RECOMMENDED PRACTICE

Geopolymer Concrete
FOREWORD

This Recommended Practice is the first edition and has been developed by a sub-committee of Concrete Institute of Australia consisting of:

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RECOMMENDED PRACTICE

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Geopolymer cement is a new kind of cement which uses a different chemistry to that found in traditional Ordinary Portland Cement (OPC). A geopolymer is made by activating amorphous alumino-silicate materials, such as fly ash and slag, with alkali-based chemicals such as sodium hydroxide and sodium silicate. Geopolymer cement does not need to contain OPC to work. Geopolymers have been known to be useful binders in concrete for over 60 years, but have recently developed rapidly in Australia due to the fact they have a CO$_2$ footprint which is approximately 80% lower than OPC cement.

Geopolymer binders may be made from a variety of alumino-silicate sources. The engineering aspects of geopolymer concrete as later described in this document relate to geopolymeric materials based primarily on low calcium (or Class F) fly ashes. Geopolymers incorporating significant quantities of calcium rich materials such as slag, for instance, may have different properties to those based on low calcium fly ash alone. While commercial availability of geopolymer concrete is a new phenomenon, not just in Australia but globally, geopolymer technology and its application in real projects is not new. Development of the technology has been undertaken in Europe for the entirety of the post-World War 2 era, predominantly in Ukraine during and following the Soviet rule, but significantly in France, Spain, Germany and other countries. This era of research and development resulted in the construction of numerous structures including civil water works, railway sleepers, pipes, pavement, roads, fire resistance coatings, conventional precast products and even a twenty story apartment building in Lipetsk, Russia. Some of these structures are now over sixty years old and their durability has been proven in both the laboratory and most importantly, in the field. Despite this level of large scale development, the commercial impetus to develop the technology into a business did not arise until the highly substantial carbon emissions from conventional OPC manufacture have become of concern.

Geopolymer concrete is now available in Australia, with the expectation that its availability and utilisation will increase in the coming years as Australia transitions to a lower carbon economy. Australia has an abundance of unutilized fly ash and slag so there is no reason why rapid scale-up of geopolymer production should not occur. As with any new development in concrete, there are some differences in designing for, making and working with geopolymer concrete compared to OPC concrete, which are covered in this Recommended Practice. These include mix design, transport, placement, workability, curing, and safety. Environmental benefits from reduced CO$_2$ emissions and industrial by-product utilization are also discussed. This note provides a quick, practical and useful entry point to guide new users, designers and decision makers.
The geopolymer binder is usually formed by the interaction of an alkaline solution ('activating solution' or activator) with a reactive aluminosilicate powder [Ref 2.1]. In commercial geopolymer production, this is usually a mixture of fly ash (waste from coal combustion) and blast furnace slag (waste from iron-making). The solid powder (binder) partially dissolves and the dissolved components rearrange into an aluminosilicate gel which then cross-links and hardens to form the geopolymer cement phase. This cement can take the place of hydrated Portland cement in concrete production. When mixed with coarse and fine aggregates, a high-performance low-CO₂ concrete can be produced.

**Geopolymer Reaction**

**2.1 Basic Chemistry**

The basis of the geopolymer structure is an alkali aluminosilicate gel; an aluminosilicate framework resembling in many ways the atomic structure of a zeolite, but lacking long-range order (crystallinity). Figure 2.1 shows a part of a geopolymer gel structure, comprised of tetrahedral (4-coordinated) Al and Si atoms arranged in a highly cross-linked framework, with the negative charges associated with tetrahedral AlO₄ groups charge-balanced by non-framework sodium ions. These ions will in most cases be associated with one or more water molecules, unless the geopolymer has been dried extensively, but these are not depicted in Figure 2.1 for the sake of simplicity.

![Figure 2.1](image)

Representation of part of the geopolymer gel atomic structure. Red: oxygen, purple: aluminium, yellow: silicon, green: sodium. The lack of long-range (crystalline) order is obvious.

**2.2 Gel System**

The microstructure of the geopolymer cement depends to a very significant extent on the details of the activating solution used and the conditions under which the geopolymer was cured. Adequate curing is essential for geopolymers, as with almost all cement-based materials, and a poorly cured concrete of any description will show a poor and porous microstructure. Addition of a higher silica content to a geopolymer activating solution can result in a more homogeneous and uniform microstructure (Ref [2.2]) which also correlates well with improved mechanical performance.

In geopolymers containing significant levels of calcium (for example those synthesised either from a high-calcium fly ash, or a mixture of low-calcium fly ash and blast furnace slag), the aluminosilicate gel is not the sole binder phase. In such systems, there appears to be a tendency towards the formation of multiple gel phases simultaneously, with aluminium-substituted calcium silicate hydrate phases forming in addition to the aluminosilicate gel. Such phases are believed to be very similar to those responsible for strength development in Portland cement/slag blends and alkali-activated slag binders, and give additional early strength to...
geopolymer concretes. Research in this area is still ongoing, and the detailed identification and separate analysis of the separate high-calcium and low-calcium phases is a highly complex scientific problem, but this mechanism does provide an explanation for much of the observed behaviour of calcium-containing geopolymer binders.

2.3 Geopolymer vs Portland Cement

2.3.1 Kinetics

While fly ash and slag are extensively used worldwide as supplementary cementing materials in Portland cement concretes (Ref [2.3, 2.4]), their reaction in Portland cement systems is generally slower than the reaction of the cement itself. This means that cements blended with a high fly ash or slag content will generally show a reduced early strength but better late strength development than a non-blended Portland cement. To compensate for this tendency towards slower reaction, geopolymers based on fly ash and slag use an alkaline activating solution instead of mix water, which accelerates the dissolution and subsequent reaction of the ash and slag particles. The kinetics of geopolymer formation have been studied by various spectroscopic, calorimetric and rheological techniques (Ref [2.5]), and a detailed mechanistic description of the interlinked dissolution-reorientation-gel formation process has been developed based on these data (Ref [2.6]). Early strength development can match the performance of low-, medium- or high-strength Portland cement concretes, and the ongoing reaction involving the alkaline pore solution following hardening can give a continued increase in strength in a well-designed mix over a period of months to years as the microstructure continues to develop. Suitably designed geopolymer concrete mixes are able to develop high strength at an acceptable rate when cured at temperatures as low as 10-15°C – contrary to the widely-repeated fallacy that heat-curing is required for all geopolymers.

2.3.2 Admixtures

Many of the admixtures commonly used in Portland cement concretes are either not necessary or not effective (or both) in geopolymer systems. In particular, the majority of commercially available superplasticisers are degraded by the alkaline activating solutions used in geopolymer synthesis. This may not be universally true as there is some evidence that conventional dispersing agents such as superplasticizers will act on the binder components if added before the alkaline activators are added to the mixture. (See 3.1.4) However, the different chemistry of geopolymers means that entirely different admixtures are useful in controlling geopolymer properties. While the standard accelerators, retarders and viscosity modifiers that are used in Portland cements are not always useful, research over the past decades has led to the development of a toolkit of admixtures which are specific to the geopolymer system and which provide an ever-developing level of control of rheology, setting time and strength development. While the level of control does not yet compete with the ability to control the setting and strength development of Portland cement, which has been developed over a period of close to 200 years of research, the rapidly developing scientific understanding of geopolymer chemistry is continuing to provide advances in this area.

2.3.3 Durability

While the durability of fly ash-derived geopolymers has obviously not yet been extensively proven, as these materials were first introduced and studied in 1993 (Ref [2.7]), there do exist extensive data regarding the performance and durability of the cements generated by alkaline activation of slags (Ref [2.8-11]). These tests have shown excellent resistance to ageing, freeze-thaw cycling, salt scaling and carbonation. Testing of geopolymer cements in each of these areas is ongoing, but initial results generally appear very promising. The aluminosilicate geopolymer phase is inherently quite highly resistant to acid attack due to the high degree of
cross-linking present and the formation of an acid-resistant leached silica phase. The strong binding of the gel phase to aggregate particles enhances flexural and tensile strength, which are particularly valuable in aiding freeze-thaw resistance. While some early and poorly-designed geopolymer concrete formulations were found to be susceptible to efflorescence as the excess alkali present was gradually released from the pore solution and reacted with atmospheric CO$_2$ to form sodium carbonate crystals, this problem is readily able to be overcome with accurate mix proportioning and adequate curing.

2.3.4 Sophistication

As was mentioned above, the level of control of Portland cement and concrete chemistry that is currently available has been developed over a period of close to 200 years of worldwide utilisation. By comparison, fly ash and slag-based geopolymers have been studied in a number of laboratories around the world for less than two decades, and are just beginning to meet commercial utilisation. Because of this, the development of geopolymer technology is still ongoing, but the technology has matured to the point where geopolymer concrete can now be produced on a commercial scale with full confidence that it will perform to specification, will not set prematurely or overly slowly, and will develop its design strength. This is in spite of the fact that the precursor fly ash in particular is an inherently variable material; the understanding of ash chemistry in geopolymerisation has reached the point where small corrections are able to be made in mix design to account directly for any deficiencies or changes in ash properties, giving a dependable geopolymer product.

2.3.5 Problems of Liquid Activators

The main difficulty associated with geopolymer technology is the use of liquid alkaline activating solutions, which are classed as highly corrosive materials. From an operational standpoint they are difficult and expensive to handle with significant occupational health and safety concerns. Having said that, alkali solutions are used in excess of 1 million tonnes per annum in Australia every year, giving an indication of their ubiquitous use in many processes and industries where the above mentioned concerns are alleviated with correct procedures and handling. With respect to use in geopolymer concrete, once these pure liquids are mixed with the aggregates and binders to form pre-mixed concrete or other pre-cast products their aggressiveness is drastically reduced. Despite this, fresh geopolymer concrete is still significantly more aggressive than traditional OPC concrete, with a pH of up to 14 compared with an OPC pH of 13. Applicators and concreters using geopolymer concrete should consult the producer to learn and be trained with appropriate handling and safety precautions and procedures.

References


Chapter 3  Geopolymer Practice

3.1 Raw Materials

As with all concretes, the basic ingredients are an aggregate skeleton (stone and sand) and a cement paste (a blend of binder components and fluids). With geopolymer concrete, the cement paste is a blend of binder components (alkali reactive binders such as fly ash, ground granulated blast furnace slag, etc and non-reactive fillers) and fluid reagents (often referred to as the activator).

3.1.1 Potential alkali reactive binder components

3.1.1.1 Fly Ash: any fine fly ash, as per AS 3582.1. Class F fly ash is preferred as the high calcium contents of class C ashes can cause early set if not blended with a retarder (Ref 3.1). Australian brown coal fly ashes tend to show little geopolymer reaction and are more likely to be classified as non-reactive fillers (Ref 3.2).

3.1.1.2 Ground Granulated Blast Furnace Slag as per AS 3582.2

3.1.1.3 Metakaolinite: kaolin clay calcined at > 650°C

3.1.1.4 Portland Cement: to AS 3972. Small quantities can be used as an accelerator (calcium effect) but larger quantities simply produce CSH phases within the geopolymer phase with consequent changes in bulk geopolymer concrete performance (Ref 3.3).

3.1.1.5 Silica fume to AS 3582.3, as a source of amorphous silicon.

3.1.1.6 Other: Any other fine material that contains significant amounts of silicon and/or aluminium held in an amorphous phase.

3.1.2 Reagents (Activator)

3.1.2.1 Na systems: blends of NaOH and/or Na silicate solutions. Na aluminate can be included if the binder feedstock is low in amorphous aluminium components. NaOH can be added as a solid if mix designs call for low water contents or if higher fresh mixture temperatures are required (eg. “winter” concreting).

3.1.2.2 K systems: blends of KOH and/or K silicate solutions as above.

3.1.2.3 Water

3.1.2.4 Availability: A typical NaOH would be solid “pearl” NaOH or a 50% solution of NaOH. A typical Na silicate solution would be PQ’s grades D or N. The Na silicate solution can be replaced with a blend of NaOH and silica fume.

3.1.2.5 Preparation: components can be preblended to form one reagent or added separately at the concrete mixer. Adding solid NaOH to the mixer or to the pre-blend generates a lot of heat.

3.1.2.6 Storage: For transport cost reasons, it is preferred to use concentrated reagent solutions. This means that reactants are close to their solubility limits and must be stored in temperature controlled containers and preferably continuously stirred immediately prior to dispensing into the concrete mixer.
3.1.3 Fine and Coarse Aggregates

The aggregate skeleton is the same as any other concrete aggregate skeleton (a blend of coarse and fine aggregates to AS 2758.1 - 1998). To minimize the use of expensive cement paste components, the skeleton particle size distribution (PSD) should be optimized to minimize gross void space in the compacted skeleton.

3.1.3.1 Reactive Aggregates: As alkali solutions are used up (or weakened) during mixing and fresh concrete placement and are not continually generated at a later age, alkali reactive aggregates commonly forbidden in OPC concrete because of the fear of later-age ASR cracking are now allowable. Indeed some pure alkali aggregate reaction may be preferred as chemical bonds then develop between the cement matrix and the aggregate particles, enhancing hardened concrete tensile strength. If this is the case then naturally occurring reactive aggregates and manufactured ones like granulated slags and recycled glass may become viable options.

3.1.4 Admixtures

Some research (Ref 3.9) suggests that conventional concrete admixtures (plasticizers, superplasticizers) designed to enhance paste workability by dispersing the binder components, work in the same manner in geopolymer concretes (Ref 3.4). Others (Chapt 2.2) suggest that the high alkalinity of the geopolymer mixture interferes with such admixtures. This suggests that the time of addition may be an important parameter. Dispersing effects are usually reduced because of reaction kinetics (dissolution and condensation reactions begin immediately reactive binders and reagents come in contact) and because fly ashes contain varying amounts of activated carbon which soaks up such chemical admixtures. If the carbon content (LOI) of the feedstock is high or increases from one batch to the next then increased quantities of admixture will be required to get the same effect and vice versa if the LOI is lowered. This latter problem normally does not arise when using a slag binder.

Air-entrainers (to AS 1478.1) would need to be trialled in the specific mixtures under investigation or new admixtures designed for geopolymer concrete.

3.2 Mix Design Criteria

3.2.1 Reactivity of binder components

The alkali reactivity of each binder component affects the fresh and hardened concrete properties. Mix designs and process designs can be produced to take into account any binder reactivity but variations from batch to batch need to be minimized or more frequent performance tests need to be carried out on the binder and/or the hardened concrete to ensure performance requirements continue to be met. Alternatively, target concrete properties need to be sufficiently greater than specified characteristic strengths to take into account any such variation in binder reactivity.

3.2.2 Key mix design parameters

3.2.2.1 Aggregate skeleton: As with any concrete mix design, the PSD of the aggregate skeleton should be optimized to produce a minimum voids content and hence minimize expensive paste requirements.

3.2.2.2 Paste: To optimize the quality of the hardened paste yet maintain optimum fresh concrete properties, a number of paste parameters need to be optimized, singly and together. These include:
3.2.2.2.1 Fluids: Binder ratio by mass. (“Fluids” = total water + sodium/potassium silicate + sodium/potassium hydroxide) Increasing this parameter increases workability (and material costs). It should be set as low as possible whilst still achieving the required paste rheology (and concrete workability). As with OPC concretes, but for some different reasons, increasing the water content of a paste proportionately reduces the quality of the hardened concrete.

To produce very high strength concretes, very low water contents (highly concentrated alkaline solutions) must be used. This usually requires the use of solid NaOH and dry (or low, controlled moisture) aggregates. Larger Fluids:Binder ratios and/or superplasticizers allow workability adjustments.

3.2.2.2.2 Si:Al ratio by atoms. As discussed in chapter 2, the ratio of silicon to aluminium ions in the hardened matrix (i.e., in the sol after dissolution has occurred) controls the physical properties of the geopolymer network. For low calcium systems the preferred ratio is about 2:1.

3.2.2.2.3 SiO₂: Na₂O ratio by mass. As solution reactions involving dissolved aluminium hydroxide ions are extremely rapid (e.g., reaction rate constants for alumino-silicate reactions are four orders of magnitude higher than those for comparable silica reactions, Ref 3.5) the sol usually needs to be pre-doped with Si ions if geopolymer “monomers” are to be formed in the sol. The amount of required Si ions in the activator varies with the reactivity of the binder feedstock but typically a SiO₂: Na₂O in the range 0.5 to 1.5 will contain the optimum, based on trial concrete strength testing.

3.2.2.2.4 H₂O: Na₂O ratio by mass. The alkali concentration determines the rate and degree of dissolution. Very high concentrations (low H₂O:Na₂O) produce stronger geopolymer matrices and very low concentrations produce zeolites instead of geopolymers.

3.3 Safety Issues and MSDS’s

Almost all geopolymer concrete production processes must deal with highly corrosive and toxic alkaline solutions. They must be transported, stored and dispensed as such.

MSDS’s are available from suppliers for all technical grade reagents and process specifications and QA work instructions must be written around the requirements of these data sheets.

NaOH solutions can be prepared on site, or solid NaOH can be added directly to the concrete mixer. Both require written safe handling procedures to ensure dust, heat evolution and potential fuming are all managed safely. Bunding of storage and dispensing areas will almost certainly be required.

Typical technical grade silicate solutions can be transported and handled without the provisions required for toxic materials.

Unlike finely abraded crystalline silica which can lead to silicosis if inhaled in frequent and significant quantities, amorphous silica, as found in most geopolymer binder components, will pass all OH&S safety biological testing, even if used in sub-5 micron form and formed by grinding (Ref 3.6).

3.4 Workability

As with OPC concrete production, acceptable workability control methods must be written into work instructions and an audit system must be in place to assure adherence to these procedures.
As in 3.2.2.2.5, water addition to increase workability will proportionately reduce the quality of the hardened concrete. The water content of the mixture must be controlled to produce consistent quality concrete.

During the mixing process the dissolution reactions proceed, as does the condensation process, to form geopolymer monomers and free water in the sol. Hence as mixing time increases so also does paste workability until setting (polycondensation) starts to occur and workability starts to decrease. Assuming negligible loss of water through aggregate absorption or evaporation, a relatively stiff mixture can become fluid with continued mixing as condensation reactions proceed. Optimum mixing times will vary with mix recipes, mixer type, mixer speeds, order of addition and ambient temperature but are typically in the range of 3 to 8 minutes after the addition of fluids. Mixer torque recordings will allow optimization for a specific set of parameters.

Provided mix design ratios are kept constant, adding more Activator (the blend of all chemical reagents) should increase workability by increasing the Fluids: Binder ratio. Provided this does not get too high (where fluids are in excess of dissolvable binder fraction) and the “fluids” formula is kept constant, hardened concrete quality should not be significantly affected by increasing fluids content.

As with all concrete manufacturing procedures, workability should be adjusted to suit the compactive effort available.

To some degree, setting rate can be increased by the addition of small quantities of calcium bearing components (eg OPC) or decreased by adding a “coating” material such as borax (Ref 3.1)

In many cases, conventional concrete workability aids such as superplasticizers can be used to increase mixture workability. Preferably they are added to the dry mixture with some of the mixture water to disperse the fine binder particles before the activator or the individual chemical reagents are added to start the dissolution process.

3.5 Batching and Delivery Process

The concrete manufacturing process is basically the same as for conventional OPC concrete manufacture.

3.5.1 Batching Equipment

Aggregate and binder are batched as per OPC concrete. As the mix water content needs to be controlled, they should be purchased, stored and batched in a controlled-moisture state (preferable in a dry, SSD or low moisture condition). Thus when purchasing it is preferred to specify moisture ranges and use self-draining and covered bins and conveyors.

Reagents (preblended or as individual components) need to be batched using an accurate chemicals dispensing system. Such equipment would normally have temperature control, stirrers and nozzle flushing facilities on each component delivery system. Bunds would be required in case of spillage.

3.5.2 Mixing Equipment

Conventional concrete mixers are adequate but dual action (folding + high shear) mixers are preferred. High shear components (“stars”) allow efficient mixing of the paste component.
3.5.2.1 Mixing Procedure and Times: As with conventional concrete mixing, the most common procedure is; stone, then sand, then binder, then reagents. Variation to this may include:

- Dispersing admixtures added with the binder.
- Adding some of the water then solid NaOH to the aggregate mixture to pre-heat the mixture.
- Preparing the paste off-line in a high shear mixer then folding it into the aggregate mixture.

Optimum mixing times will vary with the reactivity of the binder components, the mix design, mixer efficiency and the batching sequence. An initially dry mix becomes more fluid with mixing time then, as gelation begins to occur, becomes less fluid with increased mixing time. Graphs plotting fluidity (mixer torque) with time will allow optimization of the mixing cycle.

3.5.2.2 Transport: Low slump mixtures can become very sticky so transporting the fresh mixture often needs to be done in steeply sided hoppers.

3.5.2.3 Addition of water: As water is one of the measured reagent components, adding water at the end of the mixing cycle to increase workability should not be allowed. If workability is to be increased by adding fluids then small quantities of the preblended reagent ("fluids" or activator) can be added at the end of the mixing cycle.

3.5.3 Placement of Geopolymer Concrete

3.5.3.1 Mould Preparation: As hardened geopolymer concrete has strong adhesion to steel surfaces, an effective mould release coating must be applied to any steel mould surfaces. Generally thick coatings of a viscous wax based mould release agent are required to prevent mould stick.

3.5.3.2 Placement methods: Geopolymer concrete can be placed with conventional cast in-situ (transit trucks) or precast (conveyor or transport hoppers) methods.

3.5.3.3 Slump changes: As the geopolymerization reactions starts in the mixer and continues through sol and gel phases, the slump is constantly changing in a regular manner. Hence process steps need to be designed with an intimate knowledge of this slump variation with time and temperature for each mix design.

3.5.3.4 Bleed: As the reagent or activator is relatively viscous when compared with water, a well designed mixture will show little or no bleed.

3.6 Compaction

Placement and compaction methods should try to avoid physically entrapping large air voids in the compacted concrete. This can be a problem with low slump sticky mixtures when large amplitude mould or internal vibration is used. Low amplitude, internal vibration is preferred for cast in-situ and wet precast applications.

Self-levelling mixtures can be designed that need no external compaction.

No-slump mixtures can be compacted with conventional high-compactive-effort procedures; centrifugal, roller, pressure or impact compaction equipment.

For extremely high strength concretes or mortars (200 MPa and above), it is usually necessary to use high speed centrifuging and vacuum de-airing. The latter may be best employed during mixing.
3.7 Curing

3.7.1 Ambient cure: Mixtures can be designed to cure at ambient temperature by the appropriate choice of binder and reagent. Any procedures which increase the temperature of the fresh or compacted mixture will obviously offset the effects of low ambient temperatures.

3.7.2 Accelerated Cure: Compacted concrete rapidly gains strength if steam cured or encapsulated and dry cured at elevated temperatures.

3.7.2.1 Effect of curing temperature: Early age compressive strengths are almost directly proportional to curing temperature, up to a curing temperature of 90°C in the concrete; for example, a typical low slump mixture after steam curing for 6 hours at 55°C has a compressive strength of 12 MPa but if cured at 90°C for 6 hours has a compressive strength of 90 MPa.

3.7.2.2 Effect of curing time: At any curing temperature, compressive strength increases with curing time so that ultimately all specimens reach a similar strength independent of curing temperature.

Geopolymer concrete continues to increase strength with age in the initial few weeks after accelerated curing but remains constant after this. (Ref 3.7 shows results out to 3 years)

3.7.2.3 Dry Heat curing: Geopolymer concrete can be dry heat cured but the specimens need to be encapsulated or at least covered to minimize drying out at the surface.

3.7.3 Wet curing: Curing methods which allow excessive amounts of free water in contact with the geopolymer concrete surface are not recommended as the water leaches out the alkalis and dilutes the pore water producing a skin of low strength sodium metasilicate or zeolites.

3.8 Finishing

Geopolymer concretes can be screeded in the normal fashion with conventional trowels. As minimal bleed usually occurs, such trowelling is usually all that is required to finish a surface. If sticking occurs, then finishing may be aided by using an evaporative organic solution as a finishing aid.

3.9 Joints and Crack control

As shrinkage is considerably less than that experienced by an equivalent OPC concrete, the space of a well designed geopolymer concrete between joints or crack controlling cuts can be considerably increased beyond conventional spacings. There was no evidence of cracking when joints were spaced by more than 20 m apart in the Curtin University cast in situ footpath (Ref: 3.8). Although not currently recommended, it appeared that shrinkage joints or cuts may not be necessary at all in cast on-ground structures; a huge benefit in road and path design procedures.

As with OPC concrete, geopolymer concrete made with a high water content can experience plastic shrinkage (and potential cracking) if water can evaporate from the concrete surface during setting. Care must always be taken to prevent or minimize such evaporation.
References


3.9 Hardjito, D., Rangan, B.V., Development and properties of low-calcium fly ash based geopolymer concrete, Research report GC1, Faculty of Engineering, Curtin University, 2005, pp 94.
In general, geopolymer concretes can be designed and manufactured to physically perform like conventional OPC concrete. The fresh mixtures look and behave in a similar manner and the hardened concretes look and perform physically in a similar manner. However in general, the chemical resistance of geopolymer concretes is far superior. The properties of a particular geopolymer concrete can be affected by a number of parameters such as the binder design (type and proportions of fly ash or slag), composition of the alkali solution, water to geopolymer solids ratio and the curing regime. In general, a geopolymer matrix is observed to be denser than the cement mortar phase in OPC concrete and the bonds between the hardened paste and the coarse aggregate and between the paste and any reinforcing steel are much stronger. This chapter attempts to review the properties of geopolymer concrete as established by published work.

4.1 Properties of Fresh Concrete

4.1.1 Workability

Slump test has successfully been used to assess workability of geopolymer concrete (Refs 4.2, 4.8, 4.9). Provided alkali soluble calcium levels are low, slump loss of geopolymer concrete produced with low calcium fly ash or slag has shown to be equal or less than that of OPC concrete. Bleed of geopolymer concrete has also been shown to be lower than that of OPC concrete. Acceptable workability has been observed when the water to geopolymer solids ratio by mass is greater than 0.22 and low water absorption aggregates are used. Hardjito and Rangan (Ref 4.5) have shown that the workability can be increased with the use of a naphthalene based superplasticiser. The recommended dosage of liquid naphthalene SP (a 44% solids solution) is around 2% of the mass of fly ash.

4.1.2 Heat of Hydration

It has been observed that low calcium fly ash based geopolymer concrete does not show an exothermic reaction during the first 25 hours from casting at room temperature, whilst metakaolin-based geopolymer material shows a direct relationship between the exothermic reaction and the compressive strength development (Ref 4.5). It should also be noted here that heat curing is commonly adopted in geopolymer concrete with temperatures in the range of 30⁰ to 90⁰ degrees C during the first 24 hours from casting, leading to faster strength development. Strength gain at 6 hours is almost directly proportional to curing temperature (from 50°C to 90°C) and there is a large, sharp exothermic peak after about 0.5 to 1 hours curing (Ref 4.16).

![Figure 4.1](image_url)

**Figure 4.1**
Effect of curing temperature on the 6 hour compressive strength of low calcium flyash based geopolymer concrete.
4.2. Properties of hardened concrete

4.2.1 Compressive Strength, strength development and stress-strain relationship

The behaviour of concrete in compression is normally represented by compressive strength, strength development with age and the shape of the stress-strain relationship represented by the initial elastic modulus, peak stress (compressive strength), strain at the peak stress and a parameter representing the descending part of the stress-strain curve or the ultimate concrete strain.

Collins and Sanjayan (Ref 4.2) have observed that alkali activated slag concrete has comparable compressive strength to OPC concrete. Behaviour and failure mode in compression of low calcium fly ash based geopolymer concrete has also been reported to be similar to that of normal OPC concrete. Rangan (Ref 4.8) has observed that the strain at the peak stress is around 0.0024 to 0.0026 and that the stress-strain curve can be given by the equation given below which was originally proposed by Collins et al (Ref 4.3)

\[
\sigma_c = \frac{f_{cm}}{\varepsilon_{cm}^{n}} \left( \frac{\varepsilon_c}{\varepsilon_{cm}} \right)^{nk}
\]

Where \( f_{cm} \) = peak stress, \( \varepsilon_{cm} \) = strain at the peak stress, \( n=0.8+(f_{cm}/17) \) and \( k=0.67+(f_{cm}/62) \).

Sarkar (Ref 4.13) also proposed the same expression with a modified \( n \) value given by \( n=0.8+f'c/12 \).

Compressive strength development of geopolymer concrete is significantly affected by the curing regime adopted. Heat cured low calcium fly ash based geopolymer concrete has been shown to gain the full compressive strength after one day with no further increase in compressive strength with time. Indeed almost 90% of this final strength is developed within a few hours if cured at 80 to 90°C. However, geopolymer concrete cured in the ambient environment has been shown to gain strength with time as observed with OPC concrete. All curing regimes (room temperature or higher temperatures) produce similar long term strength results (Ref 4.8), the curing temperature merely altering the time to reach the ultimate compressive strength of the particular mixture under investigation.

Water to geopolymer solids ratio has been observed to have an inverse relationship with the compressive strength of concrete similar to that observed between water to cement ratio and compressive strength of OPC concrete. Geopolymer solids are calculated as the sum of mass of binder, mass of sodium silicate solids and mass of sodium hydroxide solids. Ng and Foster (Ref 4.11) reported that in a geopolymer mix with fly ash and slag, the ratio of slag to fly ash by mass is 35:65 for optimum compressive strength, but this ratio is dependent on the reactivity of the particular fly ash and slag used. Some highly reactive very fine fly ashes do not need slag addition to achieve high target strengths.

4.2.2 Tensile Strength

Tensile strength of concrete is generally measured using an indirect tensile test, which is also known as the splitting tensile test, and the flexural tensile test or modulus of rupture. These properties are important in determining the cracking stresses in concrete structural members.

Most published work agrees that the tensile strength of geopolymer concrete is superior to that
of OPC with the same compressive strength (Rangan, Ref 4.8, Sofi et al, Ref 4.9, Collins and Sanjayan, Ref 4.2). Until more data are available it would be conservative to assume that the following relationships proposed in AS3600 (2002) for tensile and flexural strength of concrete applies to geopolymer concrete as well.

Tensile strength given as:

\[ f_{ct} = 0.4 \sqrt{f_{cm}} \]

Flexural strength given as:

\[ f_r = 0.6 \sqrt{f_{cm}} \]

### 4.2.3 Elastic Modulus

Elastic modulus of concrete is a function of the individual stiffness of coarse aggregate and mortar in OPC concrete. In geopolymer concrete, the matrix is expected to be denser and as a result the elastic modulus is expected to be greater compared to OPC concrete with similar coarse aggregate. However, experimental results do not confirm this. In most published work, it is observed that for a given compressive strength of concrete, the geopolymer concrete has a lower elastic modulus than an OPC concrete (Hardjito and Rangan, Ref 4.5, Ng and Foster, Ref 4.11, Sofi et al, Ref 4.9).

Based on a two phase model originally developed by Setunge (Ref 4.14), Ng and Foster (Ref 4.11) have proposed a two phase model to calculate the elastic modulus of geopolymer concrete as a function of Elastic modulus of geopolymer mortar and coarse aggregate. The most interesting outcome of this work is the observation that geopolymer mortar has a lower elastic modulus than an OPC mortar of a concrete of similar compressive strength.

The model proposed by Setunge (Ref 4.14) is given as:

\[
\frac{1}{E_c} = \frac{0.45}{V_a E_a + (1 - V_a) E_m} + 0.55 \left( \frac{V_a}{E_a} + \frac{1 - V_a}{E_m} \right)
\]

Where \( V_a \) = volume proportion of coarse aggregate, \( E_a \) is the elastic modulus of coarse aggregate and \( E_m \) is the elastic modulus of mortar.

Ng and Foster (Ref 4.11) have proposed an equation for the elastic modulus of geopolymer mortar (\( E_m \)) as,

\[
E_m = 3710 \sqrt{f_{mm}} - 1280 (MPa)
\]

Where \( f_{mm} \) is the mortar peak stress.

### 4.2.4 Creep and Shrinkage

Creep and shrinkage of geopolymer concrete would be significantly affected by the type of geopolymer materials, activation process and the curing regime. Rangan (Ref 4.8) has observed that the shrinkage of heat cured geopolymer concrete can be as low as 100 micro strain whereas ambient cured geopolymer concrete at low maturity (low deg C hours) can have drying shrinkage values as high as 1200 micro strain as they continue to cure. Considering that the AS3600 value recommended for OPC concrete is 850 micro strains, this is an area where more
Recommended Practice, Geopolymer Concrete

work will be needed.

Collins and Sanjayan (Ref 4.2) report that creep of slag based geopolymer concrete is similar in magnitude to those of OPC concrete. Rangan (Ref 4.8) observed that the creep of a heat cured low calcium fly ash based geopolymer concrete is about 50% of that of the equivalent OPC concrete.

It is recommended that the creep and drying shrinkage of geopolymer concrete is established for a given mix recipe and a curing regime, based on measurements on the specific mixes using the AS1012 parts 13 and 16 until more comprehensive data are available. It is also important to address the possibility of plastic shrinkage in geopolymer concretes made with high water contents, by ensuring adequate early age curing. Minimizing loss of water by evaporation during the pre-setting phase is important.

**4.2.5 Thermal expansion and fire resistance**

Under normal changes in ambient temperature, thermal expansion of geopolymer concrete is observed to be less than that of OPC concrete. In general, when compared with the fire resistance of OPC concrete, geopolymer concretes have far superior fire resistance, ultimately melting at about 1200°C with no signs of spalling. However, there is some uncertainty about the behaviour of certain geopolymer concrete at such elevated temperatures. Whilst some authors report that geopolymer concrete has excellent fire resistance (Balaguru et al, Ref 4.1), recent work by Kong and Sanjayan (Ref 4.6) has shown that there is a significant incompatibility between expansion of some coarse aggregate and the geopolymer matrix under elevated temperatures. They have shown that a geopolymer matrix contracts by about 1% whilst some aggregates expand up to about 2.5% at 800 deg C. Consequently, some strength loss has been observed in some geopolymer concretes at such highly elevated temperatures. This incompatibility in thermal behaviour could have a significant effect on the fire resistance of some geopolymer concretes and requires further work.

**4.2.6 Chemical Resistance**

All OPC concretes are susceptible to deterioration under acid attack, sulphate exposure, ingress of chloride ions and carbonation. Deterioration of concrete from acid sulphate attack is due to formation of ettringite and gypsum caused by sulphate reacting with C3A and lime in cement. Since geopolymers made from fly ash and/or slag have little or no C3A content, geopolymer concrete is expected to have better resistance to sulphate attack. Work of Rangan (Ref 4.8), Wallah and Rangan (Ref 4.10) and Law et al (Ref 4.7) have confirmed this hypothesis, their work showing no sulphate attack on geopolymer concrete.

Law et al (Ref 4.7) measured the resistivity of geopolymer concrete to assess the likelihood of corrosion of reinforcing steel. Whilst dry geopolymer concrete was observed to have quite high resistivity, water saturated specimens were noted to have low resistivity. This is probably because of the continuous nano-porosity and high pore solution ionic strengths of conventional geopolymer matrices. Unlike OPC concrete where continued hydration of the cement grains over time allows micro capillaries to become segmented or discontinuous, no such mechanism occurs in geopolymer concrete. Although the pore structure is much finer than the capillary structure in OPC cement paste, if continuous after curing it will remain continuous for the life of the structure. Research is focusing on developing pore discontinuity through processing techniques or admixture design. This may have implications for the use of steel reinforced geopolymer concrete in moist environments. Future research will undoubtedly show that interactions at the steel–concrete interface are different for geopolymer concrete than for OPC concrete and that a new set of steel-in-concrete corrosion models will have to be developed. Given the significantly improved tensile and bond strength exhibited by reinforced geopolymer
concrete, there will be many instances where no, or different reinforcing materials are preferred to conventional steel wire or mesh reinforcing on both a cost and performance basis.

### 4.2.7 Unit weight

Unit weight of geopolymer concrete produced with normal weight coarse aggregate appears to be around 2000-2400 kg/m³, which is comparable with the unit weight of OPC concrete. Ng and Foster (Ref 4.11) have reported unit weights in the range of 1870 kg/m³ to 2370 kg/m³ and have also observed that some geopolymer concretes expand as they harden which is the opposite of normal OPC concrete. Sarkar (Ref 4.13) has also reported a similar phenomenon. Unit weight of a low calcium fly ash based geopolymer concrete is reported to be in the range of 2300-2400 kg/m³ (Hardjito and Rangan, Ref 4.5). Unit weight of geopolymer concrete produced with normal weight aggregate complying with the relevant Australian Standards may therefore be taken to be comparable to that of unit weight of normal strength concrete (if only because the aggregate skeletons used are identical and usually constitute about 85% of the concrete mass).

### 4.3 Testing of Concrete

Standard tests for mechanical properties of OPC concrete: compressive strength, unit weight, flexural strength, splitting tensile strength, drying shrinkage and creep have been shown to be appropriate for geopolymer concrete as well. These may be performed as per relevant part of AS1012 (Ref 4.15).

### References


4.5 Hardjito, D., Rangan, B.V., Development and properties of low-calcium fly ash based geopolymer concrete, Research report GC1, Faculty of Engineering, Curtin University, 2005, pp 94.


4.13 Sarkar, P.K., Analysis of geopolymer concrete columns, Materials and structures, Accepted for publication in RILEM July 2008.


4.16 Rocla Pty Ltd, unpublished research.
5.1 Introduction

Extensive research has been conducted on the manufacture and properties of geopolymer concrete as evident from the literature given under References. This Chapter briefly describes the engineering aspects of the low-calcium fly ash-based geopolymer concrete. The presence of calcium in high amounts may interfere with the polymerization process and produce a multi-phased microstructure (Ref 5.1, 5.2).

5.2 Constituents of Geopolymer Concrete

Geopolymer concrete can be manufactured by using the low-calcium (ASTM Class F) fly ash obtained from coal-burning power stations. Most of the fly ash available globally is low-calcium fly ash formed as a by-product of burning anthracite or bituminous coal. Although coal burning power plants are considered to be environmentally unfriendly, the extent of power generated by these plants is on the increase due to the huge reserves of good quality coal available worldwide and the low cost of power produced from these sources. The “energy returned-to-energy invested” ratio of coal burning power plants is high, and second only to the hydro-power generation plants (Ref 5.3). Therefore, huge quantities of fly ash will be available for many years in the future (Ref 5.4). The chemical composition and the particle size distribution of the fly ash must be established prior to use. An X-Ray Fluorescence (XRF) analysis may be used to determine the chemical composition of the fly ash.

A combination of sodium silicate solution and sodium hydroxide (NaOH) solution can be used as the alkaline liquid. It is recommended that the alkaline liquid is prepared by mixing both the solutions together prior to use.

In order to improve the workability without compromising compressive strength, a high-range water reducing super plasticizer may be added to the mixture. Additional water may be added to the mixture to improve workability but will affect the compressive strength in a trend similar to Portland cement concrete.

5.3 Short-Term Properties of Geopolymer Concrete

Experimental studies have shown that the aggregate-binder interfaces are stronger in geopolymers than in the case of Portland cement (Ref 5.5). This may lead to superior mechanical properties and long-term durability of geopolymer concretes (Ref 5.6).

The behaviour and failure mode of fly ash-based geopolymer concrete in compression is similar to that of Portland cement concrete. Test data show that the strain at peak stress is in the range of 0.0024 to 0.0026. The modulus of elasticity increased as the compressive strength of geopolymer concrete increased for numerous geopolymer mixtures made with a variety of Australian fly as sources (Ref 5.7, 5.8); the measured values showed a trend similar to that predicted using the provisions of the Australian Standard AS3600 (2009).

The Poisson’s ratio of fly ash-based geopolymer concrete with compressive strength in the range of 40 to 90 MPa falls between 0.12 and 0.16 and exhibits the trend of increased Poisson’s ratio with higher compressive strength. These values are similar to those of Portland cement concrete. Higher values of Poisson’s ratio, of the order 0.24-0.26, have been reported for high strength geopolymer mixtures (Ref 5.8).
The measured indirect tensile strength and flexural tensile strength of fly ash-based geopolymer concrete (Ref 5.7, 5.8, 5.9) is larger than the values recommended by the Australian Standard AS3600 (2009) for Portland cement concrete. The better performance of geopolymer under tensile stresses may be attributed to the type of matrix formation and is influenced by the source material (Ref 5.8).

The unit-weight of concrete primarily depends on the unit mass of aggregates used in the mixture. Tests show that the unit-weight of the low-calcium fly ash-based geopolymer concrete is similar to that of Portland cement concrete. When granite-type coarse aggregates were used, the unit-weight varied between 2330 and 2430 kg/m³ (Ref 5.7, 5.9). Similar results have been recorded with density of circa 2200 kg/m³ for pastes and 2400 kg/m³ for mixtures containing coarse aggregates (Ref 5.8).

5.4 Long-Term Properties of Geopolymer Concrete:

5.4.1 Creep and Drying Shrinkage

The creep and drying shrinkage behavior of heat-cured low-calcium fly ash-based geopolymer concrete was studied for a period of one year (Ref 5.10).

The creep tests commenced on the 7th day after casting the test specimens and the sustained stress was 40% of the compressive strength on that day. Test data showed that the specific creep, defined as the creep strain per unit of sustained stress, are about 50% of the values recommended by the Australian Standard AS3600 for Portland cement concrete.

Test results show that heat-cured fly ash-based geopolymer concrete undergoes very little drying shrinkage in the order of about 100 micro strains after one year (Ref 5.10). This value is significantly smaller than the range of values of 500 to 800 micro strains experienced by Portland cement concrete. On the other hand, the drying shrinkage strains of geopolymer concrete cured in ambient conditions can be many-fold larger than those experienced by the heat-cured specimens. Water is released during the chemical reaction process of geopolymerization. In the specimens cured in ambient conditions, this water is continuously generated as the material cures and may evaporate over a period of time causing significantly large drying shrinkage strains especially in first two weeks after casting (Ref 5.10).

5.4.2 Durability

Given that hardened geopolymer cement pastes have the structure of an alumino-silicate glass and not hydrates as found in Portland cement pastes, durability in general and potential corrosion mechanisms in particular are completely different in geopolymer concrete. The material itself is extremely durable behaving more like a glass than a hydrate. Sulfate resistance is not an issue. Acid resistance and fire resistance are orders of magnitude better. Pore water pH is typically about 11, sufficient to protect embedded steel from entering the Corrosion Zone of the Pourbaix diagram for steel. The only concern with current geopolymer formulations is their ability to protect embedded steel from external corrosive agents (chlorides and carbon dioxide in particular) given that they have a continuous nano-porosity. Chloride ions can diffuse through the continuous pores when they are saturated. Carbon dioxide gas can dissolve in the alkaline pore water, carbonating it and hence lowering its pH. There is a danger that steel in carbonated geopolymer concrete may start to corrode when the carbonation “front” reaches the steel surface, as it does in OPC concrete. Considerable research is required to establish a corrosion model for steel-in-geopolymer concrete, which may well be different to the conventional steel-in-OPC concrete model.
5.5 Suitability of Current Standards and Codes

Tests have been performed to study the flexure, shear, compression and bond behaviour of reinforced geopolymer concrete members. These studies show that the behavior and the strength of these members are similar to those observed in the case of reinforced Portland cement concrete members, and the provisions given in the current Australian Standard AS3600 can be used to design such members. In addition to the many cast insitu geopolymer concrete structures, geopolymer concrete has been used in the production of precast railway sleepers, sewer pipes, box culverts, and other prestressed concrete building components, all of which can be designed and manufactured to comply with the performance requirements of the relevant Australian and world standards. The fire resistance and durability of fly ash-based geopolymers have also been studied and in almost all aspects, have been shown to be superior to equivalent Portland cement concretes. Complete details are available in the publications given in References 5.11 to 5.28.

5.6 Modifications to Current Design Methods

Given the improved material strengths that are available when using geopolymer concrete, many design methods could be modified to reduce, or in some cases remove the need for steel reinforcing.

Bond to steel is significantly greater when using geopolymer concrete, meaning bond lengths can be proportionately reduced.

With selected aggregates, concrete tensile strength can be greatly increased well beyond that assumed in most design methods.

When conventional Portland cement concrete design methods are applied to steel reinforced geopolymer concrete, test results often show loads to 1st crack very close to ultimate loads. This suggests that design should either be based on a minimum ultimate load (rather than load at 1st crack), with the appropriate safety factors, or designs should incorporate more steel, less concrete or a lower strength concrete.

As it appears that chloride diffusion can be significantly higher in some geopolymer concretes, steel reinforced concrete should not be used in saline water environments without added protection to the steel (cathodic protection, galvanizing or increased cover to steel), until material and process designs can produce a hardened material with superior chloride resistance. Clearly post-stressing, stainless steel, fibres, and epoxy encapsulated glass fibre rods are acceptable alternatives to steel and will become more commercially viable as designers take advantage of high performance geopolymer concretes and the reduced dependence on reinforcing to achieve product or structure performance.

5.7 Specifications

As greener alternatives to Portland cement become commercially and technically viable in the world construction industry, it is important that writers of codes and specifications move now to convert old-world prescription specifications to performance specifications. The structure owner and his designers need only to be concerned about the initial and long term performance of the structure, out to the specified design and service lives of the structure and its components. Provided they can be assured of this, it should not matter what type of cement is used in the concrete; OPC, geopolymer cement, epoxy resin, polyester resin, sulphur, etc.

In most cases current Australian Standards for concrete and concrete products require only minor modification to the materials paragraphs to open them up to be used by geopolymer concrete manufacturers as most are already heavily slanted towards a performance-type specification. Given the past history of standard development in Australia, the cost and
The effort involved in such tasks can never be underestimated. Never-the-less if the concept of performance over prescription is initially ingrained in standard and specification writing then the battle will be less formidable.

5.8 Concluding Remarks

This Chapter briefly presents the current state-of-knowledge on the engineering aspects of fly ash-based geopolymer concrete. Information available in the literature shows considerable promise for geopolymer concrete to be used in the construction of the low-carbon infrastructure being demanded by the community.

References


5.3 Lloyd R (2009), “Fast Move to Fossil Fuels Unlikely” in Civil Engineers Australia, December, p.51.

5.4 Malhotra, 2006


5.7 Hardjito, D. and Rangan, B. V. (2005), Development and Properties of Low-Calcium Fly Ash-based Geopolymer Concrete, Research Report GC1, Faculty of Engineering, Curtin University of Technology, Perth, available at espace@curtin or www.geopolymer.org.


5.9 Lloyd, N. and Rangan, B. 2009. Geopolymer Concrete: Sustainable Cementless Concrete, in American Concrete Institute, ACI Special Publication (261 SP), pp. 33-53

5.10 Wallah, S.E. and Rangan, B.V. (2006), Low-Calcium Fly Ash-Based Geopolymer Concrete: Long-Term Properties, Research Report GC2, Faculty of Engineering, Curtin University of Technology, Perth, available at espace@curtin or www.geopolymer.org.


5.26 Siddiqui, K.S. (2007),"Strength and Durability of Low-Calcium Fly Ash-based Geopolymer Concrete", Final Year Honours Dissertation, The University of Western Australia, Perth.

5.28 Sumajouw, M.D.J. and Rangan, B.V. (2006), Low-Calcium Fly Ash-Based Geopolymer Concrete: Reinforced Beams and Columns, Research Report GC3, Faculty of Engineering, Curtin University of Technology, Perth, available at espace@curtin or www.geopolymer.org.
Many world commercial applications for geopolymer concrete are described in Geopolymer Institute publications (Ref www.geopolymer.org). These include many longstanding infrastructure projects in Ukraine, cement production (Lone Star USA’s Pyrament), fibre reinforced laminates and mine backfill operations. Blast furnace slags have been used in alkali activated cements (geopolymers) in the Ukraine since 1930’s. Industrial applications include:

- 9 storey buildings (1960)
- 20 storey building (1987)
- Sewer pipes (1966)
- Irrigation channels (1962)
- Breakwater blocks (1965)
- Road pavement (1984)
- Railway sleepers (1989)
- Fire doors (2000)

- Successful long term durability trials in seawall and freeze thaw conditions
- Strength increases with time; 40MPa to 57MPa in 5 years.
- Permeability decreases with time; $1 \times 10^{-11}$ to $1 \times 10^{-13}$ cm/sec in 7 years

In Australia, Zeobond (www.zeobond.com) have established commercial “ready mix” operations in Melbourne through their licensee Aurora Construction Materials. Steel reinforced foundation slabs and footpaths have been built using cast in situ geopolymer concrete (trade named E-Crete). One 400 square metre bicycle and pedestrian pathway was built in 2009 at the Templestowe Village for the Manningham Shire Council.

As part of the CRC for Sustainable Resource Processing’s geopolymer program, two cast in situ pathways have been constructed in Curtin University, Perth, the latest one using locally available materials (Ref www.csrp.com.au).
In New Zealand, Fletcher Building’s Golden Bay Cement constructed a path in geopolymer concrete (Inorganic Polymer Concrete). They report; “To prove the weathering performance of IPC concrete, an access track was paved with IPC concrete. This trial is adjacent to an inlet of the ocean, on reactive clay foundations and subject to light traffic and stock movements.

After 18 months, no failures have been observed. Plastic shrinkage was not evident despite weather conditions conducive to its formation. With slab lengths up to 12 metres and 1.5 metre width, no shrinkage cracks are evident, whereas concrete in the same situation has shown cracking at 3 metre centres.

No residual alkali release has been observed and grass growth adjacent to the test slabs have not been affected by any deleterious leachate release”.

Figure 6.2
Curtin University geopolymer concrete path.
Precast slabs, pipes, pavers, railway sleepers, and roof tiles have been produced, tested to the relevant Australian standards and installed by Zeobond and Rocla in Australia.

References

6.1  Boyd G, “Woronora cemetery crypt plan will be a world first.”, ACCA news, Spring 10, 2010, p 1-11.”
Chapter 7  Sustainability Issues

The application of geopolymer technology in the mining, building and construction, power and waste containment industries offers the opportunity to address a variety of current sustainability issues within these industries.

7.1 Use of Wastes (Mining and Processing By-products).

Geopolymer concretes can be made from binders which have been previously considered as waste products:

- flyash and bottom ash produced in black coal fired power stations. Some 10% of these materials (frequently considered as wastes) are used as supplementary cementitious materials (SCM’s) in blended cements (pre or post-batching blends of OPC, SCM’s, limestone and any other non-cementitious fillers) and a further 10 to 20% in “fill” type applications. The remainder is dumped in tailing ponds or dry stacks constructed adjacent to power stations throughout Australia and represents a major sustainability issue for the power generation industry,
- ground granulated blast-furnace slags,
- bauxite processing residues,
- kaolinitic clays,
- certain mine wastes; ground alumino-silicate tailings (Ref 7.12),
- naturally occurring pozzolans, or
- any fine materials that contain significant amounts of silicon and aluminium in an amorphous form.

In OPC concrete, continued cement hydration can lead to later-age alkali production within the now hardened concrete. For this reason the use of alkali reactive aggregates are not permitted for fear of ASR cracking unless the binder blend contains at least 20% by mass of SCM. This phenomenon does not occur in geopolymer concrete and hence such aggregates as recycled glass, granulated slag, sintered artificial aggregates and naturally occurring alkali reactive aggregates can now be used.

Most current formulations use a mixture of sodium hydroxide and/or sodium silicate (or the potassium alternatives) as the alkaline activator, but any strongly alkaline waste liquor can be used as a partial or full substitute.

Hence it is possible to make strong durable geopolymer concrete from 100% waste materials; for example recycled glass and granulated slag as the coarse aggregate, bottom ash and fine granulated slag as the fine aggregate, flyash as the binder and waste alkaline liquor as the activator [note that the fine fractions of glass and slag will also form part of the binder].

7.2 Greenhouse Gases

Wide-scale acceptance of Geopolymer Cements (GC) and the concretes they form could reduce the requirement for Ordinary Portland Cement (OPC) and in doing so, supplement and support the Concrete industry in order to retain concrete as the prime construction material of choice. This represents a significant opportunity to reduce global carbon dioxide emissions as:

- given that the production of OPC requires the calcining of limestone to form the calcium components of OPC, the production of 1 tonne of OPC (by milling OPC clinker) liberates approximately 0.8 to 1 tonne of carbon dioxide to the atmosphere, depending upon the fuel used in the kilns (Ref. 7.1, 7.14).
- global OPC production accounts for about 5 to 10% of worldwide CO₂ emissions (Ref :7.1, 7.14 ).
• assuming the use of a waste binder such as fly ash and standard technical grade chemical activators, the production of 1 tonne of geopolymer cement liberates just 0.16 tonnes of CO₂ (Ref: 7.1, 7.14). The use of waste alkalis would clearly reduce this further.

The conclusion is that substituting GC for OPC would reduce OPC generated CO₂ emissions by some 80% or more. For total replacement of OPC by GC, this potential saving represents some 4 to 8% of current world CO₂ emissions. (This conclusion will inevitably be disputed by some. It is based on the current industry assumption that power station ashes and blast furnace slags are waste products that do not carry any carbon emission “penalties”. This may change into the future if “waste” generators ever accept the concept of ashes and slags as “co-products” and beneficiate them to enhance user uptake. The conclusion also assumes that sodium hydroxide is a by-product of the world PVC manufacturing process and shares its carbon dioxide emissions footprint with the plastics industry.)

7.3 Structure Life Cycles

In many applications and exposure classifications, structures made from GC concrete will have enhanced life cycles, in some cases many times that of equivalent OPC concrete structures.

In applications where acid resistance is important, geopolymer concretes will provide increased structure life cycles. They are acid resistant, providing long term solutions to world infrastructure problem areas such as sewerage systems. OPC concrete sewer systems have a design life of 50 years whereas GC concrete alternatives are predicted to have service lives in excess of 300 years, with similar initial capital costs (Ref: 7.2, 7.3). Hence infrastructure replacement costs and future green house gas emissions should be greatly reduced.

Geopolymers can be designed to have very high compressive, flexural and tensile strengths (Ref: 7.2, 7.9, 7.10). This allows certain structures or structure components to be designed without the need for reinforcing steel, particularly if fibre reinforced. As an example, concrete pipes in the lower load class categories no longer need steel reinforcement to achieve the required load carrying performance values (Ref. 7.2). As steel corrosion is the major reason for reinforced concrete failure, concrete structures that no longer need steel reinforcing should have longer service lives.

Research studies into the mechanisms of steel corrosion in GC concrete are still in their infancy but irrespective of the mechanism or corrosion rate, corroding steel embedded in concrete is less likely to cause concrete spalling if the concrete tensile strength is greater. As concrete cracking and spalling is often used by the industry as an early indicator of steel reinforcement corrosion, the use of small diameter bars, which have been known to corrode away entirely without causing surface distress in high strength concrete, may need to be addressed.

Geopolymer concretes are resistant to sulphate attack (ref. 7.3). Hence geopolymer concrete marine structures that don’t contain mild steel reinforcement will not scale or crumble from seawater exposure. (Seawater contains high levels of chlorides, which are detrimental to reinforcing steel but not to either form of concrete, and sulphates which are detrimental to porous OPC concrete.)

7.4 Toxic Metal Encapsulation.

Similarly to OPC concrete, many toxic heavy metals if initially in waste aqueous solutions can be encapsulated in the geopolymer pore network as insoluble metal hydroxides. However in many cases the waste toxic metals are present as solids which do not appreciably react with the geopolymeric constituents; in this case the waste solids are encapsulated in the geopolymer. In rare cases, the waste metal ion may be able to be accommodated in the geopolymeric network.
However direct evidence for such a substitution is not available and essentially all toxic metal ions are too large to substitute in the aluminosilicate network.

So depending on the toxic metal ion concentration and the regulatory limits for toxic metal release in short-term leach tests such as the Toxicity Control Leaching Procedure (TCLP) [Ref. 7.4], geopolymers may provide intermediate level solutions for toxic waste disposal, allowing the safe disposal of solidified mining tailings, industrial chemical wastes and low level radioactive wastes. For instance, geopolymers have been shown to be many times superior to OPC for immobilising radioactive Cs [Ref .7.5].

7.5 Behaviour in Fire

Geopolymer building materials (concretes, foams, laminates, etc) offer superior fire resistance to OPC concretes and organic polymers (plastics; PVC, epoxies, polyesters, polyurethanes, etc). Unlike organic substances they do not burn or emit toxic fumes during a fire, nor do they explosively spall when subjected to intense heat (as occurs with conventional OPC concrete. Ref 7.13).

7.6 Sick Building Syndrome.

Geopolymer building materials, being inorganic, will not emit toxic organic substances into the building air space during the service life of the building.

7.7 Petroleum Industry Dependence

Being derived entirely from inorganic materials, geopolymers have no dependence on the petroleum industry.

7.8 Sustainability Challenges in the Global Concrete Industry.

In a presentation to the Concrete Summit on Sustainable Development, held by The American Concrete Institute’s Strategic Development Council in Washington DC on March 29-30, 2007 (Ref. 7.6), Mehta (University of California, Berkeley; Ref. 7.7) discussed the challenge facing the world of concrete with respect to anticipated growth of concrete volumes out to 2020 and the conflicting global requirements to reduce greenhouse gas emissions.

Figure 7.1 summarizes his predictions:
1990 and 2005 values are the actual global quantities used (cement and supplementary cementitious materials) and the CO₂ masses generated from the production of these binder masses.

2020 (1) is his prediction for “business-as-usual” but with some attempt to increase SCM proportions to 22% by mass of binder (the current hopes of the cement and concrete industry ; Ref. 7.8).

2020 (2) is his prediction if the CO₂ levels are to be kept at 2005 levels.

2020 (3) is his prediction if they are to be reduced to 1990 levels.
The CO₂ contributions are based on the following assumptions:

• the cement clinker contribution reduces from 1.0 t/t in 1990 to 0.8 t/t in 2020 as the fuels used to fire the clinker kilns change,
• the SCM contribution increases to 0.15 t/t in 2020 as milling of coarse flyash becomes necessary to provide sufficient feedstock at these high replacement levels.

Scenario (1), business-as-usual, is not an option if the construction industry is to take up its share of the burden of addressing climate change.

Scenario (2) is just possible with OPC concrete as usually OPC (the primary binder component) must be in excess of SCM content for usable concrete strengths. It should be noted that very high fly ash OPC’s are actually alkali activated cements or geopolymer cements with the OPC component providing the alkalis in a gradual fashion as the OPC hydrates, rather than acting as the continuous binding matrix.

Scenario (3) is not possible with OPC concrete and is only achievable with geopolymer concrete where the SCM (fly ash, slag, etc) becomes the dominant binder fraction.

Mehta (Ref 7.11) has since looked at other strategies to address the Concrete Industry’s sustainability issues including using less concrete (by using higher performance concrete), less binder (by designing around 90 day strengths rather than 28 day strengths) as well as a higher proportion of SCM’s in binder blends. The fundamental problem is that it is difficult to do all three in unison and still achieve the accumulative gains he hopes for; it is generally not possible to produce high performance OPC concrete with acceptable rates of gain in strength with less binder and high volumes of fly ash in the OPC binder blend.

References


7.2 Gourley, J. T., and Johnson G. B., “Developments in Geopolymer Precast Concrete.”, International Workshop on Geopolymers and Geopolymer Concrete GCC 2005, Perth,
Australia, 28 and 29 September 2005.


Chapter 8  Summary and Conclusions

With a history dating back to the mid 1900’s geopolymer concretes have proven to be a worthy addition to the spectrum of building materials available to constructors worldwide. Although often deliberately clouded in mystery by some developers in an attempt to protect intellectual property, the science of geopolymerization is steadily and systematically being brought forward into the public domain. In doing so, its many guises (from alkali activated cements, inorganic polymers, soil cements, chemically bonded ceramics, to low temperature alumina-silicate glass, etc, etc) are being grouped together and shown to have a common scientific basis in the long established technology surrounding sol-gel silica science (Ref 8.1).

As a concrete, it perform just as all concretes do, producing a range of strength categories from low strength fill applications (< 5 MPa) through to very high strength concretes with compressive strengths well in excess of 100 MPa. It differs from other concretes (Portland cement, polyester, epoxy, sulphur, etc) only in its unique cement type and setting reactions. The hardened concrete still consists of a standard aggregate skeleton bound together by rigid, inorganic cement. All Australian and world performance standards still apply to its use as a plain or reinforced concrete in the building and construction industry.

When compared with the most commonly used concrete (Portland cement concrete), geopolymer concrete offers a number of unique physical features, including:

- Very superior chemical resistance, particularly acid resistance.
- Very superior fire resistance
- Very superior bond to reinforcing steel
- Superior tensile strength
- Superior durability in naturally occurring environments (eg marine performance)
- Rapid, but controllable setting rates (the ability to gain full long term strength within one or two hours of heat curing)

These properties make it highly competitive in the field of precast concrete but, as many Australian demonstrations have shown, it is well suited to cast in-situ applications once contractors learn its special placement, finishing and curing requirements.

Perhaps of most importance is the ability of geopolymer concrete technology to address the sustainability issues which haunt the conventional Portland cement industry. Carbon dioxide emissions from Portland cement production are reduced by some 80% when switching to geopolymer cement. In addition, the most common binders used are 100% SCM’s (flyash or slag) which, except for the small amounts used as SCM’s in General Purpose or Blended Portland cement products, are currently dumped as wastes.

Although Eastern European installations of structural steel-reinforced geopolymer concrete have demonstrated over 50 years of durable service, there are still some areas of steel reinforcing durability, particularly in saline water environments that need to be investigated and modelled. Given the potential to achieve significantly higher material tensile strengths and to incorporate a wide range of fibres, there will be many applications where conventional steel reinforcing is unnecessary. There is now a considerable body of knowledge which illustrates the “glass-like” durability of geopolymer material in a wide range of naturally occurring and artificially aggressive environments; not surprising considering that a hardened geopolymer cement paste can be legitimately viewed as a low temperature thermo-setting nano-porous alumina-silicate glass with an alkaline pore solution.
References
