Durability Characteristics of GFRP rebar in Concrete

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Abstract: ***Corrosion of internal reinforcing steel is one of the major causes of failure of concrete structures. Composite rebar, glass fiber reinforced polymer (GFRP) reinforcement bar is the solution to corrosion of reinforced concrete structures. The main aim of this study is to present the performance and durability characteristics of GFRP rebar in concrete environment. GFRP rebar consists of composites of resin and glass fibers in which the resin protects the bonding of fibers from disintegration. Fibre reinforced polymer rebar has greater advantage in corrosion resistance than conventional steel rebar***.

Keywords: GFRP, Corrosion, Compressive behaviour, Ductility

1. INTRODUCTION

Reinforced concrete is a composite material in which concrete's relatively low tensile strength and ductility are counteracted by the inclusion of reinforcement having higher tensile strength. For a strong, ductile and durable construction reinforcement needs to have the following properties at least

- high relative strength,
- high toleration of tensile strain,
- good bond to concrete, irrespective of pH, moisture and similar forces
- Thermal compatibility, not causing unacceptable stresses in responce to changing temperatures
- Durability in the concrete environment, irrespective of corrosion or sustained stress.

High strength concrete is used for construction of heavy structures like bridges, tall structures and constructions near marine environments. High strength concrete can be obtained by reducing water cement ratio, using super plasticizers etc. Corrosion of reinforcing steel in concrete causes major drawback in the durability of structure constructed in harsh environmental areas.

Three physical characteristics of reinforced concrete:

i. The coefficient of thermal expansion of concrete is similar to that of steel, eliminating large internal stresses due to differences in thermal expansion or contraction.
ii. When the cement paste within the concrete hardens, this confirms to the surface details of the steel, permitting any stresses to be transmitted efficiently between the different materials. Usually steel bars are roughened or corrugated to further improve the bond cohesion between the concrete and steel.
iii. The alkaline chemical environment provided by the alkali reserve (KOH, NaOH) and the portlandite (calcium hydroxide) contained in the hardened cement paste causes a passivating film to form on the surface of steel making it much more resistant to corrosion than it would be in neutral or acidic conditions.

When the cement paste is exposed to the air and meteoric water reacts with the atmospheric CO_2, portlandite and the calcium silicate hydrate (CSH) of the hardened cement paste become progressively carbonated and the high pH gradually decreases from 13.5 – 12.5 to 8.5, the pH of water in equilibrium with calcium carbonate and the steel is no longer passivated.

Carbonation of concrete along with chloride ingress is amongst the chief reasons for the failure of reinforcement bars in concrete.

Low water to cement ratios and the use of silica fume make concrete mixes significantly less workable, which is particularly likely to be a problem in high strength concrete applications where dense rebar cages are likely to be used. To compensate for the reduced workability, superplasticizers are commonly added to high strength mixtures.

In wet and cold climates, reinforced concrete for roads, bridges, parking structures and other structures that may be exposed to deicing salt may be benefit from use of corrosion corrosion-resistant reinforcement such as uncoated, low carbon/chromium, epoxy coated, hot-dip galvanised, stainless steel rebar or FRP bars.

Reinforced concrete can fail due to inadequate strength, leading to mechanical failure or due to a reduction in its durability. Corrosion and Freeze-Thaw cycles may damage poorly designed or constructed concrete. When rebar corrodes, the oxidation products (rust) expand and tend to flake, cracking the concrete and unbonding the rebar from the concrete.

Typical mechanisms leading to durability problems are

1. Mechanical failure
2. Carbonation
3. Chlorides
4. Alkali silica reaction

5. Conversion of high alumina cement
6. Sulphates

a. FRP rebar

FRP rebar is a structural reinforcing bar made from filaments or fibers held in a polymeric resin matrix binder. Fiber reinforced polymer (FRP) is increasingly used for reinforcing new structures, and strengthening existing structures. FRP composites, in the form of sheets, cables, rods, and plates, have proven to be a cost effective alternative to steel reinforcements because of their low weight to strength ratio, corrosion resistance, and flexibility.

Glass fiber is the most popular, However basalt, carbon, aramid and other fibers are also used in FRP bars. The matrix is a thermoset compound and is usually epoxy or vinyl ester; also other polymer matrices are used.

Glass fiber reinforced polymer (GFRP) has major advantages in corrosion induced concrete compared with steel rebars. FRP rebar does not behave in the same manner as steel rebar because the mechanical and durability properties are different in some cases. FRP rebar has higher strength but lower modulus of elasticity, therefore direct replacement of steel is not always possible with FRP rebar in some cases and FRP design codes required. Fiber reinforced polymers, are proved as a successful and alternative reinforcing, will give structures a longer service life. GFRP bars have relatively higher tensile strength but lower stiffness, so that deflections are likely to be higher than for equivalent steel-reinforced units.

1.2 Advantages of GFRP rebar

- light weight
- non-corrosive
- milder stiffness (allows structures to be less rigid)
- thermal & electrical isolated
- requires low maintenance

Hence, GFRP rebar may reduce the cost of the project up to 5% and does not require any major maintenance than using steel rebar.

2. REVIEW OF LITERATURE

The GFRP reinforced columns has more load carrying capacity of up to 10% to 20% than the steel reinforced concrete column [Kalaiarasi et al., 2017].

The specimens immersing in a concentration of 10% sulfate solution no ettringite crystal seen in the pores after one month of immersion, for 3 months of immersion little amount of ettringite crystals seen in the pores and increasing the immersion time up to 8 months little destroying effect on the concrete is accompanied by small fracture and convex protrusion. After 8-month immersion massive ettringite crystals and gypsum crystals was noted in the pores. The results indicated that the sulfate solution is decreasing the durability of the concrete. The damage degree of the concrete is increasing with the immersion time since the depth of penetration of the corrosive salt solutions increasing with the immersing time increased respectively. The test results of corrosion of concrete immersed into 10% and 20% of sulfate solution has a standard deviation of 0.028 and 0.067 respectively [Feng Ming et al., 2016].

Diffusion coefficient by the influence of temperature from the test results the non steady-state diffusion coefficient decreases when the temperature decreases from 20ºC to 5ºC. Diffusion coefficient by the influence of sulfate content of 27.5 g/l Na_2SO_4 added to a 165 g/l NaCl solution has no influence on the chloride penetration depth. So a sulfate content of 55 g/l Na_2SO_4 influences the chloride penetration depth certainly [Mathias Maes et al., 2012].

By physical condition assessment test the surface disintegration varies with respect to water cement ratio mixture in which 0.4 w/c has less to 0/7 w/c mix has high. The degree of cracking increased with an increase in the water to cement ratio. The 0.4 w/c mix did not show any sign of crack whereas the 0.55 w/c mix design exhibited consistent circumferential cracking pattern close to the edge of the cylinder [Julie Ann Hartell et al., 2011].

The GFRP bars were embedded in concrete and exposed to tap water at 28, 40 and 50°C to accelerate the durability performance of the specimen. After 8 months immersion, the loss resistance is equal to 16%, 10% and 9% at 50ºC, 40ºC and 23ºC respectively [Mathieu Robert et al., 2009].

The study suggests that the increase in thickness of small specimen, i.e., with large surface area to volume ratios, may be more consistent measure than the weight loss of large specimen when comparing the effects of different sulfuric acid concentration on concrete. Both the increase in volume and the decrease in density of the concrete due to the sulfuric acid-cement paste reaction would be larger the higher the acidity (the lower the pH) of the acid solution. This implies that a stronger acid solution could produce a smaller weight loss in a concrete specimen than that produced by a weaker solution due to a significant increase in the volume of the concrete in comparison to the reduction in the density. The degree of concrete deterioration is increased by alternate wet-dry cycle of exposure to sulfuric acid. The degree of concrete deterioration and depth of penetration of sulfuric acid varies with the variation in sulfur concentration [Emmanuel et al., 1988].

The GFRP longitudinal bars provide larger deflection capacity compared to steel longitudinal bars also they provide a self-centering effect once the load is removed. Due to the low modulus of elasticity of GFRP spirals and high strength of the concrete, the GFRP spirals were ineffective in contributing to the overall axial strength and stiffness of the column. Steel longitudinal bar provides higher axial compressive load capacity and ductility compared to GFRP longitudinal bars due to their higher modulus of elasticity and yielding properties [Thomas A. Hales., 2016].

The test shows that the young's modulus in compression is approximately equal to young's modulus in tension. For non-slender rebars (15mm diameter and length less than 110mm) the ultimate compression strength is equal to approximately 50% of the ultimate tensile strength [D.H.Deitz et al., 2003].

The GFRP bars having voids, holes or other imperfections shows less durability when compared to other GFRP bars which does not have imperfections. The moisture uptake in water is slower than in NaOH and the absorption rate increases with temperature. The rebar made of 100% vinyl ester resin exhibited the highest resistance to stress corrosion in alkali. The tensile strength of all rebars slightly decreased after aging in simulated pre-water solution under a stress level of 30% for 90 days at 22˚C [Brahim Benmokrane et al., 2002].

Concrete contains calcium, sodium and potassium hydroxides creating pore water solutions of pH 13. This causes an oxide layer to form the steel surface, preventing movement of oxygen and inhibiting corrosion, which occurs after the decay of this oxide layer, either by pH-reducing carbonation or by chloride attack. The immersed E glass/vinyl ester rods in ammonium hydroxide (NH_4OH) solution (30%) at 23ºC (224 days) showed 12% tensile strength loss. The tensile strength of GFRP bar decreased by 30% in 4 months under immersed in alkali solution of 20ml/lit NaOH at 23ºC for 28 days of curing. GFRP bars exposed to chloride attack in concrete shows disintegration up to 50% loss of strength and stiffness pre-stress relaxation of up to 30% and moment loss up to 20% [Peter Waldron et al., 2015].

The tensile tests showed an elastic behavior until brittle failure occurred and the GFRP rods of thermoplastic matrix showed a tensile strength of 924MPa with a modulus of elasticity 42.6 GPa. These rods did not show a decrease in mechanical properties and the environmental cycles did not reduce the tensile strength of the bars. Tensile strength of GFRP bar with vinyl ester resin had retention properties of 100% after immersion in simulated concrete pore solution and bars with polyester resin had reduction of 30% of tensile strength after immersion in alkaline solution [Francesco Micelli 2004].

The test was carried by detention of potential penetration of alkalis into GFRP samples in a process of X-ray mapping for the elements of interest is conducted over a backscattered electron image (BEI). In this test the fiber-matrix debonding took place in some samples, the glass fibers and polymer matrix remained essentially intact and no penetration of alkalis into the bars were observed. GFRP rebars exposed to highly alkaline solutions will be interacting with all water molecules and any ions produced by dissolving metal hydroxides in water. The result showed that no alkalis penetrated into rebars for all pH values (12.5 to 13.8) and temperatures of up to 75ºC. The debonding at the fiber-matrix interface, observed at 75ºC, is very likely a result of hydrolysis of the fiber sizing by water at that high temperature [A.S.M.Kamal et al., 2011]

The specimens exposed to Na_2SO_4 solution, in a corrosion-resistant bucket, (19% of the compressive strength of uncorroded concrete) has the decrease of compressive strength is bigger than those exposed to NaCl solution (7% of the compressive strength of uncorroded concrete). Stress strain curve of concrete corroded by hydrochloric acid solutions with pH value of 2 and 3 were determined. The acid solution of pH=2 takes more significant effect on the stress strain curve of corroded concrete than the acid solution of pH=3. The compressive strength and elastic modulus of the specimens will decrease with exposure days linearly, while the maximum strain will increase with exposure days exponentially [Y.F.Fan et al., 2006].

The specimens were immersed in water tank containing 3.5% NaCl solution. Brittle failures were observed in corroded RC columns, in particular in specimens subjected to high axial loads. In this, the circular reinforced concrete column with the rebar corrosion loss ratio of 10-20% appears to have worst seismic behavior, stiffness degradation and ductility. For specimens with corrosion loss ratio less than 14%, the energy dissipation increase with increasing ultimate displacement [Ying Ma et al., 2012].

The loading rate can significantly influence the ultimate tensile strength and elongation rate of large diameter GFRP bars, especially when the loading rate is lower than 6mm/min and the loading rate has limited effects on modulus of GFRP bar. The relationship between the stress and strain was linear. The elongation of the GFRP bar increased much more slowly at the loading rates ranging from 6 to 15mm/min. The result shows that, with the increasing of loading rate, the tensile strength and elongation ratio of GFRP bar increase considerably, while the elastic modulus remains constant [Guowei Li et al 2015].

The bond strength of GFRP bars to concrete decreased by 12% when the specimen is subjected to pore-water solution. The tensile strength of GFRP bar has a reduction of up to 36%in the pore-water solution of temperature 60ºC. The surface conditions of the FRP rebar provide higher mechanically interlocking, which leads to relatively higher hoop stress and hence results in splitting failure. The increasing concrete cover leads to higher confinement pressure on the GFRP bars, thereby reducing the possibility of developing more cracks in the concrete surrounding the bars and thus delaying the splitting failure [Fei Yan et al., 2016].

The bond stress distribution in the FRP is not uniform and the mean value of the stress is about 1.287 MPa. The peak value of the bond stress and the maximum load does not occur simultaneously under the same loading level and this may related to the plastic deformation of the epoxy [Jianzhuang Xiao et al., 2004].

In normal concrete, GFRP rebar was 19% lower in pull-out capacity than steel bar. When expansive concrete was used, GFRP rebar had pull-out capacity increased by 41% comparing the normal concrete.The maximum bond stress of GFRP rebar in expansive concrete was higher by 15% when compared to steel bar [Chao Wu et al., 2016].

Investigation on concrete specimens reinforced with an FRP bar and subjected to thermal cycles with a maximum temperature value of 70˚C, the GFRP bar consists of a core of glass fibers with an outer layer of resin and sand. As a consequence of the thermal treatment there is a weakening of the matrix and thus it shears off. The specimens with an embedment length of 15 times the diameter of the rebar failed in the free length of the rebar before slip commenced. Better behavior of the specimens result with shorter embedment lengths and large concrete cover. The maximum reduction in the ultimate tensile load for the thermally treated specimen's consequent to bond degradation is 16%, caused due to the weakening of the matrix [Nestore Galati et al., 2006].

The bond strength between reinforcing bars and concrete is influenced by the bar's surface characteristics, elastic modulus, the surface of all the FRP bars were damaged when observed after pullout testing. The percentage reductions in bond strength between concrete and FRP bars reached as high as 81.5% after exposure to 325ºC when compared to steel bars [Rami J.A. Hamad 2017].

The effect of temperature ranging from 20ºC to 80ºC in dry environment on bond properties between GFRP bars and concrete, shows that a maximum of 14% reduction of the bond strength was observed for 80ºC temperature after 8 months and no significant reductions was observed for up to 60ºC temperature [Radhouane Masmoudi et al., 2011].

The headed-end bars having embedment length of heads were 75mm and 100mm for 12mm and 16mm bars respectively, showed enhanced bond stresses by about 168% and 105% compared to that of straight end bars.12mm dia bars of straight-end with clear concrete cover of 1.5 times of diameter of bar was enough to ensure pull-out failure when compared to 16mm dia straight-end bars of same cover [Sirajul Islam et al., 2015].

The failure mode of the pullout specimens having concrete cover of $3d_b$ changed from pullout of bars to concrete splitting when compared to freeze-thaw cycles.By increasing the concrete cover from $3d_b$ to $4.5d_b$, the bond strength reductions were reduced from 14%(17.3 MPa to 14.87 Mpa for $3d_b$) to 8% (18.86 MPa to17.34 Mpa for $4.5d_b$) under the coupled conditioning (FT + AS), and from 12% (17.3 Mpa to 15.31 Mpa for $3d_b$) to 3% (18.86 Mpa to 18.27 Mpa for $4.5d_b$) under the individual FT cycles [Fei Yan et al., 2016]

3. Conclusions

Based on the study of literature reviews the following conclusions were made as:

- The GFRP reinforced concrete column has more load carrying capacity up to 10% to 20% than steel reinforced concrete column.
- The tensile strength of GFRP bar decreased by 30% under immersed in alkali solution of 20ml/lit NaOH
- Resistance of concrete against chlorides is influenced by the temperature.
- The damage degree of concrete is proportionally increasing with the immersion time into the alkaline solution.
- Chemical corrosion leads to an increase of the porosity and a decrease of the matrix volume of concrete materials.
- Increasing the loading rate (6-15 mm/min) results increase in tensile strength and elongation ratio of GFRP bars while the elastic modulus remains constant.
- Resins play important role in protecting fiber and slowing the diffusion process.
- The alkali ions and moisture in the concrete penetrates or diffuse through the resin (through voids or cracks).
- FRP deteriorates much faster in alkali solution than in concrete, due to the relative mobility of OH^+ ions.
- The results shows that rebar made of 100% vinyl ester resin exhibited the highest resistance to stress corrosion in alkali.
- The reduction in pH of 12.6 in concrete pore water alkali improves the degradation of fiber and polymers.
- GFRP rods are sensitive to alkaline attack if resin does not provide adequate protection to glass fibers.
- Polyester resin does not provide proper protection to glass fibers, since its strongly damaged by alkali ion penetration.
- Vinyl ester polymer matrix effectively acts as semi-permeable membrane in GFRP composites, allowing water molecules and blocking harmful alkalis.
- The bond performance of GFRP rods were considerably increased when the surface of the rod is helically wrapped.
- Increasing concrete cover leads to higher confinement pressure on the GFRP bars and it reduces the possibility of developing more cracks in the surrounding of the bars and thus delaying the splitting failure.

- The GFRP rebar is subjected to confinement pressure from the expansive concrete results in improved bond behavior.
- The bond strength between reinforcing bars and concrete is influenced by the bar's surface characteristics and elastic modulus.
- The stiffness of GFRP bar decreases with increase of the temperature.
- Extensive degradation of bond strength up to 14% in the GFRP rods has been evidenced after exposure to alkaline solutions at high temperature of above 80ºC.
- Reduction in bond strength depends on thermal coefficients of thermal expansion.
- The bond strength was inversely proportional to the embedment length and bar diameter.
- The transfer of stresses between the concrete and the reinforcement is mainly dependent on the quality of the bond.
- The force transfer mechanism is always a serious issue of the structural design regardless of the type of reinforcement.
- GFRP rebar made with glass fibers and vinyl ester resin exhibits more corrosive resistance to alkaline environment
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- The bond strength of reinforcing bar and concrete is more for surface characteristics of GFRP bar is like conventional steel than any other surfaces.
- Research is needed to determine recommended design values of hoop strain in GFRP spiral reinforcement for both normal strength and high strength concrete columns (Thomas A. Hales et al. 2016).
- Compressive behaviour of GFRP reinforced concrete column was studied and need to study the durability characteristics of GFRP reinforced concrete columns.

References

[1] A.Katz, Bond Mechanisms of FRP rebars to Concrete, Journal of Materials and Structures, December-1999, Volume-32, pp: 761-768.

[2] A.S.M.Kamal and M.Boulfiza, "Durability of GFRP Rebars in Simulated Concrete Solutions under Accelerated Aging Conditions", Journal of Composites for Construction, August-2011, Volume-14, Issue-4, pp: 473-481.

[3] Brahim Benmokrane , Peng Wang, Tan Minh Ton-That, Habib Rahman and Jean-Francois Robert, "Durability of Glass Fiber-Reinforced Polymer Reinforcing Bars in Concrete Environment", Journal of Composites for Construction ,August-2002, Volume-6, Issue-3, pp:143-153.

[4] Chao Wu, "Improved Bond Behavior Between GFRP Rebar and Concrete using Calcium Sulfoaluminate", Journal of Construction and Building Materials, 2016, Volume-113, pp: 897-904.

[5] D.H.Deitz, I.E. Harik and H. Gesund, "Physical Properties of Glass Fiber Reinforced Polymer Rebars in Compression", Journal of Composites for Construction, November-2003, Volume-7, Issue-4, pp: 363-366.

[6] Emmanuel K. Attiogbe and Sami H. Rizkalla, "Response of Concrete to Sulfuric Acid Attack" ACI material Journal December-1988, Title no. 85-M46, pp: 481-488.

[7] Fei Yan, Zhibin Lin and Mijia Yang, "Bond Mechanism and Bond Strength of FRP bars to Concrete: A Review", Journal of Composites part B, April-2016, Volume-98, pp: 56-69.

[8] Feng Ming, You-sheng Deng and Dong-quing Li, "Mechanical and Durability Evaluation of Concrete with Sulfate Solution Corrosion" Advances in Materials Science and Engineering, Nov-2016.

[9] Francesco Micelli and Antonio Nanni, "Durability of FRP rods for concrete structures", Construction and Building Materials, April-2004, Volume-18, pp: 491-503.

[10] Guowei Li, Jiantao Wu and Wanming Ge, "Effect of Loading Rate and Chemical Corrosion on the Mechanical Properties of Large Diameter Glass/Basalt-Glass FRP bars", Journal of Construction and Building Material,May-2015.

[11] Jianzhuang Xiao, Jie Li and Quanfan Zha, "Experimental Study on Bond Behavior Between FRP and Concrete", Journal of Construction and Building Materials, April-2004, Volume-18, pp: 745-752.

[12] Julie Ann Hartell, Andrew J. Boyd, M.ASCE and Christopher C. Ferraro, "Sulfate attack on Concrete: Effect of Partial Immersion", Journal of Materials in Civil Engineering, Volume 23(5), May-2011, pp: 572-579.

[13] M.Priyashadevan, K.A.Kalaiarasi, "Experimental Investigation on Strength Behaviour between GFRP and Steel Bars Reinforced in Columns" International Journal of Science and Research, July-2017, Volume-6, Issue-7, pp: 872-875.

[14] Mathias Maes, Elke Gruyaert and Nele De Belie, "Resistance of Concrete against combined attack of chlorides and sulphates", International Congress on Durability of Concrete, ICDC-2012.

[15] Mathieu Robert, Partice Cousin and Brahim Bennmokrane, "Durability of GFRP Reinforcing bars embedded in moist Concrete" Journal of Composites for Construction, Volume 13(2), April -2009, pp: 66-73.

[16] Nestore Galati, "Thermal Effects on Bond Between FRP rebars and Concrete", Journal of Composites: Part A, May-2006, Volume-37, pp: 1223-1230.

[17] Peter Waldron, Dr.Ewan A. Byars and Valter Dejke, "Durability of FRP in Concrete – A State of the Art", Journal of Composites for Construction, pp: 91-101.
[18] Radhouane Masmoudi, Abdelmonem Masmoudi, Mongi Ben Quezdou and Atef Daoud, "Long-term Bond Performance of GFRP bars in Concrete under Temperature ranging from 20ºC to 80ºC", Journal of Construction and Building Materials,2011, Volume-25, pp:486-493.
[19] Rami J.A. Hamad, M.A.Megat Johari and Rami H. Haddad, "Mechanical Properties and Bond Characteristics of Different Fiber Reinforced Polymer Rebars at Elevated Temperatures", Journal of Construction and Building Materials, March-2017, Volume-142, pp:521-535.
[20] Thomas A. Hales, Chris P. Pantelides, and Lawrence D. Reaveley, "Experimental Evaluation of Slender High-Strength Concrete Columns with GFRP and Hybrid Reinforcement", Journal of Composites for Construction, May-2016,
[21] Y.F.Fan, Y.S.Chen, Z.Q.Hu, and X.Li, "Experimental Study on Compressive Strength of Corroded Concrete", 31st Conference on Our World in Concrete & Structures, August-2006, Singapore.
[22] Ying Ma, Yi Che and Jinxin Gong, "Behavior of Corrosion Damaged Circular Reinforced Concrete Columns under Cyclic Loading", Journal of Construction and Building Materials, 2012, Volume29, pp: 548-556.