RESEARCH PAPER

Pullout behaviour of GFRP bars with anchor head in geopolymer concrete

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Pullout behaviour of GFRP bars with anchor head in geopolymer concrete

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Abstract

The geopolymer concrete internally reinforced with fibre-reinforced polymer (FRP) bars is anticipated to offer durable, sustainable, and cost-effective civil infrastructures. In this study, the effect of the anchor head on the pullout behaviour of the sand coated glass-fibre-reinforced polymer (GFRP) bars embedded in the geopolymer concrete was investigated using a direct pullout test. Straight and headed GFRP bars with different nominal diameters Ø (12.7 mm, 15.9 mm, and 19.0 mm) and embedment lengths l_d (0Ø+l_{ah}, 5Ø+l_{ah}, and 10Ø+l_{ah} for headed bars, where l_{ah} stands for the anchor head length, and 5Ø and 10Ø for straight bars) were considered. The results showed that the provision of anchor head is an efficient method to enhance the anchorage capacity of GFRP bars in geopolymer concrete. The anchor heads improved the anchorage of the sand coated GFRP bars by as much as 49% to 77%. Furthermore, the mechanical bearing resistance provided by the anchor head alone resulted in the development of approximately 45% of the GFRP bars' nominal tensile strength. A comparison of the experimental results with the published studies showed that a much higher load is required to pullout the GFRP bars in geopolymer concrete than in Ordinary Portland Cement-based concrete.

Keywords: Geopolymer concrete; Glass-fibre-reinforced polymer (GFRP); Anchorage; Anchor head; Pullout behaviour; Headed GFRP bar.

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1. Introduction

The geopolymer concrete is currently attracting a widespread attention in Australia due to its lower embodied energy and carbon footprint, approximately 80% less CO_2 [1] compared to the Ordinary Portland Cement (OPC) concrete [2]. Geopolymer concrete has engineering properties that are suitable for structural applications, including rapid and good compressive strength development, highly durable, excellent chemical and fire resistance, and minimal thermal and drying shrinkage [3]. This type of concrete is produced from alkali-activated waste materials like fly ash and rice husk ash, that are rich in silica and alumina [4] resulting in 10% to 30% cheaper than the OPC concrete in terms of material costs [5, 6]. While the geopolymer concrete reinforced with steel bars has been successfully trialled in a number of field applications, most of the researches being conducted focus only on mix design and durability [7]. It is necessary therefore to extend the understanding into the behaviour of structures made up of geopolymer concrete to increase its acceptance and utilisation in the mainstream construction application.

In Australia, the environments are severe to use steel as reinforcement to concrete structures from the viewpoint of corrosion damage. With the limited resource of the state and the federal government to maintain existing infrastructures, the Engineers Australia has been calling for a new approach and construction of more durable infrastructures promising results as long-term solutions [8]. Thus, the materials that are environmentally friendly, requires low energy consumption in production, light weight, and with good specific mechanical properties which require low maintenance are warranted. A promising solution is to combine fibre reinforced polymer (FRP) materials and geopolymer concrete to develop a structure with the best characteristics of each material. The use of FRP bars will have a major role in attaining a more sustainable and almost maintenance free infrastructure as the corrosion problem is eliminated. Also, there is more incentive for the construction industry to switch to the use of materials that can significantly reduce carbon dioxide emissions, which is one of the main causes of global warming. However, the use of FRP-reinforced concrete is still unfamiliar to many practising Australian engineers, more so, with the use of FRP bars as internal reinforcement in geopolymer concrete structures.

In order to encourage the use of FRP-reinforced geopolymer concr ete, the anchorage of the FRP bars in this type of concrete must be investigated first as it is the key factor that influences the overall performance of structural elements in any reinforced concrete (RC) structures. Conventionally, the FRP bars are anchored to concrete through chemical adhesion, friction, and mechanical interlock through the provisions of sand coating and/or ribs on the surface of the bars. The other usual option to provide the required development is to use standard hooks such as 90 degrees- or 180 degrees-hook. However, unlike steel reinforcements, hooks should be pre-fabricated before installation because the bending of FRP bars on-site is almost impossible and the bent FRP bars are relatively weaker than the straight bars due to the redirection of the fibres in the bend [9]. Another approach is to use anchor heads to effectively utilise the strength of FRP bars, especially in a congested reinforcement area.

The use of FRP bars with anchor heads to internally reinforce the concrete is yet in its early stages with very limited studies. Hasaballa and El-Salakawy [10] investigated the seismic performance of beam-column joints reinforced with GFRP-headed bars. The results of their study showed that the straight-headed bars have excellent seismic performance than the bent ones. Johnson [11] reported that the straight double-headed GFRP bars can be effectively utilised as shear reinforcement for concrete beams. Mohamed and Benmokrane [12] studied the pullout capacity behaviour of FRP-headed bars. Their results showed that the FRP-headed bars can efficiently provide the necessary anchorage to develop the ultimate tensile strength of the bar. An in-depth investigation of the bond properties of anchorage systems for GFRP bars including straight, anchor heads, and bents were conducted by Vint [13]. It was concluded that the mechanical anchor heads greatly improved the bond capacity of the bars and are more effective for a smaller development length. Khederzadeh and Sennah [14] tested 114 pullout specimens and reported that the headed GFRP bars have a better anchorage capacity as compared with the hooked bars. However, these studies focused on the behaviour of the headed bars embedded in the OPC concrete only and not in the geopolymer concrete, which has been the key motivation of this undertaking.

This study evaluated the effects of the anchor head on the pullout behaviour of the sand coated GFRP bars in the geopolymer concrete using a direct pullout test. The results from this study will be used in developing some recommendations for the design of GFRP-reinforced geopolymer concrete (GFRP-RGC) structures, allowing their responsible introduction and wider use in civil infrastructure.

2. Experimental Details

The properties of the component materials, the method of specimen preparation, and the direct pullout test employed in this study are presented in this section.

2.1. Properties of the GFRP bars and the geopolymer concrete

The GFRP bars used in this study were provided by V-Rod® Australia [15] and were manufactured by the pultrusion process of E-glass fibres impregnated with modified vinyl ester resin. Figures 1 and 2 show the high modulus (HM) sand coated straight and headed GFRP bars (Grade III, CAN/CSA S807-10 [16]). Three types of bars having nominal diameters Ø of 12.7 mm, 15.9 mm, and 19.0m with fibre contents by weight of 84.1 %, 83.9 %, and 84 %, respectively, were considered. The fibre content was determined in accordance with Method 1, Procedure G of ASTM D3171 [17]. Table 1 summarises the guaranteed properties as well as the nominal and actual (immersion) cross-sectional areas of the bars as reported by the manufacturer. The tensile strength and the elastic modulus were calculated using a nominal cross-sectional area.

On the other hand, one batch of geopolymer concrete was used to fabricate all the pullout specimens. The geopolymer binder was made from the alkali activation of fly ash and blast furnace slag (BFS). The concrete was composed of fine aggregates (fine and medium sand) and coarse aggregates (10 mm and 20 mm gravels). Plasticizers were added to improve the workability of the geopolymer concrete. Seven 100 mm x 200 mm cylinders were also cast from the same batch of geopolymer concrete. The cylinders were subjected to compression test following the ASTM C39/C39M [18] standard using the SANS Testing Machine. Based on the test, the average compressive strength of the 32-day geopolymer concrete was 33.09 MPa.

2.2. Properties and configuration of the anchor head

Figure 2 illustrates the anchor head configuration and the overview of the bar-head interface. The anchor heads were manufactured using the same type of resin as the GFRP bars. The bar ends bars were prepared with grooves/dents on the surface before attaching the head to the bars to enhance the bond and to increase the mechanical interlocking between the bar end and the head. The headed anchorages are cast onto the deformed ends of the straight bars and hardened at elevated temperatures.

The head lengths l_{ah} is approximately 92 mm. The maximum outer diameter D_{max} of the end heads is around three times the bar diameter. The surface geometry of the anchor head has a special configuration of ribs to enhance the bond with concrete interface. It begins with a wide wedge that helps to transfer a large portion of the load from the bar into the concrete and to develop the required uniform stress for equilibrium. Beyond this wedge, the head tapers in five steps to the outer diameter of the blank bar. This configuration is responsible to develop a stronger anchoring system, making it as a suitable alternative to bent bars in some applications, and to avoid the splitting action in the vicinity of the head.

2.3. Preparation of the pullout specimens

The loaded end of the GFRP bar was inserted into the steel tube tabs having a diameter and a wall thickness of 33 mm and 3 mm, respectively, using a commercially available epoxy adhesive as shown in Figure 1. This was done to avoid the transverse failure of the bars caused by the gripping force of the machine clamps during testing. The desired embedment lengths were properly marked on the bars and were achieved by sleeving PVC pipes to disband the bars from the geopolymer concrete. Then, the bars were placed horizontally at the centre of each 150 mm x 150 mm x 300 mm rectangular plywood moulds to achieve a concentric alignment. The geopolymer concrete were poured into the moulds and were cast horizontally. A mechanical vibrator was used to compact the geopolymer concrete and to reduce the air voids present, especially near the bonded lengths. The specimens were carefully de-moulded seven days after casting to make sure that the concrete had cured properly to avoid damages upon their removal from formworks and during handling.

Embedment lengths of 0Ø+l_{ah}, 5Ø+l_{ah}, and 10Ø+l_{ah}, were considered for the headed bars while embedment lengths of 5Ø and 10Ø were adopted for the straight bars. The 0Ø, 5Ø, and 10Ø respresent the length of the straight sand coated portion of the bars. The embedment length 0Ø+l_{ah} was used to determine the pullout capacity of the anchor head. For each embedment length, three replicates were made yielding a total of 45 bond-slip specimens: 27 headed GFRP bars-geopolymer (HGG) and 18 straight GFRP bars-geopolymer (SGG) specimens. Each specimen was labelled and identified in a following manner: type of specimen-bar diameter-embedment length. For example, the specimen designated as HGG-12.7-5Ø+l_{ah} means that it is a geopolymer concrete specimen with a 12.7 mm nominal diameter headed GFRP bar with a bonded a length of five times the bar diameter (straight portion) plus the anchor head length .

2.3. Direct pullout test

All the specimens were tested on their 32nd day using a direct pullout test in accordance with ACI 440.3R-04 [19] and CAN/CSA S806-02 [20] standards. Figure 3 illustrates the schematic diagram and the actual test setup. During testing, the specimens were positioned in a reverse manner on top of a fixed circular base plate with a hole at the centre to accommodate the bars. The bars were pulled down at a constant displacement rate of 1.2 mm/min using a 500 kN AVERY testing machine, The absolute slip of the GFRP bar in the geopolymer concrete was measured using a Linear Variable Differential Transducer (LVDT) situated on top of the unloaded end of the bar. The support stand of the LVDT was isolated from the specimen so that the readings will not be affected by the movement and failure of the specimen. The load and displacement were recorded using a System5000 data logger.

3. Experimental Results and Discussion

This section summarises the experimental results such as the failure mode, the average bond stress (τ), the pullout load-slip relationship, and the tensile stress developed in the bar at failure (f_s). The effects of embedment length and bar diameter on the tensile strength development of the straight and headed GFRP bars were analysed. Empirical equations were derived to describe the relationship between the mentioned parameters and the tensile stress in the bars. Finally, the experimental outcomes were compared to verify the viability of the proposed technology for structural applications.

3.1. Mode of failure

Figure 4 shows the failure mode of the SGG bond-slip specimens that were governed by either bar pullout from the geopolymer concrete or splitting of the geopolymer concrete. The pullout type of failure happened when the radial splitting stress, generated by the bond between the bar and the geopolymer concrete, was lower than the confining strength of the geopolymer concrete prism. On the other hand, the splitting type of failure happened when the hoop tension exceeded the tensile capacity of the geopolymer concrete, thereby creating wider longitudinal cracks that propagated to the external surface. Generally, the specimens with shorter anchorage length failed due to the bar pullout while those with longer embedment lengths failed due to the concrete splitting. The specimens with larger diameter and longer embedment length, generally, exhibited wider and more visible cracks that were confined along the bonded length of the GFRP bars. The geopolymer concrete failed in an explosive brittle manner. This was also observed by Sarker [21] and Sofi et al. [22] who studied the bond behaviour of steel bars in geopolymer concrete.

Figure 5 illustrates the geopolymer concrete splitting failure of the HGG specimens. As depicted in Figure 5a, a partial splitting failure was observed in the specimens with headed bars bonded 5Ø+l_{ah} in geopolymer concrete. With the provision of anchor heads, the failure mode of straight bars embedded 5Ø in the geopolymer concrete shifted from bar pullout to concrete splitting owing to the additional bearing resistance of the anchor head that yielded a significant amount of radial splitting stress in the geopolymer concrete. The specimens with embedment lengths of 0Ø+l_{ah} and 10Ø+l_{ah}, on the other hand, exhibited full concrete splitting/breakout as shown in Figures 5b and 5c, respectively. The splitting failure of the HGG specimens, however, was more severe than their SGG counterparts due to the high tensile splitting stress radiated by the anchor heads to the geopolymer concrete. More rigorous cracking and more explosive concrete breakout accompanied with huge sound were recorded as the bar diameter and embedment length increased.

The typical failure modes of the mechanical anchor heads were depicted in Figure 6. Generally, the anchor heads failed by either the longitudinal crack formation (Figure 6a) or the anchor head breakout (Figure 6b).

3.2. Average bond stress

The average bond stress τ between the GFRP bars and the geopolymer was calculated from Eq. 1, assuming a uniform stress distribution along the bonded length of the bars,

$$\tau = \frac{P}{\pi Ø l_d} \qquad (1)$$

where P is the pullout load at failure (N), Ø is the nominal bar diameter (mm), and l_d is the embedment length (mm). Table 2 summarises the computed τ in the bars of the SGG specimens. The τ values in specimens with 12.7 mm, 15.9, and 19.0 mm GFRP bars embedded 5Ø and 10Ø in the geopolymer concrete were 24 MPa and 22 MPa, 22 MPa and 18 MPa, and 20 MPa and 15 MPa, respectively. Generally, as the embedment length increases, the average bond stress between the bars and the geopolymer concrete decreases. Likewise, as the nominal bar diameter increases, the average bond stress also decreases. The bond stress between the headed bars and the geopolymer was not computed using Eq. 1 since the anchor head would also carry part of the applied pullout load. Thus, the comparison between the headed and the straight GFRP bars was done based on the pullout and/or tensile stress developed in each bar and was presented in the following sections.

3.3. Pullout load-slip relationship

Figure 7 shows the typical relationship between the pullout load and the slip of the SGG and HGG specimens. The straight bars, represented by SGG-15.9-5Ø, that failed due to bar pullout from the geopolymer concrete showed a low stiffness characteristic during the early stage of the loading as depicted by the gradual increase of the load while the slip increases rapidly. This can be attributed to the settlement of the uneven face of the loaded end of the concrete. At this stage, the applied loads were simultaneously carried by the chemical bond between the bar and the geopolymer concrete and the mechanical interlock and friction forces provided by the sand coating. Once the specimen had stabilised, a linear behaviour occurred wherein the pullout load increased proportionally with the slip. Concurrently, longitudinal and interface cracks were developed that marked the breakdown of the chemical bond between the bars and the geopolymer concrete. The specimens, however, continued to carry additional loads owing to the mechanical interlock and friction resistance provided by the sand coating. A short non-linear behaviour was observed before reaching the maximum load that indicated the weakening of the sand coating's bond resistance due to wider cracks. The post-peak phase was characterised by a softening curve wherein only the sand friction forces sustained the remaining loads.

The initial and linear behaviour of the headed bars were generally comparable to the behaviour of the straight bars owing to the similar bond resistance mechanism provided by both bars at lower loads, the chemical bond and the friction and mechanical interlock forces provided by the sand coating. As the applied load increases, wider interface cracks occurred that weakens the sand coating resistance. The applied loads, however, were predominantly carried by the anchor head yielding higher pullout load readings compared with the straight bars. Due to the high radial splitting stress induced by the anchor heads, the specimens failed without exhibiting the nonlinear and softening behaviour.

3.4. Tensile stress developed in the bars

Table 2 shows the ratio in percent between the tensile stress developed f_s and the nominal tensile strength f_{ps} of the GFRP bars. These values were calculated to determine the efficiency of each anchorage system in developing the GFRP bars' tensile strength. Initially, the tensile stress was calculated by dividing the pullout load with the bar's nominal area. As can be seen from Table 2, the anchor head alone can develop a tensile stress of 597 MPa in the bars, which is approximately 45% of their nominal tensile strength. The pullout resistance of HGG specimens with $5Ø+l_{ah}$ embedment length was predominantly sourced from the mechanical bearing of the anchor head, resulting in their higher pullout capacities compared with their SGG counterparts. The tensile stresses in the headed bars of the HGG-12.7-5Ø+l_{ah} (834 MPa), HGG-15.9-5Ø+l_{ah} (673 MPa), and HGG-19.0-5Ø+l_{ah} (635 MPa) specimens were 64%, 57%, and 58%, respectively, of the strength of the bars and were 77 %, 49 %, and 54 %, respectively, higher than that of the SGG-12.7-5Ø (472 MPa), SGG-15.9-5Ø (451 MPa), and SGG-19.0-5Ø (411 MPa), respectively. The tensile stresses registered by the headed bars embedded 10Ø+l_{ah} in the geopolymer concrete were comparable to that of the straight bars, ranging from 91% to 109 % of the stress developed in their counterparts. This can be expected because, as the embedment length increases, the pullout resistance of the headed bars was mainly provided by the mechanical interlock and friction forces of the sand coating. In addition, both types of specimens failed by concrete splitting failure that made the anchor heads inefficient. However, given that the concrete splitting failure is avoided, it can be anticipated that the pullout capacity of the headed bars with longer embedment lengths will be higher than the straight bars. This conclusion can be verified from the experimental results obtained by Khederzadeh and Sennah [14].

3.5. Influence of the bar diameter and the embedment length

Generally, the pullout behaviour of the tested specimens was dependent on the bar diameter and the embedment length. Figure 8 shows the effect of the bar diameter (Ø/*cc*, *cc* = concrete cover) on the tensile stress developed in the GFRP bars (f_s/f_{ps}). The solid and broken straight lines represent the general trend, not the actual correlation, between the parameters for the headed and straight GFRP bars, respectively. As can be seen from the figure, the tensile stress in the bars decreases as the bar diameter increases. This finding can be attributed to the shear lag and Poisson's ratio effects. The shear lag occurs when the bars are pulled in tension through its surface, yielding a differential movement between the surface fibre and the core of the bars. This movement results in a non-uniform distribution of the normal stress on the cross-section of the bar: maximum at the outer surface while minimum in the core. The surface stress is the one that governs the bond strength of the bar which is always higher than the calculated average tensile stress. The difference between the surface stress and the average stress increases as the bar diameter increases, yielding an inverse relationship between the tensile stress and the bar diameter. Furthermore, due to the low shear stiffness of the resin coupled with lower shear strength of the resin-fibre interface, shear lag is most likely to happen in GFRP bars. The Poisson's ratio effect, on the other hand, is characterised by a decrease of the bar diameter due to the pulling stress. This size reduction can weaken the connection between the bars and the concrete. The Poisson's ratio effect also increases as the bar diameter increases.

Figure 9 illustrates the effect embedment length (l_d/Ø) on the tensile stress developed in the GFRP bars (f_s/f_{ps}). The enhancement of the HGG specimens' pullout capacity can be attributed to the mechanical bearing resistance provided by the anchor heads plus the higher mechanical interlock and friction forces coming from the longer bonded length that resulted in a stronger anchorage system of the HGG specimens. For SGG specimens, the increase in pullout load resistance was due to the increase in the amount of bar surface area that is bonded in geopolymer concrete, thereby producing higher mechanical interlock and friction forces to resist the applied load.

3.6. Prediction of the pullout load capacity

Figure 10 shows the combined effects of the bar diameter and embedment length on the tensile stress developed in the straight and headed GFRP bars, including the two equations derived from the regression analysis of the experimental results. The contribution of the anchor heads (f_{sa}) can be obtained by subtracting the tensile stresses in the straight bars from that of the headed bars and can be expressed as

$$f_{sa} = 0.2944 f_{ps}\left(e^{-6\times10^{-4}\left(\frac{l_d \times cc}{Ø^2}\right)}\right) \qquad \text{contribution of the anchor heads} \qquad (2)$$

The tensile stress in the headed GFRP bars f_{sh}, therefore, can be calculated from Eq. 3, which is the sum of Eq. 2 and the tensile stress equation for straight GFRP bars (depicted in Figure 10).

$$f_{sh} = f_{ps}\left(0.085\left(\frac{l_d \times cc}{Ø^2}\right)^{0.4916} + 0.2944\left(e^{-6\times10^{-4}\left(\frac{l_d \times cc}{Ø^2}\right)}\right)\right) \qquad (3)$$

In terms of the pullout load capacity of the headed GFRP bars (P_{sh}), the equation can be expressed as

$$P_{sh} = P_{ps}\left(0.085\left(\frac{l_d \times cc}{Ø^2}\right)^{0.4916} + 0.2944\left(e^{-6\times10^{-4}\left(\frac{l_d \times cc}{Ø^2}\right)}\right)\right) \qquad (4)$$

where P_{ps} is the nominal tensile load capacity of the GFRP bars. This equation, however, is applicable only to headed GFRP bars with embedment lengths ranging from 5Ø to l_{da}. The l_{da}, given by Eq. 5, was derived by equating the expressions, depicted in Figure 10, for straight and headed GFRP bars.

$$l_{da} = 90.19\left(\frac{Ø^2}{\text{cc}}\right) \qquad (5)$$

Table 3 summarised the predicted pullout load capacities using Eq. 4 and the corresponding estimation error in percent. It can be seen from the table that for the straight GFRP bars, the predicted values were relatively lower than the experimental values except the SGG-12.7-5Ø specimen. On the other hand, the pullout capacities of the headed bars were conservatively estimated by the proposed equation. It is notable from the table, however, that the pullout load capacity of the HGG-19.0-10Ø+l_{ah} was way higher than that of the experimental result. This is in line with the conclusion made previously wherein headed bars with longer embedment lengths would result into higher pullout capacity provided that concrete splitting can be prevented. Furthermore, the experimental capacity of this specimen is lower than that of the HGG-15.9-5Ø+l_{ah} because, unlike the HGG specimens with 5Ø+l_{ah} embedment length, this specimen does not have any unbonded geopolymer concrete in its loaded end that could prevent the early development of the longitudinal cracks, as shown in Figure 11.

3.7. Comparison between the experimental and the published results

Figure 12 shows the comparison between the experimental results and the published results on the pullout test of the straight and headed GFRP bars in normal concrete, denoted by SGN and HGN, respectively, and of the deformed steel bars in geopolymer concrete, symbolised by SG. For the specimens with headed bars, only the results of those with a portion of straight bars bonded in concrete were reflected in this figure. The results were presented in terms of the tensile stress normalised with a factor $Ø/(l_d\sqrt{(f'_c)})$. Figure 13, on the other hand, displays the comparison between the experimental outputs and Mohammad and Benmokrane's [12] results for the specimens with only the anchor head embedded in concrete. These specimens, however, were evaluated in terms of their tensile stress normalised with the concrete compressive strength. For comparison purposes, only the specimens that failed due to bar pullout (for straight bars) and concrete splitting (for headed bars) were considered. Based on these figures, the following generalisations were made:

1. The tensile stresses developed in the bars of HGG specimens are higher than that of HGN specimens. This observation leads to concluded that the headed GFRP bars, used in this study, have better pullout resistance compared with that of the previous studies and that the geopolymer concrete have superior tensile strength compared with

cement-based concrete. Further experimental works, however, should be conducted to validate this conclusion.

2. The HGG specimens showed superior pullout capacity compared with SGG and SGN specimens, indicating that the use of anchor head is an efficient method to enhance the bonding of sand-coated GFRP bars in concrete.
3. The combination of anchor head and sand coating systems showed better bonding performance compared with the ridge system of deformed steel bars.
4. Generally, the HGG and SGG specimens showed better pullout resistance than SGN and HGN specimens, suggesting the potential of the GFRP-reinforced geopolymer concrete system for structural applications.

4. CONCLUSION

This study was conducted to investigate the effect of the anchor head on the pullout behaviour of sand coated GFRP bars in the geopolymer concrete using the direct pullout test. A total of 45 bond-slip specimens were tested following the ACI 440.3R-04 [19] and CAN/CSA S806-02 [20] standards. Based on the test, the following conclusions were made:

- Based on the experimental results, the headed GFRP bars can be an efficient method to enhance the anchorage capacity of the GFRP bars in the geopolymer concrete.
- The tensile stress developed in the headed GFRP bars with only the anchor head embedded in geopolymer concrete can reach up to approximately 597 MPa, which is 45 % of the nominal tensile strength of the GFRP bars.
- With the provision of anchor heads, the tensile stresses in the 12.7 mm, 15.9 mm, and 19.0 mm straight sand coated GFRP bars embedded 5Ø in geopolymer concrete increased by 362 MPa (77%), 222 MPa (49%), and 224 MPa (54%), respectively, and thereby shifting the failure mode of the specimens from bar pullout to geopolymer concrete splitting.

- The geopolymer concrete splitting failure of the specimens with the headed bars was more severe than that of the straight bars due to the high radial splitting stress induced by the anchor heads.
- The tensile stress in the headed GFRP bars embedded in geopolymer can be estimated from the derived empirical equation, however, with several limitations. Further experimental results, therefore, are needed to calibrate the equation.
- The pullout load resistance SGG and HGG were generally higher than that of the SGN and HGN, thereby showing the potential of the GFRP-reinforced geopolymer concrete system for structural applications.
- The use of anchor heads to achieve the required development is beneficial if bending of GFRP bars is impossible, especially in a congested reinforcement area, and if long lengths cannot be produced due to limited space available to anchor the bar in the concrete.

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