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Engineering properties of inorganic polymer concretes (IPCs)

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Abstract

This paper presents the engineering properties of inorganic polymer concretes (IPCs) with a compressive strength of 50 MPa. The study includes a determination of the modulus of elasticity, Poisson's ratio, compressive strength, and the splitting tensile strength and flexural strength of IPCs, formulated using three different sources of Class-F fly ash. Six IPC mix designs were adopted to evaluate the effects of the inclusion of coarse aggregates and granulated blast furnace slag into the mixes. A total of 90 cylindrical and 24 small beam specimens were investigated, and all tests were carried out pursuant to the relevant Australian Standards. Although some variability between the mixes was observed, the results show that, in most cases, the engineering properties of IPCs compare favorably to those predicted by the relevant Australian Standards for concrete mixtures.

Keywords: Amorphous material (B); Mechanical properties (C); Fly ash (D); Concrete (E); Geopolymer

1. Introduction

Inorganic polymer concretes (IPCs) 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. These materials are often referred to as geopolymers or alkali activated cements. They contain aluminum and silicon species that are soluble in highly alkaline solutions. The dissolved species then undergo poly-condensation to produce materials with desirable mechanical properties. While pozzolanic cements generally depend on the presence of calcium, inorganic polymers do not utilise the formation of calcium–silica–hydrates (CSH) for matrix formation and strength [1]. These structural differences give IPCs certain advantages, such as an earlier gain in strength compared with conventional cement-like binders [2–4]. It has been shown previously that inorganic polymers are stable materials with proven physical and chemical properties. In many cases, IPCs outperform their ordinary Portland cement (OPC) counterparts with respect to compressive strength [2] as well as acid resistance and fire resistance [5,6]. For these reasons, IPC technology is gaining significant commercial interest, especially because it has been demonstrated that IPC formulations are cost-competitive with general-purpose cement [6,7].

There is a significant amount of literature on the chemistry of inorganic polymer concrete [1–5,8]. Some of the studies consider the environmental benefits of inorganic polymer concretes, such as the immobilisation of toxic metals [2], while others report on the mechanism of the geopolymerisation process for many different alumino-silicate minerals [9]. However, there are currently very few published studies on the engineering properties of IPCs. In order to use IPCs in structural engineering applications, a precise evaluation of these properties is essential. The engineering properties that are determined in the present work, for a variety of IPC formulations, include compressive strength, splitting tensile strength and flexural strength, static chord modulus of elasticity, and Poisson's ratio. This work will therefore serve as a basis for the future development and understanding of the structural engineering properties of IPCs.

2. Experimental program

2.1. Materials

Six IPC mixes were used in this study. The mix proportioning and other mix-design variables are presented in Table 1. Three

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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. The details of the XRF analysis are presented in Table 2.

In general, the starting materials for the synthesis of IPCs include sand, fly ash, and where specified, coarse aggregates and ground granulated blast-furnace slag. In the current study only Mix 4 contained nominal 14 mm single-size angular shaped 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), and sodium hydroxide (NaOH). When referring to the composition of fresh concrete, the proportion of water and cement is an important consideration. As cement is 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 the reference is usually made to the Al_2O_3/SiO_2 ratio of the final product, it is also important to quote the pH of the initial alkali activating solution, as well as the concentration of the soluble silicate (or Na_2O/SiO_2 ratio) [10].

2.2. Mixing, synthesis procedure and curing method

All of the six IPC mixes studied were made using the same procedure. The mixing process initially involved blending all of the solid materials to which the wet alkali (activating) solution was added. A grade D sodium silicate solution with Na_2O (14.7%), SiO_2 (29.4%) and H_2O (55.9%) (P. Q. Australia Pty Ltd.), and industrial grade sodium hydroxide and/or potassium hydroxide (Consolidate Chemical Co.) were used.

Medium and larger size bread dough mixers, depending on the size of the mix, did the mixing. The mix size was designed such that the mixers could operate efficiently while mixing the dry ingredients, and then later when adding the pre-mixed alkali solution. Approximately the same amount of mixing time, typically three to four minutes, was allowed for all six mixes in the dry and wet phases. Upon the combination and mixing of the dry and the wet phases, an inorganic polymer paste or ‘the reaction paste’ formed, which, upon curing, resulted in a hardened final product. Similar to the preparation of a wet, ordinary Portland cement-based (OPC) concrete mix, care was taken so that the dry and the wet phases were mixed thoroughly and a uniform paste was obtained throughout. Due to the highly caustic 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, which were 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 five to ten minutes are sufficient for the freshly cast concrete material to set, but it is also possible to achieve similar strength gain profiles as the OPC-based concretes, given the correct mix design. In view of the practical applications, the early setting characteristics of IPC mixes can

Table 1
Composition of IPC mixes investigated

Component *	Mix					
	1	2	3	4	5	6
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 **						
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

* Values are given as molar ratios.
** Values are given as mass ratios.

Table 2
Composition of a: fly ash and b: slag as determined XRF-analysis (mass %)

a: Fly ash

Composition	Gladstone	Port Augusta	Tarong
SiO_2	47.83	50.79	65.9
TiO_2	1.7	1.99	1.97
Al2O_3	28.49	30.77	28.89
Fe_2O_3	11.38	3.82	0.38
MnO	0.19	0.05	0
MgO	1.43	2.12	0.15
CaO	5.51	4.67	0.06
Na_2O	0.34	3.32	0.05
K_2O	0.46	1.52	0.26
P_2O_5	0.62	1.2	0.08
SO_3	0.24	0.33	0.03
LOI	1.82	0	1.24

b: Slag

Slag	Mass
Na_2O	0.2584
MgO	6.0152
Al_2O_3	13.1772
SiO_2	32.8768
SO_3	3.498
K_2O	0.3208
CaO	40.0502
TiO_2	0.6592
V_2O_5	0.0298
MnO	0.403
Fe_2O_3	0.3206
CuO	0.00876
SrO	0.05598
Y_2O_3	0.01014
ZrO_2	0.0284
LOI	1.192
SUM	98.90448

cause problems. For instance, the mix can start hardening before it is properly placed in the moulds. For most IPC researchers, it is the setting retardation that is of greatest concern, as it is vital to avoid compromising other material characteristics, such as the product's ultimate strength and durability [11].

The IPC test samples were cast and tested in accordance with the Australian Standards for OPC-based concrete. The results presented in the current work are for test specimens that were all cast in steel moulds and de-moulded after approximately 24 h in a steam room (30–35 °C, >80% RH). They were kept at standard laboratory temperature (23 °C) until testing. Unless otherwise stated, the results reported herein are those obtained at 28 days.

3. Results and discussion

3.1. Density of the IPC mixes

The weight and dimensions of three IPC cylinders per mix were measured in order to calculate the density (ρ) of a particular mix. The calculations were carried out in accordance with the requirements of AS 1012.12.1 [12]. The density, along with the respective compressive (f_c), splitting tensile (f_{sts}) and flexural strengths (f_{cf}) of each particular mix, is presented in Table 3.

The mean density of the IPC mixes without coarse aggregates was found to be 2205.8 kg/m^3, with a standard deviation of 34.5. The density of Mix 4 (containing coarse aggregate) was 2408.1 kg/m^3. The density of individual mixes is presented in Table 3a. On average the density of each IPC mix is close to the density for OPC-based concretes (where a similar aggregate type is used), which have a ρ value of between 2300 to 2600 kg/m^3. For calculating dead loads, the weight of structural concrete is often taken to be 24 or 25 kN/m^3, which includes an allowance for the presence of steel reinforcement [13]. The results in Table 3 indicate that there are no major differences between the densities of OPC-based concrete and that of IPC.

Table 3
Summary of mechanical properties of IPC mixes investigated

(a)

Mix	ρ (kg/m^3)	$f_{c,7}$ (MPa)	Std. Dev.	$f_{c,28}$ (MPa)	Std. Dev.
1	2231.3	35.2	1.2	55.4	6.0
2	2232.1	44.4	3.3	54	2.3
3	2147.7	37.6	2.2	48.6	2.3
4	2408	41.8	1.4	56.5	0.8
5	2212.1	42	6.2	47	2.1
6	2246.4	38.3	6.3	52.8	3.0

(b)

Mix	$f_{sts,7}$ (MPa)	Std. Dev.	$f_{sts,28}$ (MPa)	Std. Dev.	$f_{cf,7}$ (MPa)	Std. Dev.	$f_{cf,28}$ (MPa)	Std. Dev.
1	3.2	0.32	3.4	3.36	4.9	0.4	6.1	0.1
2	2.9	0.28	2.8	2.85	4.8	0.0	4.9	0.7
3	2.4	0.67	2.8	2.84	4.5	0.2	5.4	0.0
4	3.6	0.13	4.1	4.07	5.3	0.2	6.2	0.3
5	3.5	0.61	3.9	3.89	5.3	0.5	5.9	0.1
6	2.7	0.93	3.3	3.84	4.2	0.3	5.3	0.1

a: Seven and 28 days compressive strength (f_c).
b: Seven and 28 days results for splitting tensile and flexural strengths (f_{sps} and $f_{cf.}$).

3.2. Compressive strength

The nominal compressive strength of normal concrete is no more than 50 MPa. For ordinary concretes, the characteristic strength of the concrete in compression is defined as the strength attained at 28 days by 95% of the samples, as assessed by the standard tests [13]. The compressive strength at 28 days for the IPC mixes was equally selected to be 50 MPa. The mix design of IPC was based on numerous existing trials based on the materials listed in Table 1. Three cylinders of 150 × 300 mm (diameter × height) were used according to the standard procedures described in AS 1012.9 [14].

From Table 3 it can be seen that the average compressive strength of IPC mixes used in this investigation (f_c) are reasonably close to 50 MPa as intended, with a mean of 52.4 MPa and a standard deviation of 3.8.

It can also be seen that there is generally an improvement in compressive strength of about 10–15 MPa for each of the samples between seven days and 28 days. The increase in the strength of the mixes is due to the fact that the polymerisation reaction continues beyond seven days. IPC concretes have a distinct setting and hardening behaviour compared to OPC-based concretes. Given that the mixing, curing and the age of the samples are the same, the variation in the strength values of the mixes can be attributed to the differences in different fly ash samples and changes in activating solution composition. The variation between the mixes is further explored in the following sections.

3.3. Splitting tensile and flexural strength of IPCs

The splitting tensile and flexural strength of the IPC mixes was experimentally measured following the procedure prescribed by AS 1012.10 and 11 [15,16], respectively. To obtain splitting tensile strength, a cylinder of dimension 150 × 300 mm (diameter × height) was split along its length. A minimum of three specimens was tested, as recommended by the Australian Standards. The flexural strength values were obtained from modulus of rupture tests using 100 × 100 × 300 mm (width × depth × length) prisms. The flexural strength values were obtained in accordance with AS 1012.11 using a minimum of two recommended samples per mix.

For design calculations, it is usual to estimate the tensile strength from the compressive strength for OPC-based concretes. For instance, in clause 6.1.1.3 of AS 3600 [17] an approximate expression for the characteristic principal tensile strength at 28 days is given as:

$$f'_{ct} = 0.4\sqrt{f'_c} \tag{1}$$

In Fig. 1, the experimental results of tensile splitting strength for IPC mixes used in this study are plotted together with Eq. (1).

The European Standard (2002) [18] also denotes the characteristic axial tensile strength of concrete (f_{ctk}) in terms of the mean value of axial tensile strength of concrete (f_{ctm}):

$$f_{ctk,0.05} = 0.7 \times f_{ctm}, 5\%\text{fractile} \quad (2)$$

The relationship between f_{ctm} and characteristic compressive cylinder strength of concrete (f_{ck}) at 28 days is given by:

$$f_{ctm} = 0.3 \times f_{ck}^{2/3}, \text{for } f_{ck} \leq 50 \text{ MPa} \quad (3)$$

and,

$$f_{ctm} = 2.12 \times \ln(1 + (f_{cm}/10)), \text{for } f_{ck} > 50 \text{ MPa} \quad (4)$$

where f_{cm} is the mean value of concrete cylinder compressive strength.

It can be observed from Fig. 1 that the experimentally determined values of tensile strength remains above the required values for most of the IPC mixes. Only Mix 2 falls slightly below the AS 3600 model: all the other mixes satisfy the relationship reported by the relevant standards. The variations in properties between the mixes due to the effect of fly ash are explored in detail in Section 4.

The current results demonstrate that the tensile splitting strength of the IPC mixes falls within the range predicted for OPC-based concretes. This means that for the same compressive strength, the tensile splitting strength of IPC satisfies the design equation given by the AS 3600 and other such standards and codes.

With the small number of samples used in this study, it is not possible to establish a general relationship between the compressive and other strength properties of IPC mixes. However, some general observations can be made as follows. Similar to OPC-based concrete [19], the strength properties of IPC depend on other parameters, such as the mix composition and curing methods. It can be seen from the results in hand that there is no unique relationship between the compressive and other strength properties.

The compressive strength and splitting tensile strength values for the mixes used in the current study are listed in Table 3. Eqs. (1) and (3) suggest that the tensile strength can be a derivative of the compressive strength for a given mix. From

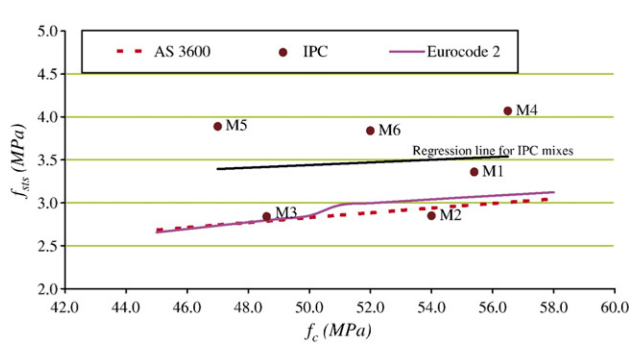

Fig. 1. Splitting tensile strength of IPC mixes (f_{sts}).

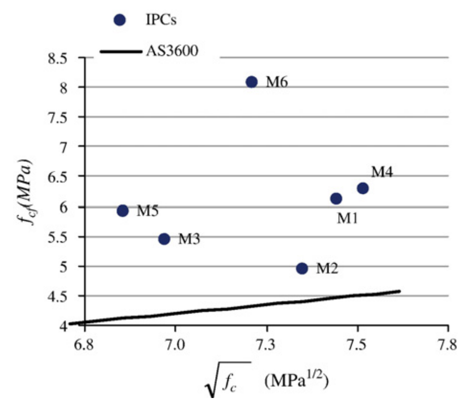

Fig. 2. Comparison of IPC flexural strength with the model reported by AS 3600.

the results presented in Table 3, a constant of proportionality can be easily calculated for the IPC mixes. It can be seen that the splitting tensile strengths of the IPC mixes are, on average, 0.48 (approximately half) of that of the square root of their compressive strengths, both for seven and 28 days of age. The constant calculated for the flexural strength is in the order of 0.7 (for seven and 28 days).

The flexural strengths of the IPC samples were experimentally determined using at least a pair of moulded flexure test specimens for each of the six mixes investigated, according to AS 1012.11 [16]. The average flexural strength values of the six IPC mixes investigated are reported in Table 3 for seven and 28 days of age. From the table it can be seen that the flexural results follow the same general trend as the splitting tensile strengths. Fig. 2 shows the variation of flexural strength of the IPC mixes with respect to their normalised compressive strengths. Clearly, the flexural strengths of IPCs are generally higher than the standard model line for OPC based concrete.

Similarities between the splitting tensile and flexural strengths of the IPC mixes can be read from Table 3b. On average the difference between flexural and splitting tensile strength of IPC mixes is about 2.0 MPa, both for seven and 28 days. Similar to the compressive strength results, Table 3b reports both a measure of central tendency and variability in the data.

Mixes 1, 2 and 3, being almost identical in mix design except that the source of the Class-F fly ash is different (Table 1), show a decreasing trend for both flexural and splitting tensile strength results. One can assume that the type of fly ash, which is the main variable amongst the first three mixes, causes this decrease. The effects of fly ash class on strength are explained in Section 4.

Clause 6.1.1.2 of the AS 3600 [17], however, allows for the estimation of the characteristic flexural tensile strength, f'_{cf}, of concrete using the following relation:

$$f'_{cf} = 0.6\sqrt{f'_c} \quad (5)$$

Similar to the splitting tensile test results (Table 3), the flexural test results shown in Fig. 2 perform considerably better

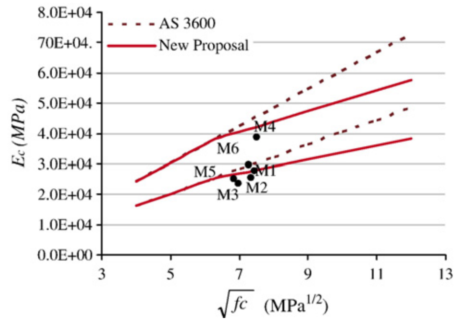

Fig. 3. Comparison of modulus of elasticity of IPC mixes with the model reported by AS 3600 for OPC-based concrete.

than the prediction of the Australian Standards design equation. This is probably due to the better performance of the material under tensile stresses compared to OPC-based concrete. It was mentioned earlier that IPCs undergo a polycondensation reaction to attain structural strength. The composition of the hardened IPCs in terms of matrix formation is not the same as OPC-based concrete. Therefore, the favorable tensile and flexural results presented can be attributed to the type of matrix formation in IPC materials.

3.4. Modulus of elasticity

Tests for the determination of the static chord modulus of elasticity and Poisson's ratio of the specimens were carried out in accordance with Australian Standards 1012.17 [20]. Three cylindrical specimens of size 150×300 (mm) were tested in order to plot each one of the results for the modulus of elasticity (E_c) of the mixes, as shown in Figs. 3 and 4.

In Fig. 3, the two dashed lines represent the upper and lower limits reported by Eq. (6) (AS 3600) [17]:

$$E_c = 0.043\rho^{1.5}\sqrt{f_{cm}} \pm 20\% \quad (6)$$

Eq. (6) is based on the mean value of compressive strength (f_{cm}) and the density (ρ). From Fig. 3 it can be seen that most of the results obtained for the IPC mixes are below the lower limit allowed by the AS 3600 model, the exception being Mix 4, which is situated near the median of the two lines. Some suppliers of ready-mix concrete have found that in some cases AS 3600 overestimates the modulus of elasticity [21]. Therefore a new model has been proposed for the next revision of AS 3600. The new model, which is also shown in Fig. 3, uses Eq. (6) for $f_{cm} \leq 40$ MPa, and Eq. (7) for $f_{cm} \geq 40$ MPa [21]:

$$E_c = [0.024\sqrt{f_{cm}} + 0.12]\rho^{1.5} \quad (7)$$

Overall, the compressive strengths of the IPC mixes are higher than 45 MPa (Table 3). Research has found that the models presented for engineering properties of normal strength concrete are not relevant for higher strength concrete (over 50 MPa) [22]. Therefore, the E_c values for IPC are compared with models reported in the literature for higher strength concretes. A comparative study of the static chord modulus of elasticity and other properties of high strength concrete has been reported by a number of researchers [23–25]. The models reported by Carrasquillo et al. [23], Ahmad and Shah [24], and Mendis et al. [25] take into account the density, and are represented by the following:

$$E_c = (3320\sqrt{f_c'} + 6900)(\rho/2320)^{1.5} \quad (8)$$

Carrasquillio et al. [23]

$$E_c = 3.38\rho^{2.5}(\sqrt{f_c'})^{0.65} \times 10^{-5} \quad (9)$$

Ahmad and Shah [24]

$$E_c = 0.043\rho^{1.5}\eta\sqrt{f_{cm}} \quad (10)$$

Mendis [25].

The model proposed by Ahmad and Shah provides a closer fit to AS 3600, and that of Carrasquillio et al. falls closer to the lower limit of the interval as shown. Acknowledging that Eq. (7) overestimates E_c for high strength concrete, Mendis et al. [25] introduced a modification (η) to the AS 3600 that is presented by Eq. (10), where $\eta = 1.1 - 0.002 f_c' \leq 1.0$. Each of these models is plotted in Fig. 4, along with the experimentally determined data for the IPC mixes.

Amongst all the IPC mixes, the elastic modulus of Mix 4, which contains some coarse aggregate (crushed rock), fits best between the limits provided by AS 3600 [17]. The positions of the remaining mixes are either on or closer to the lower limit provided by the Australian Standard. For OPC-based concrete, it is known that the values of the modulus of elasticity of concrete and of the Poisson ratio depend on the values of modulus of elasticity of the paste, and the Poisson's ratio of the paste, and on the modulus of elasticity of aggregates and the Poisson's ratio of aggregates [26]. Assuming this to be true for the IPC mixes considered, only the elastic modulus of Mix 4 would have been expected to fit the limits provided by the Standard. All the other mixes present the elastic modulus of the past, not including the properties of the coarse aggregates.

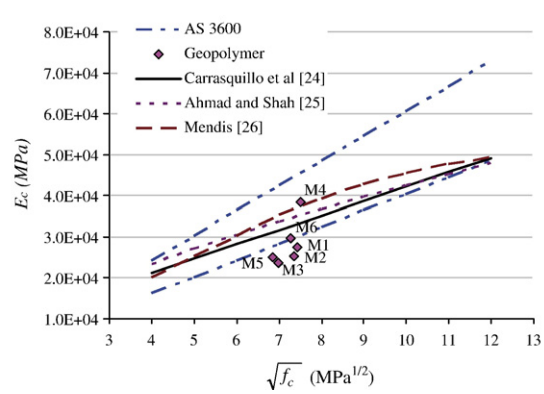

Fig. 4. Modulus of elasticity of the IPC mixes investigated compared with models for high strength concrete.

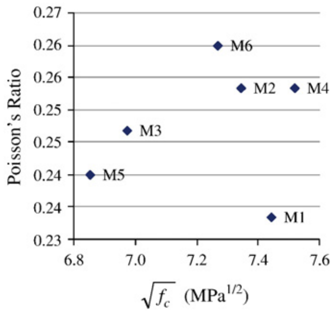

Fig. 5. Poisson's ratio of the IPC mixes investigated.

3.5. Poisson's ratio

Poisson's ratios for each of the IPC mixes investigated were measured and calculated following AS 1012.17.3 recommendations [20]. The values of longitudinal and lateral strains were recorded simultaneously on the same samples as those undergoing tests for the evaluation of static modulus of elasticity.

According to AS 1012.17, Poisson's ratio is calculated to the nearest 0.01 from the average strains from the second and successive loadings according to the following equation:

$$v = \frac{(\varepsilon_4 - \varepsilon_3)}{(\varepsilon_1 - 0.00005)} \tag{11}$$

Where v is the Poisson's ratio, ε_4 is the average transverse strain at test load, ε_3 is the average transverse strain coincident with average longitudinal strain of 50×10^{-6} m/m, and ε_1 is the average longitudinal strain at test load.

The experimental values obtained for Poisson's ratio for the IPC mixes show an overall increase with the increase of compressive strength. This conforms well with the conclusions drawn by Setunge et al. [27], which refer to the Poisson's ratio of high strength concrete. Fig. 5 presents the values of Poisson's ratio for the IPC mixes investigated. Amongst these, Mix 6 has the highest value of Poisson's ratio. It is noted that unlike other mixes, Mix 6 does not contain any slag and relies on the fly ash composition to achieve structural strength. It can be observed from Fig. 5 that the values of Poisson's ratio for all of the IPC mixes fall between 0.23 and 0.26, which is slightly higher than the values assigned for normal strength OPC-based concrete (0.11–0.21) [13]. For high strength concretes the value of Poisson's ratio ranges between 0.2 and 0.25 [25].

4. Variability in IPC mixes

IPC materials derived from aluminosilicate secondary raw materials, such as fly ash, can exhibit superior chemical and mechanical properties to ordinary Portland cement (OPC). The mechanical properties, however, may greatly depend on the chemical content of the fly ash. In the following sub-sections, the variability in engineering properties of the IPC mixes are discussed in the light of results presented in this paper. For a more elaborate evaluation of the effect of fly ash on mechanical properties refer to the work presented by Kyte et al. [28].

4.1. Mixes 1, 2 and 3

All the mixes considered in the current research work were very similar, except in the type of fly ash used. However, the fly ash content was constant at 31.25%.

Mix 1 used Port Augusta fly ash and had a water-to-binder ratio of approximately 0.52, whereas Mix 2 and 3, which used Gladstone and Tarong fly ash respectively, had water-to-binder ratios of around 0.59. This difference is due to the smaller average particle size distribution of Port Augusta, compared with Gladstone and Tarong fly ashes, which therefore requires less water to achieve desirable rheology. It can be seen from the results in Table 3 that the reduced water content accounts for the higher compressive, splitting tensile and flexural strengths of Mix 1 compared to Mixes 2 and 3 at 28 days. Gladstone fly ash contains the available calcium, which causes a more rapid setting of Mix 2 compared with Mixes 1 and 3. This may contribute to the lower seven day compressive strength results for Mix 1 compared to those of Mix 2. It can be observed that Mix 2, containing Gladstone fly ash, achieves reduced 28-day strength results. The faster setting characteristic of Mix 2 causes less dissolution and consequently less inorganic polymer phase formation. This leads to higher seven-day strengths for Mix 2, but not 28-day strengths.

Mix 3 uses Tarong fly ash, which contains very high concentrations of crystalline materials such as quartz and mullite, and has a poor reactivity as the silicon and aluminum appear in crystalline forms. Samples containing Tarong fly ash generally achieve lower strength results. The only reason they achieve any strength is due to the presence of slag.

4.2. Mixes 4, 5 and 6

Port Augusta fly ash is used in Mixes 4, 5 and 6, with Mix 4 being very similar to Mix 1 except that it contains some screenings and a lower water-to-binder ratio of 0.45. Ignoring the effects of the screenings and assuming that specimens made up of Mix 4 fail at matrix level, overall higher strength results of the mix can be attributed to its reduced water content. A comparison of strength values for Mixes 1 and 4 supports this argument and shows that the volume of water present per volume of binder affects the strength development of the mix.

Mix 5 has almost twice the concentration of Port Augusta fly ash than Mix 4, and it contains a very low amount of slag. It also has a very low water-to-binder ratio of 0.31 and, following the arguments presented above, it would have been expected to have higher strength results than Mix 4. This is not the case, however, as can be observed in the results presented in Table 3, and may be due to several reasons:

a. The concentration of dissolved OH^- ions in Mix 5 is much lower than those of other mixes and may be too low to completely activate the fly ash chemistry.
b. The silicate content of Mix 5 is higher than that of Mixes 1 to 4, which results in faster setting, lower dissolution and consequently lower inorganic polymer phase formation.

c. As sand was the only aggregate used but in a reasonably high ratio of 5 to 1, lower strengths would be expected. The strength loss was likely to occur due to the high surface area to volume ratio of the aggregate. A lower ratio of 3 to 1 is normally used with a combination of coarse aggregates and screenings, even for mixes using ordinary cements.

Finally, Mix 6 contains no slag content and equally has a low water-to-binder ratio of 0.34. It would be expected to have higher strengths than Mixes 4 and 5 but the results in Table 3 show that this is not the case. The likely reason for the lower strength values of Mix 6 is that PA fly ash does not contain the necessary amount of calcium for the initial reaction and therefore sets very slowly. As a result, segregation and bleeding effects are likely to take place due to a slow rate of reaction and setting. This leads to a density gradient throughout the samples, which in turn can result in reduced strengths.

5. Concluding remarks

It was observed that for a concrete density similar to OPC-based concretes, the average compressive strengths of IPC mixes (f_c) have been found to be close enough to the design strength, with a mean of 52.4 MPa and a standard deviation of 3.8.

The results presented here show that the splitting tensile and flexural strength of the IPC mixes compares favorably with the models presented by the standards for OPC-based concretes. Although the difference between splitting tensile and flexural strength of IPC mixes has been found to be approximately 2.0 MPa, similarities in strength gain between the mixes were apparent.

An attempt was made to determine the static chord modulus of elasticity and Poisson's ratio of IPC specimens. An evaluation of the static modulus of elasticity of IPC mixes was compared predominantly with models reported for higher strength concretes. It was found that, similar to OPC-based concrete, most mechanical properties depend upon mix design and curing method.

The results reported herein are only preliminary to a long-term experimental work in the field of IPC. It is essential that further research is undertaken using mix compositions, including coarse aggregates with or without ground granulated blast-furnace slag, to reinforce the validity of the current results.

References

[1] C.K. Yip, The Role of Calcium in Geopolymerisation, PhD Thesis, Department of Chemical and Biomolecular Engineering, The University of Melbourne, Australia, (2004).

[2] J.G.S. van Jaarsveld, The Physical and Chemical Characterisation of Fly Ash Based Geopolymers, PhD Thesis, Department of Chemical Engineering, The University of Melbourne, Australia, (2000).

[3] J.W. Phair, J.S.J. van Deventer, J.D. Smith, Mechanism of polysialation in incorporation of Zirconia into Fly Ash-based geopolymers, Industrial and Engineering Chemistry Research 39 (8) (2000) 2925–2934.

[4] C.K. Yip, J.S.J. van Deventer, Effect of granulated blast furnace slag on geopolymerisation, CD-ROM Proceedings of the 6th World Congress of Chemical Engineering, Melbourne, Australia, 2001.

[5] J. Davidovits, M. Davidovics, Geopolymer: room temperature ceramic matrix for composites, Ceramic Engineering and Science Proceedings 9 (1988) 835–842.

[6] G.C. Lukey, J.S.J. van Deventer, Drivers for the Establishment of a Geopolymer Industry, Materials 2003, Adaptive Materials for a Modern Society, Institute of Materials Engineering Australia, 2003.

[7] J.S.J. van Deventer, Emerging global and local markets for geopolymers, turn potential into profit, in: G.C. Lukey (Ed.), International Conference Proceedings, Melbourne, Australia, 2002, CD-ROM.

[8] D. Hardjito, S.E. Wallah, B.V. Rangan, Research into engineering properties of geopolymer concretes, geopolymers 2002: Turn potential into profit, in: G.C. Lukey (Ed.), International Conference Proceedings, Melbourne, Australia, 2002, CD-Rom.

[9] H. Xu, J.S.J. van Deventer, The geopolymerisation of alumino-silicate minerals, International Journal of Mineral Processing 59 (3) (2001) 247–266.

[10] J.W. Phair, Compositional Effects and Microstructure of Fly Ash-Based Geopolymers. PhD Thesis, Department of Chemical Engineering, The University of Melbourne, Australia, (2001).

[11] W.K.W. Lee, J.S.J. van Deventer, The addition of chemical additives to control the setting speed of geopolymeric binders, Proceedings of the 6th World Congress of Chemical Engineering, Melbourne, Australia, 2001, CD-ROM.

[12] AS 1012.12.1, Methods for testing concrete: determination of mass per unit volume of hardened concrete—rapid measuring method, Australian Standards (1998).

[13] R.F. Warner, B.V. Rangan, A.S. Hall, K.A. Faulkes, Reinforced Concrete, Addison Wesley Longman, 1998.

[14] AS 1012.9, Methods for Testing Concrete: Determination of Compressive Strength, Australian Standards (1999).

[15] AS 1012.10, Method of testing concrete: determination of indirect tensile strength of concrete cylinders (Brazil or Splitting Test), Australian Standards (2000).

[16] AS 1012.11, Method of testing concrete: determination of the modulus of rupture, Australian Standards (2000).

[17] AS 3600, Concrete structures, Australian Standards (2001).

[18] European Standard, Eurocode 2: Design of Concrete Structures — Part 1: General Rules and Rules for Buildings, ref. No. prEN 1992-1-1, July 2002, p. 29.

[19] A.M. Neville, Properties of Concrete, Fourth Edition, John Wiley & Sons, Inc., 1996

[20] AS 1012.17, Determination of the static chord modulus of elasticity and poisson's ratio of concrete specimens, Australian Standards (1997).

[21] B.E. Gilbert, Creep and shrinkage models for high strength concrete — proposals for inclusion in as3600, Australian Journal of Structural Engineering 4 (2) (2000) 95–106.

[22] P.A. Mendis, C.W. French, Bond strength of reinforcement in high-strength concrete, Advances in Structural Engineering Journal 3 (3) (2000) 245–253.

[23] R.L. Carrasquillo, A.H. Nilson, F.O. Slate, Properties of high strength concrete subject to short term loads, ACI Journal 78 (1981) 171–178.

[24] S.H. Ahmad, S.P. Shah, Structural properties of high strength concrete and its implications for precast pre-stressed concrete, PCI Journal 30 (1985) 92–119.

[25] P.A. Mendis, Design of High-strength Concrete Members: State-of-the-Art, EA Publishers Ltd., 2001 http://www.engaust.com.au.

[26] R.C.V.S. Kameswara, R.N. Swamy, P.S. Mangat, Mechanical behaviour of concrete as a composite material, Materials and Structures/Materiaux et Constructions 7 (1974) 265–271.

[27] S. Setunge, M.M. Attard, P.P. Darvall, Static Modulus of Elasticity and Poisson's Ratio of Very High Strength Concrete, Civil Engineering Research Reports. Monash University 1 (1990).

[28] L.M. Keyte, G.C. Lukey, J.S.J. Van Deventer, The effect of coal ash glass chemistry on the tailored design of waste-based geopolymeric products, CD-ROM Proceedings of WasteEng2005 International Conference, Albi, France, 17–20 May 2005.