

CONCRETE

VOLUME 40 ISSUE 2 JUNE 2014

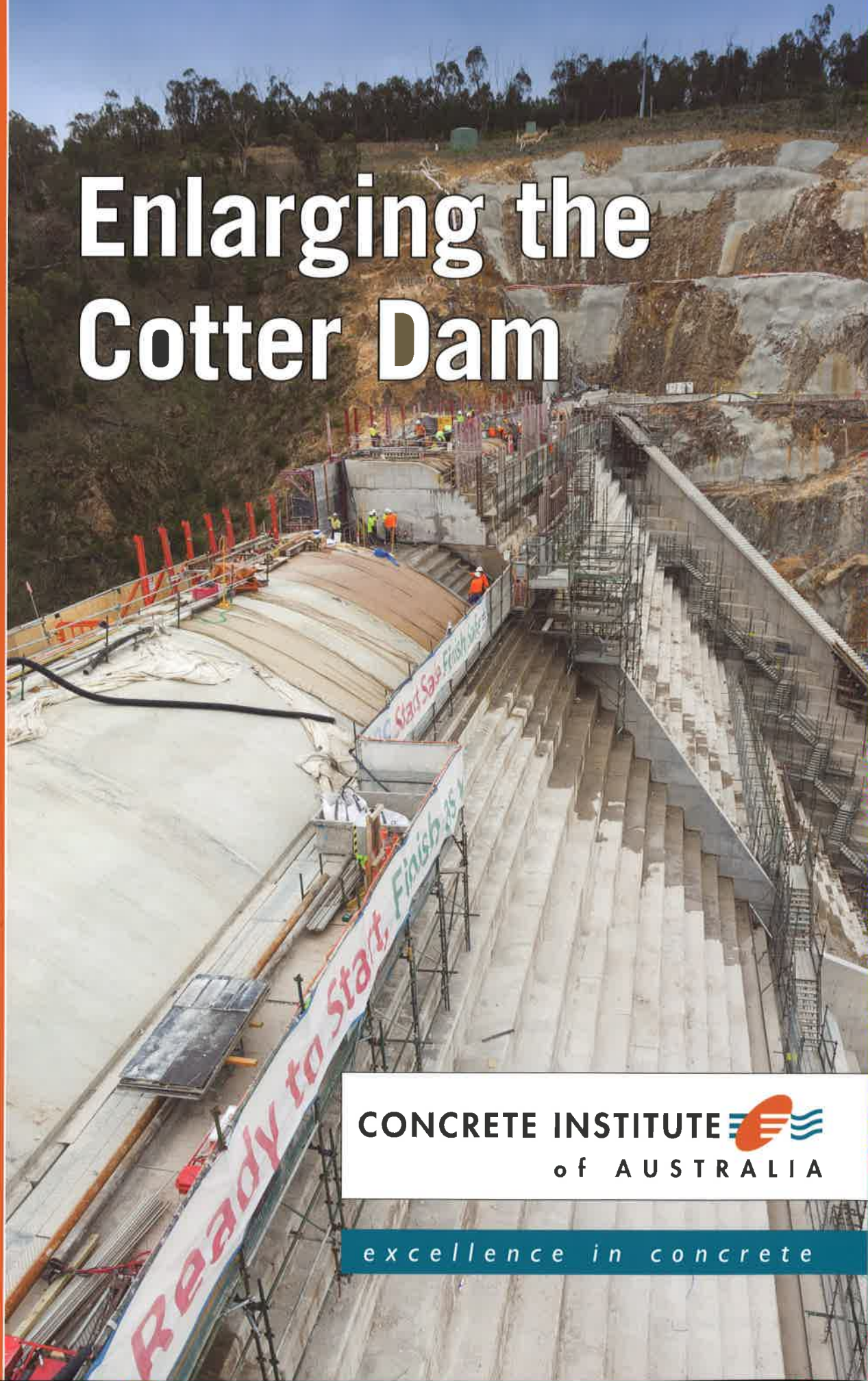
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Recent developments on FRP bars as internal reinforcement in concrete structures

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During the last two decades, fibre reinforced polymer (FRP) reinforcing bars have been extensively investigated and a number of FRP bars are now commercially available. However, the use of FRP bars as internal reinforcement in concrete structures is still unfamiliar to many practising Australian engineers. This paper provides an overview on the current research and developments on FRP bars to ensure that Australia is properly informed in the engineering research for this advanced material allowing its responsible introduction and wide use in civil infrastructure. Firstly, research and developments on the application of FRP bars as internal reinforcement in concrete beams, columns and slabs are presented. Secondly, the results of the on-going efforts on the evaluation of the potential use of FRP bars in geopolymer concrete structures are discussed. Thirdly, the concept of material hybridisation to develop a viable hybrid FRP bar for concrete structures was presented. Finally, some field applications of the GFRP bars to a number of civil infrastructures in Australia were highlighted.

1.0 INTRODUCTION

Fibre reinforced polymer (FRP) composite has gained considerable worldwide interest and growing acceptance in the construction industry as internal reinforcement in concrete structures. This composite material which typically consists of strong fibres embedded within a light polymer matrix has become an attractive construction material because of its light weight, high tensile strength, non-corrosive, and nonmagnetic properties (Gangarao et al, 2007). The use of FRP bar is particularly attractive for structures that operate in highly aggressive environments near coastlines and in mining infrastructures where corrosion of steel

reinforcing bar is a major problem. The corrosion of steel bars is a material problem as shown in Figure 1. As methods to try and overcome this problem, steel has been coated with galvanising and epoxy to try to extend the inevitable issue of corrosion or replaced with noncorrosive materials. Currently, many researchers are actively investigating FRP as reinforcement in concrete to enhance the durability and prolong life time over the serviceability of civil engineering structures. Research related to this advanced construction material has been carried out extensively in the US, Canada, Europe, and Japan (Bakis et al, 2002). Although the initial costs of using FRP composites are higher as compared to that of steel, they will even up in the long run since the costly



Figure 1: Corrosion problems of concrete structures.



Figure 2: The V-Rod GFRP bars.

repair and maintenance due to steel corrosion (Achillides & Pilakoutas, 2004) will be avoided. However, the use of FRP bars as reinforcement in concrete structures is still unfamiliar to many practising Australian engineers even though there are full material and design codes in Canada (2008) and America which they can follow to design with FRP, and the BCA allows this under the alternative provision. Garnaut⁴ indicated that builders may avoid adopting products based on new technology if they cannot assess their reliability and use more familiar, older and less efficient products. In order to encourage its development and use, a better understanding on the behaviour of concrete structures reinforced with FRP bars should be gained to ensure confidence in the design and utilisation of this new technology as adopted widely in North America for many years. For example, Pultrall the manufacturer of V-Rod, has built more than 350 major highway bridge decks using V-Rod, along with water retaining structures, underground suspended car park slabs and electrical applications, as FRP is nonferrous and will not conduct electricity. The impressive list goes on.

This paper provides an overview on the current research, development and application of FRP bars as internal reinforcement in concrete structures to ensure that Australia is properly informed in the engineering research for this advanced material allowing its responsible introduction and wider use. Furthermore, information on international codes and standards on FRP bars are briefly discussed for Australian engineers to familiarise themselves with designing and effectively utilising this material in civil infrastructure.

2.0 GFRP BARS AS INTERNAL REINFORCEMENT TO CONCRETE STRUCTURES

The extensive research and development efforts at the University of Sherbrooke in Canada have contributed to the increasing application of the FRP bars as internal reinforcement in concrete structures. The University of Sherbrooke is one of the key member universities of the Intelligent Sensing for Innovative Structures (ISIS Canada), which is a collaborative and research process established to accelerate the transfer of the technology from the laboratory to the marketplace. This section presents some of the current research and development activities at the University of Sherbrooke on the behaviour of concrete structures reinforced with GFRP bars.

2.1 GFRP bars and properties

V-Rod, produced by Pultrall in Canada, is one of the most commonly used commercially available FRP reinforcing bars. This reinforcement bar (Figure 2) is made up of fibres which provides the mechanical strength as well as resin which acts as the matrix and increases the chemical resistance of the product. The glass fibre reinforced polymer (GFRP) bars were manufactured by a pultrusion process of continuous longitudinal E-glass fibres impregnated in modified vinyl ester resin. The surface of the bar was coated with Grade 24 silica sand to promote the bonding between the concrete and the reinforcement. The fibre content of these FRP bars is almost 85% by weight and its mechanical properties as reported by the manufacturer are presented in Table 1. As previously mentioned, hundreds of major projects have been completed internationally as well as in Australia with this material, some of which are presented in the latter part of this paper.

2.2 FRP rebar as reinforcement in beams

GFRP bars are a competitive option as reinforcement in concrete beams. Benmokrane et al (1995) conducted an experimental and theoretical comparison between flexural behaviour of concrete beams reinforced with FRP reinforcing bars and deformed steel bars. Comparisons were made in relation to cracking behaviour, load-carrying capacities and modes of failure, load-deflection response, flexural rigidity, and strain distribution. The results revealed that a perfect bond exists between FRP reinforcing bars and the surrounding concrete. The crack pattern and spacing in concrete beams with FRP bars were similar to those of steel reinforced concrete beams at low load. However, there were more and wider cracks at the service load. Moreover, the results of the beam tests indicated that the ultimate strength of GFRP

Table 1: Guaranteed properties of V-Rod GFRP bars.

Bar diameter	Nominal cross-sectional area (mm ²)	Guaranteed tensile strength (MPa)	Modulus of Elasticity (GPa)	Ultimate elongation (%)
12.7 mm	129	1312	65.6 ± 2.5	2.00
15.9 mm	199	1184	62.6 ± 2.5	1.89
19.0 mm	284	1105	63.7 ± 2.5	1.71

reinforced beams is greater than that of the steel reinforced specimens but exhibited a higher deflection. More recently, El-Nemr et al (2013) investigated the flexural behaviour and serviceability of normal and high-strength concrete beams reinforced with FRP bars. They found that the crack widths were affected by the bar diameter and surface configuration while the deflections were not significantly affected. Their results further indicated that the use of high strength concrete helped enhance deflection, crack width and ultimate load capacity of the GFRP reinforced concrete beam.

Ahmed et al.⁷ evaluated the shear behaviour of concrete beams with FRP fitments. The results of the experiment showed that the behaviour of concrete beams with FRP fitments is similar to the beams with steel fitments. It enhances the concrete contribution after the formation of the first shear crack. As expected, the lesser spacing of the fitments resulted in a higher shear resistance due to the confinement, which controls the shear cracks and improves the aggregate interlocking. Due to their superior characteristics and non-corrodible nature, the use of FRP bars as near surface mounted (NSM) for flexural strengthening of beams was investigated by Soliman et al (2010). Their results indicated that the flexural stiffness and capacity of the strengthened specimens was significantly increased compared to the strengthened beams due to the NSM-FRP bar constraining the opening of the cracks thereby increasing the moment of inertia of the cracked section. These results suggest that FRP bars can be as effective as steel bars for reinforcement in concrete beam structures and should be considered in their design.

2.3 FRP rebar as reinforcement to columns

There are still few experimental and developmental activities conducted on the behaviour of GFRP bars as longitudinal reinforcement for concrete structures under compression. De Luca et al (2010) and Tobbi et al (2012) assessed the compression behaviour of square columns while Afifi et al (n.d.) and Mohamed et al (n.d.) evaluated the capacity of circular concrete columns reinforced with GFRP bars. All these studies concluded that the GFRP reinforced concrete columns exhibited almost the same strength as their steel reinforced counterparts. De Luca et al (2010) concluded that the contribution of GFRP bars to the column capacity is lower than the steel bars, thus can be ignored in evaluating the capacity of the column. However, the GFRP bars strongly influence the failure mode by delaying the buckling of the longitudinal bars, initiation and propagation of unstable cracks, and crushing of the concrete core. On the contrary, Tobbi et al (2012) Afifi et al (n.d.) and Mohamed et al (n.d.) found that the contribution of the GFRP bars is close enough to the steel contribution, indicating the applicability of using them in compression members. They further commented that the GFRP transverse reinforcement can increase the strength, toughness and ductility of the column due to the effective confinement of the concrete core. The failure of the well confined FRP reinforced concrete columns was attributed to the crushing of the concrete core and rupture of the FRP ties/spirals.

2.4 FRP rebar as reinforcement to slab

Bouguerra et al (2011) conducted an experimental study to investigate the behaviour of FRP-reinforced concrete bridge deck slabs under concentrated loads. In their investigation, they considered the effect of the slab thickness, concrete compressive strength, bottom transverse reinforcement ratio, and the type of reinforcement. They constructed eight full scale deck slabs which were supported on two parallel steel girders and tested up to failure. The results of their investigation showed that all deck slabs failed in punching shear. They also found that the bottom transverse reinforcement ratio was the main parameter that affects the crack width. Slabs with lower amount of bottom reinforcement have wider crack widths than those with higher amount of FRP bars. As expected, the thin slab as well as low compressive strength concrete has lower punching capacity than the thick slab and high compressive strength while the type of reinforcement (with similar axial stiffness) has no significant effect on the overall behaviour of the slab. Similarly, Hassan et al (n.d.) found that by increasing the reinforcement ratio and using high strength concrete will result in higher punching shear capacity and reduce the deflection of two-way concrete slabs reinforced with GFRP bars. Both studies indicated that the effective reinforcement ratio should account for the difference between the modulus of elasticity of the GFRP and steel bars. Nevertheless, these studies indicated that FRP bar is a better reinforcing material than steel in concrete structures exposed to harsh environments.

2.5 Durability of FRP bars in concrete

ISIS Canada had undertaken a study in 2004 on the durability of GFRP bars in concrete using cores taken from built structures in Canada that have been in service for five to eight years. The five field structures chosen have been subjected to a wide range of environmental conditions. Based on the results of their study, there was no degradation of the GFRP in the concrete structures exposed to natural environmental conditions for up to eight years. There is still a good bond between the GFRP and concrete, indicating that the wet-dry cycles, freeze-thaw cycles and de-icing salt had no adverse effect on the GFRP. Up to now, these structures are performing very well with very minimal maintenance, indicating the long service life of concrete structures reinforced with FRP bars. This provided them with the confidence to permit the use of GFRP as primary reinforcement in concrete structures.

3.0 GFRP BARS AS INTERNAL REINFORCEMENT TO GEOPOLYMER CONCRETE

In Australia, research in the use of FRP bars as internal reinforcement to geopolymer concrete structures is being conducted at the University of Southern Queensland (USQ). This research is motivated by the need to develop corrosion resistant, durable, environment-friendly, and highly sustainable infrastructures.

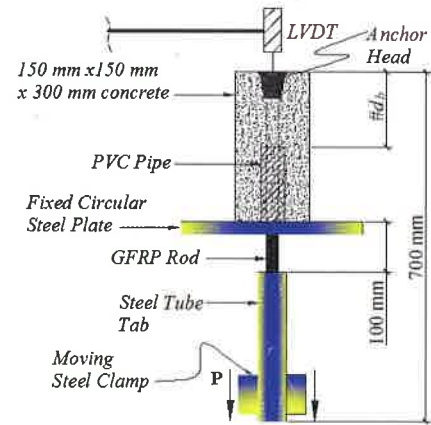
The use of geopolymer concrete is currently attracting increasingly widespread attention in Australia because



GFRP bars with and without anchor head.



Horizontally cast bond-slip specimens.



Direct pullout test (ACI 440.3R-04).

Figure 3. Preparation of specimen and test set up.

its manufacture does not directly create CO₂ emissions. Geopolymer concrete is considered as a “green cement” and several researchers found that geopolymer concrete has highly desirable properties which can lead to significant cost savings in many structural members (Lloyd & Rangan, 2010). While geopolymer concrete reinforced with steel bars has been used successfully in a number of field applications, most of the research is focusing only on geopolymer concrete mix design and durability. To encourage the use of FRP reinforced geopolymer concrete in the construction industry, a better understanding on its bond mechanism should be gained first because it is the critical factor that controls the structural performance of any concrete members reinforced with FRP bars. Up to this date, there is no research reported on the bond behaviour of FRP reinforcement to geopolymer concrete and on the effect of anchor heads on the bond resistance of FRP reinforcement.

The bond-slip behaviour of geopolymer concrete reinforced with silica sand-coated glass fibre reinforced polymer (GFRP) bars with and without mechanical anchor head under a direct pullout test is evaluated by Maranan et al (2014). Three embedment lengths of 5Ø, 10Ø, and 15Ø (where Ø is the nominal diameter of GFRP bar) were considered to assess the interface bond between the GFRP bars and the geopolymer concrete. The results were then compared to that of the pullout test of 16 mm diameter deformed steel bars embedded in geopolymer concrete.

3.1 Materials and methods

High modulus GFRP bars supplied by V-Rod Australia, having nominal diameters of 12.7 mm, 15.9 mm and 19 mm with and without mechanical anchor head, were investigated. For the purpose of comparison, 16 mm deformed steel bar with yield strength of 540 MPa was also embedded in a geopolymer concrete. Ready mix flyash based geopolymer concrete with an average compressive strength of 33 MPa was utilised to fabricate all the pull-out specimens.

The bond-slip specimens were prepared such that the bars

were positioned concentrically (before pouring) within the horizontally cast 150 mm x 150 mm x 300 mm geopolymer concrete prism as shown in Figure 3. To achieve the desired embedment lengths (5Ø, 10Ø, and 15Ø), PVC pipes were used to debond the bar from the concrete. The other end of the GFRP bar was sleeved with a steel tube to protect the bar from the gripping force of the machine’s clamps. The specimens were labelled as follows: type of specimen-bar diameter-embedment length. For example, the specimen GGA-15.9-5Ø corresponds to 15.9 mm nominal diameter GFRP bar with anchor head that is embedded five times the nominal bar diameter into the geopolymer concrete.

Figure 3 shows the GFRP bars with and without anchor head, the specimen preparation and the schematic diagram of the direct pullout test employed in this study. The test was conducted in accordance with ACI 440.3R-041 (2004). The specimens were positioned upside down while the bars were being pulled downward at a constant rate of 1.2 mm/min using an AVERY testing machine. A single Linear Variable Differential Transducer (LVDT) was placed at the unloaded end of the bar to measure the overall slip of the bar relative to the concrete. The support stand of the LVDT was placed separately from the specimen to make sure that the movements of the specimens during the loading stage or the failure of the specimens did not affect the measurements. The pullout load and end-slip were measured and recorded using a System5000 data logger.

3.2 Bond behaviour of GFRP bars into geopolymer concrete

3.2.1 Failure behaviour

The GG bond-slip specimens exhibited two types of failure: the bar pullout from geopolymer concrete and the splitting of geopolymer concrete (Figure 4). Generally, the specimens with shorter embedment (5Ø) failed due to bar pullout. This type of failure happens because the bonded length is not sufficient to induce radial splitting stress that can generate wider

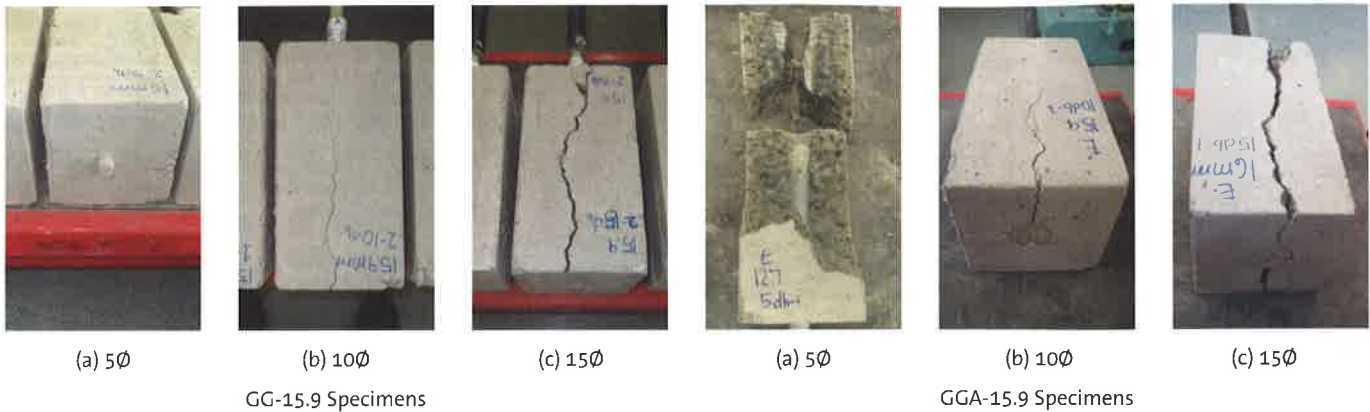


Figure 4: Typical failure mode of specimens.

longitudinal cracks in the geopolymer concrete. The concrete splitting, on the other hand, is exhibited by the specimens embedded 10Ø and 15Ø into the geopolymer concrete. These specimens have enough embedded lengths to develop splitting tensile stress within the geopolymer concrete. This stress leads to the widening of the longitudinal cracks that initiated in the interface of the geopolymer concrete and the GFRP bar and then propagating to the external surface of the concrete. The splitting of geopolymer concrete occurred in an explosive brittle manner. In the case of GGA specimens, all the specimens failed due to the splitting of geopolymer concrete as shown in Figure 4. The addition of anchor heads resulted in a more severe cracking and explosive concrete splitting failure. Finally, the SG specimens with embedment length of 5Ø failed due to bar pullout while those with 10Ø and 15Ø bonded length failed due to bar rupture.

3.2.2 Failure behaviour

A comparison between the bond strength of GFRP bars with and without anchored heads and the deformed steel bars is shown in Figure 5. It was observed that as the embedment length increases the pullout load capacity also increases. It can also be observed that there is a significant

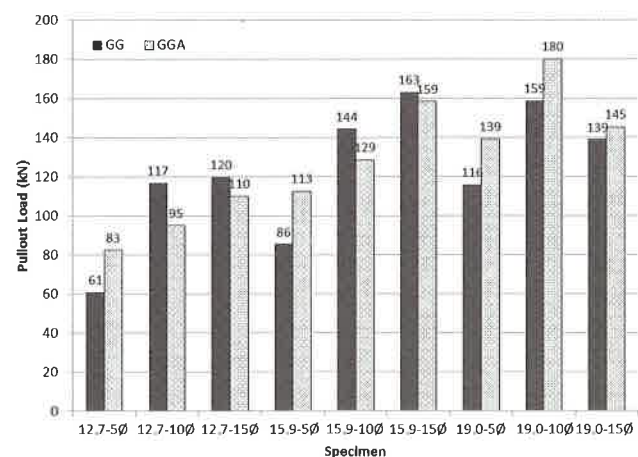


Figure 5: Influence of bar diameter and embedment length on the pullout capacity of bond-slip specimens.

increase in the pullout capacity of the GGA specimens with embedment length of 5Ø compared to the specimens without anchor heads. However, the bond strength of 12.7 mm and 15.9 mm diameter bars with end anchorage is lower than the ones without for specimens with embedment lengths of 10Ø and 15Ø. This is attributed to the splitting type of failure exhibited by these specimens which did not allow the development of the strength of the anchors and hence, of the GFRP bars. This resulted in a lower bond strength between the GFRP bars and the geopolymer concrete. A more promising result is obtained in GG-19.0 specimens. The pullout capacity of GG-19.0 specimens with embedment length of 10Ø and 15Ø increased by 13% and 4% respectively, with the provision of anchor heads. This is important, as larger diameter bars are more difficult to bend than smaller diameter bars to attain sufficient bond strength.

The results also showed that the sand-coated GFRP bars with and without anchor heads have bonding capacities comparable to that of the deformed steel bar as shown in Figure 6. It is also worth noting that the provision of anchor head significantly enhanced the pullout capacity of sand-coated GFRP bars embedded 5Ø into geopolymer concrete. The pullout capacity of GGA-15.9-5Ø specimen is 31% higher than that of the

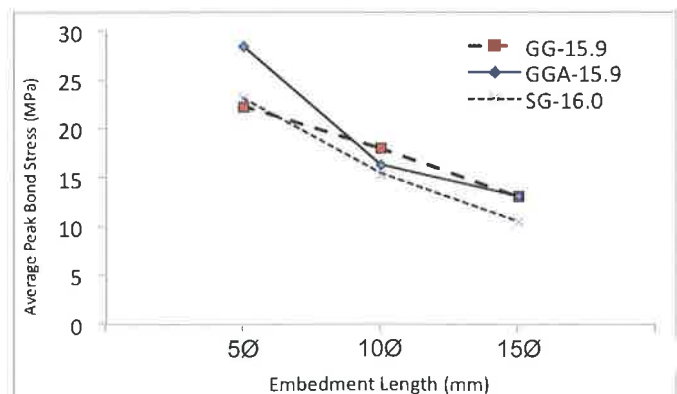


Figure 6: Comparison of bond strength between GFRP bars with and without anchor heads and steel bars.

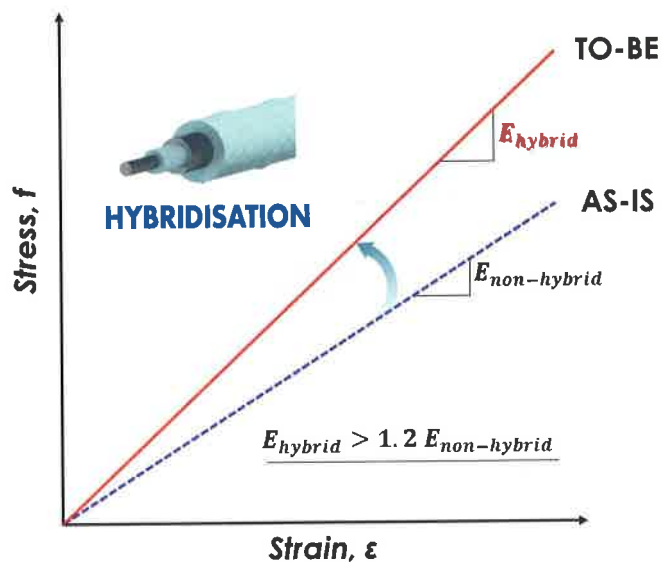


Figure 7: Improvement plan by hybridisation (As-Is: Conventional GFRP, To-Be: Hybrid GFRP).

GG-15.9-5Ø specimen. However, the addition of anchor heads in the specimens with bonded lengths of 10Ø and 15Ø resulted in lower pullout load (equivalent to 11% and 2% reduction, respectively) because these specimens have short bonded length of the sand-coated GFRP bars into the geopolymer concrete. Since the bonded length is short, the longitudinal cracks can abruptly propagate along the anchor heads thereby eliminating the mechanical bearing resistance provided by the anchors.

3.3 Research findings and future studies

The results of the current research on FRP bars as internal reinforcement in geopolymer concrete showed that the sand-coated GFRP bars have comparable bonding capacity to that of the deformed steel bars. As the embedment length increases, the pullout load capacity of the bond-slip specimen also increases. It was also found that the provision of anchor head significantly improved the anchorage of the sand-coated GFRP bars embedded 5Ø into the geopolymer concrete by as much as 36%. Moreover, the provision of an anchor head was found to significantly improve the pullout capacity of the 19.0 mm bars for all the embedment lengths considered. This is important, as larger diameter bars are more difficult to bend than smaller diameter bars to attain sufficient bond strength. Moreover, the results of the preliminary investigation demonstrated that GFRP bars are suitable reinforcement for geopolymer concrete. Further research in Australia is proving

and demonstrating that research and projects in Canada and Australia are well advanced to the extent that this technology has now full design codes and a history of its use in many major civil projects. Field studies and core samples have demonstrated that the FRP is performing better than the laboratory testing. Continued efforts are also planned towards the development of design guidelines and specifications for Australian engineers, for detailing and long term durability performance verification to increase the confidence in the use of the technology. Material developments and enhancements on FRP bars will also allow for its more economical exploitation in the construction of new concrete structures.

4.0 NEW DEVELOPMENTS IN FRP BARS

Hybrid FRP bars which can be used for newly built structures are currently under development through a national R&D program performed by the Korea Institute of Construction Technology or KICT (Park et al, 2013). The KICT focused on FRP reinforcement in terms of materials and manufacture process to make it a cost effective internal reinforcement for concrete structures.

4.1 Concept of hybrid FRP bars

Glass is the most commonly used fibre material for FRP rebars. However, low modulus of elasticity is the main disadvantage of using glass fibre, which is only a quarter of that of steel. This leads to a higher deflection when FRP bars are used as the reinforcement for flexural members. For this reason, the concept of 'hybridisation' is applied for the FRP bar to increase its elastic modulus and reduce the material cost (Figure 7).

Two different types of hybrid GFRP rebar were considered: GFRP crust with steel core and GFRP rebar with steel wires dispersed over the cross-section. The first hybrid rebar consists of a 10 mm-diameter steel bar core coated with 1.5 mm-thick GFRP layer produced by the pultrusion process. On the other hand, the second hybrid rebar consists of 13 pieces of 2 mm-diameter steel wires reinforced to the GFRP. Using E-glass fibres and unsaturated polyester resins, hybrid GFRP rebar samples of 13 mm in diameter were fabricated and tested for tensile strength. The effect of hybridisation on the tensile properties of FRP rebar was obtained by comparing the results of the tensile test of the hybrid bar with those of pure GFRP bar.

The hybrid effect associated with the quantity of the hybrid material was investigated to consider glass fibre and steel. Three types of FRP rebar samples were fabricated as summarised in Table 2 with a reference case (i.e., Type A, FRP rebar without

Table 2: Type of FRP hybrid rebars.

Type	A	B	C	D
Steel volume fraction by cross-section area (%)	None	9.5	30.8	47.9
Cross-section ^a				

^aColor key: white (glass fiber), black (steel).

Table 3: Material properties of fibre, resin and steel.

Material	Tensile strength (MPa)	Elastic modulus (GPa)
E-glass fibre	2410	79
Unsaturated polyester resin	62	3.1
Steel wire	16.5	200
Steel rebar	400	200

hybridisation). Unsaturated polyester (PE) was used as resins. A total of 12 samples consisting of three for each design parameter were fabricated and tested for the hybrid FRP samples. Types B, C and D are GFRP crust with steel core, GFRP rebar with dispersed steel wires (diameter 2 mm) and GFRP crust with deformed steel rebar, respectively.

4.2 Manufacturing of hybrid FRP rebars

The hybrid bars were fabricated with a circular cross-section of diameter of approximately 13.0 mm. E-glass fibre (SE1200-2200TEX, Owens Corning Korea), steel wire (KS D3510 C-type, Korea) and steel rebar (nominal strength 400 MPa) were used to produce the bars. Unsaturated polyesters are known as effective resins for the pultrusion process of fabrication because they offer economical advantage, low viscosity, and rapid hardening. The material properties of fibres and resins are provided in Table 3.

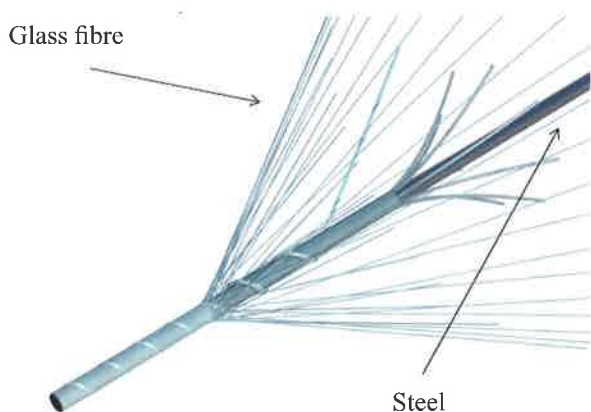
The manufacturing process for hybrid GFRP rebar combines braiding with the pultrusion process, called 'braidtrusion' (You et al.²⁰). This process was chosen to consider the production rate for economy and forming of the aforementioned deformation. This process manufactures a core using fibres and forms a deformation using a braiding machine installed in a pultrusion line. A schematic representation of this technique is shown in Figure 8.

Continuous fibres are drawn from a number roving through a resin pool, where they are saturated with resin, and are then introduced into a nozzle. When the bundle of fibres saturated with resin, the 'core', is passing into the nozzle with a diameter

of 12.7 mm, the surplus resin flows back behind the nozzle and the cross-section is maintained with a circular shape. The core passing through the nozzle is wound by strand for deformation and braided by PVA fibres for clothing. Thereafter, it is cured through a curing oven and completed as a rebar. Tension is introduced into the core between the nozzle and puller by friction force in the nozzle caused by the surplus resin being pushed out and the pulling force of the puller. The force maintains the core straight and induces initial stress. Djamaluddin et al (2013) reported that the introduction of initial stress causes the reduction of the matrix content, pushing out the trapped air in the core, and increase of the bond capacity of fibres. Moreover, the releasing of initial tensile stress will produce a compressive stress on the resin.

4.3 Final product

Figure 9 shows the hybrid GFRP rebar developed by KICT. Its pitch is 12.8 mm and the height of deformation is 0.4 mm with an inner diameter of 12.8 mm. GFRP consists of only E-glass fibre, vinyl-ester resin, hardener, and thinner and hybridised with steel wires. The diameter of 13 steel wires inserted into the GFRP core is 2 mm. The cross-section view and details of steel wire array are shown in Fig. 3(b). The array of wires was intended as a circle under the braided surface. The method of wire array is still being revised for optimising the tensile properties of hybrid GFRP rebar. For hybrid GFRP rebar, the steel ratio to GFRP by cross-section area is 31.7%.

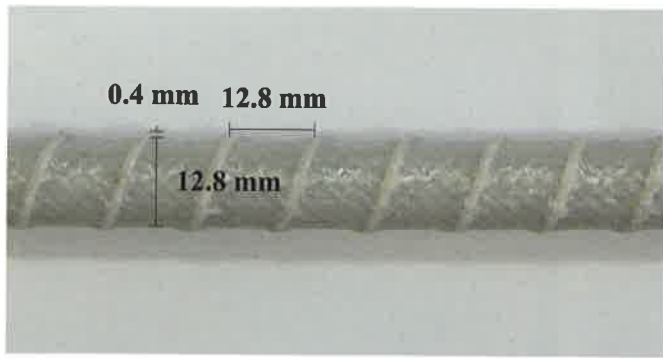


(a) Detailed view of braiding



(b) Type C manufacture device

Figure 8: Fabrication method for FRP hybrid rebar.



(a) Final product of KICT



(b) Cross-section view

Figure 9: The FRP hybrid rebar.

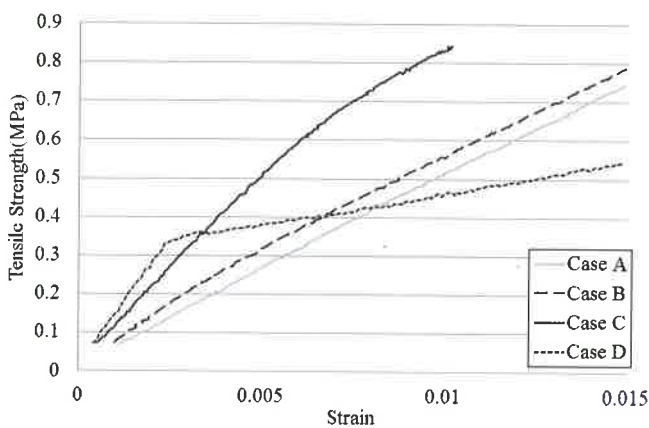


Figure 10: A comparison of tensile test results between specimens (Case A ~ D).

4.4 Mechanical properties of hybrid FRP rebar

The tensile tests of the hybrid FRP bars were carried out in accordance with ASTM D3916²² and the results are summarised in Table 4. The average values of the three tests were used and presented in this table. The hybrid effect is expressed in reference to the ultimate strain of the non-hybrid FRP rebar (i.e. Case A). As mentioned in Table 2, the steel volume fraction by cross-section area is 9.5% (Type B), 30.8% (Type C) and 47.9% (Type D).

Figure 10 compares the behaviour of the different specimens under the tensile test. Comparing with the GFRP bar without hybridisation (Type A), as the steel volume fractions are increased from 9.5% to 47.9%, the tensile strengths decreased from 6% to 15%, even though elastic modulus were increased

from 8% to 160%. Though the minimum tensile strength was 876.2MPa, this value is higher than tensile strength of the general steel bars. The elastic modulus of Type D is approximately 63% of steel rebar's elastic modulus. Therefore, Type C and D can be applied to concrete structures exposed to aggressive environments more effectively than GFRP without hybridisation. While the hybrid FRP bars showed significant potential as internal reinforcement to newly built concrete structures, the practicability of these bars has yet to be investigated. Similarly, information on the durability of hybrid bars should be established as steel is incorporated in the development of this new technology.

5.0 FIELD APPLICATIONS IN AUSTRALIA

The corrosion resistance, light weight, high strength, and electromagnetic neutrality of FRP rebars have led to the actual construction of new infrastructure projects utilising them as the main reinforcement in concrete structures. The following are some of the field applications of the commercially available V-Rod GFRP reinforcing bars in concrete structures in Australia.

5.1 Applications in structures built in or close to sea water

In Australia, the environments are too severe to use steel as reinforcement in concrete structures from the viewpoint of corrosion damage. As FRP bars will not rust, this makes them an appropriate reinforcement in areas of high salinity like mining operations or in structures near the coastal zones including water retaining structures, sewer plants, jetties and boat ramps. Balcony connection to multi-storey building is

Table 4: Results of tensile tests for specimen (Cases A to D).

Type	Tensile strength (MPa)	Improvements (%)	Elastic modulus (GPa)	Improvements
A	1035.9	1.00	49.6	1.00
B	970.4	0.94	53.7	1.08
C	876.2	0.85	98.3	1.98
D	956.1	0.92	129.2	2.60

Note: value for improvements were normalised to Case A.



Figure 11: Wyndham jetty precast panels (left) and the jetty under construction (right).

another area that is suitable for FRP, to eliminate the collapse of a balcony due to corrosion.

The Anthon's Landing Wyndham Community Jetty (Figure 11) is a \$6 million project constructed to provide recreational fishing, tourism charters, supply barges and emergency services vessels. Being in a harsh environment, V-Rod GFRP bars were chosen for the reinforcement of the precast concrete panels for their extreme durability and a life time of maintenance free infrastructure. Due to the innovative construction materials applied, this structure received the 2012 WA Engineering Excellence Award. Similarly, V-Rod GFRP bars have been selected for use on more than 10 jetty upgrades on Sydney Harbour as they provide the significant "best for project outcomes" due to its lightweight and corrosion resistance.

5.2 Structures with low electric conductivity

FRP bar is non-metallic and therefore will not interfere with the operation of sensitive electronic devices. Thus, this reinforcement was the obvious solution for the concrete shield walls around the newly constructed Neutron Beam Dance Floor at the research facility of the Australian Nuclear Science and Technology Organisation.

The FRP bars were also used to reinforce the concrete around the electromagnetic sensitive areas of the detector loop for the Gold Coast Rapid Transit project due to their completely electromagnetic neutral properties. The detector loop is a

critical area in a railway line as it enables induction into a circuit to signal the arrival of the train for the next railway station. Thus, using FRP bars results in a railway detector loop structure which does not interfere with signals sent through the reinforced concrete elements. There are many projects currently booked in which V-Rod GFRP bars are specified, showing a growing confidence in Australia for this technology.

5.3 Revetment walls and wave breaker

FRP bars are an ideal internal reinforcement in concrete structures that demand durability in harsh environmental conditions. Thus, the engineers for the new RSL site in Murray Bridge, South Australia, specified V-Rod GFRP bars as a complete reinforcing solution for the shotcreted revetment wall (Figure 13) that has been built right alongside the future bowling greens at the club. This wall can be potentially subject to high soil moisture content, and concern over future corrosion of normal steel reinforcement had to be addressed. During construction, the contractors commended the light weight of FRP bars which made them easier to handle and manage on site compared to steel. Moreover, FRP bars were used as the internal reinforcement to the precast shield walls for the Royal South Australian Yacht Squadron as shown in Figure 12.

As the wave breaker is subject to a harsh marine environment, reinforcing the precast concrete wall with FRP bars offers



Figure 12: FRP reinforcements for concrete shield walls (left) and railway lines (right).



Figure 13: FRP reinforced revetment wall, (left) and precast concrete wave breaker (right).

highly durable reinforced concrete structures requiring no maintenance.

6.0 DESIGN CODES AND STANDARDS

A large number of research projects along with a large number of monitored demonstration projects allowed the development of design codes. In 2000, the Canadian highway bridge code for the use of FRP rebar as internal reinforcement was adopted (CAN/CSA S807-10²³). The Canadian highway bridge code for the use of FRP rebar as internal reinforcement was also adopted. In 2002, CAN/CSA-S806-02²⁴ has been published by the Canadian Standards Association for design and construction of building components with FRP reinforcements. The American Concrete Institute (ACI) introduced the first and second guideline for the design and construction of concrete reinforced with FRP bars in 2001 and 2003. The North American codes and design guidelines have been updated and modified to encourage the construction industry to use FRP materials (ACI 440.1R-06, 2006). The BCA allows the use of these international codes specifically for FRP reinforcing under the alternative design solutions provision.

While a few infrastructure projects in Australia have utilised FRP bars as the main reinforcement in concrete structures, a major issue for the growth of the technological level is undoubtedly the need for continuous efforts to develop and establish criteria and specifications relevant to the use of FRP bars. As a further study, research is needed for commercialisation and design specification for various research products. Based on these efforts, the FRP material may be applied effectively to more infrastructure to advance its use in many applications.

7.0 Conclusions

The use of FRP bars as internal reinforcement in concrete structures where steel corrosion is a major concern has increasingly gained acceptance as a result of research and development efforts in the last 20 years. Still, many Australian engineers are not familiar with this technology. This paper presented recent developments and applications of FRP bars as internal reinforcement in concrete structures to increase the design knowledge of engineers working with FRP bars and

grow the acceptance of this new technology within the wider engineering community.

Extensive research programs conducted at the University of Sherbrooke have demonstrated that FRP bars are effective reinforcement to concrete beams, columns and slabs. These activities have resulted in the widespread application of FRP bars in Canada and other parts of the world. They demonstrated that the FRP bars can result in significant benefits related to both overall cost and durability if correctly applied in infrastructure.

The results of the preliminary investigation at USQ point toward the suitability of GFRP bars as internal reinforcement in geopolymer concrete. The V-Rod sand-coated GFRP bars embedded in geopolymer concrete have comparable or even higher bonding capacity than the deformed steel bars. Also, the provision of anchor heads increased the pullout capacity of the GFRP bars by as much as 31%. These results indicated that suitable bond strength is developed and composite action is achieved between FRP bars and geopolymer concrete.

This provided the necessary information to extend understanding into the behaviour of full scale structure made up of geopolymer concrete reinforced with FRP bars to increase its acceptance and utilisation in the mainstream construction applications.

Hybridisation was found to be a viable way to increase the elastic modulus and to reduce the material cost of the FRP bars. The hybrid bars, consisting of the GFRP and steel wires, were found to improve the elastic modulus compared to GFRP bars without hybridisation. These hybrid bars may be applied effectively in concrete structures and the durability and practicability for the target structures should be considered in the future study.

The successful field applications in Australia and internationally demonstrate the suitability of FRP bars as an alternative internal reinforcement to concrete in structures such as light rail, power stations, marine structures, sewer plants, and military facilities. More experimental evidence and performance testing will provide a better understanding of the behaviour of concrete structures reinforced with FRP bars. This will lead to further improvement of the product, effective and increased utilisation and acceptance of this new material, and new market opportunities for fibre composite reinforcements.

ACKNOWLEDGEMENTS

The authors would like to thank V-Rod Australia for the financial support in conducting the research and development of FRP bars in geopolymer concrete. The research on hybrid FRP bars is supported from basic government funding of KICT by the Ministry of Science, ICT, and Future Planning department of the Republic of Korea government.

REFERENCES

- Achillides, A. and Pilakoutas, K. 2004. "Bond behaviour of fibre reinforced polymer bars under direct pullout conditions", *Journal of Composites for Construction*, Vol. 8, No. 2, pp. 173-181.
- ACI 440.03R-04. 2004. "Guide test methods for FRPs for reinforcing or strengthening concrete structures." ACI, Farmington Hills, MI, USA, pp. 10-13
- ACI 440.1R-06. 2006. "Guide for the Design and Construction of Concrete Reinforced with FRP Bars." ACI, Farmington Hills, MI, USA, pp. 44 p.p.
- Affi, M.Z, Mohamed, H.M., and Benmokrane, B. n.d. "Axial capacity of circular columns reinforced with GFRP bars and spirals", *Journal of Composites for Construction*, doi: 10.1061/(ASCE)CC.1943-5614.0000438.
- ASTM D 3916. 2002. "Standard test method for tensile properties of pultruded glass-fibre-reinforced plastic rods." ASTM International, West Conshohocken, PA.
- Bakis, C.E., Bank, L.C., Brown, V.L., Cosenza, E., Davalos, J.F., Lesko, J.J., Machida, A., Rizkalla, S.H., and Triantafyllou, T.C. 2002. "FRP composites in construction – state of the art review", *ASCE Composite for Construction Journal*, Vol. 6, No. 2, pp. 78-87.
- Benmokrane, B., Chaallal, O., and Masmoudi, R. 1995. "Flexural response of concrete beams reinforced with FRP bars", *ACI Structural Journal*, Vol. 91, No. 2, pp. 46-54.
- Bouguerra, K., Ahmed, E.A, El-Gamal, S., and Benmokrane, B. 2011. "Testing of full-scale concrete bridge deck slabs reinforced with fibre-reinforced polymer (FRP) bars", *Construction and Building Materials*, Vol. 25, pp. 3956-3965.
- Canadian Standards Association (CSA). 2002. "Design and construction of building components with fibre reinforced polymers." CAN/CSA S806-02, Rexdale, Ontario, Canada.
- Canadian Standards Association (CSA). 2010. "Specification for Fibre-Reinforced Polymers." (CAN/CSA S807-10), Rexdale, Ontario, Canada, pp. 27
- De Luca, A., Matta, F and Nanni, A. 2010. "Behaviour of full-scale glass fibre-reinforced polymer reinforced concrete columns under axial load", *ACI Structural Journal*, Vol. 107, No. 5, pp. 589-596.
- Djamaluddin, R., Yamaguchi, K. and Hino, S. 2013. "Mechanical behaviour of the U-anchor of super-CFRP rod under tensile loading", *Journal of Composite Materials*, pp. 1-11.
- El-Nemr, A., Ahmed, E.A., and Benmokrane, B. 2013. "Flexural behaviour and serviceability of normal- and high-strength concrete beams reinforced with glass fibre-reinforced polymer bars", *ACI Structural Journal*, Vol. 110, No. 6, pp. 1077-1088.
- Gangarao, H.V.S., Taly, N., and Vijay, P.V. 2007. "Reinforced Concrete Design with FRP composites", CRC Press, Taylor & Francis Group, Florida, USA.
- Garnaut, R. 2008. "Issues paper – Forum 5: Transport, planning and the built environment", Garnaut Climate Change Review Draft Report, June 2008, Melbourne, pp. 13
- Hamed, E.A., El-Salakawy, E.F., and Benmokrane, B. 2010. "Performance evaluation of glass fibre-reinforced polymer shear reinforcement for concrete beams", *ACI Structural Journal*, Vol. 107, No. 1, pp. 53-62.
- Hassan, M., Ahmed, E., and Benmokrane, B. n.d. "Punching shear strength of normal and high-strength two-way concrete slabs reinforced with GFRP bars", *Journal of Composites for Construction*, doi: 10.1061/(ASCE)CC.1943-5614.0000424.
- Lloyd, N.A., Rangan, B.V. 2010. "Geopolymer concrete: A review of development and opportunities." Proceedings of 35th Conference on Our World in Concrete and Structures, Singapore.
- Maranan, G., Manalo, A.C., Karunasena, W., and Benmokrane B. 2014. "Bond stress-slip behaviour: The case of GFRP bars into geopolymer concrete", *ASCE Journal of Materials in Civil Engineering*, doi: [http://dx.doi.org/10.1061/\(ASCE\)MT.1943-5533.0001046](http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001046).
- Mohamed, H.M., Afifi, M.Z., and Benmokrane, B. n.d. "Performance evaluation of concrete columns reinforced longitudinally with FRP bars and confined with FRP hoops and spirals under axial load", *Journal of Bridge Engineering*, doi: 10.1061/(ASCE)BE.1943-5502.0000590.
- Mufti, A., Onofrei, M., Benmokrane, B., Banthia, N., Boulfiza, M., Newhook, J., Bakht, B., Tadros, G., and Brett, P. 2005. "Durability of GFRP reinforced concrete in field structures.", Proceedings of the 7th International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPPCS-7), November, New Orleans.
- Park, K.T., Kim, H.Y., You, Y.J., Lee, S.Y., and Seo, D.W. 2013. "Hybrid FRP Reinforcing Bars for Concrete Structures", 4th Asia-Pacific Conference on FRP in Structures, December, Melbourne, Australia.
- Soliman, S.M., El-Salakawy, E., and Benmokrane, B. 2010. "Flexural behaviour of concrete beams strengthened with near surface mounted fibre reinforced polymer bars", *Canadian Journal of Civil Engineering*, Vol. 37, pp. 1371-1382.
- Tobbi, H., Farghaly, A.S. and Benmokrane, B. 2012. "Concrete columns reinforced longitudinally and transversely by GFRP bars", *ACI Structural Journal*, Vol. 109, No. 4, pp. 551-558.
- You, Y.J., Park, Y.H., Kim, H.Y., and Park, J.S. 2007. "Hybrid effect on tensile properties of FRP rods with various material compositions", *Composite Structures*, Vol. 80, No. 1, pp. 117-122.