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Keywords: Corrosion; Bond; Geopolymer; Steel Fibres; Pull-out

1. Introduction

The process of the production of cement is associated with high energy consumption causing adverse environmental impact. It was estimated that the production of one tonne of cement requires about one tonne of raw materials and emits nearly one tonne of carbon dioxide (CO₂) into the atmosphere [1-3]. Hence, to reduce the adverse environmental impact associated with the production of cement, the use of alternative binders to cement such as industrial by-products are considered an attractive solution to reduce or alleviate adverse environmental impacts. During the last few decades, research investigations were carried out into the use of geopolymer concrete as an alternative to the Ordinary Portland Cement (OPC) concrete.

Geopolymer concrete consumes lower energy and causes low carbon dioxide emissions into the atmosphere. It possesses high early strength, high fire resistance and high durability against chemical attack. It has been a promising material to be used in different construction applications as an alternative to OPC concrete [4-7]. On the other hand, low tensile and flexural strengths are the main drawbacks limiting the use of geopolymer concrete in several applications including the construction of columns and beams. The addition of steel fibres was found to be a promising solution to enhance the tensile and flexural strengths of geopolymer concrete [8]. Ng et al. [9] found that shear strength of geopolymer concrete beams increased with the addition of steel fibre. Bernal et al. [10] investigated the mechanical properties and durability performance of heat cured geopolymer concrete reinforced with various proportions of steel fibre ranging from 0 to 3% by volume. The test results showed a reduction of the compressive strength with the addition of steel fibres. However, splitting tensile strength and flexural strength were significantly improved with the increase in the addition of steel fibres from 0 to 3% by volume. Also, the durability performances including

water absorption, capillarity and water penetration resistance were enhanced with the addition of steel fibres in the heat cured geopolymer concrete [10].

A large number of reinforced concrete structures are exposed to chloride attack leading to the corrosion of reinforcing steel bars [11]. The corrosion of the steel bar has significant adverse effects on the durability and serviceability of the reinforced concrete (RC) structures [12]. Several research studies reported that the corrosion of the steel bar in RC structures reduced the tensile strength of the reinforcing bars because of the loss of the cross-sectional area and loss in the bond performance between reinforcing steel bar and surrounding concrete [13, 14]. Abosrra et al. [15] studied the effect of corrosion on the bond behaviour of deformed steel bars embedded in concrete with different compressive strengths. The test results showed that higher compressive strength of concrete increased the bond strength and reduced the rate of corrosion of steel reinforcing bar.

Steel fibres are commonly used for reinforcing the precast elements, hydraulic structures, airfield pavements, and tunnel lining segments. However, steel fibres cannot be used to replace the conventional reinforcing steel bars in most concrete members. Steel fibres are used as complementary to the conventional reinforcing steel bars in RC structures. However, some studies recommended for not using steel fibre in combination with conventional reinforcing steel bars in saltwater environments because of the concerns that steel fibres might accelerate the corrosion of reinforcing steel bars in RC structures [16, 17].

Roque et al. [18] studied the durability of hooked end steel fibre of RC structural members. The test results showed that steel fibres improved the durability of RC structures in non-submerged saltwater environments. It was recommended that steel fibres should not be used in combination with reinforcing steel bars in seawater environments because steel fibres in contact with reinforcing steel bars accelerated the corrosion of the reinforcing steel bars [18].

Grubb et al. [19] investigated the effect of micro steel fibres on the corrosion of reinforcing steel bars. Mortar specimens with and without micro steel fibres were exposed to a corrosive environment. Steel bars embedded in mortar reinforced with micro steel fibres showed better resistance to corrosion than steel bars embedded in plain mortar. Someh and Saeki [20] studied the durability of concrete reinforced by zinc-coated steel fibres. Steel bars embedded in zinc-coated steel fibre reinforced concrete remained free from corrosion for a longer period of time compared to steel bar embedded in plain concrete when exposed to similar corrosive environments.

Sofi et al. [21] investigated the bond strength of geopolymer concrete with reinforcing steel bar. The test results showed that all specimens failed by splitting of geopolymer concrete surrounding the steel bar and the bond strength increased with a decrease in the diameter of the reinforcing steel bar. The bond strength of geopolymer concrete and OPC concrete with reinforcing steel bars was also studied by Sarker [22]. The test results showed that both geopolymer concrete and OPC concrete specimens failed by splitting of concrete around the region bonded with the reinforcing steel bar. The test results also showed that geopolymer concrete had higher bond strength than OPC concrete with reinforcing steel bars [22]. Castel and Foster [23] also reported that the bond strength of reinforcing steel bar embedded in the geopolymer concrete was slightly higher than the bond strength of reinforcing steel bar embedded in the OPC concrete.

Different test methods were adopted in the previous research studies for measuring the bond between reinforcing steel bars and concrete including pull-out test [21], beam end test [22], beam anchorage test [24] and splice test [25]. In this study, the pull-out test was used because of the ease of fabrication and the simplicity of the test. Several research studies investigated the bond of reinforcing steel bars embedded in geopolymer concrete. However, the effect of

corrosion on the bond performance of reinforcing steel bars embedded in steel fibre reinforced geopolymer concrete has not yet been investigated. The objective of this study, therefore, is to evaluate the effect of corrosion on the bond between steel bars and fibre reinforced geopolymer concrete. The objective of this study is achieved through extensive experimental investigations. The development of a mathematical model is considered beyond the scope of this paper.

2. Experimental program

2.1 Materials

The materials used in this study included ground granulated blast furnace slag (GGBS) and fly ash (FA). The GGBS was used as the source of aluminosilicate materials for the production of geopolymer concrete and the FA was used as an additive to increase the setting time of geopolymer concrete under ambient curing conditions. The GGBS was supplied by the Australian Slag Association [26]. The FA was supplied by Eraring Power Station, Australia [27]. The X-Ray Fluorescent (XRF) was used to analyse the chemical composition of FA and GGBS. The chemical composition analysis of GGBS and FA was conducted in the School of Earth Science at the University of Wollongong Australia. The chemical compositions of GGBS and FA are shown in Table 1. The results of XRF classified the FA as low calcium FA (Type F) according to ASTM C618-08 [28]. The sum of SiO_2 , Al_2O_3 and Fe_2O_3 content were higher than 70% of the FA components. The CaO content was less than 8% of the FA components. Coarse aggregate with a maximum size of 10 mm and river sand as a fine aggregate were used in this study.

The roles of alkaline activator solution are to dissolve the reactive portion of the source materials (aluminate (Al) and silicate (Si)) present in GGBS and FA and to provide a high alkaline liquid medium. The alkaline activator solution was a blend of sodium hydroxide

(NaOH) and sodium silicate (Na_2SiO_3) solutions. The sodium hydroxide (NaOH) solution was prepared by dissolving caustic soda pellets in potable water. The NaOH solution was prepared 24 hours before casting geopolymer concrete. The Na_2SiO_3 solution included 44.1% solids, 29.4% silicate and 14.7% sodium oxide. The Na_2SiO_3 was supplied by PQ Australia [29]. High range water reducer (Glenium 8700) supplied by BASF Australia [30] was used to improve the workability of the geopolymer concrete.

In this study, three types of steel fibres were used: straight micro steel (MIS) fibres, deformed macro steel (DES) fibres and hybrid steel (HYS) fibres. The straight micro steel (MIS) fibres were 6 mm in length and 0.2 mm in diameter with a tensile strength of 2600 MPa [31]. The deformed macro steel (DES) fibres were 18 mm in length and 0.55 mm in diameter with a tensile strength of 800 MPa [32]. The HYS fibres were a combination of MIS fibres and DES fibres. The MIS fibres were supplied by Ganzhou Daye Metallic Fibres Company, China [31]. The DES fibres were supplied by Fibercon Company, Australia [32]. The properties of steel fibres are presented in Table 2. Deformed steel bars of 16 mm diameter were used as reinforcement. Five samples of 16 mm deformed steel bars were tested according to AS1391-2007 [33]. The deformed steel bars have two longitudinal ribs and rows of alternately inclined transverse ribs on both sides of the bars. These ribs contribute positively to the bond strength between reinforcing steel bar and concrete. The average yield tensile strength and corresponding yield strain of the deformed steel bar were 612 MPa and 0.003 mm/mm, respectively.

2.2 Preparation of concrete sample

A total of ten geopolymer concrete mixes were used to evaluate the effect of the corrosion on the bond between reinforcing steel bars and geopolymer concrete. The bond was evaluated using pull-out tests. The dimensions of the specimens were chosen according to the European

Standard pull-out test EN-10080 [34], as shown in Fig. 1. The pull-out test specimens were geopolymer concrete cube specimens with a side length of 160 mm and reinforced centrally with a 16 mm diameter deformed steel bar. The length of the steel bar was 510 mm in order to facilitate the loading of the specimen using the 500 kN Universal Instron testing machine. The bonded length of the tested steel bar in the specimens was five times the diameter of the steel bar (i.e., 80 mm), as shown in Fig. 1. The unbounded length of the steel bar in the specimen was obtained by using a polyvinyl chloride (PVC) pipe at one end of the specimens (Fig. 2). Before mixing of concrete, the deformed steel bars were carefully cleaned and the mass of the deformed steel bars in each specimen was recorded.

In this study, three types of moulds were used. Plywood moulds were used for preparing pull-out test specimens. Polyvinyl chloride (PVC) cylindrical moulds of 100 mm diameter and 200 mm length were used for preparing concrete cylinders to measure the compressive strength of concrete. Also, PVC cylindrical moulds of 150 mm diameter and 300 mm length were used for preparing concrete cylinders to measure the splitting tensile strength of concrete. Table 3 shows the mix proportion of geopolymer concrete which was adopted from a previous study by Hadi et al. [35]. The dry materials including binder (GGBS+FA), coarse and fine aggregate were first mixed for about 3 minutes. Afterwards, alkaline activator (combination sodium hydroxide with sodium silicate) was slowly added into the mixer together with the superplasticiser and water. The mixing continued for another 5 minutes. The geopolymer concrete mix was poured from the pan mixer into plywood moulds prepared for plain geopolymer concrete specimens. For the fibre reinforced geopolymer concrete specimens, after the dry materials and liquid components were mixed thoroughly, steel fibres were added gradually to the wet mix. Mixing continued until the steel fibres were well dispersed in the geopolymer concrete mixes. Adequate care was taken during the mixing to ensure a uniform distribution of the steel fibres in the geopolymer concrete mixes.

The geopolymer concrete was poured into the plywood moulds prepared for the geopolymer concrete specimens. The geopolymer concrete specimens were cast and compacted in three stages. Each stage was internally vibrated using an electric vibrator to remove air voids and to compact the fresh concrete. Afterwards, the geopolymer concrete specimens were kept in the moulds for 24 hours. The specimens were then demoulded and kept under ambient conditions until age of 28 days.

2.3 Labelling system

In this study, each concrete mix has been identified with an acronym (Table 4). The symbol GC refers to plain geopolymer concrete. The symbols GCMIS and GCDES refer to geopolymer concrete reinforced with straight micro and deformed macro steel fibres, respectively. The numbers (1, 1.5, and 2) afterwards refer to the percentages of steel fibres by volume used in this study. The symbol GCHYS refers to geopolymer concrete with hybrid steel fibres. The GCHYS mixes included combinations of micro steel and deformed steel fibres in different proportions. In this study, the GCHYS mixes included 2% hybrid steel fibres by volume. The GCHYS2a included 0.5% micro steel fibres and 1.5% deformed steel fibres (0.5%MIS+1.5%DES), GCHYS2b included 1% micro steel fibres and 1% deformed steel fibres (1%MIS+1%DES) and GCHYS2c included 1.5% micro steel fibres and 0.5% deformed steel fibres (1.5%MIS+0.5%DES).

2.4 Accelerated corrosion method

In this study, an electrochemical method was used to accelerate the corrosion of deformed steel bars. The specimens were submerged in a plastic tank filled with sea water for three days before being exposed to an accelerated corrosion process to ensure full saturation of the tested specimen [36]. The accelerated corrosion process was obtained using a direct current

(D.C.) supply providing 30 Volt constant potential at 0 to 4 Amperes (Amp). The direct current was applied to the steel bars embedded in the concrete using the steel bars as the anode. The cathode was made from a galvanised mesh, which was placed around the specimens in the salt solution. The current passed from the steel bars to the galvanised mesh placed inside the salt solution. The end of the steel bar was insulated during the corrosion in order to ensure that only the bonded zone would be corroded. One end of the steel bar was coated with paraffin and wrapped with an insulating plastic membrane. A cushion made from PVC was also used under the specimens to insulate the specimens from the base of the plastic tank. The schematic of the accelerated corrosion set-up is shown in Fig. 3. The experimental setup for the accelerated corrosion process is shown in Fig. 4. The calculated mass loss of the steel bars due to corrosion was calculated according to Faraday's law using Equation (1) [37, 38].

$$Mass\ loss = \frac{t \times I \times 55.847}{2 \times 96487} \quad (1)$$

where t is the duration of exposure (hour) and I is the average current to which the reinforcing bar was exposed. The actual mass loss of the steel bars due to corrosion was calculated using Equation (2) [37, 38].

$$Mass\ loss = \frac{G_0 - G_1}{G_0} \times 100\% \quad (2)$$

where G_0 is the initial weight of the steel bars before corrosion and G_1 is the weight of the steel bar at the end of the test. Badawi and Soudki [39] and El Maaddawy and Soudki [40] observed that the use of current density for accelerated corrosion tests provided a similar result estimated by Faraday's law equations, as presented in Equation (1).

2.5 Testing of specimens

The compressive strength tests of geopolymer concrete specimens were carried out according to AS 1012.9-1999 [41] at 28 days. A compression testing machine with a capacity of 1800 kN was used to conduct the compressive strength tests. The splitting tensile strength tests of geopolymer concrete specimens were performed according to AS 1012.10-2000 [42] at 28 days. The specimens were tested at the loading rate of 106 kN/min until the specimen failed.

The concentric pull-out tests were performed for the corroded and non-corroded specimens according to EN-10080 [34]. The pull-out tests were performed using a 500 kN Universal Instron testing machine, as shown in Fig. 5. A specially designed loading frame was used for the pull-out test. The loading frame consisted of two plates in which the bottom plate was clamped to the base of the universal Instron testing machine. The reinforcing steel bar passing through the central hole of the top plate was clamped to the upper head of testing machine (Fig. 5). The specimens were tested up to failure with a displacement controlled loading at 0.1 mm/min. The data were recorded at every two seconds. None of the reinforcing steel bars reached the yield strength during the tests. The axial loads applied by the testing machine were recorded to establish the bond stress. The bond stress was computed from the applied axial loads on the steel bar divided by the surface area of the embedded length of the reinforcing steel bar using Equation (3).

$$\tau = \frac{P}{\pi \times D \times L} \quad (3)$$

where τ is the bond stress, P is the applied load, D and L are the diameter and the bond length of the reinforcing steel bars, respectively.

3. Results and discussions

3.1 Mechanical properties

The average compressive strength and average splitting tensile strength of all concrete mixes are presented in Table 5. For each mix, three specimens for the compressive strength and three specimens for the splitting tensile strength were tested and the average results have been reported. It can be seen in Table 5 that the average compressive strengths and average splitting tensile strengths of GC specimens were lower than the average compressive and average splitting tensile strengths of geopolymer concrete specimens with different types of steel fibre.

The average compressive strength was found to be 41.1 MPa for the GC specimens at 28 days. It can be observed that the increase of MIS fibre content from 0 to 2% by volume, the average compressive strength of the geopolymer concrete increased by 6.3%. With the increase of DES fibre content from 0 to 2% by volume, the average compressive strength of the geopolymer concrete increased by 3.6%. The addition of HYS fibres also increased the average compressive strength of the geopolymer concrete. The enhancement in the average compressive strength of the HYS fibre reinforced geopolymer concrete ranged from 11.9% to 14.8%. Specimens GHYS2b (1%MIS+1%DES) achieved the highest average compressive strength. The increase in the compressive strength of geopolymer concrete with the addition of steel fibre can be attributed to the role of the steel fibre in bridging the cracks, which restrained the initiation and propagation of cracks.

The average splitting tensile strength of the GC specimens was 3.7 MPa for 28 days (Table 5). For the increase of MIS fibre content from 0 to 2% by volume, the average splitting tensile strength of the geopolymer concrete increased by 37.8%. For the increase of DES fibre content from 0 to 2% by volume, the average splitting tensile strength of the geopolymer concrete increased by 43.2%. Finally, the addition of 2% HYS fibre by volume significantly increased the splitting tensile strength. The improvements in the average

splitting tensile strength ranged from 51.4% to 64.8%. The highest average splitting tensile strength of the geopolymer concrete was achieved for GCHYS2b (1%MIS+1%DES) specimens. The increase in the splitting tensile strength with the addition of the steel fibre is attributed to the uniform distribution of steel fibre throughout the geopolymer concrete mixes. Consequently, greater efficiencies in delaying the initiation and propagation of cracks were achieved, which improved the splitting tensile strength of reinforced geopolymer concrete.

3.2 Corrosion and cracking behaviour

In the corrosion process, the electrical potential applied to the positively charged steel bars attracts negatively charged chloride ions from the salt solution into the concrete. When the chloride ions reached the steel bar, the surface of steel bars began to corrode [43]. The specimens were monitored to determine the beginning of the corrosion of steel bars. Figure 6 shows the variation of current applied with time in GC and steel fibre reinforced geopolymer concrete specimens.

The variation of applied current with time was obtained by calculating the average current at every 24 hour using Digitech QM1575 Multimeter. Figure 6a indicates that the average current in the Specimen GC decreased from 440 mA to 145 mA in 96 hours. Afterwards, the current increased from 145 mA to 180 mA during the next 48 hours. The Specimen GC showed ferrous oxides (brown rust) on the top of the specimens after 240 hours of accelerated corrosion exposure. On the other hand, the average current of the steel fibre reinforced geopolymer concrete specimens decreased for about 96 hours and remained nearly steady for about 500 hours. Afterwards, the average current increased. The MIS fibre reinforced geopolymer concrete specimen showed no sign of brown rust for the same period (after 240 hours of accelerated corrosion exposure). As the experiment continued, ferrous oxides

(brown rusts) were observed on the top of the MIS fibre reinforced geopolymer concrete specimens after about 400 hours. The brown rust stains seen on the top of the specimens indicated the beginning of corrosion in the embedded steel bars. Figures 6 (a-c) shows that the trends of the current for the steel fibre (MIS, DES and HYS) reinforced geopolymer concrete specimens were almost similar. The possible reason for the initial decreases in the current was due to the filling of the pores in the concrete by salt and other deposits of the salt water. The increase in the current flow indicated the beginning of the corrosion of reinforcing bar. It can be observed that the initial current readings recorded for the steel fibre reinforced geopolymer concrete specimens were lower than the current readings recorded for Specimen GC. The current readings for geopolymer concrete specimens did not show any significant increase during the accelerated corrosion process. This indicates that the steel fibre reinforced geopolymer concrete demonstrated better resistance against chloride penetration than the Specimen GC.

Initial cracks were observed on the bottom of Specimen GC after about 240 hours of accelerated corrosion. On the other hand, the initial cracks were observed on the bottom of specimens after about 500 hours of accelerated corrosion of steel fibre reinforced geopolymer concrete specimens. The cracking started with increasing the current in the power supply, where the current increased from 1.6 Amp to 3.9 Amp.

At the end of the accelerated corrosion process, all specimens exhibited longitudinal cracks running parallel to the steel bars. The maximum measured crack width was in the range of 0.15-0.25 mm and the crack depth was in the range of 1.5-4.5 mm for the Specimen GC. However, only micro cracks were noticed on the steel fibre reinforced geopolymer concrete specimens. The accelerated corrosion test was stopped at 600 hours. It is apparent that the steel fibre reinforced geopolymer concrete specimens demonstrate better resistance against

chloride penetration compared to the Specimen GC in a corrosive environment. The specimens were removed from the tank for visual inspection and pull-out testing.

3.3 Mass loss measurement

The level of corrosion in the embedded steel bar was determined from the mass loss measurement. The level corrosion in terms of the mass loss of the corroded steel bar due to corrosion were first estimated based on Faraday's law using Equation (1). The electric current and the time of corrosion in the accelerated corrosion test was calculated from Equation (1) based on the calculated mass loss. The accelerated corrosion test was stopped at 600 hours due to the sudden increases in the current reading, which occurred with the cracking at the bottom of the specimens. The actual corrosion levels were measured by the mass loss of the corroded steel bar using Equation (2). At the end of the test, the corroded steel bars were retrieved to determine the mass loss. The corroded steel bars for each specimen were cleaned in order to remove all corrosion residues before weighing. The corroded steel bars were cleaned with deionized water using a metal brush in order to ensure that the steel bars were free from any corrosion residue. Figure 7 shows the steel bars before and after corrosion. The steel bars were weighed and the percentage of mass loss was computed using Equation (2).

The specimens with the highest volume fraction (2%) of MIS, DES and HYS (1%MIS+1%DES) steel fibres together with steel bars before and after corrosion process are shown in Fig. 8. It can be observed from Fig. 8 that the steel bars embedded in Specimen GC noticeably suffered from corrosion damage. On the other hand, the steel bars embedded in steel fibre reinforced geopolymer concrete specimens had lower corrosion effects. The measured corrosion levels and calculated corrosion levels are reported in Table 6. It can be seen from Table 6 that the measured corrosion levels were lower than the calculated corrosion levels. The difference in measured corrosion levels and the calculated corrosion

levels can be attributed to the fact that the permeability of the concrete played an important role in the actual level of corrosion. The permeability of the concrete was not included in Equation (1) for the calculation of the theoretical level of corrosion. Although the specimens were immersed in the water for three days prior to the accelerated corrosion process, it would have taken a longer period for the saltwater to reach the steel reinforcing bar [36].

Based on the test results, the percentage mass losses of the corroded steel bar were 5.90% for Specimen GC. On the other hand, for the steel fibre reinforced geopolymer concrete specimens, there was a slight mass loss of corroded steel bars after 600 hours of accelerated corrosion testing. Hence, the steel fibre reinforced geopolymer concrete exhibited better corrosion resistance in the marine environment compared to the plain geopolymer concrete. The addition of steel fibres to the geopolymer concrete provided positive effects on the control of the corrosion of steel bar and concrete cracking. Steel fibres in geopolymer concrete led to smaller and more closely spaced cracks, resulting in reduced permeability of the concrete. Also, Specimen GC showed higher mass loss of the corroded steel bar due to the formation of wide cracks on the bottom of the specimens (Fig. 8). The cracks allowed the chloride ions to reach the steel bar quicker and accelerated the rate of corrosion.

3.4 Bond failure modes

Figure 9 shows the failure patterns of specimens after the pull-out tests. It can be observed that the bond failure of non-corroded specimens was almost similar, except Specimen GC. The failure of the steel fibre (MIS, DES and HYS) reinforced geopolymer concrete specimens occurred by splitting cracks during the pull-out test while the failure of Specimen GC occurred by pull-out failure. The typical splitting cracks of the steel fibre reinforced geopolymer concrete specimens started from the loading end and extended to the free end.

For corroded specimens, the bond failure of Specimen GC was caused by newly generated splitting cracks around the steel bar in addition to the existing corrosion induced longitudinal cracks. This is because of the brittle behaviour of Specimen GC (without steel fibre) due to the corrosion of steel bar. Thus, more cracks generated when sudden loss of bond strength occurred. The steel fibre reinforced geopolymer concrete specimens failed because of the widening of the existing longitudinal crack due to corrosion. The splitting cracks generated or existing longitudinal cracks widened continuously from the loading end to the free end. After the pull-out test, only slip of the steel fibres has been observed.

3.5 Bond versus free-end slip behaviour

Results of pull-out tests are shown in Table 7. The axial load and free-end slip were obtained directly from the 500 kN Universal Instron testing machine. To record the axial load and the free-end slip, an electronic data acquisition system was used.

The behaviour of of bond stress versus free-end slip comprises three stages as shown in Fig. 10. In the first stage (stage I), the bond stress increased until the chemical adhesion is exhausted and slips occurred between the steel bar and the concrete. This stage is limited by the tensile strength of the concrete. The bond stress-slip response remains linear during the first stage. In the second stage (stage II), when the applied axial load increased towards the maximum bond stress, the rate of slip started to increase and the bond stress-slip response became distinctly non-linear. The second stage corresponds to the occurrence of micro-cracking in the concrete specimens. In the last stage (stage III), the specimen reached the maximum bond stress and some longitudinal splitting cracks developed parallel to the steel bar. In this stage, the bond stress decreased with the increase of the slip.

Figure 11 shows typical bond stress versus free end slip for non-corroded concrete specimens. It can be seen from Fig. 11 that the maximum bond stress of non-corroded Specimen GC was 16.46 MPa with a corresponding slip of 1.96 mm. The addition of MIS, DES and HYS fibres to the geopolymer concrete increased the maximum bond stress and the corresponding slip (Table 7). The addition of 1%, 1.5% and 2% by volume of MIS fibre increased the maximum bond stress by 28.3%, 32.9% and 38.3%, respectively. The addition of 1%, 1.5% and 2% by volume of DES fibre increased the maximum bond stress by 24.9%, 28.9% and 32.8%, respectively. Also, the addition of MIS and DES fibre increased the slip corresponding to the maximum bond stress noticeably. The slip corresponding to the maximum bond stress of fibre reinforced geopolymer concrete with MIS fibre of 1%, 1.5% and 2% by volume increased by 25.5%, 30.1% and 52.1%, respectively. The slip corresponding to the maximum bond stress of fibre reinforced geopolymer concrete with DES fibre of 1%, 1.5% and 2% by volume increased by 24.5%, 32.7% and 36.7%, respectively. Finally, the addition of hybrid steel fibre increased the maximum bond stress significantly. The improvement of the bond stress ranged from 39% (GCHYS2a) to 65.9% (GCHYS2b). Specimen GCHYS2b achieved the highest bond stress of geopolymer concrete. The slip corresponding to the maximum bond stress of Specimen GCHYS2b was 71.4% higher than the slip corresponding to the maximum bond stress of Specimen GC. It is apparent that the highest increase in the bond stress of geopolymer concrete was achieved by the addition of HYS fibre. This is due to the highest increase in the strength of geopolymer concrete as a result of the addition of HYS fibre, which affected the bond strength of the geopolymer concrete effectively.

The bond stress of all the specimens was adversely affected by the corrosion of reinforcing steel bar. The effect of corrosion on the bond stress versus free-end slip are shown in Fig. 12. It can be seen that the bond stress of Specimen GC noticeably dropped due to the loss of

interlocking action between the corroded steel reinforcing bar and concrete. The maximum bond stress of Specimen GC was 5.85 MPa with the corresponding slip of 1.35 mm. It was observed that the reduction in the bond stress of Specimen GC was greater than the reduction in the bond stress of the steel fibre reinforced geopolymer concrete specimens under the same corrosion condition. This indicates that the steel fibre reinforced geopolymer concrete specimens exhibited better corrosion resistance compared to Specimen GC. The main reason for the higher losses of the bond stress of Specimen GC might be due to the wide longitudinal cracks that were developed on the specimens, which allowed chloride ions to penetrate quickly into the concrete and accelerate the rate of corrosion.

The maximum bond stress of fibre reinforced geopolymer concrete with MIS fibre of 1%, 1.5% and 2% by volume increased by 41.9%, 53.5% and 75.38%, respectively, compared to Specimen GC. The strain corresponding to the maximum bond stress of fibre reinforced geopolymer concrete with MIS fibre of 1%, 1.5% and 2% by volume increased by 49.6%, 71.8% and 114.1%, respectively. Also, the addition of DES fibre to the geopolymer concrete with 1%, 1.5% and 2% by volume increased the maximum bond stress by about 26.2%, 31.3% and 47.5%, respectively, compared to Specimen GC. The strain corresponding to the maximum bond stress of fibre reinforced geopolymer concrete with DES fibre of 1%, 1.5% and 2% by volume increased by 5.2%, 9.6% and 58.5%, respectively. In general, the addition of steel fibre in the geopolymer concrete resulted in an increase in the bond stress. This might be due to the fact that the formation of corrosion on the surface of steel fibres increased the friction between the steel fibre and the geopolymer concrete.

Finally, the addition of HYS fibre increased the maximum bond stress significantly. The improvement of the bond stress ranged from 83.8% (Specimen GCHYS2a) to 185.6% (Specimen GCHYS2b). The highest bond stress of geopolymer concrete was achieved by

Specimen GCHYS2b. The slip corresponding to the maximum bond stress was increased by 138.5%. It can be seen from Fig. 12 that the HYS fibre reinforced geopolymer concrete with 1% MIS and 1% DES achieved the highest bond stress for corroded specimens compared to the geopolymer concrete specimens with other types of steel fibres. This can be attributed to the high volume fraction of steel fibres with different shapes and sizes which led to the increase in the availability of fibres crossing the cracked section. Hence, greater efficiency in delaying the growth of micro and macro cracks was obtained. Therefore, the highest improvement in the bond stress of geopolymer concrete specimens with HYS fibres was achieved.

4. Conclusions

An experimental study was carried out to evaluate the effect of corrosion on the bond behaviour of reinforcing steel bars embedded in steel fibre reinforced geopolymer concrete. Based on the results of the experimental investigations, the following conclusions can be drawn:

1. The addition of MIS, DES, and HYS fibres significantly improved the compressive strength and splitting tensile strength of geopolymer concrete mixes. The addition of 2% HYS (1% MIS and 1% DES) fibre by volume achieved the highest compressive strength and splitting tensile strength. All steel fibre reinforced geopolymer concrete specimens failed due to the splitting of concrete along the bonded length of reinforcing steel bar. The splitting failure occurred when the reinforcing steel bar reached the peak axial load, and cracks generated parallel to the applied axial load on the front face of the specimens as the bar pulled out. The failure of control plain geopolymer concrete specimen occurred due to the pull-out of the reinforcing steel bar. The pull-out failure occurred when the reinforcing steel

bar reached the peak axial load and pulled out from the specimen without splitting on any face of the concrete.

2. Due to accelerated corrosion process, the maximum measured cracks width was in the range of 0.15-0.25 mm and maximum measured crack depth was in the range of 1.5-4.5 mm for control plain geopolymer concrete specimen. However, only micro cracks were noticed on the steel fibre reinforced geopolymer concrete specimens.

3. The steel fibre reinforced geopolymer concrete specimens showed good resistance to chloride attack than control plain geopolymer concrete specimen. The addition of steel fibres to the geopolymer concrete significantly enhanced the bond stress and improved the corrosion resistance of the specimens.

4. The bond strength of the tested specimens increased with the increase in the volume content of steel fibres in the geopolymer concrete. The addition of 2% MIS, 2% DES and 2% HYS (1% MIS and 1% DES) fibres by volume achieved an increase in the bond strength by 38.27%, 32.86% and 65.98%, respectively, compared to the control plain geopolymer concrete specimen (Specimen GC). Due to the accelerated corrosion process, the bond strength of fibre reinforced geopolymer concrete with 2% MIS, 2% DES and 2% HYS (1% MIS and 1% DES) fibres by volume reduced by 54.92%, 60.54% and 38.84%, respectively.

The steel fibre reinforced geopolymer concrete exhibited better resistance to corrosion induced damage than plain geopolymer concrete specimens. The addition of steel fibres to the geopolymer concrete provided positive effects on the control of the corrosion of steel bar and concrete cracking. Steel fibres in geopolymer concrete led to smaller and more closely spaced cracks, which reduced the permeability of the geopolymer concrete.

Acknowledgments

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643

List of Tables

Table 1 Chemical compositions (mass %) of GGBS and FA.

Table 2 Properties of steel fibres.

Table 3 Mix proportion of geopolymer concrete [35].

Table 4 Test matrix.

Table 5 Properties of geopolymer concrete without and with steel fibres.

Table 6 Calculated and measured corrosion level.

Table 7 Results of pull-out tests for geopolymer concrete mixes.

644
645
646
647
648
649
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656
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662 **List of Figures**

663 Fig. 1 Schematic of the test specimens: (a) Elevation and (b) Plan (Dimensions are in mm).

664 Fig. 2 Pull-out test specimens.

665 Fig. 3 Schematic of the accelerated corrosion test set-up.

666 Fig. 4 Specimens during accelerated corrosion test.

667 Fig. 5 Pull-out test: (a) Schematic diagram and (b) Actual setup.

668 Fig. 6 Variation of current with time: (a) Geopolymer concrete specimens without and with
669 MIS fibres, (b) Geopolymer concrete specimens without and with DES fibres, and (c)
670 Geopolymer concrete specimens without and with HYS fibres.

671 Fig. 7 Non-corroded and corroded reinforcing steel bars.

672 Fig. 8 Specimens before and after the corrosion process: (a) Specimen GC, (b) Specimen
673 GCMIS2, (c) Specimen GCDES2, and (d) Specimen GCHYS2b.

674 Fig. 9 Failure pattern: (a) Specimen GC, (b) Specimen GCMIS2, (c) Specimen GCDES2, and
675 (d) Specimen GCHYS2b.

676 Fig. 10 General behaviour of bond stress versus slip.

Fig. 11 Bond stress versus slip for non-corroded: (a) Specimens GC and GCMIS, (b) Specimens GC and GCDES, and (c) Specimens GC and GCHYS.

Fig. 12 Bond stress versus slip for corroded: (a) Specimens GC and GCMIS, (b) Specimens GC and GCDES, and (c) Specimens GC and GCHYS.

Table 1

Chemical compositions (mass %) of GGBS and FA.

Component	GGBS	FA
SiO ₂	32.40	62.2
Al ₂ O ₃	14.96	27.5
Fe ₂ O ₃	0.83	3.92
CaO	40.70	2.27
MgO	5.99	1.05
K ₂ O	0.29	1.24
Na ₂ O	0.42	0.52
TiO ₂	0.84	0.16
P ₂ O ₅	0.38	0.30
Mn ₂ O ₃	0.40	0.09
SO ₃	2.74	0.08
LOI	NA	0.89

LOI: Loss on ignition

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Table 2
Properties of steel fibres.

Type of steel fibre	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Density (kg/m ³)
Micro steel (MIS) fibres [31]	6±1	0.2±0.05	>2600	7900
Deformed macro steel (DES) fibres [32]	18	0.55	800	7865

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728 **Table 3**

729 Mix proportion of geopolymer concrete [35].

Geopolymer mix	Quantity
FA (kg/m ³)	225
GGBS (kg/m ³)	225
Al/Binder	0.35
Aggregate (kg/m ³)	1164
Sand (kg/m ³)	627
Na ₂ SiO ₃ /NaOH	2.5
Na ₂ SiO ₃ (kg/m ³)	112.5
NaOH (kg/m ³)	45
NaOH (mole/liter)	14
Superplasticizer (kg/m ³)	22.5
Water (kg/m ³)	45

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Table 4

Test matrix.

Concrete mix	Type of steel fibre	Percentage by volume (%)
GC	Plain geopolymer concrete	0
GCMIS1	Micro steel fibre (MIS)	1 (1% MIS)
GCMIS1.5		1.5 (1.5% MIS)
GCMIS2		2 (2% MIS)
GCDES1		1 (1% DES)
GCDES1.5	Deformed steel fibre (DES)	1.5 (1.5% DES)
GCDES2		2 (2% DES)
GCHYS2a		2 (0.5% MIS+1.5% DES)
GCHYS2b	Hybrid steel fibre (HYS)	2 (1% MIS+1% DES)
GCHYS2c		2 (1.5% MIS+0.5% DES)

Table 5

Properties of geopolymer concrete without and with steel fibres.

Concrete mix	Average Compressive Strength (MPa) at 28 days	Average Splitting Tensile Strength (MPa) at 28 days
GC	41.1	3.7
GCMIS1	42.7	4.0
GCMIS1.5	42.8	4.9
GCMIS2	43.7	5.1
GCDES1	41.7	4.6
GCDES1.5	41.9	4.8
GCDES2	42.6	5.3
GCHYS2a	46.0	5.8
GCHYS2b	47.2	6.1
GCHYS2c	46.3	5.6

774 **Table 6**

775 Calculated and measured corrosion level.

Concrete mix	Calculated corrosion (%)	Measured corrosion (%)
GC	6.28	5.90
GCMIS1	3.36	2.25
GCMIS1.5	3.18	2.85
GCMIS2	3.15	2.19
GCDES1	3.68	2.40
GCDES1.5	3.30	2.31
GCDES2	3.22	2.13
GCHYS2a	3.12	2.11
GCHYS2b	2.40	1.94
GCHYS2c	3.14	2.04

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Table 7

Results of pull-out tests for geopolymer concrete mixes.

Concrete mix	Non-corroded specimens		Corroded specimens	
	Maximum bond stress (MPa)	Slip at maximum bond stress (mm)	Maximum bond stress (MPa)	Slip at maximum bond stress (mm)
GC	16.46	1.96	5.85	1.35
GCMIS1	21.12	2.46	8.30	2.02
GCMIS1.5	21.87	2.55	8.98	2.32
GCMIS2	22.76	2.98	10.26	2.89
GCDES1	20.56	2.44	7.38	1.42
GCDES1.5	21.22	2.60	7.68	1.48
GCDES2	21.87	2.68	8.63	2.14
GCHYS2a	22.88	2.94	10.75	2.68
GCHYS2b	27.32	3.36	16.71	3.22
GCHYS2c	23.87	3.06	11.75	2.52

(a) Elevation

(b) Plan

Fig. 1. Schematic of the test specimens: (a) Elevation and (b) Plan

(Dimensions are in mm).

Fig. 2. Pull-out test specimens.

Fig. 3. Schematic of the accelerated corrosion test set-up.

Fig. 4. Specimens during accelerated corrosion test.

Fig. 5. Pull-out test: (a) Schematic diagram and (b) Actual setup.

Fig. 6. Variation of current with time: (a) Geopolymer concrete specimens without and with MIS fibres, (b) Geopolymer concrete specimens without and with DES fibres, and (c) Geopolymer concrete specimens without and with HYS fibres.

Non-corroded reinforcing steel bars Corroded reinforcing steel bars

Fig. 7. Non-corroded and corroded reinforcing steel bars.

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(b)

(c)

(d)

Fig. 8. Specimens before and after the corrosion process: (a) Specimen GC, (b) Specimen GCMIS2, (c) Specimen GCDES2, and (d) Specimen GCHYS2b.

(a)

(b)

(c)

(d)

Fig. 9. Failure pattern: (a) Specimen GC, (b) Specimen GCMIS2, (c) Specimen GCDES2, and (d) Specimen GCHYS2b.

Fig. 10. General behaviour of bond stress versus slip.

(a) Specimens GC and GCMIS.

(b) Specimens GC and GCDES.

(c) Specimens GC and GCHYS.

Fig. 11. Bond stress versus slip for non-corroded: (a) Specimens GC and GCMIS, (b) Specimens GC and GCDES, and (c) Specimens GC and GCHYS.

(a) Specimens GC and GCMIS.

(b) Specimens GC and GCDES.

(c) Specimens GC and GCHYS.

Fig. 12. Bond stress versus slip for corroded: (a) Specimens GC and GCMIS, (b) Specimens GC and GCDES, and (c) Specimens GC and GCHYS.