dove, J.E. and Frost, J.D. (1999). Peak friction behaviour of smooth geomembrane particle interfaces. J. Geotech. and Geoenviron. Engrg., ASCE, 125(7):544-555.

Dove, J.E., Bents, D.D., Wang, J. and Gao, B. (2006). Particle-scale surface interactions of non-dilative interface systems. Geotextile and Geomembranes, 24(3): 156-168.

Evgin, E. and Fakharian, K. (1996). Effect of stress paths on the behaviour of sand-steel interface. Can. Geotech. Journal, 33: 853-865.

Frost, J.D. and Han, J. (1999). Behavior of interfaces between fiber-reinforced polymers and sands. J. Geotech. and Geoenviron. Engrg., ASCE, 125(8): 633–640.

Frost, J.D., De Jong, J.T. and Recalde, M. (2002). Shear failure behaviour of granular-continuum interfaces. Eng. Fract. Mech., 69(17): 2029-2048.

Heerema, E.P. (1979). Relationship between wall friction, displacement velocity, and horizontal stress in clay and in sand, for pile driveability analysis. Ground Engrg., 12(9): 55-60.

Iskander, M.G. and Hassan, M. (2001). Accelerated Degradation of Recycled Plastic Piling in Aggressive Soils. J. Composites for Constr., 5(3): 179-187.

O'Rourke, T.D., Druschel, S.J. and Netravali, A.N. (1990). Shear strength characteristics of sand-polymer interfaces. J. Geotech. Engrg., ASCE, 116(3): 451-469.

Paikowsky, S.G., Player, C.M. and Connors, E. J. (1995). A dual interface apparatus for testing unrestricted friction of soil along solid surfaces. Geotech. Testing Journal, ASTM, 18(2): 168-193.

Pando, M.A., Filz, G.M., Dove, J.E. and Hoppe, E.J. (2002). Interface shear tests on FRP composite piles. Proc. Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance, ASCE, Reston, Va:1486-1500.

Poulos, H.G. (1989). Cyclic axial loading analysis of piles in sand. J. Geotech. Engrg., ASCE, 115(6): 836-852.

Potyondy J.G. (1961). Skin friction between various soils and construction materials. Geotechniquè. 2(4): 339-353.

Sakr, M., El Naggar, M. H., and Nehdi, M. (2005). Interface characteristics and laboratory constructability tests of novel fiber-reinforced polymer/concrete piles. J. of Composites for Constr., 9(3): 274-283.

Tabucanon, J. T., Airey, D, W., and Poulos, H. G. (1995). Pile friction in sands from constant normal stiffness tests. Geotech. Testing Journal, ASTM, l5(3): 350-365.

Tsubakihara Y., Nisiyama T. and Kishida H. (1993). Friction between cohesive soil and steel. Soils Found., 33(2):145-156.

Uesugi, M. and Kishida, H. (1986). Frictional resistance at yield between dry sand and mild steel. Soils Found., 26(4):139–149.

Yoshimi, Y. and Kishida, T. (1981). Friction between sand and metal surface. Proc. 10th Int. Conference on Soil Mech. Found. Engrg., 1: 83l-834.