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Bond performance of reinforcing bars in inorganic polymer concrete (IPC)

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Abstract The basic mechanical and chemical properties of fly-ash-based inorganic polymer concretes (IPC) have been studied widely, but, key engineering and structural properties of the material for instance modulus of elasticity, compressive, tensile, flexural strengths and bonding strength of the material to reinforcement have received little attention. Structural applications of reinforced IPC depend on the bond performance of the material to the reinforcement. Due to their difference with ordinary Portland cement (OPC) based concrete in terms of chemical reaction and matrix formation it is not known whether IPC exhibit different bonding performance with the reinforcement. Simply relying on compressive strength of the material and extrapolating models and equations meant for OPC based concrete may lead to unsafe design of structural members. To that end, 27 beam-end specimens, 58 cubic direct pullout type specimens and number of laboratory test specimens were tested to evaluate bonding performance of IPC with reinforcement. The results of beam-end specimens and direct pullout type specimens correlate favourably, although the results of direct pullout tests are in general more conservative than those of beam-end specimens. Overall, it can be concluded that bond performance of IPC mixes are comparable to OPC based concrete and therefore IPC and steel can be used as a composite material to resist tension in addition to compression.

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Introduction

Inorganic polymer concretes (IPC) are emerging materials with diverse applications ranging from waste management to the building industry. IPC can be made predominantly from industrial waste materials such as fly ash (a coal combustion by-product), granulated blast furnace slag (GBFS), mine tailings and contaminated soil. They are becoming one of the more popular solidification/stabilisation methods since they can be applied to a variety of waste sources at low cost, yielding added-value products [1]. IPCs are also commonly referred to as alkaline cements or geocements [2]. While pozzolanic cements generally depend on the presence of calcium, IPC do not utilise the formation of calcium-silica-hydrates (CSH) for matrix formation and strength [3]. Instead, they utilise the polycondensation of silica and alumina precursors and a high alkali content to attain structural strength.

Waste materials such as fly ash and slag are widely available, and they provide a replacement for the silicates concentrations required for matrix formation. The character of the polycondensation is relatively different from that associated with ordinary cement formation. These structural differences give IPC certain advantages compared with conventional cement-like binders [4]. An IPC is often viewed as a three-dimensional X-ray amorphous aluminosilicate with a similar chemical composition as the natural zeolitic materials, but without the extensive crystalline zeolitic structure [5]. Therefore, an IPC is made by combining aggregates (fine or coarse) with the inorganic polymer gel before it is cured [6]. Typical aggregates include ordinary sand and crushed rock depending on the application. IPCs are known to be suitable for use as a substitute for ordinary concretes for mainly pre-cast construction materials. Their primary advantage lies in their ability to withstand extreme, variable temperatures and loads [7]. Other properties of IPCs including early gain in compressive strength, durability and their higher acid and fire resistance when compared to ordinary concrete, make them an appealing construction materials.

There are numerous environmental benefits and cost savings associated with using industrial wastes such as fly ash and GBFS in construction materials. Cement manufacture generates carbon dioxide (CO_2) emissions from calcination of the limestone in the raw materials, and from fuel combustion at the rate of approximately 1 ton of CO_2 per ton of cement [8, 9]. Developed countries are already considering regulations and mandatory quotas on emission of greenhouse gases [10]. Developing countries are also considering an increased usage of fly ash and other supplementary cementing materials in the construction industry, in an attempt to limit the usage of cement [11].

The consumption of coal for electricity generation is common around the world and an increase is envisaged in the third world countries. In the United States, coal-fired plants produce almost 60% of the electricity [12]. The disposal of industrial by-products such as fly ash is becoming a significant environmental and cost issue. Land scarcity for disposal of such large volumes of waste and ground water contamination by heavy metals contained in fly ash are some of the main concerns. Research has proven the use of fly ash as a part replacement of cement (typically 30% by mass), for structural concrete in masonry mortars, plaster and in mass concrete [13, 14].

Despite these benefits, practical problems in the field application of fly ash remain. For instance, concretes containing high volumes of fly ash as partial cement replacement do not attain high enough early age strengths in order to provide for the fast moving routine construction requirements. To eliminate this problem, many studies have explored methods of accelerating the pozzolanic properties of fly for use in blended cement systems [15–17].

Although there have been numerous worldwide studies carried out on IPC, until recently the majority of research on IPC has focused on material characterisation [18, 19], enhancement of the physical and chemical properties of the material [4–20], effects of source materials [21], the interface between natural silicious aggregates and IP matrix [22] and the effect of GBF slag on polymerisation [3]. Some studies have investigated the potential application of the IPC in solving practical building related problems [23]. However, there is practically no literature on the engineering properties of IPC and bonding behaviour with the reinforcing bars (henceforth referred to as rebars).

Due to their difference with ordinary Portland cement (OPC) based concretes, both in terms of chemical reaction and matrix formation, IPC may exhibit different bonding properties with rebars. Simply relying on compressive strength of the material and extrapolating models and equations meant for OPCs may lead to unsafe designs. Therefore, it is imperative to be aware of the structural behaviour and the properties of IPC before it is considered as a suitable substitute for OPC based concrete in reinforced structural applications. One of the main objectives of the current experimental work was to investigate the bond performance of rebars in IPC. An OPC based concrete mix is also provided for comparison. This paper reports the experimental results of beam-end pullout tests which are set against various design recommendations and standards for OPC based concrete. In summary, a total of 23 beam-end specimens and 58 direct pullout type specimens were tested. In addition, 4 beam-end specimens were made from OPC based concrete for comparison purposes. The authors are not aware of any other research project or published work around the world that has investigated the bond performance of IPC with rebars. In addition, a comparison of two types of bond tests, namely direct pullout and beam-end type specimens, are presented in this paper.

Bond mechanism of rebars in concrete

Reinforced concrete functions effectively as a composite material because the steel reinforcement is bonded to the surrounding concrete [24]. Bond between the rebar and the surrounding concrete matrix ensures the rebar does not slip relative to the concrete and therefore allows local forces to be transferred across the steel-concrete interface. Without any bond, or other mechanical connection, the steel is completely ineffective and does not contribute to a greater stiffness and flexural resistance of the structural member. The most effective means of achieving an effective bond is by the use of deformed rebars which have a pattern of large deformation rolled into the surface. Standards guidelines provide an equation to calculate the development length, i.e., the bonded length for OPC based concrete to ensure that yield strength of a rebar can be developed.

Since bond stresses modify the steel stresses along the length of the rebar by transferring the load between the rebar and the surrounding concrete, the following expression for a straight rebar anchored in concrete may be derived from the equilibrium of the concrete and rebar forces:

$$A_b f_s = U \pi d_b l_d \quad (1)$$

where, A_b and d_b are the area and diameter of the rebar, l_d is the bond length of rebar, f_s is the stress developed in the rebar, and U is the average bond stress. The average bond stress can be related to the bar diameter, bar stress and bond length by simplifying Eq 1:

$$U = \frac{f_s d_b}{4 l_d} \quad (2)$$

This formula is used to determine the average bond stress developed between the rebar and concrete.

It is essential that the rebar force is transferred to the concrete to maintain structural integrity. The rebar force is transferred to the concrete by adhesion, friction and mechanical bearing between the deformation and concrete [25]. Figure 1 illustrates schematically the three mechanisms of a bond. Upon initial loading the forces are transferred by adhesion created through chemical bonding between the steel and concrete. At low rebar stresses the adhesion is lost. After the loss of adhesion, the rebar slips relative to the concrete which enables the development of the friction and mechanical bearing mechanisms. Due to the rib face angle the forces are transferred to the concrete by bearing perpendicular to the rib face. As shown in Fig. 1, the friction between the rib face and the adjacent concrete also contributes to this force. The resultant force of the bearing and friction forces on the ribs produces radial tension in the concrete surrounding the rebar.

Bond behaviour of concrete to rebar and the influence of different variables are generally investigated experimentally due to the many problems that make a theoretical study harder to achieve. Two types of bond tests, pullout and beam-end, are reported here.

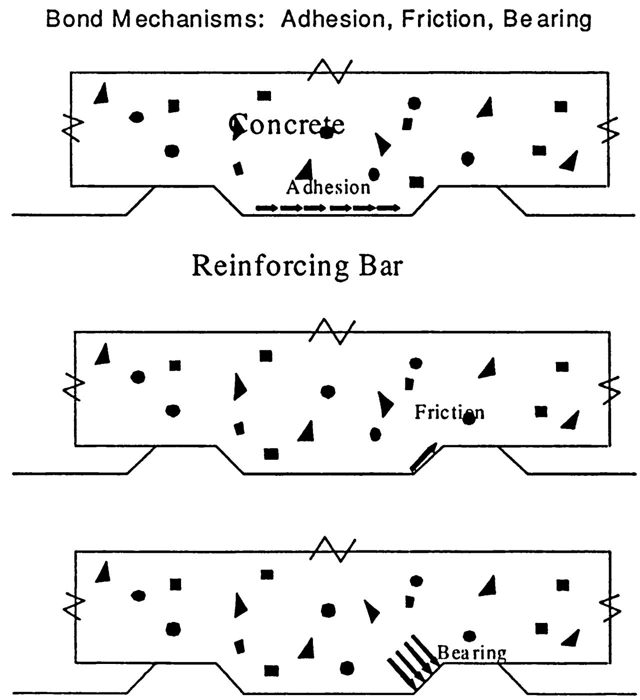

Fig. 1 Bond mechanisms

Direct pullout type specimens consist of a test rebar cast uni-axially in a $150 \times 150 \times 150$ mm cube of concrete. The test rebar is usually loaded by reacting off the concrete surrounding the rebar. The construction and testing of direct pullout is carried out using ASTM C 234-91 [26]. Direct pullout tests are both useful and a cost effective method towards evaluating preliminary relative comparisons. However, critics have expressed concerns about the compression state of concrete while undergoing tests and therefore validity of the test results [27, 28]. Direct pullout tests were carried out to compare the bond behaviour of IPC mixes with rebars with respect to ordinary concrete. A summary of the direct pullout test results will be presented in this paper.

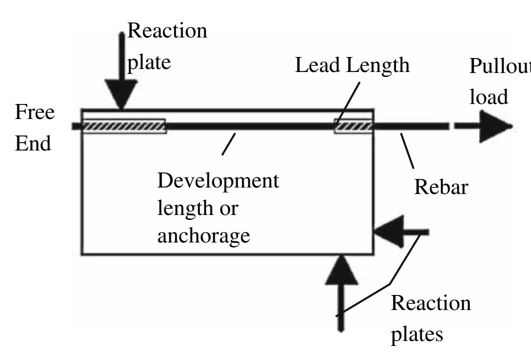

Fig. 2 Beam-end specimen and terminology

Beam-end specimens (also referred to as inverted half-beam specimens) are used as a more realistic bond test. They are used extensively in experiments to evaluate bond strength of rebars with concrete and its derivatives [25, 29]. The specimen allows the test rebar to be in an area of flexural tension as shown in Fig. 2. ASTM A 944-99 [30] provides a description of the methods of construction and testing of beam-end specimens, which was adopted in this investigation.

Both direct type pullout tests and beam-end specimens were tested for this investigation. The results are briefly presented in section Experimental results.

Experimental investigation

Materials

Six IPC mixes were used in this study. The mix proportioning and other mix-design variables are presented in Table 1. Three different sources of Class-F Australian fly ash were used, namely Port Augusta (PA), Gladstone (G) and Tarong (T). X-ray fluorescence spectroscopy (XRF) analysis was performed on the fly ashes used. The details of the XRF analysis are presented in Table 2.

In general, the starting materials for the synthesis of IPC include sand, fly ash, and where specified, coarse aggregates and ground granulated blast-furnace slag. The basis for the IPC mixes are explained elsewhere [3–4]. Literature reports that IPC binder formed in the presence of GGBFS is to some extent similar to the binder formed in the absence of GGBFS [31]. It is also postulated that calcium dissolved from the GGBFS when activated by alkaline solution will participate in the formation of semi-crystalline calcium silicate hydrate, which is the major building phase in any cement based cementitious material, in preference to the formation of a calcium based IPC [3, 31].

Table 2 Composition of the fly ash as determined XRF-analysis (mass%)

Sample	G	PA	T	Slag
SiO_2	47.83	50.79	65.9	33.7
TiO_2	1.7	1.99	1.97	1.1
Al_2O_3	28.49	30.77	28.89	13.84
Fe_2O_3	11.38	3.82	0.38	0.24
MnO	0.19	0.05	0	0.41
MgO	1.43	2.12	0.15	5.73
CaO	5.51	4.67	0.06	41.42
Na_2O	0.34	3.32	0.05	0.31
K_2O	0.46	1.52	0.26	0.31
P_2O_5	0.62	1.2	0.08	0
SO_3	0.24	0.33	0.03	3.13
LOI	1.82	0	1.24	0

In the current study only mix 4 contained nominal 14 mm single size angular shape Basalt crushed rock (coarse aggregate).

The solution phase (commonly referred to as the activating solution) consists of one or more of the following components: sodium carbonate (Na_2CO_3), sodium silicate (Na_2SiO_3), sodium hydroxide (NaOH) and/or potassium hydroxide (KOH). When referring to the composition of fresh concrete the proportion of water and cement is an important consideration. Cement being the active binding material, the concrete mix proportions are referred to as having a water–cement (w:c) ratio of a certain value depending on their respective weights. IPC mix proportions are commonly quoted as the mass percentage of ingredient within the mix, although reference is usually made to the Al_2O_3/SiO_2 ratio of the final product as well as the pH of the initial alkali activating solution (or Na_2O/SiO_2 ratio) in order to standardise some of the basic mixing parameters [32].

Table 1 Composition of the IPC mixes investigated

	Mix					
	1	2	3	4	5	6
Component[a]						
Na_2CO_3/SiO_2	0.681	0.681	0.681	0.681	0.217	0.000
Na_2O/SiO_2	1.617	1.617	1.617	1.617	0.702	0.970
K_2O/SiO_2	–	–	–	–	0.003	–
Component[b]						
Fly ash type	PA	G	T	PA	PA	PA
H_2O/fly ash	1.280	1.500	1.520	1.067	0.300	0.208
Slag	0.146	0.143	0.143	0.097	0.069	–
Coarse aggregates	–	–	–	0.336	–	–
Sand	0.635	0.626	0.625	0.430	0.763	0.667
Fly ash	0.066	0.065	0.065	0.044	0.092	0.222

[a] Values are given as molar ratios

[b] Values are given as mass ratios

Mixing, synthesis procedure and curing method

All of the 6 IPC recipes were mixed using the same procedure. The mixing process constituted initially blending all of the solid materials to which the wet alkali (activating) solution was added. Mixing was done by medium and larger size bread dough mixers, depending on the size of the mix. The mix size was designed such that the mixers could operate efficiently while mixing the dry and then later when adding the pre-mixed alkali solution. The mixing of the dry and wet phases was carried out by allowing approximately the same amount of time, typically 3–4 min for all six mixes. Upon combination and mixing of the dry and the wet phases, an inorganic polymer (geopolymer) paste or ''the reaction paste'' forms which, subsequently, upon curing results in a hardened final product. Similar to preparing a wet OPC based concrete mix, care has been taken so that the dry and the wet phases are mixed thoroughly so that a uniform paste is obtained throughout. Due to the highly acid nature of the mix paste, appropriate safety measures were taken throughout the mixing procedure. The fresh IPC paste was then poured into the steel moulds placed on a vibrating table so as to remove the entrapped air from the mix.

Unlike fresh OPC based concrete, IPC paste can harden in a matter of a few minutes, depending on the mix design. The fast setting characteristics of IPC can be taken as an advantage or a disadvantage depending on the intended civil engineering application. Usually 5–10 min are sufficient before the freshly cast concrete material sets, but it is also possible to achieve similar strength gain profiles with time as OPC based concretes given correct mix design. To most IPC researchers, it is the setting retardation that is the most problematic because it is vital to avoid compromising other material characteristics such as product ultimate strength and durability [33].

The IPC test samples were prepared and tested in accordance with their respective Australian Standards. The beam specimens of which the results are presented in the current work were all cast in steel moulds, demoulded after approximately 12 h in a steam room (30–35 °C, >80% RH), wrapped in plastic bags and kept at ambient temperature until testing. Unless otherwise stated, the results reported herein are those obtained at 28 days.

The idea of storing the material in plastic sheeting was to prevent the moisture from evaporating rapidly especially when the hardness of IPC mixes is known to develop over time and the geopolymeric reaction being an on-going one.

IPC engineering properties

Initially, a total of 90 cylindrical (150 mm diameter × 300 mm height) and 24 small beam specimens (100 × 100 × 300 mm) were tested to evaluate the basic engineering properties of IPC mixes such as compressive, tensile and flexural strengths, modulus of elasticity and Poisson's ratio of the mixes. A brief summary of the results relevant to the current paper is presented here. Complete test results are given elsewhere [35].

Figure 3 depicts a plot of 28 day compressive strength (f_c) of the mixes against their respective splitting tensile strength (f_{sts}). Each value was obtained following the Australian Standard methods of testing (AS 1012.9 and 10) guidelines. They are presented along with the specified models for the characteristic principal tensile strength at 28 days by AS 3600 [36], and the Eurocode 2 [37] and splitting tensile strength, ACI-02 [38]. It is noted that ACI-02 model is based splitting type specimens whereas the Australian and European models represent principal tensile strengths.

As demonstrated in Fig. 3, mixes 1–6 (M1–M6) fall between the ACI-02 model and those from AS 3600 and Eurocode 2. Apart from M2 which falls slightly below the model provided by AS 3600, for all the other mixes European and Australian provisions can safely be used to estimate the tensile strength. ACI-02 model seems almost like a linear trendline for half of the mixes (M4–M6) while the other half fall well below the model (M1–M3). Other than the discrepancy due to experimental error, the variability in the results can be attributed to differences in mix compositions (Table 1).

The effects of mix composition are further elaborated under the Effect of mix variables section. However, it is reasonable to assume that the splitting tensile strength of IPC also depends on other

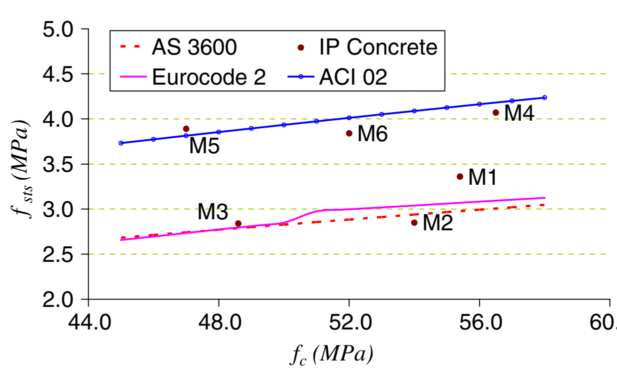

Fig. 3 Splitting tensile (f_{sps}) and compressive strength (f_c) of the mixes

parameters such as the mix compositions and curing methods. Neville [39] reported that splitting tensile strength has a close relationship with the compressive strength, but there is no direct proportionality. The tensile to compressive strength ratio of OPC based concrete depends on the general level of the strength of the material.

Beam-end specimens

The main purpose of the current investigation on bond strength of IPC mixes with rebar is to obtain the required development lengths. Due to the fact that the relationship between the bond stress (U) and development length (l_d) is not linear, it was desirable to test specimens that develop rebar stresses close to the desired design code rebar stresses. In doing so, the prominent assumption was that IPC bonds to the rebar in a similar fashion as OPC based concrete, for the same compressive strength. The approach used in this study was to select development lengths that would produce bond failures at stresses near the nominal yield stress of the rebar without exceeding it. To estimate these development lengths, the relationship for bond stress derived by the Orangun, Jirsa and Breen (OJB) is used [40]:

$$U_{\mathrm{OJB}} = 0.083\sqrt{f'_c}\left[1.2 + 3\left(\frac{c}{d_b}\right) + 50\left(\frac{d_b}{l_d}\right)\right] \quad (3)$$

where,

U_{OJB} = ultimate bond stress, MPa
f'_c = concrete compressive strength, MPa
c = lesser of the side cover and bottom cover, mm

The equation reflects in turn the effects of development length (l_d), cover (c), rebar spacing, rebar diameter (d_b), concrete strength (f'_c) and transverse reinforcement on the strength of anchored rebars.

The dimensions and details of each beam-end specimen are reported in Table 3. The test rebars were extended out from the face of the specimen to a distance of approximately 1.5 m for gripping and pullout purposes. The standard test method for comparing bond strength of steel reinforcing bars to concrete using beam-end specimens (ASTM A 944-99, 2000) was followed for constructing and testing the specimens.

Experimental results

A splitting type failure was observed for all beam-end specimens (Fig. 4). In almost all of the specimens, the bond-splitting cracks happened perpendicular to the smallest concrete cover. Only mixes containing coarse aggregates (M4 and M7) failed with more irregular cracks joining the rebar to the smallest cover. The splitting type failures were explosive and sudden for all samples denoting the brittle nature of the material irrespective of the composition. The failures were mainly over the development length irrespective of the rebar size.

Table 3 Beam-end specimen dimensions and details

Mix	l_d		
	N12 (c = 36)	N16 (c = 48)	N20 (c = 70)
1	148.7	189.9	204.7
2	164.3	210.7	227.4
3	166.5	213.7	230.6
4	140.7	179.2	193.1
5	140.7	179.2	193.1
6	168.8	216.8	234.0
7	175.0	225.0	242.9

Note:
A uniform length of 625.0 and height of 400 was chosen
A variable width of 225.0, 229.0 and 233.0 mm was used for N12, N16 and N20 rebars, respectively
All dimensions are in (mm)

Bond stress values for direct type pullout specimens (U_{Direct}) and beam-end specimens (U_{Beam}) were estimated using the failure load of the specimen using Eq 2. They are presented in Tables 4 and 5, respectively. The U_{Direct} values are the average of two pullout test results whereas U_{av} values for beam-end specimens are the average of U_{Beam} values obtained from the beam-end specimens with N12, N16 and N20 rebars. The ultimate bond stress values were derived from the maximum pullout load before failure of the test specimen. The compressive strengths (f_c) of the mixes are also listed. Generally, f_c associated with beam-end specimens are lower than those of direct pullout type specimens because direct type specimens were steam cured for 24 h whereas the beam-end specimens were in a steam room for only 12 h.

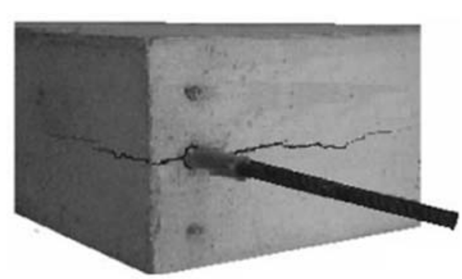

Fig. 4 Splitting failure in beam-end specimens

Table 4 Bond strength results obtained using beam-end specimens

	U_{Beam} (MPa)	U_{Beam} (MPa)	U_{Beam} (MPa)	U_{av} (MPa)	f_c (MPa)$^{1/2}$	$\sqrt{f_c}$ (MPa)	$\frac{U_{\text{av}}}{\sqrt{f_c}}$
Rebar size	12	16	20				
Mix							
1	11.4	8.5	7.0	9.0	45.9	6.8	1.3
2	9.8	6.5	11.6	9.3	39.9	6.3	1.5
3	9.2	11.5	7.0	9.2	41.6	6.5	1.4
4	13.3	10.6	10.3	11.4	44.7	6.7	1.7
5	11.4	8.9	8.3	9.5	44.5	6.7	1.4
6	9.5	6.8	5.8	7.3	30.0	5.5	1.3
7	8.8	14.4	8.3	10.5	32.4	5.7	1.8

Table 5 Bond strength values obtained using direct pullout type specimens

Mix	$U_{\text{Direct}}^{a,b}$(MPa)	f_c (MPa)	$\sqrt{f_c}$ (MPa)$^{1/2}$	$\frac{U_{\text{Direct}}}{\sqrt{f_c}}$
1	11.0	64.4	8.0	1.4
2	10.5	39.9	6.3	1.7
3	10.9	39.9	6.3	1.7
4	14.7	64.9	8.1	1.8
5	14.6	81	9.0	1.6
6	10.9	59.8	7.7	1.4
7	14.2	40.5	6.4	2.2

[a] N12 standard deformed rebar

[b] Average bond strength values listed

Representative bond stress values obtained for beam-end specimens (U_{av}) varies from 7.3 to 11.4 MPa while this range is generally higher for direct (U_{Direct}) from 10.53 to 14.65 MPa. On average U_{Direct} values overestimate U_{av} specimens by 2.9 ± 1.3 MPa (Tables 4 and 5). In order to take into account the effects of differences in compressive strength, bond stress values have been normalised with respect to their corresponding compressive strengths. The normalised bond stress values of beam-end specimens ($\frac{U_{\text{av}}}{\sqrt{f_c}}$) and those of direct pullout type tests $\frac{U_{\text{Direct}}}{\sqrt{f_c}}$ are compared in Fig. 5. It is demonstrated that the normalised bond stress values using both testing methods complement each other very well i.e., follow a similar pattern. The variation with respect to various mixes is also apparent.

From Fig. 5, there appears to be a small reduction in $\frac{U_{\text{Direct}}}{\sqrt{f_c}}$ to $\frac{U_{\text{av}}}{\sqrt{f_c}}$. This is explained by the state of stress surrounding the test rebars that concrete is subjected to. The radial tensile state of stress in the concrete matrix surrounding the rebar in a beam-end specimen reduces the bond stress capacity. Contrarily, for the direct type pullout specimens the compressive stresses induce a clamping load on the rebar which is then translated into a small percentage of the bond stress. Also, a large confinement is provided in direct pullout tests and the state of stress around the rebar is considerably different from the stress in actual structures [41]. Therefore, as mentioned earlier, it is expected that the beam-end specimens provide a better representation of the actual bond stresses.

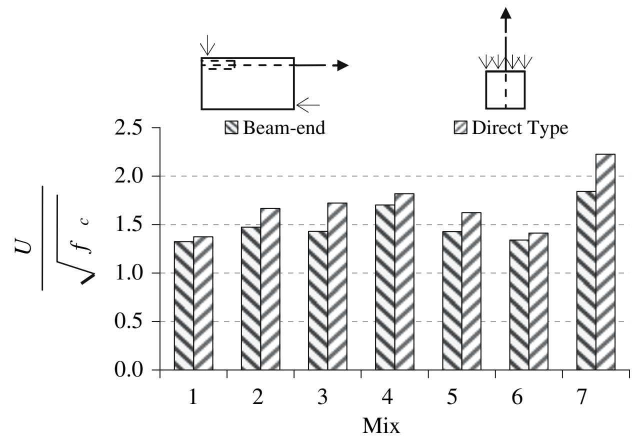

Fig. 5 Normalised bond strengths of beam-end and direct type specimens

Similar to bond stress, rebar slip is also a function of three main components: adhesion, friction and the wedge action in front of the rebar deformation. The rebar slip was measured continuously at the free end of the rebar using Linear Variable Differential Transducers (LVDT). Free end slip represents the overall displacement of the rebar due to the tensile load at the opposite end of the beam. One of the most important features of the bond stress-slip relationships is the initial slope of the curve. The slip rate was estimated from the initial slope of stress-slip data. The study of stress-slip relations confirm the bond stress results reported herein. It was also found that for the same amount of rebar stress, there is a greater amount of slip for larger size rebars in IPC mixes. Further details are reported in reference [35].

The similarity between bond stress (U_{av}) and splitting tensile strengths (f_{sts})

Bond failure occurs when the hoop tension exceeds the tensile capacity of the concrete. When this occurs, longitudinal cracking develops and since the force in the 'struts' can no longer be equilibrated, failure occurs, the cover breaks off and the rebar pulls out [42]. In beam-end specimens, tensile strength of the material relates closely with bond strengths (Fig. 6). The results show that the first three mixes and M6 have

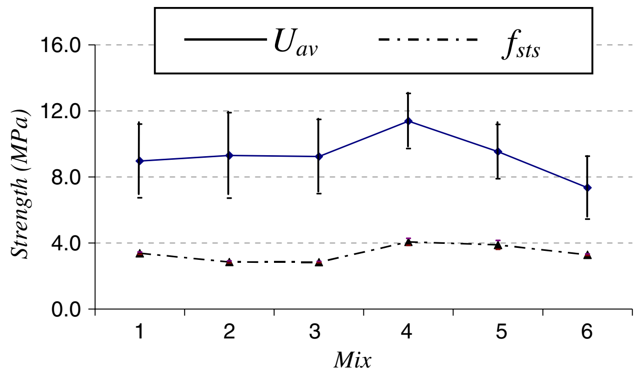

Fig. 6 Average beam-end bond strength (U_{av}) and corresponding tensile strength (f_{sts})

lower f_{sts} and U_{Beam} values while, M4 has the highest f_{sts} and U_{av} values. M5 has the lowest water/fly ash ratio but has a similar average compressive strength to M4 (i.e., f_c = 44.7 MPa). Both the tensile and bond stress values tend to be lower for M5 than for M4. One observation in this case is that the presence of coarse aggregates (in M4 and M7) affects favourably the performance of concrete. Conversely, lower results obtained for the remaining IPC mortar-like mixes maybe due to their mix compositions not including any coarse aggregate.

The effect of IPC mix variables

In general, there appears to be some variability in bond stress and other strength values with respect to different IPC mix formulations. It is important to inspect each mix at a time and have a comparative approach when analysing their bond properties because the constitution of each mix is different. The intention behind having different mixes was to compare the effect of inclusion of fly ash of different sources and coarse aggregate on bond.

Type of fly ash constitutes the main difference in composition of mixes 2, 3 and those of 1, 5 and 6 (Table 1). Although M2 and M3 achieve slightly higher average bond stress values than M1, the difference is minor and cannot easily be attributed to the fly ash type. A comparison of M2 and M3 with that of OPC-based concrete (M7) show that M2 and M3 reach 75.5% of U_{Direct} for M7 while this difference is much less with a value of 88.4% when considering U_{av}. It is noted that M5 achieves lower U_{av} and U_{Direct} values than that of M7 in spite of having a higher compressive strength than that of M7. M5 is a relatively dry mix with a water-to-fly ash ratio of 0.3 compared with 0.15 for those of mixes 1–3. An elaboration of the effect of fly ash on the mechanical properties of IPCs is reported elsewhere [34].

U_{av} And U_{Direct} values indicate that M4 attains the highest bond strength values amongst all IPC mixes. In particular, M4 achieves approximately 25% higher bond stress values than those of M1 and M6, all containing PA class fly ash. Table 1 indicates that the water to fly ash ratio for M1 and M4 are comparable whereas that of M6 is much less with a value of 0.208. While other mixes attain consistently less bond strength values, both U_{av} And U_{Direct} for M4 containing coarse aggregates is comparable to the OPC based concrete. Given the small number of samples, it would be premature to associate higher performance of M4 to the presence of coarse aggregates. However, this is an adequate observation.

Due to the small number of specimens and limited resources, it is difficult to decisively report on the effects of fly ash types on bond stress of rebars with IPC concrete. The bond stress results were further examined considering the bond stress–slip relationship of each individual beam-end specimen. Only a brief summary is reported here. For detailed information reference should be made to [35].

Comparison with the code provisions

A comparison of the standard design equations with the experimental bond stress results have been carried out [35]. It gave valuable insights into the level of bond stress attained by the IPC mixes in comparison with the models provided by the code provisions. The code provisions give the l_d values required at yield strength of rebars in tension. The experimental bond stress values were normalised by the standard models, for example, U_{test}/U_{AS3600} for the Australian standards. Although the provisions of AS 3600 are for OPC based concretes, they have been used in this research work to check for the validity of IPC mixes, should they replace concrete. Comparison of bond stress values from the current investigation with AS 3600 [36], EC2 [37] and ACI-02 [38] recommendations showed that the provisions are conservative for predicting l_d values for IPC mixes.

The bond strength results of the IPC mixes reported above have been re-examined by carrying out t-tests. Of particular interest is the 95% confidence interval (CI) for the mean or the width of CI which is a measure of precision of the estimation. This will allow the establishment of conservativeness order of the design equations for the average bond strength values of the tests. Figure 7 shows a list of 95% CI, as read from the

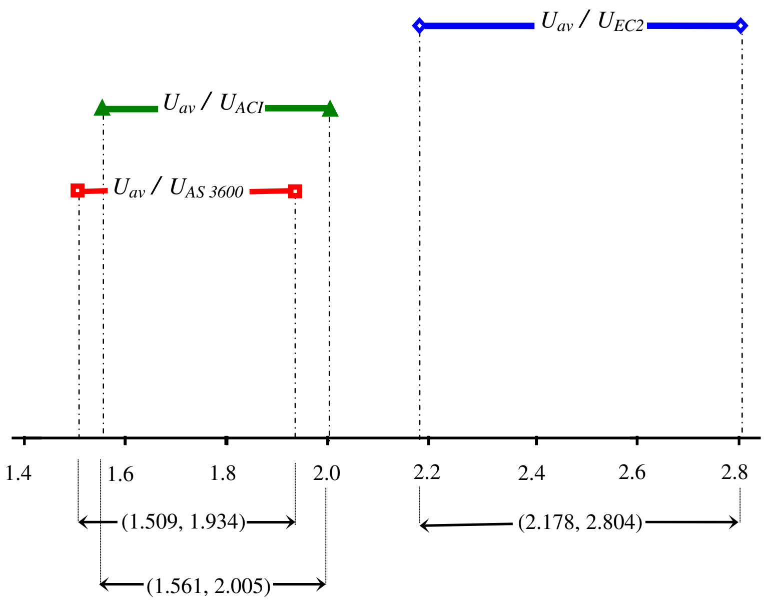

Fig. 7 95% means test to predict the ratios (U_{avt}/U_{model})

results of the *t*-tests. Beam-end test results have proven to be most conservative when compared to EC2 [37] design equations while they are less conservative when compared with that the ACI-02 [38] and the AS 3600 [36] codes.

Conclusions

The main conclusions from the analysis of beam-end test results are:

- All beam specimens failed by splitting of the concrete surrounding the rebar. Hence, the cracking of the concrete cover and the splitting type failure were due to tensile splitting stresses imposed by the rib of the rebar.
- A comparison of the normalised bond strengths obtained from the beam-end specimen showed that the bond strengths of beam-end specimens were somewhat lower than those of the direct pullout tests. However, the direct pullout tests can be useful for bond strength comparisons.
- The bond stress behaviour of IPC samples generally abide by the variances of the tensile strength of the material.
- Similar to the effect of different size rebar bond strengths in OPC based concretes, it was found that the normalised bond strength increased with a reduction in rebar size.
- Comparison of bond stress from the current tests with AS 3600, ACI 318-02 and EC2 recommendations showed that they are applicable for IPC. EC2 gave the most conservative results compared to test results. While ACI 318-02 and AS 3600 gave less conservative results. However, are safe to predict the development lengths for IPC concrete.

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