

**Figure 2. Schematic view of direct pull-out test setup.**

### **3. Experimental results and discussion**

The failure mode of the different samples, and the different bond strength values of the different types of concrete and bars were observed and the results may be summarized as follows.

#### **3.1 Failure of the test specimens**

##### **3.1.1 Pullout failure**

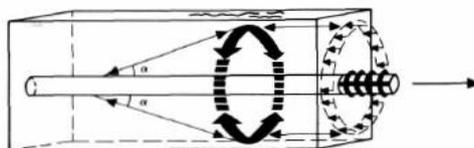
All plain bar embedded lollipop specimens failed by the bar pulling out of the concrete matrix. The pull-out procedure could last a long time and result in a very large displacement. So the maximum failure load was defined as being the load when displacement recorded by the LVDT reached 200 microns. The failed samples did not show obvious cracks on the surface. As shown in Figure 3, the four types of concrete tested samples still kept their integrity.



**Figure 3. The test apparatus of lollipop pull-out test.**

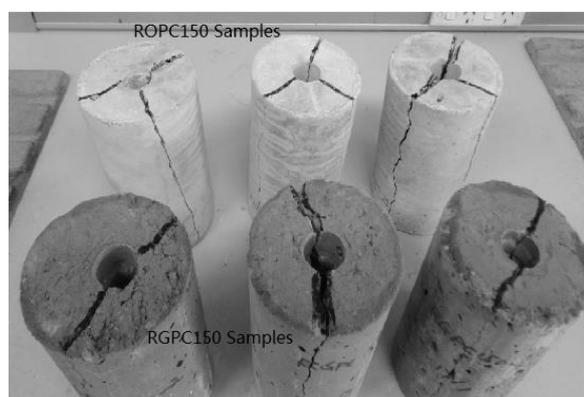
### 3.1.2 **Splitting failure**

However, the ribbed bars showed a totally different mode of failure-splitting failure. The ribs on the bars transferred the longitudinal tensile stresses to the surrounding concrete in the form of compressive stresses in an oblique direction (Figure 4).



**Figure 4. Schematic representation the bond forces in ribbed bar reinforced concrete (Tepfers 1979).**

According to Tepfers (1979) the oblique bond stress on the surrounding concrete could be divided into tangential and radial components. The radial components could be imagined as hydrostatic pressure, which results in a ring of tensile stress. Splitting cracks develop when the radial component of the bond stress exceed the tensile resistance of the concrete section. Without obstacles, inner cracks finally reach the surface of cylinder and split the concrete matrix into pieces. This mode of failure is called splitting failure. Figure 5 shows the splitting failure of GPC and OPC concrete samples. At the failure moment, the concrete matrix suddenly fractured and broke into sections without warning. Splitting failure is a sudden mode of brittle failure which is not welcomed by engineers.



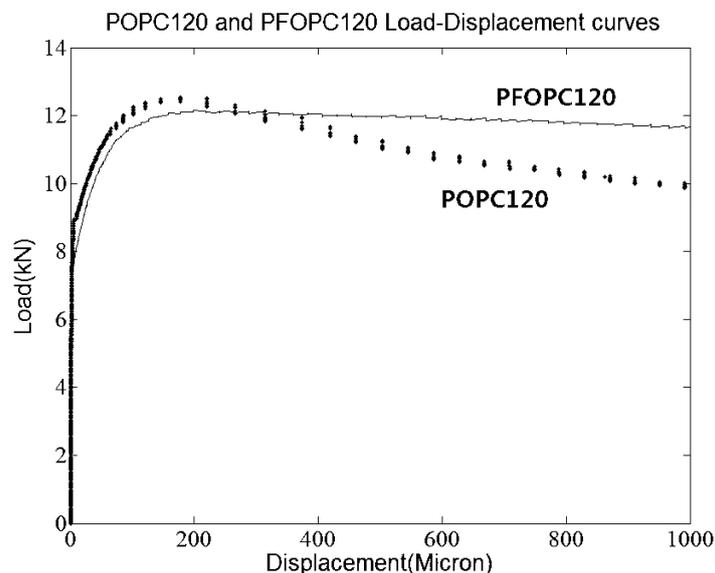
**Figure 5. Tested ribbed bar embedded GPC and OPC samples.**

### 3.2 **Influence of fibres**

Extensive experimental and analytical studies have shown that the addition of fibres to concrete matrix improves most of the mechanical properties of cement-based composites, especially the ductility. In this research, generally the fibre reinforced concrete samples showed much higher ductility in pull-out tests than plain concrete samples.

### 3.2.1 Plain bar tests

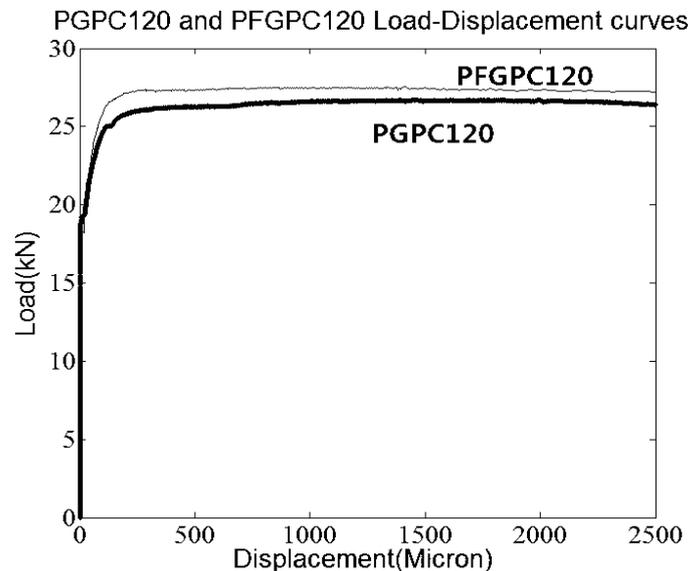
In plain bar reinforced FOPC samples the ductility was demonstrated by mild descending branch on the Load-Displacement curves. Comparing the Load-Displacement curves of POPC120 and PFOPC120 (Figure 6), it is clear that at the beginning, the pull-out load values of the two kinds of samples ascend similarly and the slopes of the two curves at the ascending branch are almost the same. After climbing to similar peak values, the descending branch of the two curves behave differently. In the pull-out process, the load value of POPC120 samples dropped sharply while the curve representing PFOPC120 samples gently decreased. At the 1000 micron displacement point the load value of POPC120 has already fallen to 10kN from 12.5kN (peak load), whereas the load values of PFOPC120 has only slightly declined by 7% (from 12.6kN to 11.7kN). The area surrounded by the Load-Displacement curve of PFOPC is larger than in the case of POPC. This means more energy was stored during the FOPC samples' pull-out procedure.



**Figure 6. POPC120 and PFOPC120 Load-Displacement curves.**

When it comes to PGPC and PFGPC samples, however, there is no evident difference in the characteristics of their Load-Displacement curves. As shown in Figure 7, the shape of the bond Load-Displacement response of geopolymer composites is not influenced by the addition of fibres. The curves of the PGPC120 and PFGPC120 samples ascend similarly and then locate on a flat period after reaching the similar peak load value. This flat stage on the curves represents the stable pull-out process in tests. This process started after the chemical adhesion between concrete and steel was overcome, when the relative slip between bar and concrete matrix started and further developed. In the figure it can be seen that the relative slip (displacement) kept increasing at a constant residual bond resistance contributed by friction. The close values of residual bond stress for PGPC and PFGPC indicate that the introduction of fibres does not influence the

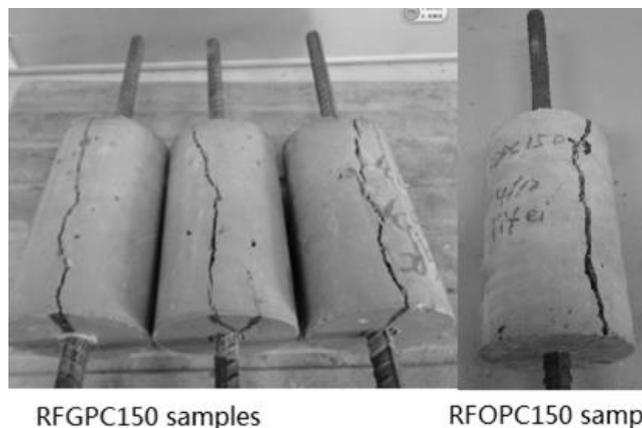
value of friction on the interfacial area of geopolymer concrete and plain bars. By comparing the bond performance of PGPC and PFGPC, it may therefore be concluded that the presence of steel fibres does not have a significant effect on the bond resistance of geopolymer composites with embedded plain bars.



**Figure 7. PGPC120 and PFGPC120 Load-Displacement curves.**

### **3.2.2 Ribbed bar tests**

In the case of ribbed bars embedded in the two types of fibre reinforced samples (RFOPC and RFGPC), an improvement of ductility over the case of plain bars, was observed more. Though RFOPC and RFGPC samples still failed because of the splitting of the concrete matrix, the failure was much gentler than in plain concrete. The fibres seem to have disturbed the developing of inner cracks, thus obstructed the residual splitting cracks from quickly and suddenly reaching the surface of the sample, and hence delayed the occurrence of matrix splitting as well as reduced the crack width. Thus, by the end of the test the fibres kept the sample in one whole piece (Figure 8).



**Figure 8. Tested ribbed bar embedded FGPC and FOPC samples.**

### 3.3 Comparison of bond strength

The average ultimate pull-out load results are listed in Tables 5 and 6 (The number in each cell represents the average value of 3 identical samples). The average ultimate pull-out load of each specimen is divided by the surface area of the bonded length of the bar to get the average bond strength. This has been the conventional method used for determining the value of bond strength (Kayali 2004).

**Table 5. Bond strength of plain bar embedded samples.**

Specime n	Average Pull -out load,P(K N)	Average Bond strength u(Mpa)
PGPC12 0	26.6	4.4
PGPC15 0	30.0	4.0
POPC12 0	12.5	2.1
POPC15 0	14.4	2.0
PFGPC1 20	27.1	4.5
PFGPC1 50	28.9	3.9
PFOPC1 20	12.6	2.1
PFOPC1 50	14.2	1.9

The most striking observation in the results shown in Table 5 is that in the case of plain bars embedded in plain concrete, GPC has been clearly superior to OPC in its bond strength. In fact, the improvement has been as high as 125% and 110% for 120 mm and 150 mm embedment, respectively. In the case of plain bars in fibre reinforced concrete, the improvement in bond strength of GPC compared to OPC concrete was 47% and 58% for 120 mm and 150 mm embedment length respectively. The results of plain bars illustrated that the inorganic chemical composition of geopolymers could provides much higher adhesion with steel.

According to the test results of plain bars shown in Table 5, it may be observed that the presence of fibres did not have a significant effect on the bond resistance as far as embedded plain bars are concerned. Neither PFGPC nor PFOPC show obvious change in the magnitude of peak bond strength in comparison with PGPC or POPC. This could be explained in that

before the appearance of relative slip, the bond resistance between plain bar and concrete is mainly attributed to the chemical adhesion between concrete and steel bars. The magnitude of chemical adhesion is dependent on the chemical composition on the interfacial area between concrete and steel. Adding fibres into the concrete is not expected to influence the chemical composition of the interface.

Another observed result, as shown in the Table is that, the ultimate loading has increased when changing the embedment length from 120mm to 150mm, yet the average bond strength values calculated from the traditional way (simply by dividing the load by the cylindrical area) have reduced. This is not expected, as the bond strength is one of the properties that are expected to be irrelevant to embedment length. This observation may lead to the conclusion that the traditional calculation method for bond strength is imprecise in the case of plain bars. Other factors beyond the scope of this paper must also be influencing this behavior.

**Table 6. Bond strength of ribbed bar embedded samples.**

Specimen	Average Pull-out load, P(KN)	Average Bond strength u(Mpa)
RGPC120	56.6	9.4
RGPC150	70.0	9.3
ROPC120	47.7	7.9
ROPC150	59.6	7.9
RFGPC120	65.6	10.9
RFGPC150	86.5	11.5
RFOPC120	62.5	11.4
RFOPC150	71.1	9.4

The test results for ribbed bars illustrate some different effects. Firstly, all fibre reinforced concretes showed much higher bond strength here. In Table 6 we could see that compared with RGPC, the bond strength of RFGPC increased 124% and 116% for 120 mm and 150 mm embedment length, respectively. In the case of ribbed bars in FOPC and OPC, the improvement in bond strength of FOPC over OPC, was 44% and 19% for 120 mm and 150 mm embedment length respectively. This improvement could be explained in that the bond between ribbed bar and concrete mainly comes from mechanical interlock between the bar and concrete. Thus the failure of ribbed bars embedded samples was all manifested by the splitting of concrete matrix. Adding fibres into the matrix could prevent the splitting failure of concrete by improving its tensile strength and arresting the development of inner cracks. In this way, the bond strength has benefited considerably.

Secondly, the same trend where the GPC/FGPC was showing superiority to OPC/FOPC in pull-out loads and bond strengths has continued. In spite of

the improvement being much less significant than that seen in the plain bars case, it should be pointed out that here the effective contribution to bond strength comes largely from the ribs. The improvement in the bond strength of GPC/FGPC compared to that of OPC/FOPC could be explained by the higher splitting tensile strength of GPC/FGPC at similar compressive strength (As shown in Tables 2 and 3). The increase in tensile strength has delayed the splitting failure of the fibre reinforced concrete samples.

Thirdly, it is also noticeable that, unlike plain bars, the average bond strength values calculated using the traditional method are more or less the same for different embedment lengths. In other words, the calculations of bond strength are more reliable here. It therefore seems, that when the ribs are involved, the factors influencing the accuracy of bond strength calculations of plain bars, become insignificant compared to the effect of the ribs.

### **3.4 Micro explanation**

The very different bond behavior of bond between GPC and OPC could be explained by the different microstructures at the bond interfaces. For reference to the microstructure of intimate contact surface between OPC and steel, compressive reviews are available and, in the former contributions, concerns have been solely directed to crystal structures formed at the interfacial layer. Compare with the bulk, the interfacial zone between steel and OPC has quite unique characteristics in the form of higher porosity and larger crystals (Obada 2004). There is formed a dense layer consisting largely of hexagonal lamellar crystals of calcium hydroxide (portlandite) (Lee 2016) and needlelike hydrous calcium aluminium sulfate (ettringite).

## **4. Conclusions**

This study has investigated the bond strength of plain geopolymer concrete and fibre reinforced geopolymer concrete. The following conclusions are drawn:

Firstly, Geopolymer concrete showed modes of failure similar to those of OPC concrete under pull-out load. Both ribbed bar reinforced GPC and OPC specimens failed in a brittle manner by splitting of concrete along the bonded length of the pull-out bar. Both plain bar reinforced geopolymer and OPC concrete specimens failed in slippage caused by losing adhesion between concrete and steel.

Secondly, FGPC showed much higher bond with ribbed bars than plain GPC. However if the bars were smooth, no significant difference was found between these two concrete types.

Thirdly, GPC and FGPC both showed higher bond strength with ribbed bars than OPC concrete and FOPC concrete, respectively. This is because of the higher splitting tensile strength of GPC and FGPC compared to their OPC counterparts at similar compressive strength.

Lastly, compared with OPC and FOPC, GPC and FGPC both showed remarkable bond with plain bars. This is believed to be a result of the strong chemical adhesion between the geopolymer binder and steel.

## 5. Acknowledgement

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