EFFECT OF ENVIRONMENTAL CONDITIONING ON BOND BETWEEN COMMERICAL FRP RODS AND CONCRETE

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ABSTRACT

The long-term durability of fiber reinforced plastic (FRP) rods in concrete need to be investigated and analyzed. Accordingly, the knowledge of how aging of FRP affects the bond behavior with concrete is essential. The approach taken in this study is to subject the FRP rods, subsequent to casting into direct pull-out specimens, to accelerated environmental aging regimes, and then quantify bond degradation using the direct pullout test. Two commercial available FRP rods were evaluated: International Grating (IG) and Corrosion Proof (CP). For both rods FRP rods, three environmental conditioning media were used, alkaline environment (10% ammonia solution), acidic environment (0.6% acetic acid), and neutral environment (deionized water). For all solution, the temperature of exposure is 80 °C. The results indicate that bond between concrete and pre-conditioned FRP rods subsequent to casting degrade to varying degrees, depending on the type of environment. High temperature combined with an alkaline solution is the most aggressive environment on both rod types.

KEYWORDS

Fiber reinforced plastic (FRP) bars; bond strength; durability; accelerated degradation.

INTRODUCTION

Even though steel reinforcement has been used in concrete structures for many years, there has always been a major problem with this type of construction, namely, the corrosion of the reinforcement. Since neither an effective nor an economic solution has yet been developed to prevent corrosion-related degradation of concrete structures, a new solution is considered a development in the construction industry. This new solution involves substituting steel with a material that is immune to common corrosive agents. This material is fiber reinforced plastic (FRP) composite. The use of FRP composites as building construction materials has increased in recent years. In particular, FRP reinforcement for concrete has recently been introduced into the market. The recent advance in the fields of plastics and fiber composites have resulted in the development of FRP reinforcement that surpasses the strength and fatigue properties of steel. Other features include low weight, which is about 1/4 that of steel, corrosion resistance, electric and magnetic insulation, easy handling, and economy. These reinforcements have advantages over conventional steel rebars in concrete structures in corrosive environments such as where deicing salts are present, marine or soil environments, environments with corrosive gas, and chemical environments. These reinforcements are also advantageous in concrete structures where electric or electromagnetic insulation is required, such as aluminum and copper smelting plants, manholes for electric and telecommunication equipment, and airport control towers; or when high strength-to-weight ratio is necessary. There are also some notable disadvantages in FRP rods, such as a low modulus of elasticity which may result in excessive deflections of the structural member, linear elastic behavior up to failure which leads to lack of ductility of the structural member, and durability issues. Nanni (1993); Al-Dulaijan (1996).

The most important issue that is addressed in this study is the application of an accelerated test method uses an accelerating mechanism to increase the rate of degradation of the FRP material, and then an evaluation is made to see how this accelerating mechanism effecting the bond of FRP reinforcement to concrete. Accelerating mechanism will only include environmental conditioning (temperature and concentration of a given environment).

EXPERIMENTAL PHASE

Environmental Conditioning Scheme.

The environmental conditioning scheme includes pre-conditioning of stand-alone FRP system. Three solutions were involved: 10% ammonia @ 80°C (AM), 0.6% acetic acid @ 80°C (AC) , and deionized water @ 80°C (W), in addition to virgin condition (V).

In the pre-conditioning of stand-alone FRP Rods scheme, only part of the rod which was to be embedded in concrete was conditioned prior to its use. Glass jars 25 cm in height with a rubber cap secured by an aluminum ring were used. Six holes were drilled in each rubber cap to insert an equal number of FRP rods. Each FRP rod is 100 cm long, of which 15 cm is immersed in the solution. After conditioning, the treated rods were cast in concrete for pull-out testing. Al-Dulaijan (1996).

Test Methods.

The primary bond testing methods that were employed in this study is the direct pull-out test method.

Direct Pull-out Bond Test Method.

The pull-out specimen used in this research consists of a concrete cube of 15 cm per side with a FRP rod placed concentrically through both ends of the specimen to allow slip measurement. The embedment length is adjusted by inserting two plastic tubes on both ends of the rod.

The universal testing machine used has a stationary top cross head and a lower cross head that can move at a predetermined speed. The load cell in the universal testing machine has two load ranges: low and high. The lower range is either 3000 N or 12000 N, while the upper range is 60,000 N or 300,000 N.

The LVDTs are Robinson-Halpern 285A-0200 models. These LVDTs have a gage head that can be compressed linearly up to 10 mm.

The strain gages are FLA-3-11-1L type, manufactured by Tokyo Sokki Kenkyujo Co., Ltd. Each strain gage is 3 mm long and has a resistivity of 120 Ω. The gage factor for these strain gages is 2.13. Al-Dulaijan (1996).

To prepare for testing, the specimen is seated on a steel plate over a thin layer of plaster of Paris on the stationary cross-head of the universal testing machine. The steel plate and the plaster of Paris allow for proper alignment and full contact. Slip is measured through three LVDTs positioned at both the free and loaded ends of the rod, as shown in Fig. 1., where the pull-out test method set-up is presented. The FRP rod is subjected to a pull-out load by a mechanical grip consisting of a four-piece wedge set against the moving cross-head of the universal testing machine. The load monotonically increases with displacement control at a rate of 1.25 mm/minute. The movement of the concrete specimen relative to the stationary cross-head is also monitored through a seventh LVDT attached to the side of the concrete. Longitudinal strain in the rod outside the bonded area is measured with one strain gage applied to the FRP rod surface (228 mm from concrete surface). The purpose of this measurement is to account for the elongation in the rod due to the applied load. The effective loaded-end slip is computed by subtracting both the relative movement of the concrete specimen and the elongation of the rod from the loaded-end slip directly measured by the three LVDTs at the loaded end. For the units of the collected data, the pull-out load is in Newton, the slips in millimeters, and the strain in microstrain. Al-Dulaijan (1996); Al-Zahrani (1995). The collected data were reduced to bond stress and slips at the free and loaded ends. Each pull-out test was summarized by one diagram where bond-stress was plotted versus free and loaded end slips.

Testing Program.

The FRP materials used in this program include two commercially available FRP rods, International Grating (IG) and Corrosion Proof (CP) .

Throughout this phase, the embedment length of the cast rods is 5 d_b, where d_b is the diameter of the rod. Three repetitions were used for all types of testing.

RESULTS AND DISSCUSION

CP Rods.

A summary of the experimental values of pull-out results in terms of average load, average bond stress, average free-end slip, and average loaded-end slip at onset of free-end slip and maximum is given in Table 1. Bond stress is defined as the pull-out load divided by the surface area between the FRP rod and concrete. The onset of free-end slip is defined as 0.01 mm slip.

A typical diagram obtained from the direct pull-out test for CP rods (virgin and environmentally conditioned) is given in Fig. 2. The curves in this diagram represent bond stress vs. free-end slips for CP-V, CP-AM, CP-AC, and CP-W specimens. This diagram shows that AM was the most aggressive environment followed by AC environment, and finally the W environment.

The average load at onset of free-end slip increased 25% for CP-AM specimens when compared to CP specimens. On the other hand, it decreased by 53% for CP-AC specimens, and by 40% for CP-W specimens.

The failure mode for the CP specimens consisted of bond failure represented by free-end slipping followed by concrete splitting. When the concrete split, the maximum pull-out load was reached at an average free-end slip of 1.284 mm. This indicates that the concrete split after considerable free-end slipping; therefore, the post bond failure is not relevant. The failure mode for CP-AM specimens consisted of bond failure represented by continuous free-end slipping without rod failure and splitting of concrete. Both CP-AC and CP-W specimens had the same failure mode which was consisted of bond failure represented by an average free-end slips of 1.4 mm and 2.6 mm, respectively, followed by rod failure. This indicates that in both cases rod failure happened after considerable free-end slipping; therefore, the post bond failure is also not relevant.

Table 1. Results for CP rods pull-out specimens (virgin and environmentally conditioned)

Specimen Code	At Onset of Free End Slip				At Maximum			
	Ave. Load (N)	Ave. Bond Stress (MPa)	Ave. F.E. Slip (mm)	Ave. L.E. Slip (mm)	Ave. Load (N)	Ave. Bond Stress (MPa)	Ave. F.E. Slip (mm)	Ave. L.E. Slip (mm)
CP-V	6550	2.6	0.010	0.026	30,419	12	1.28	1.39
cv*	16.86	16.86	0	6.34	2.23	2.23	3.34	3.38
CP-AM	8192	3.24	0.010	0.082	19991	7.89	8.01	8.78
cv*	3.86	3.86	0	9.35	5.04	5.04	4.65	1.63
CP-AC	3076.5	1.21	0.01	0.018	28783	11.36	2.26	3.21
cv*	8.11	8.11	0	3.09	3.07	3.07	10.21	18.08
CP-W	3950	1.56	0.01	0.076	27085	10.69	1.4	2.80
cv*	1.79	1.79	0	11.16	5.66	5.66	9.62	12.83

cv* = Coefficient of variation

N.A = Not applicable

Since different failure modes were experienced after differing amounts of slippage with each specimen type, a comparison scheme using a single criterion is necessary. an average pull-out load at 1 mm free-end slip as a criterion. Using this criterion, the average bond stress for CP-V specimens was 11.9 MPa; for CP-AM specimens it was 4.88 MPa (59% reduction). For CP-AC specimens it was 7.66 MPa (36% reduction), and for CP-W specimens it was 10.45 MPa (12% reduction). Fig. 3. is a bar chart for the pull-out load at 1 mm free-end slip for CP-V, CP-AM, CP-AC, and CP-W specimens.

The bond for CP specimens is most likely controlled by both friction and mechanical interlock mechanisms. The friction results mainly from the fine sand particles on the surface, while the interlock develops between the concrete and the deformations between the spiral indentations along the rod. Also, the presence of sand particles on the rod surface provides another bond mechanism between the rod and concrete and that is the adhesion factor. However, this factor is probably the main resisting mechanism only at the very early stages of the pull-out loading and vanishes once there is relative movement between the rod and concrete. The loss of adhesion is a gradual process that starts when the loaded-end slips and continues until the free-end starts to slip. Al-Zahrani (1995); Al-Zahrani et al. (1996); Nanni (1995).

The bond for CP-AM specimens is also most likely controlled by mechanical interlock and to a lesser degree by friction mechanisms. The friction results mainly from the large cracks and swelling induced by the conditioning, but the conditioning also caused the sand particles to fall off so they had no role in either friction or adhesion mechanisms.

IG Rods.

A summary of the experimental values of pull-out results in terms of average load, average bond stress, average free-end slip, and average loaded-end slip at onset of free-end slip and maximum is given in Table 2. Bond stress is defined as the pull-out load divided by the surface area between the FRP rod and concrete. The onset of free-end slip is defined as 0.01 mm slip.

A typical diagram obtained from the direct pull-out test for IG rods (virgin and environmentally conditioned) is given in Figure 4. The curves in this diagram represent bond stress vs. free-end slips for IG-V, IG-AM, IG-AC, and IG-W specimens. This diagram follows the global trend that all environmentally conditioned specimens have weaker bond strength than virgin specimens.

All IG specimens (virgin and environmentally conditioned) experienced the same bond behavior. The average bond stress at maximum was 18.2 MPa for IG-V specimen, 8.28 MPa for IG-AM (a reduction of 55%), 4.32 MPa for IG-AC (a reduction of 76%), and 4.37 MPa for IG-W specimen (a reduction of 76%). Fig. 5. is a bar chart of the maximum pull-out load for all IG specimens (virgin and environmentally conditioned)

The failure mode for IG-V specimens consisted of bond failure at maximum pull-out load. Also IG-AM, IG-AC, and IG-W experienced the same failure mode but at much lower maximum pull-out load when compared to virgin specimens.

Table 2. Results for IG rods pull-out specimens (virgin and environmentally conditioned)

Specimen Code	At Onset of Free End Slip				At Maximum			
	Ave. Load (N)	Ave. Bond Stress (MPa)	Ave. F.E. Slip (mm)	Ave. L.E. Slip (mm)	Ave. Load (N)	Ave. Bond Stress (MPa)	Ave. F.E. Slip (mm)	Ave. L.E. Slip (mm)
IG-V	N.A	N.A	N.A	N.A	58,180	18.2	1.665	3.855
cv*	N.A	N.A	N.A	N.A	16.10	16.10	5.67	5.56
IG-AM	N.A	N.A	N.A	N.A	26434	8.28	3.754	5.621
cv*	N.A	N.A	N.A	N.A	8.11	8.11	2.69	7.91
IG-AC	N.A	N.A	N.A	N.A	13795	4.32	3.142	3.572
cv*	N.A	N.A	N.A	N.A	11.39	11.39	11.98	10.08
IG-W	N.A	N.A	N.A	N.A	13932	4.36	2.723	2.878
cv*	N.A	N.A	N.A	N.A	10.11	10.11	1.89	8.64

cv* = Coefficient of variation
N.A = Not applicable

The free-end slip started early during the pull-out process for IG-V, IG-AM, IG-AC, and IG-W specimens, indicating that the adhesion factor is insignificant in this rod type. Subsequently, the rod moved as a rigid body (no increase in longiudinal strain with load) with continuous increase in pull-out load until reaching the maximum bond stress, indicated by the peaks of the bond stress vs. free-end slip curves. For IG-V specimens, this phase is controlled by both friction and interlock factors caused by the coarse sand particles and the spiral indentations on the rod surface. For IG-AM specimens, the whole thick coating surface, which includes the sand particles, is peeled off completely during conditioning in the AM environment. This environment also causes large matrix cracking. The bond mechanisms for the IG-AM specimen are mainly controlled by the mechanical interlock and to a lesser degree by friction. The friction results mainly from the large cracks (0.3-0.45 mm) induced by conditioning, while the mechanical interlock resulted from the spiral indentation of the rod. For IG-AC and IG-W specimens, the main controlling bond mechanisms are mechanical interlock and to a lesser degree friction. The friction is generated mainly from the induced small cracks and partially detached sand particles that resulted from the conditioning. The width of the cracks for these specimens is around 45 μm. The effects of AC and W environments on the IG rods are very comparable. The results show that the AM environment had the most dramatic effect on the IG rods. Pre-conditioning removed the coating surfaces and induced large matrix cracking, causing higher pull-out loads for these specimens compared to the IG-AC and the IG-W specimens. On the other hand, the AC and W environments caused the coating to weaken. This coating acts as a lubricant between the rod and concrete during the pull-out process. That is why the IG-AC and IG-W specimens produced weaker bond strength than

IG-AM, although they were less deteriorated. Al-Dulaijan (1996); Al-Zahrani (1995); Al-Zahrani et al.(1996); Nanni (1995).

CONCLUSIONS

- Bond strength between concrete and pre-conditioned CP and IG rods degrade to varying degrees, depending on the type of environmental exposure.
- An alkaline environment at high temperature represented by the AM environment is the most aggressive environment on both CP and IG rods.
- Bond strength for pre-conditioned CP and IG rods depend mostly on mechanical interlock and to a lesser degree on friction between these rods and concrete.
- Pre-conditioning of CP and IG rods in alkaline environments at high temperatures causes large cracking and swelling of the CP rods, and large cracking and complete peeling off of the thick coating on the IG rods. This induced degradation on the surfaces of these rods may alter the bond behavior and give a misleading picture of the bond behavior, especially for IG rods.

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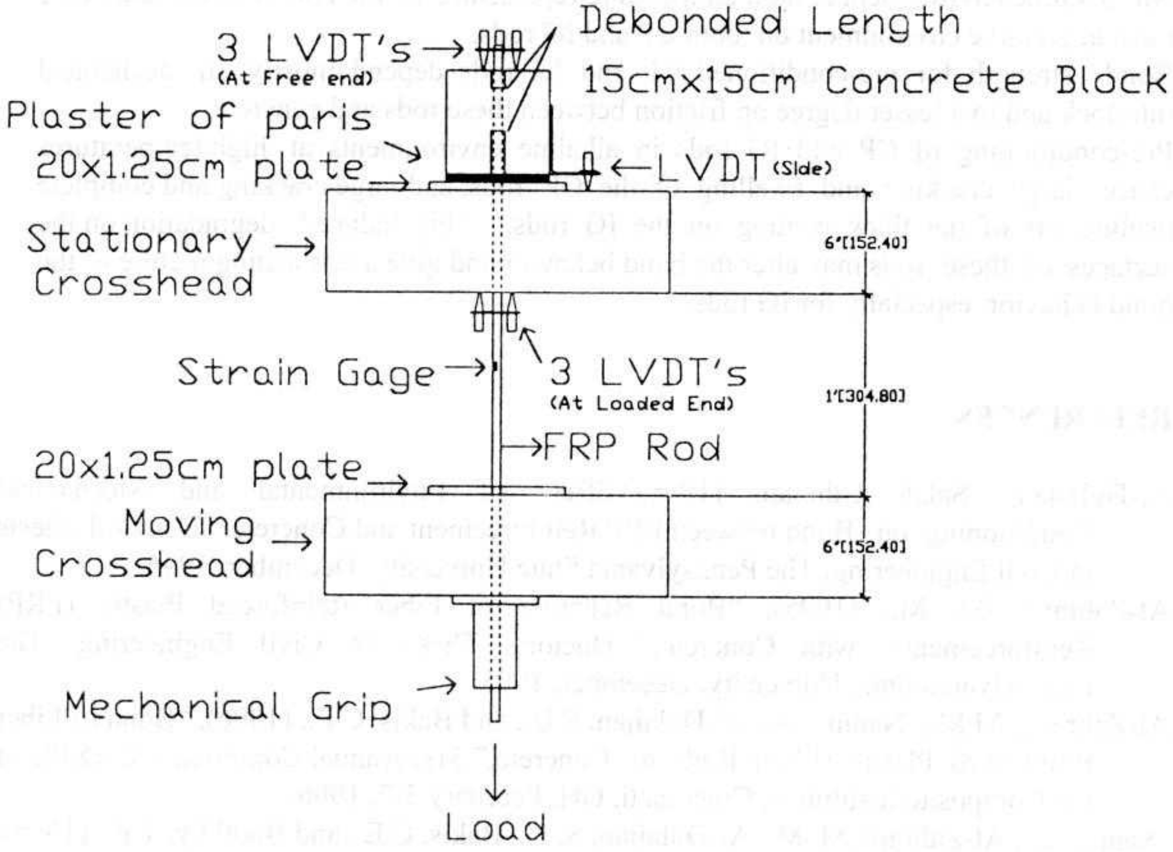

Fig. 1. Schematic diagram for direct pull out test setup

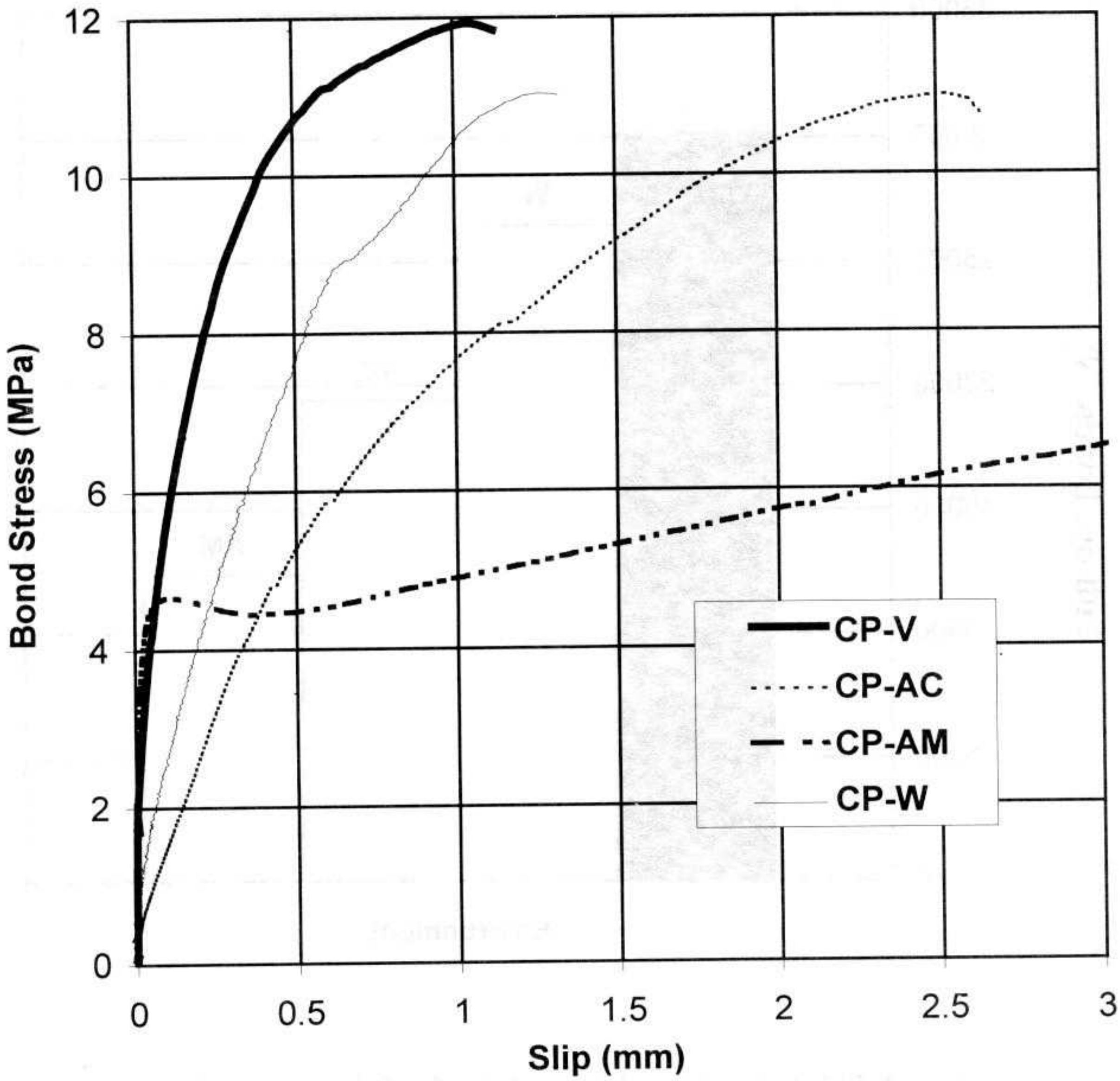

Fig. 2. Bond stress vs. free-end slip for CP-V, CP-AM, CP-AC, and CP-W specimens

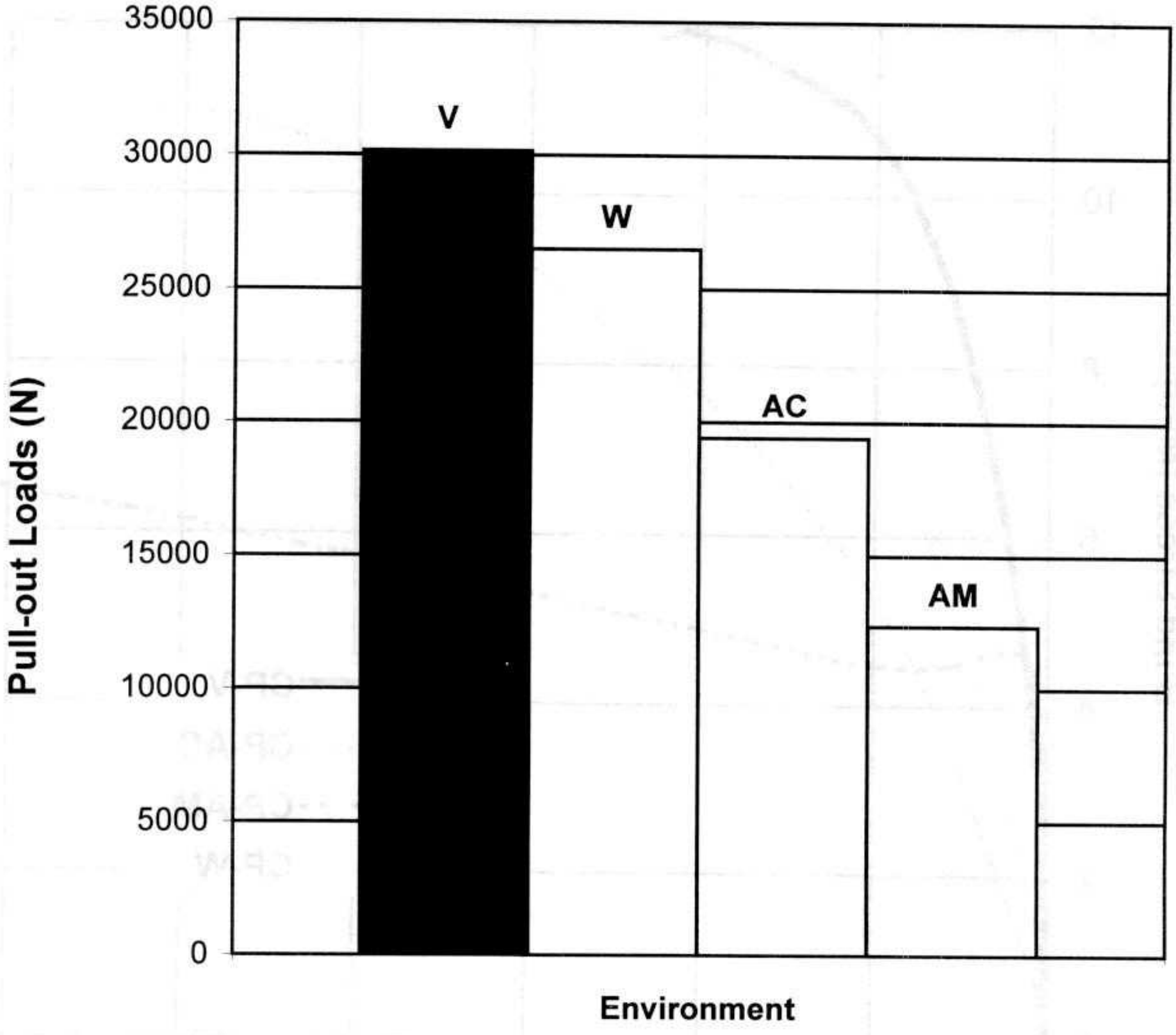

Fig. 3. Pull-out at 1 mm free-end slip for CP rods at different environments

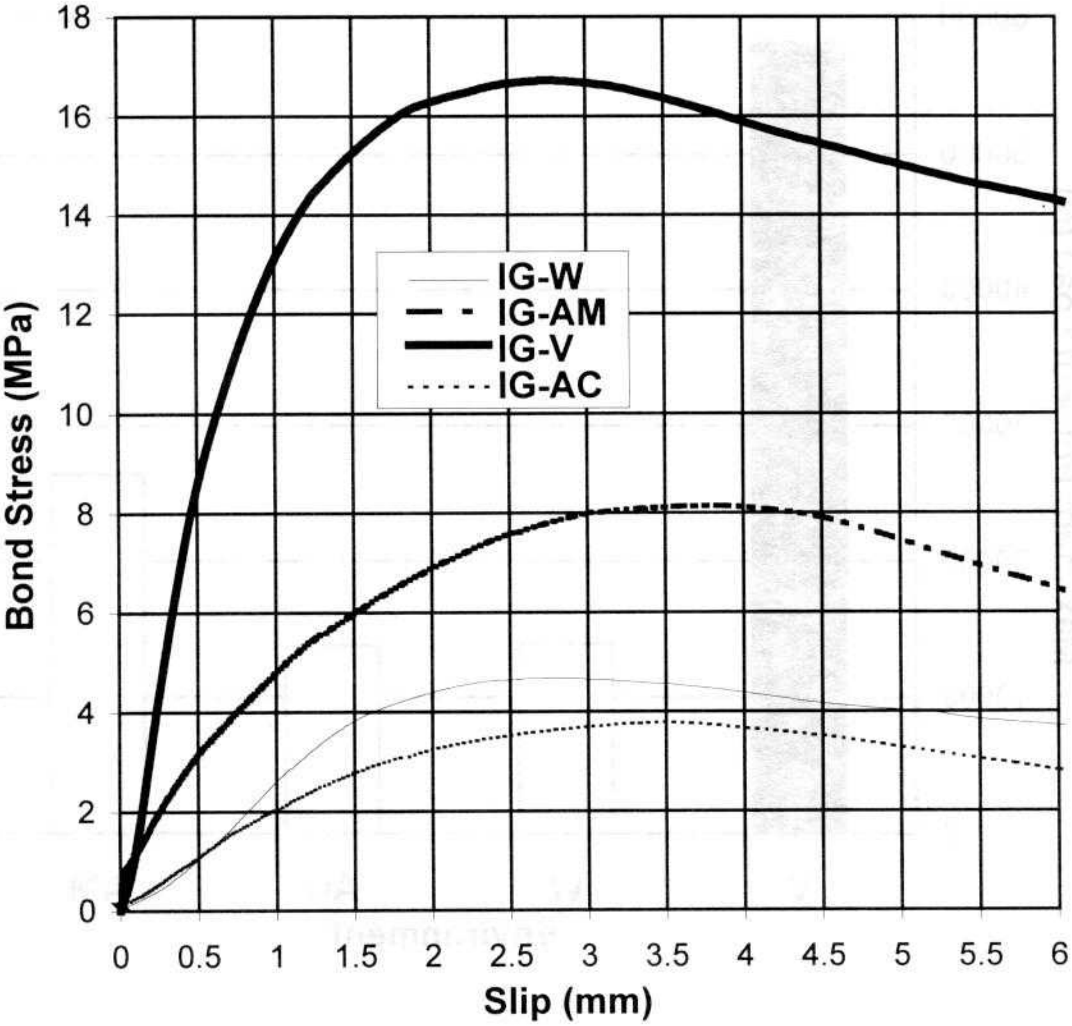

Fig.4. Bond stress vs. free-end slip for IG-V, IG-AM, IG-AC, and IG-W specimens

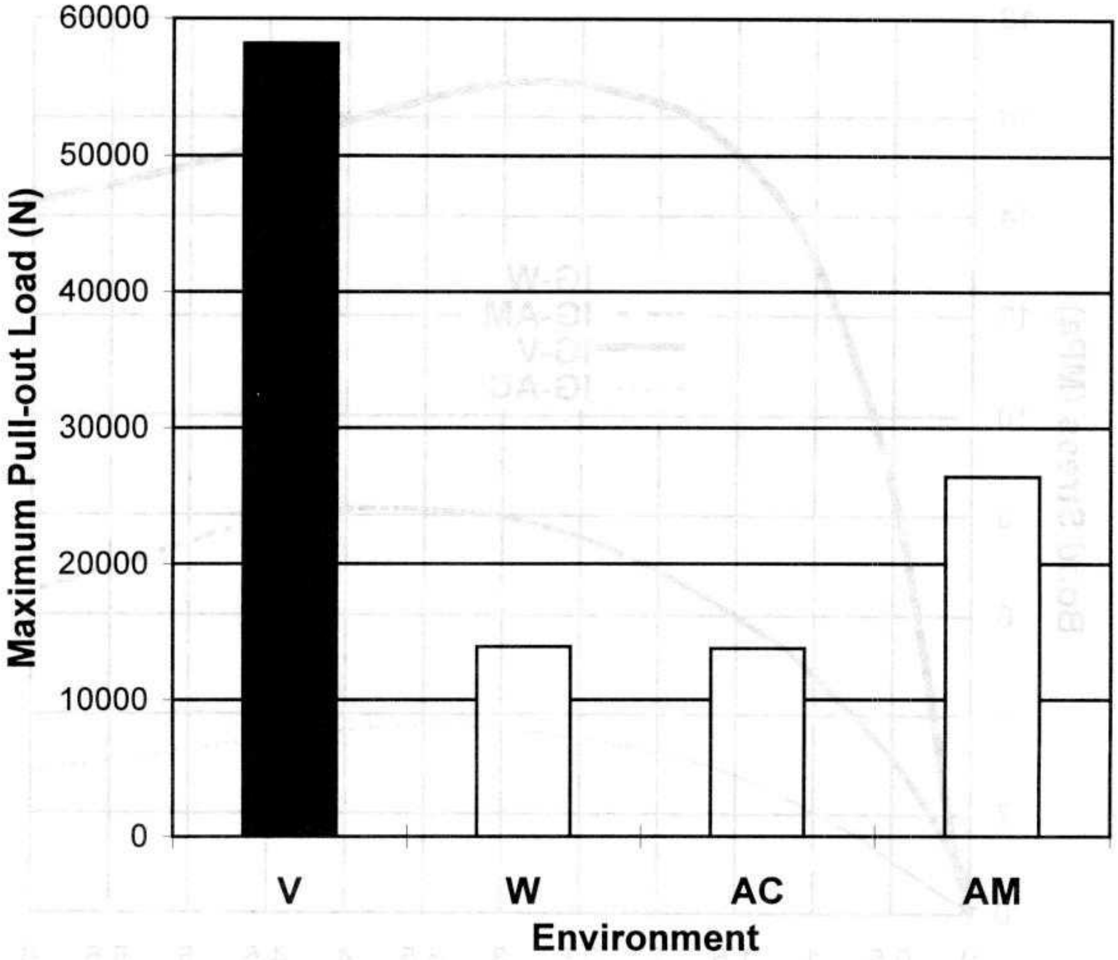

Fig.5. Maximum pull-out load for IG rods after exposure to different environments