

# Bond behaviour of geopolymer concrete in structural application: A review

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**Abstract.** Sustainable manufacturing materials are being developed and utilized until now due to its remarkable reduction of carbon footprint along with significant structural and mechanical performances. To gain wide acceptance in the construction industries, the bond between geopolymer concrete and the reinforcing bar should be investigated beforehand. It is a critical factor that influences the behaviour of structures, specifically bond strength that will be very crucial for structural applications. Therefore, this paper review aims to describe and summarize the utilization of GPC on previous pull-out testing. A total of 10 papers on the pull-out test with different bond strengths and parameters have been summarized and discussed. Findings from the results show that effect of geopolymer blending, compressive strength, cover-to-diameter (C/D) ratio and embedment length of GPC specimens have a significant influence on the bond strength. Based on the parameters from previous experimental studies, GPC is comparable with OPC concrete, but further research needs to be carried out to investigate the structural behaviour utilizing GPC for construction application.

## 1. Introduction

As the world highest consumed building material, it is estimated that worldwide concrete consumption is currently at 1 m<sup>3</sup> per person. This result in about 7 billion tonnes of carbon dioxide (CO<sub>2</sub>) released into the atmosphere [1]. Apart from that, concrete research has been widened towards the use of industrial by-products and wastes [2,3]. The materials have the potential to substitute Ordinary Portland Cement (OPC) as the conventional concrete, since their performances have been proven. Thus, there is a possibility for the materials to be utilized in construction industries. To produce such cement-less concrete, a process termed as ‘geopolymerization’ will be required to trigger the chemical reaction between aluminosilicate materials and alkaline activator under a high temperature to produce geopolymer concrete (GPC). Such mechanism is important for further bond analysis for GPC. To now, fly ash, slag, rice husk ash and palm oil fuel ash are discovered as aluminosilicate materials, in which capable to govern the structural performance of concrete [4].

Figure 1 depicts one of the latest applications of GPC in structural application. Known as the first geopolymer structure in the world, Global Change Institute in The University of Queensland has successfully utilized fly ash/slag-based GPC as precast floor beams to form three suspended floor levels of the innovative and sustainable building technologies for future generations [4].





**Figure 1.** Structural geopolymer concrete in Queensland's University (Global Change Institute) with three suspended floors [4].

The bond behavior between steel reinforcement and GPC has been evaluated in many studies in past due to its similar attributes with OPC. Flexural behavior at serviceability, ultimate limit states and shear capacity are strongly influenced the bond interaction. In addition, the formation of cracks in terms of width and spacing for tension stiffening and anchorage of reinforcement are governed by the bond as well [5-8]. Hence, current study will review the bond behaviour of GPC affected by geopolymer blending, compressive strength, concrete-to-cover ( $C/D$ ) ratio, and embedded length to be utilized for the structural application.

## 2. Importance of Bond Behavior to Structural Application

One of the main contributors to the structural behaviour of reinforced concrete (RC) is the concrete-steel bond properties [9]. It is represented as shear stress at the interface between the reinforcing bar and concrete. In conventional RC application, efficient and reliable force transfer between reinforcement and concrete is required for optimal design for safety measure in structural components [10]. The transfer of forces from the reinforcement to the surrounding concrete occurs for a deformed bar by adhesion, friction and mechanical bearing [11]. The mechanism will then affect the bearing capacity of structural members, crack spacing and crack width in tension stiffening [12].

In determining bond behaviour, failure mode of concrete is the key especially for development of accurate local bond stress-slip for reinforcing bars in both concretes. In GPC aspects, this will determine the material properties based on bond test performed and very useful for prediction of concrete structural performances, specifically bond strength [13]. Bond strength was obtained from bond test of concrete specimens in the experimental work. Some of previous studies derived bond strength equation based on several parameters in the specimens such as compressive strength,  $C/D$  ratio and embedment length that influence tension stiffening, in governing the ability of the reinforcement to transfer tensile stresses to the concrete [14].

GPC utilization in structural application is being widely studied. Generally, the advantage of GPC is over OPC especially in terms of bond strength, depending on efficiency of bond interaction from material and mechanical properties. The criterion is important to examine the structural performance of the specimens. Besides, due to many common similarities between the GPC and OPC, existing design equation and code provision used for bond strength of OPC can be applied for GPC [10,16].

### 2.1. Evaluation and Code Provision of Bond Behaviour for Geopolymer Concrete

Bond test was performed to assess the bond between concrete and reinforcing steel bar. In terms of GPC, generally, it exhibits comparable bond strength to OPC [10,16]. Various types of GPC were utilized in recent studies, including fly ash (FA), palm oil fuel ash (POFA), metakaolin (MK) and granulated ground blast furnace slag (GGBFS). Those materials could lead to promising results of bond strength, for partial replacement or full replacement. This test was being widely used because of its ease of specimen fabrication and the simplicity of the test [20]. Bond force-slip and bond stress-slip curves were tabulated for better understanding of the nature of bond response [11]. The most common bond tests for assessing the behaviour is pull-out test [10,16]. Table 1 depicts different provisions for bond tests that were previously applied in determining the bond strength.

**Table 1.** Summary of bond tests from previous studies using GPC.

| Authors (Years)              | Test standard                            |
|------------------------------|--|
| [12], [20], [21]             | Pull-out test<br>(BS EN 10080:2005)      |
| [14], [26], [22], [15], [17] | Pull-out test<br>(RILEM 7-II-128)        |
| [18]                         | Pull-out test<br>(IS-2770-1967-Part-I)   |
| [23]                         | Pull-out test<br>(ASTM C234 (ASTM 2000)) |

Code provision is one of the important things in bond evaluation of concrete. Currently, there are no specific provisions utilized in structural and mechanical performance evaluation for GPC. However, provision for conventional concrete is conservative and can be applied for GPC. Although different regions implement different types of code provision, eventually, the behaviour of GPC have the same trend like OPC when the pull-out test was performed. From previous studies, bond investigations were carried out using direct pull-out test in accordance to EN-10080, RILEM, IS 2770 and ASTM C234 for bond strength prediction and bond comparison with OPC concrete [20].

Based on reviewed papers, EN-10080:2005 was utilized for studies on different volume of fly ash, compressive strength, reinforcement diameters, corrosion level, types and volume of steel fibres used [12,20,31]. The range of bond strength was between 27.32 MPa and 35.61 MPa, among the highest compared to bond strength using other standards. RILEM 7-II-128 standard was applied for studies on different C/D ratio, compressive strength, types of rebar, curing schemes, volume of binder and water-to-binder (W/B) ratio [14,15,17,22,26]. This test was commonly used as a comparison between OPC as control specimen and experimental GPC specimen [28].

ASTM C234-91 was applied as a standard test method for studies on different concentration of alkaline activator,  $\text{Na}_2\text{SiO}_3/\text{NaOH}$  ratio and curing schemes [23]. This testing method, however, was later disbanded due to the high level of inconsistency that the test yields [28]. IS 2770-1967-Part 1 was utilized for studies applying additional of steel fibres as additional reinforcement to the steel bar with different volume fraction, as well as the diameter of rebar [18]. Regardless of standards and code provision applied in performing the bond test, generally, the bond strength from the literature studies were evaluated through the interaction between the steel reinforcing bar the concrete surrounding it. It is very useful in determining development length, cover depths and bar spacing as reinforcement details according to respective provision for further prediction of performance of structural components [12,31].

### 2.2. Failure mode for GPC from previous studies

It was assumed that the interaction of reinforcing steel bar and GPC to be uniformly distributed along the embedded length of the steel bar, known as interfacial bond stress. From the maximum applied

loading during pull-out test, average bond stress ( $\tau$ ) was calculated in order to determine the ultimate bond strength ( $\tau_u$ ) of GPC [15]. As a result, failure mode could be observed from the specimens tested. From a pull-out test performed by [21], splitting failure mode can be observed from the study which is in line with [23]. The main contributor of the failure were the fly ash content in the design mixes and concentration of alkaline activator. Table 2 below shows the summary of failure mode after pull-out test was performed.

**Table 2.** Summary of failure mode from previous studies

| Author | Failure mode  | Findings  |
|--------|---|---|
| [21]   | Splitting   | Volume of fly ash replacing aggregates increase bond strength   |
| [22]   | Pull-out and splitting                                | The higher binder content, improved the bond strength   |
| [14]   | Pull-out and splitting                                | Bond behaviour increases with increasing duration of thermal curing in wet conditions   |
| [15]   | Pull-out, splitting and splitting-bond failure        | GPC exhibits similar or better bond properties than OPC concrete, both at ambient temperature and after exposure to elevated temperatures |
| [17]   | Pull-out, splitting and yielding of the reinforcement | Addition of FA has resulted in decreased of compressive strength which will affect bond strength  |
| [26]   | Pull-out and splitting                                | Smaller reinforcing diameter and larger concrete cover size gave higher bond strength to the bond specimens                               |
| [18]   | Pull-out and yielding of the reinforcement            | The bond may be affected by the addition of steel fibres, since the contact area is larger in these specimens                             |
| [12]   | Pull-out  | Bond stresses decreased as the diameter of reinforcement increased  |
| [20]   | Pull-out and splitting                                | Addition of steel fibres in GPC significantly enhanced the bond strength of reinforcing steel bar   |
| [23]   | Splitting   | High bond strength was due to the relatively high splitting tensile strength  |

It was found that the bond strengths resulted in pull-out and splitting failure utilizing lightweight GPC, attributed by the greater binder content used for the replacing coarse aggregate [22], same like what was observed by [21] but in context of fly ash content. For [7], the failure mode for all specimens was due to the pull-out of the steel bar, leading the concrete splitting, for 2 days curing and for the 7 days heat curing, yielding of the steel bar followed by concrete splitting at failure was observed. Bond strength for GPC based on a study carried out by [15] resulted in typical splitting failure, bond failure (pull-out failure), a combination of splitting and bond failure (splitting-bond failure), and rebar fracture according to the curing schemes. Regardless of curing schemes, GPC performance is similar or better than corresponding OPC. Three types of failure mode, namely bar pull-out, yielding of steel bar (steel fracture) and splitting of concrete was observed by [17], depending on the W/B ratio, fly ash volume and type of steel reinforcing bar used.

In another investigation, [26] observed pull-out and splitting failure for different cover, reinforcing bar diameter and their C/D ratio. However, the studies utilized oil palm shell concrete (OPSC) instead

of commonly used FA with interlocking effect of oil palm shell (OPS). Using different volume fraction of steel fibres blended with GPC mixtures, [18] found out failure mode of yielding of the reinforcement and pull-out. Another study observed pull-out failure mode only from the bond test with different compressive strength and reinforcement diameters [12] whereas [20] performed a study on bond behaviour of reinforcing steel bars and fibre reinforced geopolymer concrete with failure mode of splitting cracks and pull-out, in which the bond strength was calculated based on accelerated corrosion schemes. Lastly, a study performed by [23] utilizing high calcium fly ash found bond behaviour with failure mode of concrete rupture, which is identical to concrete splitting.

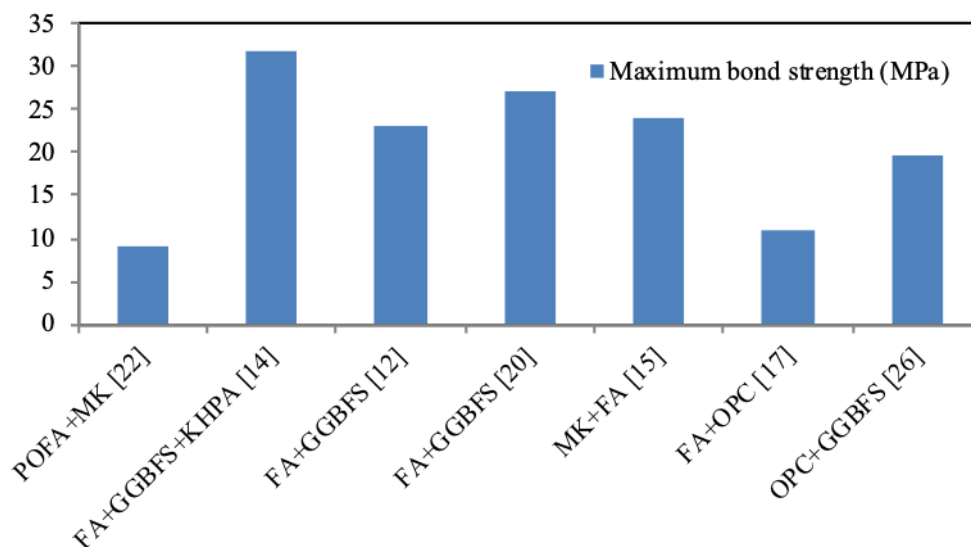
### 3. Parameters controlling the bond strength

Knowledge of the bond between reinforcement and the surrounding concrete is essential in the analysis and design of RC members at both the serviceability and ultimate limit states, especially for GPC [24]. This includes the parameters governing the bond behavior that are very wide including geopolymers blend, compressive strength, C/D ratio and embedment length where all of them are taken into account as crucial factors contributing to the bond behavior of GPC [25].

Commonly, normalized ultimate bond strength was utilized since the concrete compressive strength of specimens differs to each other, and to eliminate the effect of variation in the compressive strength [16,22,26]. Those varieties are most probably attributed to the differences in the composition of the geopolymer binder, such as type of binder material and molarity of solution as well as the curing method and these aspects would require further investigation [22]. The following subsection shows the bond strength from 10 previous studies performed in terms of geopolymer blending, compressive strength, C/D ratio and embedment length.

#### 3.1. Influence of geopolymer blending on bond behaviour

Figure 2 shows the summary of bond strength in terms of geopolymer blending. It was recommended to apply the addition of slag in geopolymer matrix, especially FA to accelerates the curing process and gain higher bond strength as what can be observed from [14] that obtained the highest maximum bond strength.



**Figure 2.** Maximum bond strength from previous studies in terms of geopolymer blending.

Out of 10 papers reviewed, seven papers utilized blending of various types of sources. They exhibit many of the characteristics of traditional concretes, despite their vastly different chemical composition and reactions [10,19]. Based on a study by [22], the GPC consisted of predominantly blending of POFA and metakaolin (MK) that having an inherent irregular shape. They are capable in entrapping

air and result in more porous geopolymer binder. Compared to fly ash and slag, POFA have higher water absorption and porosity, resulting in degradation of the performance of such concrete in structural application. The maximum bond strength obtained from this study was 9.12 MPa for the blending of the lightweight GPC due to higher binder content adopted, which will enhance quality of binder matrix. Eventually, adhesion between lightweight concrete and steel bar can be improved [22].

Blending of low-calcium FA, high performance ash (KHPA) and GGBFS was performed by [14] in fabricating GPC specimen. However, those blends emphasized on the curing schemes, where temperature effect was taken into account. The maximum bond strength obtained from this study was 31.9 MPa with a longer period in heated water bath at 80 °C. It was observed that longer duration of wet thermal curing could lead to higher bond strength due to longer polymerization process took place, inducing bond development [14]. This study applied wet curing scheme but not for [22]. There are huge difference in terms of maximum bond strength, where [14] achieved 71.41 % higher bond strength compared to [22], most probably attributed due to the different curing condition.

A bond test for GPC was conducted by blending MK and FA [15]. The study also focused more on curing temperature, as the main parameters affecting the bond behaviour of geopolymer concrete with reinforcing steel bar, either plain or ribbed. The maximum bond strength obtained from this study was about 24 MPa. In line with the [14], this study agreed that higher curing temperature would lead to increment in bond strength, but up to 300 °C only. If higher than that, the bond strength will be degraded, attributed to the incompatibility in deformations between GPC and rebar during thermal expansion under heating state and thermal shrinkage under cooling stage [15]. However, [14] achieved 24.76 % higher maximum bond strength compared to [15].

By blending FA and OPC, [17] found that the maximum bond strength was about 11 MPa by 30 % replacement ratio of FA replacing OPC using ribbed rebar. Addition of FA volume as binder resulted in change in microstructure, especially porosity that eventually reduce the compressive strength by lowering gripping capacity of concrete, which is in line with observation made by [22] and [14]. Maximum bond strength for this study is 17.09 % higher than what was observed by [22] and 65.51 % lower than what was observed by [14].

Another study performed by [26] utilizing blending of OPC and GGBFS as binder with oil palm shell (OPS) as the coarse aggregate found that the maximum bond strength obtained was 19.63 MPa. Higher bond strength for such concrete compared to corresponding OPC concrete was most probably attributed to higher cement content as well as good aggregate interlocking effect of oil palm shell (OPS) [26-27]. However, the studies focused more on the effect of C/D ratio of specimens instead of the geopolymer blending itself. This study is a precursor for the POFA and metakaolin blended GPC discussed previously and it was found that bond strength in the precursor study is 53.54 % higher compared to [22], attributed to minimization of OPC utilization.

Blending of FA with GGBFS was performed by [12] and it was found that, the maximum bond strength was 23.06 MPa for different compressive strengths of concrete and various reinforcement diameters. The bond stresses decreased as the diameter of reinforcement increased for all the specimens. Compared to [14] with same blending scheme, [12] observed a maximum bond strength of 27.71% lower, attributed to the curing scheme provided to the latter study. However, former study did not study into detail regarding the blending of FA and GGBFS, but it is recommended to blend FA with GGBFS to accelerate the curing time and enhance the strength of specimens [32].

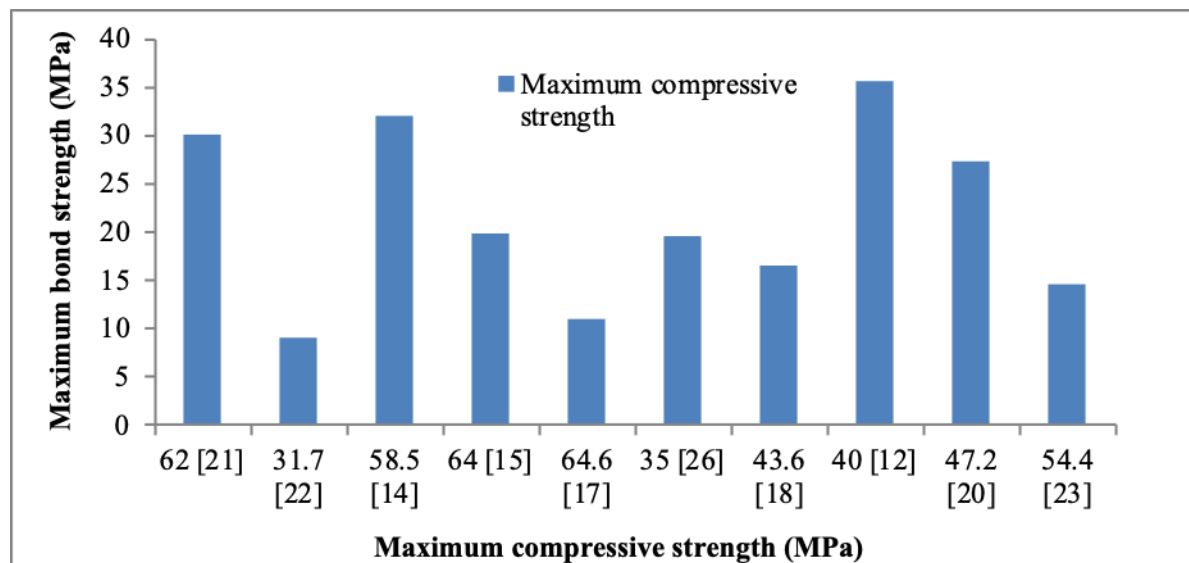
Lastly, [20] performed pull-out test and found that the maximum bond strength was 27.32 MPa by blending various types of steel fibres with FA and GGBFS, same schemes with [14] and [12]. This study obtained maximum strength of 15.59% higher than what was obtained by [12], whereas 12.13% lower than what was obtained by [14], attributed to different curing scheme, accelerated corrosion effect on the steel bar and addition of steel fibre on the specimens.

### *3.2. Influence of compressive strength on bond behaviour*

Most of the previous studies discussed effect of compressive strength on the bond behaviour of GPC and OPC. It was found that the bond strength between the GPC and the steel reinforcement increases significantly with increasing the corresponding compressive strength, with maximum value of 62 MPa [21]. This observation depends on different sources of FA, fly ash content and  $\text{Na}_2\text{SiO}_3/\text{NaOH}$

(sodium silicate-to-sodium hydroxide) ratio in the GPC mixture. Different sources will give different chemical composition of the respective FA. Higher SiO<sub>2</sub> content also will lead to a higher compressive strength, leading a higher bond strength compared to other sources [21].

However, a study performed by [12] concluded that compressive strength levels of GPC showed no significant influence on bond strength, with maximum value of 40 MPa. This may be attributed to the blending of the GGBFS with the FA in that study, altering the SiO<sub>2</sub> content, which will contribute to an insignificant effect in terms of bond strength. The study by [20] also utilized the same binder scheme just like [12], however, the effect of corrosion and additional of steel fibre was more significant compared to the effect of compressive strength, with maximum value of 47.2 MPa, on its bond strength. Figure 3 depicts the relationship of compressive strength and respective bond strength from previous studies.



**Figure 3.** Summary of maximum bond strength from previous studies in terms of compressive strength.

Bond strength of GPC and OPC are comparable, even though GPC failed at an earlier stage, attributed to the durability of GPC that are less porous and more compact compared to OPC [29]. This was in line with a study performed by [22], where higher bond strength of geopolymer lightweight concrete compared to the geopolymer normal weight concrete attributed to the greater binder content and lesser coarse aggregates content used in the mix design for the former to produce comparable concrete compressive strength, with maximum value of 31.7 MPa. Another studies performed by [26] also shows the same observation, with better mechanical interlocking effect due to the use of lightweight expanded shale aggregate improved the bond strength of lightweight concrete, with maximum compressive strength of 35 MPa. It was concluded that a higher compressive strength, with maximum value of 35 MPa, increases the resistance to concrete crushing and shearing between the ribs, and therefore the resistance to pull-out of the steel bar [26].

It was observed that for equivalent compressive strength, with maximum value of 58.5 MPa, GPC performs slightly better than OPC, where on average, 10 % of increment was observed [14]. However, this was applicable to ribbed bars. For smooth bar, OPC performs better compared to GPC. So, better chemical adhesion between concrete and steel bar for GPC compared to OPC was not the main reason for the better bond performance. It was the tensile strength that improves the shear resistance of concrete between ribs which in the end increasing the bond strength [14].

In another study by [15], although GPC and OPC concretes exhibited similar compressive and splitting tensile strengths, GPC concrete exhibited higher bond strength than that of OPC concrete, both at ambient and after exposure to elevated temperatures, with maximum compressive strength of 64 MPa which is the second highest compared to other reviewed studies [15]. It was found out that

[17] achieved highest compressive strength of 64.6 MPa. Compared to other reviewed papers, the compressive strength has a significant influence on the bond strength and slip of steel bars in FA concrete or high volume fly ash concrete (HVFAC), especially when fly ash replaces 50 % of cement. The bond strength of the bar in concrete decreasing gradually as concrete's internal porosity increased because more FA is added in the concrete. At the same time, the degradation of the concrete compressive strength caused by the addition of FA also significantly affects the gripping or wrapping capacity of the concrete to steel bar [17].

However, [18] did not highlight the effect of compressive strength on the bond strength in the study, with maximum value of 43.60 MPa. Instead, it was concluded that the bond strength decreases with increasing fibre percentage, attributed by local disturbance in the concrete matrix, preventing proper compaction in the vicinity of the reinforcing bar, leading to bond strength, regardless of the compressive strength [18].

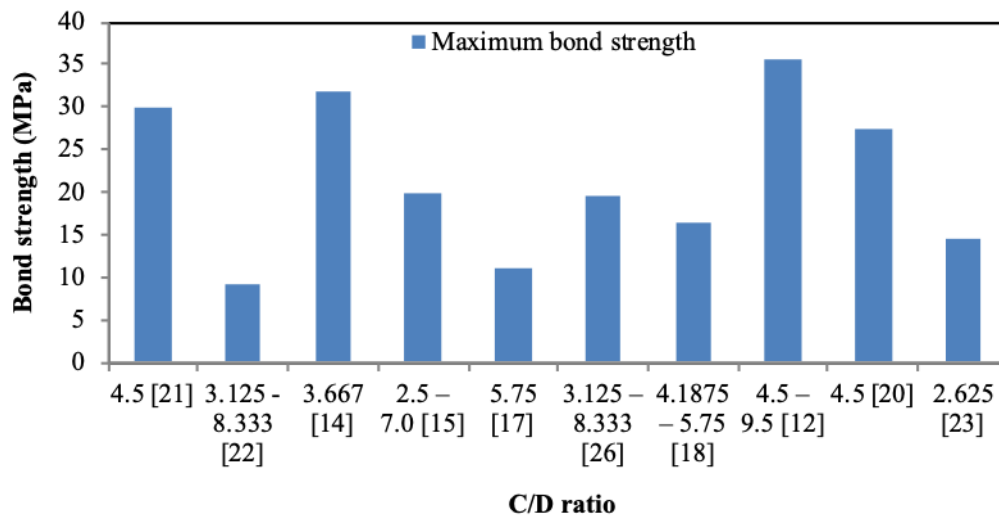
It was observed that peak bond resistance of all the corroded specimens is lower than the uncorroded one and decreases as the corrosion level increases, due to the occurrence of corrosion cracking as studied by [20]. The confinement action from the cracking could be reduced, leading to lower bond strength, especially at higher corrosion levels. It was in line with [30] that supported this observation, where with increased corrosion, the mechanical interlocking between the ribs and concrete deteriorates, reducing the compressive strength eventually the bond strength. Specimens with hybrid steel fibre (HYS), from the blending of micro steel fibre (MIS) and deformed steel fibre (DES), performs better compared to the others, where there were increase in the compressive strength of geopolymer concrete, attributed to the role of the steel fibre in bridging the cracks, which restrained the initiation and propagation of cracks [20]. Even though compressive strength was not highlighted in the study, from the data tabulated, the bond strength increases as the compressive strength increases, with maximum value of 47.2 MPa regardless of the steel fibre scheme and corrosion level.

Lastly, [23] investigated high calcium fly ash-based geopolymer concrete (HCGC) and concluded that bond strength of high-calcium geopolymer concrete was related to compressive strength of the concrete, with maximum compressive strength of 54.4 MPa. The high bond strength was due to the relatively high splitting tensile strength as reported by several authors on bond strength between deformed bar and low-calcium geopolymer concrete [10,16]. The high splitting tensile strength was related to interfacial transition zone (ITZ) strength and was also influenced by the amount  $\text{Na}_2\text{O}$  and  $\text{Na}_2\text{SiO}_3$ . The NaOH concentration also played an important role in bond strength. However, this study was not in line with what was observed by [33] in which stated that low calcium fly ash is mainly chosen over high calcium fly ash due to the high amount of calcium. It may interfere with the geopolymerisation process as it tends to produce calcium silicate hydrates [33]. Besides, only [23] observed the behaviour of the Class C fly ash compared to other reviewed papers. The chemical composition for such type of fly ash is still being investigated to be used as construction materials.

### *3.3. Influence of concrete cover-to-diameter (C/D) of reinforcing bar on bond behaviour*

From the reviewed papers, there are four studies highlighted on the C/D ratio including [22] and [26] for two different investigations. One of them includes the blending of POFA and MK as the binder. The splitting cracks were observed due to lower C/D ratio provided, which was 3.125 with bond strength of 6.81 MPa, whereas for C/D ratio of 8.33, the bond strength was 9.12 MPa, as the highest among all the GPC. There are no splitting cracks observed for the GPC mix. This was due to lower adherence of GPC to steel bar compared to conventional concrete, resulting in weaker mechanical interlocking between GPC and steel bar [22]. Figure 4 depicts the summary of C/D ratio and its effect on bond behaviour of GPC.





**Figure 4.** C/D ratio effect on the maximum bond strength from previous studies.

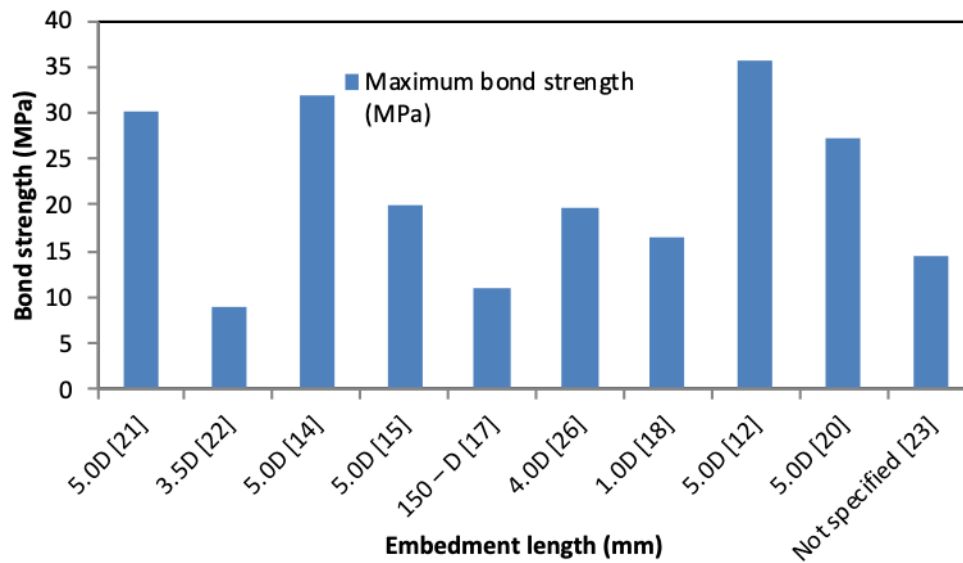
Another studies by [26] using oil palm shell (OPS) as coarse aggregate blended with OPC and GGBFS. For specimens with C/D ratio of 3.13 utilizing different compressive strength, no significant effect of the C/D ratio was found on the bond strength of oil palm shell concrete (OPSC). The specimens exhibited splitting failures since the C/D ratio was not sufficient to prevent splitting cracks from occurring due to the low confinement effect provided. When C/D ratio was increased to 4.17, the confinement effect was increased, and, hence, induced pull-out failure in all of the concrete specimens, causing an increase in the bond strength compared to the corresponding specimens with splitting failures [26]. However, following increment in the C/D ratio up to 8.33 had insignificant effect on the bond strength, with only a slight increment.

The C/D ratio ranging from 2.5 to 7.0 at ambient and after exposure to elevated temperature was also discussed by [15]. GPC specimens with higher diameter of ribbed steel bar experienced splitting or splitting-bond failure prior to the occurrence of bond failure, due to lower ratio of concrete cover thickness to rebar diameter. Regardless of the diameter of reinforcement, when the specimens are exposed to an elevated temperature of more than 300°C, it will induce degradation in bond strength [15]. Another study by [17] only mentioned 5.75 as the C/D ratio utilized in his study but varies the types of diameter used, which were plain and ribbed steel bar. It was observed that the bond strength of ribbed steel bar is higher than the bond strength of plain steel bar due to superficial deformed ribs of the former can produce considerable interlocking action between the ribs and the surrounding concrete and improve their bond interaction significantly [17].

Basically, C/D ranged between 2.5 and 8.33 could be observed from those reviewed studies. Most researchers reported that the minimum C/D ratio required to avoid splitting failure was about 2.5 and 3.0. Also, when the C/D ratio was varied up to a maximum of 2.1 to ensure splitting failure, the bond strength increased as the C/D ratio increased [26]. Further improvement of the C/D ratio could be implemented in the future with those recommended studies in experimental works to minimize the slippage of rebar thus increasing the bond strength.

#### 3.4. Influence of embedment length of reinforcing steel bar on bond behaviour

From the reviewed papers, embedment length is not highlighted as one of the important parameters in their studies. However, it is another factor that contributes to the development of bond strength of concrete, especially for the performance in the total structure at later stages, such as the rotation of the hinge region [17]. Figure 5 shows the effect of embedment length on bond strength from previous studies.



**Figure 5.** Embedment length effect on the maximum bond strength from previous studies.

A study performed by [17] proposed embedment length of steel bar for fly ash concrete. It was observed that experimental embedment lengths was higher than the calculated embedment length, when the replacement ratio was lower than 50 % and lower than the ratio of specimens in which FA exceeds 50 % of cement with W/B of 0.34 and 0.30. It indicates that steel bars cannot be pulled out in the specimens using under 50 % of FA in concrete but can be pulled out when FA composes over 50 % of the cement [17].

Some of researchers reported that the bond strength was higher when the reinforcing bar embedded in the concrete was smaller. However, [26] observed that when comparing concrete specimens with pull-out failure, the area of the reinforcing bar embedded into concrete showed little influence on the bond strength. The most possible reason given for this was the different characteristics of the reinforcing bars of varying diameters and length embedded inside the specimens since the relative rib area is known to be one of the reasons affecting the bond strength [26]. It was contradicted with [12], where it was concluded that bond stresses or development lengths in GPC are much larger than those in normal concrete obtained and thus leading to a new equation of bond stress estimation. The equation of bond stress estimation for GPC was required for proper and economic design and analysis of structural applications [12].

Most of the reviewed papers did not highlight the embedment length as one of their main parameters. From another additional study performed by [34], short and long embedment length beam-end specimens were fabricated for determining bond slip behaviour of glass fibre reinforced polymer (GFRP) bar with conventional OPC and GPC. In this study, the C/D ratio was not considered as the specimen used is beam-end type. Generally, specimens with longer embedment length have lower average bond stress. This is due to higher bond stress variation along the embedment length by increasing the embedment length [34]. However, [5] observed an increment of local bond stress up to a peak point until the peak bond strength become constant. Longer embedment length have longer gripped area with the steel reinforcing bar, increasing the average bond stress. When the bonded length is less than the critical bond length, increasing the bond length also increases the peak bond stress. Once the critical bond length is provided, excess bond length does not increase the peak bond stress [5].

#### 4. Conclusion

Based on the previous literature studies, most of them focused on the geopolymer blending, compressive strength, C/D ratio and embedment length in governing the interaction between reinforcing steel bar and surrounding GPC around it. Uniaxial pull-out specimen was utilized due to ease of fabrication, simplicity of the test, cost effective and time saving compared to the beam-end specimen [28]. However, GPC does not have any particular standard and design provision for design mixture proportion like OPC but only referring to those codes. Thus, additional studies regarding the comparison of EN-10080:2005, RILEM 7-II-128, ASTM C234-91 and IS 2770-1967-Part 1 code provision need to be carried out for utilization of this by-product material in terms of compressive strength, C/D ratio and embedment length especially.

Variation in the type of geopolymer blending plays important role in governing the bond behaviour of GPC including compressive strength. Determination of compressive strength from previous studies can be referred, but results of the strength could be unpredictable, thus making it hard to design GPC with optimum strength. Most of the study normalized bond strength to eliminate the effect of variation in the compressive strength. Higher compressive strength will lead to a higher bond strength, which was agreed by most of the reviewed papers. The C/D ratio and embedment can still be found from those papers although information on the parameters were quite limited previously. It can be seen that, C/D ratio ranged between 2.5 to 8.33 and embedment length ranged between 1.0D to 5.0D could be the optimum range but still need experimental works as validation. Generally, lower C/D ratio will lead to splitting failure and higher C/D ratio will lead to pull-out failure whereas higher embedment length will result in higher bond strength [26].

The structural performance of RC components depends on the bond between concrete and reinforcement, in which the mechanism of bond influences the embedded length of reinforcing bar and consequently the bond resistance, tension stiffening, and deflection, especially for GPC application in construction industries [32]. Therefore, further research needs to be performed regarding the tension stiffening and deflection of GPC as post-bond behavior testing to clarify the suitability and capability of GPC to be used as green reinforced concrete components, replacing the commonly used OPC.

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