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Effect of Ageing Environment on Fiber-Reinforced Polymer/Granular Interface Shear Behaviour

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ABSTRACT: The aim of this paper is to investigate the ageing induced changes in Fiber-Reinforced Polymer (FRP)/Granular interface shear behaviour under different aging environments. The testing materials in this study include two different FRP materials; Glass Fiber Reinforced Polymer (GFRP) and Carbon Fiber Reinforced Polymer (CFRP), and two different granular materials in terms of particle shape and D_{50}. Acidic and alkaline aging environments were adopted in this study. The experimental program involves assessing the ageing effect on the testing FRP materials in terms of the changes in their hardness and surface roughness properties. Furthermore interface shear tests were conducted, using the unaged and aged FRP materials, to evaluate the effect of aging environments on FRP-granular interface shear coefficient. The test results indicated that FRP-granular interface shear behaviour was improved after subjected to the adopted aging environments. This behaviour could be attributed to the observed increase in the surface roughness of the aged FRP testing specimens.

KEYWORDS: Interface shear, FRP, Laboratory study, Long-term

1. INTRODUCTION

Fiber-Reinforced Polymer (FRP) is a two-phase composite material. It comprises fiber and matrix materials. The fiber provides FRP with strength and stiffness whereas the matrix gives it rigidity and environmental protection. The main types of fiber in civil engineering industry are glass, carbon, and aramid whereas the most common matrixes are epoxy, polyester, and vinyl-ester. In general FRP has attractive engineering properties over traditional construction materials. This includes high strength-to-weight ratio, high stiffness-to-weight ratio, corrosion and fatigue resistance, ease of handling, and ease of fabrication. Therefore, during the last two decades, Carbon Fiber-Reinforced Polymers (CFRP) and Glass Fiber-Reinforced Polymers (GFRP) have received considerable attention as alternative to the conventional structural materials in the civil engineering field. In fact, FRPs have been used in different forms to repair or reinforce the concrete structures instead of the traditional steel reinforcement.

In the geotechnical engineering field, FRP-tube confined concrete piles were used to overcome the low durability of conventional concrete piles in waterfront and aggressive environments. In fact, FRP-tube plays two roles; strengthening the concrete by the confinement effect, and protecting the concrete from the aggressive environment (Iskander and Hassan 2001). Several studies have investigated the geotechnical behaviour of FRP-tube confined concrete piles (Pando et al. 2002a, Frost and Han 1999, Sakr et al. 2005). Furthermore, as the service life of this new composite pile should be about 100 years, the possible degradation of FRP under different aging environments was also assessed in terms of FRP mechanical properties such as compressive, tensile, and flexural strength (Pando et al. 2002b, Iskander and Hassan 2001).

However, as FRP-soil interface shear behaviour controls pile's shaft resistance, attention should also be paid to the possible effect of FRP degradation on FRP-soil interface shear behaviour. To the authors' knowledge this subject is not yet covered in the existing literature of FRP-geotechnology. The aim of this study is to investigate experimentally the influence of ageing environment on FRP-granular interface shear behaviour. In the following sections, the testing materials and the conducted experimental program will be presented. Then, the obtained results will be discussed and interpreted, and finally the conclusions of this study will be drawn.

2. TESTING MATERIALS AND EXPERIMENTAL PROGRAM

Two different FRP materials namely; Glass Fiber Reinforced Polymer (GFRP), and Carbon Fiber Reinforced Polymer (CFRB) are selected as testing materials in this study. These two FRP materials have different hardness (HV) and average maximum roughness (R_{max}) values as listed in Tables 1. The term R_{max} is defined as the absolute vertical distance between the highest and lowest valley along the surface profile over a sample length equal to D_{50} (Uesugi and Kishida 1986). Furthermore, two different granular materials in terms of D_{50} and particle shape were selected to be used to assess the FRP-granular interface shear coefficients under different aging environments. The engineering properties of the granular testing materials are listed in Tables 2. The main mineral composition of Congleton sand is a silica sand.

Table 1 Properties of FRP materials

	Hardness, HV*	R_{max} (micron)
GFRP	65	24.5
CFRB	49	14.83

*Vickers Hardness

Table 2 Properties of granular materials

	Glass beads (GB)	Congleton sand (CG)
Max. dry density (kN/m^3)	16.26	17.11
Min. dry density (kN/m^3)	14.9	14.91
D_{50}(mm)	0.31	0.12
Coefficient of uniformity, C_u	-	2.33
Coefficient of curvature, C_c	-	0.96
Residual friction angle (degree)	24	31.5

The testing program involves immersing the GFRP and CFRP testing sheets in two different aqueous solutions; NaOH (pH=12), and HCl (pH=2) which represent acidic and alkaline soil environments, respectively, for 24 weeks. Furthermore, as the chemical reaction can be accelerated as the temperature increases (Arrhenius 1912), FRP specimens exposed to each pH level were aged under two different elevated temperatures (45, 80^{o}C) to obtain different specimen ages within the duration of the experiment (24 weeks). At the end of ageing process, the hardness, surface roughness, and FRP-granular interface shear coefficient of the aged FRP testing specimens were determined to compare them with the results of the control FRP sheets (aging time= zero). The surface average maximum roughness, R_{max}, was measured using a stylus profilometer whereas Vickers Hardness, HV, was used to measure the surface hardness of the testing FRP materials.

In order to assess the FRP-granular interface shear coefficient of unaged and aged FRP testing specimens, direct shear test apparatus was used for this purpose as shown in Figure 1. 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 FRP 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. The testing granular materials were prepared at 85% relative density using air pluviation technique. The tests were performed at horizontal displacement rate of 0.52 mm/min and under normal stress of 98 kPa.

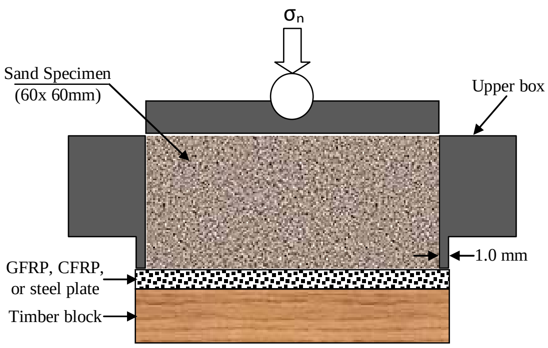


Figure 1 Modified shear box (cross section normal to the shearing direction)

3. TEST RESULTS AND DISCUSSION

3.1 Aging effects on HV and R_{max} of testing FRP materials

Figure 2 shows the aging induced changes in HV and R_{max} of the FRP testing specimens under different aging environment conditions. The values between the brackets represent the temperature of the aging environment. The control specimen points at temperature of 20^{o}C represent HV and R_{max} of the testing FRP materials as received from the manufacturer. The results in Figure 2 illustrate that for both FRP materials (GFRP and CFRP), HV and R_{max} have been increased after subjected to the adopted aging environments in this study. The results in Figure 2 also show that the increase in R_{max} value for each testing FRP material (GFRP and CFRP) is almost similar under the acidic (pH=2), and alkaline (pH=12) aging environments. However, the alkaline aging environment induces a greater increase in HV than the acidic aging environment. In general, the results in Figure 2, suggest that the applied aging environments in this study have more effects on GFRP than on CFRP.

It should be mentioned that the observed difference in the ageing effects on GFRP and CFRP has no relation with the type of reinforced fiber (glass and carbon) as the tested engineering properties in this study (HV and R_{max}) are mainly matrix-dominated properties. Therefore, the observed difference in ageing effects should be explained in terms of the possible difference in matrix properties of GFRP and CFRP testing materials. However, as epoxy was the matrix material for both of them, the observed difference in aging effects could be attributed to the possible difference in GFRP and CFRP epoxy curing process which controls the properties of cross-linked polymer network. It is known that the extent and distribution of cross-links dictate the physical, mechanical, and thermal properties of the epoxy material (Bandyopadhyay and Odegard 2012). Therefore, any change in the curing method could affect the engineering properties of the matrix materials (Xu et al. 2009).

The observed increase in the hardness of GFRP and CFRP after subjected to the applied ageing environments could be attributed to the expected additional epoxy curing process that could take place during the ageing process. It is a common practice in FRP-manufacturing process to under-cure the epoxy in order to avoid the inherently brittleness of the fully cured epoxy (Perrin et al. 2009). This deliberately under-curing process of epoxy resin produces low cross-linked polymer network density. As the adopted ageing process involves immersing the testing specimens in aqueous solutions at elevated temperatures, plasticization of the epoxy resin is expected (De'Neve and Shanahan 1993). This behaviour allows the polymer chains to become mobile, and promotes cross-linking process. Consequently, this allows the curing reaction to tend to completion (Kajorncheappunngam et al. 2002). Gupta et al. (1985) have shown that the mechanical properties of epoxy improve as its cross-link density increases. Therefore, the epoxy mechanical properties such as surface hardness are expected to improve under wet ageing condition.

In addition to that, Lee and Peppas (1993) indicate that immersing the epoxy in aqueous solutions could also generate micro-cracking due to polymer chain scission that can be caused either by water-induced hydrolysis or by swelling. Therefore, the generation of micro-cracking during the ageing process could explain the increase in the surface roughness of the testing FRP specimens after subjected to the different aging environments as shown in Figure 2.

Based on the above discussion, the results in Figure 2 suggest that the alkaline aging environment (pH=12) promotes better curing reaction and better cross-linking properties than the acidic aging environment. In fact, this difference can be attributed to the difference in the amount of liquid that could diffuse into GFRP and CFRP specimens which is function of the chemical properties of the aqueous solution and the affinity of the diffusing molecule to specific groups present in the epoxy (Diamant et al. 1981).

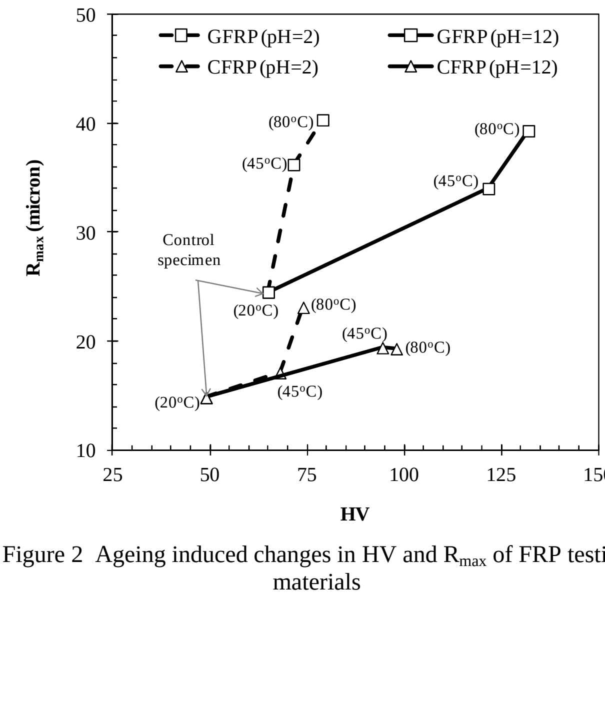


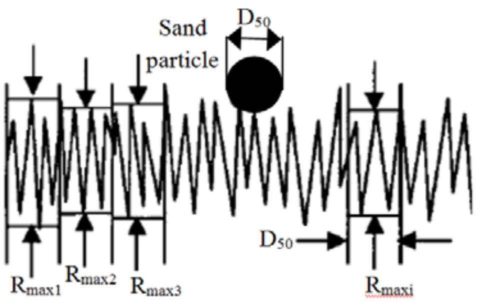
Figure 2 Ageing induced changes in HV and R_{max} of FRP testing materials

The observed greater ageing effect at temperature of 80°C than at 45°C could be attributed to the fact that both moisture diffusion and chemical reaction are faster when the aqueous temperature increases (Arrhenius 1912; Iskander and Hassan 2001). Consequently, for a certain aging time, better FRP curing rate can be achieved as the aqueous temperature increases.

Finally, it should be mentioned that the reported ageing deterioration of the structural mechanical properties of FRP materials such as compressive and tensile strength (Pando et al. 2002, Iskander and Hassan 2001) did not contradict with the observed ageing induced improvement in the FRP hardness property. As the surface hardness property of FRP is a matrix-dominated property whereas the compressive and tensile strength depend on matrix and fiber properties, and more importantly the fiber-matrix interfacial bond condition. Under the wet ageing environment, the matrix properties could improve due to aging induced curing process, however, the interfacial bond could be significantly deteriorated due to wicking of the diffused moisture along the fibre matrix interface which resulting in loss of micro structural integrity (Thomason 1995; Bond and Smith 2006).

3.2 Aging effects on FRP-granular interface shear coefficient

As FRP-granular interface shear behaviour is mainly controlled by the engineering properties of the granular and FRP-matrix materials, the observed aging effects on hardness and surface roughness of FRP material, as show in Figure 2, would control the aging evolution of FRP-granular interface shear coefficient, μ, under the different adopted aging environments. Uesugi and Kishida (1986) 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 Figure 3.Several previous studies in the literature have discussed the effect of the surface hardness (HV), and the surface roughness on continuum-granular interface shear coefficient using the relative surface roughness coefficient, R_n, (Kishida and Uesugi 1987; O'Rourke et al. 1990; Frost and Han 1999; Frost et al. 2002; DeJong et al. 2009). Although these studies have concluded that μ increases as R_n increases, there is no agreement about the effect of HV on μ. Dove et al. (2006) have shown that μ increases as HV increases whereas the O'Rourke et al. (1990) and Frost et al. (2002) have shown an opposite behaviour.



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

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

Figure 3 Normalized relative roughness, R_n

The peak interface shear coefficient, μ_p, of each unaged (control) and aged FRP testing materials was presented between brackets, as shown in Figure 4, for Glass beads and Congleton sand. The presentation of μ_p results in HV-R_n plan, where the ageing paths could be recognized, was adopted to link the ageing induced changes in surface roughness and hardness with the interface shear property. In general, the results in Figure 4 show that subjecting GFRP and CFRP to the different adopted aging environments in this study increases its interface shear coefficient. However, the results in Figure 4b imply that the aging evolution of μ_p for Congleton sand is insignificant compared to the results of Glass beads (Figure 4a). In fact, this behaviour can be explained in terms of the differences between μ_p of the control specimens and the internal shear coefficient of the granular material, μ_i. For Glass beads and Congleton sand, μ_i is equal to 0.52 and 0.62, respectively. Uesugi and Kishida (1986) have shown that μ_p increases as R_n increases.

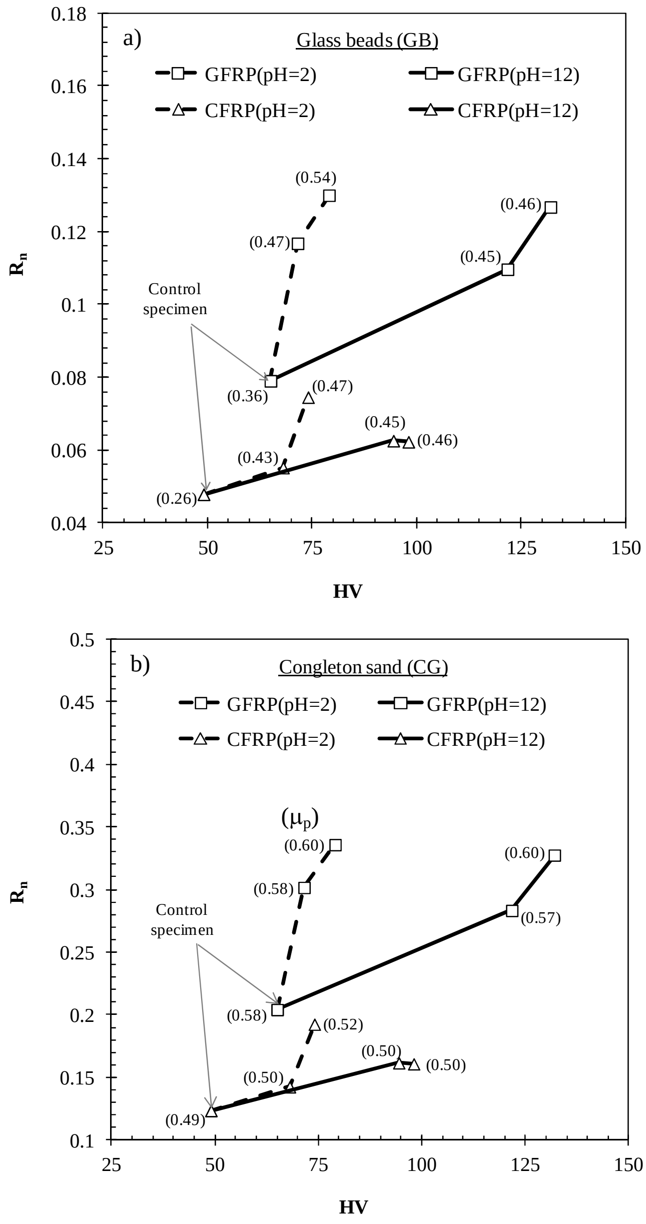
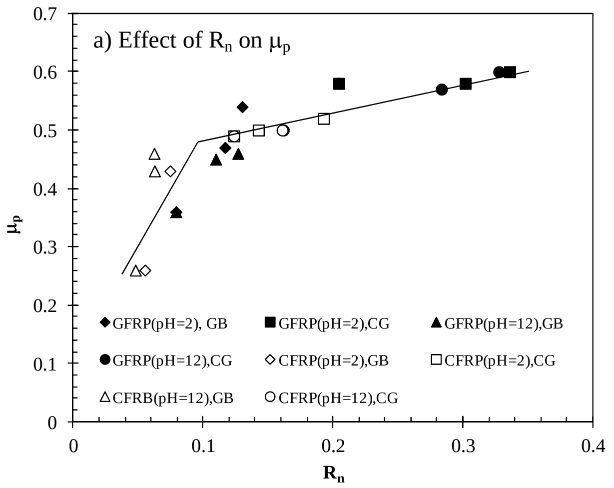


Figure 4 The effect of ageing induced changes in HV and R_{max} of FRP testing materials on interface shear coefficient, μ_p (the value between the brackets)

However, when μ_p approaches μ_i at a critical R_n value, the value of μ_p will be R_n independent and almost equal to μ_i. Therefore, as the values of μ_p of the control specimens of Congleton sand are very close to the μ_i value of Congleton sand, the room for μ_p improvement as R_n increases due to aging effect is very limited compared to the tests where Glass beads is used.

In order to understand the effect of HV and R_n changes on μ_p, the interface test results were presented in R_n-μ_p and HV-μ_p plots as shown in Figure 5. The test results suggest a reasonable bilinear relation between R_n and μ_p where μ_p increases as R_n increases as shown in Figure 5a. In fact this finding is in line with the outputs of the previous studies in literature (Kishida and Uesugi 1987; Frost and Han 1999). On the other hand, the results in Figure 5b indicate that the surface hardness changes have a minor effect on μ_p at least for the testing FRP materials in this study.



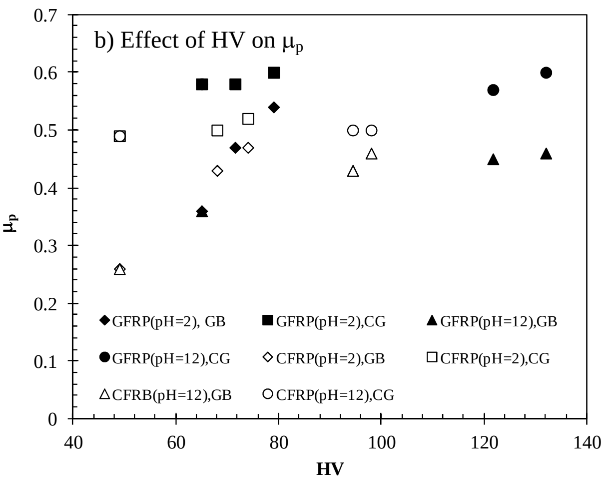


Figure 5 Effect of R_n and HV on μ_p

4. CONCLUSION

Experimental program was conducted in this study to assess the effect of different ageing environment conditions on FRP-granular interface shear coefficient. The results of this study indicated that although aging under the adopted environments in this study could have detrimental effects on the structural mechanical properties of FRP, it improves the FRP interface shear property as it is a matrix-dominated property. In fact, this improvement in the FRP interface shear behaviour could be mainly attributed to the observed increase in surface roughness under aging process. Finally, it should be mentioned that further study is required to assess the effect of the soil confining pressure on the aging process as this will likely lead to embedment of soil particles in the FRP surface.

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