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DURABILITY AND FIELD APPLICATIONS OF FIBRE REINFORCED POLYMER (FRP) COMPOSITES FOR CONSTRUCTION

DURABILITÉ ET APPLICATIONS DES COMPOSITES EN POLYMÈRES RENFORCÉS DE FIBRES (PRF) POUR LA CONSTRUCTION

DURABILITY OF GFRP INTERNAL REINFORCEMENT: MECHANICAL PROPERTIES AFTER MOISTURE ABSORPTION

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ABSTRACT

Glass fibre-reinforced polymers are not susceptible to corrosion yet may suffer other degradation mechanisms due to adverse environments such as moisture and high temperature. In this study, three groups of tests have been conducted on some new-generation GFRP bars, produced by Pultrall Inc. at the Université de Sherbrooke environmental laboratory. The first group purported to quantify the amount of water absorbed by GFRP bars (12.7 mm and 15.9 mm in diameter) under the combined effect of elevated temperature (60^{o}C) and immersion in water. The samples used were GFRP bars with a single layer of sand coating, two layers of coating as well as the conventionally coated GFRP bars commercially available. Conditioning took place for a period of 120 days. Results from the tests were compared to results of identical tests on bars exhibiting the single effect of elevated temperature (60^{o}C). The second and third groups, for flexure tests and shear tests respectively, were conducted on the same type of bars after exposure to the same aforementioned conditions. Results showed that the size of the tested samples proved to be parameters that affect GFRP water absorption. Samples of 102 mm length retain a moisture percentage, in weight, less than half that of the 25 mm samples. Increasing the number of sand-coating layers on the bars significantly increases the absorbed moisture percentage. Furthermore, the reduction in flexural strength of the bars tested, after being exposed to the combined effect of elevated temperature (60^{o}C) and immersion in water, was in the order of 14 to 19%. Companion shear strength samples showed a reduction in the order of 14%.

1. INTRODUCTION

The main environmental factors that cause the degradation of GFRP reinforcing bars and sheets are temperature, moisture, alkalinity, freeze-thaw and ultraviolet rays. The effect of moisture, in particular, on the performance of GFRP as internal reinforcement has been widely investigated due to the susceptibility of glass to water. In many cases, the combination of moisture and elevated temperature is used to accelerate the diffusion and reaction within composite materials or to determine the synergistic effect of moisture and temperature [1].

When present in the resin, moisture can act as a plasticizer and cause interruptions of Van der Waals bonds between the polymer chains. This would in turn cause sizable changes in the young's modulus, strain to failure and toughness. These effects may be reversible, but the swelling stresses induced by moisture uptake can cause permanent damage such as matrix hydrolysis and fiber-matrix debonding [2]. In an earlier investigation [3] E-glass/vinyl ester rods were immersed in water for 224 days at a temperature range of 23-80°C. At temperatures of 40 and 80 °C, the reduction in flexural strength was 14% and 45% respectively. At 23°C, with the same exposure time, no significant reduction was measured. The flexural modulus of the specimens did not appear to be affected by exposure. Moisture diffusion is typically at a much slower rate than temperature changes yet its effect is often more dramatic. The diffusion coefficient *D* of water in a neat resin or a composite is known to be dependent upon temperature and is commonly modeled using Fick's Law [2].

The single free phase model, based on Fick's law, for the diffusion of chemicals or moisture through an FRP was used by Saadatmanesh and Tannous [4] to simulate moisture diffusion into rebar specimens of length = 102mm. The driving force for diffusion is the concentration gradient of the absorbent. Both ends of each sample were epoxy-coated in order allow diffusion occurrence only normal to the surface of the sample as shown in Figure 1.

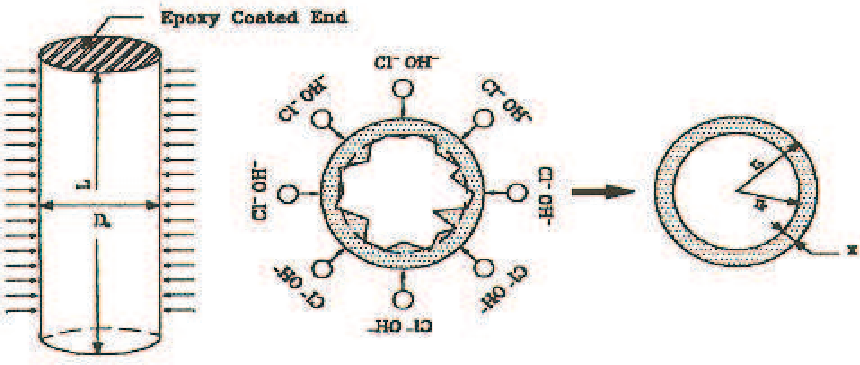


Fig. 1: Moisture diffusion in FRP rebars and tendons in alkaline and salt solutions [4]

Results showed that Fick's law could be used to model the increase in moisture content as well as predict the tensile strength for the interval of time during which Fickian diffusion is valid. It was reported that diffusivity depends on the temperature and solution types. The mass diffusion coefficient, *D*, can be obtained by moisture absorption tests and calculation by Equation 1 below:

$$\Delta = \frac{\pi.\rho^2}{16}(\frac{M_2 - M_1}{M_\mu})^2(\frac{1}{\sqrt{\tau_2} - \sqrt{\tau_1}})^2 \quad (1)$$

where M_1 and M_2: are the moisture contents at times t_1 and t_2; M_m is the moisture content at saturation. For experimental purposes, the moisture M is calculated as the percentage of weight gain of the FRP specimen as shown in Equation 2.

$$M = \frac{(W - W_d)}{W_d}100 \quad (2)$$

where W is the wet weight and W_d is the dry weight of the specimen.

2. OBJECTIVES

The main purpose of this paper is to evaluate the change/degradation in the flexural and shear properties of aged GFRP bars after being subjected to hygrothermal conditions for a specified time period. Another concern is whether or not the type and number of layers of sand coating has an impact on GFRP-bar moisture absorption properties and, in turn, the over all residual properties.

3. EXPERIMENTAL PROGRAM

In this project, the durability characteristics of six types of GFRP reinforcement bars, from one manufacturer, have been investigated. The bars differ with respect to the type of cover, resin and bar-size. All bars are composed of 73 % E-glass fibres impregnated in vinyl ester resin, cured and sand-coated by.

Table 1: Tensile properties of un-aged GFRP bars

Designation	Diameter (mm)	Type of cover	Tensile strength (MPa)	Modulus of Elasticity (GPa)
PN#4	12.7	Normal production	765 ± 27	41 ± 2.2
SR#4	12.7	Single cover	758 ± 36	42 ± 1.2
DR#4	12.7	Double cover	771 ± 25	42 ± 1.3
PN#5	15.9	Normal production	733 ± 33	42 ± 2.1
SR#5	15.9	Single cover	770 ± 35	41 ± 1.5
DR#5	15.9	Double cover	752 ± 22	41 ± 1.8

Table 1 shows the tensile properties and a view of the tested sand-coated bars, prior to aging and testing of the residual properties. The series of tests that took place, and relevant details, are available in Table 2.

Table 2: Details of tested samples

Test Purpose	Series	Diameter (mm)	Total Length (mm)	Span Length	Number of specimens
Increase in moisture content	1	12.7 (#4)	25	–	5
	2				5
	3				5
	4	15.9 (#5)			5
	5				5
	6				5
	7	12.7 (#4)	102		5
	8				5
	9				5
Flexure	1	12.7 (#4)	350	250	5
	2				5
	3				5
	4	15.9 (#5)	420	320	5
	5				5
	6				5
Shear	1	12.7 (#4)	200	–	5
	2				5
	3				5
	4	15.9 (#5)			5
	5				5
	6				5

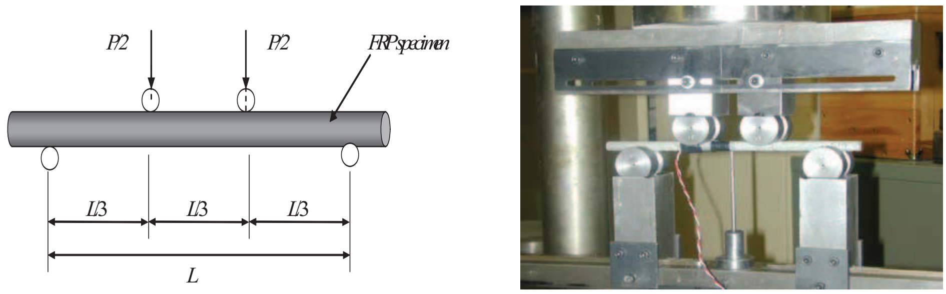
3.1 Moisture Absorption Tests

As per ASTM D 570 [5], all specimens were cut into 25 mm-long pieces. Five specimens per bar-type were provided. To obtain the as-received moisture content, all test samples were first preconditioned/heated at 60 °C for approximately eight days, in accordance with procedure D of the ASTM 5229 [6]. The samples were weighed, prior to conditioning, to obtain the baseline mass W_b then put on trays in the oven at 60 °C. Samples were taken out, to be weighed, every twelve hours. Finally, the destined weight W was recorded with the total elapsed time. Mass change, at each time interval for each specimen, was calculated by Equation 2. The average weight was taken for the mass changes of all 5 replicates of the same material on an analytical balance of ± 0.001 g sensitivity.

As-received moisture content of the specimens was determined, for each specimen, at the end of the eight-day period. The difference between the successive average moisture contents for 5 specimens of each material had narrowed down to 0.01 % so preconditioning ceased as per ASTM D 5229 [6]. After preconditioning, absorption tests were conducted where, this time, the oven dry mass serves as the base line W_b. All samples were submerged in tap water and brought to the specified steady state environment (60 °C). For the 120 day period, specimens were removed from the oven and weighed every 24 hours, after drying the surface of the specimen. Equation 2 was used to calculate the diffusion coefficient values D for the materials at hand.

3.3 Flexural Strength Tests

Within this study, the ASTM 4475-02 [7] method was followed with some modifications such as testing full bars rather than half-bar samples. Moreover, an overhang of 10 % of the supported span was allowed on each support (See Figure 2). The maximum tensile stress in the outer fibers, and the Modulus of elasticity in bending can be calculated according to equations (3) and (4).



a) b)

Fig. 2: Four points bending test a) Schematic and b) Experimental set-up

$$\sigma_{flexural} = \frac{2PL}{3\pi R^3} \quad (3)$$

$$E = \frac{23PL^3}{1296\Delta I} \quad (4)$$

where P is the ultimate applied load (N); $I = \frac{\pi R^4}{4}$ is the moment of inertia of the FRP rebar (mm^4); L is the span length in millimetres; R is the radius of the test specimen (mm) and Δ is the maximum deflection measured during the test (mm)

Flexural tests were conducted using a manually operated, universal testing machine with a capacity of 270-kN. As shown in Figure 2, the machine includes a loading device, load indicator, supports and loading nose. The specimen was inserted into the frame and adjusted accordingly. The specimens were loaded at a rate of approximately 300 MPa/min [7]. An LVDT was attached to some specimens at the sample mid-span to measure the resulting deformation.

3.3 Direct Shear Strength Test

The failure of GFRP bars by direct shear strength can be the cause of failure of GFRP reinforced concrete structural elements. The direct shear apparatus, the schematic of which is in Figure 3 was fabricated in accordance with the Japanese recommendations for design and construction of concrete structures using continuous fiber reinforcing materials [8]. Shear displacement was measured using the frame crosshead displacement. GFRP samples with a length of 200 mm were exposed to elevated temperature and tap water at 60 °C for 120 days. After conditioning and proper drying, the 12.7 mm and 15.9 mm, in diameter, samples were tested at room temperature in a direct shear test apparatus holding a shear span of 0.5 mm. The shearing stress was applied at a rate of 45 MPa per minute. Load was applied uniformly without subjecting the test specimen to shocks [9]. During testing, the bars were loaded until a reduction in the applied load was observed.

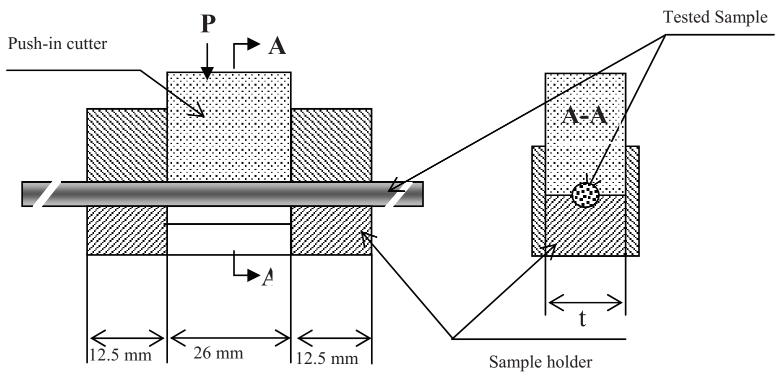


Fig. 3: Double shear testing machine

4. TEST RESULTS AND DISCUSSION

For moisture absorption tests, Figures 4 and 5 show that evolution of water absorption within the FRP samples is in agreement with the Fickian law. The initial portion of the curve depicting moisture percentage versus the square root of time (M vs. $\sqrt{t}$) is linear. After a period of time which is dependent on the type of fiber, matrix material, temperature, and type of solution, the curve levels off towards an asymptotic value corresponding to M_m. In figure 4, it can be noticed that 12.7 mm-diameter samples absorb a greater percentage of moisture than their 15.9 counterparts. Moreover, double-covered bars absorb up to 60% extra moisture than single or normal production bars. Resin cover increases with the number of layers and, in turn, plays a role in withdrawing more moisture to the FRP material.

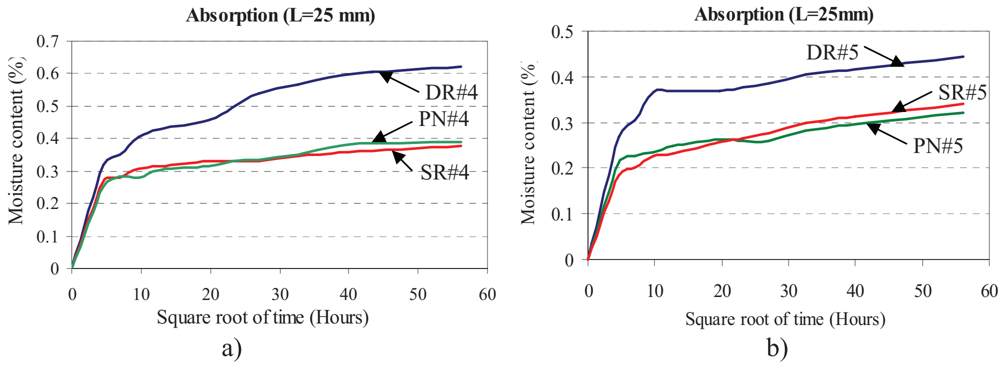


Fig. 4: Moisture absorption for a) 12.7 mm bars and b) 15.9 mm bars

Another absorption test took place on companion yet longer 12.7 mm samples (102 mm). This purports to monitor the effect of sample length on the percentage of absorbed moisture (See Figure 5). The latter samples exhibited a moisture absorption percentage = 50% that of the former in Figure 6. This is due to the much higher rate of moisture penetration through sample cross-section versus that along the radial perimeter of the bar.

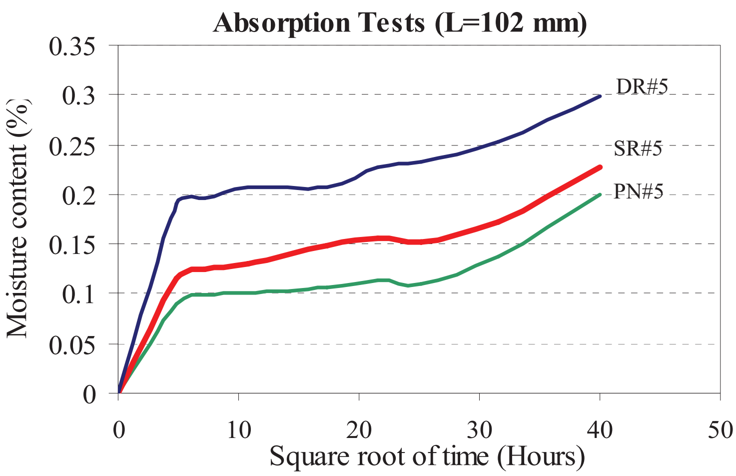


Fig. 5: Moisture absorption for 12.7 mm bars (L = 102 mm)

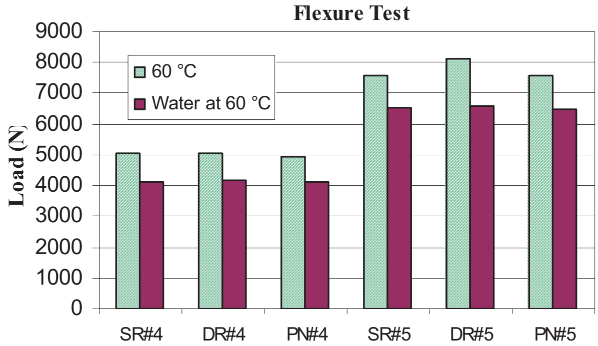


Fig. 6: Histogram depicting the effect of elevated temperature and moisture on the flexural ultimate failure load of GFRP bars

For the flexural strength of specimens submerged in water at 60 ^{o}C for 120 days: Results below (Figure 6 and Table 3) show that the flexural strength of the studied GFRP bars was reduced by elevated temperature as well as the coupled effect of elevated temperature and water. Changes in flexural strength ranged from 16.5 to 18.8% for #4 bars and 13.4 to 19.3% for #5 bars.

Table 3: Effect of moisture and temperature on the flexural ultimate failure load of GFRP bars

Bars	Duration (days)	Ultimate failure load (N)		Residual Flexural Strength (MPa)		Changes in Flexural Strength (%)
		At 60 °C	Water+ 60 °C	At 60 °C	Water+ 60 °C	
SR#4	120	5064 ± 150	4111 ± 138	1050.44	852.72	18.82
DR#4		5029 ± 151	4158 ± 65	1043.03	862.45	17.31
PN#4		4945 ± 94	4128 ± 95	1025.77	856.29	16.52
SR#5		7546 ± 400	6536 ± 257	1020.93	884.22	13.39
DR#5		8134 ± 269	6564 ± 222	1100.42	888.09	19.30
PN#5		7541 ± 101	6446 ± 118	1020.26	872.10	14.52

Table 4: Effect of moisture and temperature on the ultimate shear load of GFRP bars

Bars	Duration (days)	Ultimate failure load (N)		Changes in Ultimate failure load (%)
		At 60 °C	Water+ 60 °C	
SR#4	120	98815,18	84502,73	14,48
DR#4		87665,45	79798,73	8,97
PN#4		93946,36	80627,27	14,18
SR#5		69090,00	55815,45	19,21
DR#5		58310,00	50274,00	13,78
PN#5		56394,55	54229,64	3,84

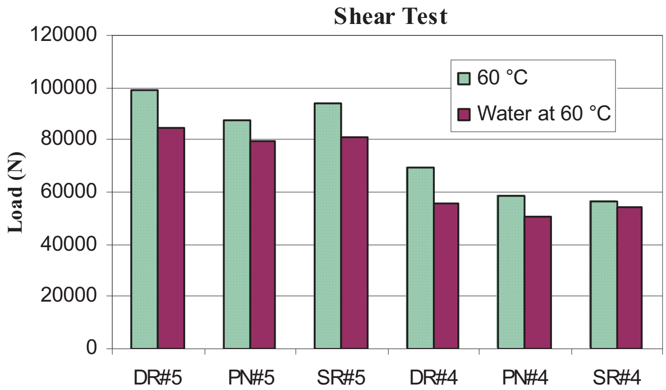


Fig. 7: Histogram depicting the effect of elevated temperature and moisture on the ultimate transverse shear load of GFRP bars

For shear strength tests shown in Figure 7 and Table 4, the reduction in shear strength was in the order of 14% for #4 bars and varied from 4 to 19% for #5 bars.

5. CONCLUSION

For absorption tests: After 4 months of immersion in water at 60^{o}C, #4 samples (Length = 25 mm) of double cover exhibited an increase in weight equal to 0.62 %. The increase in normal production and single covered bars was 0.39 % and 0.38% respectively. For #5 bars exposed to the same environmental conditions, the double cover bars showed a weight increase of 0.44%. Whereas normal production and single covered bars increased by 0.32 and 0.34 % respectively. This indicates that the resin cover plays an important role in moisture absorption. For the #4, 102mm long samples, the absorbed moisture percentage dropped to less than half. The amount of moisture entering through the capping at the bar ends of both samples (25 mm and 102 mm) is supposed to be identical. Thus shorter samples attain a higher moisture percentage.

For flexure tests: It was realised that #4 bars suffered a degradation percentage ranging from 16.5 to 18.8 %, for the three cover types. For # 5 bars, this degradation percentage was in the range of 14% for both single cover and normal production bars. However, double cover bars experienced a slightly higher degradation of 19% (i.e. 5% more) due to the extra amount of water being saved in the two layers of cover. Observing the results at whole, it is evident that the degradation of bars with smaller diameter is greater than those of bigger diameter. As **for shear tests:** Single covered and double covered #5 bars exhibit higher degradation percentages than their #4 counterparts; a value in the order of 5%. For normal production bars, the contrary takes place which may be an experimental flaw.

From the results obtained above, using longer bar samples for absorption tests is advised since GFRP rebar in real life is of greater lengths. Moreover, the cover resin is the main factor influencing FRP moisture absorption. The more the layers, the more the moisture saved around the bar. Water absorption has also influenced the flexure and shear properties of the tested FRP samples. Thus, increasing the number of cover layers is not a solution to prevent moisture ingress into the bars. The quality of cover resin should be investigated further.

6. ACKNOWLEDGMENTS

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