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UNIVERSITAS INDONESIA

**STUDI LITERATUR PENGARUH KONSENTRASI NAOH DAN RASIO
NAOH:NA₂SIO₃, RASIO AIR/PREKURSOR, SUHU CURING, DAN JENIS
PREKURSOR TERHADAP KUAT TEKAN BETON GEOPOLIMER**

SKRIPSI

**Diajukan Sebagai Salah Satu Syarat Untuk Memperoleh Gelar Sarjana
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DEPOK
JANUARI 2011**

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UNIVERSITY OF INDONESIA

LITERATURE STUDY COMPARATIVE EFFECT OF
CONCENTRATION OF NAOH AND RATIO OF NAOH:NA₂SIO₃, RATIO
OF WATER/PRECURSOR, CURING TEMPERATURE, AND TYPE OF
PRECURSOR TO COMPRESSION STRENGTH OF GEOPOLYMER
CONCRETE

UNDERGRADUATE THESIS

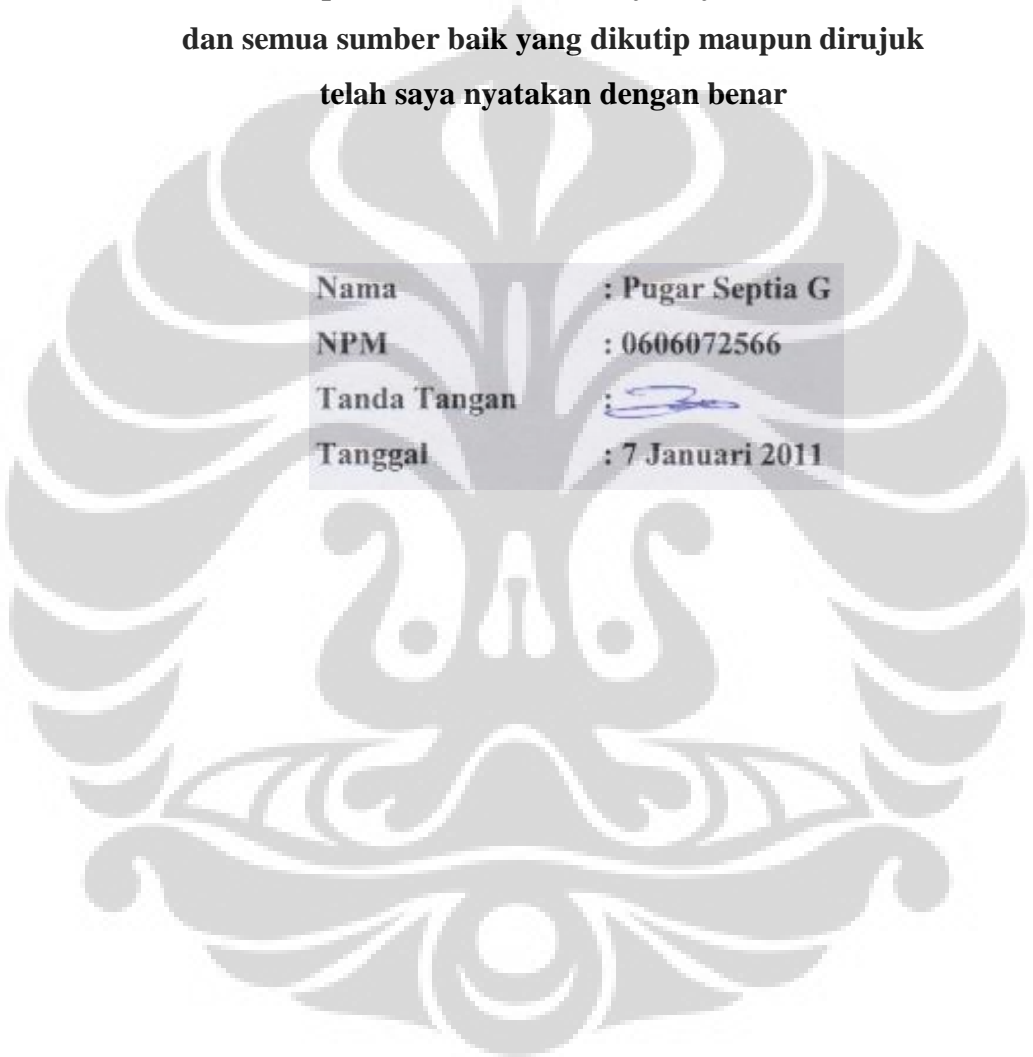
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ONE OF THE REQUIREMENT TO ACHIEVE
AN ENGINEERING BACHELOR DEGREE


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JANUARY 2011

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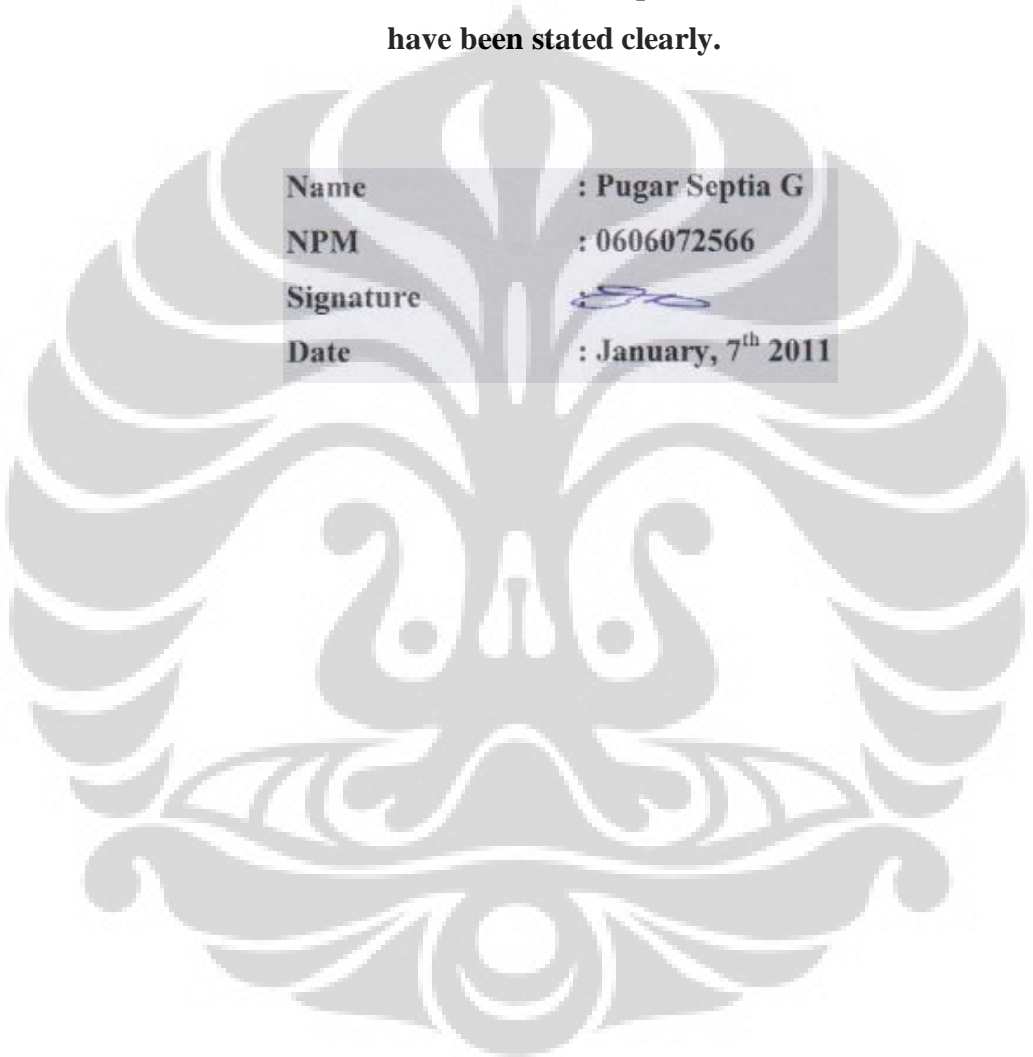
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Telah berhasil dipertahankan di hadapan Dewan Penguji dan diterima sebagai bagian persyaratan yang diperlukan untuk memperoleh gelar Sarjana Teknik pada Program Studi Teknik Sipil, Fakultas Teknik, Universitas Indonesia

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KATA PENGANTAR

Puji dan syukur penulis panjatkan kepada Allah SWT karena atas berkat rahmat dan hidayah-Nya penulis sebagai penulis dapat menyelesaikan skripsi yang berjudul “Studi Literatur Pengaruh Konsentrasi NaOH dan Rasio NaOH:Na₂SiO₃, Rasio Air/Prekursor, Suhu Curing, dan Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer”. Penyusunan skripsi ini dimaksudkan untuk memenuhi salah satu syarat dalam mencapai gelar kesarjanaan khususnya Teknik pada Departemen Teknik Sipil Fakultas Teknik Universitas Indonesia. Selama pelaksanaan penyusunan skripsi ini, penulis banyak mendapat bantuan dan bimbingan dari berbagai pihak. Oleh karena itu, pada kesempatan ini penulis ingin mengucapkan terima kasih yang sebesar-besarnya, kepada :

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Penulis mohon maaf atas segala kekurangan yang ada di dalam skripsi ini. Segala kritik dan saran sangat penulis harapkan guna memperbaiki kesalahan tersebut dan sebagai penyempurna penulisan naskah skripsi ini. Akhir kata, penulis berharap semoga skripsi ini dapat bermanfaat bagi pengembangan ilmu.

Depok, Januari 2011

Penulis

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Rasio Air/Prekursor, Suhu Curing, dan Jenis Prekursor Terhadap Kuat
Tekan Beton Geopolimer**

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ABSTRAK

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Judul : Studi Literatur Pengaruh Konsentrasi NaOH dan Rasio NaOH:Na₂SiO₃, Rasio Air/Prekursor, Suhu Curing, dan Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer

Skripsi ini membahas mengenai pengaruh konsentrasi NaOH dan rasio NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor terhadap kuat tekan beton geopolimer pada beberapa penelitian. Analisa dilakukan berdasarkan data yang sudah dikelompokkan berdasarkan empat faktor yang mempengaruhi kuat tekan beton geopolimer yaitu konsentrasi NaOH dan rasio NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor yang digunakan. Hasil penelitian dari data-data yang telah dikelompokkan ke dalam empat kategori tersebut dianalisa dengan cara membandingkan hasil penelitian yang ditinjau dengan dasar teori tentang geopolimer dan hasil-hasil penelitian yang telah dilakukan sebelumnya. Hasil penelitian-penelitian yang ditinjau dalam studi literatur ini menunjukkan bahwa konsentrasi NaOH dan rasio massa NaOH:Na₂SiO₃ yang optimum, rasio massa air/prekursor yang optimum, dan suhu curing yang lebih tinggi akan menghasilkan beton geopolimer dengan kuat tekan paling tinggi. Namun, pengaruh faktor jenis prekursor pada penelitian yang ditinjau pada studi literatur ini menunjukkan bahwa penggunaan fly ash tipe C sebagai precursor menghasilkan mortar geopolimer dengan kuat tekan yang lebih tinggi daripada mortar geopolimer yang menggunakan fly ash tipe F sebagai precursor. Hasil penelitian yang bertentangan dengan dasar teori yang ada ini dapat disebabkan oleh pengaruh faktor dominan lain seperti suhu curing dan kandungan atom Si pada geopolimer.

Kata kunci:

Beton geopolimer, kuat tekan, konsentrasi NaOH, rasio NaOH:Na₂SiO₃, rasio air-prekursor, suhu curing, jenis prekursor

ABSTRACT

Nama : Pugar Septia G
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Judul : Literature Study Comparative Effect of Concentration of NaOH and Ratio of NaOH:Na₂SiO₃, Ratio of Water/Precursor, Curing Temperature, and Type of Precursor To Compression Strength of Geopolymer Concrete

This literature study discusses about the effect of concentration of NaOH and ratio of NaOH:Na₂SiO₃, ratio of water/precursor, curing temperature, and type of precursor to the compressive strength of geopolymer concrete in several studies. The analysis was made based on datas that has been classified according four factors that affect the value of compression strength of geopolymer concrete such as concentration of NaOH and ratio of NaOH:Na₂SiO₃, ratio of water/precursor, curing temperature, and type of precursor those are used. Result of datas that has been classified to four catagories analyzed with compare them to basic theory of geopolymer and results of studies that has been performed before. Result of this literature study show that concentration of NaOH and optimum ratio of NaOH:Na₂SiO₃, optimum ratio of water/precursor, and higher curing temperature will produce highest compressive strength of geopolymer concrete. In the other hand, affect of type of precursor in this literatute study show that compressive strength of geopolymer mortar with fly ash type C as precursor is higher than geopolymer mortar with fly ash type F as precursor. The result which contra with basic theory is caused by affect of another dominant factors such as curing temperature and content of Si in geopolymer.

Keywords:

Geopolymer concrete, compressive strength, concentration of NaOH and NaOH:Na₂SiO₃ ratio, water/precursor ratio, curing temperature, type of precursor

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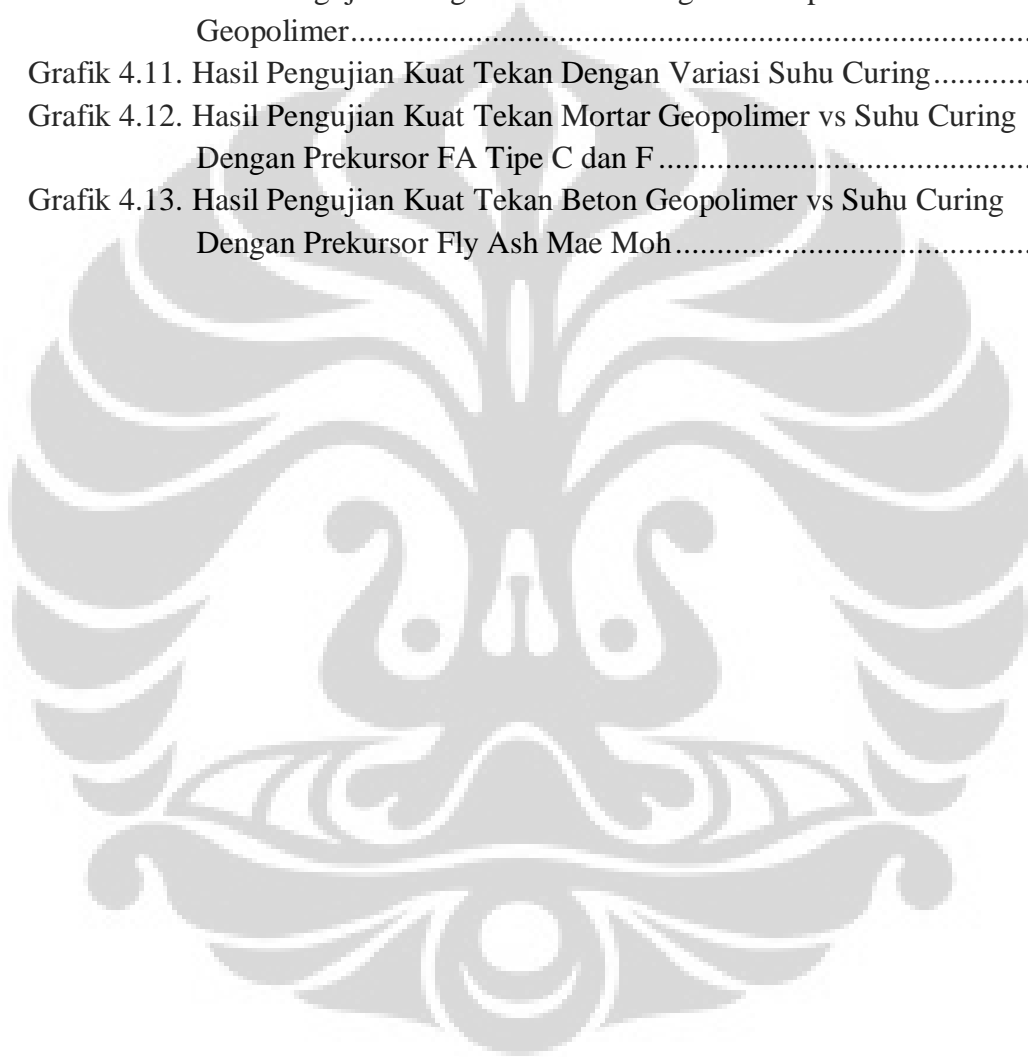
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BAB 1

PENDAHULUAN

1.1. Latar Belakang

Sebagai negara yang sedang berkembang, Indonesia sedang gencar melakukan pembangunan di segala bidang. Pembangunan di bidang fisik adalah salah satu pembangunan yang sangat terlihat perkembangannya dalam beberapa dekade terakhir. Hal ini terlihat dengan munculnya banyak konstruksi bangunan bertingkat, jembatan dan jalan. Dalam pelaksanaan pembangunan konstruksi, tuntutan akan kualitas yang baik dengan budget yang ideal serta proses pengerjaan yang mudah, telah menjadi tantangan bagi para sarjana teknik sipil di Indonesia. Dalam menjawab tantangan itu, konstruksi beton muncul sebagai salah satu solusi yang kemudian menjadi sangat sering dijumpai pada setiap proyek konstruksi di Indonesia akhir akhir ini. Beton yang digunakan dalam proyek konstruksi terdiri dari air, agregat kasar(batu pecah, kerikil), agregat halus (pasir) dan semen portland yang dalam proses produksinya menghasilkan gas CO₂ dalam jumlah besar.

Dari konferensi bumi yang diselenggarakan di Kyoto, Jepang tahun 1997, dan di Bali pada bulan desember 2007 yang bertajuk *Climate Change* dinyatakan bahwa emisi gas rumah kaca ke atmosfer yang tak terkendali adalah agen utama penyebab terjadinya perubahan iklim di dunia. Dari data tahun 1995, jumlah produksi semen di dunia tercatat 1,5 miliar ton. Hal ini berarti industri semen melepaskan karbon dioksida sejumlah 1,5 miliar ton ke alam bebas Menurut *International Energy Authority : World Energy Outlook*, jumlah karbon dioksida yang dihasilkan tahun 1995 adalah 23,8 miliar ton. Berdasarkan data tersebut produksi semen portland menyumbang tujuh persen dari keseluruhan karbon dioksida yang dihasilkan dari berbagai sumber. Jika tidak ada perubahan berarti dalam teknologi produksi semen atau didapatkan bahan pengganti semen, tahun 2010 diperkirakan total produksi semen di dunia mencapai angka 2,2 miliar ton (Malhotra, 1999). Merujuk pada besarnya sumbangan industri semen terhadap

total emisi karbon dioksida, perlu segera dicarikan upaya untuk bisa menekan angka produksi gas yang mencemari lingkungan. Penggantian sejumlah atau seluruh bagian semen dalam proses pembuatan beton dengan bahan lain yang lebih ramah lingkungan menjadi pilihan yang lebih menjanjikan.

Dalam perkembangannya, para pakar teknologi beton mulai melakukan riset pembuatan beton dengan memanfaatkan ikatan geopolimer. Geopolimer dapat didefinisikan sebagai material yang dihasilkan dari geosintesis aluminosilikat polimerik dan alkali-silikat yang menghasilkan kerangka polimer SiO_4 dan AlO_4 yang terikat secara tetrahedral (Davidovits, 1994). Dalam pembuatannya, beton geopolimer dapat memanfaatkan mineral alami dengan kandungan SiO_2 yang tinggi seperti *rice husk ash* (abu sekam padi), *fly ash*, metakaolin, dan *silica fume* sebagai prekursor. Bahan tersebut tidak memiliki kemampuan mengikat. Namun, dengan kehadiran air dan aktivator seperti KOH, NaOH dan Na_2SiO_3 , oksida silika yang terdapat dalam bahan tersebut akan bereaksi secara kimia dan membentuk ikatan polimer.

Berdasarkan penelitian, terdapat beberapa parameter yang mempengaruhi kuat tekan beton geopolimer antara lain jenis prekursor yang digunakan, suhu curing, Konsentrasi NaOH dan rasio NaOH: Na_2SiO_3 , dan rasio air/prekursor. Namun, hingga saat ini belum ditemukan mix design komposisi optimal yang dapat menghasilkan kuat tekan beton geopolimer yang tinggi. Oleh karena itu dilakukan studi literatur mengenai beton geopolimer dengan meninjau pengaruh jenis prekursor yang digunakan, suhu curing, Konsentrasi NaOH dan rasio NaOH: Na_2SiO_3 , dan rasio air/prekursor terhadap kuat tekan beton geopolimer.

1.2. Tujuan Penelitian

Penelitian dengan judul "*Studi Literatur Pengaruh Konsentrasi NaOH dan Rasio NaOH:Na₂SiO₃, Rasio Air/Prekursor, Suhu Curing, dan Jenis Prekursor Terhadap Kuat tekan Beton Geopolimer*" ini merupakan salah satu prasyarat kelulusan penulis sebagai sarjana teknik sipil pada Departemen Teknik Sipil Fakultas Teknik Universitas Indonesia.

Selain tujuan utama di atas, secara lebih mendalam penulis melakukan penelitian ini dengan maksud untuk :

- Mempelajari dan menganalisa beton geopolimer secara umum.
- Mempelajari dan menganalisa faktor faktor yang mempengaruhi kuat tekan beton geopolimer secara umum.
- Mempelajari dan menganalisa pengaruh konsentrasi NaOH dan rasio NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor terhadap kuat tekan beton geopolimer.

1.3. Ruang Lingkup Penelitian

Lingkup atau batasan penelitian ini yaitu:

1. Penelitian dilakukan dengan studi literatur mengenai pengaruh konsentrasi NaOH dan rasio NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor terhadap kuat tekan beton geopolimer.
2. Data yang dikumpulkan berasal dari literatur yang ada misalnya dari buku, skripsi, jurnal internasional dan bahan yang mendukung lainnya.

1.4. Manfaat Penelitian

Penelitian ini diharapkan akan memberi manfaat untuk menambah pengetahuan dan wawasan mengenai beton geopolimer secara umum serta pengaruh konsentrasi NaOH dan rasio NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor terhadap kuat tekan beton geopolimer.

1.5. Sistematika Penulisan

Sistematika penyusunan seminar skripsi ini secara garis besar dibagi dalam lima bagian sebagai berikut :

BAB I : PENDAHULUAN

Menjelaskan mengenai latar belakang penelitian, tujuan penelitian, batasan penelitian, metode penelitian, hipotesa awal dan sistematika yang dilakukan dalam penulisan penelitian.

BAB II : LANDASAN TEORI

Berisikan kajian yang mengacu pada beberapa referensi.

BAB III : STUDI LITERATUR

Berisikan penelitian-penelitian dan jurnal-jurnal internasional tentang beton geopolimer

BAB IV : ANALISA STUDI LITERATUR

Berisikan hasil penelitian dan analisa dari penelitian-penelitian dan jurnal-jurnal internasional tentang pengaruh konsentrasi NaOH dan rasio NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor terhadap kuat tekan beton geopolimer.

BAB V : KESIMPULAN DAN SARAN

Berisi mengenai kesimpulan yang didapat dari analisis pada bab sebelumnya beserta saran – saran yang diberikan guna penelitian / penulisan lebih lanjut.

BAB 2

LANDASAN TEORI

2.1. Definisi Beton

Beton adalah material yang umum digunakan sebagai bahan konstruksi. Secara global beton terdiri dari dua bagian utama yaitu matriks dan agregat. Bagian pertama adalah matriks (pasta) yang mempunyai fungsi utama sebagai pengikat antar material. Selain sebagai pengikat, matriks juga memberikan sumbangan kekuatan pada beton. Bagian kedua adalah bahan inklusi (agregat) yang menyumbangkan sebagian besar kekuatan dari beton itu sendiri. Agregat terdiri dari material anorganik yang biasanya berupa pecahan batu/kerikil dan pasir.

2.1.1. Material Penyusun Beton

2.1.1.1. Semen Portland

Menurut ASTM C-150 (1985) semen portland adalah semen hidraulis yang terutama terdiri dari silikat-silikat kalsium yang bersifat hidraulis dengan gips sebagai bahan tambahan. Unsur utama yang terkandung dalam semen dapat digolongkan ke dalam empat bagian yaitu:

- $3\text{CaO} \cdot \text{SiO}_2$ (*Tricalcium Silicate*) disingkat C_3S
- $2\text{CaO} \cdot \text{SiO}_2$ (*Dicalcium Silicate*) disingkat C_2S
- $3\text{CaO} \cdot \text{Al}_2\text{O}_3$ (*Tricalcium Aluminate*) disingkat C_3A
- $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$ (*Tetracalcium Aluminoferrit*) disingkat C_4AF

Selain itu, pada semen juga terdapat unsur-unsur lainnya dalam jumlah kecil, misalnya : MgO , TiO_2 , Mn_2O_3 , K_2O dan Na_2O .¹

C_3S dan C_2S merupakan senyawa yang membuat sifat - sifat perekat, unsur C_3S dan C_2S merupakan bagian terbesar (70% - 80%) dan paling dominan dalam memberikan sifat semen. Bila semen terkena air, maka C_3S akan segera berhidrasi dan memberikan pengaruh yang besar dalam proses pengerasan semen, terutama sebelum mencapai umur 14 hari. Unsur C_2S bereaksi dengan air lebih lambat sehingga hanya berpengaruh setelah beton berumur 7 hari. Unsur C_3A bereaksi sangat cepat dan memberikan kekuatan setelah 24 jam, sedangkan C_4AF berfungsi menurunkan temperatur pembakaran dalam pembentukan Calcium Silicate Hydrate. Dengan mengubah - ubah kadar masing - masing komponen tersebut, kita dapat membuat berbagai tipe semen. Saat ini terdapat 5 tipe semen dengan karakteristik berbeda. Standar industri di Amerika (ASTM) maupun di Indonesia (SNI) mengenal 5 jenis semen, yaitu:

- Jenis I, yaitu semen portland untuk penggunaan umum yang tidak memerlukan persyaratan-persyaratan khusus.
- Jenis II, yaitu semen portland untuk penggunaan yang memerlukan ketahanan sulfat dan panas hidrasi sedang.
- Jenis III, yaitu semen portland yang dalam penggunaannya menuntut persyaratan kekuatan awal yang tinggi setelah pengikatan terjadi.
- Jenis IV, yaitu semen portland yang dalam penggunaannya menuntut panas hidrasi yang rendah.
- Jenis V, yaitu semen portland yang dalam penggunaannya memerlukan ketahanan yang sangat baik terhadap sulfat.

Secara lengkap, persentase komponen penyusun tiap jenis semen portland menurut SNI 15 -2049-2004 ditunjukkan pada tabel 2.1

Tabel 2.1. Komposisi Portland Semen dan Batasan SNI 15-2049-2004

| Semen | Persentase komponen penyusun | | | | | | | |
|-----------|------------------------------|------------------|------------------|-------------------|-------------------|-----------|--------------|----------------|
| | C ₃ S | C ₂ S | C ₃ A | C ₄ AF | CaSO ₄ | CaO Bebas | MgO | Hilang Pijar |
| Jenis I | 49 | 25 | 12 | 8 | 2,9 | 0,8 | 2,4 (≤ 6) | 1,2 (≤ 5) |
| Jenis II | 46 | 29 | 6 (≤ 8) | 12 | 2,8 | 0,6 | 3,0 (≤ 6) | 1,0 (≤ 3) |
| Jenis III | 56 | 15 | 12 (≤ 15) | 8 | 3,9 | 1,4 | 2,6 (≤ 6) | 1,9 (≤ 3) |
| Jenis IV | 30 (≤ 35) | 46 (≥ 40) | 5 (≤ 7) | 13 | 2,9 | 0,3 | 2,7 (≤ 6) | 1,0 (≤ 2,5) |
| Jenis V | 43 | 36 | 4 (≤ 5) | 12 (≤ 25) | 2,7 | 0,4 | 1,6 (≤ 6) | 1,0 (≤ 3) |

Saat semen portland bercampur dengan air maka akan terjadi reaksi hidrasi sebagai berikut: ¹

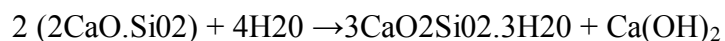
a) Reaksi Hidrasi Tricalcium Silikate (C₃S)

Senyawa C₃S adalah senyawa yang paling reaktif pada portland semen. Jika terkena air C₃S akan segera berhidrasi dan memberikan kontribusi yang besar dalam proses pengerasan semen, terutama sebelum mencapai umur 14 hari. Pada proses reaksi hidrasi, C₃S akan membentuk CSH gel atau tobermorite yang memberikan kekuatan pada beton dan senyawa sisa berupa Ca(OH)₂. Secara keseluruhan reaksi hidrasi C₃S dapat dituliskan sebagai berikut :



b) Reaksi Hidrasi Dicalcium Silikate (C₂S)

Secara keseluruhan, reaksi hidrasi dari C₂S mirip dengan reaksi hidrasi C₃S, dan dapat dituliskan sebagai berikut:

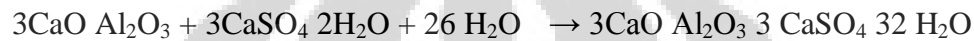


Senyawa C₂S bereaksi sangat lambat dengan air untuk membentuk CSH gel dan membentuk lebih sedikit Ca(OH)₂. Kecepatan reaksi hidrasi C₂S 20 kali lebih

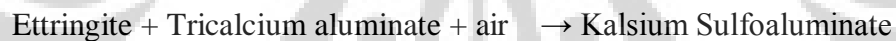
lambat dari reaksi C_3S , bahkan setelah 4 tahun masih tersisa sekitar 15% dari C_2S yang belum bereaksi.

c) Reaksi Hidrasi Tricalcium aluminate (C_3A)

Reaksi hidrasi dari C_3A pada beton berlangsung dalam dua tahap. Pada tahap pertama, Tricalcium Aluminate akan bereaksi dengan gypsum dan air dan membentuk ettringite. Reaksinya dapat dituliskan sebagai berikut



Selanjutnya, ettringite yang terbentuk akan bereaksi dengan C_3A dan membentuk senyawa baru yang disebut kalsium monosulfoaluminat yang memiliki densitas lebih tinggi dari ettringite. Persamaan reaksinya dapat dituliskan sebagai berikut



d) Reaksi Hidrasi Tetracalcium Aluminoferrit (C_4AF)

C_4AF bereaksi cepat dengan air. Namun, reaksinya tidak secepat reaksi C_3A dan C_2S . Hasil reaksi dari C_4AF adalah senyawa kristal $C_3(AF) \cdot 6H$ yang berfungsi menurunkan temperatur pembakaran dalam pembentukan Calcium Silicate Hydrate.

2.1.1.2. Agregat Kasar³

Agregat kasar mempunyai ukuran butiran 5mm atau lebih besar. Agregat kasar merupakan penyumbang sebagian besar kekuatan dari beton. Beton pada umumnya dan beton pada percobaan ini menggunakan pecahan batu (*Gravel*) sebagai agregat kasar. Faktor penting yang perlu diperhatikan adalah gradasi atau distribusi ukuran butir agregat. Apabila butir-butir agregat mempunyai ukuran yang seragam, dapat

menimbulkan volume pori lebih besar. Tetapi jika ukuran butirnya bervariasi, maka volume pori menjadi kecil. Hal ini disebabkan butir yang lebih kecil akan mengisi pori di antara butiran yang lebih besar dan memungkinkan antar agregat dapat saling mengunci (*interlocking*).

2.1.1.3. Agregat Halus ²

Agregat halus mempunyai ukuran butiran 0.15 mm - 5mm. Beton pada umumnya dan pada percobaan ini menggunakan pasir sebagai agregat halusnya. SNI 03-2834-1992 mengklasifikasikan distribusi ukuran butiran agregat halus (pasir) menjadi empat daerah atau zone yaitu: zona I (kasar), zona II (agak kasar), zona III (agak halus) dan zona IV (halus) sebagaimana ditunjukkan pada Tabel 2.2.

Tabel 2.2 Batas-Batas Gradasi Agregat Halus Menurut SNI 03-2834-1992

| Ukuran Saringan | Persentase berat yang lolos saringan | | | |
|-----------------|--------------------------------------|-----------------|------------------|-----------------|
| | Gradasi Zona I | Gradasi Zona II | Gradasi Zona III | Gradasi Zona IV |
| 9,60 mm | 100 | 100 | 100 | 100 |
| 4,80 mm | 90-100 | 90-100 | 90-100 | 95-100 |
| 2,40 mm | 60-95 | 75-100 | 85-100 | 95-100 |
| 1,20 mm | 30-70 | 55-90 | 75-100 | 90-100 |
| 0,60 mm | 15-34 | 35-59 | 60-79 | 80-100 |
| 0,30 mm | 5-20 | 8-30 | 12-40 | 15-50 |
| 0,15 mm | 0-10 | 0-10 | 0-10 | 0-15 |

2.1.1.4. Air

Proporsi air yang sedikit pada beton akan memberikan kekuatan tekan yang tinggi pada beton, sebaliknya kadar air yang berlebihan akan mengurangi kekuatan beton. Namun, faktor kadar air akan sangat berpengaruh dalam kemungkinan pekerjaan beton. Semakin encer beton akan semakin mudah dikerjakan, dan sebaliknya semakin sedikit kadar air maka beton akan semakin sukar dikerjakan. Proporsi air dalam beton biasa dinyatakan dalam rasio air-semen (*water-cement ratio*), yaitu angka yang menyatakan perbandingan antara massa air terhadap massa semen dalam campuran beton.

2.1.2 Karakteristik Beton

Karakteristik beton ditinjau dalam dua fase, yaitu karakteristik pada beton muda dan karakteristik pada beton keras

2.1.2.1 Karakteristik Beton Muda

Karakteristik pada beton muda berupa kelecakan (*workability*). *Workability* atau kelecakan dipakai untuk menggambarkan kemudahan beton untuk dapat dikerjakan dalam hal pembentukan, pemadatan dan transportasi. Kelecakan (*workability*) beton dipengaruhi oleh:

- Komposisi beton
- Konsistensi normal semen
- Admixture yang digunakan
- Mobilitas, setelah aliran dimulai
- Kohesi atau perlawanan terhadap pemisahan bahan-bahan
- Banyaknya air yang digunakan dalam campuran beton
- Gradasi campuran agregat kasar dan agregat halus

Newman menambahkan bahwa rumusan *workability* sekurang-kurangnya harus memiliki tiga sifat, yaitu :

a) Kompaktibilitas

Kemudahan beton untuk dapat dipadatkan sehingga rongga-rongga udara dapat dihilangkan.

b) Stabilitas

Kemampuan beton untuk tetap sebagai masa yang homogen, koheren dan stabil selama dikerjakan tanpa terjadi segregasi.

c) Mobilitas

Kemudahan dimana beton dapat mudah mengalir ke dalam cetakan disekitar tulangan.

Pengukuran kelecakan (*workability*) slump dilakukan dengan menggunakan slump test. Slump merupakan besarnya nilai keruntuhan beton secara vertical yang diakibatkan karena beton belum memiliki batas yield stress yang cukup untuk

menahan berat sendiri karena ikatan antar pertikelnya masih lemah sehingga tidak mampu untuk mempertahankan ikatan semulanya. Nilai dapat menggambarkan tingkat kelecakan dari beton tersebut. Semakin tinggi nilai slump maka semakin tinggi tingkat kelecakan beton muda tersebut, sebaliknya semakin rendah nilai slump semakin rendah tingkat kelecakan beton tersebut. Beton segar seiring dengan penambahan waktu akan mengalami kehilangan slump dan akan berakhir pada nilai slump nol secara otomatis juga kehilangan kelecakannya (*loss workability*). Nilai slump ini dapat hilang karena penambahan waktu pada selang waktu tertentu. Hilangnya slump disebabkan karena terjadinya proses pengikatan pada beton yang semakin kuat. Standard Internasional yang digunakan pada metode pengujian slump beton mengacu pada ASTM C 143, atau SNI 03-1972-1990 menurut standard Indonesia.

2.1.2.2 Karakteristik Beton Keras³

a) Kuat Tekan

Sifat kekuatan tekan merupakan sifat utama yang umum harus dimiliki oleh beton, sebab beton yang tidak cukup kekuatannya menurut kebutuhannya menjadi tidak berguna. Secara umum kekuatan beton dipengaruhi oleh faktor air semen dan kepadatannya. Beton dengan faktor air semen kecil sampai dengan jumlah air semen yang cukup untuk hidrasi semen secara sempurna akan memiliki kekuatan yang optimal. Kuat tekan beton adalah besarnya beban persatuan luas yang menyebabkan benda uji beton hancur bila dibebani dengan gaya tekan tertentu, yang dihasilkan oleh mesin tekan.

b) Kuat Tarik Belah

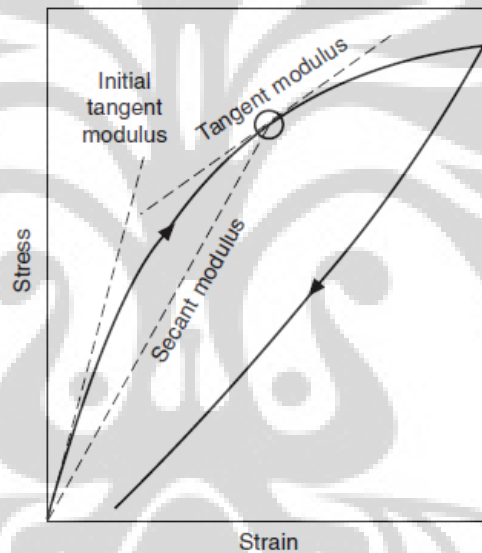
Pengukuran kuat tarik belah beton atau disebut juga kuat geser beton mengacu pada ASTM C 496 atau SNI 03-2491-2002. Besarnya beban garis P yang dicatat pada pengujian ini adalah beban pada saat benda uji patah.

c) Kuat Lentur

Pengukuran kuat lentur beton mengacu pada ASTM C 78 dengan metode third point loading, dimana dua beban garis P diberikan tepat pada jarak 1/3 bentang.

d) Modulus Elastisitas

Modulus elastisitas adalah rasio antara tegangan-regangan sampai pada *elastic limit* disebut modulus elastisitas (E-value). Beton tidak memiliki *elastic limit* yang jelas. Untuk pendekatannya dan aplikasinya pada design structural, digunakan tiga macam E-value, yaitu tangent modulus, secant modulus, dan initial tangent modulus. Seperti terlihat pada gambar



Gambar 2.1 Diagram Tegangan-Regangan Beton

e) Kekedapan Air (*Permeability*)

Beton cenderung berisi rongga. Ada rongga yang terjadi akibat evaporasi air dan rongga langsung pada saat pekerjaan. Sisa air pada proses hidrolisis setelah menguap akan menyisakan ruang kosong pada beton. Keberadaan pori-pori menyebabkan porositas pada beton. Rembesan cairan mungkin terjadi melalui keberadaan pori-pori ini. Kejadian rembesan dapat menyebabkan kerusakan pada beton. Faktor-faktor yang mempengaruhi kekedapan air antara lain :

- Mutu dan porositas dari agregat
- Gradasi agregat. Gradasi agregat yang baik memudahkan pekerjaan pembuatan beton dan penyebaran material pada ruang dengan lebih baik.
- Umur, Kekedapan beton berkurang dengan perkembangan umur
- Perawatan (Curing and Maintenance)

f) Susut (*Shrinkage*)

Shrinkage adalah perubahan volume beton yang tidak berhubungan dengan pembebanan. Rambatan suhu (perubahan suhu) pada beton selama pengikatan dan proses pengerasan, yang disebabkan adanya hidrasi semen oleh air menyebabkan terjadinya efek pemuaian pada beton. Setelah proses pengikatan suhu berangsur-angsur turun kembali. *Shrinkage* disebabkan oleh reaksi kimia ini sering disebut sebagai *antogeneous shrinkage*. Perubahan suhu tersebut dapat menyebabkan adanya muai susut pada beton yang nantinya dapat mengakibatkan timbulnya retak rambut pada beton. Retak retak rambut pada beton nantinya akan menjadi celah bagi zat luar untuk masuk sehingga dapat menyebabkan korosi pada tulangan logam. Beton yang telah mengeras, dapat memuai dan menyusut tetapi tidak merusak beton, maka harus disediakan sambungan untuk pemuaian dan penyusutan. Penyusutan kering dan perubahan kadar air, beton menyusut bila mengalami kekeringan, dan juga terjadi pada saat pengerasan. Beton juga memuai dan menyusut saat basah dan kering.

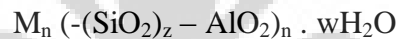
g) Rangkak (*Creep*)

Rangkak adalah perubahan bentuk yang non-elastis dibawah suatu pembebanan tetap dalam waktu tertentu. Rangkak diduga disebabkan oleh penutupan pori-pori dalam, aliran dari pasta semen, pergerakan kristal didalam agregat, dan terjadinya penekanan air dari gel semen karena adanya tekanan.

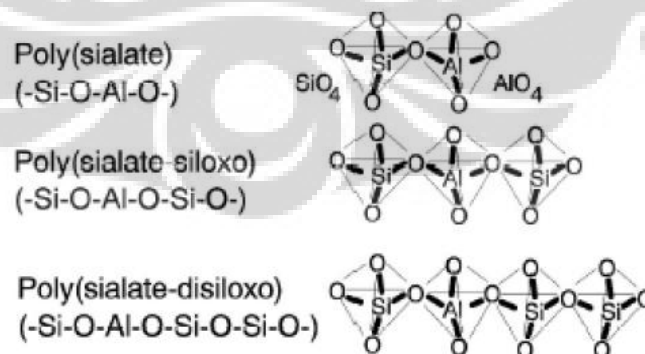
2.2. Beton Geopolimer

2.2.1. Defenisi Beton Geopolimer

Geopolimer dapat didefinisikan sebagai material yang dihasilkan dari geosintesis aluminosilikat polimerik dan alkali-silikat yang menghasilkan kerangka polimer SiO_4 dan AlO_4 yang terikat secara tetrahedral (Davidovits, 1994). Geopolimer memiliki komposisi kimia menyerupai zeolit tetapi memiliki *amorphous microstructure*⁴. Beton geopolimer adalah beton yang dihasilkan dengan sepenuhnya mengganti semen portland dengan material geopolimer. Sepanjang proses sintesifikasi, silika dan aluminium digabung untuk membentuk blok bangunan, yang secara kimiawi dan struktural dapat dibandingkan dengan ikatan batu alam. Davidovits juga menggunakan istilah ‘poly(siallate)’ untuk geopolimer berbasis silika-aluminat⁵. Siallate adalah kependekan dari silikon-okso-aluminat (siloxo-oxo-aluminate). Rumus empiris dari poly(siallate) adalah:⁶



Dimana z adalah bilangan 1, 2, atau 3, sampai dengan 32; M adalah kation monovalen seperti kalium atau natrium, dan “ n ” adalah derajat polikondensasi. Davidovits juga membedakan tiga tipe polysiallate yaitu, tipe poly(siallate) (-Si-O-Al-O), tipe poly(siallate-siloxo) (-Si-O-Al-O-Si-O), dan tipe poly(siallate-disiloxo) (-Si-O-Al-O-Si-O-Si-O).⁷ struktur dari polysiallate dapat dilihat pada gambar 2.3



Gambar 2.2 Struktur Geopolimer

Penelitian lebih lanjut dilakukan oleh Davidovits dan Sawyer (1985) dengan menggunakan *ground blast furnace slag*. Penelitian tersebut menghasilkan suatu mortar semen siap pakai dimana hanya perlu tambahan air untuk menghasilkan material yang tahan lama dan cepat mengeras. Produk tersebut kemudian dipatenkan dan didokumentasikan ke dalam jurnal ilmiah di AS dengan judul *Early High Strength Mineral Polymer Was Used as A Supplementary Cementing Material In The Production Of Precast Concrete Products*. Material tersebut kemudian diproduksi dan dimanfaatkan pada renovasi airport baik untuk landasan pacu, landasan hubung dan apron, pembangunan jalan raya, geladak jembatan, dan beberapa konstruksi dimana kekuatan awal beton yang sangat besar sangat diperlukan.⁸

Palomo, Grutzeck, dan Blanco (1999) mempelajari pengaruh temperature, waktu, dan rasio larutan alkali : *fly ash* pada kekuatan awal geopolimer. Dilaporkan bahwa faktor temperature dan waktu perawatan mempengaruhi kuat tekan material geopolimer. Penggunaan larutan *sodium silikat* (Na_2SiO_3) dan *sodium hidroksida* (NaOH) sebagai larutan alkali menghasilkan kuat tekan yang paling tinggi. Kuat tekan yang dihasilkan pada penelitian tersebut mencapai 60 MPa dengan suhu curing 85°C selama 5 jam.⁹

Xu dan Van Deventer (2000) meneliti proses geopolimerisasi dari 15 unsur alami Al-Si. Telah ditemukan bahwa tingginya jumlah mineral yang mengalami dissolusi yang sempurna akan menghasilkan kuat tekan lebih baik setelah proses polimerisasi. Persentase dari kalsium dioksida (CaO), kalium dioksida (K_2O), rasio molaritas Si-Al pada *Fly Ash*, jenis larutan alkali dan rasio molaritas Si/Al di dalam larutan alkali selama proses dissolusi merupakan faktor – faktor penting yang mempengaruhi kuat tekan dari material geopolimer.¹⁰

Van Jaarsveld, Van Deventer dan Lukey (2002) mempelajari hubungan timbal balik dari berbagai parameter yang mempengaruhi kekuatan material geopolimer berbahan dasar *fly ash*. Mereka melaporkan bahwa properti material geopolimer dipengaruhi oleh proses dissolusi yang tidak sempurna, jumlah air, waktu dan temperature *curing*.

Berdasarkan penelitian tersebut, ketika benda uji di-*curing* pada suhu 70°C selama 24 jam, terjadi peningkatan kuat tekan. *Curing* dengan periode yang lebih lama justru mengurangi kuat tekan material.¹¹

Palomo et al (2004) menyelidiki karakteristik mekanis dari beton geopolimer berbahan dasar *fly ash*. Ditemukan bahwa karakteristik material kebanyakan ditentukan oleh metode *curing*, terutama faktor waktu dan temperatur masa *curing*.

2.2.3. Material Penyusun Geopolimer¹²

Material polimerik anorganik alkali aluminosilikat (*geopolymer*) dapat disintesis dengan mencampurkan prekursor dengan larutan alkali sebagai aktivator. Prekursor adalah bahan utama pembentuk polimer yang mengandung senyawa alumina dan silika dengan konsentrasi tinggi. Prekursor dapat berupa mineral alami maupun limbah industri. Unsur unsur kimia dalam prekursor bila dicampur dengan larutan alkali aktivator akan menghasilkan material pasta geopolimer yang mempunyai kemampuan mengikat seperti pasta semen. Pasta geopolimer menggantikan penggunaan pasta semen dalam material penyusun beton. Beton yang menggunakan pasta geopolimer sebagai pengikat agregat inilah yang disebut beton geopolimer.

2.2.3.1. Prekursor

Prekursor adalah bahan utama pembentuk polimer yang mengandung senyawa alumina dan silika dengan konsentrasi tinggi. Prekursor dapat berupa mineral alami maupun limbah industri. Bahan bahan yang biasa digunakan sebagai prekursor antara lain *fly ash*, *blast furnace slag*, *silica fume*, metakaolin, dan *rice husk ash*

a) *Fly Ash*.

Fly ash adalah hasil pemisahan sisa pembakaran yang halus dari pembakaran batu bara yang dialirkan dari ruang pembakaran melalui ketel berupa semburan asap. Sekitar 75-90% abu yang keluar dari cerobong asap dapat ditangkap oleh system elektrostatis precipitator. Sisa yang lain didapat di dasar tungku (disebut *bottom*

ash). Mutu *fly ash* tergantung pada kesempurnaan proses pembakarannya. Material ini mempunyai sifat pozzolanik. Kandungan *fly ash* sebagian besar terdiri dari silikat dioksida (SiO_2), alumunium (Al_2O_3), besi (Fe_2O_3), dan kalsium (CaO), serta magnesium, potassium, sodium, titanium, dan sulfur dalam jumlah yang lebih sedikit.

Sifat fisik dari *fly ash* adalah : (ACI *Manual of Concrete Practice 1993 Parts 1 226.3R-6*)

- *Specific Gravity* : 2,2 – 2,8
- Ukuran : \varnothing 1 mikron – \varnothing 1 mm, dengan kehalusan 70% - 80% melewati saringan no.200 (75 mikron)
- Kehalusan :

| | |
|----------------------------|-------|
| % tertahan ayakan 0,075 mm | 3,5 |
| % tertahan ayakan 0,045 mm | 19,3 |
| % sampai ke dasar | 77,22 |

Sebagian besar komposisi kimia dari abu terbang tergantung tipe batu bara. Menurut ASTM C618-86, terdapat dua jenis abu terbang, kelas F dan C. Kelas F dihasilkan dari pembakaran batubara jenis antrasit dan bituminous, sedangkan kelas C dari batubara jenis lignite dan subbituminous. Kelas C memiliki kadar kapur tinggi. *Fly ash* dapat dibedakan menjadi 3 jenis (ACI *Manual of Concrete Practice 1993 Parts 1 226.3R-3*), yaitu :

1) Kelas C

Fly ash yang mengandung CaO di atas 10% yang dihasilkan dari pembakaran lignite atau sub-bitumen batubara (batubara muda).

- Kadar ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) > 50%.
- Kadar CaO mencapai 10%.

Dalam campuran beton digunakan sebanyak 15% - 35% dari total berat binder.

2) Kelas F

Fly ash yang mengandung CaO lebih kecil dari 10% yang dihasilkan dari pembakaran anthracite atau bitumen batubara.

- Kadar ($\text{SiO}_2 + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$) > 70%.
- Kadar CaO < 5%.

Dalam campuran beton digunakan sebanyak 15% - 25% dari total berat binder.

3) Kelas N

Pozzolan alam atau hasil pembakaran yang dapat digolongkan antara lain tanah diatomic, opaline chert dan shales, tuff dan abu vulkanik, yang mana biasa diproses melalui pembakaran atau tidak melalui proses pembakaran. Selain itu juga mempunyai sifat pozzolan yang baik.

Penggunaan *fly ash* dalam campuran beton konvensional dengan portland cement mempunyai beberapa keunggulan, yaitu :

Pada beton segar

- Kehalusan dan bentuk partikel *fly ash* yang bulat dapat meningkatkan *workability*.

Pada beton keras

- Kontribusi peningkatan kuat tekan beton pada umur setelah 52 hari.
- Meningkatkan durabilitas beton.
- Meningkatkan kepadatan (*density*) beton.
- Mengurangi terjadinya penyusutan beton.

Pada beton geopolimer, *fly ash* digunakan sebagai prekursor yang merupakan material dasar dari pasta geopolimer. *fly ash* sendiri tidak memiliki kemampuan mengikat seperti halnya semen. Tetapi dengan kehadiran air dan *alkaline activator*, oksida silica yang dikandung oleh *fly ash* akan bereaksi secara kimia dengan *alkaline activator*. Apabila *fly ash* tidak dimanfaatkan tetapi dibuang begitu saja, maka akan memiliki potensi mencemari lingkungan karena beterbangan dan menjadi debu. Oleh karena itu, pemanfaatan *fly ash* akan mendatangkan manfaat ganda yaitu mengurangi dampak negatif terhadap

lingkungan sekaligus menggantikan penggunaan semen sebagai bahan utama dalam pembuatan beton.

b) Rice Husk Ash

Rice husk ash (abu sekam padi) didapatkan dari pembakaran kulit sekam padi. Abu yang dihasilkan dari pembakaran normal, permukaan partikelnya akan terkristalisasi dan memiliki aktivitas pozzolan yang rendah. Namun, jika pembakaran dikontrol pada suhu antara 500 - 700°C lapisan pozzolan pada permukaan partikel abu dapat terbentuk¹. Hasil dari pembakaran tersebut akan melepaskan carbon dan meninggalkan silika sebagai residu dalam jumlah besar. Namun, abu sekam padi sama sekali tidak mengandung alumina (Al_2O_3) seperti halnya *fly ash*. Karakteristik abu sekam padi ditunjukkan oleh tabel 2.3.

Tabel 2.3. Karakteristik Abu Sekam Padi

| Karakteristik Fisika | Nilai |
|------------------------------------|--------------|
| Specific Gravity | 2,28 |
| Finnes-median size | 7 |
| Surface Area | 30,24 |
| Karakteristik Kimia | (%) |
| Silicon dioxide (SiO_2) | 87,90 |
| Carbon (C) | 5,32 |

(Sumber : *Strength and durability of rice Husk Ash-Modified Concrete in the Marina Environment*, Marcelina Alvarez)

2.2.3.2. Aktivator

Alkaline activator dibutuhkan untuk reaksi polimerisasi. Alkali mengaktifkan prekursor dengan mendisolusikan mereka ke dalam monomer $\text{Si}(\text{OH})_4$ dan $\text{Al}(\text{OH})_4^-$. Selama proses curing, monomer monomer tadi terkondensasi dan membentuk jaringan polimer tiga dimensi dan berikatan silang. Ion alkali bertindak sebagai penetral muatan (*charger balancer*) untuk tiap molekul tetrahedron $\text{Al}(\text{OH})_4^-$.

Aktivator yang secara umum digunakan adalah kombinasi antara larutan *sodium silikat* dan *sodium hidroksida*.

a) *Sodium Silikat* (Na_2SiO_3)

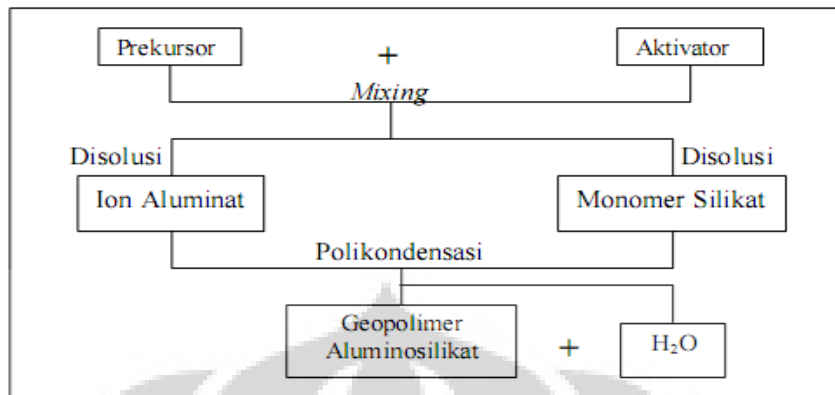
Sodium silikat (Na_2SiO_3) atau biasa disebut *waterglass* berfungsi untuk mempercepat reaksi polimer. Campuran antara *fly ash* dan *sodium silikat* membentuk ikatan yang sangat kuat namun banyak terjadi retakan-retakan antar mikrostruktur.

b) *Sodium Hidroksida* (NaOH)

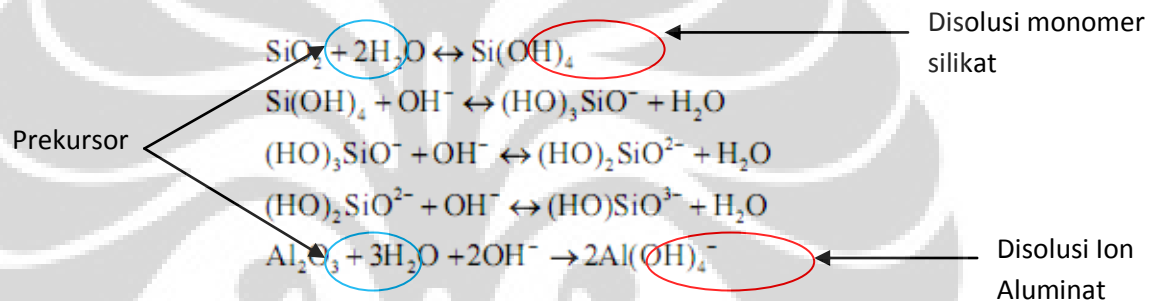
Sodium hidroksida (NaOH) berfungsi untuk mereaksikan unsur-unsur Al dan Si dengan menambah ion Na^+ . Campuran *fly ash* dan *sodium hidroksida* membentuk ikatan yang kurang kuat tetapi menghasilkan ikatan yang lebih padat dan tidak ada retakan.

2.2.4. Proses Polimerisasi

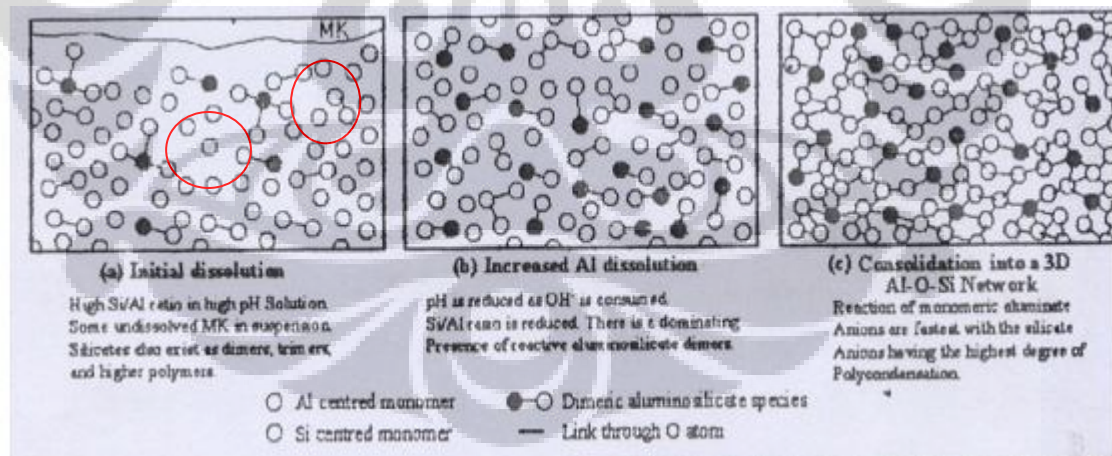
Seperti yang telah dijelaskan sebelumnya, material geopolimer dibuat dengan mencampurkan prekursor dengan larutan alkali sebagai aktivator. Prekursor dan aktivator akan bersintesa membentuk material padat melalui proses polimerisasi, dimana proses polimerisasinya yang terjadi adalah disolusi yang diikuti oleh polikondensasi. Dalam reaksi polimerisasi ini Aluminium (Al) dan Silica (Si) mempunyai peranan penting dalam ikatan polimerisasi (Davidovits, 1994). Reaksi Al dan Si dengan alkaline akan menghasilkan $\text{Al}(\text{OH})_4$ dan $\text{Si}(\text{OH})_4$. Berikut adalah diagram alur polimerisasi pada beton geopolimer hingga menghasilkan produk akhir berupa Geopolimer Aluminosilikat dan hasil sampingan H_2O .



Gambar 2.3 Alur Polimerisasi



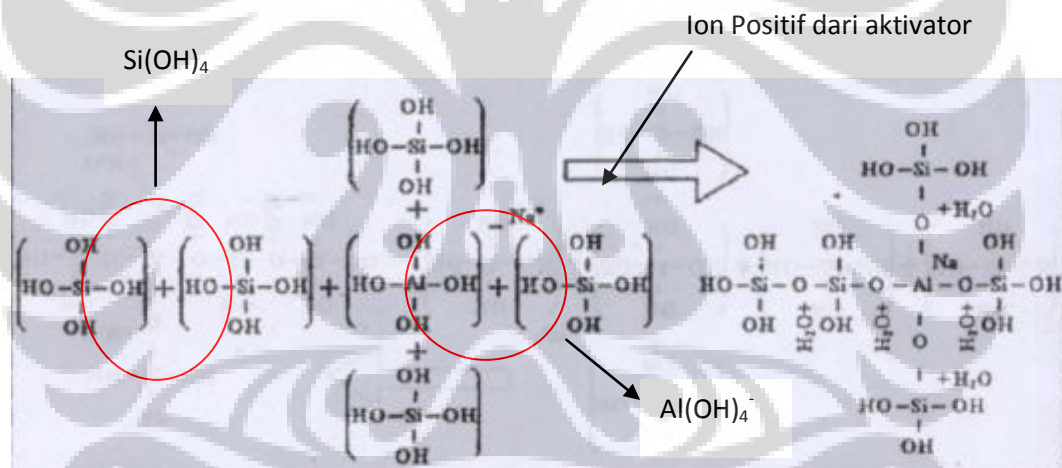
Gambar 2.4 Dissolusi Ion Aluminat dan Monomer Silikat

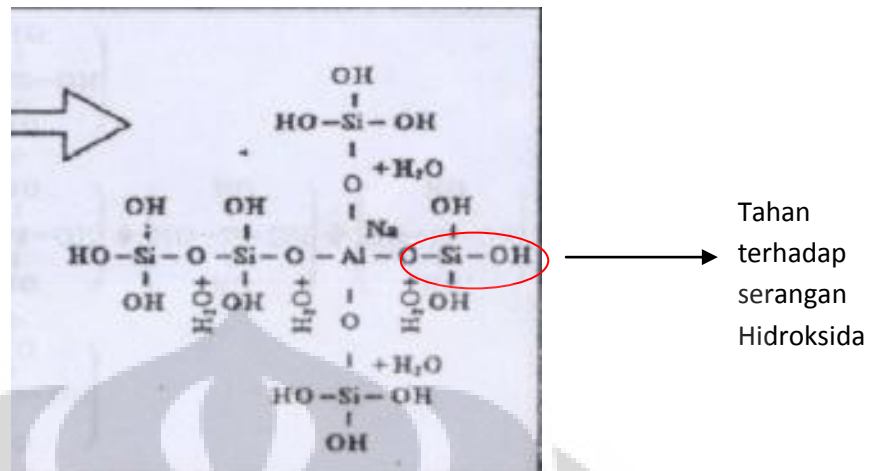


Gambar 2.5 Tahap disolusi

Keterangan Gambar

- Tahap awal dimana rasio Si/Al tinggi, karena kecepatan pelepasan Al dari prekursor bersifat lambat. Lebih dari satu monomer berinti Si yang berikatan dengan satu anion Aluminat, sehingga hanya terdapat beberapa ikatan.
- Penambahan disolusi Al menyebabkan pengurangan rasio Si/Al sehingga OH semakin dikonsumsi dan pH campuran akan turun. Hal ini menyebabkan pengurangan monomer berinti -Si dan peningkatan grup hidroksil (OH) yang terikat pada monomer berinti -Si.
- Peningkatan grup hidroksil (OH) meningkatkan kemungkinan reaksi polikondensasi antara monomer berinti -Si dengan $\text{Al}(\text{OH})_4^-$. Seiring dengan waktu, produk polikondensasi akan terkonsolidasi ke dalam jaringan aluminosilikat yang mengandung rantai -Si-O-Si dan -Si-O-Al

Gambar 2.6 Skema Reaksi Polikondensasi Monomer $\text{Al}(\text{OH})_4^-$ dan $\text{Si}(\text{OH})_4$



Gambar 2.7 Struktur Kimia Geopolimer Aluminosilikat (Pasta Geopolimer)

Pada disolusi alumina, OH dikonsumsi untuk menghidrolisis unsure Al untuk membentuk anion aluminat $\text{Al}(\text{OH})_4$. Maka, untuk mencapai disolusi yang sempurna pada pembentukan monomer aluminat dan silikat dibutuhkan larutan alkali activator yang mencukupi.

Proses sintesis terbagi atas proses aktivasi bahan alumina-silika oleh ion alkali dan proses curing untuk mendorong terjadinya polimerisasi dari monomer alumina-silika menjadi struktur jaringan molekul tiga dimensi. Untuk menjaga koordinasi tetrahedral monomer Al yang terdapat pada larutan alkali, rasio ion logam alkali dengan Al haruslah satu. Nilai 1 pada rasio Na:AL memperlihatkan jumlah minimum kation Na yang dibutuhkan untuk menjaga keseimbangan muatan di dalam geopolimer.

2.2.5. Karakteristik Beton Geopolimer

Beton geopolimer adalah beton yang terbuat dari material geopolimer sebagai matriks dan mineral agregat sebagai inklusi. Seperti halnya beton semen portland pada umumnya, penggunaan agregat berfungsi dalam memberikan sumbangan kekuatan yang terbesar pada beton. Agregat yang digunakan untuk beton geopolimer sebaiknya memiliki gradasi yang menerus. Hal ini bertujuan agar terjadi komposisi yang padat pada saat beton mengeras. Fungsi agregat kasar adalah sebagai penyusun

kekuatan pada beton, sedangkan agregat halus lebih berfungsi sebagai pengisi ruang kosong untuk mengurangi void pada beton.

Karakteristik beton geopolimer muda sangat berbeda dengan karakteristik beton portland semen muda. Pasta geopolimer yang sangat cepat mengeras menyebabkan beton geopolimer muda memiliki workability yang rendah sehingga dibutuhkan kecepatan kerja yang tinggi dan penambahan admixture *superplasticizer* untuk meningkatkan workability dari beton geopolimer. Tanpa penambahan superplasticizer nilai slump dari beton geopolimer bahkan dapat sama dengan nol.

Karakteristik beton geopolimer keras belum banyak diketahui secara pasti. Sampai saat ini pada umumnya penelitian terhadap karakteristik mekanis pada beton geopolimer keras masih terbatas pada pengamatan kuat tekan (*compressive strength*), sedangkan penelitian terhadap kuat tarik, kuat lentur, dan karakteristik mekanis lainnya masih sangat terbatas. Adapun faktor faktor yang mempengaruhi karakteristik beton geopolimer antara lain suhu curing dan waktu curing, jenis prekursor, konsentrasi NaOH dan rasio massa NaOH:Na₂SiO₃, dan rasio air/prekursor.

2.2.6. Aplikasi Geopolimer

Aplikasi dari material material geopolimer ditentukan oleh struktur kimia dalam *polysialate*, seperti yang ditunjukkan pada tabel 2.4

Tabel 2.4 Rasio Si/Al Pada *polysialate*

| Si:Al ratio | Applications |
|-------------|---|
| 1 | <ul style="list-style-type: none"> - Bricks - Ceramics - Fire protection |
| 2 | <ul style="list-style-type: none"> - Low CO₂ cements and concretes - Radioactive and toxic waste encapsulation |
| 3 | <ul style="list-style-type: none"> - Fire protection fibre glass composite - Foundry equipments - Heat resistant composites, 200°C to 1000°C - Tooling for aeronautics titanium process |
| >3 | <ul style="list-style-type: none"> - Sealants for industry, 200°C to 600°C - Tooling for aeronautics SPF aluminium |
| 20 - 35 | <ul style="list-style-type: none"> - Fire resistant and heat resistant fibre composites |

Rasio Si:Al yang semakin tinggi akan menghasilkan material geopolimer yang semakin getas. Untuk aplikasi geopolimer dalam bidang teknik sipil khususnya untuk kepentingan struktural akan lebih cocok jika menggunakan material geopolimer dengan rasio Si:Al yang rendah (B V Rangan, 2004).

2.2.7. Kelebihan dan Kekurangan Beton Geopolimer

2.2.7.1 Kelebihan Beton Geopolimer

Kelebihan – kelebihan aplikasi beton geopolimer adalah sebagai berikut (Skvara, dkk)

- Beton geopolimer mempunyai nilai susut yang kecil
- Beton geopolimer lebih tahan reaksi alkali – silika
- Mengurangi polusi udara

2.2.7.2 Kekurangan Beton Geopolimer

Kekurangan beton geopolimer adalah sebagai berikut:

- Proses pembuatannya lebih rumit daripada beton konvensional karena jumlah material yang dibutuhkan lebih banyak daripada beton konvensional.
- Belum adanya *mix design* yang pasti.
- Beton geopolimer mempunyai workability yang lebih rendah dari beton konvensional.

2.2.8. Faktor Faktor yang Mempengaruhi Kuat Tekan Beton Geopolimer

Beberapa faktor yang mempengaruhi kuat tekan geopolimer antara lain perbedaan metode dan suhu curing, waktu curing, jenis prekursor, konsentrasi NaOH dan rasio massa NaOH:Na₂SiO₃, rasio air/prekursor, rasio pasir/prekursor, dan rasio pasir:kerikil. Namun, pada studi literatur ini hanya akan dibahas pengaruh konsentrasi NaOH dan rasio massa NaOH:Na₂SiO₃, rasio air/prekursor, suhu curing, dan jenis prekursor yang digunakan terhadap kuat tekan beton geopolimer.

2.2.8.1. Jenis Prekursor

a) Kandungan Kalsium

Fly ash tipe F yang memiliki kandungan CaO yang lebih rendah cenderung lebih dipilih sebagai prekursor dibandingkan *fly ash* tipe C. Hal ini disebabkan kandungan kalsium yang tinggi dapat mengganggu proses polimerisasi dan mengubah mikrostructure (Gourley, 2003; Gourley and Johnson, 2005). Namun, pada beberapa penelitian ditemukan kasus dimana beton geopolimer yang menggunakan *fly ash* tipe C sebagai prekursor menghasilkan kuat tekan yang lebih tinggi dari beton geopolimer yang menggunakan *fly ash* tipe F sebagai prekursor.

b) Kehalusan

Prekursor dengan ukuran butiran yang lebih halus cenderung dapat menghasilkan beton geopolimer dengan kuat tekan yang lebih baik. Oleh karena itu usaha penyaringan dan penghalusan prekursor sangat dianjurkan dikarenakan permukaan yang lebih halus akan memiliki bidang kontak yang lebih besar untuk terjadinya proses polimerisasi.

2.2.8.2. Metode, Suhu dan Waktu Curing

Reaksi polimerisasi membutuhkan panas dalam prosesnya, oleh karena itu metode curing dengan menggunakan oven atau microwave dengan suhu curing yang lebih tinggi dan waktu curing yang lebih lama cenderung lebih baik untuk menghasilkan beton geopolimer dengan kuat tekan yang tinggi. Namun, dalam kondisi tertentu suhu curing yang tinggi dapat menyebabkan penurunan kuat tekan beton geopolimer. Berdasarkan penelitian yang dilakukan oleh J.G.S. van Jaarsveld, J.S.J. van Deventer, dan G.C. Lukey. 2002. Ketika benda uji di-curing pada suhu 70⁰C selama 24 jam, terjadi peningkatan kuat tekan. Curing dengan periode yang lebih lama justru mengurangi kuat tekan material.

2.2.8.3. Konsentrasi NaOH dan Rasio Massa NaOH:Na₂SiO₃ Dalam Larutan Alkali

Sodium silikat (Na₂SiO₃) berfungsi untuk mempercepat reaksi polimer. Campuran antara *fly ash* dan *sodium silikat* membentuk ikatan yang sangat kuat namun banyak terjadi retakan-retakan antar mikrostruktur. *Sodium hidroksida* (NaOH) berfungsi untuk mereaksikan unsur-unsur Al dan Si dengan menambah ion Na⁺. Campuran *fly ash* dan *sodium hidroksida* membentuk ikatan yang kurang kuat tetapi menghasilkan ikatan yang lebih padat dan tidak ada retakan. Peningkatan rasio berat Na₂SiO₃:NaOH menurunkan porositas geopolimer yang dihasilkan, (Fansuri Hamzah, 2008). Ion Na dalam larutan alkali juga berperan menjaga koordinasi tetrahedral monomer Al. Rasio ion logam alkali dengan Al haruslah satu. Nilai 1 pada rasio Na:Al memperlihatkan jumlah minimum kation Na yang dibutuhkan untuk menjaga keseimbangan muatan di dalam geopolimer.

2.2.8.4. Rasio Massa Air/Prekursor

Rasio air/prekursor pada beton geopolimer mirip dengan FAS (faktor air semen) pada beton konvensional yang menggunakan portland semen. Semakin besar rasio air/prekursor pada geopolimer kuat tekan relatif akan semakin kecil. Pada beton geopolimer rasio air/prekursor optimum akan menghasilkan kuat tekan paling tinggi.

BAB 3

STUDI LITERATUR

3.1. Komposisi *Alkaline Activator* dan *Fly Ash* Untuk Beton Geopolimer Mutu Tinggi

Penelitian ini dilakukan oleh Andi Sanjaya dan Calvin dan Yuwono dari Universitas Kristen Petra pada tahun 2006. Penelitian ini bertujuan untuk mendapatkan komposisi *alkaline activator* dan *fly ash* yang optimal untuk menghasilkan beton geopolimer mutu tinggi.

3.1.1. Material Geopolimer

3.1.1.1. Agregat Kasar

Agregat kasar yang digunakan adalah batu pecah berukuran 1 – 2 cm yang diperoleh dari PT Jaya Ready Mix.

3.1.1.2. Agregat Halus

Agregat halus yang diperoleh dari PT Jaya Ready Mix berasal dari kota Lumajang dengan karakteristik fisik tekstur yang bulat dan berwarna hitam keabu-abuan dengan kandungan kadar organik yang rendah. Agregat halus yang digunakan dalam mix design adalah pasir yang telah lolos ayakan \varnothing 2,36 mm.

3.1.1.3 Prekursor

Prekursor yang digunakan dalam penelitian ini adalah *fly ash* yang berasal dari PLTU paiton. Kandungan kimia dari *fly ash* dapat dilihat pada tabel 3.1.

Tabel 3.1. Kandungan Kimia *Fly Ash* PLTU Paiton

| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | LOI |
|----------|------------------|--------------------------------|--------------------------------|-------|-----|-----|
| %Mass | 45,8 | 14,05 | 3,4 | 24,15 | 5,6 | - |

Berdasarkan kandungan kimia yang terlihat pada table 3.1 dapat disimpulkan bahwa *fly ash* yang digunakan pada penelitian ini adalah *fly ash* tipe C.

3.1.1.4. *Alkaline Activator*

Alkaline activator yang digunakan dalam penelitian ini adalah kombinasi dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃).

3.1.1.5. *Superplasticizer (Sikament-NN dan Plastiment-VZ)*

Pada penelitian ini digunakan campuran dari *Sikament-NN* yang berfungsi sebagai *water reducer* dalam menghasilkan beton yang mudah mengalir dan *Plastiment-VZ* yang merupakan campuran antara *water reducer* dan *retarder* sehingga dapat meningkatkan *workability* dan memperlambat waktu pengikatan.

3.1.2. Proses Pencampuran dan Curing

Proses pencampuran beton geopolimer dilakukan perhitungan *mix design*. Langkah langkah pencampuran beton geopolimer antara lain sebagai berikut :

- Mempersiapkan bahan bahan yang dibutuhkan sesuai dengan perhitungan *mix design*.
- Membuat larutan *alkaline activator* dengan mencampur NaOH, Na₂SiO₃ dan air sesuai dengan komposisi *mix design*.
- Agregat halus, agregat kasar, dan prekursor dimasukkan kedalam ember dan diaduk selama ± 3 menit.
- Setelah agregat halus, agregat kasar dan prekursor tercampur rata *alkaline activator* dicampurkan kedalam ember dan diaduk sampai tercampur rata seperti pada gambar 3.1



Gambar 3.1 Pencampuran Agregat, Prekursor, dan *Alkaline Activator*

- Setelah selesai dicampur, beton segar dimasukkan ke dalam bekisting silinder 10 x 20 cm³. Masing masing sample beton dilakukan penumbukan sebanyak 25 kali setiap pengisian 1/3 bekisting.
- Kemudian bekisting dilapisi dengan plastik agar air yang terkandung dalam beton tidak menguap. Bekisting dibiarkan dalam suhu ruang selama 30 menit. Kemudian dimasukkan ke dalam oven dengan suhu curing 90⁰C selama 24 jam.



Gambar 3.2 Proses Curing Sample Beton Geopolimer.

- Setelah 24 jam bekisting dikeluarkan dari dalam oven dan dibiarkan dalam suhu ruang selama 6 jam agar sample beton tidak mengalami perubahan suhu secara drastis. Selanjutnya bekisting dapat dibongkar dan sample beton dapat dikeluarkan.

3.1.3. Proporsi Campuran

Untuk mendapatkan komposisi mix design yang optimal untuk beton geopolimer, terlebih dahulu dilakukan trial mix terhadap mortar dengan menggunakan sample silinder berukuran $5 \times 10 \text{ cm}^3$. Penelitian ini dilakukan dalam 4 tahap dengan dengan 4 variabel bebas, yaitu konsentrasi NaOH, rasio perbandingan *sodium silikat* dan *sodium hidroksida*, rasio alkali dan prekursor, dan rasio pasir dan *fly ash*.

3.1.3.1. Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 3 sample mortar berbentuk silinder berukuran $5 \times 10 \text{ cm}^3$ dengan konsentrasi NaOH masing masing adalah 8M, 10M, dan 12M. Masing masing sample memiliki rasio alkali/prekursor = 0.5, rasio pasir/*fly ash* = 2. Mix design pada penelitian pertama ditunjukkan oleh tabel 3.2.

Tabel 3.2. Mix Design Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No | Prekursor | NaOH | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|----|------------------|------|---------------|-----------------------|-------------|--------------------|-------------|
| 1 | <i>Fly Ash C</i> | 8 M | 0.5 | 2 | 90°C | 24 + 6 | 7 |
| 2 | <i>Fly Ash C</i> | 10 M | 0.5 | 2 | 90°C | 24 + 6 | 7 |
| 3 | <i>Fly Ash C</i> | 12 M | 0.5 | 2 | 90°C | 24 + 6 | 7 |

3.1.3.2. Penelitian Pengaruh Rasio Massa NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 9 sample mortar berbentuk silinder berukuran $5 \times 10 \text{ cm}^3$ dengan 9 rasio NaOH:Na₂SiO₃ yang berbeda. Masing masing sample memiliki rasio air/prekursor = 0.5, dan rasio pasir/*fly ash* = 2. Mix design pada penelitian kedua ditunjukkan oleh tabel 3.3

Tabel 3.3. Mix Design Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|-----|------------------|------|---|---------------|-----------------------|-------------------|--------------------|-------------|
| 1 | <i>Fly Ash C</i> | 8 M | 3:1 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | <i>Fly Ash C</i> | 8 M | 2.5:1 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 3 | <i>Fly Ash C</i> | 8 M | 2:1 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 4 | <i>Fly Ash C</i> | 8 M | 1:1 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 5 | <i>Fly Ash C</i> | 8 M | 1:2 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 6 | <i>Fly Ash C</i> | 8 M | 1:2.25 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 7 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 8 | <i>Fly Ash C</i> | 8 M | 1:2.75 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 9 | <i>Fly Ash C</i> | 8 M | 1:3 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |

3.1.3.3. Penelitian Pengaruh Rasio Massa Air/Prekursor Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 6 sample mortar berbentuk silinder berukuran 5 x 10 cm³ dengan 6 rasio air/prekursor yang berbeda. Masing masing sample memiliki rasio pasir/*fly ash* = 2. Mix design pada penelitian ketiga ditunjukkan oleh tabel 3.4.

Tabel 3.4. Mix Design Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|-----|------------------|------|---|---------------|-----------------------|-------------------|--------------------|-------------|
| 1 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.4 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 3 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.35 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 4 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 5 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.25 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 6 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.2 | 2 | 90 ⁰ C | 24 + 6 | 7 |

3.1.3.4. Penelitian Pengaruh Rasio Pasir:*Fly Ash* Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 3 sample mortar berbentuk kubus berukuran silinder berukuran 5 x 10 cm³ dengan 3 rasio pasir/*fly ash* yang berbeda. Masing masing

sample memiliki rasio massa air/prekursor = 0,5. Mix design pada penelitian keempat ditunjukkan oleh tabel 3.5.

Tabel 3.5. Mix Design Penelitian Pengaruh Rasio Pasir/*Fly Ash* Terhadap Kuat Tekan Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly</i> <i>Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|-----|------------------|------|--|---------------|---------------------------------|-------------------|--------------------------|----------------|
| 1 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 1 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 3 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 3 | 90 ⁰ C | 24 + 6 | 7 |

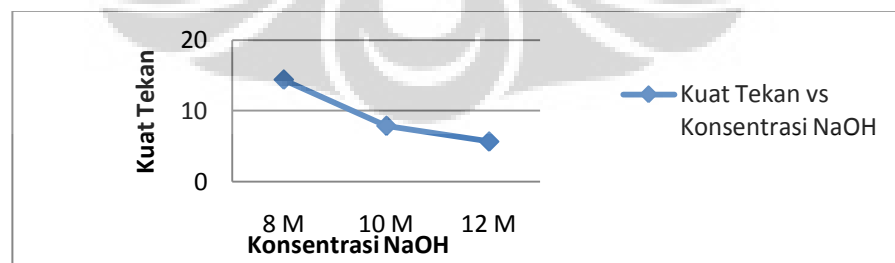
3.1.4. Hasil Penelitian

3.1.4.1. Hasil Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar

Hasil penelitian pertama ditunjukkan oleh tabel 3.6.

Tabel 3.6. Hasil Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No | Prekursor | NaOH | Air/Prekursor | Pasir / <i>Fly</i> <i>Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|----|------------------|-------------|---------------|----------------------------------|-------------------|--------------------------|----------------|------------------------|
| 1 | <i>Fly Ash C</i> | 8 M | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 | 14.42 |
| 2 | <i>Fly Ash C</i> | 10 M | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 | 7.87 |
| 3 | <i>Fly Ash C</i> | 12 M | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 | 5.64 |



Grafik 3.1. Hasil Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

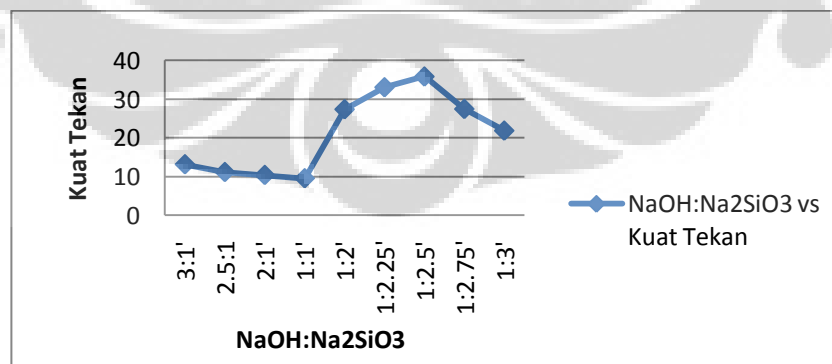
Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan konsentrasi NaOH 8M

3.1.4.2. Hasil Penelitian Pengaruh Rasio Massa NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar

Penelitian kedua dilakukan untuk menentukan rasio massa NaOH:Na₂SiO₃ dengan menggunakan konsentrasi NaOH sebesar 8M seperti yang telah didapat dari percobaan pertama. Hasil penelitian kedua ditunjukkan oleh tabel 3.7.

Tabel 3.7. Hasil Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|-----|------------------|------|---|---------------|-----------------------|-------------------|--------------------|-------------|------------------|
| 1 | <i>Fly Ash C</i> | 8 M | 3:1 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 13.13 |
| 2 | <i>Fly Ash C</i> | 8 M | 2.5:1 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 11.12 |
| 3 | <i>Fly Ash C</i> | 8 M | 2:1 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 10.36 |
| 4 | <i>Fly Ash C</i> | 8 M | 1:1 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 9.5 |
| 5 | <i>Fly Ash C</i> | 8 M | 1:2 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 27.38 |
| 6 | <i>Fly Ash C</i> | 8 M | 1:2.25 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 33.09 |
| 7 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 35.87 |
| 8 | <i>Fly Ash C</i> | 8 M | 1:2.75 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 27.46 |
| 9 | <i>Fly Ash C</i> | 8 M | 1:3 | 0.5 | 2 | 90 ^o C | 24 + 6 | 7 | 21.85 |



Grafik 3.2. Hasil Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

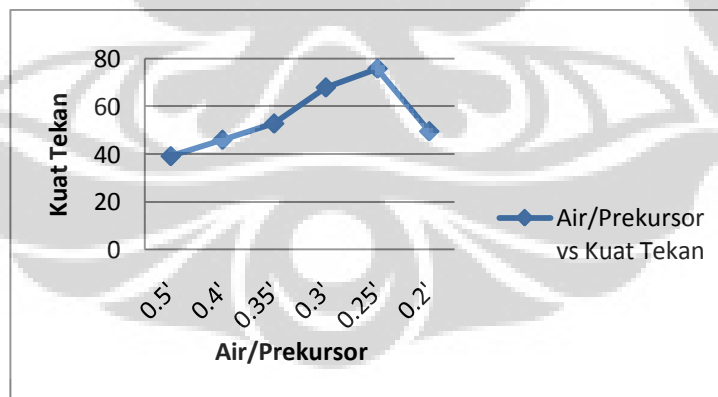
Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan rasio $\text{NaOH}:\text{Na}_2\text{SiO}_3 = 1:2,5$.

3.1.4.3. Hasil Penelitian Pengaruh Rasio Massa Air/Prekursor Terhadap Kuat Tekan Mortar

Penelitian ketiga dilakukan untuk menentukan rasio massa air/prekursor dengan menggunakan konsentrasi NaOH sebesar 8M dan rasio $\text{NaOH}:\text{Na}_2\text{SiO}_3 = 1:2,5$. Hasil penelitian kedua ditunjukkan oleh tabel 3.8.

Tabel 3.8. Hasil Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na_2SiO_3 | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (Jam) | Umur Mortar | Kuat Tekan (MPa) |
|-----|------------------|------|-------------------------------------|---------------|--------------------------|-------------------|--------------------------|----------------|------------------------|
| 1 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 | 39.25 |
| 2 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.4 | 2 | 90 ⁰ C | 24 + 6 | 7 | 46.05 |
| 3 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.35 | 2 | 90 ⁰ C | 24 + 6 | 7 | 52.85 |
| 4 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 67.9 |
| 5 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.25 | 2 | 90 ⁰ C | 24 + 6 | 7 | 75.77 |
| 6 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.2 | 2 | 90 ⁰ C | 24 + 6 | 7 | 49.6 |



Grafik 3.3. Hasil Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

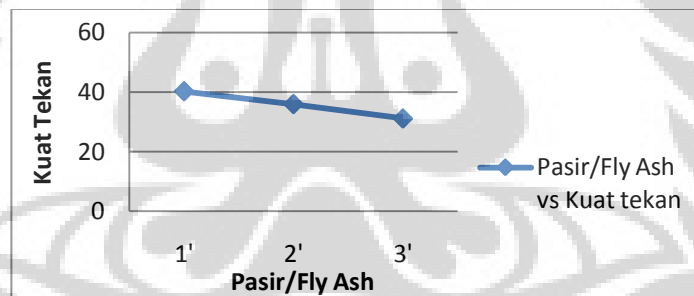
Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan rasio air/prekursor = 0,25.

3.1.4.4. Hasil Penelitian Pengaruh Rasio Pasir:Fly Ash Terhadap Kuat Tekan Mortar

Penelitian keempat dilakukan untuk menentukan rasio pasir/fly ash dengan menggunakan konsentrasi NaOH sebesar 8M dan rasio NaOH:Na₂SiO₃ = 1:2,5. Hasil penelitian kedua ditunjukkan oleh tabel 3.9.

Tabel 3.9. Hasil Penelitian Pengaruh Rasio Pasir /Fly Ash Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor Fly Ash PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir /Fly Ash | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|-----|-----------|------|---|---------------|----------------|-------------------|--------------------|-------------|------------------|
| 1 | Fly Ash C | 8 M | 1:2.5 | 0.5 | 1 | 90 ⁰ C | 24 + 6 | 7 | 40.2 |
| 2 | Fly Ash C | 8 M | 1:2.5 | 0.5 | 2 | 90 ⁰ C | 24 + 6 | 7 | 35.91 |
| 3 | Fly Ash C | 8 M | 1:2.5 | 0.5 | 3 | 90 ⁰ C | 24 + 6 | 7 | 31.09 |



Grafik 3.4. Hasil Penelitian Pengaruh Rasio Pasir : Fly Ash Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor Fly Ash PLTU Paiton

Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan rasio pasir/ fly ash = 1.

Dari hasil keempat penelitian terhadap mortar yang telah dilakukan, komposisi *alkaline activator* dan *fly ash* yang optimal untuk diaplikasikan pada beton geopolimer ditunjukkan pada tabel 3.10.

Tabel 3.10. Komposisi *Alkaline Activator* dan *Fly Ash* Untuk Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekur sor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Beton | Kuat Tekan (MPa) |
|-----|------------------|------|--|-------------------|--------------------------|-------------------|--------------------------|---------------|------------------------|
| 1 | <i>Fly Ash</i> C | 8 M | 1:2.5 | 0.25 | 1 | 90 ^o C | 24 + 6 | 7 | 51.78 |

3.2. Komposisi dan Karakteristik Beton Geopolimer dari *Fly Ash* tipe C dan F

Penelitian ini dilakukan oleh Johanes Prasetio Utomo dan Sandi Kosnatha dari Universitas Kristen Petra pada tahun 2007. Penelitian ini bertujuan untuk membandingkan beton geopolimer yang dibuat dengan dua jenis *Fly Ash* yang berbeda, yaitu tipe C dan tipe F.

3.2.1. Material Geopolimer

3.2.1.1. Agregat Kasar

Agregat kasar yang digunakan adalah batu pecah berukuran 1 – 2 cm.

3.2.1.2. Agregat Halus

Agregat halus yang digunakan pada penelitian ini adalah pasir. Namun, spesifikasi dari pasir yang digunakan tidak disebutkan.

3.2.1.3 Prekursor

Prekursor yang digunakan dalam penelitian ini adalah :

1. *Fly ash* tipe C yang berasal dari PLTU paiton yang diperoleh dari PT Jaya Ready Mix.
2. *Fly ash* tipe F yang berasal dari PLTU Suralaya yang diperoleh dari PT Indocement.

Kandungan kimia dari *fly ash* dapat dilihat pada table 3.11.

Tabel 3.11. Kandungan Kimia *Fly Ash* Tipe C PLTU Paiton dan Tipe F PLTU Suralaya

| Oksida | <i>Fly Ash</i> Tipe C (%) | <i>Fly Ash</i> Tipe F (%) |
|--------------------------------|---------------------------|---------------------------|
| SiO ₂ | 46.39 | 54 |
| Al ₂ O ₃ | 20.08 | 29.12 |
| Fe ₂ O ₃ | 13.32 | 9.81 |
| CaO | 13.07 | 1.33 |
| SO ₃ | 2.16 | 0.65 |
| MgO | 1.09 | 0.81 |
| Mn ₂ O ₃ | 0.15 | 0.04 |
| Cr ₂ O ₃ | 0.01 | --- |
| Na ₂ O | 0.17 | < 0.01 |
| K ₂ O | 0.77 | 0.96 |
| TiO ₂ | 1.64 | 1.35 |
| P ₂ O ₅ | 1.03 | 0.16 |

3.2.1.4. *Alkaline Activator*

Alkaline activator yang digunakan dalam penelitian ini adalah kombinasi dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃) dengan kemurnian 80%.

3.2.2. Proses Pencampuran dan Curing

Proses pencampuran beton geopolimer dilakukan perhitungan mix design. Langkah langkah pencampuran beton geopolimer antara lain sebagai berikut :

- Mempersiapkan bahan bahan yang dibutuhkan sesuai dengan perhitungan mix design.
- Membuat larutan *alkaline activator* dengan mencampur NaOH, Na₂SiO₃ dan air sesuai dengan komposisi mix design.
- Agregat halus, agregat kasar, dan prekursor dimasukkan kedalam ember dan diaduk hingga rata.
- Setelah agregat halus, agregat kasar dan prekursor tercampur rata, *alkaline activator* dicampurkan kedalam ember dan diaduk sampai tercampur rata seperti pada gambar 3.3



Gambar 3.3 Pencampuran Agregat, *Precursor*, dan *Alkaline activator*

- Setelah selesai dicampur, beton segar dimasukkan ke dalam bekisting silinder 10 x 20 cm³. Masing masing sample beton dilakukan penggetaran dengan alat penggetar setiap pengisian 1/3 bekisting.
- Kemudian bekisting dilapisi dengan plastik agar air yang terkandung dalam beton tidak menguap. Bekisting dibiarkan dalam suhu ruang selama 30 menit. Kemudian dimasukkan ke dalam oven dengan suhu curing 90⁰C selama 24 jam.



Gambar 3.4 Proses Curing Sample Beton Geopolymer.

- Setelah 24 jam bekisting dikeluarkan dari dalam oven dan dibiarkan dalam suhu ruang selama 6 jam agar sample beton tidak mengalami perubahan suhu

secara drastis. Selanjutnya bekisting dapat dibongkar dan sample beton dapat dikeluarkan.

3.2.3. Proporsi Campuran

Untuk mendapatkan komposisi mix design yang optimal untuk beton geopolimer, terlebih dahulu dilakukan trial mix terhadap mortar dengan menggunakan sample silinder berukuran $5 \times 10 \text{ cm}^3$. Penelitian ini dilakukan dalam 4 tahap dengan dengan 4 variabel bebas, yaitu konsentrasi NaOH, rasio perbandingan massa NaOH:Na₂SiO₃, rasio massa air/prekursor, dan rasio massa pasir/ *fly ash*.

3.2.3.1. Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 10 sample mortar berbentuk silinder berukuran $5 \times 10 \text{ cm}^3$. 5 sample menggunakan *fly ash* tipe C dan 5 sample lainnya menggunakan *fly ash* tipe F dengan konsentrasi NaOH untuk masing masing tipe *fly ash* adalah 6M, 7M, 8M, 10M, dan 12M. Masing masing sample memiliki rasio air/prekursor = 0.3, rasio pasir / *fly ash* = 2. Mix design pada penelitian pertama ditunjukkan oleh tabel 3.12.

Tabel 3.12. Mix Design Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | Air/Prekursor | Pasir / <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|----|------|---------------|------------------------|-------------|--------------------|-------------|
| 1 | 6 M | 0.3 | 2 | 90°C | 24 + 6 | 7 |
| 2 | 7 M | 0.3 | 2 | 90°C | 24 + 6 | 7 |
| 3 | 8 M | 0.3 | 2 | 90°C | 24 + 6 | 7 |
| 4 | 10 M | 0.3 | 2 | 90°C | 24 + 6 | 7 |
| 5 | 12 M | 0.3 | 2 | 90°C | 24 + 6 | 7 |

3.2.3.2. Penelitian Pengaruh Rasio Massa NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 10 sample mortar berbentuk silinder berukuran $5 \times 10 \text{ cm}^3$. 5 sample menggunakan *fly ash* tipe C dan 5 sample lainnya menggunakan *fly*

ash tipe F. 5 rasio massa NaOH:Na₂SiO₃ yang berbeda diaplikasikan pada sample mortar yang menggunakan *fly ash* tipe C dan F. Masing masing sample memiliki rasio air/prekursor = 0.3, dengan konsentrasi NaOH 8M dan rasio pasir:*fly ash* = 2:1. Mix design pada penelitian kedua ditunjukkan oleh tabel 3.13.

Tabel 3.13. Mix Design Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|----|------|--|---------------|-----------------------|-------------------|--------------------|-------------|
| 1 | 8 M | 1:1 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 3 | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 4 | 8 M | 1:3 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 5 | 8 M | 1:3.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |

3.2.3.3. Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Mortar

Pada penelitian ini digunakan 6 sample mortar berbentuk silinder berukuran 5 x 10 cm³. 3 sample menggunakan *fly ash* tipe C dan 3 sample lainnya menggunakan *fly ash* tipe F dengan rasio Air/Prekursor untuk masing masing tipe *fly ash* adalah 0.25, 0.3, dan 0.35. Masing masing sample memiliki rasio massa NaOH:Na₂SiO₃ = 1 : 2, rasio pasir/ *fly ash* = 2. Mix design pada penelitian ketiga ditunjukkan oleh tabel 3.14.

Tabel 3.14. Mix Design Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar |
|----|------|--|---------------|-----------------------|-------------------|--------------------|-------------|
| 1 | 8 M | 1:2 | 0.25 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 3 | 8 M | 1:2 | 0.35 | 2 | 90 ⁰ C | 24 + 6 | 7 |

3.2.3.4. Penelitian Pengaruh Umur dan Metode Curing Pada Mortar

Pada penelitian ini digunakan 12 sample mortar berbentuk silinder berukuran 5 x 10 cm³. 6 sample menggunakan *fly ash* tipe C dan 6 sample lainnya menggunakan *fly ash* tipe F. Metode curing untuk 3 sample menggunakan oven dengan suhu 90⁰C dan curing untuk 3 sample lainnya dilakukan pada suhu ruang tanpa menggunakan oven dengan umur mortar untuk masing masing tipe *fly ash* adalah 7, 14, dan 28 hari. Masing masing sample memiliki rasio massa NaOH:Na₂SiO₃ = 1 : 2, dengan molaritas NaOH sebesar 8M, rasio pasir/ *fly ash* = 2. Mix design pada penelitian keempat ditunjukkan oleh tabel 3.15.

Tabel 3.15. Mix Design Penelitian Pengaruh Umur Mortar dan Suhu Curing Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir : <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) |
|----|------|---|---------------|------------------------|-------------------|--------------------|--------------------|
| 1 | 8 M | 1:2 | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | 8 M | 1:2 | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 14 |
| 3 | 8 M | 1:2 | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 28 |
| 4 | 8 M | 1:2 | 0.3 | 2:1 | Non Oven | - | 7 |
| 5 | 8 M | 1:2 | 0.3 | 2:1 | Non Oven | - | 14 |
| 6 | 8 M | 1:2 | 0.3 | 2:1 | Non Oven | - | 28 |

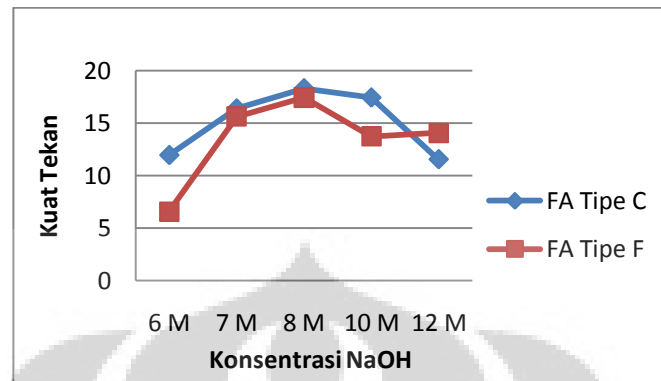
3.2.4. Hasil Penelitian

3.2.4.1. Hasil Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar

Hasil penelitian pertama ditunjukkan oleh tabel 3.16.

Tabel 3.16. Hasil Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | Air/Prekursor | Pasir : <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) | Kuat Tekan (MPa) | |
|----|------|---------------|------------------------|-------------------|--------------------|--------------------|------------------|-----------|
| | | | | | | | FA tipe C | FA tipe F |
| 1 | 6 M | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 7 | 11.94 | 6.56 |
| 2 | 7 M | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 7 | 16.38 | 15.64 |
| 3 | 8 M | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 7 | 18.31 | 17.45 |
| 4 | 10 M | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 7 | 17.43 | 13.75 |
| 5 | 12 M | 0.3 | 2:1 | 90 ⁰ C | 24 + 6 | 7 | 11.54 | 14.08 |



Grafik 3.5. Hasil Penelitian Pengaruh Konsentrasi NaOH Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

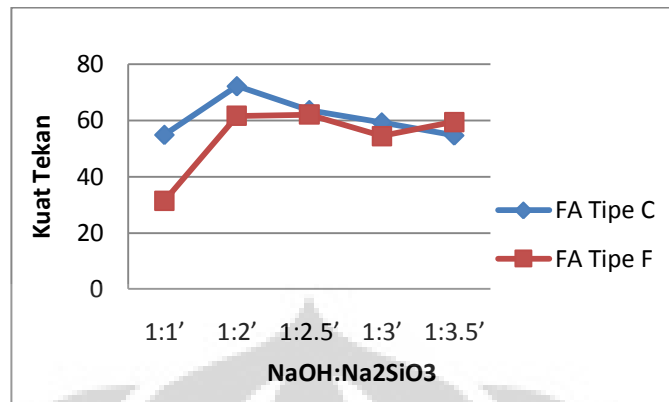
Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan konsentrasi NaOH 8M.

3.2.4.2. Hasil Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar

Penelitian kedua dilakukan untuk menentukan rasio NaOH:Na₂SiO₃ dengan menggunakan konsentrasi NaOH sebesar 8M seperti yang telah didapat dari percobaan pertama. Hasil penelitian kedua ditunjukkan oleh tabel 3.17.

Tabel 3.17. Hasil Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir / <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) | Kuat Tekan (MPa) | |
|----|------|--|---------------|------------------------|-------------------|--------------------|--------------------|------------------|-----------|
| | | | | | | | | FA tipe C | FA tipe F |
| 1 | 8 M | 1:1 | 0.3 | 2 | 90 ^o C | 24 + 6 | 7 | 54.87 | 31.42 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90 ^o C | 24 + 6 | 7 | 72.23 | 61.69 |
| 3 | 8 M | 1:2.5 | 0.3 | 2 | 90 ^o C | 24 + 6 | 7 | 63.71 | 62.11 |
| 4 | 8 M | 1:3 | 0.3 | 2 | 90 ^o C | 24 + 6 | 7 | 59.3 | 54.44 |
| 5 | 8 M | 1:3.5 | 0.3 | 2 | 90 ^o C | 24 + 6 | 7 | 54.66 | 59.44 |



Grafik 3.6. Hasil Penelitian Pengaruh Rasio NaOH:Na₂SiO₃ Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

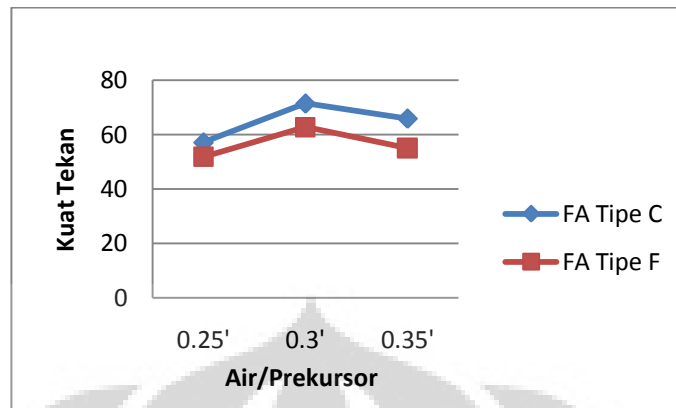
Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan rasio massa NaOH:Na₂SiO₃ = 1 : 2.

3.2.4.3. Hasil Penelitian Pengaruh Rasio Massa Air/Prekursor Terhadap Kuat Tekan Mortar

Penelitian ketiga dilakukan untuk menentukan rasio air/prekursor dengan menggunakan konsentrasi NaOH sebesar 8M dan rasio massa NaOH:Na₂SiO₃ = 1:2. Hasil penelitian kedua ditunjukkan oleh tabel 3.18.

Tabel 3.18. Hasil Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) | Kuat Tekan (MPa) | |
|----|------|---|---------------|-----------------------|-------------------|--------------------|--------------------|------------------|-----------|
| | | | | | | | | FA tipe C | FA tipe F |
| 1 | 8 M | 1:2 | 0.25 | 2 | 90 ⁰ C | 24 + 6 | 7 | 57.22 | 51.91 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 71.59 | 62.88 |
| 3 | 8 M | 1:2 | 0.35 | 2 | 90 ⁰ C | 24 + 6 | 7 | 66.04 | 55.11 |



Grafik 3.7. Hasil Penelitian Pengaruh Rasio Air/Prekursor Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

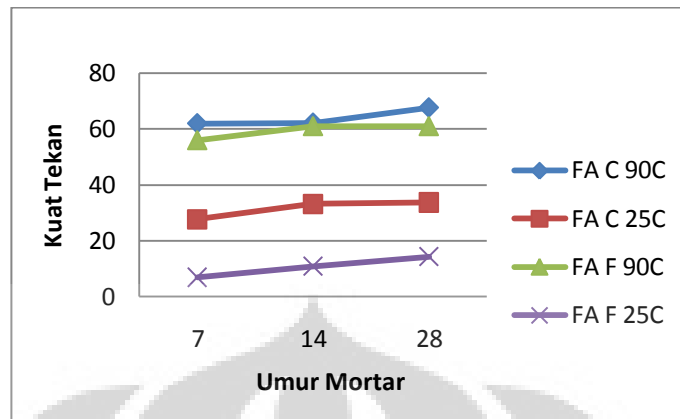
Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar dengan rasio air/prekursor = 0,3.

3.2.4.4. Hasil Penelitian Pengaruh Suhu Curing Terhadap Kuat Tekan Mortar

Penelitian keempat dilakukan untuk menentukan umur mortar dan metode curing menggunakan konsentrasi NaOH sebesar 8M dan rasio massa NaOH:Na₂SiO₃ = 1:2. Hasil penelitian kedua ditunjukkan oleh tabel 3.19.

Tabel 3.19. Hasil Penelitian Pengaruh Umur Mortar dan Metode Curing Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) | Kuat Tekan (MPa) | |
|----|------|---|---------------|-----------------------|-------------|--------------------|--------------------|------------------|-----------|
| | | | | | | | | FA tipe C | FA tipe F |
| 1 | 8 M | 1:2 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 61.96 | 55.97 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90°C | 24 + 6 | 14 | 62.17 | 61.01 |
| 3 | 8 M | 1:2 | 0.3 | 2 | 90°C | 24 + 6 | 28 | 67.6 | 61 |
| 4 | 8 M | 1:2 | 0.3 | 2 | 25°C | 24 + 6 | 7 | 27.69 | 6.99 |
| 5 | 8 M | 1:2 | 0.3 | 2 | 25°C | 24 + 6 | 14 | 33.21 | 10.9 |
| 6 | 8 M | 1:2 | 0.3 | 2 | 25°C | 24 + 6 | 28 | 33.74 | 14.35 |



Grafik 3.8. Hasil Penelitian Pengaruh Umur Mortar dan Metode Curing Terhadap Kuat Tekan Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

Dari hasil penelitian pertama diketahui bahwa sample mortar menghasilkan kuat tekan paling besar pada saat mortar berusia 28 hari dengan metode curing menggunakan oven dengan suhu 90°C .

Dari hasil keempat penelitian terhadap mortar yang telah dilakukan, komposisi *alkaline activator* dan *fly ash* yang optimal untuk diaplikasikan pada beton geopolimer ditunjukkan pada tabel 3.20.

Tabel 3.20. Komposisi *Alkaline Activator* dan *Fly Ash* Untuk Beton Geopolimer Mortar Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir /Fly Ash | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) |
|----|------|--|---------------|----------------------|-------------------|--------------------------|--------------------------|
| 1 | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 |
| 2 | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 14 |
| 3 | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 28 |
| 4 | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 56 |

3.3. Recent Research of Geopolymer Concrete

Penelitian ini dilakukan oleh Nguyen Van Chanh¹ - Assoc. Professor. PhD., Bui Dang Trung, Dang Van Tuan - Candidate M.E. dari University of Technology HCM City, Vietnam pada tahun 2008.

3.3.1. Material Geopolimer

3.3.1.1 Prekursor

Prekursor yang digunakan pada penelitian ini adalah *fly ash* dengan kandungan kimia dari *fly ash* berdasarkan hasil uji XRF ditunjukkan oleh tabel 3.21

Tabel 3.21. Kandungan Kimia *Fly Ash* dari PLTU di Vietnam

| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | K ₂ O | Na ₂ O | MgO | SO ₃ | LOI |
|----------|------------------|--------------------------------|--------------------------------|-----|------------------|-------------------|------|-----------------|------|
| %Mass | 52 | 33,9 | 4 | 1,2 | 0,83 | 0,27 | 0,81 | 0,28 | 6,23 |

Berdasarkan uji XRF, *fly ash* yang digunakan digolongkan sebagai *fly ash* tipe F

3.3.1.2 Alkaline Activator

Alkaline activator yang digunakan dalam penelitian ini adalah campuran dari *sodium silikat* (Na₂SiO₃) dan *sodium hidroksida* (NaOH).

3.3.2. Proporsi Campuran dan Curing

Pada penelitian ini terdapat 5 proporsi campuran yang berbeda seperti yang ditunjukkan pada tabel 3.22.

Tabel 3.22. Proporsi Campuran Beton *Fly Ash* dari PLTU di Vietnam

| Code Mix | FA | SA | AL | W | SP | AL/FA | W/AL |
|----------|------|------|-----------|----|------|-------|------|
| | (kg) | | | | | | |
| Cp1 | 527 | 1586 | 157 (18M) | 40 | 5.27 | 0.3 | 0.25 |
| Cp2 | 527 | 1586 | 182 (18M) | 46 | 5.27 | 0.35 | 0.25 |
| Cp3 | 527 | 1586 | 211 (18M) | 52 | | 0.4 | 0.25 |
| Cp4 | 527 | 1586 | 237 (18M) | 59 | | 0.45 | 0.25 |
| Cp5 | 527 | 1586 | 192 (14M) | 48 | | | |

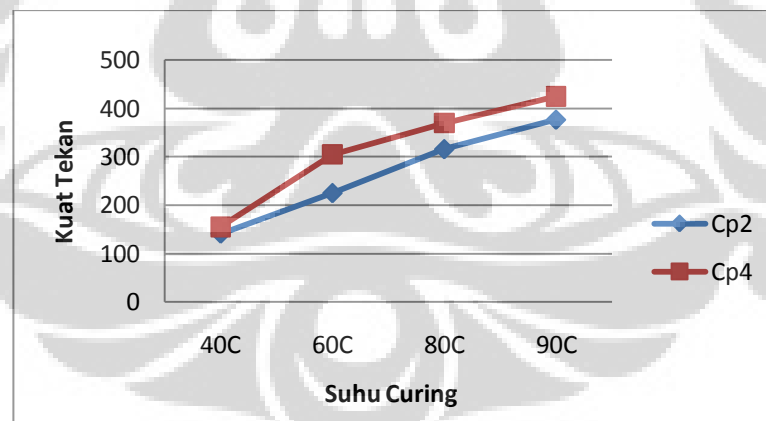
Masing masing sample memiliki kandungan *fly ash* 527 kg/m³. Sample di curing dengan suhu curing 40°C, 60°C, 80°C dan 90°C selama 24 - 72 jam.

3.3.3. Hasil Penelitian

Setelah sample silinder beton berusia 7 hari dilakukan pengujian kuat tekan beton. Hasil pengujian kuat tekan beton komposisi 2 dan 4 ditunjukkan pada tabel 3.23

Tabel 3.23. Hasil Pengujian Kuat Tekan Beton Geopolimer Komposisi 2 dan 4 Dengan Prekursor *Fly Ash* dari PLTU di Vietnam

| No | Prekursor | Air/Prekursor | Pasir : <i>Fly Ash</i> | Kerikil : <i>Fly Ash</i> | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (Mpa) |
|-----|------------------|---------------|------------------------|--------------------------|-------------|---------------------|-------------------|------------------|
| cp2 | <i>Fly Ash</i> F | 0.4 | 1.63 | 2.876 | 40°C | 2 | 7 | 141 |
| cp2 | <i>Fly Ash</i> F | 0.4 | 1.63 | 2.876 | 60°C | 2 | 7 | 225 |
| cp2 | <i>Fly Ash</i> F | 0.4 | 1.63 | 2.876 | 80°C | 2 | 7 | 316 |
| cp2 | <i>Fly Ash</i> F | 0.4 | 1.63 | 2.876 | 90°C | 2 | 7 | 377 |
| cp4 | <i>Fly Ash</i> F | 0.4 | 1.2 | 2.1 | 40°C | 2 | 7 | 155 |
| cp4 | <i>Fly Ash</i> F | 0.4 | 1.2 | 2.1 | 60°C | 2 | 7 | 305 |
| cp4 | <i>Fly Ash</i> F | 0.4 | 1.2 | 2.1 | 80°C | 2 | 7 | 370 |
| cp4 | <i>Fly Ash</i> F | 0.4 | 1.2 | 2.1 | 90°C | 2 | 7 | 425 |



Grafik 3.9. Hasil Pengujian Kuat Tekan Beton Geopolimer Komposisi 2 dan 4 Dengan Prekursor *Fly Ash* dari PLTU di Vietnam

Dari hasil pengujian kuat tekan paling besar didapatkan dengan suhu curing 90°C.

3.4. Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

Penelitian ini dilakukan oleh M Olivia, P Sarker, dan H Nikraz dari Curtin University of Technology, Australia pada tahun 2008

3.4.1. Material Geopolimer

3.4.1.1 Prekursor

Prekursor yang digunakan pada penelitian ini adalah *fly ash* PLTU Collie yang terdapat di sebelah tenggara Australia. Komposisi kimia dari *fly ash* tersebut ditunjukkan pada tabel 3.24.

Tabel 3.24. Komposisi Kimia *Fly Ash* PLTU Collie

| Element | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | K ₂ O | MgO | Na ₂ O | P ₂ O ₅ | SO ₃ | LOI |
|---------|------------------|--------------------------------|--------------------------------|------|------------------|------|-------------------|-------------------------------|-----------------|------|
| % Mass | 50.3 | 26.3 | 13.6 | 2.27 | 0.55 | 1.44 | 0.36 | 1.58 | 0.32 | 0.54 |

Berdasarkan komposisi kimianya, *fly ash* PLTU Collie digolongkan sebagai *fly ash* tipe F.

3.4.1.2 Alkaline Activator

Alkaline activator yang digunakan pada penelitian ini adalah gabungan dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃).

3.4.2. Proporsi Campuran dan Curing

Pada penelitian ini dibuat 9 komposisi beton yang terdiri dari 7 komposisi beton geopolimer dan 2 komposisi beton Portland semen. Untuk uji kuat tekan beton, masing masing komposisi akan diwakili oleh 12 sample beton silinder dengan diameter 10 cm dan tinggi 20 cm untuk pengujian beton pada usia 7 hari dan 28 hari. Proporsi campuran beton ditunjukkan oleh tabel 3.25.

Tabel 3.25. Mix Design Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Collie

| Mixture no | Prekursor | NaOH | NaOH / Na ₂ SiO ₃ | Air/Prekursor | Pasir / Fly Ash | Superplasticizer (Kg/m ³) | Suhu Curing |
|------------|------------------|------|---|---------------|-----------------|---------------------------------------|-------------------|
| GP1 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.23 | 1,586 | 6,1 | 60 ⁰ C |
| GP2 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.22 | 1,586 | 6,1 | 60 ⁰ C |
| GP3 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.2 | 1,586 | 6,1 | 60 ⁰ C |
| GP4 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.25 | 1,586 | 6,1 | 60 ⁰ C |
| GP5 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.22 | 1,419 | 6,1 | 60 ⁰ C |
| GP6 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.24 | 1,888 | 6,1 | 60 ⁰ C |
| GP7 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.23 | 1,358 | 6,1 | 60 ⁰ C |

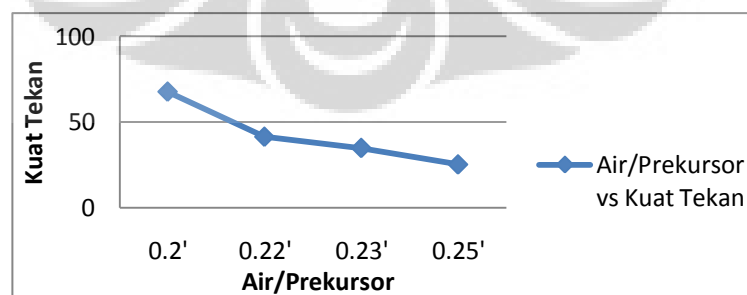
Masing masing sample beton di curing dengan suhu curing 60⁰C selama 24 jam. Pada penelitian ini digunakan larutan *sodium silikat* dengan konsentrasi 14 M dan penambahan *superplasticizer* 6.1 kg/m³. Rasio antara pasir/*fly ash* = 1,586 dan rasio massa NaOH:Na₂SiO₃ = 0,398

3.4.3. Hasil Penelitian

Setelah dicuring selama 24 jam dengan suhu 60⁰C, sample beton disimpan dalam suhu ruang hingga hari pengujian. Hasil pengujian kuat tekan beton pada umur 28 hari ditunjukkan oleh tabel 3.26.

Tabel 3.26. Hasil Pengujian Kuat Tekan Mix Design Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Collie

| Mixture no | Prekursor | NaOH | NaOH / Na ₂ SiO ₃ | Air/Prekursor | Pasir / Fly Ash | Superplasticizer (Kg/m ³) | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (Mpa) |
|------------|------------------|------|---|---------------|-----------------|---------------------------------------|-------------------|---------------------|-------------------|------------------|
| GP1 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.23 | 1,586 | 6,1 | 60 ⁰ C | 1 | 28 | 34.86 |
| GP2 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.22 | 1,586 | 6,1 | 60 ⁰ C | 1 | 28 | 41.36 |
| GP3 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.2 | 1,586 | 6,1 | 60 ⁰ C | 1 | 28 | 67.53 |
| GP4 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.25 | 1,586 | 6,1 | 60 ⁰ C | 1 | 28 | 25.28 |

Grafik 3.10. Hasil Pengujian Kuat Tekan Mix Design Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Collie

Dari hasil pengujian kuat tekan, diketahui bahwa kuat tekan beton geopolimer terbesar dihasilkan oleh mix design GP3. Hal ini dapat disebabkan mix design GP3 memiliki rasio air/prekursor yang paling kecil dibandingkan dengan mix design lainnya

3.5. Feasibility Study of Geopolymer

Penelitian ini dilakukan oleh Wine Figeys, Dionys van Gemert dan Jose Aguiar dari University of Minho, Azurem, Guimaraes, Portugal, pada September 2007. Tujuan dari penelitian ini adalah untuk mempelajari karakteristik mekanis beton geopolimer berbahan dasar metakaolin dan *fly ash*.

3.5.1. Material Geopolimer

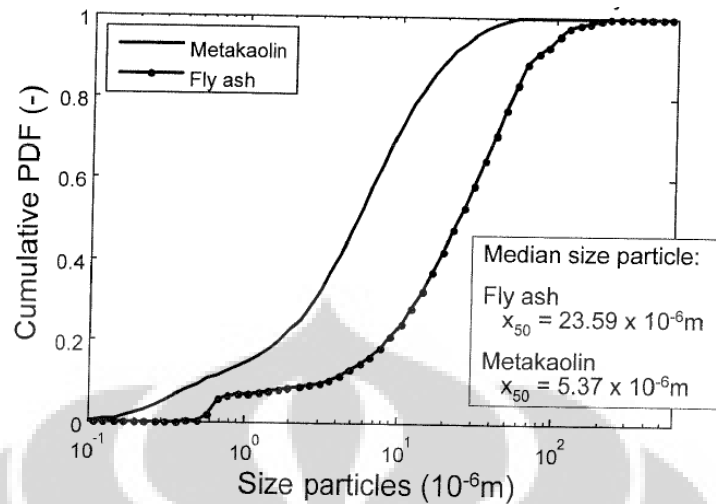
3.5.1.1 Prekursor

Prekursor yang digunakan pada penelitian ini adalah *fly ash* dan metakaolin. Komposisi kimia dari *fly ash* dan metakaolin ditunjukkan pada tabel 3.27.

Tabel 3.27. Komposisi Kimia *Fly Ash* dan Metakaolin

| Composition (%) | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | Na ₂ O | K ₂ O | MgO | SO ₃ |
|-----------------|------------------|--------------------------------|--------------------------------|-----|-------------------|------------------|-----|-----------------|
| Metakaolin | 53,3 | 37,5 | 1,7 | 0,8 | n.d | n.d | n.d | n.d |
| <i>Fly Ash</i> | 46 | 18,6 | 8,6 | 5,8 | 0,4 | 2,8 | 1,5 | 0,5 |

Berdasarkan kandungan kimia, *fly ash* yang digunakan termasuk dalam *fly ash* tipe F. Distribusi partikel dari metakaolin dan *fly ash* ditunjukkan pada gambar 3.5



Gambar 3.5. Distribusi Partikel *Fly Ash* dan Metakaolin

3.5.1.2 Alkaline Activator

Alkaline activator yang digunakan dalam penelitian ini adalah campuran antara *sodium hidroksida* (NaOH) dan *sodium silikat* (Na_2SiO_3).

3.5.2. Proporsi Campuran dan Curing

Pada penelitian ini dilakukan penelitian terhadap dua variabel. Pada penelitian pertama, variabel yang diteliti adalah pengaruh komposisi dari larutan alkali terhadap kuat tekan dari geopolimer, sedangkan pada penelitian kedua variabel yang diteliti adalah pengaruh jenis prekursor terhadap kuat tekan dari geopolimer. Pada masing-masing penelitian digunakan sampel beton silinder dengan diameter 10 cm dan tinggi 20 cm. Semua sampel beton pada penelitian ini dicuring dalam suhu ruang ($\pm 20^\circ\text{C}$).

3.5.2.1 Penelitian Pengaruh Komposisi Larutan Alkali Terhadap Kuat Tekan Beton Geopolimer.

Pada penelitian ini digunakan metakaolin sebagai prekursor, sedangkan larutan alkali yang digunakan adalah kombinasi dari *sodium silikat* (Na_2SiO_3) dan *sodium hidroksida* (NaOH) dengan konsentrasi 14 M. Pada penelitian ini digunakan 8

komposisi beton dengan rasio perbandingan massa NaOH:Na₂SiO₃ yang berbeda seperti yang ditunjukkan oleh tabel 3.28.

Tabel 3.28. Penelitian Pengaruh Komposisi larutan Alkali Terhadap Kuat Tekan Beton Geopolimer

| No. | Metakaolin (g) | NaOH 14M (g) | Na ₂ SiO ₃ (g) | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) |
|-----|----------------|--------------|--------------------------------------|---|---------------|-------------------|---------------------|-------------------|
| 1 | 750 | 0 | 1070 | 0:100 | 0,62 | 20 ⁰ C | 1 | 7 |
| 2 | 750 | 107 | 963 | 10:90 | 0,62 | 20 ⁰ C | 1 | 7 |
| 3 | 750 | 214 | 856 | 20:80 | 0,63 | 20 ⁰ C | 1 | 7 |
| 4 | 750 | 321 | 749 | 30:70 | 0,64 | 20 ⁰ C | 1 | 7 |
| 5 | 750 | 428 | 642 | 40:60 | 0,64 | 20 ⁰ C | 1 | 7 |
| 6 | 750 | 535 | 535 | 50:50 | 0,65 | 20 ⁰ C | 1 | 7 |
| 7 | 518 | 749 | 321 | 70:30 | 0,84 | 20 ⁰ C | 1 | 7 |
| 8 | 628 | 1070 | 0 | 100:0 | 0,77 | 20 ⁰ C | 1 | 7 |

3.5.2.2. Penelitian Pengaruh Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer.

Pada penelitian ini larutan alkali yang digunakan adalah kombinasi dari *sodium silikat* (Na₂SiO₃) dan *sodium hidroksida* (NaOH) dengan konsentrasi 14 M. Komposisi dari larutan alkali dibuat tetap, sedangkan prekursor yang digunakan adalah kombinasi dari metakaolin dan *fly ash*. Pada penelitian ini digunakan 5 komposisi beton dengan rasio perbandingan metakaolin: *fly ash* yang berbeda seperti yang ditunjukkan oleh tabel 3.29.

Tabel 3.29. Penelitian Pengaruh Komposisi Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer

| No | Metakaolin (g) | <i>Fly Ash</i> (g) | NaOH 14M (g) | Na ₂ SiO ₃ (g) | H ₂ O (g) | Alkali/ <i>Fly Ash</i> | Metakaolin : <i>Fly Ash</i> | Suhu Curing | Waktu Curing (Hari) | Umur Beton (Hari) |
|----|----------------|--------------------|--------------|--------------------------------------|----------------------|------------------------|-----------------------------|-------------------|---------------------|-------------------|
| 1 | 747 | 0 | 267 | 660 | 83,4 | 0,66 | 100:0 | 20 ⁰ C | 1 | 7 |
| 2 | 600 | 150 | 267 | 660 | 83,5 | 0,34 | 80:20 | 20 ⁰ C | 1 | 7 |
| 3 | 900 | 600 | 267 | 660 | 83,6 | 0,36 | 60:40 | 20 ⁰ C | 1 | 7 |
| 4 | 300 | 1200 | 267 | 660 | 83,7 | 0,38 | 20:80 | 20 ⁰ C | 1 | 7 |
| 5 | 0 | 1500 | 267 | 660 | 83,8 | 0,38 | 0:100 | 20 ⁰ C | 1 | 7 |

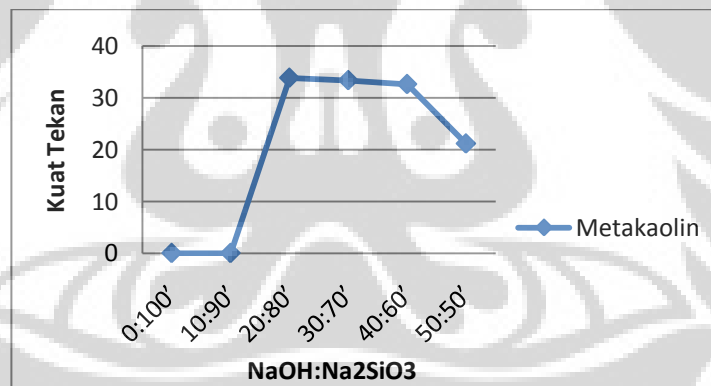
3.5.3. Hasil Penelitian

3.5.3.1 Hasil Penelitian Pengaruh Komposisi Larutan Alkali Terhadap Kuat Tekan Beton Geopolimer.

Hasil penelitian pengaruh komposisi larutan alkali ditunjukkan oleh tabel 3.30.

Tabel 3.30. Hasil Penelitian Pengaruh Komposisi larutan Alkali Terhadap Kuat Tekan Beton Geopolimer Dengan Prekursor Metakaolin

| No. | Prekursor | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (MPa) |
|-----|------------|--|---------------|-------------------|---------------------|-------------------|------------------|
| 1 | Metakaolin | 0:100 | 0,62 | 20 ⁰ C | 1 | 7 | - |
| 2 | Metakaolin | 10:90 | 0,62 | 20 ⁰ C | 1 | 7 | - |
| 3 | Metakaolin | 20:80 | 0,63 | 20 ⁰ C | 1 | 7 | 33,84 |
| 4 | Metakaolin | 30:70 | 0,64 | 20 ⁰ C | 1 | 7 | 33,37 |
| 5 | Metakaolin | 40:60 | 0,64 | 20 ⁰ C | 1 | 7 | 32,62 |
| 6 | Metakaolin | 50:50 | 0,65 | 20 ⁰ C | 1 | 7 | 21,14 |
| 7 | Metakaolin | 70:30 | 0,84 | 20 ⁰ C | 1 | 7 | 6,79 |
| 8 | Metakaolin | 100:0 | 0,77 | 20 ⁰ C | 1 | 7 | 2,58 |



Grafik 3.11. Hasil Penelitian Pengaruh Komposisi larutan Alkali Terhadap Kuat Tekan Beton Geopolimer

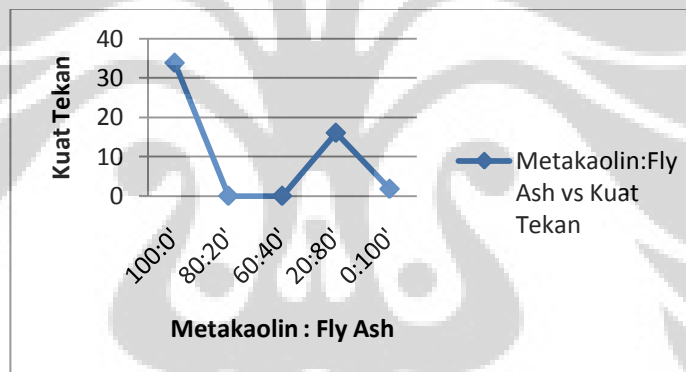
Dari hasil penelitian diketahui bahwa komposisi larutan alkali optimal yang dapat menghasilkan kuat tekan beton paling tinggi adalah larutan alkali dengan komposisi massa NaOH : Na₂SiO₃ = 20:80.

3.5.3.2. Hasil Penelitian Pengaruh Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer.

Hasil penelitian pengaruh komposisi jenis prekursor ditunjukkan oleh tabel 3.31.

Tabel 3.31. Hasil Penelitian Pengaruh Komposisi Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer Dengan Prekursor Metakaolin + *Fly Ash*

| No | Prekursor | Air/ <i>Fly Ash</i> | Metakaolin: <i>Fly Ash</i> | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (MPa) |
|----|-----------------------------|---------------------|----------------------------|-------------------|---------------------|-------------------|------------------|
| 1 | Metakaolin + <i>Fly Ash</i> | 0,66 | 100:0 | 20 ⁰ C | 1 | 7 | 33,84 |
| 2 | Metakaolin + <i>Fly Ash</i> | 0,34 | 80:20 | 20 ⁰ C | 1 | 7 | - |
| 3 | Metakaolin + <i>Fly Ash</i> | 0,36 | 60:40 | 20 ⁰ C | 1 | 7 | - |
| 4 | Metakaolin + <i>Fly Ash</i> | 0,38 | 20:80 | 20 ⁰ C | 1 | 7 | 16,04 |
| 5 | Metakaolin + <i>Fly Ash</i> | 0,38 | 0:100 | 20 ⁰ C | 1 | 7 | 1,77 |



Grafik 3.12. Hasil Penelitian Pengaruh Komposisi Jenis Prekursor Terhadap Kuat Tekan Beton Geopolimer Dengan Prekursor Metakaolin + *Fly Ash*

Dari hasil penelitian diketahui bahwa komposisi jenis prekursor optimal yang dapat menghasilkan kuat tekan beton paling tinggi adalah dengan menggunakan metakaolin 100%.

3.6. Studies On Fly Ash Based Geopolymer Concrete

Penelitian ini dilakukan oleh Hardjito Djuwanto dari Curtin University of Technology, Australia pada bulan November 2005. Penelitian ini membahas secara

rinci tentang pembuatan beton geopolimer. Karena keterbatasan literature dan referensi pada saat itu, penelitian ini melakukan metode trial eror untuk mengetahui parameter yang mempengaruhi sifat beton geopolimer.

3.6.1. Material Geopolimer

3.6.1.1. Agregat

Agregat yang digunakan dalam penelitian ini berasal dari industry beton lokal yang terdapat di Australia bagian barat. Agregat halus dan kasar terlebih dahulu dikondisikan sesuai dengan kondisi *saturated surface dry* (SSD) dengan standard Australia, AS 1141.5-2000 dan AS 1141.6-2000 (2000). Agregat kasar dalam kondisi crushed form dan mayoritas dari jenis granit, sedangkan agregat halus dalam kondisi uncrushed form dengan *Fineness Modulus* (FM). Pada penelitian ini digunakan 3 kombinasi agregat yang berbeda. Tiga kombinasi agregat dibuat sesuai dengan persyaratan gradasi menurut British Standard BS 882:92 (Neville 2000). *Fineness Modulus* dari kombinasi agregat tipe I sebesar 5.01, sedangkan *Fineness Modulus* dari kombinasi agregat tipe II dan III adalah 4.5 dan 4.6.

Tabel 3.32 Gradasi Agregat Tipe 1

| Sieve Size | Aggregates | | | | Combination *) | BS 882:92 |
|------------|------------|-------|--------|--------|----------------|-----------|
| | 20 mm | 14 mm | 7 mm | Fine | | |
| 19.00 mm | 93.34 | 99.99 | 100.00 | 100.00 | 99.00 | 95-100 |
| 9.50 mm | 3.89 | 17.40 | 99.90 | 100.00 | 69.03 | |
| 4.75 mm | 0.90 | 2.99 | 20.10 | 100.00 | 37.77 | 35-55 |
| 2.36 mm | 0.88 | 1.07 | 3.66 | 100.00 | 31.63 | |
| 1.18 mm | 0.87 | 0.81 | 2.05 | 99.99 | 31.01 | |
| 600 µm | 0.85 | 0.70 | 1.52 | 79.58 | 24.67 | 10-35 |
| 300 µm | 0.75 | 0.59 | 1.08 | 16.53 | 5.57 | |
| 150 µm | 0.54 | 0.42 | 0.62 | 1.11 | 0.72 | 0-8 |

*) 15% (20 mm) + 20% (14 mm) + 35% (7 mm) + 30% (Fine)

Tabel 3.33. Gradasi Agregat Tipe 2.

| Sieve Size | Aggregates | | | Combination *) | BS 882:92 |
|------------|------------|--------|--------|----------------|-----------|
| | 10 mm | 7 mm | Fine | | |
| 19.00 mm | 100.00 | 100.00 | 100.00 | 100.00 | 95-100 |
| 9.50 mm | 74.86 | 99.99 | 100.00 | 92.42 | |
| 4.75 mm | 9.32 | 20.10 | 100.00 | 44.83 | 35-55 |
| 2.36 mm | 3.68 | 3.66 | 100.00 | 37.39 | |
| 1.18 mm | 2.08 | 2.05 | 100.00 | 36.34 | |
| 600 µm | 1.47 | 1.52 | 79.60 | 28.83 | 10-35 |
| 300 µm | 1.01 | 1.08 | 16.50 | 6.47 | |
| 150 µm | 0.55 | 0.62 | 1.11 | 0.77 | 0-8 |

*) 30% (10 mm) + 35% (7 mm) + 35% (Fine)

Tabel 3.34. Gradasi Agregat Tipe 3.

| Sieve Size | Aggregates | | Combination *) | BS 882:92 |
|------------|------------|--------|----------------|-----------|
| | 7 mm | Fine | | |
| 19.00 mm | 100.00 | 100.00 | 100.00 | 95-100 |
| 9.50 mm | 99.99 | 100.00 | 99.93 | |
| 4.75 mm | 20.10 | 100.00 | 44.07 | 35-55 |
| 2.36 mm | 3.66 | 100.00 | 32.56 | |
| 1.18 mm | 2.05 | 100.00 | 31.43 | |
| 600 µm | 1.52 | 79.60 | 24.94 | 10-35 |
| 300 µm | 1.08 | 16.50 | 5.72 | |
| 150 µm | 0.62 | 1.11 | 0.77 | 0-8 |

*) 70% (7 mm) + 30% (Fine)

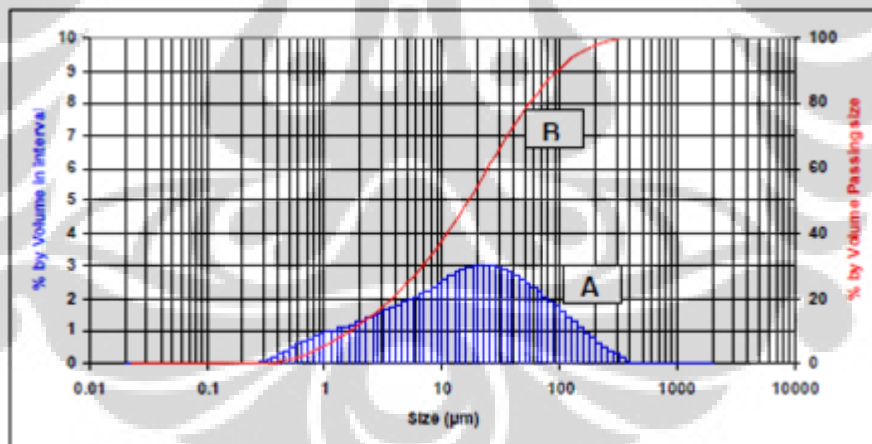
3.6.1.2 Prekursor

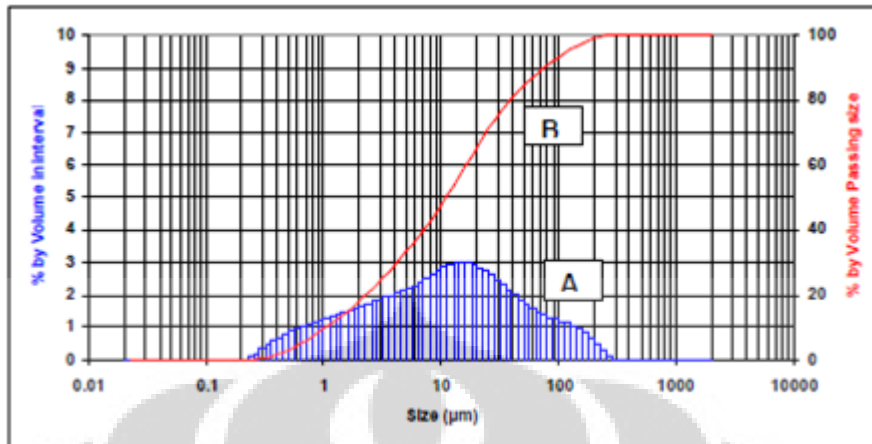
Prekursor yang digunakan dalam penelitian ini adalah *fly ash* PLTU Collie yang terletak di Australia bagian tenggara. Pada penelitian ini *fly ash* yang didatangkan dari PLTU Collie dikirim dalam tiga batch. Kandungan kimia *fly ash* dari masing masing batch *fly ash* ditunjukkan oleh tabel 3.35.

Tabel 3.35. Kandungan Kimia *Fly Ash* PLTU Collie

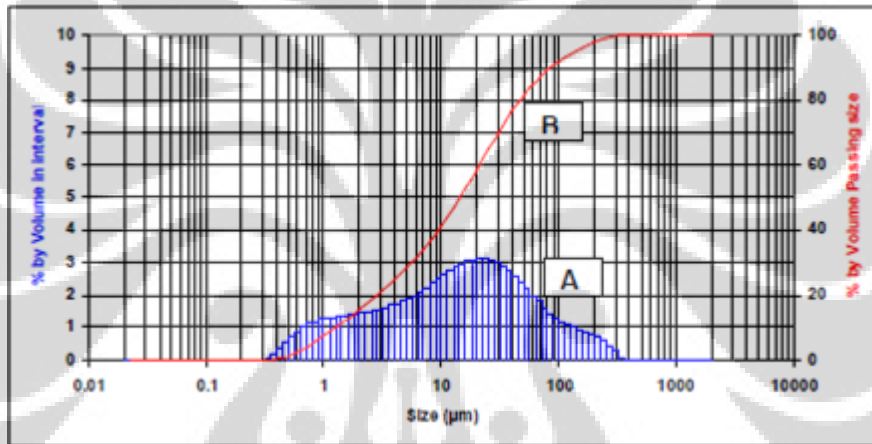
| Oxides | Batch I | Batch II | Batch III |
|--------------------------------|---------|----------|-----------|
| SiO ₂ | 53.36 | 47.80 | 48.00 |
| Al ₂ O ₃ | 26.49 | 24.40 | 29.00 |
| Fe ₂ O ₃ | 10.86 | 17.40 | 12.70 |
| CaO | 1.34 | 2.42 | 1.78 |
| Na ₂ O | 0.37 | 0.31 | 0.39 |
| K ₂ O | 0.80 | 0.55 | 0.55 |
| TiO ₂ | 1.47 | 1.328 | 1.67 |
| MgO | 0.77 | 1.19 | 0.89 |
| P ₂ O ₅ | 1.43 | 2.00 | 1.69 |
| SO ₃ | 1.70 | 0.29 | 0.50 |
| ZrO ₂ | - | - | 0.06 |
| Cr | - | 0.01 | 0.016 |
| MnO | - | 0.12 | 0.06 |
| LOI | 1.39 | 1.10 | 1.61 |

Berdasarkan kandungan kimia, *fly ash* PLTU Collie digolongkan sebagai *fly ash* tipe F.

Gambar 3.6. Distribusi Ukuran Partikel *Fly Ash* Batch I



Gambar 3.7. Distribusi Ukuran Partikel *Fly Ash* Batch 2



Gambar 3.8. Distribusi Ukuran Partikel *Fly Ash* Batch 3

3.6.1.3. Alkaline Activator

Alkaline activator yang digunakan dalam penelitian ini adalah gabungan antara *sodium silikat* (Na_2SiO_3) dan *sodium hidroksida* (NaOH).

- *Sodium Hidroksida* (NaOH)

Sodium hidroksida yang digunakan ada dua jenis, yaitu :

Sodium hidroksida dari Sigma-Aldrich Pty Ltd, Australia

Specific Gravity = 2,13

Kemurnian 98%

Sodium hidroksida dari Lomb Scientific, Australia

Kemurnian 97%.

- *Sodium Silikat* (Na_2SiO_3)
Specific Gravity = 1.53 g/cc
Viscosity pada suhu 20°C = 400 cp
 Komposisi kimia terdiri dari :
 - Na_2O =14.7%
 - SiO_2 =29.4%
 - Air = 55.9%

3.6.1.4. *Superplasticizer*

Untuk meningkatkan *workability* dari beton muda, digunakan *superplasticizer* naphthalene sulphonate dengan merk Rheobuild 1000. *Superplasticizer* yang berbentuk cair ini diperoleh dari Master Builders Technologies, Perth, Australia.

3.6.2. Proporsi Campuran dan Curing

Pada penelitian ini digunakan *fly ash* tipe F yang berasal dari PLTU Collie sebagai prekursor dengan spesifikasi seperti yang telah diuraikan sebelumnya. Alkaline activator digunakan adalah kombinasi antara Na_2SiO_3 dan NaOH. Pada penelitian ini dilakukan trial mix dengan variasi parameter sebagai berikut :

- Konsentrasi NaOH yang digunakan berkisar antara 8M hingga 16M.
- Rasio perbandingan massa NaOH: Na_2SiO_3 berkisar antara 0.4 hingga 2.5.
- Rasio Air/Prekursor yang digunakan adalah 0.3 dan 0.4.
- Persentase massa agregat berkisar antara 75% hingga 80% dari massa sample beton.
- *Superplasticizer* yang digunakan berkisar antara 0% - 2% dari massa Prekursor.

Pada penelitian ini sample beton di curing dengan variasi metode curing dengan oven dan curing dalam suhu ruang. Variasi suhu curing 30°C , 45°C , 60°C , 75°C , dan 90°C dengan variasi waktu curing selama 4 dan 24 jam. Secara lengkap komposisi pada penelitian ini ditunjukkan oleh tabel 3.36.

Tabel 3.36. Mix Design Beton Geopolimer Dengan *Fly Ash* PLTU Collie

| Mix No | Aggregate | | | | | <i>Fly Ash</i> (kg) | NaOH Solution | | Sodium Silicate (kg) | Added Water (kg) | <i>Superplasticizer</i> (kg) |
|--------|------------|------------|------------|-----------|----------------|---------------------|---------------|--------------------|----------------------|--------------------|------------------------------|
| | 20 mm (kg) | 14 mm (kg) | 10 mm (kg) | 7 mm (kg) | Fine Sand (kg) | | Mass (kg) | Molarity | | | |
| 1 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 120 | 8M ^{*)} | 48 | - | - |
| 2 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 48 | 8M ^{*)} | 120 | - | - |
| 3 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 120 | 14M ^{*)} | 48 | - | - |
| 4 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 48 | 14M ^{*)} | 120 | - | - |
| 5 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | - |
| 6 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | 4.1 |
| 7 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | 8.2 |
| 8 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | 16.3 |
| 9 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{**)} | 103 | 14.3 ^{y)} | 6.1 |
| 10 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{**)} | 103 | 17.6 ^{y)} | 6.1 |
| 11 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 12M ^{*)} | 103 | 14.3 ^{y)} | 6.1 |
| 12 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 8M ^{*)} | 103 | - | 6.1 |
| 13 | 277 | 370 | - | 647 | 554 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | - | 8.2 |
| 14 | 277 | 370 | - | 647 | 554 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | 10.7 ^{y)} | 8.2 |
| 15 | 277 | 370 | - | 647 | 554 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | 21.3 ^{y)} | 8.2 |
| 16 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 8M ^{*)} | 103 | - | 6.1 |
| 17 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 10M ^{*)} | 103 | 7.5 ^{y)} | 6.1 |
| 18 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 12M ^{*)} | 103 | 14.4 ^{y)} | 6.1 |
| 19 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{*)} | 103 | 20.7 ^{y)} | 6.1 |
| 20 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 16M ^{*)} | 103 | 26.5 ^{y)} | 6.1 |
| 21 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{**)} | 103 | 20.7 ^{y)} | 6.1 |
| 22 | - | - | - | 1294 | 554 | 408 ^{c)} | 41 | 14M ^{**)} | 103 | 16.5 ^{x)} | 6.1 |
| 23 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{*)} | 103 | - | 8.2 |
| 24 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 8M ^{*)} | 103 | - | 6.1 |
| 25 | - | - | 554 | 647 | 647 | 408 ^{b)} | 55.4 | 8M ^{*)} | 103 | - | 6.1 |
| 26 | - | - | 554 | 647 | 647 | 408 ^{b)} | 55.4 | 8M ^{*)} | 103 | - | 6.1 |

Note:

*) Technical Grade

a) *Fly Ash*: Batch I

x) Tap water

***) Commercial Grade

b) *Fly Ash*: Batch II

y) Distilled water

c) *Fly Ash*: Batch III

3.6.3. Hasil Penelitian

Hasil pengujian kuat tekan dari sample beton ditunjukkan oleh table 3.37

Tabel 3.37. Mix Design Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Collie

| Mix No | Curing | | | Umur (Hari) | Slump (mm) | Density (kg/m ³) | Kuat Tekan (MPa) |
|--------|-------------|-----------------|--------|-------------|------------|------------------------------|------------------|
| | Waktu (jam) | Temperatur (°C) | Metode | | | | |
| 1 | 24 | 60 | Oven | 7 | na | 2365 | 17 |
| 2 | 4 | 30 | Oven | 7 | na | 2376 | 8 |
| | 4 | 60 | Oven | 7 | na | 2378 | 24 |
| | 4 | 90 | Oven | 7 | na | 2341 | 37 |
| | 24 | 30 | Oven | 7 | na | 2364 | 20 |
| | 24 | 60 | Oven | 7 | na | 2377 | 57 |
| | 24 | 90 | oven | 7 | na | 2341 | 66 |
| 3 | 24 | 60 | oven | 7 | na | 2386 | 48 |
| 4 | 48 | 30 | oven | 7 | na | 2367 | 49 |
| | 4 | 60 | oven | 7 | na | 2320 | 25 |
| | 4 | 90 | oven | 7 | na | 2376 | 30 |
| | 24 | 30 | oven | 7 | na | 2367 | 29 |
| | 24 | 60 | oven | 7 | na | 2386 | 68 |
| | 24 | 90 | oven | 7 | na | 2385 | 70 |
| 5 | 24 | 60 | Steam | 3 | 39 | 2340 | 42 |
| 6 | 24 | 60 | Steam | 3 | 59 | 2375 | 41 |
| 7 | 24 | 60 | Steam | 3 | 80 | 2347 | 41 |
| 8 | 24 | 60 | Steam | 3 | 93 | 2336 | 36 |
| 9 | 24 | 60 | Steam | 7 | 209 | - | 40 |
| | 24 | 60 | Steam | 7 | 209 | - | 41 |
| | 24 | 60 | Steam | 7 | 209 | - | 48 |
| | 24 | 60 | Steam | 7 | 209 | - | 50 |
| | 24 | 60 | Steam | 7 | 209 | - | 49 |
| 10 | 24 | 60 | Steam | 7 | 215 | 2298 | 43 |
| | 24 | 60 | Steam | 7 | 215 | 2299 | 53 |
| | 24 | 60 | Steam | 7 | 215 | 2298 | 56 |
| | 24 | 60 | Steam | 7 | 215 | 2305 | 57 |
| | 24 | 60 | Steam | 7 | 215 | 2306 | 57 |
| | 24 | 60 | Steam | 7 | 215 | 2303 | 58 |
| 11 | 24 | 60 | Steam | 7 | 225 | 2305 | 38 |
| | 24 | 60 | Steam | 7 | 225 | 2309 | 53 |
| | 24 | 60 | Steam | 7 | 225 | 2314 | 56 |
| | 24 | 60 | Steam | 7 | 225 | 2318 | 59 |
| | 24 | 60 | Steam | 7 | 225 | 2318 | 59 |
| | 24 | 60 | Steam | 7 | 225 | 2314 | 59 |

| Mix No | Curing | | | Umur (Hari) | Slump (mm) | Density (kg/m ³) | Kuat Tekan (MPa) |
|--------|-------------|-----------------|--------|-------------|------------|------------------------------|------------------|
| | Waktu (jam) | Temperatur (°C) | Metode | | | | |
| 12 | 24 | 60 | oven | 7 | 60 | 2357 | 63 |
| | 24 | 60 | oven | 7 | 60 | 2364 | 74 |
| | 24 | 60 | oven | 7 | 60 | 2363 | 73 |
| | 24 | 60 | oven | 7 | 60 | 2361 | 76 |
| | 24 | 60 | oven | 7 | 60 | 2369 | 75 |
| | 24 | 60 | oven | 7 | 60 | 2368 | 77 |
| 13 | 24 | 30 | oven | 7 | na | 2387 | 44 |
| | 24 | 45 | oven | 7 | na | 2377 | 55 |
| | 24 | 60 | oven | 7 | na | 2375 | 59 |
| | 24 | 75 | oven | 7 | na | 2375 | 65 |
| | 24 | 90 | oven | 7 | na | 2376 | 71 |
| 14 | 24 | 30 | oven | 7 | na | 2338 | 35 |
| | 24 | 45 | oven | 7 | na | 2336 | 42 |
| | 24 | 60 | oven | 7 | na | na | Na |
| | 24 | 75 | oven | 7 | na | 2337 | 60 |
| | 24 | 90 | oven | 7 | na | 2334 | 59 |
| 15 | 24 | 30 | oven | 7 | na | 2326 | 32 |
| | 24 | 45 | oven | 7 | na | 2322 | 37 |
| | 24 | 60 | oven | 7 | na | 2321 | 44 |
| | 24 | 75 | oven | 7 | na | 2301 | 44 |
| | 24 | 90 | oven | 7 | na | 2318 | 44 |
| 16 | 24 | 60 | oven | 7 | 32 | 2381 | 55 |
| | 24 | 60 | steam | 7 | 32 | 2385 | 47 |
| 17 | 24 | 60 | oven | 7 | 113 | 2352 | 53 |
| | 24 | 60 | steam | 7 | 113 | 2362 | 45 |
| 18 | 24 | 60 | oven | 7 | 162 | 2361 | 51 |
| | 24 | 60 | steam | 7 | 162 | 2364 | 42 |
| 19 | 24 | 60 | oven | 7 | 214 | 2343 | 45 |
| | 24 | 60 | steam | 7 | 214 | 2341 | 40 |
| 20 | 24 | 60 | oven | 7 | 240 | 2341 | 47 |
| | 24 | 60 | steam | 7 | 240 | 2342 | 40 |
| 21 | 24 | 60 | steam | 21 | 234 | 2345 | 37 |
| | 24 | 60 | steam | 21 | 234 | 2367 | 40 |
| | 24 | 60 | steam | 21 | 226 | 2373 | 45 |
| | 24 | 60 | steam | 21 | 219 | 2378 | 45 |
| | 24 | 60 | steam | 21 | 219 | 2387 | 47 |
| | 24 | 60 | steam | 21 | 206 | 2397 | 49 |
| | 24 | 60 | steam | 21 | 206 | 2399 | 52 |

| Mix No | Curing | | | Umur (Hari) | Slump (mm) | Density (kg/m ³) | Kuat Tekan (MPa) |
|--------|-------------|-----------------|--------|-------------|------------|------------------------------|------------------|
| | Waktu (jam) | Temperatur (°C) | Metode | | | | |
| 22.a | 4 | 90 | steam | 3 | 91 | 2331 | 40 |
| .b | 4 | 90 | steam | 3 | 67 | 2344 | 47 |
| .c | 4 | 90 | steam | 3 | 49 | 2368 | 56 |
| 23 | 24 | 90 | oven | 90 | 46 | - | 89 |
| 24 | 24 | 60 | oven | 90 | 135 | - | 68 |
| 25 | 24 | 60 | oven | 90 | 207 | - | 55 |
| 26 | 24 | 60 | steam | 90 | 219 | - | 44 |

3.7. Engineering Properties of Mae Moh Fly Ash Geopolymer Concrete

Penelitian ini dilakukan oleh Smith Songpiriyakij, dari King Mongkut,s Institute Of Technology North Bangkok, Thailand, Pada bulan Mei 2007.

3.7.1. Material Geopolimer

3.7.1.1 Prekursor

Prekursor yang digunakan dalam penelitian ini adalah *fly ash* yang berasal dari PLTU Mae Moh, Thailand. Kandungan kimia dari *fly ash* ditunjukkan oleh tabel 3.38.

Tabel 3.38. Kandungan Kimia *Fly Ash* PLTU Mae Moh

| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | SO ₃ | LOI |
|----------|------------------|--------------------------------|--------------------------------|-----|-----------------|-----|
| %Mass | 45,32 | 20,92 | 10,7 | 7,6 | 1,8 | 0,2 |

Berdasarkan kandungan kimia, *fly ash* PLTU Mae Moh digolongkan sebagai *fly ash* tipe F.

3.7.1.2 Alkaline Activator

Alkaline activator yang digunakan dalam penelitian ini adalah campuran dari *sodium hidroksida* (NaOH) dengan kemurnian 98% dan *sodium silikat* (Na₂SiO₃) dengan kandungan Na₂O =14.7%, SiO₂ =29.4%, air = 55.9%.

3.7.2. Proporsi Campuran dan Curing

Pada penelitian ini digunakan sampel beton kubus berukuran 10 cm x 10 cm x 10 cm. Jumlah agregat yang digunakan pada penelitian ini dibuat konstan, sedangkan komposisi pasta geopolimer dijadikan sebagai variable bebas. Larutan NaOH yang digunakan memiliki konsentrasi 15 M dan 20 M. Pada penelitian ini digunakan 7 komposisi dengan 7 rasio air/prekursor yang berbeda. Untuk masing masing komposisi dibandingkan pengaruh metode curing pada suhu ruang (25⁰C) dan pemanasan dengan oven dengan suhu 60⁰C selama 24 jam. Secara lengkap proporsi campuran dan metode curing pada penelitian ini ditunjukkan oleh tabel 3.39.

Tabel 3.39. Komposisi Campuran Beton Geopolimer *Fly Ash* Mae Moh

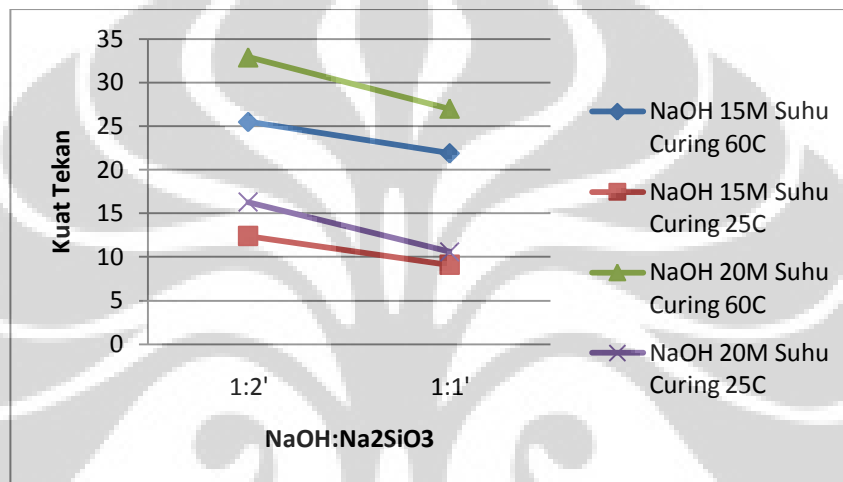
| No. | NaOH | <i>Fly Ash</i> F | NaOH | Na ₂ SiO ₃ | Kerikil | Pasir | Air/Prekursor | Suhu Curing | NaOH:Na ₂ SiO ₃ |
|-----|------|-------------------|------|----------------------------------|---------|-------|---------------|-------------------|---------------------------------------|
| | | Kg/m ³ | | | | | | | |
| 1 | 15 M | 514 | 55 | 127 | 1056 | 700 | 0,4 | 60 ⁰ C | 1:2.3 |
| 2 | 15 M | 514 | 79 | 79 | 1056 | 700 | 0,42 | 60 ⁰ C | 1:1 |
| 3 | 15 M | 475 | 79 | 158 | 1056 | 700 | 0,47 | 60 ⁰ C | 1:2 |
| 4 | 15 M | 475 | 119 | 119 | 1056 | 700 | 0,48 | 60 ⁰ C | 1:1 |
| 5 | 20 M | 514 | 79 | 79 | 1056 | 700 | 0,41 | 60 ⁰ C | 1:2 |
| 6 | 20 M | 475 | 79 | 158 | 1056 | 700 | 0,46 | 60 ⁰ C | 1:2 |
| 7 | 20 M | 475 | 119 | 119 | 1056 | 700 | 0,46 | 60 ⁰ C | 1:1 |
| 1 | 15 M | 514 | 55 | 127 | 1056 | 700 | 0,4 | 25 ⁰ C | 1:2.3 |
| 2 | 15 M | 514 | 79 | 79 | 1056 | 700 | 0,42 | 25 ⁰ C | 1:1 |
| 3 | 15 M | 475 | 79 | 158 | 1056 | 700 | 0,47 | 25 ⁰ C | 1:2 |
| 4 | 15 M | 475 | 119 | 119 | 1056 | 700 | 0,48 | 25 ⁰ C | 1:1 |
| 5 | 20 M | 514 | 79 | 79 | 1056 | 700 | 0,41 | 25 ⁰ C | 1:2 |
| 6 | 20 M | 475 | 79 | 158 | 1056 | 700 | 0,46 | 25 ⁰ C | 1:2 |
| 7 | 20 M | 475 | 119 | 119 | 1056 | 700 | 0,46 | 25 ⁰ C | 1:1 |

3.7.3. Hasil Penelitian

Pengujian kuat tekan dilakukan pada usia 1, 3, 7, dan 28 hari. Hasil pengujian kuat tekan pada usia 7 hari dan 28 hari untuk sampel 3,4,6, dan 7 ditunjukkan oleh tabel 3.40.

Tabel 3.40. Hasil Pengujian Komposisi Campuran Beton Geopolimer Dengan Prekursor *Fly Ash*
PLTU Mae Moh

| No | Prekursor | Suhu Curing | NaOH : Na ₂ SiO ₃ | Pasir : <i>Fly Ash</i> | Kerikil : <i>Fly Ash</i> | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (Mpa) | |
|----|------------------|-------------|--|---------------------------|-----------------------------|---------------------|-------------------|------------------|-----------|
| | | | | | | | | NaOH 15 M | NaOH 20 M |
| 1 | <i>Fly Ash F</i> | 60C | 1:2 | 1,474 | 1,509 | 1 | 7 | 25.5 | 32.9 |
| 2 | <i>Fly Ash F</i> | 60C | 1:1 | 1,474 | 1,509 | 1 | 7 | 21.9 | 27 |
| 3 | <i>Fly Ash F</i> | 25C | 1:2 | 1,474 | 1,509 | 1 | 7 | 12.4 | 16.3 |
| 4 | <i>Fly Ash F</i> | 25C | 1:1 | 1,474 | 1,509 | 1 | 7 | 9.1 | 10.6 |



Grafik 3.13. Hasil Pengujian Komposisi Campuran Beton Geopolimer Dengan Prekursor *Fly Ash*
PLTU Mae Moh

Berdasarkan hasil penelitian, diketahui bahwa komposisi optimal yang dapat menghasilkan kuat tekan paling tinggi adalah komposisi No 6 dengan suhu curing 60°C.

3.8. Factor Influencing The Compressive Strength of Fly Ash Based Geopolymer Concrete

Penelitian ini dilakukan oleh Djwantoro Hardjito, Steenie E. Wallah, Dody M.J.Sumajouw, and B.V. Rangan, dari Curtin University Of Technology, Australia pada September 2004.

3.8.1. Material Geopolimer

3.8.1.1 Prekursor

Prekursor yang digunakan dalam penelitian ini adalah *fly ash* PLTU Collie yang terletak di Australia bagian tenggara. Kandungan kimia *fly ash* ditunjukkan oleh tabel 3.41.

Tabel 3.41. Kandungan Kimia *Fly Ash* PLTU Collie

| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | Na ₂ O | K ₂ O | TiO ₂ | MgO | P ₂ O ₅ | SO ₃ | LOI |
|----------|------------------|--------------------------------|--------------------------------|------|-------------------|------------------|------------------|------|-------------------------------|-----------------|------|
| %Mass | 53,36 | 26,49 | 10,86 | 1,34 | 0,37 | 0,8 | 1,47 | 0,77 | 1,43 | 1,7 | 1,39 |

Berdasarkan kandungan kimia, *fly ash* PLTU Collie digolongkan sebagai *fly ash* tipe F.

3.8.1.2 Alkaline Activator

Alkaline activator yang digunakan pada penelitian ini adalah gabungan dari *sodium hidroksida* (NaOH) dengan kemurnian 98% dan *sodium silikat* (Na₂SiO₃) dengan kandungan Na₂O = 14.7%, SiO₂ = 29.4% dan air = 55.9%.

3.8.2. Proporsi Campuran dan Curing

Pada penelitian ini digunakan sampel beton silinder dengan diameter 10 cm dan tinggi 20 cm. berdasarkan penelitian yang telah dilakukan sebelumnya, digunakan larutan alkali dengan rasio perbandingan NaOH (8M) : Na₂SiO₃ = 2 : 5. Pada penelitian ini rasio air/prekursor ditetapkan sebagai variable bebas. Semua sampel beton dicuring dengan suhu 60⁰C selama 24 jam. Secara jelas, komposisi pada penelitian ini ditunjukkan oleh tabel 3.42.

Tabel 3.42. Komposisi Campuran Beton Geopolimer *Fly Ash* PLTU Collie

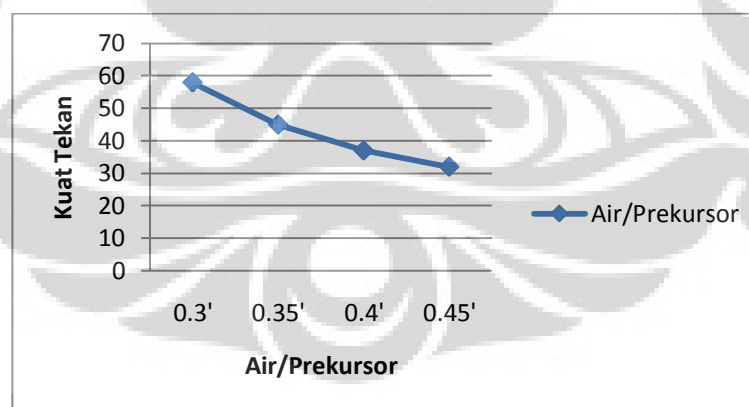
| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Suhu Curing | Waktu curing (hari) | Umur Beton (hari) | Air/Prekursor |
|-----|------------------|------|--|----------------|------------------------|----------------------|---------------|
| 1 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.3 |
| 2 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.35 |
| 3 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.4 |
| 4 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.45 |

3.8.3. Hasil Penelitian

Hasil pengujian kuat tekan sampel beton pada usia 28 hari ditunjukkan oleh tabel 3.43.

Tabel 3.43. Hasil Pengujian Campuran Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Collie

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Air/Prekursor | Kuat Tekan (MPa) |
|-----|------------------|------|--|----------------|---------------------------|-------------------------|---------------|------------------------|
| 1 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.3 | 58 |
| 2 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.35 | 45 |
| 3 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.4 | 37 |
| 4 | <i>Fly Ash</i> F | 8 M | 2:5 | 60°C | 1 | 28 | 0.45 | 32 |

Grafik 3.14. Hasil Pengujian Campuran Beton Geopolimer Dengan Prekursor *Fly Ash* PLTU Collie

Berdasarkan hasil uji sample beton pada umur 28 hari diperoleh kuat tekan yang optimal dari rasio air/prekursor = 0,3.



Universitas Indonesia

BAB 4

ANALISA STUDI LITERATUR

Berdasarkan penelitian penelitian yang telah dipaparkan pada bab3, selanjutnya kita dapat mengelompokkan dan membandingkan pengaruh rasio massa air/prekursor, suhu curing, konsentrasi NaOH dan rasio massa NaOH:Na₂SiO₃ dan jenis prekursor yang digunakan terhadap kuat tekan beton geopolimer.

4.1. Konsentrasi NaOH dan Rasio Perbandingan Massa NaOH:Na₂SiO₃ Terhadap Kuat Tekan Beton Geopolymer

Sodium silikat (Na₂SiO₃) berfungsi untuk mempercepat reaksi polimer. Campuran antara *fly ash* dan *sodium silikat* membentuk ikatan yang sangat kuat namun banyak terjadi retakan-retakan antar mikrostruktur. *Sodium hidroksida* (NaOH) berfungsi untuk mereaksikan unsur-unsur Al dan Si dengan menambah ion Na⁺. Campuran *fly ash* dan *sodium hidroksida* membentuk ikatan yang kurang kuat tetapi menghasilkan ikatan yang lebih padat dan tidak ada retakan. Peningkatan rasio berat Na₂SiO₃/NaOH menurunkan porositas geopolimer yang dihasilkan, (*Fansuri Hamzah, 2008*).

4.1.1. Komposisi Alkaline Aktivator dan *Fly Ash* Untuk Beton Geopolimer Mutu Tinggi

Penelitian ini dilakukan oleh Andi Sanjaya dan Calvin Yuwono dari Universitas Kristen Petra tahun 2006.

4.1.1.1 Alkaline Aktivator

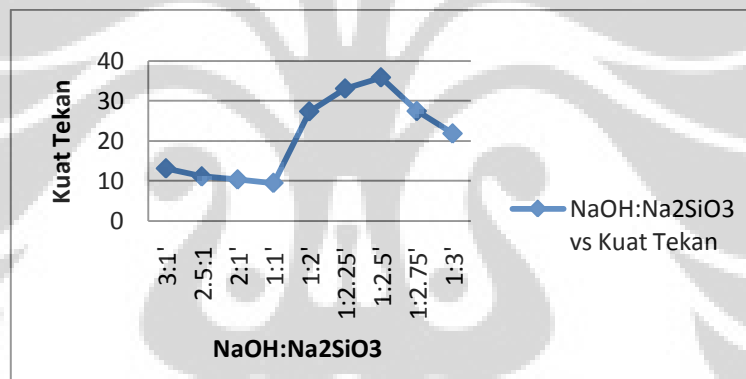
Alkaline Aktivator yang digunakan dalam penelitian ini adalah kombinasi dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃). Namun, pada penelitian ini spesifikasi dari NaOH dan Na₂SiO₃ tidak disebutkan secara jelas.

4.1.1.2 Hasil Penelitian

Hasil pengujian kuat tekan beton pada umur 7 hari ditunjukkan oleh tabel 4.1

Tabel 4.1 Hasil Pengujian Kuat Tekan Terhadap NaOH:Na₂SiO₃ Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|----|------------------|------|---|---------------|-----------------------|-------------|--------------------|-------------|------------------|
| 1 | <i>Fly Ash</i> C | 8 M | 3:1 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 13.13 |
| 2 | <i>Fly Ash</i> C | 8 M | 2.5:1 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 11.12 |
| 3 | <i>Fly Ash</i> C | 8 M | 2:1 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 10.36 |
| 4 | <i>Fly Ash</i> C | 8 M | 1:1 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 9.5 |
| 5 | <i>Fly Ash</i> C | 8 M | 1:2 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 27.38 |
| 6 | <i>Fly Ash</i> C | 8 M | 1:2.25 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 33.09 |
| 7 | <i>Fly Ash</i> C | 8 M | 1:2.5 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 35.87 |
| 8 | <i>Fly Ash</i> C | 8 M | 1:2.75 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 27.46 |
| 9 | <i>Fly Ash</i> C | 8 M | 1:3 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 21.85 |



Grafik 4.1 Hasil Pengujian Kuat Tekan Terhadap NaOH:Na₂SiO₃ Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

Dari hasil pengujian kuat tekan, diketahui bahwa kuat tekan beton geopolimer terbesar dihasilkan oleh mix design dengan rasio massa NaOH:Na₂SiO₃ = 1:2,5 dengan konsentrasi NaOH sebesar 8 M

4.1.2. Komposisi dan Karakteristik Beton Geopolimer dari *Fly Ash* tipe C dan F

Penelitian ini dilakukan oleh Johanes Prasetio Utomo dan Sandi Kosnatha dari Universitas Kristen Petra tahun 2007.

4.1.2.1 Alkaline Aktivator

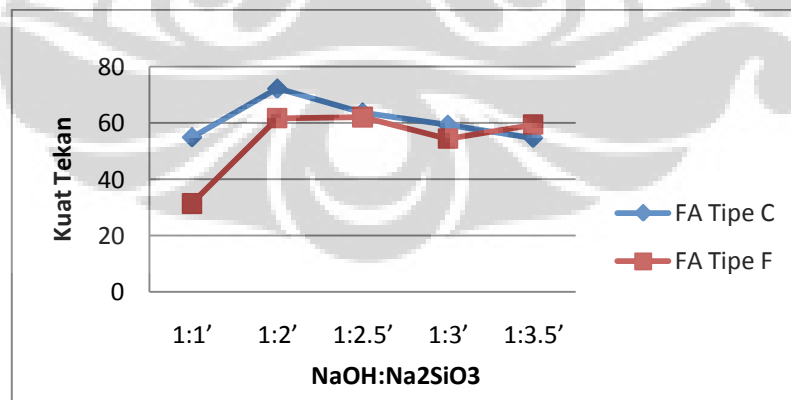
Alkaline Aktivator yang digunakan dalam penelitian ini adalah kombinasi dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃) dengan kemurnian 80%

4.1.2.2 Hasil Pengujian

Hasil pengujian kuat tekan ditunjukkan oleh tabel 4.2

Tabel 4.2 Hasil Pengujian Kuat Tekan Terhadap NaOH:Na₂SiO₃ Beton Geopolimer Dengan *Fly Ash* Tipe C dan F

| No | NaOH | NaOH : Na ₂ SiO ₃ | Air/Pre kursor | Pasir/ <i>Fly</i> <i>Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar (hari) | Kuat Tekan (MPa) | |
|----|------|--|-------------------|---------------------------------|----------------|--------------------------|--------------------------|------------------|-----------|
| | | | | | | | | FA tipe C | FA tipe F |
| 1 | 8 M | 1:1 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 54.87 | 31.42 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 72.23 | 61.69 |
| 3 | 8 M | 1:2.5 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 63.71 | 62.11 |
| 4 | 8 M | 1:3 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 59.3 | 54.44 |
| 5 | 8 M | 1:3.5 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 54.66 | 59.44 |



Grafik 4.2 Hasil Pengujian Kuat Tekan Terhadap NaOH:Na₂SiO₃ Beton Geopolimer Dengan *Fly Ash* Tipe C dan F

Berdasarkan hasil uji sample beton pada umur 7 hari diperoleh kuat tekan yang optimal dengan rasio massa $\text{NaOH}:\text{Na}_2\text{SiO}_3 = 1:2$ dan konsentrasi *sodium hidroksida* sebesar 8 M.

4.1.3. Engineering Properties of Mae MOH Fly Ash Geopolymer Concrete

Penelitian ini dilakukan oleh Smith Songpiriyakij, dari King Mongkut,s Institute Of Technology North Bangkok, Thailand, Pada bulan Mei 2007.

4.1.3.1 Alkaline Aktivator

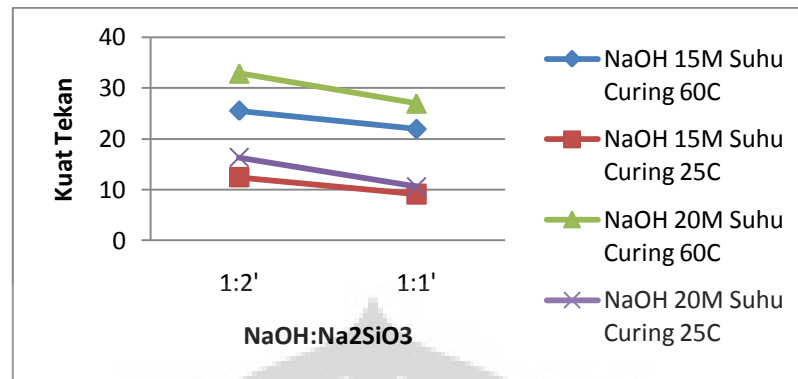
Alkaline Aktivator yang digunakan dalam penelitian ini adalah campuran dari *sodium hidroksida* (NaOH) dengan kemurnian 98% dan *sodium silikat* (Na_2SiO_3) dengan kandungan $\text{Na}_2\text{O} = 14.7\%$, $\text{SiO}_2 = 29.4\%$, dan air = 55.9%.

4.1.3.2 Hasil Penelitian

Hasil pengujian kuat tekan pada usia 7 hari ditunjukkan oleh tabel 4.3.

Tabel 4.3. Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Konsentrasi NaOH dan Rasio $\text{NaOH}:\text{Na}_2\text{SiO}_3$ Fly Ash Mae Moh

| No | Prekursor | Suhu Curing | Air/Prekursor | NaOH : Na_2SiO_3 | Pasir/ Fly Ash | Kerikil /Fly Ash | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (MPa) | |
|----|-----------|-------------|---------------|----------------------------------|----------------|------------------|---------------------|-------------------|------------------|-----------|
| | | | | | | | | | NaOH 15 M | NaOH 20 M |
| 1 | Fly Ash F | 60°C | 0.16632 | 1:2 | 1,474 | 1,509 | 1 | 7 | 25.5 | 32.9 |
| 2 | Fly Ash F | 60°C | 0.16632 | 1:1 | 1,474 | 1,509 | 1 | 7 | 21.9 | 27 |
| 3 | Fly Ash F | 25°C | 0.16632 | 1:2 | 1,474 | 1,509 | 1 | 7 | 12.4 | 16.3 |
| 4 | Fly Ash F | 25°C | 0.16632 | 1:1 | 1,474 | 1,509 | 1 | 7 | 9.1 | 10.6 |



Grafik 4.3. Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Konsentrasi NaOH dan Rasio NaOH:Na₂SiO₃ Fly Ash Mae Moh

Berdasarkan hasil penelitian, diketahui bahwa komposisi optimal yang dapat menghasilkan kuat tekan paling tinggi adalah komposisi No 1 dengan rasio massa NaOH:Na₂SiO₃ = 1:2, NaOH 20 M dan suhu curing 60⁰C

4.1.4. Feasibility Study of Geopolymer

Penelitian ini dilakukan oleh Wine Figeys, Dionys van Gemert dan Jose Aguiar dari University of Minho, Azurem, Guimaraes, Portugal, pada September 2007.

4.1.4.1. Alkaline Aktivator

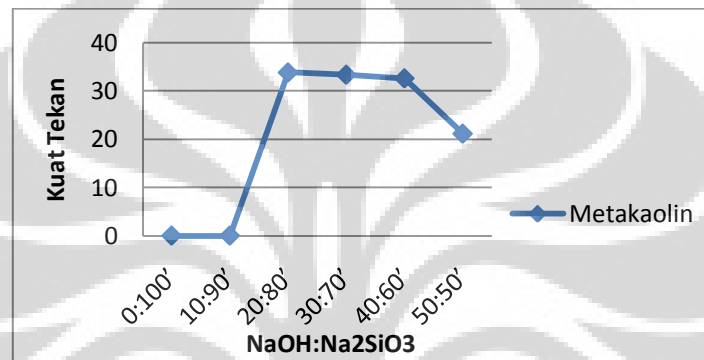
Alkaline Aktivator yang digunakan dalam penelitian ini adalah campuran antara *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃). Namun Spesifikasi dari NaOH dan Na₂SiO₃ tidak disebutkan.

4.1.4.2 Hasil Penelitian

Hasil pengujian kuat tekan sampel beton pada usia 7 hari ditunjukkan oleh tabel 4.4

Tabel 4.4 Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Rasio NaOH:Na₂SiO₃ Dengan Prekursor Metakaolin

| No. | Prekursor | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (MPa) |
|-----|------------|---|---------------|-------------------|---------------------|-------------------|------------------|
| 1 | Metakaolin | 0:100 | 0,62 | 20 ⁰ C | 1 | 7 | - |
| 2 | Metakaolin | 10:90 | 0,62 | 20 ⁰ C | 1 | 7 | - |
| 3 | Metakaolin | 20:80 | 0,63 | 20 ⁰ C | 1 | 7 | 33,84 |
| 4 | Metakaolin | 30:70 | 0,64 | 20 ⁰ C | 1 | 7 | 33,37 |
| 5 | Metakaolin | 40:60 | 0,64 | 20 ⁰ C | 1 | 7 | 32,62 |
| 6 | Metakaolin | 50:50 | 0,65 | 20 ⁰ C | 1 | 7 | 21,14 |



Tabel 4.4 Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Rasio NaOH:Na₂SiO₃ Dengan Prekursor Metakaolin

Berdasarkan hasil penelitian, diketahui bahwa komposisi optimal yang dapat menghasilkan kuat tekan paling tinggi adalah komposisi No 3 dengan rasio massa NaOH:Na₂SiO₃ = 1 : 4.

4.1.5. Studies On Fly Ash Based Geopolymer Concrete

Penelitian ini dilakukan oleh Hardjito Djuwanto dari Curtin University of Technology, Australia pada bulan November 2005.

4.1.5.1. Alkaline Aktivator

Alkaline Aktivator yang digunakan dalam penelitian ini adalah gabungan antara *sodium silikat* (Na₂SiO₃) dan *sodium hidroksida* (NaOH).

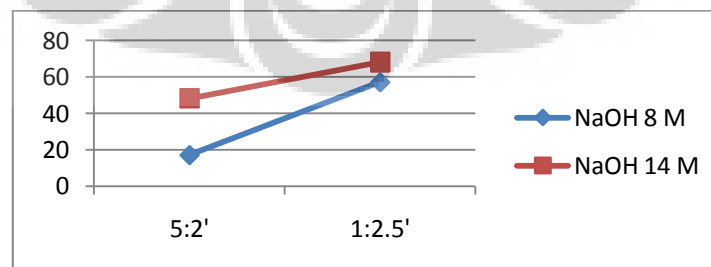
- *Sodium Hidroksida* (NaOH)
Sodium hidroksida yang digunakan ada dua jenis, yaitu :
Sodium hidroksida dari Sigma-Aldrich Pty Ltd, Australia
Specific Gravity = 2,13
 Kemurnian 98%
Sodium hidroksida dari Lomb Scientific, Australia
 Kemurnian 97%.
- *Sodium silikat* (Na₂SiO₃)
Specific Gravity = 1.53 g/cc
 Viscosity pada suhu 20⁰C = 400 cp
 Komposisi kimia terdiri dari :
 - Na₂O=14.7%
 - SiO₂=29.4%
 - Air = 55.9%

4.1.5.2. Hasil Penelitian

Hasil pengujian kuat tekan sampel beton pada usia 7 hari ditunjukkan oleh tabel 4.5.

Tabel 4.5 Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Konsentrasi NaOH dan Rasio NaOH:Na₂SiO₃ Dengan Prekursor *Fly Ash* PLTU Collie

| No. | Prekursor | NaOH : Na ₂ SiO ₃ | Suhu Curing | Waktu Curing (jam) | Umur Beton | Kuat tekan (MPa) | |
|-----|------------------|--|-------------------|--------------------------|---------------|------------------|---------------|
| | | | | | | NaOH (8M) | NaOH (14M) |
| 1 | <i>Fly Ash</i> F | 5:2 | 60 ⁰ C | 24 | 7 | 17 | 48 |
| 2 | <i>Fly Ash</i> F | 1:2.5 | 60 ⁰ C | 24 | 7 | 57 | 68 |



Grafik 4.5 Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Konsentrasi NaOH dan Rasio NaOH:Na₂SiO₃ Dengan Prekursor *Fly Ash* PLTU Collie

Berdasarkan hasil penelitian, diketahui bahwa komposisi optimal yang dapat menghasilkan kuat tekan paling tinggi adalah komposisi dengan konsentrasi NaOH 14 M dan rasio massa NaOH:Na₂SiO₃ = 1:2.5.

Berdasarkan lima penelitian yang telah diuraikan di atas kuat tekan optimum akan tercapai pada rasio massa Na₂SiO₃:NaOH yang relatif lebih kecil. Untuk menghasilkan kuat tekan yang optimum komposisi massa Na₂SiO₃ dalam larutan alkali sebaiknya lebih besar dari massa NaOH. Hal ini disebabkan semakin banyak senyawa SiO₃ akan menghasilkan beton geopolimer dengan porositas yang rendah, sehingga beton akan menjadi lebih padat. Kuat tekan paling tinggi akan tercapai pada rasio perbandingan massa NaOH:Na₂SiO₃ yang Optimum.

4.2. Rasio Perbandingan Massa Air/Prekursor Terhadap Kuat Tekan Beton Geopolymer

Rasio perbandingan massa alkali/prekursor pada beton geopolimer mirip dengan FAS (Faktor air semen) pada beton konvensional yang menggunakan portland semen, semakin kecil nilai FAS kuat tekan beton relatif akan semakin tinggi. Pada beton geopolimer rasio air/prekursor optimal akan menghasilkan kuat tekan paling tinggi.

4.2.1. Komposisi Alkaline Aktivator dan *Fly Ash* Untuk Beton Geopolimer Mutu Tinggi

Penelitian ini dilakukan oleh Andi Sanjaya dan Calvin Yuwono dari Universitas Kristen Petra tahun 2006.

4.2.2.1. Alkaline Aktivator

Alkaline Aktivator yang digunakan dalam penelitian ini adalah kombinasi dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃). Namun, pada penelitian ini spesifikasi dari NaOH dan Na₂SiO₃ tidak disebutkan secara jelas.

4.2.2.2 Prekursor

Prekursor yang digunakan dalam penelitian ini adalah *fly ash* yang berasal dari PLTU paiton. Kandungan kimia dari *fly ash* dapat dilihat pada tabel 4.6.

Tabel 4.6. Kandungan Kimia *Fly Ash* PLTU Paiton

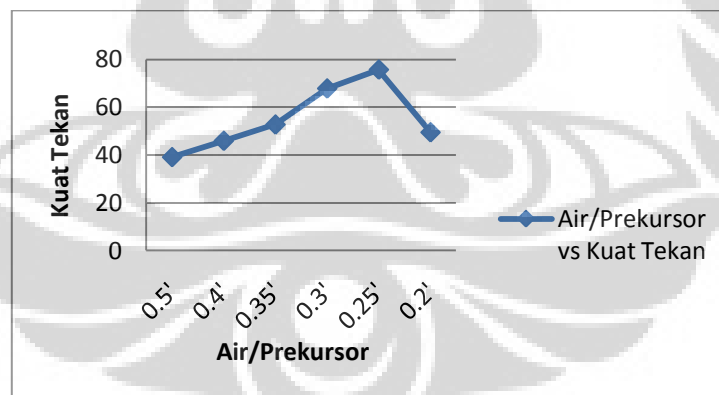
| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | LOI |
|----------|------------------|--------------------------------|--------------------------------|-------|-----|-----|
| %Mass | 45,8 | 14,05 | 3,4 | 24,15 | 5,6 | - |

4.2.2.3. Hasil Penelitian

Hasil pengujian kuat tekan beton pada umur 7 hari ditunjukkan oleh tabel 4.7.

Tabel 4.7 Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Rasio Air/Prekursor Dengan Prekursor *Fly Ash* PLTU Paiton

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir : <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|-----|------------------|------|---|---------------|------------------------|-------------|--------------------|-------------|------------------|
| 1 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.5 | 2 | 90°C | 24 + 6 | 7 | 39.25 |
| 2 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.4 | 2 | 90°C | 24 + 6 | 7 | 46.05 |
| 3 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.35 | 2 | 90°C | 24 + 6 | 7 | 52.85 |
| 4 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 67.9 |
| 5 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.25 | 2 | 90°C | 24 + 6 | 7 | 75.77 |
| 6 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.2 | 2 | 90°C | 24 + 6 | 7 | 49.6 |



Grafik 4.6 Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Rasio Air/Prekursor Dengan Prekursor *Fly Ash* PLTU Paiton

Dari hasil pengujian kuat tekan, diketahui bahwa kuat tekan beton geopolimer terbesar dihasilkan oleh mix design dengan rasio massa air/prekursor = 0,25.

4.2.2. Komposisi dan Karakteristik Beton Geopolimer dari *Fly Ash* tipe C dan F

Penelitian ini dilakukan oleh Johanes Prasetio Utomo dan Sandi Kosnatha dari Universitas Kristen Petra tahun 2007.

4.2.2.1. Alkaline Aktivator

Alkaline Aktivator yang digunakan dalam penelitian ini adalah kombinasi dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃) dengan kemurnian 80%

4.2.2.2. Prekursor

Prekursor yang digunakan dalam penelitian ini adalah :

1. *Fly ash* tipe C yang berasal dari PLTU paiton yang diperoleh dari PT Jaya Ready Mix.
2. *Fly ash* tipe F yang berasal dari PLTU Suralaya yang diperoleh dari PT Indocement.

Kandungan kimia dari *fly ash* dapat dilihat pada table 4.8.

Tabel 4.8. Kandungan Kimia *Fly Ash* Tipe C dan F

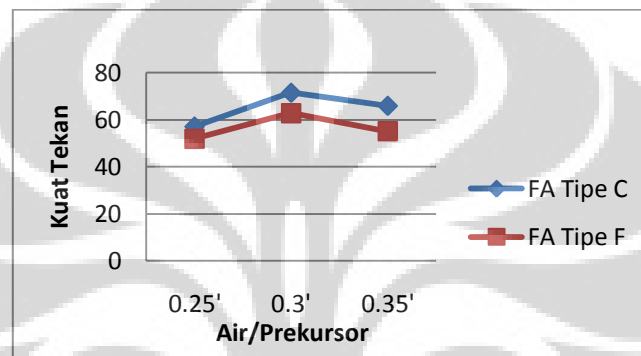
| Oksida | <i>Fly Ash</i> Tipe C (%) | <i>Fly Ash</i> Tipe F (%) |
|--------------------------------|---------------------------|---------------------------|
| SiO ₂ | 46.39 | 54 |
| Al ₂ O ₃ | 20.08 | 29.12 |
| Fe ₂ O ₃ | 13.32 | 9.81 |
| CaO | 13.07 | 1.33 |
| SO ₃ | 2.16 | 0.65 |
| MgO | 1.09 | 0.81 |
| Mn ₂ O ₃ | 0.15 | 0.04 |
| Cr ₂ O ₃ | 0.01 | --- |
| Na ₂ O | 0.17 | < 0.01 |
| K ₂ O | 0.77 | 0.96 |
| TiO ₂ | 1.64 | 1.35 |
| P ₂ O ₅ | 1.03 | 0.16 |

4.2.2.3. Hasil Pengujian

Hasil pengujian kuat tekan ditunjukkan oleh tabel 4.9.

Tabel 4.9 Hasil Pengujian Kuat Tekan Campuran Mortar Geopolimer Dengan *Fly Ash* Tipe C dan F

| No. | NaOH | NaOH : Na ₂ SiO ₃ | Air/prekursor | Pasir /Fly Ash | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) | |
|-----|------|--|---------------|-------------------|-------------------|--------------------------|----------------|------------------|-----------|
| | | | | | | | | Fly Ash C | Fly Ash F |
| 1 | 8 M | 1:2 | 0.25 | 2 | 90 ⁰ C | 24 + 6 | 7 | 57.22 | 51.91 |
| 2 | 8 M | 1:2 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 71.59 | 62.88 |
| 3 | 8 M | 1:2 | 0.35 | 2 | 90 ⁰ C | 24 + 6 | 7 | 66.04 | 55.11 |



Grafik 4.7 Hasil Pengujian Kuat Tekan Campuran Mortar Geopolimer Dengan *Fly Ash* Tipe C dan F

Berdasarkan hasil uji sample beton pada umur 7 hari diperoleh kuat tekan yang optimal dengan rasio perbandingan air/prekursor = 0,3 dan konsentrasi *sodium hidroksida* sebesar 8 M.

4.2.3. Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

Penelitian ini dilakukan oleh M Olivia, P Sarker, dan H Nikraz dari Curtin University of Technology, Australia pada tahun 2008

4.2.3.1. Alkaline Aktivator

Alkaline Aktivator yang digunakan pada penelitian ini adalah gabungan dari *sodium hidroksida* (NaOH) dan *sodium silikat* (Na₂SiO₃).

4.2.3.2. Prekursor

Prekursor yang digunakan pada penelitian ini adalah *fly ash* PLTU Collie yang terdapat di sebelah tenggara Australia. Komposisi kimia dari *fly ash* tersebut ditunjukkan pada tabel 4.10.

Tabel 4.10. Komposisi Kimia *Fly Ash* PLTU Collie

| Element | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | K ₂ O | MgO | Na ₂ O | P ₂ O ₅ | SO ₃ | LOI |
|---------|------------------|--------------------------------|--------------------------------|------|------------------|------|-------------------|-------------------------------|-----------------|------|
| % Mass | 50.3 | 26.3 | 13.6 | 2.27 | 0.55 | 1.44 | 0.36 | 1.58 | 0.32 | 0.54 |

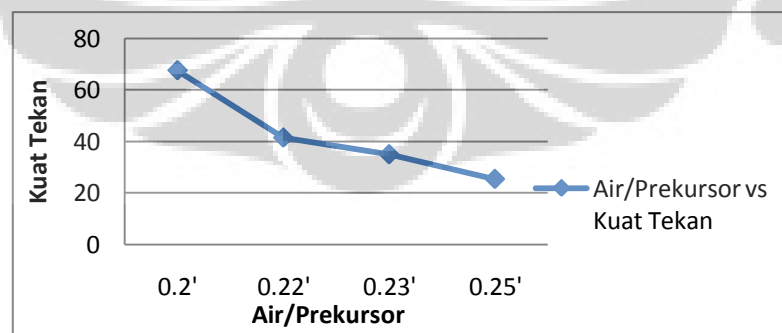
Berdasarkan komposisi kimianya, *fly ash* PLTU Collie digolongkan sebagai *fly ash* tipe F.

4.2.3.3. Hasil Penelitian

Hasil pengujian pada umur beton 28 hari ditunjukkan pada table 4.11.

Tabel 4.11 Hasil Pengujian Kuat Tekan Terhadap Rasio Air/Prekursor Dengan Prekursor *Fly Ash* PLTU Collie

| Mix no | Prekursor | NaOH | NaOH / Na ₂ SiO ₃ | Air/Prekursor | Pasir / <i>Fly Ash</i> | Superplastisizer (Kg/m ³) | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (Mpa) |
|--------|------------------|------|---|---------------|------------------------|---------------------------------------|-------------------|---------------------|-------------------|------------------|
| GP1 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.23 | 1,586 | 6,1 | 60 ^o C | 1 | 28 | 34.86 |
| GP2 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.22 | 1,586 | 6,1 | 60 ^o C | 1 | 28 | 41.36 |
| GP3 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.2 | 1,586 | 6,1 | 60 ^o C | 1 | 28 | 67.53 |
| GP4 | <i>Fly Ash</i> F | 14 M | 0,398 | 0.25 | 1,586 | 6,1 | 60 ^o C | 1 | 28 | 25.28 |



Grafik 4.8 Hasil Pengujian Kuat Tekan Terhadap Rasio Air/Prekursor Dengan Prekursor *Fly Ash* PLTU Collie

Berdasarkan hasil uji sample beton pada umur 28 hari diperoleh kuat tekan yang optimal dengan rasio perbandingan massa air/prekursor = 0,2 dan konsentrasi *sodium hidroksida* sebesar 14 M.

4.2.4. Factor Influencing The Compressive Strength of Fly Ash Based Geopolymer Concrete

Penelitian ini dilakukan oleh Djwantoro Hardjito, Steenie E. Wallah, Dody M.J.Sumajouw, and B.V. Rangan, dari Curtin University Of Technology, Australia pada September 2004.

4.2.4.1. Alkaline Aktivator

Alkaline activator yang digunakan pada penelitian ini adalah gabungan dari *sodium hidroksida* (NaOH) dengan kemurnian 98% dan *sodium silikat* (Na₂SiO₃) dengan kandungan Na₂O = 14.7%, SiO₂ = 29.4% dan air = 55.9%.

4.2.4.2. Prekursor

Prekursor yang digunakan dalam penelitian ini adalah *fly ash* PLTU Collie yang terletak di Australia bagian tenggara. Kandungan kimia *fly ash* ditunjukkan oleh tabel 4.12

Tabel 4.12. Kandungan Kimia *Fly Ash* PLTU Collie

| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | Na ₂ O | K ₂ O | TiO ₂ | MgO | P ₂ O ₅ | SO ₃ | LOI |
|----------|------------------|--------------------------------|--------------------------------|------|-------------------|------------------|------------------|------|-------------------------------|-----------------|------|
| %Mass | 53.36 | 26.49 | 10.86 | 1.34 | 0.37 | 0,8 | 1,47 | 0,77 | 1,43 | 1,7 | 1,39 |

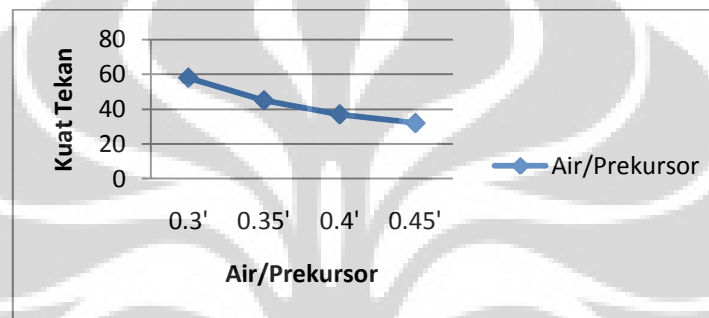
Berdasarkan kandungan kimia, *fly ash* PLTU Collie digolongkan sebagai *fly ash* tipe F.

4.2.4.3. Hasil Pengujian

Hasil pengujian pada umur 28 hari ditunjukkan pada table 4.13.

Tabel 4.13 Hasil Pengujian Kuat Tekan Terhadap Rasio Air/Prekursor Dengan Prekursor *Fly Ash* PLTU Collie

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Air/Prekur sor | Kuat Tekan (MPa) |
|-----|------------------|------|--|----------------|---------------------------|-------------------------|-------------------|------------------------|
| 1 | <i>Fly Ash F</i> | 8 M | 2:5 | 60°C | 1 | 28 | 0.3 | 58 |
| 2 | <i>Fly Ash F</i> | 8 M | 2:5 | 60°C | 1 | 28 | 0.35 | 45 |
| 3 | <i>Fly Ash F</i> | 8 M | 2:5 | 60°C | 1 | 28 | 0.4 | 37 |
| 4 | <i>Fly Ash F</i> | 8 M | 2:5 | 60°C | 1 | 28 | 0.45 | 32 |



Grafik 4.9. Hasil Pengujian Kuat Tekan Terhadap Rasio Air/Prekursor Dengan Prekursor *Fly Ash* PLTU Collie

Berdasarkan hasil uji sample beton pada umur 28 hari diperoleh kuat tekan yang optimal dengan rasio perbandingan massa air/prekursor = 0,3 dan konsentrasi *sodium hidroksida* sebesar 8 M.

Berdasarkan empat penelitian yang telah diuraikan di atas dapat disimpulkan bahwa pada beton geopolimer rasio massa air/prekursor optimal akan menghasilkan kuat tekan beton geopolimer paling tinggi.

4.3. Pengaruh Suhu Curing Terhadap Kuat Tekan Beton Geopolymer

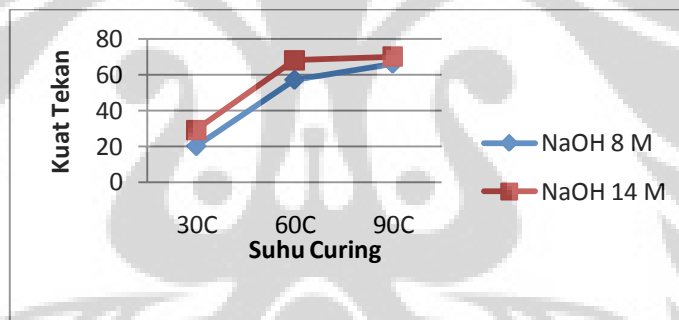
Reaksi polimerisasi membutuhkan panas dalam prosesnya, oleh karena itu metode curing dengan menggunakan oven atau microwave dengan suhu curing yang lebih tinggi dan waktu curing yang lebih lama cenderung lebih baik untuk menghasilkan beton geopolimer dengan kuat tekan yang tinggi.

4.3.1. Studies On Fly Ash Based Geopolymer Concrete

Penelitian ini dilakukan oleh Hardjito Djuwantoro dari Curtin University of Technology, Australia pada bulan November 2005. Penelitian ini membahas secara rinci tentang pembuatan beton geopolimer. Karena keterbatasan literature dan referensi pada saat itu, penelitian ini melakukan metode trial eror untuk mengetahui parameter yang mempengaruhi sifat beton geopolimer. Salah satu percobaan dengan variasi terhadap suhu curing ditunjukkan oleh table 4.14

Tabel 4.14 Hasil Pengujian Pengaruh Suhu Curing Terhadap Kuat Tekan Beton Geopolimer

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekurs or | Suhu Curing | Waktu Curing (jam) | Umur Beton | Kuat Tekan (MPa) | |
|-----|------------------|------|--|-------------------|----------------|--------------------------|---------------|------------------|---------------|
| | | | | | | | | NaOH (8M) | NaOH (14M) |
| 1 | <i>Fly Ash F</i> | 8M | 1:2.5 | 0.35 | 30 | 24 | 7 | 20 | 29 |
| 2 | <i>Fly Ash F</i> | 8M | 1:2.5 | 0.35 | 60 | 24 | 7 | 57 | 68 |
| 3 | <i>Fly Ash F</i> | 8M | 1:2.5 | 0.35 | 90 | 24 | 7 | 66 | 70 |



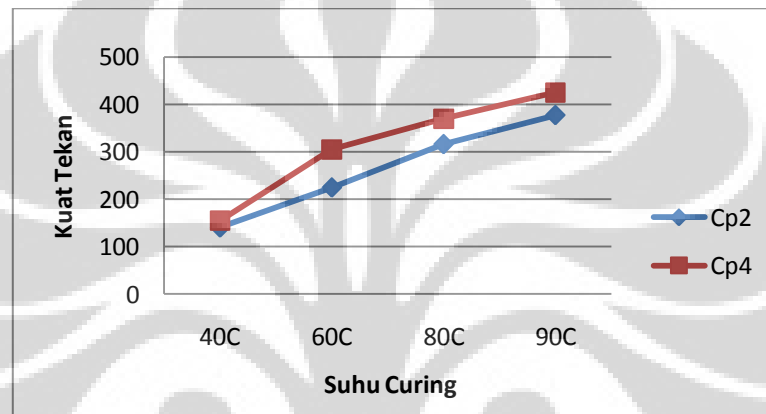
Grafik 4.10 Hasil Pengujian Pengaruh Suhu Curing Terhadap Kuat Tekan Beton Geopolimer

4.3.2. Recent Research Of Geopolymer Concrete

Penelitian ini dilakukan oleh Nguyen Van Chanh1- Assoc. Professor. PhD., Bui Dang Trung, Dang Van Tuan- Candidate M.E dari Faculty of Civil Engineering -University of Technology HCM City, Vietnam pada tahun 2008. Penelitian dengan variasi suhu curing ditunjukkan oleh table 4.15.

Tabel 4.15 Hasil Pengujian Kuat Tekan Dengan Variasi Suhu Curing

| No | Prekursor | Air/Prekursor | Pasir/ Fly Ash | Kerikil/Fly Ash | Suhu Curing | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (MPa) |
|-----|-----------|---------------|----------------|-----------------|-------------|---------------------|-------------------|------------------|
| cp2 | Fly Ash F | 0.4 | 1.63 | 2.876 | 40°C | 2 | 7 | 141 |
| cp2 | Fly Ash F | 0.4 | 1.63 | 2.876 | 60°C | 2 | 7 | 225 |
| cp2 | Fly Ash F | 0.4 | 1.63 | 2.876 | 80°C | 2 | 7 | 316 |
| cp2 | Fly Ash F | 0.4 | 1.63 | 2.876 | 90°C | 2 | 7 | 377 |
| cp4 | Fly Ash F | 0.4 | 1.2 | 2.1 | 40°C | 2 | 7 | 155 |
| cp4 | Fly Ash F | 0.4 | 1.2 | 2.1 | 60°C | 2 | 7 | 305 |
| cp4 | Fly Ash F | 0.4 | 1.2 | 2.1 | 80°C | 2 | 7 | 370 |
| cp4 | Fly Ash F | 0.4 | 1.2 | 2.1 | 90°C | 2 | 7 | 425 |



Grafik 4.11 Hasil Pengujian Kuat Tekan Dengan Variasi Suhu Curing

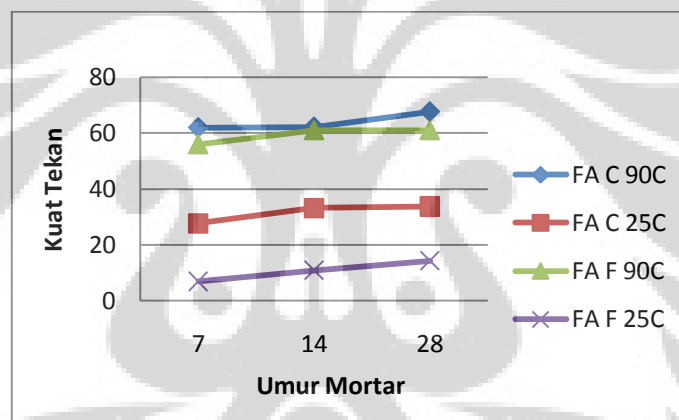
Berdasarkan hasil uji sample beton pada umur 7 hari diperoleh kuat tekan yang optimal dengan suhu curing 90°C.

4.3.3. Komposisi dan Karakteristik Beton Geopolimer dari Fly Ash tipe C dan F

Penelitian ini dilakukan oleh Johannes Prasetio Utomo dan Sandi Kosnatha dari Universitas Kristen Petra tahun 2007. Penelitian dengan variasi suhu curing ditunjukkan oleh table 4.16.

Tabel 4.16 Hasil Pengujian Kuat Tekan Mortar Geopolimer Terhadap Suhu Curing Dengan Prekursor *Fly Ash* Tipe C dan F

| No | Prekursor | NaOH | Air/Prekursor | NaOH : Na ₂ SiO ₃ | Pasir/ <i>Fly</i> <i>Ash</i> | Suhu Curing | Waktu Curing (hari) | Umur Mortar (hari) | Kuat Tekan (MPa) |
|----|------------------|------|---------------|--|---------------------------------|-------------------|---------------------------|--------------------------|------------------------|
| 1 | <i>Fly Ash</i> C | 8 M | 0.3 | 1:2 | 2 | 90 ⁰ C | 24 + 6 | 7 | 61.96 |
| 2 | <i>Fly Ash</i> C | 8 M | 0.3 | 1:2 | 2 | 90 ⁰ C | 24 + 6 | 14 | 62.17 |
| 3 | <i>Fly Ash</i> C | 8 M | 0.3 | 1:2 | 2 | 90 ⁰ C | 24 + 6 | 28 | 67.6 |
| 4 | <i>Fly Ash</i> C | 8 M | 0.3 | 1:2 | 2 | 25 ⁰ C | - | 7 | 27.69 |
| 5 | <i>Fly Ash</i> C | 8 M | 0.3 | 1:2 | 2 | 25 ⁰ C | - | 14 | 33.21 |
| 6 | <i>Fly Ash</i> C | 8 M | 0.3 | 1:2 | 2 | 25 ⁰ C | - | 28 | 33.74 |
| 7 | <i>Fly Ash</i> F | 8 M | 0.3 | 1:2 | 2 | 90 ⁰ C | 24 + 6 | 7 | 55.97 |
| 8 | <i>Fly Ash</i> F | 8 M | 0.3 | 1:2 | 2 | 90 ⁰ C | 24 + 6 | 14 | 61.01 |
| 9 | <i>Fly Ash</i> F | 8 M | 0.3 | 1:2 | 2 | 90 ⁰ C | 24 + 6 | 28 | 61 |
| 10 | <i>Fly Ash</i> F | 8 M | 0.3 | 1:2 | 2 | 25 ⁰ C | - | 7 | 6.99 |
| 11 | <i>Fly Ash</i> F | 8 M | 0.3 | 1:2 | 2 | 25 ⁰ C | - | 14 | 10.9 |
| 12 | <i>Fly Ash</i> F | 8 M | 0.3 | 1:2 | 2 | 25 ⁰ C | - | 28 | 14.35 |



Grafik 4.12 Hasil Pengujian Kuat Tekan Mortar Geopolimer Terhadap Suhu Curing Dengan Prekursor *Fly Ash* Tipe C dan F

Berdasarkan hasil uji sample beton pada umur 7,14, dan 28 hari hari diperoleh kuat tekan yang optimal dengan suhu curing sebesar 90⁰C.

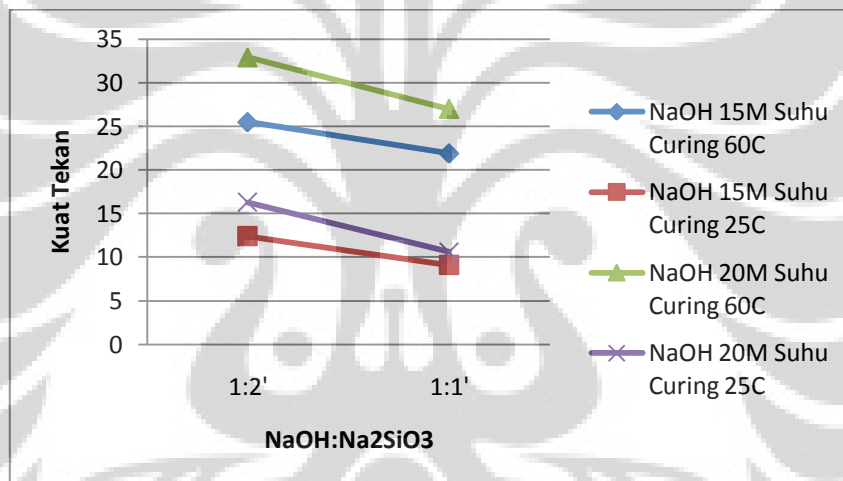
4.3.4. Engineering Properties of Mae MOH Fly Ash Geopolymer Concrete

Penelitian ini dilakukan oleh Smith Songpiriyakij, dari King Mongkut,s Institute of Technology North Bangkok, Thailand, Pada bulan Mei 2007. Hasil penelitian variasi

suhu curing terhadap kuat tekan beton geopolimer pada usia 7 hari ditunjukkan oleh tabel 4.17.

Tabel 4.17. Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Suhu Curing Dengan Prekursor *Fly Ash Mae Moh*

| No | Prekursor | NaOH | Air/Prekursor | NaOH : Na ₂ SiO ₃ | Pasir /Fly Ash | Kerikil /Fly Ash | Waktu Curing (hari) | Umur Beton (hari) | Kuat Tekan (MPa) | |
|----|------------------|------|---------------|--|-------------------|---------------------|---------------------------|-------------------------|------------------------|------------------------|
| | | | | | | | | | Suhu Curing 60°C | Suhu Curing 25°C |
| 3 | <i>Fly Ash F</i> | 15 M | 0.1663158 | 1:2 | 1,474 | 1,509 | 1 | 7 | 25,5 | 12,4 |
| 4 | <i>Fly Ash F</i> | 15 M | 0.1663158 | 1:1 | 1,474 | 1,509 | 1 | 7 | 21,9 | 9,1 |
| 6 | <i>Fly Ash F</i> | 20 M | 0.1663158 | 1:2 | 1,474 | 1,509 | 1 | 7 | 32,9 | 16,3 |
| 7 | <i>Fly Ash F</i> | 20 M | 0.1663158 | 1:1 | 1,474 | 1,509 | 1 | 7 | 27 | 10,6 |



Grafik 4.13. Hasil Pengujian Kuat Tekan Beton Geopolimer Terhadap Suhu Curing Dengan Prekursor *Fly Ash Mae Moh*

Berdasarkan hasil penelitian, diketahui bahwa komposisi optimal yang dapat menghasilkan kuat tekan paling tinggi adalah komposisi No 6 dengan rasio massa NaOH:Na₂SiO₃ = 1 : 2.

Berdasarkan paparan hasil pengujian dari penelitian penelitian diatas, dapat disimpulkan bahwa suhu curing yang lebih tinggi cenderung akan menghasilkan kuat tekan yang lebih besar.

4.4. Pengaruh Jenis Prekursor Terhadap Kuat Tekan Beton Geopolymer

Fly ash tipe F yang memiliki kandungan CaO yang lebih rendah cenderung lebih dipilih sebagai prekursor dibandingkan *fly ash* tipe C. Hal ini disebabkan kandungan kalsium yang tinggi dapat mengganggu proses polimerisasi dan mengubah mikrostructure (Gourley, 2003; Gourley and Johnson, 2005).

4.4.1. Komposisi Alkaline Aktivator dan *Fly Ash* Untuk Beton Geopolimer Mutu Tinggi

Penelitian ini dilakukan oleh Andi Sanjaya dan Calvin Yuwono dari Universitas Kristen Petra tahun 2006.

4.4.1.1 Prekursor

Prekursor yang digunakan dalam penelitian ini adalah *fly ash* yang berasal dari PLTU paiton. Kandungan kimia dari *fly ash* dapat dilihat pada table 4.18.

Tabel 4.18. Kandungan Kimia *Fly Ash* PLTU Paiton

| Elements | SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | LOI |
|----------|------------------|--------------------------------|--------------------------------|-------|-----|-----|
| %Mass | 45,8 | 14,05 | 3,4 | 24,15 | 5,6 | - |

4.4.1.2. Hasil Penelitian

Hasil pengujian kuat tekan mortar pada umur 7 hari ditunjukkan oleh tabel 4.19

Tabel 4.19 Hasil Pengujian Kuat Tekan Mix Design Mortar Geopolimer Dengan Prekursor *Fly Ash* PLTU Paiton

| No | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Preku rsor | Pasir/ <i>Fly</i> <i>Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|----|------------------|------|--|-------------------|---------------------------------|----------------|--------------------------|----------------|------------------------|
| 1 | <i>Fly Ash</i> C | 8 M | 1:2.5 | 0.3 | 2 | 90°C | 24 + 6 | 7 | 67.9 |

4.4.2. Komposisi dan Karakteristik Beton Geopolimer dari *Fly Ash* tipe C dan F

Penelitian ini dilakukan oleh Johanes Prasetio Utomo dan Sandi Kosnatha dari Universitas Kristen Petra tahun 2007.

4.4.2.1. Prekursor

Prekursor yang digunakan dalam penelitian ini adalah :

1. *Fly ash* tipe C yang berasal dari PLTU paiton yang diperoleh dari PT Jaya Ready Mix.
2. *Fly ash* tipe F yang berasal dari PLTU Suralaya yang diperoleh dari PT Indocement.

Kandungan kimia dari *fly ash* dapat dilihat pada table 4.20.

Tabel 4.20. Kandungan Kimia *Fly Ash* Tipe C dan F

| Oksida | <i>Fly Ash</i> Tipe C (%) | <i>Fly Ash</i> Tipe F (%) |
|--------------------------------|---------------------------|---------------------------|
| SiO ₂ | 46.39 | 54 |
| Al ₂ O ₃ | 20.08 | 29.12 |
| Fe ₂ O ₃ | 13.32 | 9.81 |
| CaO | 13.07 | 1.33 |
| SO ₃ | 2.16 | 0.65 |
| MgO | 1.09 | 0.81 |
| Mn ₂ O ₃ | 0.15 | 0.04 |
| Cr ₂ O ₃ | 0.01 | --- |
| Na ₂ O | 0.17 | < 0.01 |
| K ₂ O | 0.77 | 0.96 |
| TiO ₂ | 1.64 | 1.35 |
| P ₂ O ₅ | 1.03 | 0.16 |

4.4.2.2. Hasil Penelitian

Hasil pengujian kuat tekan mortar pada umur 7 hari ditunjukkan oleh tabel 4.21

Tabel 4.21 Hasil Pengujian Kuat Tekan Mix Design Beton Geopolimer Dengan Prekursor *Fly Ash* Tipe C dan F

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Preku rsor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|-----|------------------|------|--|-------------------|--------------------------|-------------------|--------------------------|----------------|------------------------|
| 1 | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 63.71 |
| 2 | <i>Fly Ash F</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 62.11 |

Berdasarkan hasil pengujian kuat tekan, pada penelitian ini *fly ash* tipe C menghasilkan kuat tekan yang lebih besar dari *fly ash* tipe F

Karena parameter yang digunakan pada kedua penelitian ini mirip, kita dapat membandingkan penelitian yang dilakukan oleh Sanjaya dan Yuwono dengan penelitian yang dilakukan oleh Johannes Prasetio Utomo dan Sandi Kosnatha secara langsung. Perbandingan hasil pengujian kedua penelitian tersebut ditunjukkan oleh table 4.22

Table 4.22 Perbandingan Penelitian Sanjaya-Yuwono dan Johannes Prasetio Utomo-Sandi Kosnatha

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/Prekursor | Pasir/ <i>Fly Ash</i> | Suhu Curing | Waktu Curing (jam) | Umur Mortar | Kuat Tekan (MPa) |
|-----------------------------|------------------|------|--|---------------|---------------------------|-------------------|--------------------------|----------------|------------------------|
| Sanjaya- Yuwono | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 67.9 |
| Prasetio Utomo- Sandi | <i>Fly Ash C</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 63.71 |
| Kosnatha | <i>Fly Ash F</i> | 8 M | 1:2.5 | 0.3 | 2 | 90 ⁰ C | 24 + 6 | 7 | 62.11 |

Berdasarkan kedua penelitian di atas, *fly ash* tipe C akan menghasilkan geopolimer dengan kuat tekan yang lebih besar dari *fly ash* tipe F. Dengan kata lain hasil yang ditunjukkan oleh kedua penelitian ini kontra dengan dasar teori yang ada. Berdasarkan teori yang berlaku secara umum, penggunaan *fly ash* tipe F sebagai prekursor akan menghasilkan beton geopolimer dengan kuat tekan yang lebih baik daripada beton geopolimer yang menggunakan *fly ash* tipe C sebagai prekursor. Perbedaan ini dapat disebabkan oleh pengaruh dari faktor dominan lain seperti suhu curing dan kandungan atom Si dalam geopolimer.

BAB 5

KESIMPULAN DAN SARAN

5.1. Kesimpulan

Berdasarkan analisa studi literatur yang telah dipaparkan pada bab 4, kita dapat menarik kesimpulan sebagai berikut.

1. Komposisi optimum pada kelompok penelitian konsentrasi NaOH dan rasio massa NaOH:Na₂SiO₃ adalah sebagai berikut

| | NaOH | NaOH:Na ₂ SiO ₃ |
|--|-------------------|---------------------------------------|
| Komposisi Alkaline Aktivator dan <i>Fly Ash</i> Untuk Beton Geopolimer Mutu Tinggi | 8 M | 1:2,5 |
| Komposisi dan Karakteristik Beton Geopolimer dari <i>Fly Ash</i> tipe C dan F | 8 M | 1:2 |
| Engineering Properties Of Mae MOH Fly Ash Geopolymer Concrete | 20 M | 1:2 |
| Feasibility Study Of Geopolymer | Tidak diberi tahu | 1:4 |
| Studies On Fly ash Based Geopolymer Concrete | 14 M | 1:2,5 |

Berdasarkan kelompok penelitian tersebut kuat tekan optimum akan tercapai pada rasio massa Na₂SiO₃:NaOH yang relatif lebih kecil. Kuat tekan paling tinggi akan tercapai pada rasio massa NaOH:Na₂SiO₃ yang optimum.

2. Komposisi optimum pada kelompok penelitian rasio massa air/prekursor adalah sebagai berikut

| | Air/Prekursor |
|--|---------------|
| Komposisi Alkaline Aktivator dan <i>Fly Ash</i> Untuk Beton Geopolimer Mutu Tinggi | 0,25 |
| Komposisi dan Karakteristik Beton Geopolimer dari <i>Fly Ash</i> tipe C dan F | 0,3 |
| Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete | 0,2 |
| Factor Influencing The Compressive Strength Of Fly Ash Based Geopolymer Concrete | 0,3 |

Berdasarkan kelompok penelitian tersebut kuat tekan yang lebih tinggi tercapai pada rasio massa air/prekursor yang relatif lebih kecil. Rasio air/prekursor yang terlalu kecil juga tidak menghasilkan kuat tekan yang tinggi. Hal ini disebabkan tingkat workability yang tinggi dari beton geopolimer akan menyebabkan proses mixing menjadi kurang sempurna sehingga agregat, prekursor, dan larutan alkali tidak dapat terdistribusi dengan baik. Kuat tekan paling tinggi akan tercapai pada rasio massa air/prekursor yang optimum.

3. Suhu Curing

Suhu curing yang menghasilkan kuat tekan paling tinggi pada kelompok penelitian suhu curing adalah sebagai berikut

| | Suhu Curing |
|---|-------------|
| Studies On Fly Ash Based Geopolymer Concrete | 90°C |
| Recent Research Of Geopolymer Concrete | 90°C |
| Komposisi dan Karakteristik Beton Geopolimer dari <i>Fly Ash</i> tipe C dan F | 90°C |
| Engineering Properties Of Mae MOH Fly Ash Geopolymer Concrete | 60°C |

Berdasarkan kelompok penelitian tersebut kuat tekan yang lebih tinggi tercapai pada suhu curing yang lebih tinggi.

4. Jenis Prekursor yang menghasilkan kuat tekan lebih tinggi pada kelompok penelitian jenis prekursor adalah sebagai berikut

| No. | Prekursor | NaOH | NaOH : Na ₂ SiO ₃ | Air/pre kursor | Suhu curing |
|--|------------------|------|--|-------------------|----------------|
| Komposisi Alkaline Aktivator dan <i>Fly Ash</i> Untuk Beton Geopolimer Mutu Tinggi | <i>Fly Ash</i> C | 8 M | 1:2.5 | 0.3 | 90°C |
| Prasetio Utomo-Sandi Komposisi dan Karakteristik Beton Geopolimer dari <i>Fly Ash</i> tipe C dan F | <i>Fly Ash</i> C | 8 M | 1:2.5 | 0.3 | 90°C |
| | <i>Fly Ash</i> F | 8 M | 1:2.5 | 0.3 | 90°C |

Berdasarkan teori yang berlaku secara umum, penggunaan *fly ash* tipe F sebagai prekursor akan menghasilkan beton geopolimer dengan kuat tekan

yang lebih baik daripada beton geopolimer yang menggunakan *fly ash* tipe C sebagai prekursor. Oleh karena itu hasil penelitian ini bertentangan dengan dasar teori yang berlaku secara umum. Perbedaan ini kemungkinan disebabkan oleh pengaruh dari faktor dominan lain seperti suhu curing, dan kandungan atom Si dalam geopolimer.

5.2. Saran

Mengingat faktor faktor yang mempengaruhi kuat tekan beton geopolimer sangat banyak dan saling mempengaruhi satu sama lain, terdapat beberapa saran untuk penelitian selanjutnya :

1. Perlu dilakukan penelitian yang meninjau komposisi kandungan kimia yang optimal, seperti rasio Al;Si, dan Al:Na yang dapat menghasilkan kuat tekan beton geopolimer paling baik.
2. Perlu dilakukan penelitian yang meninjau faktor lain yang mempengaruhi kuat tekan geopolimer seperti metode mixing, metode curing, rasio pasir/prekursor, dan lain lain,
3. Perlu dilakukan penelitian untuk mencari komposisi optimal untuk pasta dan mortar terlebih dahulu. Hal ini perlu dilakukan untuk mengetahui komposisi agregat yang optimal dan metode mixing yang tepat untuk mendapatkan kuat tekan beton geopolimer yang optimal.

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A.18

RECENT RESEARCH GEOPOLYMER CONCRETE

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ABSTRACT: *Geopolymer is a type of amorphous alumino-silicate cementitious material. Geopolymer can be synthesized by polycondensation reaction of geopolymeric precursor, and alkali polysilicates. Comparing to Portland cement, the production of geopolymers has a relative higher strength, excellent volume stability, better durability. Geopolymer concrete based on pozzolana is a new material that does not need the presence of Portland cement as a binder. This paper presents the results of studying materials ,mixture composite, microstructure of Geopolymer, and parameters affecting properties of geopolymer concrete.*

KEYWORDS: Geopolymer, mixture composite, microstructure, properties of concrete.

1- GENERAL

An important ingredient in the conventional concrete is the Portland cement. The production of one ton of cement emits approximately one ton of carbon dioxide to the atmosphere. Moreover, cement production also consumes significant amount of natural resources.



Figure 1. Cement production consumes a lot of limestone and emits carbon dioxide



Figure 2. A huge volume of fly ash is not effectively used

On the other hand, already huge volume of fly ash is generated around the world; most of the fly ash is not effectively used, and a large part of it is disposed in landfills. In Viet Nam, volumes of fly ash are generated about 600,000 tons, but 100,000 is used to produce concrete. As the need for power increases, the volume of fly ash would increase. It is necessary and significant to use fly ash as material to produce concrete without Portland cement.

2- THE POLYMERIZATION AND MICROSTRUCTURE

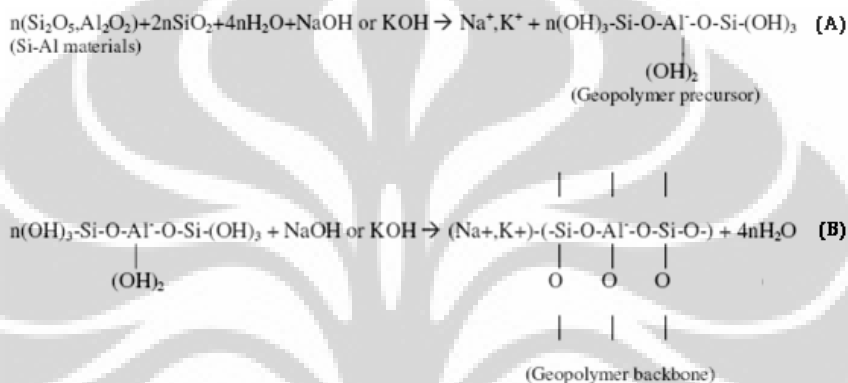
2.1. The chemical composition, polymerization of the geopolymer cement

The polymerisation process involves a substantially fast chemical reaction under alkaline condition on Si-Al minerals, that results in a three dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds, as follows:



Where: M = the alkaline element or cation such as potassium, sodium or calcium; the symbol – indicates the presence of a bond, n is the degree of polycondensation or polymerisation; z is 1, 2, 3, or higher.

The schematic formation of geopolymer material can be shown as described by Equations (A) and (B)



To date, the exact mechanism of setting and hardening of the geopolymer material is not clear. However, most proposed mechanism consist The chemical reaction may comprise the following steps:

- Dissolution of Si and Al atoms from the source material through the action of hydroxide ions.
- Transportation or orientation or condensation of precursor ions into monomers.
- Setting or polycondensation/polymerisation of monomers into polymeric structures.

However, these three steps can overlap with each other and occur almost simultaneously, thus making it difficult to isolate and examine each of them separately.

A geopolymer can take one of the three basic forms (Fig.3).

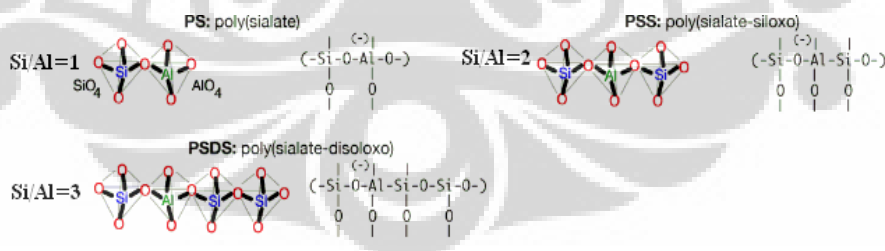


Figure 3. Three basic forms of geopolymer.

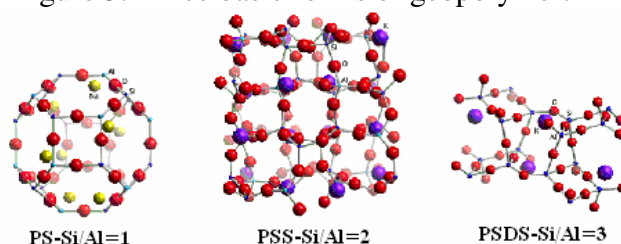


Figure 4. Polymeric structures from polymerisation of monomers.

2.2. Microstructure of the geopolymer cement

Unlike ordinary Portland/pozzolanic cements, geopolymer do not form calciumsilicate-hydrates (CSHs) for matrix formation and strength, but utilize the polycondensation of silica and alumina precursors and a high alkali content to attain structural strength. Composition of the geopolymer is similar to natural zeolitic materials, but the microstructure is amorphous instead of crystalline.

Fly ash particle: SEM was used to investigate the surface of fly ash, before and after reacting with NaOH. NaOH reacted with fly ash particles resulted in the roughness of surface as shown in Figure 5, 6, 7.

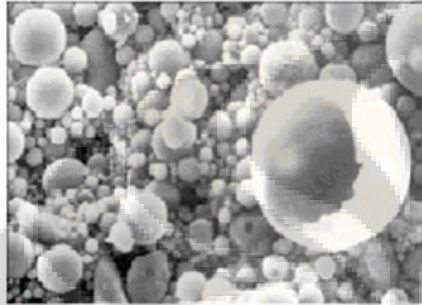


Figure 5. Fly ash before reacting with NaOH

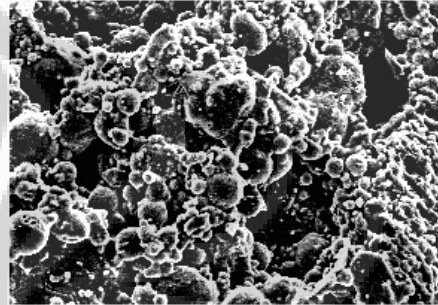


Figure 6. Fly ash after reacting with NaOH

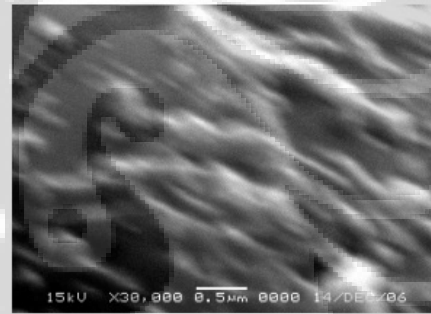
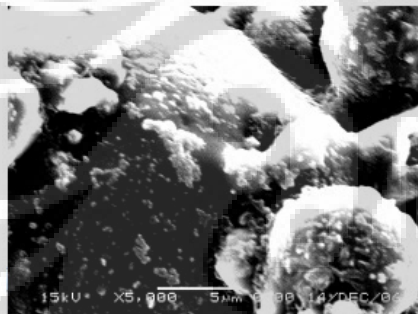


Figure 7. Fly ash after reacting with NaOH (x5000 and x30 000)

3- THE PROPERTIES OF GEOPOLYMER CEMENT

3.1. Materials

Materials includes Fly ash (FA), sand Aggregates (SA), Alkaline Liquid (AL), water (W), Super plasticizer (SP). In the batches of fly ash, the molar Si-to-Al ratio was about 1-3.

A combination of sodium silicate solution and sodium hydroxide solution was chosen as the alkaline liquid. The sodium hydroxide (NaOH) solution was prepared by dissolving either the flakes or the pellets in water. The mass of NaOH solids in a solution varied depending on the concentration of the solution expressed in terms of molar, M.

Sand is small Aggregates in geopolymer mortar. To improve the workability of the fresh geopolymer mortar, Super plasticizer was used in most of the mixtures.

3.2. Setting time and stable volume of geopolymer mortar

Setting time of geopolymer mortar depends on many factors. Such as types of fly ash, composition of alkaline liquid and ratio of alkaline liquid to fly ash by mass. However, the curing

temperature is the most important factor. Figure 8 shows the effect of curing temperature on setting time. As the curing temperature increases, the setting time decreases. The effect of curing temperature on initial setting and final setting time is similar to setting time.

Table 1. Composition of Fly Ash (mass %)

| Oxides | | Oxides | |
|------------------------------------|------|--|------|
| SiO ₂ (%) | 52.0 | Na ₂ O (%) | 0.27 |
| Al ₂ O ₃ (%) | 33.9 | MgO (%) | 0.81 |
| Fe ₂ O ₃ (%) | 4.0 | SO ₃ (%) | 0.28 |
| CaO (%) | 1.2 | LOI (%) | 6.23 |
| K ₂ O (%) | 0.83 | SiO ₂ /Al ₂ O ₃ | 1.5 |

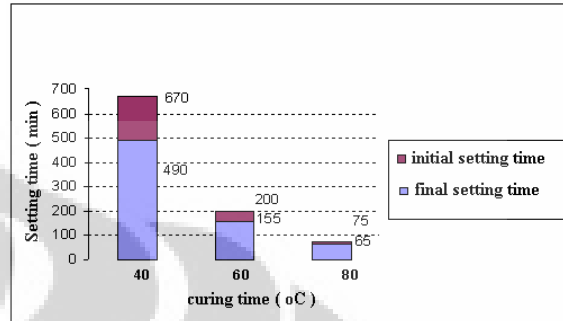


Figure 8. Effect of curing temperature on setting time

The stable volume of geopolymer mortar depends on many factors. However, curing temperature and curing time are primary factors. Geopolymer mortar specimen cakes are boiled in water about 4 hours after curing at 60^oC for 2 hours. It is not cracked. That means its volume is still stable.

3.3. Compressive strength.

Table 2. Mixture proportion

| Kí hiệu | FA | SA | AL | W | SP | AL/FA | W/AL |
|---------|------|------|----------|----|------|-------|------|
| | (kg) | | | | | | |
| Cp1 | 527 | 1586 | 157(18M) | 40 | 5.27 | 0.3 | 0.25 |
| Cp2 | 527 | 1586 | 182(18M) | 46 | 5.27 | 0.35 | 0.25 |
| Cp3 | 527 | 1586 | 211(18M) | 52 | | 0.4 | 0.25 |
| Cp4 | 527 | 1586 | 237(18M) | 59 | | 0.45 | 0.25 |
| Cp5 | 527 | 1586 | 192(14M) | 48 | | | |

Compressive strength depends on curing time and curing temperature. As the curing time and curing temperature increase, the compressive strength increase. Curing temperature in (60^oC-90^oC), curing time in (24h-72h), compressive strength 400-500 kG/cm².

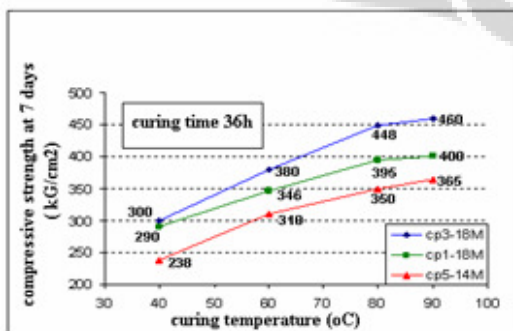


Figure 9. Effect of extra water on compressive strength.

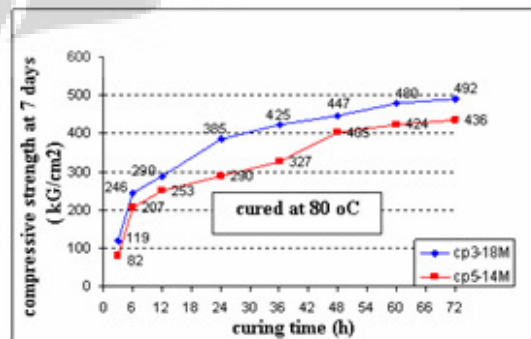


Figure 10. Effect of curing time on compressive strength.

3.4. Resistance to corrosion

Since no limestone is used as a material, geopolymer cement has excellent properties within both acid and salt environments. It is especially suitable for tough environmental conditions. Sea water can be used for the blending of the geopolymer cement. This can be useful in marine environments and on islands short of fresh water. (It is impossible to make Portland cement with sea water).

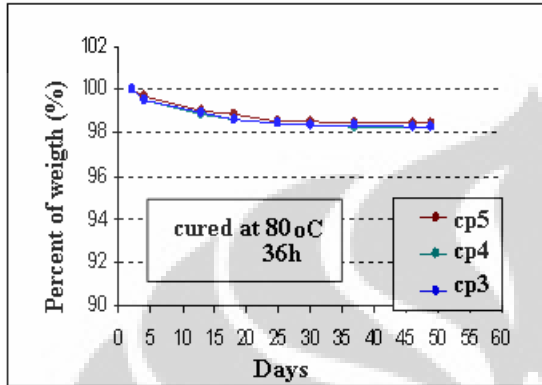


Figure 11. The loss weight of samples put into 5% HCl

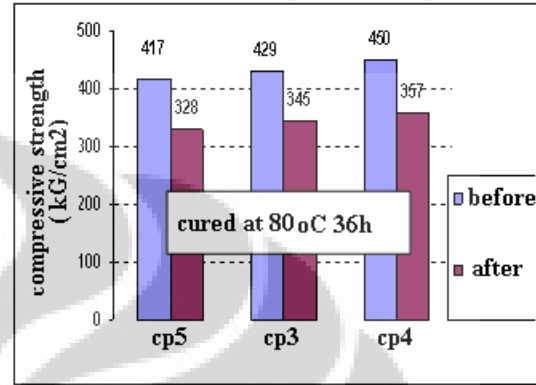


Figure 12. Change compressive strength after putting into 5% HCl for 7 weeks

4- THE PROPERTIES OF GEOPOLYMER CONCRETE

4.1. Materials

Geopolymer cement, sand (SA) and coarse aggregates (CA), total Aggregates (A)

Table 3. Mixture proportion

| Mix | CA | SA | FA | AL | W | SP | A/FA |
|-----|------|-----|-----|-----|---|----|------|
| | kg | | | | | | |
| Cp1 | 1050 | 595 | 329 | 132 | 0 | 5 | 5 |
| Cp2 | 1050 | 595 | 365 | 147 | 0 | 5 | 4.5 |
| Cp3 | 1050 | 595 | 411 | 165 | 0 | 6 | 4 |
| Cp4 | 1050 | 595 | 498 | 199 | 0 | 7 | 3.5 |
| Cp5 | 1050 | 595 | 538 | 210 | 0 | 8 | 3 |

4.2. Workability of the fresh geopolymer concrete

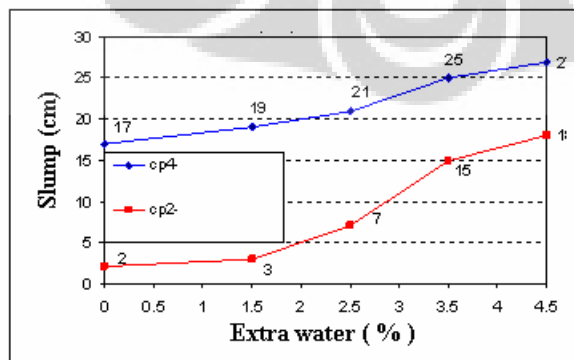


Figure 13. Effect of extra water on slump.

Extra water was added to improve the workability. Figure 13 shows the variation of measured slump of fresh concrete with the ratio of extra water to fly ash, by mass.

4.3. Compressive strength

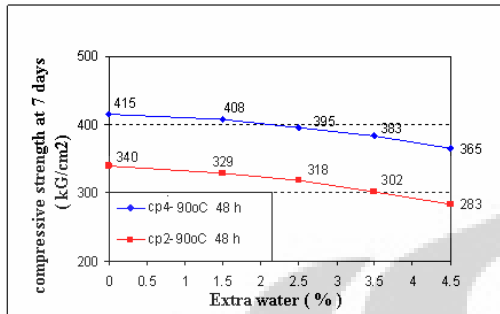


Figure 14. Effect of extra water on compressive strength

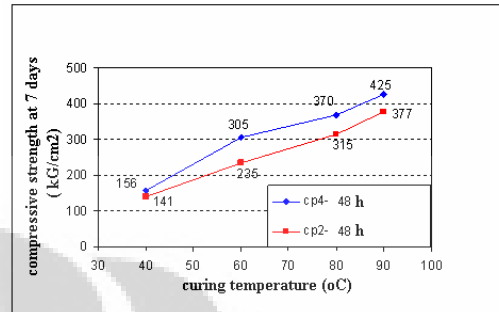


Figure 15. Effect of curing temperature on compressive strength

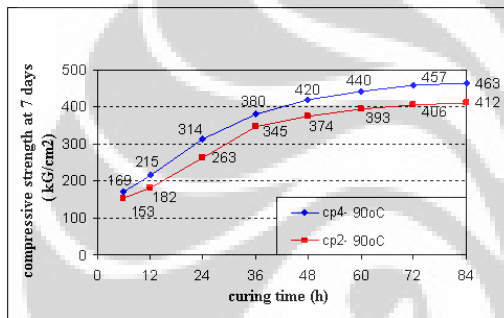


Figure 16. Effect of curing time on compressive strength

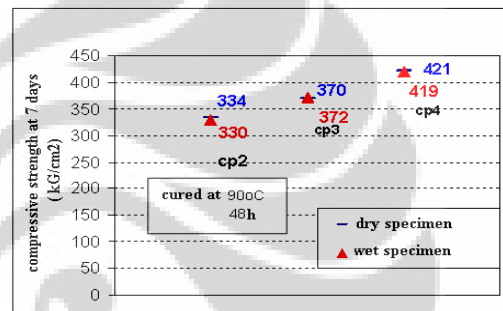


Figure 17. The compressive strength of saturated water specimens

Figure 14 shows as the extra water increases, the compress strength decreases.

Figure 15, 16 show as the curing time or curing temperature increases, the compressive strength increases.

4.4. Resistance to corrosion

The same geopolymer cement, geopolymer concrete has excellent properties within both acid and salt environments.

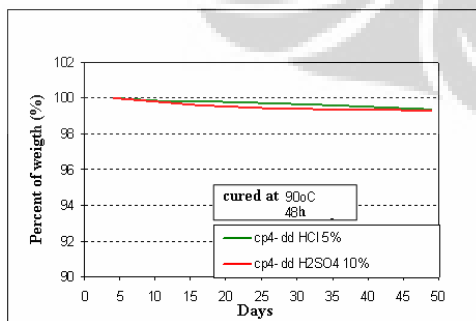


Figure 18. The loss weight of samples put into 5% HCl and 10% H₂SO₄

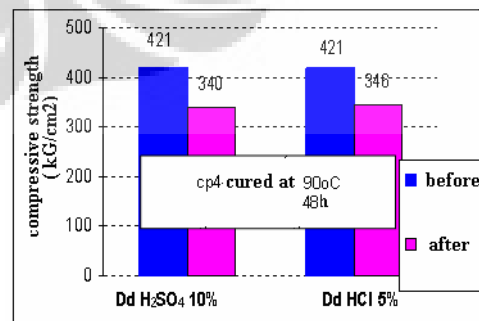


Figure 19. Change compressive strength after putting into 5% HCl and 10% H₂SO₄ for 7 weeks

4- CONCLUSIONS

Based on the the use of fly ash as a basic Si-Al ingredient of geopolymer was investigated. The following conclusions are drawn.

- ❖ As the curing temperature in the range of 60°C to 90°C increases, the compressive strength of fly ash-based geopolymer concrete also increases.
- ❖ Longer curing time, in the range of 24 to 72 hours (4 days), produces higher compressive strength of fly ash-based geopolymer concrete. However, the increase in strength beyond 48 hours is not significant.
- ❖ The slump value of the fresh fly-ash-based geopolymer concrete increases with the increase of extra water added to the mixture.
- ❖ The compressive strength of heat-cured fly ash-based geopolymer concrete does not depend on age.
- ❖ Geopolymer concrete has excellent properties within both acid and salt environments. Comparing to portland cement, the production of geopolymers have a relative higher strength, excellent volume stability, better durability.

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ICCBT2008

Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

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ABSTRACT

This paper presents a study on water penetrability properties, namely water absorption, volume of permeable voids, permeability and sorptivity of low calcium fly ash geopolymer concrete. In this research, geopolymer concrete is made from fly ash with a combination of sodium hydroxide and sodium silicate as alkaline activator. Seven mixes were cast in 100x200mm cylinders and cured for 24 hours at 60⁰C in the steam curing chamber. After 28 days, the cylinders were cut into slices for permeability, sorptivity and volume of permeable voids tests. In addition, a microstructure characteristic of geopolymer concrete was studied using Scanning Electron Microscopy (SEM). Results indicate that geopolymer concrete has low water absorption, volume of permeable voids and sorptivity. It is found that the geopolymer concrete could be classified as a concrete with an average quality according to water permeability value. Moreover, a low water/binder ratio and a well-graded aggregate are some important factors to achieve low water penetrability of geopolymer concrete.

Keywords: *absorption, durability, geopolymer, porosity, sorptivity, water permeability*

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1. INTRODUCTION

Water penetrability, namely absorption, permeability and sorptivity are some important measurements to control concrete durability. Penetrability of liquid into the concrete consists of permeability through a porous medium, diffusion and absorption. Regarding to this, pores in concrete have an important role to allow the liquid/fluid move through the concrete. However, the tendency of concrete to absorb and transmit water by capillary action not only depends on the porosity but also on its pore diameter, distribution, continuity and tortuosity.

Geopolymer concrete is a new type of concrete that can be made from fly ash/metakaolin/slag and activated with alkaline solutions. Many studies confirmed that fly ash geopolymer concrete has good engineering properties (Hardjito, 2005; Fernandez-Jimenez, *et al.* 2006; Sofi, *et al.* 2007). Other studies also show that low calcium fly ash geopolymer concrete has good durability on acid and sulphate condition (Wallah, 2005), alkali-aggregate reaction (Garcia-Lodeiro, *et al.* 2007), corrosion (Yodmune & Yodsujai, 2006) and fire resistance (Kong, *et al.*, 2007). Despite the superior resistance of the low calcium fly ash geopolymer concrete in various severe environments, according to Kong, *et al.* (2007) and Sindhunata (2006), the fly ash geopolymer paste contains higher proportion of pores in the mesopores size. This condition may lead water to penetrate easily and will affect the durability of the material.

Limited studies made on geopolymer concrete show that metakaolin geopolymer concrete has permeability 10^{-11} m/s (Davidovits, 1994a), while Shi (1996) found that permeability of slag geopolymer concrete is more than 10^{-12} m/s. Since the water penetrability of fly ash geopolymer concrete is rarely reported, hence the aim of this investigation is to determine water penetrability of low calcium fly ash geopolymer, namely water permeability, sorptivity and water absorption.

2. GEOPOLYMER CONCRETE

Geopolymer is a mineral polymer from the geochemistry process (Davidovits, 1994b). This alumina silicate polymer is synthesised from silica and alumina in the source material. Silica and alumina are obtained from natural material and industry by-products such as fly ash, metakaolin and slag. Although different source materials are used to manufacture geopolymers, basically, the activation of the source materials using an alkaline solution results in compact well cemented composites.

The geopolymerization process consists of chemical reaction of Si-Al mineral in alkaline condition that involves the dissolution of Si-O-Al-O bond. The process is described as $Mn [-(Si - O_2)_z - Al - O]_n, wH_2O$, with Mn = alkaline element, - = bond, z = 1, 2, 3, and n = degree of polymerization. The alkaline chemicals used in geopolymerization are $Ca(OH)_2$, NaOH, Na_2SiO_3 (sodium silicate), a combination of NaOH and sodium silicate, a combination of KOH and NaOH, KOH, potassium silicate and its combination, and sodium carbonate. A combination of alkaline solution determines the final product and geopolymer strength. Research on the effects of alkaline solution on the final product of geopolymer (Fernandez-Jimenez, *et al.* 2005) showed that a combination of NaOH and Na_2SiO_3 (sodium silicate)

produced a solid material almost without pores and has a strong bond between aggregate and geopolymer matrix.

Some researchers reported a mesoporous character of geopolymer paste/concrete (Chang, *et al.* 1999; Kong, *et al.* 2007; Shindunata, *et al.* 2006). This has resulted from a fusion of fly ash highly in Si and Al elements with alkaline solution. Fernandez-Jimenez, *et al.* (2005), revealed that type of activator plays an important role to convert fly ash into mesoporous product. According to Sindhunata *et al.* (2006), the fly ash geopolymer gel is porous because evaporation of the aqueous pore solution leaving the empty voids, insufficient geopolymer gel to fill the gaps in between an unreacted fly ash, and porosity of partially reacted fly ash particles. It is found that the total pore volume of concrete increases as the curing temperature is elevated.

4. EXPERIMENTAL PROGRAM

4.1 Materials and Mixtures

Geopolymer concrete in this study was made from low calcium fly ash with a combination of sodium hydroxide (NaOH) and sodium silicate solution (Na₂SiO₃). Table 1 shows the chemical composition of fly ash from Collie power station, Western Australia.

Table 1. Chemical analysis fly ash

| Elements | Fly ash |
|--------------------------------|---------|
| SiO ₂ | 50.3 |
| Al ₂ O ₃ | 26.3 |
| Fe ₂ O ₃ | 13.6 |
| CaO | 2.27 |
| K ₂ O | 0.55 |
| MgO | 1.44 |
| Na ₂ O | 0.36 |
| P ₂ O ₅ | 1.58 |
| SO ₃ | 0.32 |
| LOI | 0.54 |

Table 2 displays the mixture proportion of fly ash geopolymer concrete in this research. The basic geopolymer mixture proportion (mix GP1) was selected from some mixtures proposed by Hardjito (2005). The mixture is primarily used to produce geopolymer concrete with properties and performance that is equivalent to OPC concrete with strength 35 MPa. Different mixes of low calcium fly ash geopolymer concrete were made by varying the water/binder ratio (0.20-0.25), aggregate/binder ratio (3.5, 3.9, 4.7) and aggregate grading (7:10mm, 7:10:20mm). Two mixes of OPC concrete were made by varying the water/cement ratio to achieve the same level of strength with geopolymer concrete.

Sodium hydroxide in a form of pellets was dissolved in the water. In this research, the concentration of sodium hydroxide used was 14M. Sodium silicate solution with SiO₂ to Na₂SiO₃ ratio approximately 2 was supplied by PQ Australia. Superplasticizer (naphthalene based) was included in the mixes to improve workability. The granite coarse aggregate used

Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

was 20mm maximum size. The aggregates were conditioned to meet SSD requirement (3-5% moisture content).

Table 2. Mixture proportion

| Mixture no | w/c | w/b | a/b | Quantity (kg/m ³) | | | | | | | | | |
|------------|------|------|-----|-------------------------------|--------|------------------|------|------|------|---------|------------|-----|-----|
| | | | | Water | Cement | Coarse Aggregate | | | Sand | Fly ash | NaOH (14M) | S.S | S.P |
| | | | | | | 7mm | 10mm | 20mm | | | | | |
| C1 | 0.53 | - | - | 205 | 386 | 621 | 562 | - | 637 | - | - | - | - |
| C2 | 0.50 | - | - | 188 | 377 | 635 | 574 | - | 642 | - | - | - | - |
| GP1 | - | 0.23 | 3.9 | 25.8 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP2 | - | 0.22 | 3.9 | 20.7 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP3 | - | 0.20 | 3.9 | 16.5 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP4 | - | 0.25 | 3.9 | 36.2 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP5 | - | 0.22 | 3.5 | 25.8 | - | 630 | 540 | - | 630 | 444 | 44 | 111 | 6.1 |
| GP6 | - | 0.24 | 4.7 | 25.8 | - | 672 | 576 | - | 672 | 356 | 36 | 89 | 6.1 |
| GP7 | - | 0.23 | 3.9 | 25.8 | - | 645 | 370 | 277 | 554 | 408 | 41 | 103 | 6.1 |

Note: A = OPC/control mixture, B = Geopolymer mixture, S.S = Sodium Silicate; S.P = Superplasticizer

4.2 Specimens preparation and curing

OPC concrete specimens were prepared according to AS 1012.2-1983. Low calcium fly ash geopolymer concrete were made using a mixing procedure developed by Hardjito (2005). A chemical solution consists of NaOH (14M), Sodium Silicate, extra water and Superplasticizer was prepared approximately 2 hours before mixing process. In this process, firstly, the fly ash and aggregates were mixed for three minutes. Then a chemical solution was poured slowly to the dry mix. The pan mixer continued to mix all ingredients for another four minutes to achieve uniform mix.

All OPC and geopolymer concrete specimens were cast in concrete cylinders of 100mm diameter by 200mm height. Fifteen concrete cylinders from each of the nine concrete mixtures were cast. Those samples were cured using a steam curing process at temperature of 60°C for 24 hours. Then the specimens were left for air curing in a control environment with a temperature of 23-25°C until testing. Six cylinders from each mixture were used to determine compressive strength at 7 and 28 days (three specimens tested as each date). Three specimens for each mixture were prepared for water absorption and AVPV test, while other three were used for sorptivity test at 28 days age of concrete. For water permeability test, only two slices of individual specimens were used. Small samples with a thickness 5mm and area of 1cm² were taken for Scanning Electron Microscopy (SEM) analysis. These samples were coated with carbon and undergone a vacuuming process for overnight prior to SEM.

4.3 Test Procedure

Compressive strength tests were performed at 7 and 28 days using an Avery testing machine with a loading rate 16 MPa/minute.

Water absorption and volume of permeable voids determination were carried out according to ASTM C 642. For each concrete mix, three specimens were cut into slices with maximum thickness of 50mm for water absorption and AVPV test. These specimens were dried in the oven at 105°C until constant mass. Water absorption is measured by drying the specimen to

constant mass, immersing it in water and measuring the increase in mass as a percentage of dry mass. Volume of permeable voids is determined by boiling the concrete for at least 5 hours, weighing them in water, then measuring the percentage of boiled specimens with dried mass and mass in the water.

Sorptivity test was carried out according to Hall (1989). In this test, three specimens were dried in the oven at 105⁰C to constant mass. After cooling, the bottom surface of the specimen was cut and this cut surface was made to contact with water. The test was carried out by measuring the weight gain of the specimen at the set time intervals of 5 min, 10 min, 30 min, 1 h, 2 h, 3 h and 4 h. Then uptake of water per unit area of concrete surface I (g/mm) followed a linear relationship with the square root of time for the suction periods (t), hence

$$I = C + St^{0.5} \quad (4.3.1)$$

where S , the sorptivity is the slope of the I vs $t^{0.5}$ plot and can be obtained by linear regression.

Water permeability test were carried out for mixes GP1, GP2, GP4 and GP5 based on GHD Water Permeability method (previously Taywood Engineering Ltd), that modified according to DIN 1048. These specimens were dried in the oven at 105⁰C until constant mass. The specimens were coated with epoxy coating in the circular side to prevent water penetration from that side during the test. A pressure of 850 kPa was given to the samples at pressure head of 92.5 m. After the specimen saturated, then the flow rate reading was taken using burette by measuring the changing of volume of water with time. Permeability is defined using Darcy's Law,

$$k = \frac{QL}{AH} \quad (4.3.2)$$

where k = permeability coefficients (m/s), Q = flow rate (m³/s), A = area (m²), L = depth of specimen (m), H = head of water (m).

5. RESULTS AND DISCUSSIONS

5.1 Properties of fresh and hardened concrete

The slump and compressive strength of OPC and geopolymer concrete are shown in Table 3. The high slump of geopolymer mixes were achieved by addition of superplasticizer. Although the slump values are higher than 200mm for the geopolymer concrete, the compressive strength values are different for each mixture. It shows that geopolymer concrete has high workability for compressive strength than 30 MPa. It was found that an increase of amount of water will improve the workability, but decrease the strength of concrete (Hardjito, *et al.* 2004). When the water content is increased drastically, it will tend to produce bigger crystals of geopolymer and decrease the specific surface area of concrete. This will eventually lead to a decrease in strength (van Jaarsveld, *et al.* 2002).

Table 3. Properties of fresh and compressive strength of hardened concrete

| Mixture no | Slump (mm) | Compressive strength | |
|------------|------------|----------------------|---------|
| | | 7 days | 28 days |
| C1 | 200 | - | 34.09 |
| C2 | 80 | 39.68 | 47.50 |
| GP1 | 260 | 30.92 | 34.86 |
| GP2 | 230 | 38.32 | 41.36 |
| GP3 | 270 | 67.09 | 67.53 |
| GP4 | 270 | - | 25.28 |
| GP5 | 260 | 45.96 | 48.06 |
| GP6 | 240 | 24.19 | 25.44 |
| GP7 | 260 | 32.45 | 36.13 |

5.2 Water Absorption and Apparent Volume of Permeable Voids

The results of water absorption and AVPV of geopolymer concrete for mixes with different water/binder ratio is presented in Figure 1. The water absorption and AVPV increases with an increase in water content of the mix. The results indicated that the water absorption and AVPV were much affected by the extra water added into the mixture since it increases capillary porosity of concrete. As shown, water absorption and AVPV for mix GP4 with water/binder ratio 0.25 was significantly higher than those for other geopolymer mixes. Geopolymer concrete uses a very small amount of water in the mixture. The additional extra water is useful to achieve a particular strength. However, a relatively higher water/binder ratio produces a weaker and pervious matrix, leading to higher capillary porosity that is turn responsible for the increase in water absorption and AVPV of geopolymer mixes.

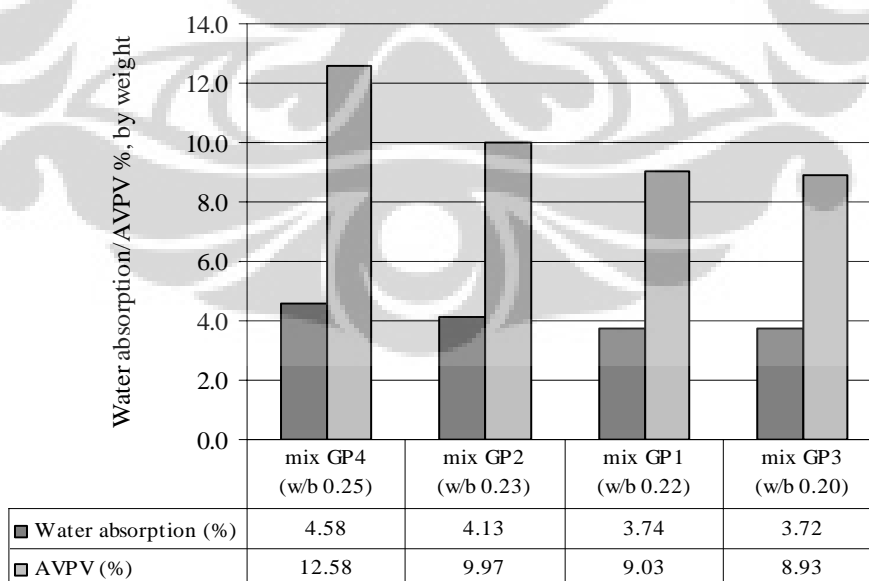


Figure 1. Water absorption and AVPV of geopolymer concrete for mixes with different water/binder ratio

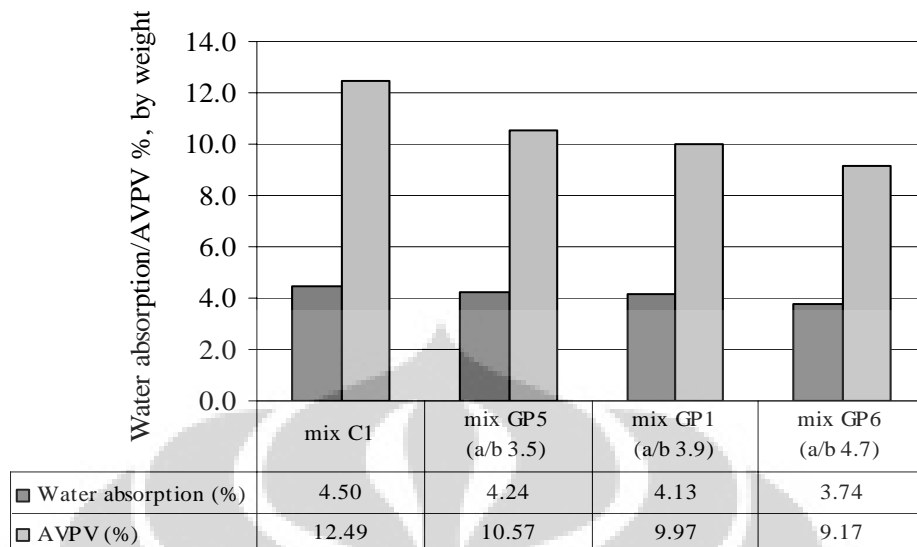


Figure 2. Water absorption and AVPV of OPC concrete and geopolymer concrete with different variation of aggregate binder ratio

Figure 2 shows water absorption and AVPV for different variation of aggregate binder ratio. Furthermore, mix GP5 resulted in higher compressive strength with high water absorption and AVPV than mix GP1. This mix represents more binder content than aggregate results on more porous concrete. Inclusion of sodium silicate addition in high amount is vulnerable to create more channels in the concrete during the steam curing process. This phenomenon confirmed the observations made by Sindhunata (2006) and Chang (1999).

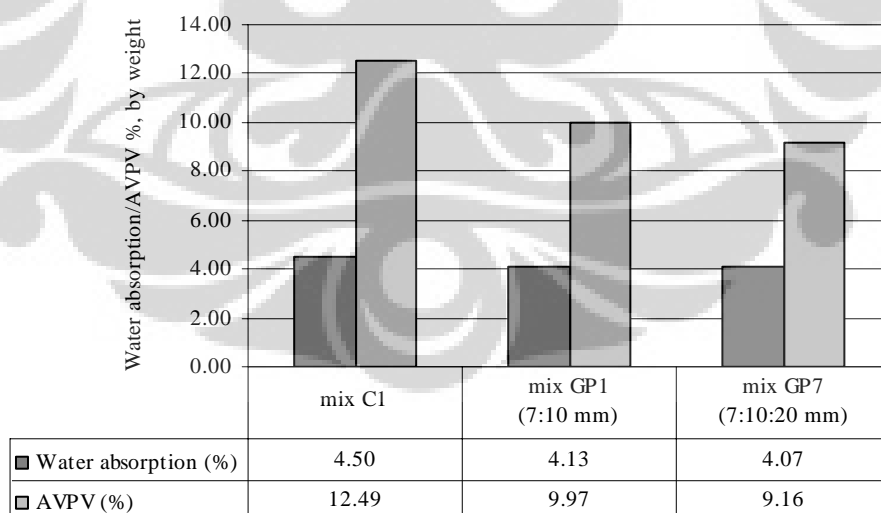


Figure 3. Water absorption and AVPV of OPC concrete and geopolymer concrete with different variation of aggregate grading

It can be seen from Figure 3 that for all mixes with the same water binder ratio, except for mix C1, a well-graded aggregate result on lower absorption and AVPV. In this case, aggregates

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composition using 7, 10, 20mm shows a lower capillary porosity compared to mix GP1 with only two different types of aggregates, which is 7 and 10mm. A better distribution of aggregate size reduces the size and continuity of concrete pores.

OPC concrete mixes (C1 and C2) that steam cured with the same strength with geopolymer concrete exhibits higher water absorption and AVPV (Figure 4). It indicates that for OPC concrete cured with steam curing resulted on high capillary porosity concrete. In this stage, there is no continuous hydration to fill and reduce the continuity of the pores. This condition results on coarser microstructure and higher porosity on the concrete. A similar increase in water absorption for steam cured OPC was reported by Ho, *et al.* (2003) and Campbell & Detwiler (1993).

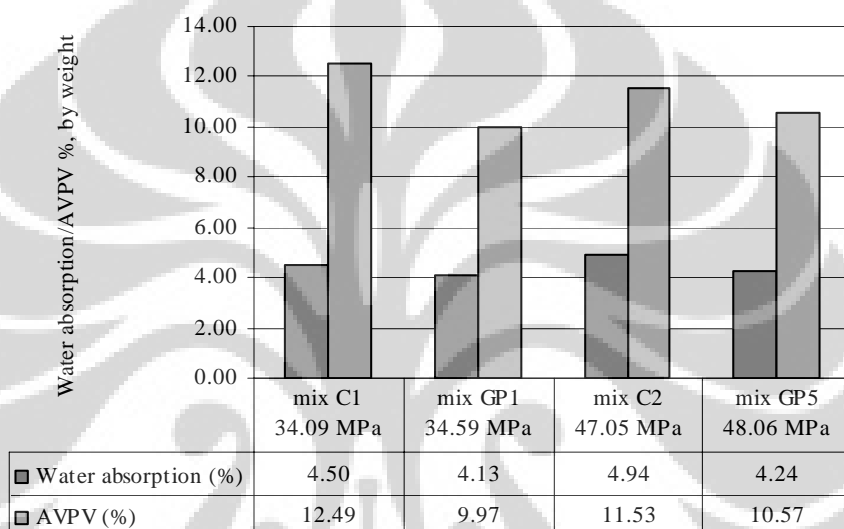


Figure 4. Water absorption and AVPV of control mixes and geopolymer concrete with the same strength

For both OPC and geopolymer mixes, a decrease in water/binder or water/cement ratios exhibits a marginal reduction of water absorption and AVPV. From the results, it can be seen that durability is more related to water/binder ratio than compressive strength. As the water content reduces, the paste content increases reducing the volume of capillary pores and thus showed a decreasing trend of water absorption and AVPV.

5.3 Sorptivity

Table 4 shows sorptivity values for control and geopolymer concrete at various water/binder ratio, aggregate binder ratio and aggregate grading. As shown, the results indicated that the sorptivity was significantly lower for all the geopolymer mixes than for the control mix with a water/cement ratio 0.50 (around 40 MPa strength level). For all geopolymer mixes, the sorptivity reduces with a decrease of water content and better grading distribution. These sorptivity values are in the range of Hall (1989) observation on concrete with water cement ratio 0.40-0.60 with sorptivity values in the range 0.094-0.170.

Table 4. Sorptivity of control and geopolymer concrete with regression coefficients

| Mixture no | Sorptivity (mm/min ^{0.5}) | R ² value |
|------------|-------------------------------------|----------------------|
| C2 | 0.2080 | 0.9971 |
| GP1 | 0.1262 | 0.9897 |
| GP2 | 0.1503 | 0.9924 |
| GP4 | 0.2038 | 0.9963 |
| GP5 | 0.1478 | 0.9912 |
| GP7 | 0.1507 | 0.9930 |

Figure 5 shows comparison of sorptivity value of geopolymer with different water/binder ratio. It is revealed that the water/binder ratio has significantly influenced the sorptivity as per water absorption and AVPV. This suggests that the increase of amount of water resulted in high porosity concrete, hence increases capillary suction.

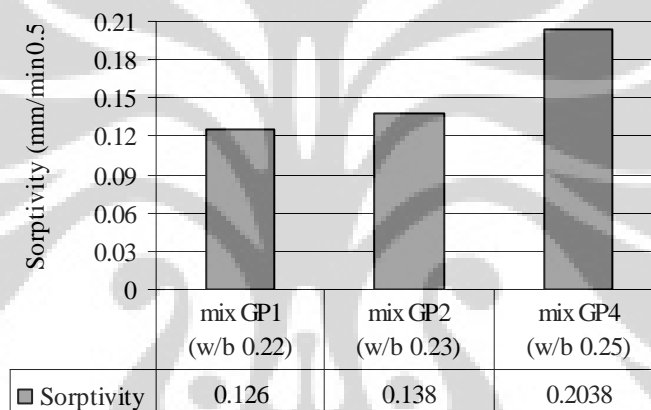


Figure 4. Sorptivity of geopolymer concrete with different water/binder ratio

Figure 5 shows comparison of sorptivity of geopolymer concrete and the corresponding control mix. A typical geopolymer concrete mix (GP2) exhibits lower sorptivity than the corresponding control mix (A2), which again illustrates the effect of binder content and thus the capillary pores on the sorptivity. Lower slope of geopolymer concrete showed reduced moisture intake as compared to the corresponding control mix. Although geopolymer concrete is known to have more pores in mesopore size, in general the results show that it has a lower capillary porosity than OPC concrete cured with steam. There is a need to investigate such a phenomenon to correlate the lower sorption characteristics with the pore structure of geopolymer concrete.

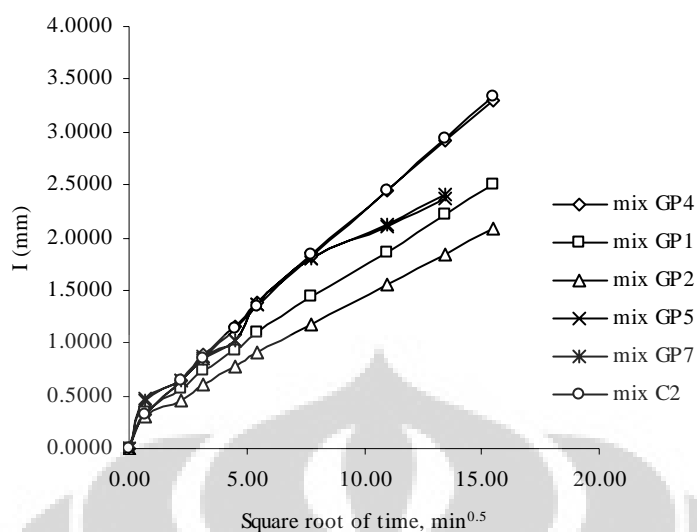


Figure 6. Comparison of capillary absorption rate of geopolymer concrete with control mix

5.4 Water Permeability

Table 5 indicates that the water permeability coefficient of geopolymer also has a tendency to increase with an increase of water/binder ratio. The permeability of high water/binder ratio concrete is greater because of the presence of larger capillary pores. However, those values are still in the range of water permeability coefficient for concrete with an average quality (10^{-11} - 10^{-12} m/s) according to Concrete Society Technical Report 54 (Rendell, *et al.* 2002).

It is also obvious that the percentage of void content might not affect the water permeability coefficient of geopolymer concrete significantly. It can be assumed that pore continuity has more contribution to higher water permeability coefficient for mix GP1. In the case of geopolymer concrete, blocking of the pores may be stopped after the accelerated steam curing process ceased. Thus, the ability to fill the pore structure depends mainly on the curing process. The increase of strength, eventually, is only a continuing effect of geopolymerization without any hydration.

Table 5. Water permeability coefficients of geopolymer concrete with different mixes

| Mixture no | Water permeability coefficient ($\times 10^{-11}$ m/s) | Void content (%) |
|------------|---|------------------|
| GP1 | 4.67 | 10.5 |
| GP2 | 3.95 | 13 |
| GP3 | 2.46 | 10.8 |
| GP5 | 2.91 | 10 |
| GP7 | 2.61 | 8.2 |

As observed from Table 5, mix GP3 with water/binder ratio 0.20 shows the lowest water permeability coefficient. It is found also that mix GP7 with aggregate grading (7, 10, 20mm)

shows low water permeability and void content. This indicates that the low water/binder ratio and a well-graded aggregate have large influences on geopolymer concrete permeability. As for OPC concrete, low water content and continuous grading contributes to lower porosity and discontinuity of concrete pores.

5.5 SEM Analysis

The microstructure of fly ash based geopolymer concrete is presented in Figures 6a and 6b. Figure 7 shows a typical SEM micrograph of mix GP2. This micrograph shows the geopolymer gel with partially or completely unreacted fly ash particles. Geopolymer product has unshaped and uniform microstructure. Some cracks were observed in the surface that might be due to mechanical damage during the sample preparation. The geopolymer microstructure from this research looks like many types of geopolymer from similar observations by Fernandez-Jimenez, *et al.* (2005) and Skvara, *et al.* (2006).

Figure 8 shows the holes in the microstructure resulted from air bubbles in the mixture. Those voids are distributed around the layer of geopolymer matrix. It is also found that there are some unreacted fly ash particles in the microstructure. Fly ash is known to have a significant proportion of particles with hollow spheres that possible to create porosity when they partially dissolved. As the result, the geopolymer matrix contains more dispersed small sized pores that can contribute to the overall porosity.

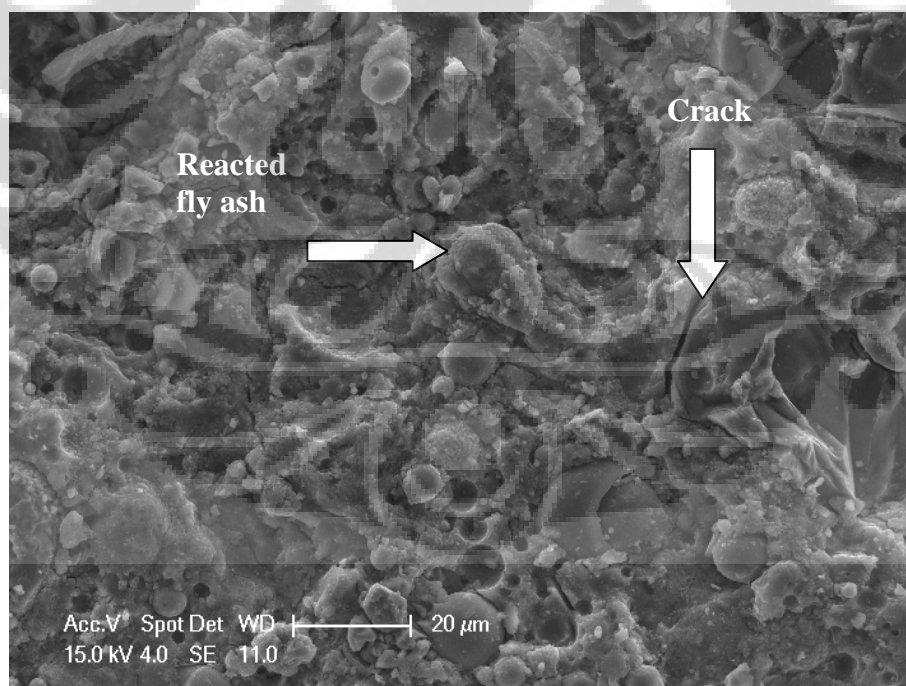


Figure 7. Typical SEM micrograph of geopolymer concrete (mix GP2)

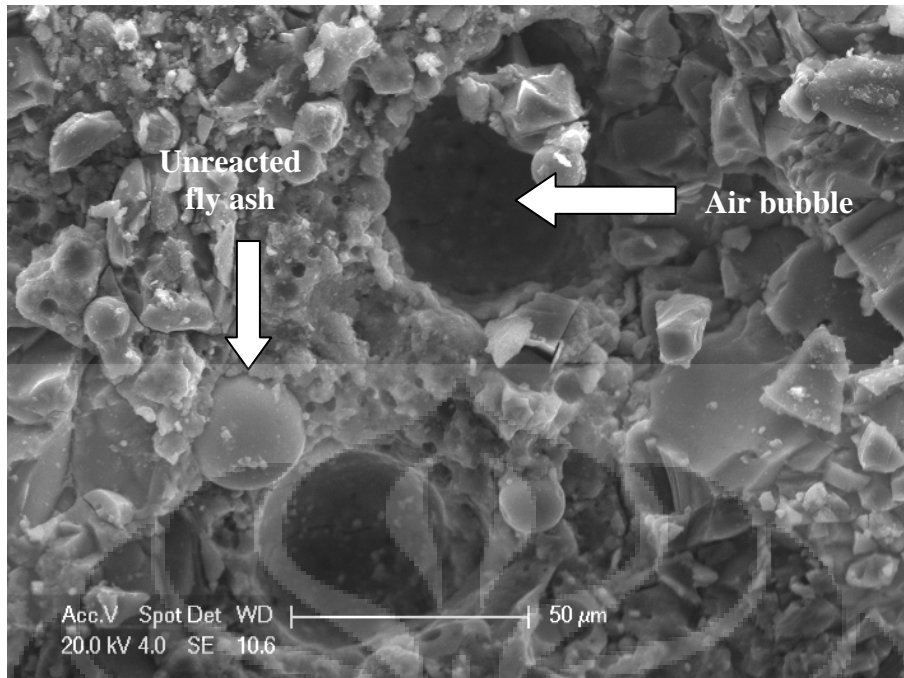


Figure 8. Air bubbles and unreacted fly ash of geopolymer concrete (mix GP2)

6. CONCLUSIONS

The following conclusions can be drawn based on the test results and discussion of the present study for measuring water penetrability of geopolymer concrete:

1. Fly ash geopolymer concrete exhibits low water absorption and sorptivity.
2. Geopolymer could be classified as a concrete with average quality according to water permeability coefficient values.
3. A water/binder ratio and well-graded aggregate are some important parameters that influence the water penetrability of low calcium fly ash geopolymer concrete. It is found that the higher water/binder ratio, then the lower water absorption and AVPV, sorptivity and water permeability. It is recommended to have low water/binder ratio and a better grading to reduce the capillary porosity and the overall porosity of geopolymer concrete.
4. Water absorption, AVPV, and sorptivity of low calcium fly ash geopolymer concrete are lower than the corresponding OPC concrete mixes. Steam cured OPC concrete shows higher capillary porosity than steam cured geopolymer concrete.
5. Geopolymer concrete with lower aggregate/binder ratio also indicates a high porous matrix. Sodium silicate inclusion to the mix might be the main cause of this finding.
6. From the microstructural analysis, the partially dissolved fly ash particles with hollow spheres mainly contribute to the porosity of the geopolymer matrix.

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Studies on Fly Ash-Based Geopolymer Concrete

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of
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ABSTRACT

The use of Portland cement in concrete construction is under critical review due to high amount of carbon dioxide gas released to the atmosphere during the production of cement. In recent years, attempts to increase the utilization of fly ash to partially replace the use of Portland cement in concrete are gathering momentum. Most of this by-product material is currently dumped in landfills, creating a threat to the environment.

Geopolymer concrete is a 'new' material that does not need the presence of Portland cement as a binder. Instead, the source of materials such as fly ash, that are rich in Silicon (Si) and Aluminium (Al), are activated by alkaline liquids to produce the binder. Hence concrete with no Portland cement.

This thesis reports the details of development of the process of making fly ash-based geopolymer concrete. Due to the lack of knowledge and know-how of making of fly ash-based geopolymer concrete in the published literature, this study adopted a rigorous trial and error process to develop the technology of making, and to identify the salient parameters affecting the properties of fresh and hardened concrete. As far as possible, the technology that is currently in use to manufacture and testing of ordinary Portland cement concrete were used.

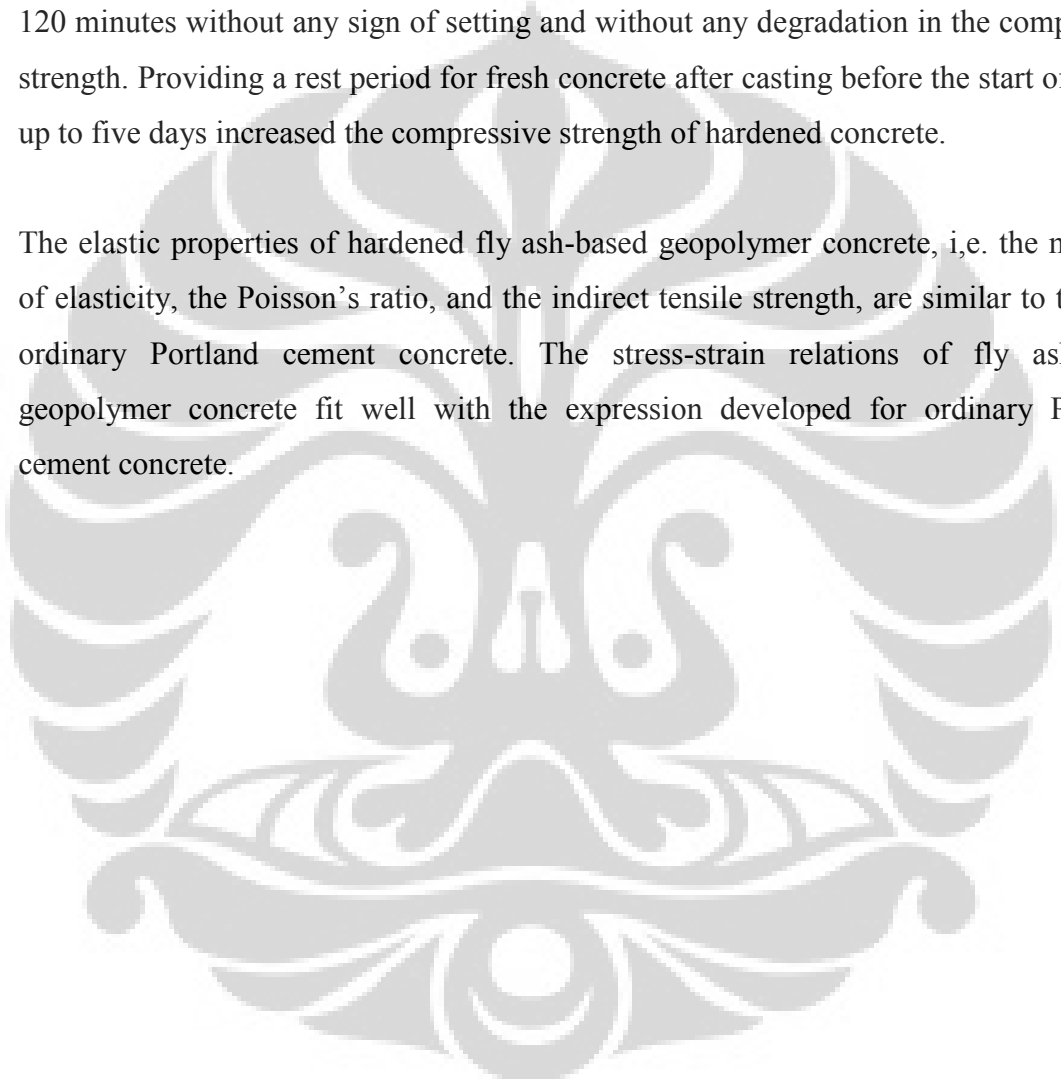
Fly ash was chosen as the basic material to be activated by the geopolymerization process to be the concrete binder, to totally replace the use of Portland cement. The binder is the only difference to the ordinary Portland cement concrete. To activate the Silicon and Aluminium content in fly ash, a combination of sodium hydroxide solution and sodium silicate solution was used.

Manufacturing process comprising material preparation, mixing, placing, compaction and curing is reported in the thesis. Napthalene-based superplasticiser was found to be

useful to improve the workability of fresh fly ash-based geopolymer concrete, as well as the addition of extra water. The main parameters affecting the compressive strength of hardened fly ash-based geopolymer concrete are the curing temperature and curing time, the molar H_2O -to- Na_2O ratio, and mixing time.

Fresh fly ash-based geopolymer concrete has been able to remain workable up to at least 120 minutes without any sign of setting and without any degradation in the compressive strength. Providing a rest period for fresh concrete after casting before the start of curing up to five days increased the compressive strength of hardened concrete.

The elastic properties of hardened fly ash-based geopolymer concrete, i.e. the modulus of elasticity, the Poisson's ratio, and the indirect tensile strength, are similar to those of ordinary Portland cement concrete. The stress-strain relations of fly ash-based geopolymer concrete fit well with the expression developed for ordinary Portland cement concrete.



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*Give thanks to the LORD, for he is good;
his love endures forever (Psalm 118:1).*

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Djwantoro Hardjito

LIST OF PUBLICATIONS

The following publications were produced using the results reported in this thesis:

- Hardjito, D.,** Wallah, S. E. & Rangan, B. V., 2002a, 'The Engineering Properties of Geopolymer Concrete', *Concrete in Australia*, vol. 28, no. 4, pp. 24-29.
- Hardjito, D.,** Wallah, S. E. & Rangan, B. V., 2002b, 'Study on Engineering Properties of Fly Ash-Based Geopolymer Concrete', *Journal of the Australasian Ceramic Society*, vol. 38, no. 1, pp. 44-47.
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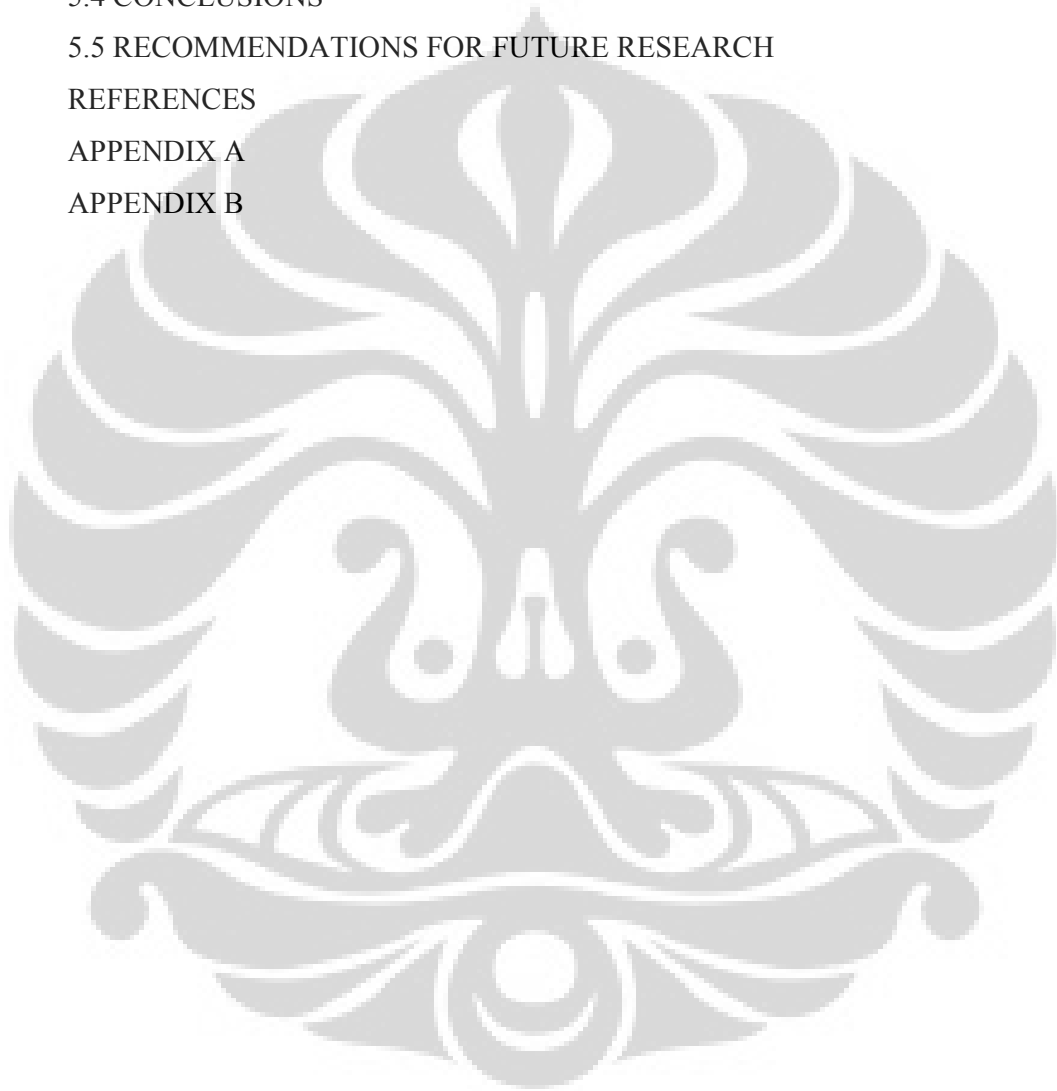
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1. INTRODUCTION

1.1 GENERAL

After wood, concrete is the most often used material by the community. Concrete is conventionally produced by using the ordinary Portland cement (OPC) as the primary binder. The environmental issues associated with the production of OPC are well known. The amount of the carbon dioxide released during the manufacture of OPC due to the calcination of limestone and combustion of fossil fuel is in the order of one ton for every ton of OPC produced. In addition, the amount of energy required to produce OPC is only next to steel and aluminium.

On the other side, the abundance and availability of fly ash worldwide create opportunity to utilise this by-product of burning coal, as partial replacement or as performance enhancer for OPC. Fly ash in itself does not possess the binding properties, except for the high calcium or ASTM Class C fly ash. However, in the presence of water and in ambient temperature, fly ash reacts with the calcium hydroxide during the hydration process of OPC to form the calcium silicate hydrate (C-S-H) gel. This pozzolanic action happens when fly ash is added to OPC as a partial replacement or as an admixture. The development and application of high volume fly ash concrete, which enabled the replacement of OPC up to 60-65% by mass (Malhotra 2002; Malhotra and Mehta 2002), can be regarded as a landmark in this attempt.

In another scheme, pozzolans such as blast furnace slag and fly ash may be activated using alkaline liquids to form a binder and hence totally replace the use of OPC in concrete. In this scheme, the alkalinity of the activator can be low to mild or high. In the first case, with low to medium alkalinity of the activator, the main contents to be activated are silicon and calcium in the by-product material such as blast furnace slag. The main binder produced is a C-S-H gel, as the result of a hydration process. In the later case, the main constituents to be activated with high alkaline solution are

mostly the silicon and the aluminium present in the by-product material such as low calcium (ASTM Class F) fly ash (Palomo, Grutzeck et al. 1999). The binder produced in this case is due to polymerisation. Davidovits (1999) in 1978 named the later as Geopolymers, and stated that these binders can be produced by a polymeric synthesis of the alkali activated material from geological origin or by-product materials such as fly ash and rice husk ash.

In 2001, when the research reported in this thesis began, several research publications were available regarding geopolymer pastes and geopolymer coating materials (Davidovits 1991; Davidovits 1994; Davidovits, Davidovits et al. 1994; Balaguru, Kurtz et al. 1997; van Jaarsveld, van Deventer et al. 1997; Balaguru 1998; van Jaarsveld, van Deventer et al. 1998; Davidovits 1999; Kurtz, Balaguru et al. 1999; Palomo, Grutzeck et al. 1999; Barbosa, MacKenzie et al. 2000). However, not a great deal was known regarding using the geopolymer technology to make fly ash-based geopolymer concrete.

The research reported in this thesis was dedicated to investigate the process of making fly ash-based geopolymer concrete and the short-term engineering properties of the fresh and hardened concrete.

1.2 FLY ASH-BASED GEOPOLYMER CONCRETE

In this work, fly ash-based geopolymer is used as the binder, instead of Portland or any other hydraulic cement paste, to produce concrete. The fly ash-based geopolymer paste binds the loose coarse aggregates, fine aggregates and other un-reacted materials together to form the geopolymer concrete, with or without the presence of admixtures. The manufacture of geopolymer concrete is carried out using the usual concrete technology methods.

As in the OPC concrete, the aggregates occupy the largest volume, i.e. about 75-80 % by mass, in geopolymer concrete. The silicon and the aluminium in the low calcium (ASTM Class F) fly ash are activated by a combination of sodium hydroxide and sodium silicate solutions to form the geopolymer paste that binds the aggregates and other un-reacted materials.

1.3 AIMS OF THE RESEARCH

As mentioned earlier, most of the published research on geopolymers studied the behaviour of pastes with various types of source materials. The present study deals with the manufacture of low calcium (ASTM Class F) fly ash-based geopolymer concrete, the parameters influencing the mixture proportioning, and the short-term engineering properties in the fresh and hardened states. The research reported in this thesis is the first stage of a research project on fly ash-based geopolymer concrete currently in progress in the Faculty of Engineering and Computing at Curtin University of Technology, Perth, Australia.

The aims of the research are:

1. To develop a mixture proportioning process of making fly ash-based geopolymer concrete.
2. To identify and study the effect of salient parameters that affects the properties of fly ash-based geopolymer concrete.
3. To study the short-term engineering properties of fresh and hardened fly ash-based geopolymer concrete.

1.4 SCOPE OF WORK

The research utilized low calcium (ASTM Class F) fly ash as the base material for making geopolymer concrete. The fly ash was obtained from only one source, because the main focus of this study was the short-term behaviour and the engineering properties of fly ash-based geopolymer concrete. As far as possible, the technology and the equipment currently used to manufacture OPC concrete were also used to make the geopolymer concrete.

The concrete properties studied included the compressive and indirect tensile strengths, the elastic constants, the stress-strain relationship in compression, and the workability of fresh concrete.

1.5 THESIS ARRANGEMENT

The remainder of the thesis is arranged as follow: Chapter 2 describes the need to find alternatives to make concrete more environmentally friendly, and the availability and the potential use of low calcium (ASTM Class F) fly ash. This chapter also provides a brief literature review of geopolymer technology.

Chapter 3 describes the experimental program carried out to develop the mixture proportions, the mixing process, and the curing regime of geopolymer concrete. The tests performed to study the behaviour and the short term engineering properties of the fresh concrete and the hardened concrete are also described.

Chapter 4 presents and discusses the test results. Chapter 5 states the summary and the conclusions of this study, followed by a set of recommendations for future work. The thesis ends with a Reference List and several Appendices.

2. LITERATURE REVIEW

This chapter presents a background to the needs on the development of a fly ash-based geopolymer technology. The available published literature on geopolymer technology is also briefly reviewed.

2.1 CONCRETE AND ENVIRONMENT

The trading of carbon dioxide (CO₂) emissions is a critical factor for the industries, including the cement industries, as the greenhouse effect created by the emissions is considered to produce an increase in the global temperature that may result in climate changes. The 'tradeable emissions' refers to the economic mechanisms that are expected to help the countries worldwide to meet the emission reduction targets established by the 1997 Kyoto Protocol. Speculation has arisen that one ton of emissions can have a trading value about US\$10 (Malhotra 1999; Malhotra 2004).

The climate change is attributed to not only the global warming, but also to the paradoxical global dimming due to the pollution in the atmosphere. Global dimming is associated with the reduction of the amount of sunlight reaching the earth due to pollution particles in the air blocking the sunlight. With the effort to reduce the air pollution that has been taken into implementation, the effect of global dimming may be reduced, however it will increase the effect of global warming (Fortune 2005). In this view, the global warming phenomenon should be considered more seriously, and any action to reduce the effect should be given more attention and effort.

The production of cement is increasing about 3% annually (McCaffrey 2002). The production of one ton of cement liberates about one ton of CO₂ to the atmosphere, as the result of de-carbonation of limestone in the kiln during manufacturing of cement and the combustion of fossil fuels (Roy 1999).

The contribution of Portland cement production worldwide to the greenhouse gas emission is estimated to be about 1.35 billion tons annually or about 7% of the total greenhouse gas emissions to the earth's atmosphere (Malhotra 2002). Cement is also among the most energy-intensive construction materials, after aluminium and steel. Furthermore, it has been reported that the durability of ordinary Portland cement (OPC) concrete is under examination, as many concrete structures, especially those built in corrosive environments, start to deteriorate after 20 to 30 years, even though they have been designed for more than 50 years of service life (Mehta and Burrows 2001).

The concrete industry has recognized these issues. For example, the U.S. Concrete Industry has developed plans to address these issues in 'Vision 2030: A Vision for the U.S. Concrete Industry'. The document states that *'concrete technologists are faced with the challenge of leading future development in a way that protects environmental quality while projecting concrete as a construction material of choice. Public concern will be responsibly addressed regarding climate change resulting from the increased concentration of global warming gases.* In this document, strategies to retain concrete as a construction material of choice for infrastructure development, and at the same time to make it an environmentally friendly material for the future have been outlined (Mehta 2001; Plenge 2001).

In order to produce environmentally friendly concrete, Mehta (2002) suggested the use of fewer natural resources, less energy, and minimise carbon dioxide emissions. He categorised these short-term efforts as *'industrial ecology'*. The long-term goal of reducing the impact of unwanted by-products of industry can be attained by lowering the rate of material consumption. Likewise, McCaffrey (2002) suggested three alternatives to reduce the amount of carbon dioxide (CO₂) emissions by the cement industries, i.e. to decrease the amount of calcined material in cement, to decrease the amount of cement in concrete, and to decrease the number of buildings using cement.

2.2 FLY ASH

According to the American Concrete Institute (ACI) Committee 116R, fly ash is defined as *'the finely divided residue that results from the combustion of ground or*

powdered coal and that is transported by flue gasses from the combustion zone to the particle removal system' (ACI Committee 232 2004). Fly ash is removed from the combustion gases by the dust collection system, either mechanically or by using electrostatic precipitators, before they are discharged to the atmosphere. Fly ash particles are typically spherical, finer than Portland cement and lime, ranging in diameter from less than 1 μm to no more than 150 μm .

The types and relative amounts of incombustible matter in the coal determine the chemical composition of fly ash. The chemical composition is mainly composed of the oxides of silicon (SiO_2), aluminium (Al_2O_3), iron (Fe_2O_3), and calcium (CaO), whereas magnesium, potassium, sodium, titanium, and sulphur are also present in a lesser amount. The major influence on the fly ash chemical composition comes from the type of coal. The combustion of sub-bituminous coal contains more calcium and less iron than fly ash from bituminous coal. The physical and chemical characteristics depend on the combustion methods, coal source and particle shape. The chemical compositions of various fly ashes show a wide range, indicating that there is a wide variations in the coal used in power plants all over the world (Malhotra and Ramezaniapour 1994).

Fly ash that results from burning sub-bituminous coals is referred as ASTM Class C fly ash or high calcium fly ash, as it typically contains more than 20 percent of CaO . On the other hand, fly ash from the bituminous and anthracite coals is referred as ASTM Class F fly ash or low calcium fly ash. It consists of mainly an aluminosilicate glass, and has less than 10 percent of CaO . The colour of fly ash can be tan to dark grey, depending upon the chemical and mineral constituents (Malhotra and Ramezaniapour 1994; ACAA 2003). The typical fly ash produced from Australian power stations is light to mid-grey in colour, similar to the colour of cement powder. The majority of Australian fly ash falls in the category of ASTM Class F fly ash, and contains 80 to 85% of silica and alumina (Heidrich 2002).

Aside from the chemical composition, the other characteristics of fly ash that generally considered are loss on ignition (LOI), fineness and uniformity. LOI is a measurement of unburnt carbon remaining in the ash. Fineness of fly ash mostly depends on the operating conditions of coal crushers and the grinding process of the

coal itself. Finer gradation generally results in a more reactive ash and contains less carbon.

In 2001, the annual production of fly ash in the USA was about 68 million tons. Only 32 percent of this was used in various applications, such as in concrete, structural fills, waste stabilisation/solidification etc. (ACAA 2003). Ash production in Australia in 2000 was approximated 12 million tons, with some 5.5 million tons have been utilised (Heidrich 2002). Worldwide, the estimated annual production of coal ash in 1998 was more than 390 million tons. The main contributors for this amount were China and India. Only about 14 percent of this fly ash was utilized, while the rest was disposed in landfills (Malhotra 1999). By the year 2010, the amount of fly ash produced worldwide is estimated to be about 780 million tons annually (Malhotra 2002). The utilization of fly ash, especially in concrete production, has significant environmental benefits, viz, improved concrete durability, reduced use of energy, diminished greenhouse gas production, reduced amount of fly ash that must be disposed in landfills, and saving of the other natural resources and materials (ACAA 2003).

2.3 THE USE OF FLY ASH IN CONCRETE

One of the efforts to produce more environmentally friendly concrete is to reduce the use of OPC by partially replacing the amount of cement in concrete with by-products materials such as fly ash. As a cement replacement, fly ash plays the role of an artificial pozzolan, where its silicon dioxide content reacts with the calcium hydroxide from the cement hydration process to form the calcium silicate hydrate (C-S-H) gel. The spherical shape of fly ash often helps to improve the workability of the fresh concrete, while its small particle size also plays as filler of voids in the concrete, hence to produce dense and durable concrete. Generally, the effective amount of cement that can be replaced by fly ash is not more than 30% (Neville 2000).

An important achievement in the use of fly ash in concrete is the development of high volume fly ash (HVFA) concrete that successfully replaces the use of OPC in concrete up to 60% and yet possesses excellent mechanical properties with enhanced

durability performance. HVFA concrete has been proved to be more durable and resource-efficient than the OPC concrete (Malhotra 2002). The HVFA technology has been put into practice, for example the construction of roads in India, which implemented 50% OPC replacement by the fly ash (Desai 2004).

Activation of fly ash with alkaline solutions enables this by-product material to be a cement-like construction material. In this case, concrete binder can be produced without using any OPC; in other words, the role of OPC can be totally replaced by the activated fly ash. Palomo et al (1999) described two different models of the activation of fly ash or other by-product materials. For the first model, the silicon and the calcium in the material is activated by a low to mild concentration of alkaline solution. The main product of the reaction is believed to be a calcium silicate hydrate (C-S-H) that results from the hydration process. On the contrary, the material used in the second model contains mostly silicon and aluminium, and is activated by a highly alkaline solution. The chemical process in this case is polymerisation.

A well known example of the first model is the activation of blast furnace slag, that has a long history in the former Soviet Union, Scandinavia and Eastern Europe (Roy 1999). On the other hand, studies on the second model are limited (Palomo, Grutzeck et al. 1999). Many aspects of the material characteristics and reaction mechanisms are still not clear. For the second model, Davidovits (1999) coined the term Geopolymer in 1978 to describe the alkali activated material from geological origin or by-product materials such as fly ash and rice husk ash. Davidovits (1994) also revealed the fact that very few scientific literatures on geopolymer material available was caused by the patent oriented schemes of research works. Only from the late 1990s scientific information were becoming available in the published literature.

2.4 GEOPOLYMERS

Polymer is a class of materials made from large molecules that are composed of a large number of repeating units (monomers). The molecular structure of the unit that makes up the large molecules controls the properties of the material. The non-crystalline or amorphous state is the state when the regularity of atomic packing is

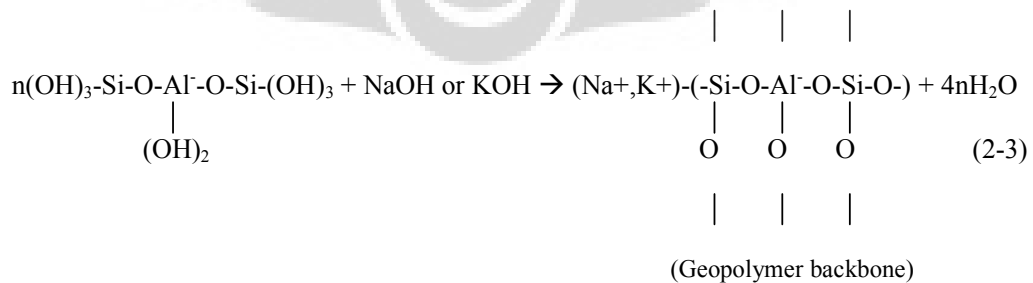
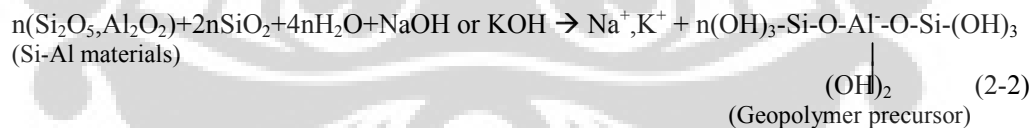
completely absent. The most familiar kind of an amorphous solid is glass (Young, Mindness et al. 1998).

Geopolymers are a member of the family of inorganic polymers, and are a chain structures formed on a backbone of Al and Si ions. The chemical composition of this geopolymer material is similar to natural zeolitic materials, but they have amorphous microstructure instead of crystalline (Palomo, Grutzeck et al. 1999; Xu and van Deventer 2000). The polymerisation process involves a substantially fast chemical reaction under highly alkaline condition on Si-Al minerals, that results in a three-dimensional polymeric chain and ring structure consisting of Si-O-Al-O bonds, as follows (Davidovits 1999):



Where: M = the alkaline element or cation such as potassium, sodium or calcium; the symbol – indicates the presence of a bond, n is the degree of polycondensation or polymerisation; z is 1,2,3, or higher, up to 32.

The schematic formation of geopolymer material can be shown as described by Equations (2-2) and (2-3) (van Jaarsveld, van Deventer et al. 1997; Davidovits 1999). These formations indicate that all materials containing mostly Silicon (Si) and Aluminium (Al) can be processed to make the geopolymer material.



To date, the exact mechanism of setting and hardening of the geopolymer material is not clear, as well as its reaction kinetics. However, most proposed mechanism consist of the following (Davidovits 1999; Xu and van Deventer 2000):

- Dissolution of Si and Al atoms from the source material through the action of hydroxide ions.
- Transportation or orientation or condensation of precursor ions into monomers.
- Setting or polycondensation/polymerisation of monomers into polymeric structures.

However, these three steps can overlap with each other and occur almost simultaneously, thus making it difficult to isolate and examine each of them separately (Palomo, Grutzeck et al. 1999).

A geopolymer can take one of the three basic forms (Davidovits 1999), i.e:

- Poly(sialate), which has $[-\text{Si-O-Al-O-}]$ as the repeating unit.
- Poly(sialate-siloxo), which has $[-\text{Si-O-Al-O-Si-O-}]$ as the repeating unit.
- Poly(sialate-disiloxo), which has $[-\text{Si-O-Al-O-Si-O-Si-O-}]$ as the repeating unit.

Sialate is an abbreviation of silicon-oxo-aluminate.

Davidovits (1999) proposed the possible applications of the geopolymer material depending on the molar ratio of Si to Al, as given in Table 2.1.

Table 2.1: Applications of Geopolymer Material

| Si/Al | Application |
|-------------|--|
| 1 | Bricks, ceramics, fire protection |
| 2 | Low CO ₂ cements, concrete, radioactive & toxic waste encapsulation |
| 3 | Heat resistance composites, foundry equipments, fibre glass composites |
| >3 | Sealants for industry |
| 20<Si/Al<35 | Fire resistance and heat resistance fibre composites |

2.4.1 Constituents of Geopolymer

2.4.1.1 Source Materials

Any material that contains mostly Silicon (Si) and Aluminium (Al) in amorphous form is a possible source material for the manufacture of geopolymer. Several minerals and industrial by-product materials have been investigated in the past. Metakaolin or calcined kaolin (Davidovits 1999; Barbosa, MacKenzie et al. 2000; Teixeira-Pinto, Fernandes et al. 2002), ASTM Class F fly ash (Palomo, Grutzeck et al. 1999; Swanepoel and Strydom 2002), natural Al-Si minerals (Xu and van Deventer 2000), combination of calcined mineral and non calcined materials (Xu and van Deventer 2002), combination of fly ash and metakaolin (Swanepoel and Strydom 2002; van Jaarsveld, van Deventer et al. 2002), and combination of granulated blast furnace slag and metakaolin (Cheng and Chiu 2003) were investigated as source materials.

Metakaolin is preferred by the niche geopolymer product developers due to its high rate of dissolution in the reactant solution, easier control on the Si/Al ratio and the white colour (Gourley 2003). However, for making concrete in a mass production state, metakaolin is very expensive.

Low calcium (ASTM Class F) fly ash is preferred as a source material than high calcium (ASTM Class C) fly ash. The presence of calcium in high amount may interfere with the polymerisation process and alter the microstructure (Gourley 2003).

Davidovits (1999) calcined kaolin clay for 6 hours at 750°C. He termed this metakaolin as KANDOXI (**KA**olinite, **Nac**rite, **Dick**ite **OXI**de), and used it to make geopolymers. For the purpose of making geopolymer concrete, he suggested that the molar ratio of Si-to-Al of the material should be about 2.0 (Table 2.1).

On the nature of the source material, it was stated that the calcined source materials, such as fly ash, slag, calcined kaolin, demonstrated a higher final compressive strength when compared to those made using non-calcined materials, for instance kaolin clay, mine tailings, and naturally occurring minerals (Barbosa, MacKenzie et al. 2000). However, Xu and van Deventer (Xu and van Deventer 2002) found that using a combination of calcined (e.g. fly ash) and non-calcined material (e.g. kaolinite or kaolin clay and albite) resulted in significant improvement in compressive strength and reduction in reaction time.

Natural Al-Si minerals have shown the potential to be the source materials for geopolymerisation, although quantitative prediction on the suitability of the specific mineral as the source material is still not available, due to the complexity of the reaction mechanisms involved (Xu and van Deventer 2000). Among the by-product materials, only fly ash and slag have been proved to be the potential source materials for making geopolymers. Fly ash is considered to be advantageous due to its high reactivity that comes from its finer particle size than slag. Moreover, low calcium fly ash is more desirable than slag for geopolymer feedstock material.

The suitability of various types of fly ash to be geopolymer source material has been studied by Fernández-Jiménez and Palomo (2003). These researchers claimed that to produce optimal binding properties, the low-calcium fly ash should have the percentage of unburned material (LOI) less than 5%, Fe₂O₃ content should not exceed 10%, low CaO content, the content of reactive silica should be between 40-

50%, and 80-90% of particles should be smaller than 45 μm . On the contrary, van Jaarsveld et al (2003) found that fly ash with higher amount of CaO produced higher geopolymer compressive strength, due to the formation of calcium aluminate hydrate and other calcium compounds, especially in the early ages. The other characteristics that influenced the suitability of fly ash to be a source material for geopolymers are the particle size, amorphous content, as well as morphology and the origin of fly ash.

2.4.1.2 Alkaline Activators

The most common alkaline activator used in geopolymerisation is a combination of sodium hydroxide (NaOH) or potassium hydroxide (KOH) and sodium silicate or potassium silicate (Davidovits 1999; Palomo, Grutzeck et al. 1999; Barbosa, MacKenzie et al. 2000; Xu and van Deventer 2000; Swanepoel and Strydom 2002; Xu and van Deventer 2002). The use of a single alkaline activator has been reported (Palomo, Grutzeck et al. 1999; Teixeira-Pinto, Fernandes et al. 2002),

Palomo et al (1999) concluded that the type of activator plays an important role in the polymerisation process. Reactions occur at a high rate when the alkaline activator contains soluble silicate, either sodium or potassium silicate, compared to the use of only alkaline hydroxides. Xu and van Deventer (2000) confirmed that the addition of sodium silicate solution to the sodium hydroxide solution as the alkaline activator enhanced the reaction between the source material and the solution. Furthermore, after a study of the geopolymerisation of sixteen natural Al-Si minerals, they found that generally the NaOH solution caused a higher extent of dissolution of minerals than the KOH solution.

2.4.2 Mixtures Proportions

Most of the reported works on geopolymer material to date were related to the properties of geopolymer paste or mortar, measured by using small size specimens. In addition, the complete details of the mixture compositions of the geopolymer paste were not reported.

Palomo et al (1999) studied the geopolymerisation of ASTM Class F fly ash (molar Si/Al=1.81) using four different activator solutions with the solution-to-fly ash ratio by mass of 0.25 to 0.30. The molar SiO₂/K₂O or SiO₂/Na₂O of the solutions was in the range of 0.63 to 1.23. The specimens were 10x10x60 mm in size. The best compressive strength obtained was more than 60 MPa for mixtures that used a combination of sodium hydroxide and sodium silicate activator solution, after curing the specimens for 24 hours at 65°C. Xu and van Deventer (2000) reported that the proportion of alkaline solution to alumino-silicate powder by mass should be approximately 0.33 to allow the geopolymeric reactions to occur. Alkaline solutions formed a thick gel instantaneously upon mixing with the alumino-silicate powder. The specimen size in their study was 20x20x20 mm, and the maximum compressive strength achieved was 19 MPa after 72 hours of curing at 35°C with stilbite as the source material. On the other hand, van Jaarsveld et al (1998) reported the use of the mass ratio of the solution to the powder of about 0.39. In their work, 57% fly ash was mixed with 15% kaolin or calcined kaolin, and was activated by 3.5% sodium silicate, 20% water and 4% sodium or potassium hydroxide. In this case, they used specimen size of 50x50x50 mm. The maximum compressive strength obtained was 75 MPa for the case of using fly ash and builders' waste as the source material.

Following the earlier work of Davidovits (1982) and using calcined kaolin as source material, Barbosa et al (2000) prepared seven mixture compositions of geopolymer paste for the following range of molar oxide ratios: $0.2 < \text{Na}_2\text{O}/\text{SiO}_2 < 0.48$; $3.3 < \text{SiO}_2/\text{Al}_2\text{O}_3 < 4.5$ and $10 < \text{H}_2\text{O}/\text{Na}_2\text{O} < 25$. From the tests performed on the paste specimens, they found that the optimum composition occurred when the ratio of Na₂O/SiO₂ was 0.25, the ratio of H₂O/Na₂O was 10.0, and the ratio of SiO₂/Al₂O₃ was 3.3. Mixtures with high water content, i.e. H₂O/Na₂O = 25, developed very low compressive strengths, and thus underlying the importance of water content in polymerisation. There was no information regarding the size of the specimens, while the moulds used were of a thin polyethylene film.

2.4.3 Fresh Geopolymers and Manufacturing Process

Only limited information on the behaviour of the fresh geopolymers has been reported. Using metakaolin as the source material, Teixeira Pinto et al (2002) found

that the fresh geopolymer mortar became very stiff and dry while mixing, and exhibited high viscosity and cohesive nature. They suggested that the forced mixer type should be used in mixing the geopolymer materials, instead of the gravity type mixer. An increase in the mixing time increased the temperature of the fresh geopolymers, and hence reduced the workability. To improve the workability, they suggested the use of admixtures to reduce the viscosity and cohesion.

While Teixeira Pinto et al (2002) concluded that Vicat needle apparatus is not appropriate to measure the setting time of fresh geopolymer concrete, Cheng and Chiu (2003) reported the only information available to date on the quantitative measure of the setting time of geopolymer material using the Vicat needle. For the fresh geopolymer paste based on metakaolin and ground blast furnace slag, they measured the setting time of the geopolymer material both at room and elevated temperature. In the elevated temperature, the measurement was done in the oven. They found that the initial setting time was very short for geopolymers cured at 60°C, in the range of 15 to 45 minutes.

(Barbosa, MacKenzie et al. 1999) measured the viscosity of fresh metakaolin-based geopolymer paste, and reported that the viscosity of the geopolymer paste increased with time.

Most of the manufacturing process of making geopolymer paste involved dry mixing of the source materials, followed by adding the alkaline solution and then further mixing for another specified period of time (van Jaarsveld, van Deventer et al. 1998; Swanepoel and Strydom 2002; Teixeira-Pinto, Fernandes et al. 2002).

However, Cheng and Chiu (2003) reported the mixing of the KOH and metakaolin first for ten minutes. Sodium silicate and ground blast furnace slag were then added, followed by a further mixing for another five minutes. The paste samples were then cast in 50x50x50 mm cube moulds and vibrated for five minutes.

For curing, a wide range of temperatures and curing periods were used, ranging from room temperature to about 90°C, and from 1 hour to more than 24 hours. Geopolymers produced by using metakaolin have been reported to set at ambient

temperature in a short time (Davidovits 1999). However, curing temperature and curing time have been reported to play important roles in determining the properties of the geopolymer materials made from by-product materials such as fly ash. Palomo et al (1999) stated that increase in curing temperature accelerated the activation of fly ash, and resulted in higher compressive strength.

Barbosa et al (2000) elaborated the process of manufacturing geopolymers by allowing the fresh mixtures to mature in room temperature for 60 minutes, followed by curing at 65°C for 90 minutes, and then drying at 65°C.

2.4.4 Factors Affecting the Properties of Geopolymers

Several factors have been identified as important parameters affecting the properties of geopolymers. Palomo et al (1999) concluded that the curing temperature was a reaction accelerator in fly ash-based geopolymers, and significantly affected the mechanical strength, together with the curing time and the type of alkaline activator. Higher curing temperature and longer curing time were proved to result in higher compressive strength. Alkaline activator that contained soluble silicates was proved to increase the rate of reaction compared to alkaline solutions that contained only hydroxide.

Van Jaarsveld et al (2002) concluded that the water content, and the curing and calcining condition of kaolin clay affected the properties of geopolymers. However, they also stated that curing at too high temperature caused cracking and a negative effect on the properties of the material. Finally, they suggested the use of mild curing to improve the physical properties of the material. In another report, van Jaarsveld et al (2003) stated that the source materials determine the properties of geopolymers, especially the CaO content, and the water-to-fly ash ratio.

Based on a statistical study of the effect of parameters on the polymerisation process of metakaolin-based geopolymers, Barbosa et al (1999; 2000) reported the importance of the molar composition of the oxides present in the mixture and the water content. They also confirmed that the cured geopolymers showed an amorphous microstructure and exhibited low bulk densities between 1.3 and 1.9.

Based on the study of geopolymerisation of sixteen natural Si-Al minerals, Xu and van Deventer (2000) reported that factors such as the percentage of CaO, K₂O, and the molar Si-to-Al ratio in the source material, the type of alkali activator, the extent of dissolution of Si, and the molar Si-to-Al ratio in solution significantly influenced the compressive strength of geopolymers.

2.4.5 Geopolymer Concrete Products

Palomo et al (2004) reported the manufacture of fly ash-based geopolymer concrete railway sleepers. They found that the geopolymer concrete structural members could easily be produced using the existing current concrete technology without any significant changes. The engineering performances of the products were excellent, and the drying shrinkage was small.

Earlier, Balaguru et al (1997; 1999) reported the use of geopolymer composites layers to strengthen concrete structures as well as geopolymer coating to protect the transportation infrastructures. They reported that geopolymer composites have been successfully applied to strengthen reinforced concrete beams. The performance of geopolymers was better than the organic polymer in terms of fire resistance, durability under ultra violet light, and did not involve any toxic.

3. EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

This chapter presents the details of development of the process of making fly ash-based geopolymer concrete. In 2001, very little knowledge and know-how of making of fly ash-based geopolymer concrete were available in the published literature. Due to this lack of information, the study began based on limited available literature on geopolymer pastes and mortars.

The published papers on geopolymers available at that time mostly reported the use of metakaolin or calcined kaolin as source material of geopolymer paste. Moreover, most of the information available was part of the patent literature or commercially oriented research, and many details were kept undisclosed.

Therefore, the present study adopted a rigorous trial and error process in order to develop the fly ash-based geopolymer concrete technology. The focus of the study was to identify the salient parameters that influence the mixture properties and the properties of fly ash-based geopolymer concrete.

As far as possible, the technology that is currently in use to manufacture and test ordinary Portland cement (OPC) was used. The aim of this action was to ease the promotion of this 'new' material later on to the concrete industry.

In order to simplify the development process, the compressive strength was selected as the benchmark parameter. This is not unusual because compressive strength has an intrinsic importance in the structural design of concrete structures (Neville 2000).

Although geopolymer concrete can be made using various source materials, the present study used only low calcium (ASTM Class F) fly ash. Also, as in the case of OPC, the aggregates occupy 75-80 % of the total mass of concrete. In order to

minimize the effect of the properties of the aggregates on the properties of fly ash-based geopolymer, the study used aggregates from only one source.

3.2 MATERIALS

3.2.1 Fly Ash

In the present experimental work, low calcium, Class F (American Society for Testing and Materials 2001) dry fly ash obtained from the silos of Collie Power Station, Western Australia, was used as the base material. Three different batches of fly ash were used; the first batch was obtained in the middle of 2001, the second batch arrived in the middle of 2003, and the last batch was obtained in 2004. The chemical compositions of the fly ash from all batches, as determined by X-Ray Fluorescence (XRF) analysis, are given in Table 3.1. The XRF analysis was carried out by the Department of Applied Chemistry, Curtin University of Technology, Perth, Australia.

It can be seen from Table 3.1, that the three batches of fly ash contained a very low percentage of carbon as indicated by the low Loss on Ignition (LOI) values. In all three batches, the molar Si-to-Al ratio was about 2, and the calcium oxide content was very low. The iron oxide (Fe_2O_3) contents from all batches are relatively high, especially in the fly ash from Batch II. The colour of the fly ash from Batch II was therefore darker than the ashes from the other two Batches.

The particle size distributions of the fly ashes are given in Figures 3.1, 3.2 and 3.3. Both graph A and graph B show the particle size distribution of the fly ash. In these Figures, graph A shows the particle size distribution in percentage by volume in interval, while graph B shows the particle size distribution in percentage by volume passing size or cumulative. For fly ash from Batch I, 80% of the particles were smaller than 55 μm , and the Specific Surface Area was 1.29 m^2/cc . For Batch II, 80% of the particles were smaller than 39 μm , and the Specific Surface Area was 1.94 m^2/cc . For fly ash from Batch III, 80% of the particles were smaller than 46 μm , and the Specific Surface Area was 1.52 m^2/cc . The particle size distribution tests

were performed using the Malvern Instruments Mastersizer MS2000, and were carried out by CSIRO Minerals, Waterford, Australia.

The Scanning Electron Microscopy (SEM) image of fly ash from Batch I is shown in Figure 3.4. As can be seen, the particle shapes of the fly ash were generally spherical.

The fly ash from Batch I was used in Mixtures 1 to 4 and 13 to 15, the fly ash from Batch III was used in the mixture 5 to 8 and 22, while other Mixtures utilised the fly ash from Batch II.

Table 3.1: Composition of Fly Ash as Determined by XRF (mass %)

| Oxides | Batch I | Batch II | Batch III |
|--------------------------------|---------|----------|-----------|
| SiO ₂ | 53.36 | 47.80 | 48.00 |
| Al ₂ O ₃ | 26.49 | 24.40 | 29.00 |
| Fe ₂ O ₃ | 10.86 | 17.40 | 12.70 |
| CaO | 1.34 | 2.42 | 1.78 |
| Na ₂ O | 0.37 | 0.31 | 0.39 |
| K ₂ O | 0.80 | 0.55 | 0.55 |
| TiO ₂ | 1.47 | 1.328 | 1.67 |
| MgO | 0.77 | 1.19 | 0.89 |
| P ₂ O ₅ | 1.43 | 2.00 | 1.69 |
| SO ₃ | 1.70 | 0.29 | 0.50 |
| ZrO ₂ | - | - | 0.06 |
| Cr | - | 0.01 | 0.016 |
| MnO | - | 0.12 | 0.06 |
| LOI | 1.39 | 1.10 | 1.61 |

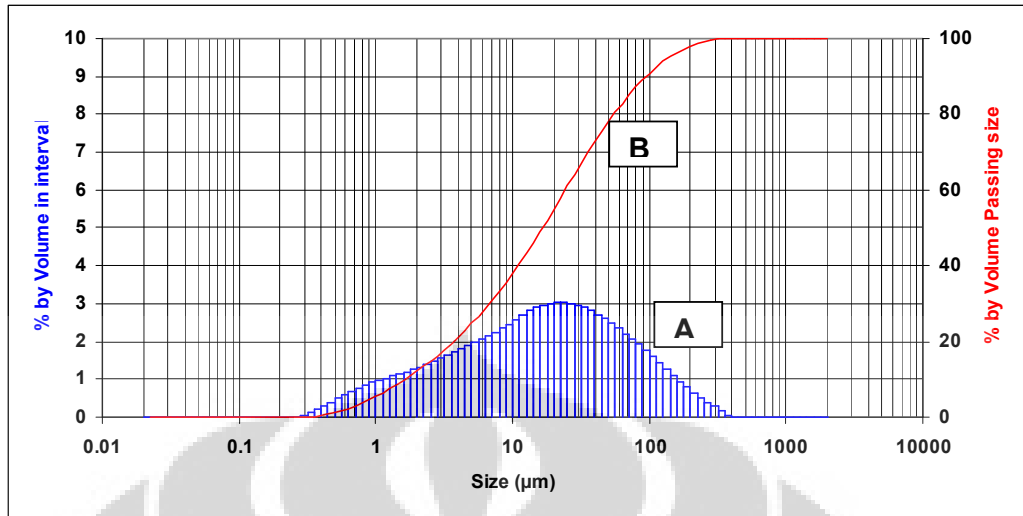


Figure 3.1: Particle Size Distribution of Fly Ash from Batch I

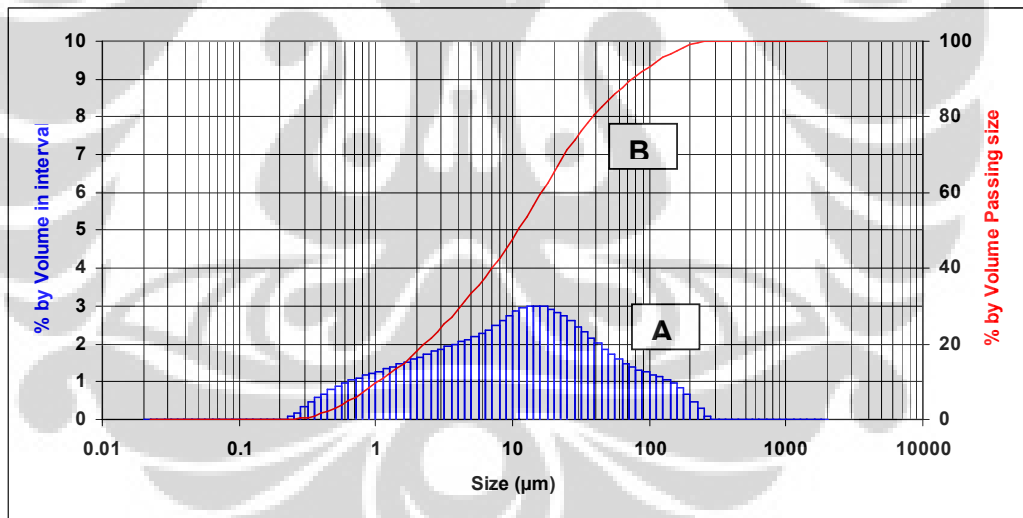


Figure 3.2: Particle Size Distribution of Fly Ash from Batch II

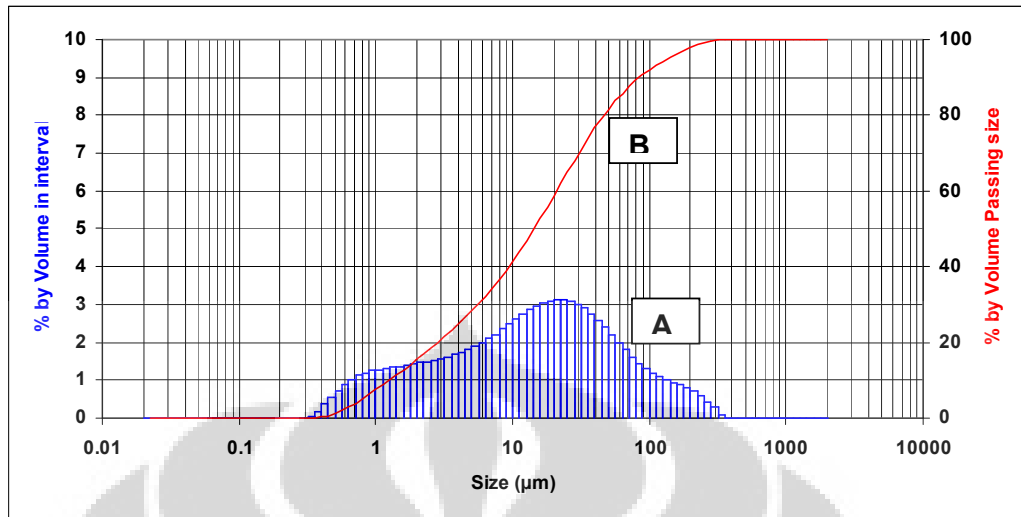


Figure 3.3: Particle Size Distribution of Fly Ash from Batch III

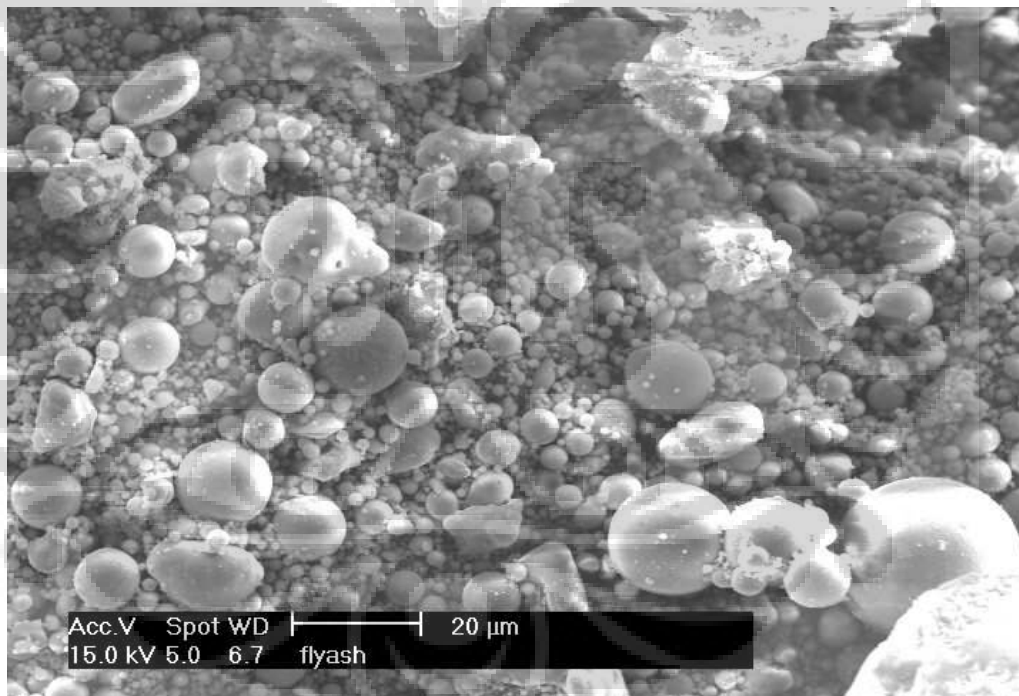


Figure 3.4: SEM Image of Fly Ash from Batch I

3.2.2 Alkaline Activators

To activate the fly ash, a combination of sodium hydroxide solution and sodium silicate solution was chosen as the alkaline activator. Sodium-based activators were

chosen because they were cheaper than Potassium-based activators. The sodium hydroxide used was either a technical grade sodium hydroxide in flakes form (3 mm), with a specific gravity of 2.130, 98% purity, and obtained from Sigma-Aldrich Pty Ltd, Australia, or a commercial grade in pellets form with 97% purity, obtained from Lomb Scientific, Australia.

The sodium hydroxide (NaOH) solution was prepared by dissolving either the flakes or the pellets in water. The mass of NaOH solids in a solution varied depending on the concentration of the solution expressed in terms of molar, M. For instance, NaOH solution with a concentration of 8M consisted $8 \times 40 = 320$ grams of NaOH solids (in flake or pellet form) per litre of the solution, where 40 is the molecular weight of NaOH. The mass of NaOH solids was measured as 262 grams per kg of NaOH solution of 8M concentrations. Similarly, the mass of NaOH solids per kg of the solution for other concentrations were measured as 10M: 314 grams, 12M: 361 grams, 14M: 404 grams, and 16M: 444 grams. Note that the mass of NaOH solids was only a fraction of the mass of NaOH solution, and water is the major component.

Sodium silicate solution (Vitrosol D - A53) obtained from PQ Australia was used. The chemical composition of the sodium silicate solution was $\text{Na}_2\text{O}=14.7\%$, $\text{SiO}_2=29.4\%$, and water 55.9% by mass. The other characteristics of the sodium silicate solution were specific gravity=1.53 g/cc and viscosity at $20^\circ\text{C}=400$ cp.

3.2.3 Aggregates

Aggregates currently used by the local concrete industry in Western Australia, and supplied by BGC Concrete and Asphalt were used. Both coarse and fine aggregates were in saturated surface dry (SSD) condition, in accordance to relevant Australian Standards, AS 1141.5-2000 and AS 1141.6.1-2000 (2000; 2000). Coarse aggregates were obtained in crushed form; majority of the particles were of granite type. The fine aggregate was obtained from the sand dunes in uncrushed form.

Three different aggregate combinations were used, as given in Table 3.2, Table 3.3, and Table 3.4. All of these combinations comply with the grading requirements for

combined aggregates in accordance with the British Standard BS 882:92 (Neville 2000). The Fineness Modulus (FM) of the aggregates combination I was 5.01, while the FM of the aggregates combination II and III were 4.5 and 4.6 respectively.

Table 3.2: Grading of Combined Aggregates I

| Sieve Size | Aggregates | | | | Combination *) | BS 882:92 |
|------------|------------|-------|--------|--------|----------------|-----------|
| | 20 mm | 14 mm | 7 mm | Fine | | |
| 19.00 mm | 93.34 | 99.99 | 100.00 | 100.00 | 99.00 | 95-100 |
| 9.50 mm | 3.89 | 17.40 | 99.90 | 100.00 | 69.03 | |
| 4.75 mm | 0.90 | 2.99 | 20.10 | 100.00 | 37.77 | 35-55 |
| 2.36 mm | 0.88 | 1.07 | 3.66 | 100.00 | 31.63 | |
| 1.18 mm | 0.87 | 0.81 | 2.05 | 99.99 | 31.01 | |
| 600 µm | 0.85 | 0.70 | 1.52 | 79.58 | 24.67 | 10-35 |
| 300 µm | 0.75 | 0.59 | 1.08 | 16.53 | 5.57 | |
| 150 µm | 0.54 | 0.42 | 0.62 | 1.11 | 0.72 | 0-8 |

*) 15% (20 mm) + 20% (14 mm) + 35% (7 mm) + 30% (Fine)

Table 3.3: Grading of Combined Aggregates II

| Sieve Size | Aggregates | | | Combination *) | BS 882:92 |
|------------|------------|--------|--------|----------------|-----------|
| | 10 mm | 7 mm | Fine | | |
| 19.00 mm | 100.00 | 100.00 | 100.00 | 100.00 | 95-100 |
| 9.50 mm | 74.86 | 99.99 | 100.00 | 92.42 | |
| 4.75 mm | 9.32 | 20.10 | 100.00 | 44.83 | 35-55 |
| 2.36 mm | 3.68 | 3.66 | 100.00 | 37.39 | |
| 1.18 mm | 2.08 | 2.05 | 100.00 | 36.34 | |
| 600 µm | 1.47 | 1.52 | 79.60 | 28.83 | 10-35 |
| 300 µm | 1.01 | 1.08 | 16.50 | 6.47 | |
| 150 µm | 0.55 | 0.62 | 1.11 | 0.77 | 0-8 |

*) 30% (10 mm) + 35% (7 mm) + 35% (Fine)

Table 3.4: Grading of Combined Aggregates III

| Sieve Size | Aggregates | | Combination *) | BS 882:92 |
|------------|------------|--------|----------------|-----------|
| | 7 mm | Fine | | |
| 19.00 mm | 100.00 | 100.00 | 100.00 | 95-100 |
| 9.50 mm | 99.99 | 100.00 | 99.93 | |
| 4.75 mm | 20.10 | 100.00 | 44.07 | 35-55 |
| 2.36 mm | 3.66 | 100.00 | 32.56 | |
| 1.18 mm | 2.05 | 100.00 | 31.43 | |
| 600 µm | 1.52 | 79.60 | 24.94 | 10-35 |
| 300 µm | 1.08 | 16.50 | 5.72 | |
| 150 µm | 0.62 | 1.11 | 0.77 | 0-8 |

*) 70% (7 mm) + 30% (Fine)

3.2.4 Super plasticiser

To improve the workability of the fresh geopolymer concrete, a naphthalene sulphonate super plasticiser in liquid form, supplied by Master Builders Technologies, Perth, Australia, under the brand name of Rheobuild 1000, was used in nearly all cases.

Another type of super plasticiser, a polycarboxylic ether hyperplasticiser in liquid form, under the brand name of Glenium 27, supplied by Master Builders Technologies, Perth, Australia, was also tried. However, this type of super plasticiser was not used due to the cost.

3.3 PRELIMINARY LABORATORY WORK

In the beginning, numerous trial mixtures of geopolymer concrete were manufactured, and test specimens in the form of 75x75x75 mm cubes or 100x200 mm cylinders were made. Initially, the mixing was done in a Hobart mixer. However, this was considered to be not practical in large applications. Therefore, the

mixing changed to an eighty litre capacity pan mixer with rotating drum available in the concrete laboratory for making OPC concrete. The details of the preliminary mixtures can be seen in Appendix A.

The main objectives of the preliminary laboratory work were:

- to familiarize with the making of fly ash-based geopolymer concrete;
- to understand the effect of the sequence of adding the alkaline activator to the solids constituents in the mixer;
- to observe the behaviour of the fresh fly ash-based geopolymer concrete;
- to develop the process of mixing and the curing regime; and
- to understand the basic mixture proportioning of fly ash-based geopolymer concrete.

The preliminary laboratory work revealed the following:

3.3.1 Mixing

It was found that the fresh fly ash-based geopolymer concrete was dark in colour (due to the dark colour of the fly ash), and was cohesive. The amount of water in the mixture played an important role on the behaviour of fresh concrete. When the mixing time was long, mixtures with high water content bled and segregation of aggregates and the paste occurred. This phenomenon was usually followed by low compressive strength result of hardened concrete.

Communication with Davidovits (2002), suggested that it is preferable to mix the sodium silicate solution and sodium hydroxide solution before adding it to the solid constituents. He also suggested that the sodium silicate liquid obtained from the market usually is in the form of a dimer or a trimer, instead of a monomer, and mixing it together with the sodium hydroxide solution assists the polymerisation process. When this suggestion was followed, it was found that the occurrence of bleeding and segregation ceased.

The effects of water content in the mixture and the mixing time were identified as test parameters in the detailed study (see Chapter 4). From the preliminary work, it was decided to observe the following standard process of mixing in all further studies.

- Mix sodium hydroxide solution and sodium silicate solution together prior to adding to the dry materials.
- Mix all dry materials in the pan mixer for about three minutes. Add the liquid component of the mixture at the end of dry mixing, and continue the wet mixing for another four minutes.

3.3.2 Curing

Geopolymer concrete specimens should be wrapped during curing at elevated temperatures in a dry environment (in the oven) to prevent excessive evaporation. Unlike the small geopolymer paste specimens, which can easily be wrapped by placing a lid on the mould, a suitable method was needed for large size geopolymer concrete specimens. Extensive trials revealed wrapping of concrete specimens by using vacuum bagging film is effective for temperatures up to 100°C for several days of curing. To tighten the film to the concrete moulds, a quick lock seal (Figure 3.5) or a twist tie wire (Figure 3.6) was utilized. The later was used in all further experimental work due to its simplicity and economics.

Preliminary tests also revealed that fly ash-based geopolymer concrete did not set immediately at room temperature. When the room temperature was less than 30°C, the setting did not occur at least for 24 hours. Also, the handling time is a more appropriate parameter (rather than setting time used in the case of OPC concrete) for fly ash-based geopolymer concrete.



Figure 3.5: Wrapping of Concrete Specimens before Curing (1)



Figure 3.6: Wrapping Concrete Specimens Before Curing (2)

3.4 MIXTURE PROPORTION

Based on the limited past research on geopolymer pastes available in the literature (Chapter 2) and the experience gained during the preliminary experimental work (Section 3.3), the following ranges were selected for the constituents of the mixtures used in further studies described in Chapter 4.

- Low calcium (ASTM Class F) fly ash as given in Section 3.2.1.
- Alkaline activators as given in Section 3.2.2.
 - Ratio of sodium silicate solution-to-sodium hydroxide solution, by mass, of 0.4 to 2.5. This ratio was fixed at 2.5 for most of the mixtures because the sodium silicate solution is considerably cheaper than the sodium hydroxide solution.
 - Molarity of sodium hydroxide (NaOH) solution in the range of 8M to 16M.
 - Ratio of activator solution-to-fly ash, by mass, in the range of 0.3 and 0.40.
- Coarse and fine aggregates as given in Section 3.2.3, of approximately 75% to 80%, of the entire mixture by mass. This value is similar to that used in OPC concrete.
- Super plasticiser, as given in Section 3.2.4, in the range of 0% to 2% of fly ash, by mass.
- Extra water, when added, in mass.

3.5 MIXING, CASTING AND CURING

For mixing, rotating pan mixer of 80 litres capacity with fixed blades was used (Fig. 3.7). The aggregates were prepared in saturated surface dry condition, and were kept in plastic buckets with lid (Figure 3.8).



Figure 3.7: Pan Mixer Used for Manufacturing Geopolymer Concrete



Figure 3.8: Dry Materials for Making Geopolymer Concrete



Figure 3.9: Addition of Liquid Component



Figure 3.10: Fresh Fly Ash Geopolymer Concrete Ready for Placing

The solids constituents of the fly ash-based geopolymer concrete, i.e. the aggregates and the fly ash, were dry mixed in the pan mixer for about three minutes. The liquid part of the mixtures, i.e. the sodium silicate solution, the sodium hydroxide solution, added water (if any), and the super plasticiser (if any), were premixed then added to the solids (Figure 3.9). The wet mixing usually continued for another four minutes.

The fresh fly ash-based geopolymer concrete was dark in colour and shiny in appearance (Figure 3.10). The mixtures were usually very cohesive. The workability of the fresh concrete was measured by means of the conventional slump test (Figure 3.11).

Compaction of fresh concrete in the cylinder steel moulds was achieved by applying sixty manual strokes per layer in three equal layers (Figure 3.12), followed by compaction on a vibration table for ten seconds. After casting, the specimens were covered using vacuum bagging film.



Figure 3.11: Slump Measurement of Fresh Concrete



Figure 3.12: Compaction into Moulds



Figure 3.13: Steam Boiler and Controls



Figure 3.14: Specimens in Steam Curing Chamber

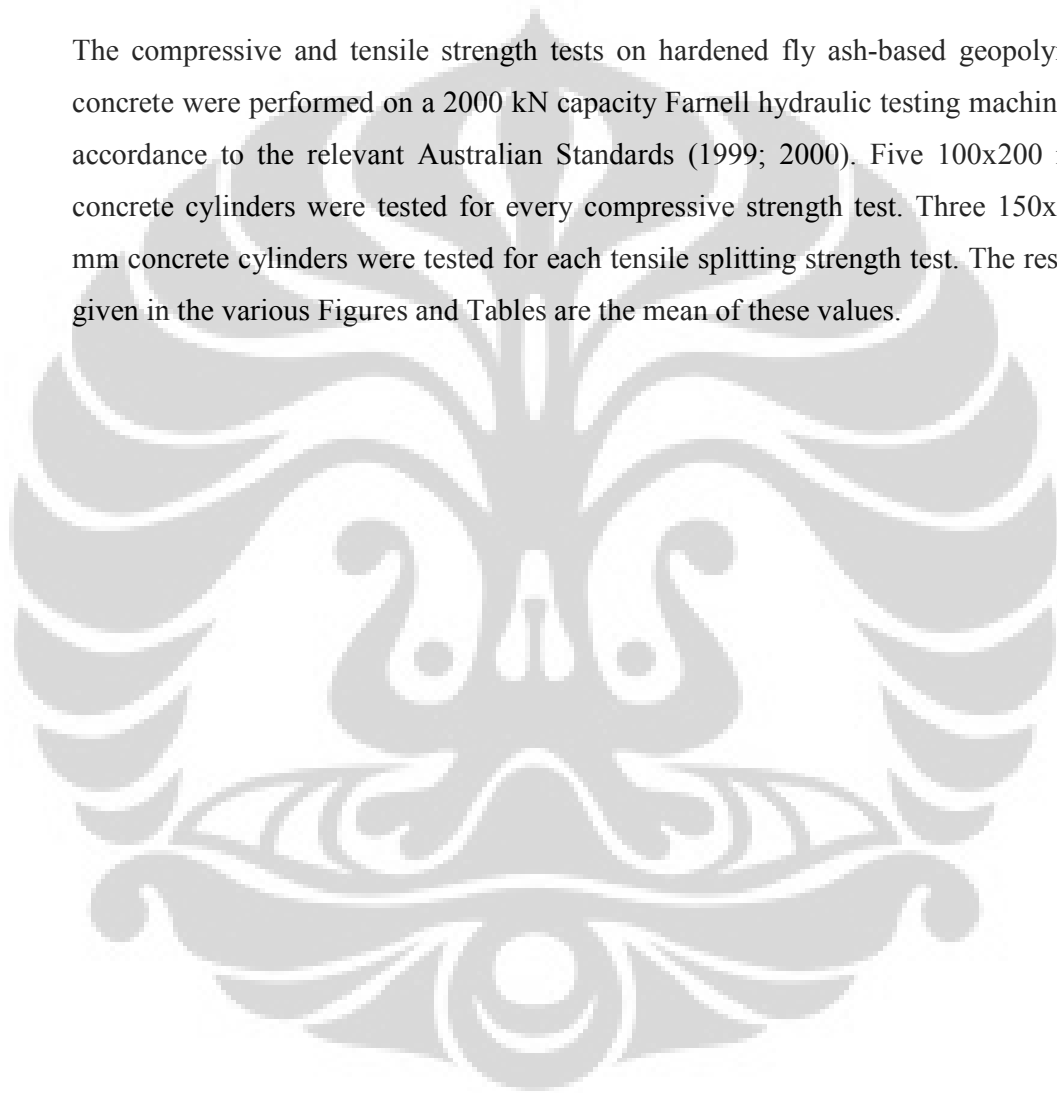


Figure 3.15: Steam Curing in Progress

Curing at elevated temperatures was done in two different ways, i.e. dry curing in the laboratory oven or steam curing in a chamber. A boiler was used to generate the steam at a specified temperature (Figure 3.13). Figures 3.14 and 3.15 show curing process in the steam curing chamber.

3.6 COMPRESSIVE AND TENSILE STRENGTH TESTS

The compressive and tensile strength tests on hardened fly ash-based geopolymer concrete were performed on a 2000 kN capacity Farnell hydraulic testing machine in accordance to the relevant Australian Standards (1999; 2000). Five 100x200 mm concrete cylinders were tested for every compressive strength test. Three 150x300 mm concrete cylinders were tested for each tensile splitting strength test. The results given in the various Figures and Tables are the mean of these values.



4. EXPERIMENTAL RESULTS AND DISCUSSION

4.1 INTRODUCTION

In this Chapter, the experimental results are presented and discussed. Each of the compressive strength test data points plotted in various graphs or stated in various Tables corresponds to the mean value of the compressive strengths of five test concrete cylinders in a series. The standard deviations are plotted on the test data points as the error bar.

In Section 4.2 of the Chapter, the effects of various salient parameters on the compressive strength of fly ash-based geopolymer concrete are discussed. The parameters considered are as follows:

1. Ratio of activator liquid-to-fly ash, by mass
2. Concentration of sodium hydroxide (NaOH) solution, in Molar
3. Ratio of sodium silicate solution-to-sodium hydroxide solution, by mass
4. Curing temperature
5. Curing time
6. Handling time
7. Addition of super plasticiser
8. Rest period prior to curing
9. Water content of mixture
10. Dry curing versus steam curing
11. Mixing Time
12. Age of concrete

In all cases, low calcium (ASTM Class F) fly ash from Batch I, Batch II or Batch III (Section 3.2.1) was used. The mass of aggregates (Section 3.2.3) was approximately 75 to 80 percent of the mass of the entire mixture.

Section 4.3 of the Chapter presents the measured elastic constants, while Section 4.4 describes the stress-strain relations in compression for different grades of fly ash-based geopolymer concrete. Section 4.5 and 4.6 report the indirect tensile strength and the density of the fly ash-based geopolymer concrete respectively.

Temperature history during curing at elevated temperature was measured, and the results are reported in Section 4.7. The Chapter ends with Section 4.8, where a mixture design process for fly ash-based geopolymer concrete is proposed.

In all, twenty-six different Mixtures were made to study the effect of various parameters. The details of these Mixtures are given in Table 4.1 and Table 4.2, and the properties of the Mixtures are presented in Tables 4.3 to 4.8.

In Tables 4.1 and 4.2, the mass of each component of a Mixture is given in terms of kg per cubic metre of concrete.

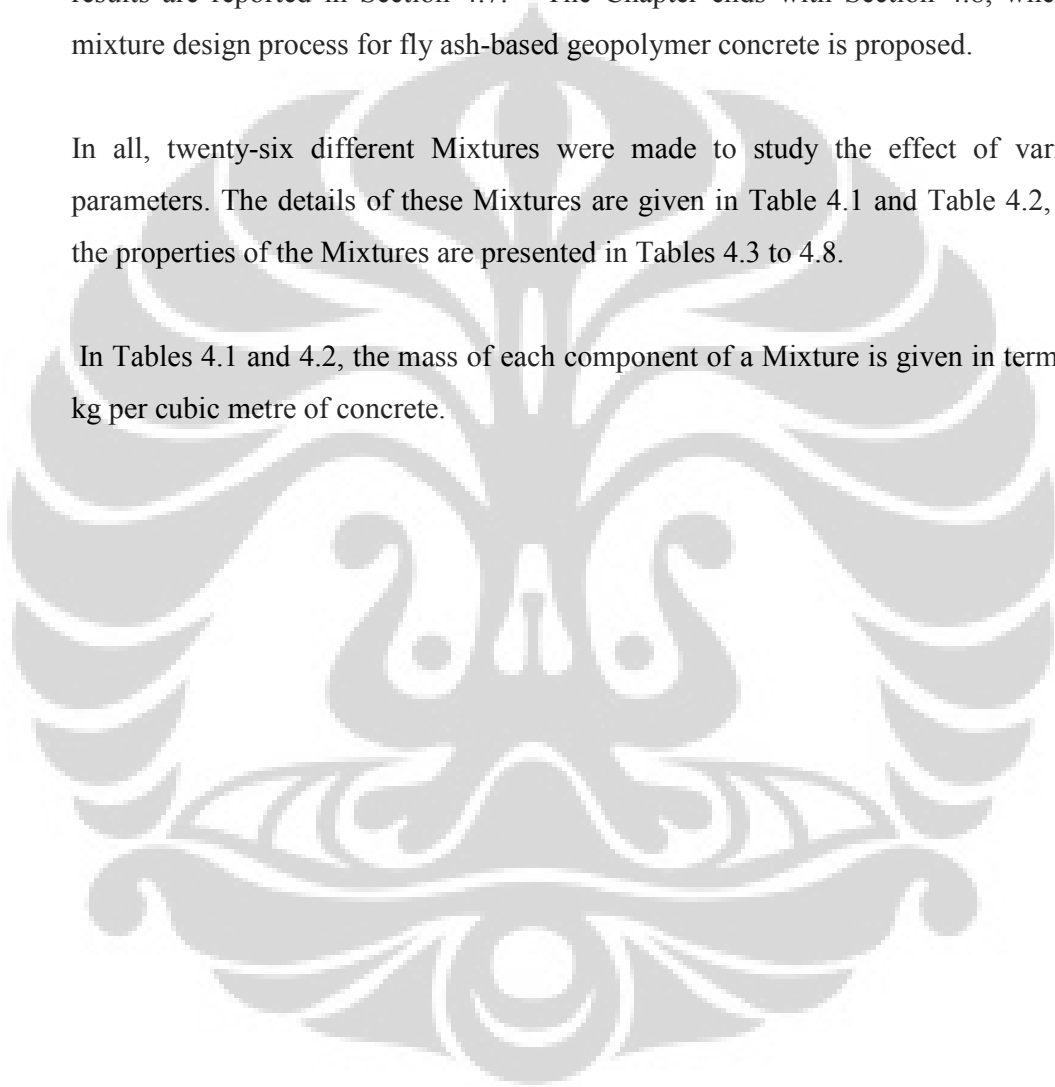


Table 4.1: Details of Mixtures 1 to 13

| Mixture No | Aggregate | | | | | Fly Ash (kg) | NaOH Solution | | Sodium Silicate (kg) | Added Water (kg) | Super-plasticiser (kg) |
|------------|------------|------------|------------|-----------|----------------|-------------------|---------------|--------------------|----------------------|--------------------|------------------------|
| | 20 mm (kg) | 14 mm (kg) | 10 mm (kg) | 7 mm (kg) | Fine Sand (kg) | | Mass (kg) | Molarity | | | |
| 1 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 120 | 8M ^{*)} | 48 | - | - |
| 2 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 48 | 8M ^{*)} | 120 | - | - |
| 3 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 120 | 14M ^{*)} | 48 | - | - |
| 4 | 277 | 370 | - | 647 | 554 | 476 ^{a)} | 48 | 14M ^{*)} | 120 | - | - |
| 5 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | - |
| 6 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | 4.1 |
| 7 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | 8.2 |
| 8 | - | - | - | 1294 | 554 | 408 ^{c)} | 51.5 | 14M ^{**)} | 103 | 16.5 ^{x)} | 16.3 |
| 9 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 12M ^{**)} | 103 | 14.3 ^{y)} | 6.1 |
| 10 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{**)} | 103 | 17.6 ^{y)} | 6.1 |
| 11 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 12M ^{*)} | 103 | 14.3 ^{y)} | 6.1 |
| 12 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 8M ^{*)} | 103 | - | 6.1 |
| 13 | 277 | 370 | - | 647 | 554 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | - | 8.2 |

Note:

^{*)} Technical Grade
^{**)} Commercial Grade

^{a)} Fly Ash: Batch I
^{b)} Fly Ash: Batch II
^{c)} Fly Ash: Batch III

^{x)} Tap water
^{y)} Distilled water

Table 4.2: Details of Mixtures 14 to 26

| Mixture No | Aggregate | | | | | Fly Ash (kg) | NaOH Solution | | Sodium Silicate (kg) | Added Water (kg) | Super-plasticiser (kg) |
|------------|------------|------------|------------|-----------|----------------|-------------------|---------------|--------------------|----------------------|--------------------|------------------------|
| | 20 mm (kg) | 14 mm (kg) | 10 mm (kg) | 7 mm (kg) | Fine Sand (kg) | | Mass (kg) | Molarity | | | |
| 14 | 277 | 370 | - | 647 | 554 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | 10.7 ^{y)} | 8.2 |
| 15 | 277 | 370 | - | 647 | 554 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | 21.3 ^{y)} | 8.2 |
| 16 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 8M ^{*)} | 103 | - | 6.1 |
| 17 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 10M ^{*)} | 103 | 7.5 ^{y)} | 6.1 |
| 18 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 12M ^{*)} | 103 | 14.4 ^{y)} | 6.1 |
| 19 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{*)} | 103 | 20.7 ^{y)} | 6.1 |
| 20 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 16M ^{*)} | 103 | 26.5 ^{y)} | 6.1 |
| 21 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{**)} | 103 | 20.7 ^{y)} | 6.1 |
| 22 | - | - | - | 1294 | 554 | 408 ^{c)} | 41 | 14M ^{**)} | 103 | 16.5 ^{x)} | 6.1 |
| 23 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 14M ^{*)} | 103 | - | 8.2 |
| 24 | - | - | 554 | 647 | 647 | 408 ^{b)} | 41 | 8M ^{*)} | 103 | - | 6.1 |
| 25 | - | - | 554 | 647 | 647 | 408 ^{b)} | 55.4 | 8M ^{*)} | 103 | - | 6.1 |
| 26 | - | - | 554 | 647 | 647 | 408 ^{b)} | 55.4 | 8M ^{*)} | 103 | - | 6.1 |

Note:

*) Technical Grade
 **) Commercial Grade

a) Fly Ash: Batch I
 b) Fly Ash: Batch II
 c) Fly Ash: Batch III

x) Tap water
 y) Distilled water

Table 4.3: Properties of Mixtures 1 to 9

| Mixture No | Curing | | | Age at Test (days) | Slump (mm) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Features |
|------------|--------------|------------|--------|--------------------|------------|------------------------------|----------------------------|--------------------|----------------------|
| | Time (hours) | Temp. (°C) | Method | | | | | | |
| 1 | 24 | 60 | Oven | 7 | na | 2365 | 17 | 0.91 | - |
| 2 | 4 | 30 | Oven | 7 | na | 2376 | 8 | 0.27 | - |
| | 4 | 60 | Oven | 7 | na | 2378 | 24 | 0.47 | - |
| | 4 | 90 | Oven | 7 | na | 2341 | 37 | 4.39 | - |
| | 24 | 30 | Oven | 7 | na | 2364 | 20 | 1.13 | - |
| 3 | 24 | 60 | Oven | 7 | na | 2377 | 57 | 2.51 | - |
| | 24 | 90 | Oven | 7 | na | 2341 | 66 | 5.46 | - |
| | 24 | 60 | Oven | 7 | na | 2386 | 48 | 1.62 | - |
| | 48 | 30 | Oven | 7 | na | 2367 | 49 | 1.6 | - |
| 4 | 4 | 60 | Oven | 7 | na | 2320 | 25 | 2.57 | - |
| | 4 | 90 | Oven | 7 | na | 2376 | 30 | 3.71 | - |
| | 24 | 30 | Oven | 7 | na | 2367 | 29 | 1.46 | - |
| | 24 | 60 | Oven | 7 | na | 2386 | 68 | 4.09 | - |
| | 24 | 90 | Oven | 7 | na | 2385 | 70 | 2.68 | - |
| | 24 | 60 | Steam | 3 | 39 | 2340 | 42 | 0.8 | Superplasticiser 0% |
| 5 | 24 | 60 | Steam | 3 | 59 | 2375 | 41 | 0.5 | Superplasticiser 1% |
| 6 | 24 | 60 | Steam | 3 | 80 | 2347 | 41 | 2.7 | Superplasticiser 2% |
| 7 | 24 | 60 | Steam | 3 | 93 | 2336 | 36 | 1.3 | Superplasticiser 4% |
| 9 | 24 | 60 | Steam | 7 | 209 | - | 40 | 2.9 | Rest Period = 0 day |
| | 24 | 60 | Steam | 7 | 209 | - | 41 | 2.1 | Rest Period = 1 day |
| | 24 | 60 | Steam | 7 | 209 | - | 48 | 1.9 | Rest Period = 2 days |
| | 24 | 60 | Steam | 7 | 209 | - | 50 | 1.2 | Rest Period = 3 days |
| | 24 | 60 | Steam | 7 | 209 | - | 49 | 1.8 | Rest Period = 4 days |

Table 4.4: Properties of Mixtures 10 to 13

| Mixture No | Curing | | | Age at Test (days) | Slump (mm) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Features |
|------------|--------------|------------|--------|--------------------|------------|------------------------------|----------------------------|--------------------|--|
| | Time (hours) | Temp. (°C) | Method | | | | | | |
| 10 | 24 | 60 | Steam | 7 | 215 | 2298 | 43 | 1.1 | Rest Period = 0 day |
| | 24 | 60 | Steam | 7 | 215 | 2299 | 53 | 1.5 | Rest Period = 1 day |
| | 24 | 60 | Steam | 7 | 215 | 2298 | 56 | 1.3 | Rest Period = 2 days |
| | 24 | 60 | Steam | 7 | 215 | 2305 | 57 | 2.3 | Rest Period = 3 days |
| | 24 | 60 | Steam | 7 | 215 | 2306 | 57 | 1.6 | Rest Period = 4 days |
| | 24 | 60 | Steam | 7 | 215 | 2303 | 58 | 5.0 | Rest Period = 5 days |
| 11 | 24 | 60 | Steam | 7 | 225 | 2305 | 38 | 2.8 | Rest Period = 0 day |
| | 24 | 60 | Steam | 7 | 225 | 2309 | 53 | 2.2 | Rest Period = 1 day |
| | 24 | 60 | Steam | 7 | 225 | 2314 | 56 | 1.9 | Rest Period = 2 days |
| | 24 | 60 | Steam | 7 | 225 | 2318 | 59 | 2.5 | Rest Period = 3 days |
| | 24 | 60 | Steam | 7 | 225 | 2318 | 59 | 2.3 | Rest Period = 4 days |
| | 24 | 60 | Steam | 7 | 225 | 2314 | 59 | 3.0 | Rest Period = 5 days |
| 12 | 24 | 60 | Oven | 7 | 60 | 2357 | 63 | 4.2 | Rest Period = 0 day |
| | 24 | 60 | Oven | 7 | 60 | 2364 | 74 | 4.1 | Rest Period = 1 day |
| | 24 | 60 | Oven | 7 | 60 | 2363 | 73 | 2.7 | Rest Period = 2 days |
| | 24 | 60 | Oven | 7 | 60 | 2361 | 76 | 3.5 | Rest Period = 3 days |
| | 24 | 60 | Oven | 7 | 60 | 2369 | 75 | 3.2 | Rest Period = 4 days |
| | 24 | 60 | Oven | 7 | 60 | 2368 | 77 | 5.3 | Rest Period = 5 days |
| 13 | 24 | 30 | Oven | 7 | na | 2387 | 44 | 0.51 | H ₂ O/Na ₂ O=10.00 |
| | 24 | 45 | Oven | 7 | na | 2377 | 55 | 1.69 | |
| | 24 | 60 | Oven | 7 | na | 2375 | 59 | 2.52 | |
| | 24 | 75 | Oven | 7 | na | 2375 | 65 | 4.81 | |
| | 24 | 90 | Oven | 7 | na | 2376 | 71 | 4.69 | |

Table 4.5: Details of Mixtures 14 to 20

| Mixture No | Curing | | | Age at Test (days) | Slump (mm) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Features |
|------------|--------------|------------|--------|--------------------|------------|------------------------------|----------------------------|--------------------|---|
| | Time (hours) | Temp. (°C) | Method | | | | | | |
| 14 | 24 | 30 | Oven | 7 | na | 2338 | 35 | 1.79 | H ₂ O/Na ₂ O=11.25 |
| | 24 | 45 | Oven | 7 | na | 2336 | 42 | 4.17 | |
| | 24 | 60 | Oven | 7 | na | na | na | na | |
| | 24 | 75 | Oven | 7 | na | 2337 | 60 | 2.04 | |
| | 24 | 90 | Oven | 7 | na | 2334 | 59 | 3.13 | |
| 15 | 24 | 30 | Oven | 7 | na | 2326 | 32 | 1.02 | H ₂ O/Na ₂ O=12.50 |
| | 24 | 45 | Oven | 7 | na | 2322 | 37 | 0.73 | |
| | 24 | 60 | Oven | 7 | na | 2321 | 44 | 2.49 | |
| | 24 | 75 | Oven | 7 | na | 2301 | 44 | 0.63 | |
| | 24 | 90 | Oven | 7 | na | 2318 | 44 | 3.35 | |
| 16 | 24 | 60 | Oven | 7 | 32 | 2381 | 55 | 1.50 | Na ₂ O/SiO ₂ =0.097 |
| | 24 | 60 | Steam | 7 | 32 | 2385 | 47 | 1.24 | |
| 17 | 24 | 60 | Oven | 7 | 113 | 2352 | 53 | 3.00 | Na ₂ O/SiO ₂ =0.103 |
| | 24 | 60 | Steam | 7 | 113 | 2362 | 45 | 0.82 | |
| 18 | 24 | 60 | Oven | 7 | 162 | 2361 | 51 | 1.70 | Na ₂ O/SiO ₂ =0.109 |
| | 24 | 60 | Steam | 7 | 162 | 2364 | 42 | 1.55 | |
| 19 | 24 | 60 | Oven | 7 | 214 | 2343 | 45 | 2.17 | Na ₂ O/SiO ₂ =0.115 |
| | 24 | 60 | Steam | 7 | 214 | 2341 | 40 | 1.16 | |
| 20 | 24 | 60 | Oven | 7 | 240 | 2341 | 47 | 1.93 | Na ₂ O/SiO ₂ =0.120 |
| | 24 | 60 | Steam | 7 | 240 | 2342 | 40 | 2.30 | |

Table 4.6: Properties of Mixtures 21 to 26

| Mixture No | Curing | | | Age at Test (days) | Slump (mm) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Features |
|------------|--------------|------------|--------|--------------------|------------|------------------------------|----------------------------|--------------------|--------------------|
| | Time (hours) | Temp. (°C) | Method | | | | | | |
| 21 | 24 | 60 | Steam | 21 | 234 | 2345 | 37 | 1.44 | Mixing time 2 min |
| | 24 | 60 | Steam | 21 | 234 | 2367 | 40 | 1.92 | Mixing time 4 min |
| | 24 | 60 | Steam | 21 | 226 | 2373 | 45 | 3.36 | Mixing time 6 min |
| | 24 | 60 | Steam | 21 | 219 | 2378 | 45 | 3.06 | Mixing time 8 min |
| | 24 | 60 | Steam | 21 | 219 | 2387 | 47 | 0.25 | Mixing time 10 min |
| | 24 | 60 | Steam | 21 | 206 | 2397 | 49 | 2.08 | Mixing time 13 min |
| | 24 | 60 | Steam | 21 | 206 | 2399 | 52 | 1.01 | Mixing time 16 min |
| 22 a | 4 | 90 | Steam | 3 | 91 | 2331 | 40 | 0.78 | Mixing time 4 min |
| b | 4 | 90 | Steam | 3 | 67 | 2344 | 47 | 1.24 | Mixing time 8 min |
| c | 4 | 90 | Steam | 3 | 49 | 2368 | 56 | 4.28 | Mixing time 16 min |
| 23 | 24 | 90 | Oven | 90 | 46 | - | 89 | 4.45 | |
| 24 | 24 | 90 | Oven | 90 | 135 | - | 68 | 4.56 | |
| 25 | 24 | 60 | Oven | 90 | 207 | - | 55 | 1.80 | |
| 26 | 24 | 60 | Steam | 90 | 219 | - | 44 | 1.20 | |

Table 4.7: Data from Additional Studies for Mixture 2 (1)

| Super-plasticiser (kg) | Curing | | | Age at Test (days) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Feature/s |
|------------------------|--------------|------------|--------|--------------------|------------------------------|----------------------------|--------------------|---|
| | Time (hours) | Temp. (°C) | Method | | | | | |
| - | 24 | 60 | Oven | 3 | 2404 | 61 | 5.49 | Age at test 3 days |
| - | 24 | 60 | Oven | 7 | 2401 | 58 | 4 | Age at test 7 days |
| - | 24 | 60 | Oven | 14 | 2387 | 64 | 3.65 | Age at test 14 days |
| - | 24 | 60 | Oven | 28 | 2373 | 60 | 5.16 | Age at test 28 days |
| - | 24 | 60 | Oven | 56 | 2362 | 61 | 1.95 | Age at test 56 days |
| - | 24 | 60 | Oven | 91 | 2362 | 63 | 3.02 | Age at test 91 days |
| - | 4 | 60 | Oven | 7 | 2396 | 25 | 0.46 | Curing time 4 hrs |
| - | 8 | 60 | Oven | 7 | 2398 | 31 | 3.67 | Curing time 8 hrs |
| - | 12 | 60 | Oven | 7 | 2394 | 41 | 2.31 | Curing time 12 hrs |
| - | 24 | 60 | Oven | 7 | 2391 | 61 | 5.52 | Curing time 16 hrs |
| - | 48 | 60 | Oven | 7 | 2387 | 72 | 10.03 | Curing time 24 hrs |
| - | 72 | 60 | Oven | 7 | 2403 | 77 | 2.7 | Curing time 72 hrs |
| - | 96 | 60 | Oven | 7 | 2400 | 82 | 6.2 | Curing time 96 hrs |
| 4.1 | 24 | 60 | Oven | 7 | 2379 | 56 | 1.86 | Superplasticiser 1.0%, No Rest Period |
| 6.1 | 24 | 60 | Oven | 7 | 2374 | 58 | 3.02 | Superplasticiser 1.5%, No Rest Period |
| 8.2 | 24 | 60 | Oven | 7 | 2362 | 57 | 2.33 | Superplasticiser 2.0%, No Rest Period |
| 10.2 | 24 | 60 | Oven | 7 | 2354 | 50 | 3.28 | Superplasticiser 2.5%, No Rest Period |
| 12.2 | 24 | 60 | Oven | 7 | 2364 | 50 | 0.76 | Superplasticiser 3.0%, No Rest Period |
| 14.3 | 24 | 60 | Oven | 7 | 2335 | 46 | 2.82 | Superplasticiser 3.5%, No Rest Period |
| 4.1 | 24 | 60 | Oven | 7 | 2379 | 56 | 1.86 | Superplasticiser 1.0%, 1 hr Rest Period |
| 6.1 | 24 | 60 | Oven | 7 | 2374 | 58 | 3.02 | Superplasticiser 1.5%, 1 hr Rest Period |
| 8.2 | 24 | 60 | Oven | 7 | 2362 | 57 | 2.33 | Superplasticiser 2.0%, 1 hr Rest Period |

Table 4.8: Data from Additional Studies for Mixture 2 (2)

| Super-plasticiser (kg) | Curing | | | Age at Test (days) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Feature/s |
|------------------------|--------------|------------|--------|--------------------|------------------------------|----------------------------|--------------------|---|
| | Time (hours) | Temp. (°C) | Method | | | | | |
| 10.2 | 24 | 60 | Oven | 7 | 2354 | 50 | 3.28 | Superplasticiser 2.5%, 1 hr Rest Period |
| 12.2 | 24 | 60 | Oven | 7 | 2364 | 50 | 0.76 | Superplasticiser 3.0%, 1 hr Rest Period |
| 14.3 | 24 | 60 | Oven | 7 | 2335 | 46 | 2.82 | Superplasticiser 3.5%, 1 hr Rest Period |
| 6.1 | 24 | 60 | Oven | 7 | 2363 | 59 | 2.32 | Handling time = 0 Mnts |
| 6.1 | 24 | 60 | Oven | 7 | 2376 | 59 | 2.36 | Handling time = 30 Mnts |
| 6.1 | 24 | 60 | Oven | 7 | 2365 | 61 | 4.26 | Handling time = 45 Mnts |
| 6.1 | 24 | 60 | Oven | 7 | 2366 | 65 | 1.46 | Handling time = 60 Mnts |
| 6.1 | 24 | 60 | Oven | 7 | 2374 | 64 | 1.49 | Handling time = 75 Mnts |
| 6.1 | 24 | 60 | Oven | 7 | 2370 | 65 | 1.15 | Handling time = 90 Mnts |
| 6.1 | 24 | 60 | Oven | 7 | 2370 | 62 | 4.06 | Handling time = 120 Mnts |
| 6.1 | 24 | 30 | Oven | 7 | - | 35 | 1.22 | Curing Temperature = 30 °C |
| 6.1 | 24 | 45 | Oven | 7 | - | 41 | 2.11 | Curing Temperature = 45 °C |
| 6.1 | 24 | 60 | Oven | 7 | - | 63 | 1.17 | Curing Temperature = 60 °C |
| 6.1 | 24 | 75 | Oven | 7 | - | 64 | 3.42 | Curing Temperature = 75 °C |
| 6.1 | 24 | 90 | Oven | 7 | - | 63 | 3.75 | Curing Temperature = 90 °C |
| 6.1 | 6 | 45 | Oven | 7 | 2378 | 33 | 1.01 | Curing Temperature = 45 °C |
| 6.1 | 6 | 60 | Oven | 7 | 2386 | 42 | 1.07 | Curing Temperature = 60 °C |
| 6.1 | 6 | 75 | Oven | 7 | 2383 | 48 | 2.68 | Curing Temperature = 75 °C |
| 6.1 | 6 | 90 | Oven | 7 | 2369 | 51 | 2.73 | Curing Temperature = 90 °C |
| 4.1 ¹⁾ | 24 | 60 | Oven | 7 | 2388 | 61 | 4.08 | Rest Period 1 hr |
| 4.1 ¹⁾ | 24 | 60 | Oven | 7 | 2393 | 61 | 3.84 | No Rest Period |

¹⁾ Polycarboxylic ether hyperplasticiser

4.2 EFFECT OF SALIENT PARAMETERS

4.2.1 Ratio of Activator Liquid-to-Fly Ash

The ratio of activator liquid-to-fly ash, by mass, was not varied. This ratio remained approximately around 0.35.

4.2.2 Concentration of Sodium Hydroxide (NaOH) Solution

Mixtures 1 to 4 (Table 4.1) were made to study the effect of concentration of sodium hydroxide solution on the compressive strength of concrete. Complete details of these mixtures and their properties are given in Tables 4.1 and 4.3. The test cylinders were left at ambient conditions for about 30 minutes prior to start of dry curing in an oven. The curing time was 24 hours at various temperatures. The measured 7th day compressive strengths of test cylinders are given in Table 4.9.

Table 4.9: Mixtures 1 to 4

| Mixture | Concentration of NaOH liquid (in Molars) | Ratio of sodium silicate to NaOH solution (by mass) | Compressive strength at 7 th day (MPa) |
|---------|--|---|---|
| | | | Cured for 24 hours at 60°C |
| 1 | 8M | 0.4 | 17 |
| 2 | 8M | 2.5 | 57 |
| 3 | 14M | 0.4 | 48 |
| 4 | 14M | 2.5 | 67 |

In Table 4.9, the difference between Mixture 1 and Mixture 3 is the concentration of NaOH solution in terms of Molar (second column). Mixture 3 with a higher concentration of NaOH solution yielded higher compressive strength than Mixture 1. A similar trend is also observed for the Mixtures 2 and 4.

4.2.3 Ratio of Sodium Silicate Solution-to-Sodium Hydroxide Solution

The effect of sodium silicate solution-to-NaOH solution by mass on compressive strength of concrete can be seen by comparing the results of Mixtures 1 and 2 as well as Mixtures 3 and 4 in Table 4.9. For Mixtures 1 and 2, although the concentration of NaOH solution (in terms of Molarity) is the same, in Mixture 2 the sodium silicate solution-to-NaOH solution ratio is higher than that of Mixture 1. This change increased the compressive strength of Mixture 2. A similar trend is also observed in the results of Mixture 3 and Mixture 4; the compressive strength of Mixture 4 is higher than that of Mixture 3. The results given in Table 4.9 reveal that the interrelation of various oxides contained in the mixture composition affects the compressive strength.

Mixtures 2 and 4, with sodium silicate solution-to-NaOH solution ratio by mass of 2.5 were selected as the basic mixtures to study the effect of other parameters for two reasons. Firstly, the cost of activator liquid is economical when the ratio of sodium silicate solution-to-NaOH solution is 2.5 (rather than 0.4). Secondly, the test results were remarkably consistent when this ratio was 2.5.

4.2.4 Curing Temperature

Figure 4.1 shows the effect of curing temperature on the compressive strength for Mixture 2 and Mixture 4 after dry curing the test cylinders in an oven for 24 hours. All other test variables were held constant. Higher curing temperature resulted in larger compressive strength, although an increase in the curing temperature beyond 60°C did not increase the compressive strength substantially.

Figure 4.2 presents further results. Five different curing temperatures were used, i.e. 30°C, 45°C, 60°C, 75°C, and 90°C. Curing was performed in an oven for 24 hours in the case of Mixture 2 and 4, and 6 hours for Mixture 2 only. The results shown in Table 4.8 and Figure 4.2 confirm that higher curing temperature resulted in higher compressive strength, for both 6 hours and 24 hours of curing.

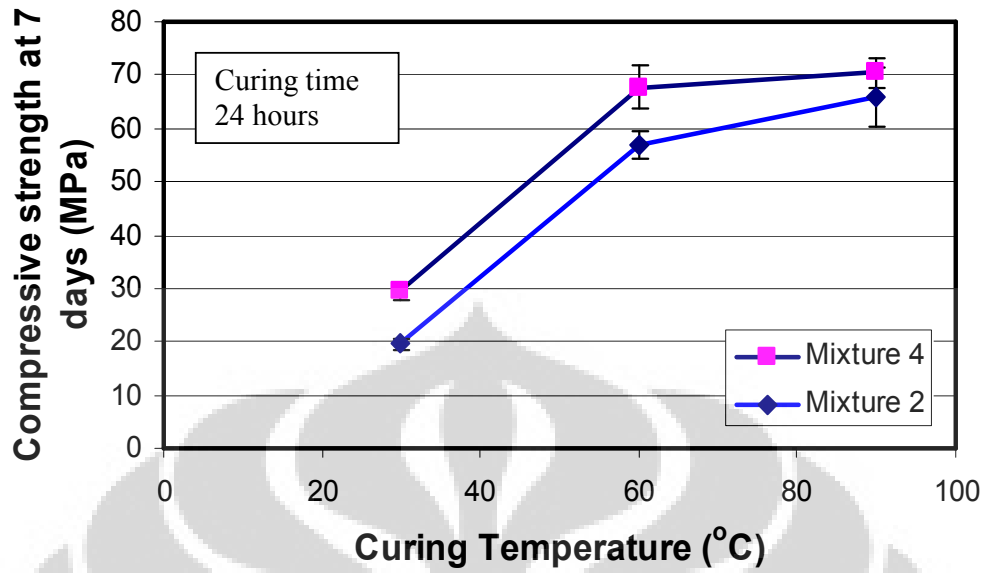


Figure 4.1: Effect of Curing Temperature on Compressive Strength (1)

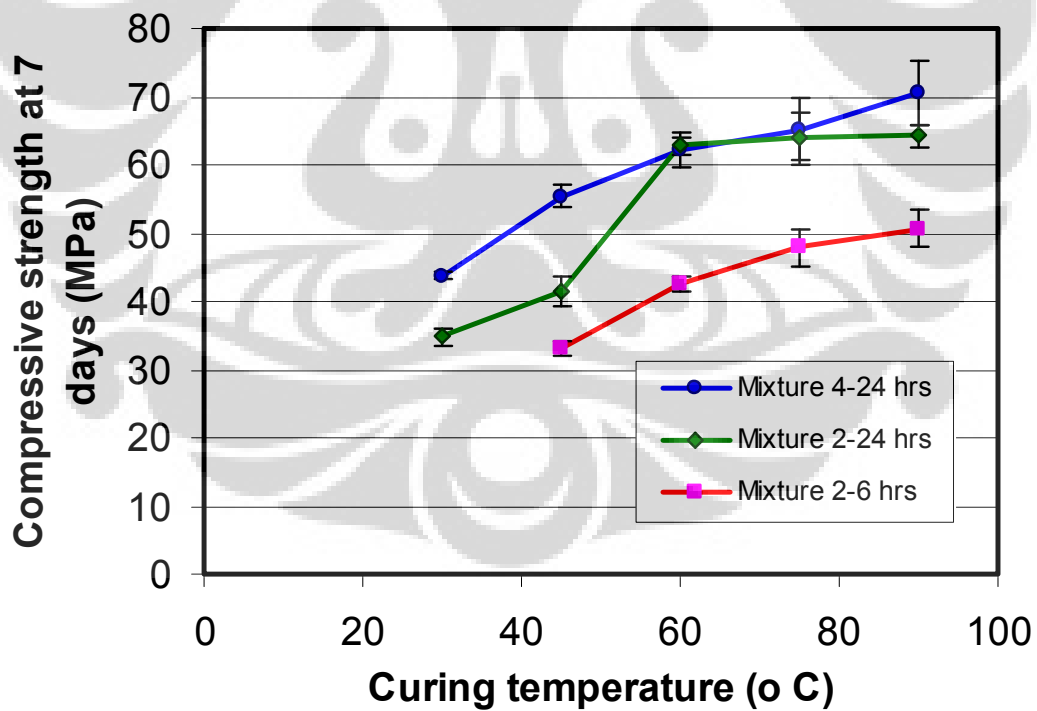


Figure 4.2: Effect of Curing Temperature on Compressive Strength (2)

4.2.5 Curing Time

In order to investigate the effect of curing time, tests were prepared using Mixture 2. The test cylinders were cured for various curing periods from 4 hours to 96 hours (4 days). Table 4.7 and Figure 4.3 show the results of these tests cured at 60°C. Longer curing time improved the polymerisation process resulting in higher compressive strength. The rate of increase in strength was rapid up to 24 hours of curing time. The results indicate that longer curing time did not produce weaker material as claimed by van Jaarsveld et al (2002).

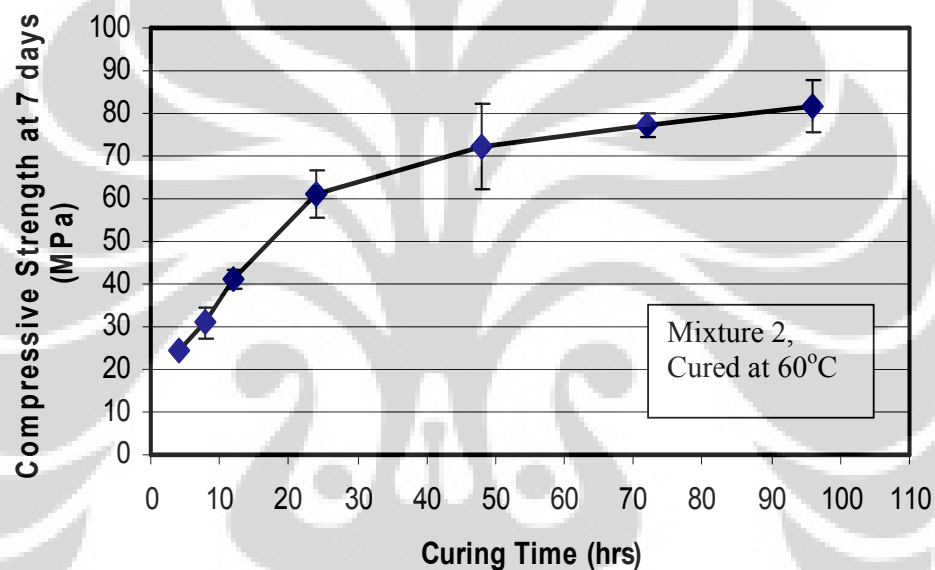


Figure 4.3: Influence of Curing Time on Compressive Strength for Mixture 2

4.2.6 Handling Time

Due to lack of a suitable method to determine the initial setting time of geopolymer concrete, the setting time of the fresh concrete could not be measured.

In order to establish how long the fly ash-based geopolymer concrete could be handled without any degradation in compressive strength, a series of tests were performed. For these tests, Mixture 2 was used. After mixing, the geopolymer

concrete was left in the pan mixer for various periods of time ranging from 0 to 120 minutes. These periods were identified as ‘Handling Time’. At the end of the ‘handling time’, cylinder specimens were cast. The test cylinders were cured for 24 hours at 60°C. The test results are plotted in Figure 4.4. In Figure 4.4, the ‘handling time’ of zero minute mean that the test cylinders were cast immediately after mixing, whereas the handling time of, say 120 minutes, indicates that the fresh concrete was handled and placed in the moulds only after 120 minutes. The test results shown in Figure 4.4 as well as the laboratory experience showed that the fresh fly ash-based geopolymer concrete could be handled up to 120 minutes after mixing without any sign of setting and without any degradation in the compressive strength.

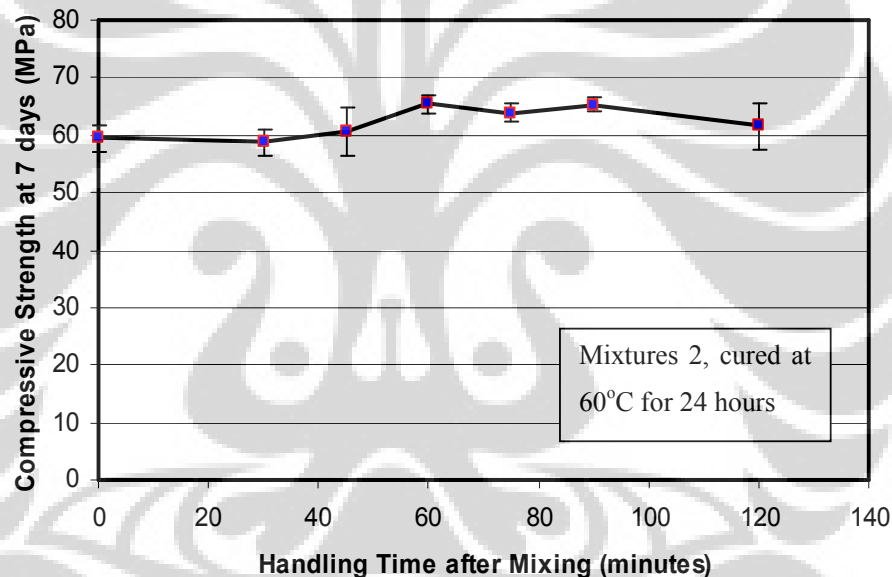


Figure 4.4: Influence of Handling Time on Compressive Strength for Mixture 2

4.2.7 Addition of Superplasticiser

In fresh state, the geopolymer concrete has a stiff consistency. Although adequate compaction was achievable, an improvement in the workability was considered as desirable. A series of mixtures were prepared to investigate the possibility of using the new generation polycarboxylic ether hyper plasticiser. However, this type of

super plasticiser did not show any significant difference in the workability of the fresh fly ash-based geopolymer concrete.

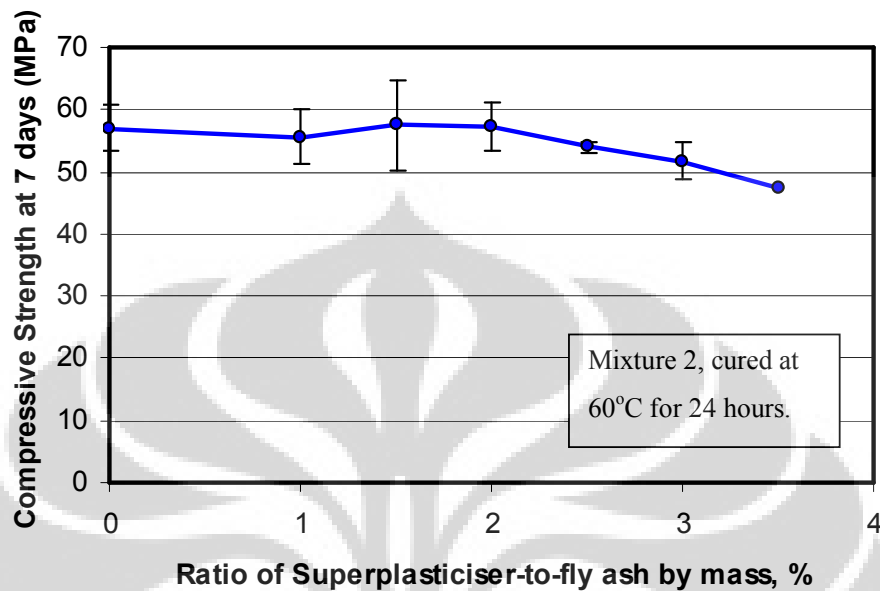


Figure 4.5: Effect of Super plasticiser Addition on Compressive Strength

Therefore, another series of tests were performed to study the effect of adding conventional commercially available Naphthalene Sulphonate based super plasticiser. Mixture 2 was selected for this study. The test cylinders were cured for 24 hours at 60°C in an oven. The results of these tests are given in Table 4.7, Table 4.8 and Figure 4.5. The addition of super plasticiser improved the workability of the fresh concrete but had very little effect on the compressive strength up to about two percent of this admixture to the amount of fly ash by mass. Beyond this value, there was some degradation of the compressive strength.

In addition, four other mixtures, i.e. Mixtures 5 to 8, were prepared. In these Mixtures, the cylinders were steam cured at 60°C for 24 hours, the maximum size of aggregates was 7 mm, and extra water was added to improve workability. Other details of these Mixtures are given in Table 4.1. The ratio of super plasticiser-to-fly ash, by mass, was the test variable.

Figure 4.6 shows that the addition of naphthalene-based super plasticiser improved the workability of the fresh fly ash-based geopolymer concrete. Figure 4.6 shows the variation of measured slump of fresh concrete with the ratio of super plasticiser-to-fly ash, by mass. The slump test was chosen to measure the workability of the fresh state concrete, as it is a simple test used extensively in practice. Slump test is useful in detecting the variations in the uniformity of a mix given for a certain mixture proportion (Neville 2000). As expected, it can be seen from Figure 4.6 that slump values increased as the content of super plasticiser in the mixtures increased.

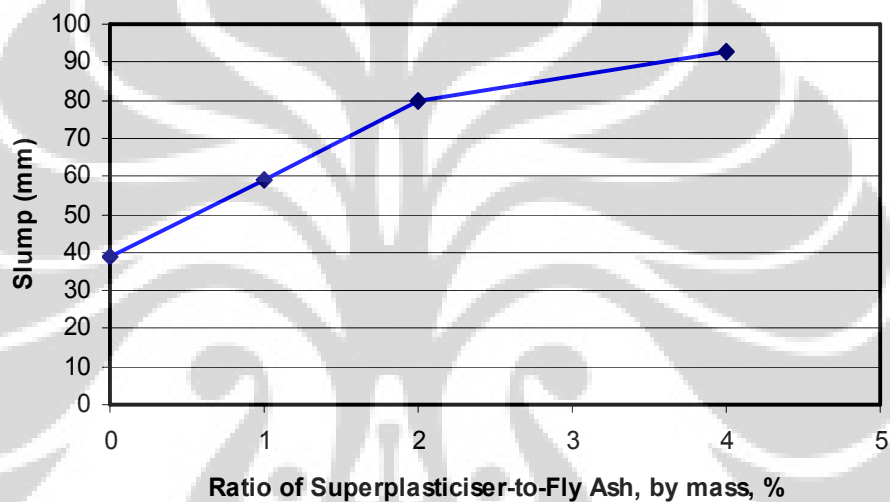


Figure 4.6: Effect of Superplasticiser Content on Slump of Concrete

The variation in the compressive strength with the content of super plasticiser in the mixture is shown in Figure 4.7. These data confirm the test trend observed in Figure 4.5. The addition of naphthalene-based super plasticiser improved the workability of fresh concrete, but did not affect the compressive strength of the hardened concrete, except when the content of super plasticiser was 4% a slight reduction in compressive strength occurred.

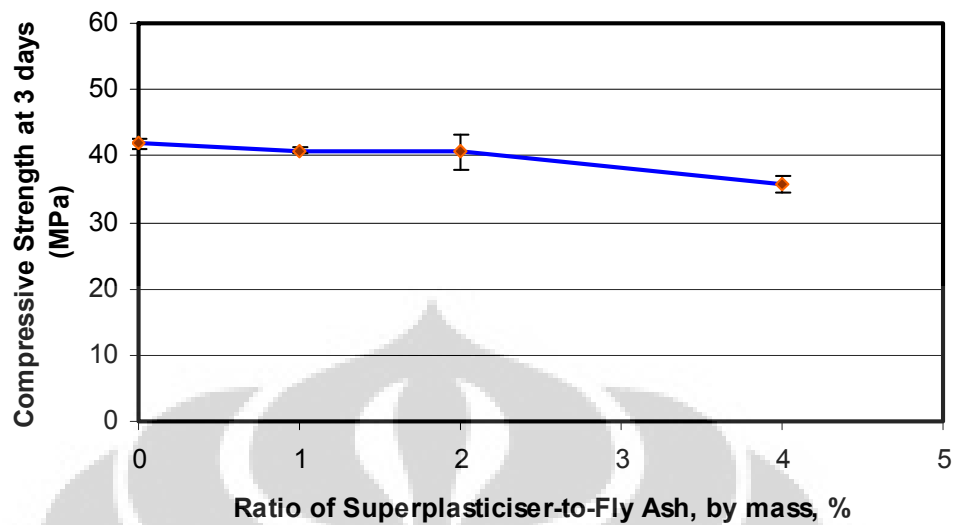


Figure 4.7: Effect of Super plasticiser Content on Compressive Strength

Based on these test results, it is recommended that naphthalene sulphonate-based superplasticiser may be used to improve the workability of fresh fly ash-based geopolymer concrete. However, the content of the super plasticiser need not be more than 2% of the mass of fly ash. Beyond this amount, the addition of super plasticiser can cause a slight reduction in the compressive strength of hardened concrete; moreover, amounts greater than 2% may be uneconomical in practice.

4.2.8 Rest Period Prior to Curing

The term ‘Rest Period’ was coined to indicate the time taken from the completion of casting of test specimens to the start of curing at an elevated temperature. This may be important in certain practical applications. For instance, when fly ash-based geopolymer concrete is used in precast concrete industry, there must be sufficient time available between casting of products and sending them to the curing chamber.

In order to study the effect of Rest Period, Mixtures 9, 10, 11, 12 were made. The details of these Mixtures are given in Table 4.1. The test cylinders from Mixtures 9, 10, and 12 were left in ambient conditions for specified periods of time before the

start of curing. During this period, the test cylinders were covered to avoid the loss of moisture. The tests cylinders from Mixture 11 were placed in an oven during the Rest Period. The oven temperature on the first day was 32°C; from the second day until the end of Rest Period the temperature was increased to 40°C. This variation in the temperature simulated the hot weather condition during the Rest Period. At the end of the Rest Period, the test cylinders were steam-cured at 60°C.

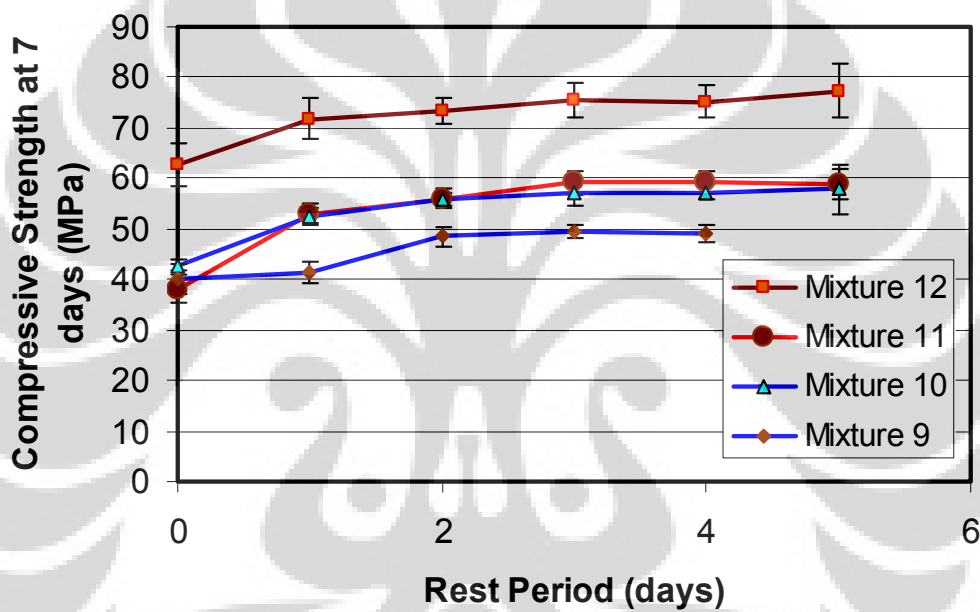


Figure 4.8: Effect of Rest Period on Compressive Strength

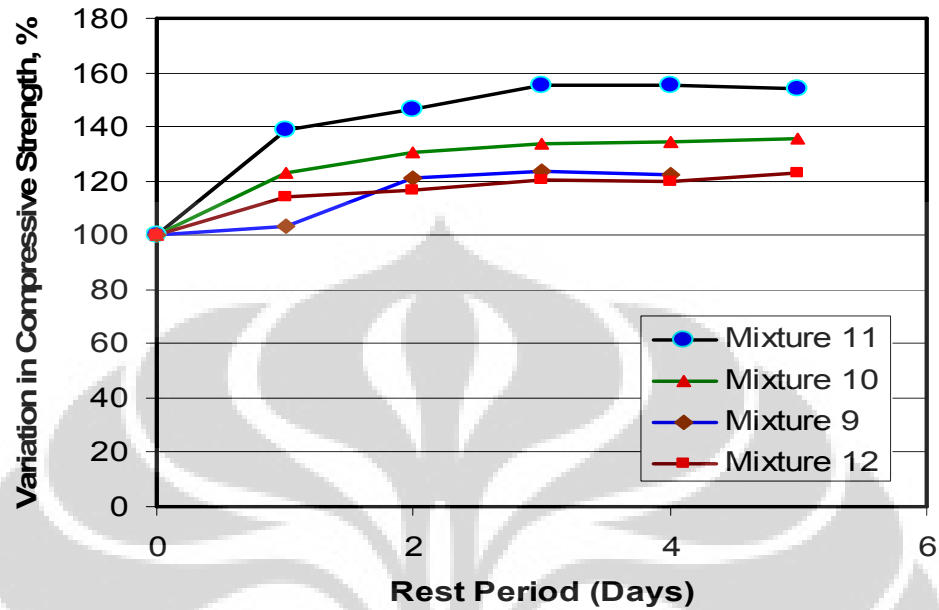


Figure 4.9: Effect of Rest Period on Variation in Compressive Strength (in percentage of the compressive strength with no Rest Period)

The test results are plotted in Figures 4.8 and 4.9. It can be seen that all the specimens from Mixtures 9 to 12 gained strength after the Rest Period. The strength gain was maximum when the Rest Period was three days; beyond that very little further strength gain was attained. The extent of strength gain was significant, in the range of 20 to 50 percent (Figure 4.9) of the compressive strength of specimens with no Rest Period. In the case of specimens from Mixture 11, the maximum strength gain was more than 50 percent.

The exact reason for this strength gain is not clear. However, the benefits shown by the Rest Period may be exploited in practice.

4.2.9 Water Content of Mixture

In ordinary Portland cement (OPC) concrete, water in the mixture chemically reacts with the cement to produce a paste that binds the aggregates. In the fly ash-based geopolymer concrete, water in the mixture does not cause a chemical reaction because the chemical process that occurs to produce the binder is due to polymerisation. However, laboratory experience showed that water content in the geopolymer concrete mixture affected the properties of concrete in the fresh state as well as in the hardened state. In order to establish the effect of water content in the mixture, tests were performed.

In order to plan this series of tests, the past research on geopolymer pastes was first considered. Davidovits (1982) proposed that the ranges of the oxide molar ratios suitable to produce geopolymeric materials may be as follows: $0.2 < \text{Na}_2\text{O}/\text{SiO}_2 < 0.28$, $3.5 < \text{SiO}_2/\text{Al}_2\text{O}_3 < 4.5$, and $15 < \text{H}_2\text{O}/\text{Na}_2\text{O} < 17.5$, where Na_2O , SiO_2 , Al_2O_3 are respectively the sodium, silicon and aluminium oxides, and H_2O is the water. Based on tests performed on geopolymer pastes using calcined kaolin as the source material, Barbosa et al (2000) found that the optimum composition occurred when the ratio of $\text{Na}_2\text{O}/\text{SiO}_2$ was 0.25 and the ratio of $\text{H}_2\text{O}/\text{Na}_2\text{O}$ was 10.0.

The mixture proportions for these series of tests were derived from many trial mixes. The test variables were H_2O -to- Na_2O molar ratio and the Na_2O -to- SiO_2 molar ratio. With regard to H_2O -to- Na_2O molar ratio, only the range from 10.0 to 14.0 was found to be feasible. For H_2O -to- Na_2O molar ratio less than 10.0, the concrete mixtures were not easily workable; on the other hand, for values of this ratio greater than about 14.0, considerable segregation of mixture ingredients occurred due to the presence of excess water.

No suitable concrete mixture could be prepared within the range of Na_2O -to- SiO_2 molar ratio as proposed by Davidovits (1982). This might be due to the difference in the type of source material and the aggregates used in the manufacture of concrete. Davidovits used pure calcined kaolinite, named **KANDOXI** (**KA**olinite, **Nac**rite, **Dickite OX**ide), by calcining kaolin clay at 750°C for 6 hours as the source material

(Davidovits 1999). In contrast, low calcium (ASTM Class F) fly ash was used as the source material in the current research. Also, the mixtures used by Davidovits were geopolymer pastes with no aggregates. In order to suit the solid materials and the activator liquids used, the range of Na_2O -to- SiO_2 ratio between 0.095 and 0.120 was selected for this series of tests.

In order to investigate the effect of water content in the mixture, two sets of mixtures were made. In the first set, Mixtures 13, 14, and 15 were made. The details of these Mixtures are given in Table 4.1 and 4.2. The purpose of this set was to investigate the effect of H_2O -to- Na_2O molar ratio on the compressive strengths of concrete, while the molar ratios of other oxides in the mixtures, viz, Na_2O -to- SiO_2 and SiO_2 -to- Al_2O_3 were kept constant at 0.115 and 3.89 respectively. The calculations of molar ratios of various oxides in the Mixtures are given in Appendix B.

The H_2O -to- Na_2O molar ratio of Mixture 13 was 10.01. By adding extra water of 10.6 kg/m^3 to this mixture, the H_2O -to- Na_2O molar ratio became 11.25, and by adding extra water of 21.2 kg/m^3 , this ratio was 12.49.

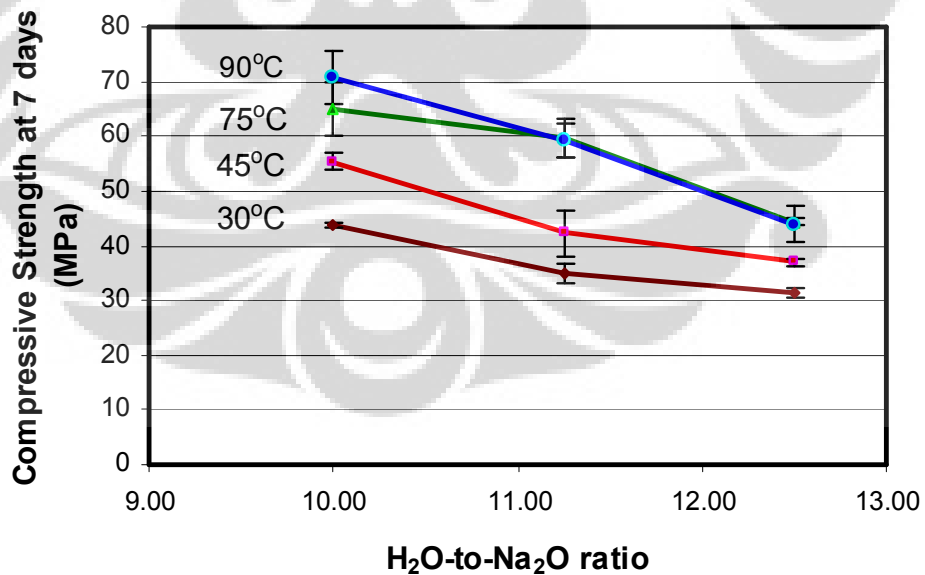


Figure 4.10: Effect of H_2O -to- Na_2O Molar Ratio on Compressive Strength

The test cylinders were cured for 24 hours at various temperatures. Figure 4.10 shows the effect of H₂O-to-Na₂O molar ratio on the compressive strength of geopolymer concrete for various curing temperatures. An increase in this ratio decreased the compressive strength of concrete. Obviously, as the H₂O-to-Na₂O molar ratio increased, the mixtures contained more water and became more workable.

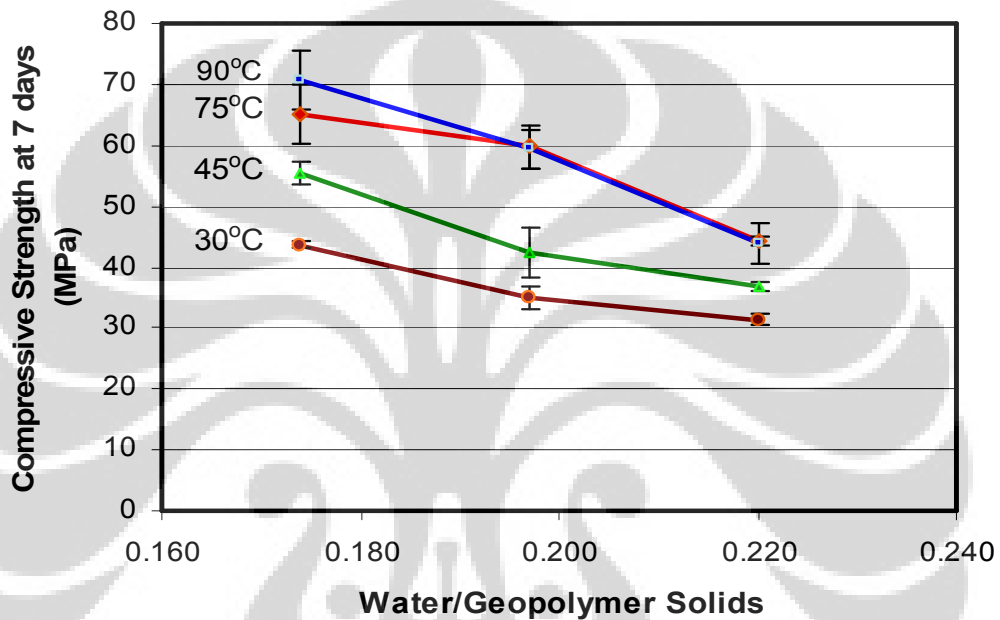


Figure 4.11: Effect of Water-to-Geopolymer Solids Ratio by Mass on Compressive Strength

The test results shown in Figure 4.10 are recast in engineering terms in Figure 4.11 in order to illustrate the effect of water-to-geopolymer solids ratio by mass on the compressive strength. The total mass of water is the sum of the mass of water contained in the sodium silicate solution, the mass of water in the sodium hydroxide solution, and the mass of extra water, if any, added to the mixture. The mass of geopolymer solids is the sum of the mass of fly ash, the mass of sodium hydroxide solids, and the mass of solids in the sodium silicate solution (i.e. the mass of Na₂O and SiO₂). The calculations of water-to-geopolymer solids ratio by mass of Mixtures

13, 14, and 15 are given in Appendix B. The test data presented in Figure 4.11 show that the compressive strength of geopolymer concrete decreased as the ratio of water-to-geopolymer solids by mass increased. This test trend is analogous to the well-known effect of water-to-cement ratio on the compressive strength of Portland cement concrete.

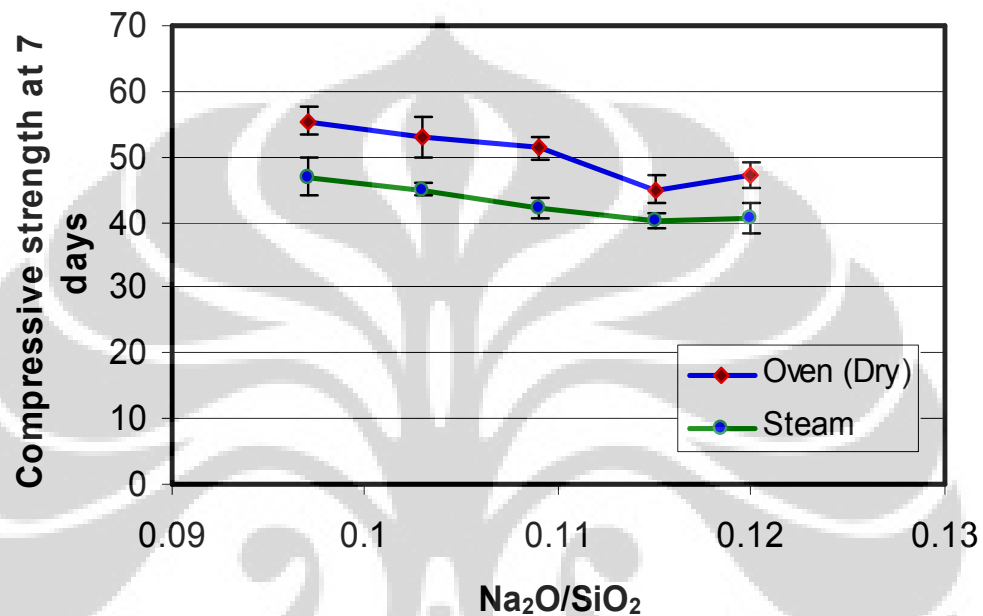


Figure 4.12: Effect of the Molar Na₂O-to-SiO₂ Ratio on Compressive Strength

In the second set, Mixtures 16 to 20 were made to study the effect of the molar Na₂O-to-SiO₂ ratio on the compressive strength. The details of these Mixtures are given in Table 4.2. The test cylinders were cured at 60°C for 24 hours. Ten cylinders were made for each Mixture; five of the cylinders were cured in an oven, and the other five were cured in the steam curing chamber.

In Mixtures 16 to 20, the molar ratio of SiO₂-to-Al₂O₃ was 3.89, and the molar ratio of H₂O-to-Na₂O was approximately constant around 12.42. The calculations of molar ratios of various oxides in these Mixtures are given in Appendix B.

Figure 4.12 shows the influence of Na_2O -to- SiO_2 molar ratio on the compressive strength of fly ash-based geopolymer concrete. It can be seen that the compressive strength decreased only marginally when the Na_2O -to- SiO_2 molar ratio increased from 0.098 to 0.120. In these Mixtures, as can be observed from the data given in Table 4.2, the required Na_2O -to- SiO_2 molar ratio was achieved by increasing the sodium hydroxide concentration and by adding extra water to keep the H_2O -to- Na_2O molar ratio approximately constant. Therefore, Mixture 17 contained more water than Mixture 16, and so on. These test data show that any change in the water content alone does not affect the compressive strength of geopolymer concrete, provided that the H_2O -to- Na_2O molar ratio is kept constant. This test trend is true for specimens cured in the oven (dry) as well as for the specimens cured in the steam curing chamber (Figure 4.12). However, the presence of extra water in the mixture improved the workability fresh concrete, as illustrated by the slump test data of these Mixtures plotted in Figure 4.13.

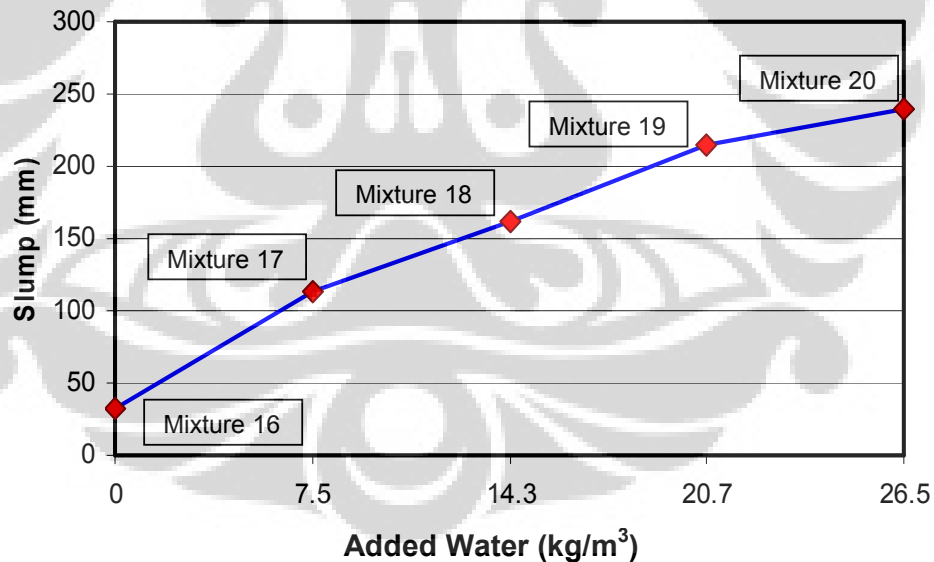


Figure 4.13: Slump Values for Mixtures 16 to 20

4.2.10 Mixing Time

In order to study the effect of mixing time of fresh concrete on the compressive strength of hardened concrete, two sets of tests were performed.

Discontinuous Mixing

Mixture 21 was used for the first set of tests. The details of the Mixture 21 are given in Table 4.2. In this case, the dry materials and the liquids were mixed together for two minutes. The mixing then stopped for about twenty minutes to take some of the fresh concrete in order to make five test cylinders. The mixing of the remaining concrete continued for another two minutes and stopped again for about twenty minutes to extract fresh concrete to make five more test cylinders. This process continued for several steps until the total mixing time reached sixteen minutes.

The test cylinders were steam cured at 60°C for 24 hours, and tested in compression at an age of 21 days. The results are shown in Figure 4.14. The test data plotted in Figure 4.14 shows that the compressive strengths significantly increased as the mixing time increased.

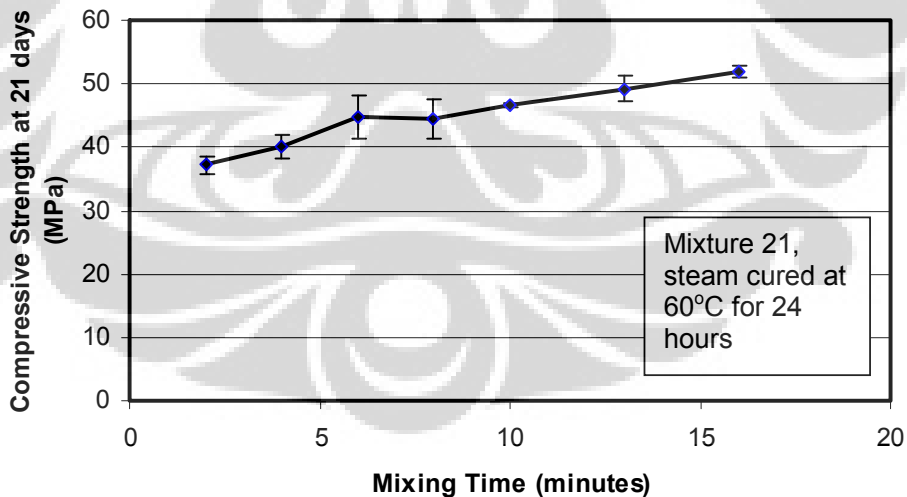


Figure 4.14: Effect of Mixing Time on Compressive Strength: Discontinuous Mixing

The slumps of fresh concrete at each step of mixing were also measured. These results showed that the slump values decreased from 240 mm for two minute mixing time to 210 mm when the mixing time increased to sixteen minutes.

Continuous Mixing

The second set of tests used Mixture 22. The details of Mixture 22 are given in Table 4.2. It can be seen in Table 4.2, Mixture 22 considered less quantity of added water and the maximum size of coarse aggregate was smaller than used in the case of Mixture 21. Therefore, the slump of fresh concrete made using Mixture 22 was expected to be smaller than that of Mixture 21.

In this case, three different batches of concrete were made. The dry materials and the liquids of each batch of concrete were continuously mixed for a certain period of time. At the end of the mixing, each batch of concrete was used to make five test cylinders.

The mixing time for the first batch of concrete was four minutes, for the second batch eight minutes, and for the third batch sixteen minutes.

The test cylinders were steam cured at 90°C for 4 hours, and tested in compression at an age of 3 days. The results are shown in Figure 4.15.

The test trend observed in Figure 4.15 is similar to that shown in Figure 4.14. The compressive strength significantly increased as the mixing time increased. Also, similar to the case of Mixture 21, the measured slump of the fresh concrete using Mixture 22 decreased from 90 mm for a mixing time of four minutes to 50 mm when the mixing time increased to sixteen minutes.

The above test data show that the compressive strength of fly ash-based geopolymer concrete can be increased by an increase in the mixing time for a slight loss in the slump of fresh concrete. This is true whether the mixing process is discontinuous or continuous, as demonstrated above.

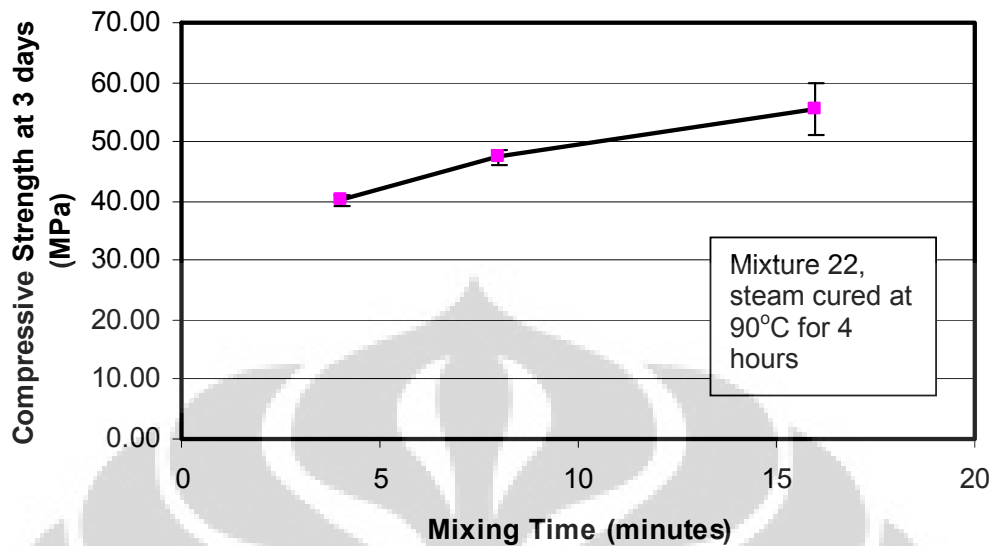


Figure 4.15: Effect of Mixing Time on Compressive Strength: Continuous Mixing

4.2.11 Age of Concrete

Figure 4.16 shows the effect of age of concrete on the compressive strength. The test cylinders were prepared using Mixture 2 (see Table 4.1 and 4.7), and cured in the oven at 60°C for 24 hours.

Because the chemical reaction of the heat-cured geopolymer concrete is due to substantially fast polymerisation process, the compressive strength does not vary with the age of concrete. This observation is in contrast to the well-known behaviour of OPC concrete, which undergoes hydration process and hence gains strength over time.

Another series of tests was performed to investigate the effect of age on the compressive strength of fly ash-based geopolymer concrete. The test cylinders were prepared using Mixture 22 (See Table 4.2), with mixing times of 4, 8 and 16 minutes, and steam cured at 90°C for 4 hours. Figure 4.17 shows the effect of age on the compressive strength for these specimens. This Figure confirms that the compressive

strength of heat-cured fly ash-based geopolymer concrete does not vary with age of concrete.

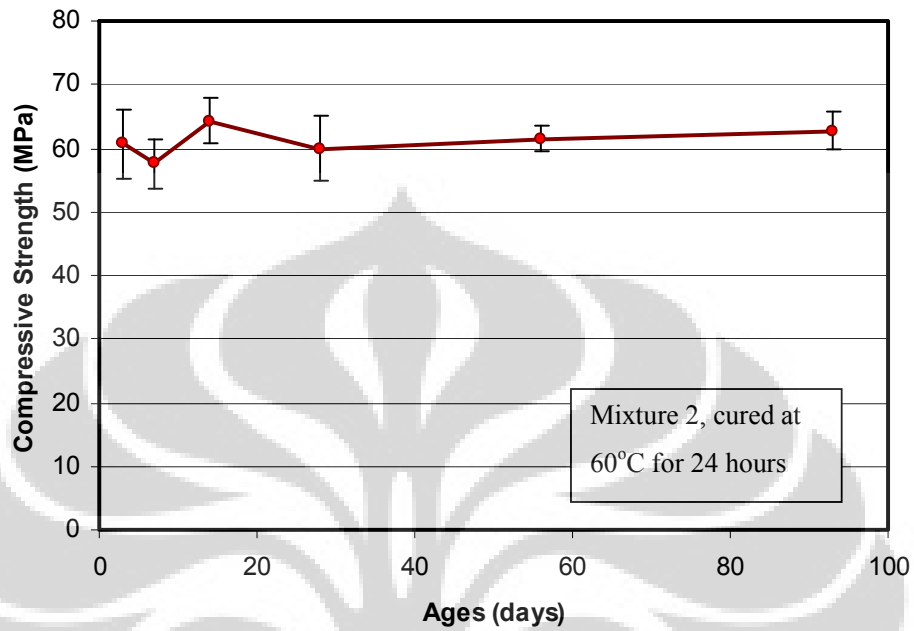


Figure 4.16: Compressive Strength at Different Ages for Mixture 2

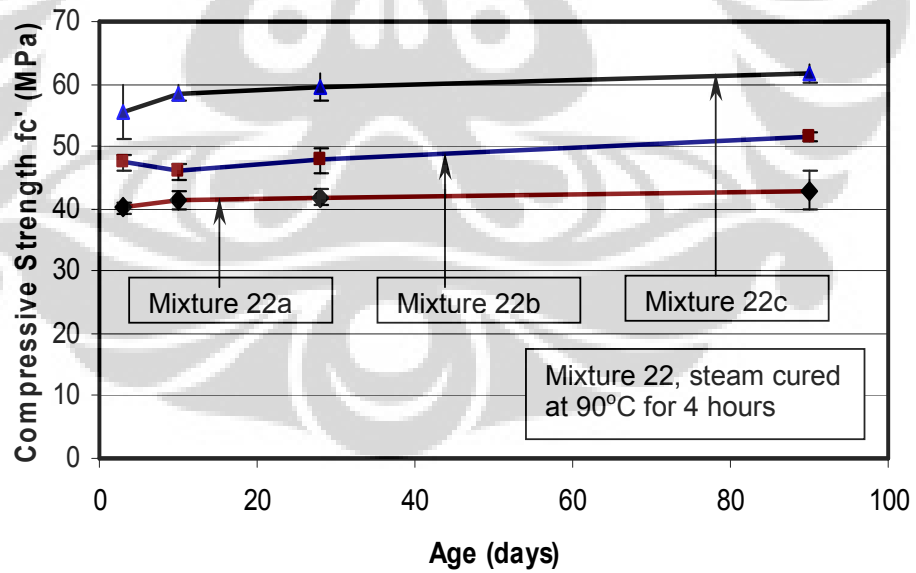


Figure 4.17: Compressive Strength at Different Ages for Mixture 22

4.3 MODULUS OF ELASTICITY AND POISSON'S RATIO

Mixtures 23 to 26 were made in order to measure the modulus of elasticity and Poisson's ratio. The details of these four Mixtures are given in Table 4.2. These Mixture proportions covered compressive strengths ranging from 40 to 90 MPa.



Figure 4.18: Test Set-Up for Measuring the Elastic Constants

The Young's modulus or elastic modulus, E_c , of fly ash-based geopolymer concrete was determined as the secant modulus measured at the stress level equal to 40 percent of the average compressive strength of concrete cylinders. Tests were carried out in accordance with the Australian Standard AS 1012.17 (1997).

For each Mixture, five 100x200 mm concrete cylinders were made. Three of these cylinders were used to determine the elastic modulus and Poisson's ratio. Two other cylinders were tested to determine the average compressive strength. All the specimens were capped in accordance with the Australian Standard AS 1012.9 (1999). The tests were performed in a 2500 kN capacity Avery-Denison universal test machine.

Two LVDTs (Linear Voltage Differential Transducers) were used to measure the axial deformation of the concrete cylinders, while one LVDT was used to measure the lateral deformation of the test cylinder at mid-height. The test set-up for measuring the elastic constants is shown in Figure 4.18.

Table 4.10: Young's Modulus and Poisson's Ratio

| Mixture No. | Mean compressive strength | Age of concrete (days) | Modulus of Elasticity (GPa) | Poisson's Ratio |
|-------------|---------------------------|------------------------|-----------------------------|-----------------|
| 23 | 89 | 90 | 30.8 | 0.16 |
| 24 | 68 | 90 | 27.3 | 0.12 |
| 25 | 55 | 90 | 26.1 | 0.14 |
| 26 | 44 | 90 | 23.0 | 0.13 |

Table 4.10 shows the values of modulus of elasticity and Poisson's ratio of specimens from Mixtures 23 to 26. As expected, the modulus of elasticity increased as the compressive strength of concrete increased.

For OPC concrete, the Australian Standard (2005) recommends the following expression to calculate the value of the modulus of elasticity within an error of plus or minus 20 %:

$$E_c = \rho^{1.5} \times (0.024 \sqrt{f_{cm}} + 0.12) \quad (\text{MPa}) \quad (4.1)$$

where ρ is the density of concrete in kg/m^3 , and f_{cm} is the mean compressive strength in MPa.

American Concrete Institute (ACI) Committee 363 (1992) has recommended the following expression to calculate the modulus of elasticity.:

$$E_c = 3320 \sqrt{f_{cm}} + 6900 \quad (\text{MPa}) \quad (4.2)$$

The average density of fly ash-based geopolymer concrete was 2350 kg/m³. Table 4.11 shows the comparison between the measured value of modulus of elasticity of fly ash-based geopolymer concrete with the values determined by Equation 4.1 and Equation 4.2.

Table 4.11: Comparison between Calculated Values using Equation 4.1 and 4.2 and Measured Values of Modulus Elasticity

| f_{cm} | E_c measured (GPa) | E_c (Equation 4.1) (GPa) | E_c (Equation 4.2) (GPa) |
|----------|-------------------------|-------------------------------|-------------------------------|
| 89 | 30.8 | 39.5 ± 7.9 | 38.2 |
| 68 | 27.3 | 36.2 ± 7.2 | 34.3 |
| 55 | 26.1 | 33.9 ± 6.8 | 31.5 |
| 44 | 23.0 | 31.8 ± 6.4 | 28.9 |

It can be seen from Table 4.11, the measured values were consistently lower than the values calculated using Equation 4.1 and Equation 4.2. This is due to the type of coarse aggregates used in the manufacture of geopolymer concrete.

The type of the coarse aggregate used in the test programme was of granite type. Even in the case of specimens made of Mixture No. 26 ($f_{cm}=44$ MPa), the failure surface of test cylinders cut across the coarse aggregates, thus resulting in a smooth failure surface. This indicates that the coarse aggregates were weaker than the geopolymer matrix and the matrix-aggregate interface (Zia et al. 1997).

For OPC concrete using granite type coarse aggregate, Aitcin and Mehta (1990) reported Young's modulus values of 31.7 GPa and 33.8 GPa when $f_{cm}=84.8$ MPa and 88.6 MPa, respectively. These values are similar to those measured for geopolymer concrete reported in Table 4.10.

The Poisson's ratio of geopolymer concrete falls between 0.12 and 0.16 (Table 4.10). For Portland cement concrete, the Poisson's ratio is usually between 0.11 and 0.21, with the most common value taken as 0.15 (Warner et al. 1998) or 0.15 for high strength concrete and 0.22 for low strength concrete (Neville 2000). These ranges are similar to those measured for the geopolymer concrete.

4.4 STRESS-STRAIN RELATION IN COMPRESSION

Tests to obtain the stress-strain curves in compression were performed using an Instron Testing Machine at the Laboratory of School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia.

Mixtures 23 to 26 were chosen to study the stress-strain relation of the fly ash-based geopolymer concrete. The details of these four Mixtures are given in Table 4.2.

The tests on 100x200 mm concrete cylinders were performed by using the displacement-control mode available in the test machine. It took approximately 50 to 90 minutes to complete each test in order to obtain both the ascending and the descending branches of the stress-strain curves.

According to Neville (2000), loading in compression over a period between 30 and 240 minutes has been found to cause about 15% reduction in the measured value of the compressive strength of test cylinders. The loading rate also influences the measured compressive strength of concrete (Zia et al. 1997). Therefore, the measured compressive strength of test cylinders made using Mixtures 23 to 26 in this series of tests were lower than those reported in Table 4.10.

Figure 4.19 shows the stress-strain relation of fly ash-based geopolymer concrete made using Mixtures 23, 24 and 26. Due to unknown technical problems in the

process of gathering the data, the stress-strain relation for the test cylinder made using Mixture 25 was lost.

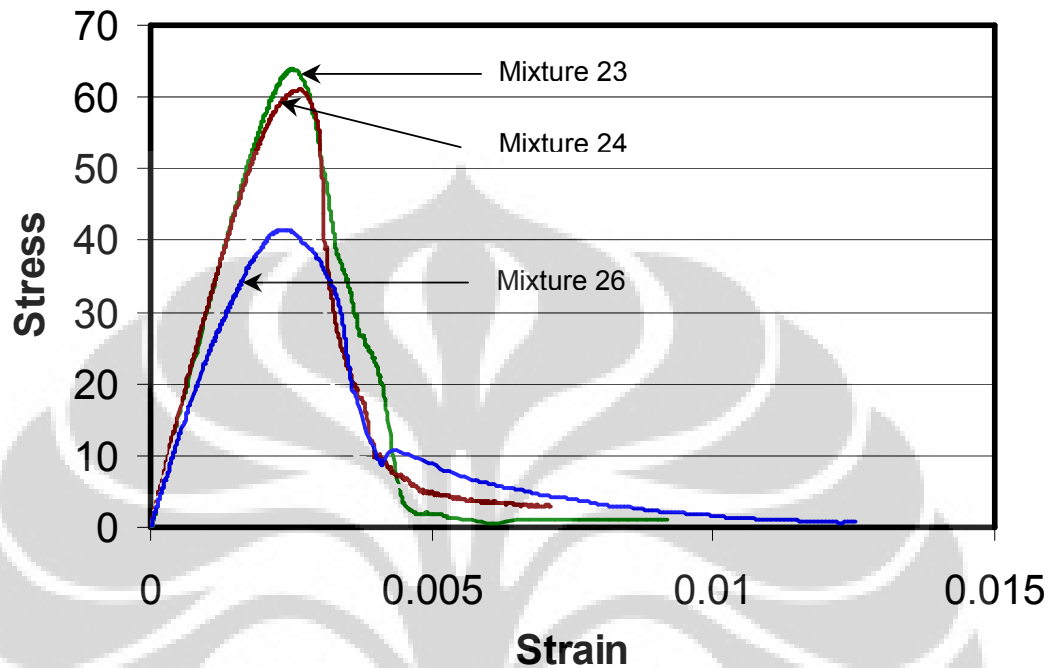


Figure 4.19: Stress-Strain Relations of Geopolymer Concrete

The values of compressive strength, the strain at peak stress, and the modulus of elasticity obtained from the stress-strain curve are given in Table 4.12.

Table 4.12: Test Data from Stress-Strain Curves

| Mixture No | Compressive Strength (MPa) | Strain at Peak Stress | Modulus of Elasticity (GPa) |
|------------|----------------------------|-----------------------|-----------------------------|
| 23 | 64 | 0.0025 | 30.6 |
| 24 | 61 | 0.0026 | 30.8 |
| 26 | 41 | 0.0024 | 24.7 |

The strains at the peak stress are in the range of 0.0024 to 0.0026. These values are similar to those reported for OPC concrete (Warner et al. 1998). The values of modulus of elasticity are similar to those given in Table 4.10.

Collins et al (1993) have proposed that the stress-strain relation of OPC concrete in compression can be predicted using the following expression:

$$\sigma_c = f_{cm} \frac{\varepsilon_c}{\varepsilon_{cm}} \frac{n}{n - 1 + (\varepsilon_c / \varepsilon_{cm})^{nk}} \quad (4.3)$$

where

f_{cm} = peak stress

ε_{cm} = strain at peak stress

$n = 0.8 + (f_{cm}/17)$

$k = 0.67 + (f_{cm}/62)$ when $\varepsilon_c/\varepsilon_{cm} > 1$

$= 1.0$ when $\varepsilon_c/\varepsilon_{cm} \leq 1$

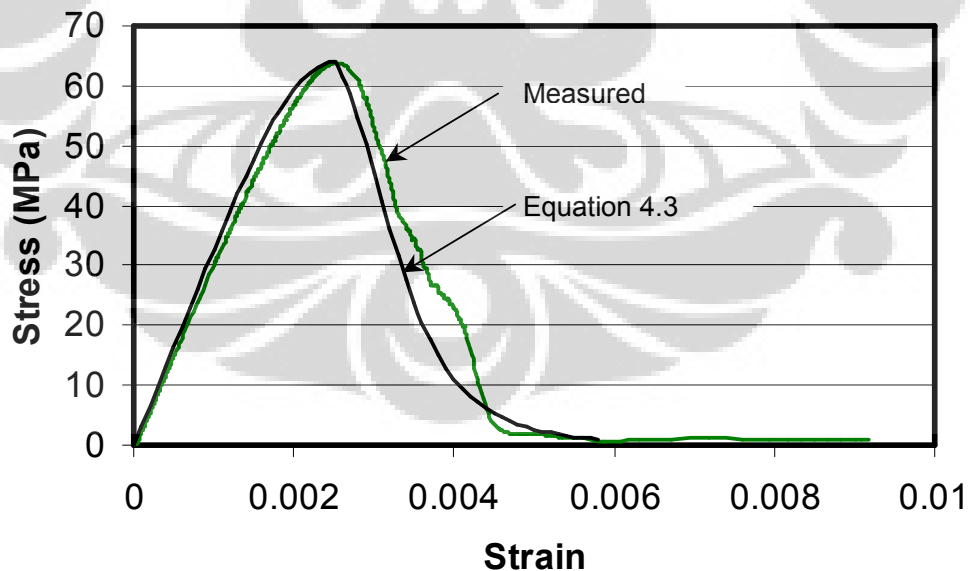


Figure 4.20: Predicted and Test Stress-Strain Relations for Concrete made from Mixture 23

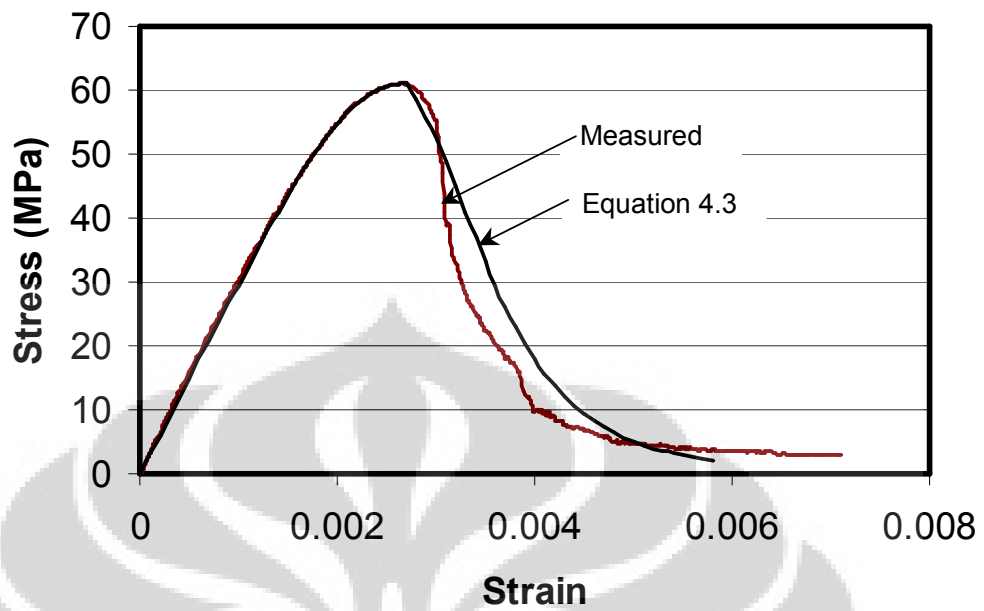


Figure 4.21: Predicted and Test Stress-Strain Relations for Concrete made from Mixture 24

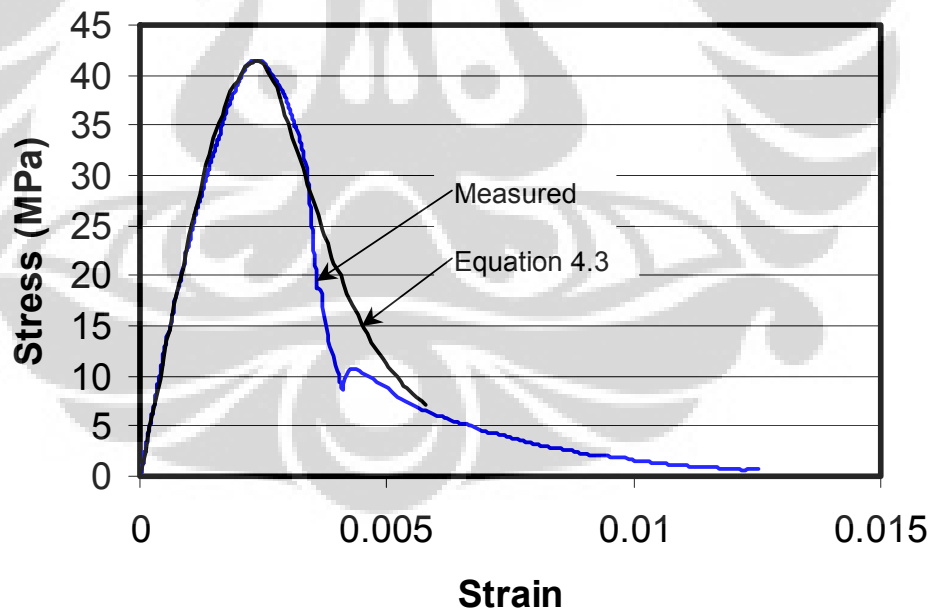


Figure 4.22: Predicted and Test Stress-Strain Relations for Concrete made from Mixture 26

In Figures 4.20 to 4.22, the stress-strain relations predicted by Equation 4.3 are compared with the test curves given in Figure 4.19. The analytical curves were obtained by using the measured values of f_{cm} and ϵ_{cm} in Equation 4.3. This comparison reveals that the stress-strain relations of fly ash-based geopolymer concrete can be predicted by using Equation 4.3 developed for Portland cement concrete.

4.5 INDIRECT TENSILE STRENGTH

The tensile strength of fly ash-based geopolymer concrete was measured by performing the cylinder splitting test on 150x300 mm concrete cylinders in accordance with the Australian Standard 1012.10-2000 (2000). The test results are given in Table 4.13.

These test results show that the tensile splitting strength of geopolymer concrete is only a fraction of the compressive strength, as in the case of Portland cement concrete.

Standards Australia (2001) recommends the following design expression to determine the characteristic principal tensile strength of OPC concrete:

$$f_{ct}^* = 0.4 \sqrt{f_{cm}} \quad (\text{MPa}) \quad (4.4)$$

Neville (2000) recommended that the relation between the tensile splitting strength and the compressive strength of OPC concrete may be expressed as:

$$f_{ct}^* = 0.3 (f_{cm})^{2/3} \quad (\text{MPa}) \quad (4.5)$$

The calculated values of f_{ct}^* using Equations 4.4 and 4.5 are also tabulated in Table 4.13.

Table 4.13: Indirect Tensile Splitting Strength

| Mixture No | Mean Compressive Strength (MPa) | Mean Indirect Tensile Strength (MPa) | Characteristic principal tensile strength, Equation (4.4) (MPa) | Splitting Strength, Equation (4.5) (MPa) |
|-------------------|--|---|--|---|
| 23 | 89 | 7.43 | 3.77 | 5.98 |
| 24 | 68 | 5.52 | 3.30 | 5.00 |
| 25 | 55 | 5.45 | 3.00 | 4.34 |
| 26 | 44 | 4.43 | 2.65 | 3.74 |

Table 4.13 shows that the indirect tensile strength of fly ash-based geopolymer concrete is larger than the values recommends by the Standards Australia (2001) and Neville (2000) for OPC concrete.

4.6 DENSITY

The density of concrete primarily depends on the unit mass of aggregates used in the mixture. Because the type of aggregates in all mixes did not vary, the density of the fly ash-based geopolymer concrete varied only marginally between 2330 to 2430 kg/m³.

4.7 TEMPERATURE HISTORY DURING CURING

Davidovits (1999) found that geopolymer material manufactured using calcined kaolin, called KANDOXI, is strongly exothermic. The test specimen was cured in an oven at 85°C and at atmospheric pressure (see Figure 4.23).

To obtain the geopolymerisation thermograph for fly ash-based geopolymer material during curing at elevated temperature, fly ash-based geopolymer mortar specimens of 75x75x75 mm were prepared. The mixture composition of the mortar is given in

Table 4.14. The mean compressive strength of these cubes was 47 MPa with density of 2035 kg/m³ at 7 days.

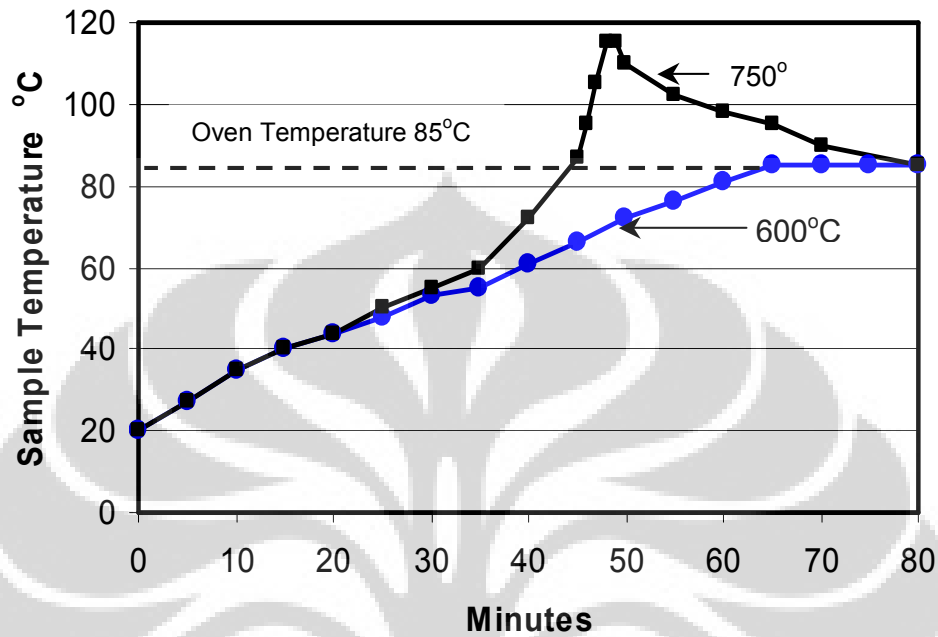


Figure 4.23: Geopolymerization Thermograph for Standard KANDOXI, after Firing of Standard Kaolinitic Clay for 6 Hours at 600°C and 750°C (Davidovits 1999)

Table 4.14: Mixture Composition for Geopolymer Mortar

| Materials | Mass, in percentage |
|--------------------------------|-----------------------------|
| Fine Sand, in SSD | 50.1 |
| Fly Ash (ASTM Class F) | 36.9 |
| Sodium hydroxide solution (8M) | 3.7 |
| Sodium silicate solution | 9.3 |
| Super plasticiser | 1.5% of the mass of fly ash |

The geopolymer mortar specimen was cured in an oven at 65°C. The temperature of the specimen during curing was measured using a thermocouple. Data were measured every minute using a data taker for the duration of 24 hours. The geopolymerization thermograph of fly ash-based mortar specimen is shown in Figure 4.24.

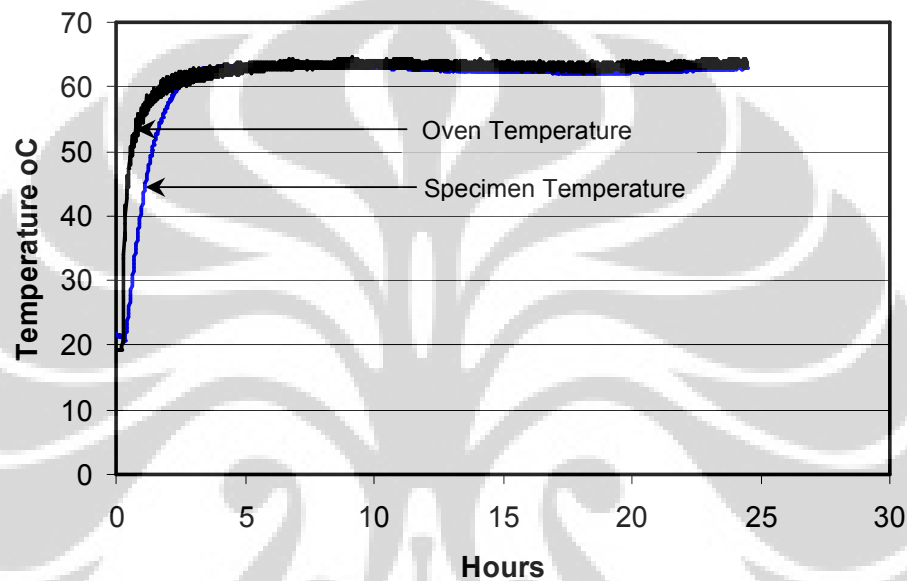


Figure 4.24: Geopolymerization Thermograph of Fly Ash-Based Geopolymer Mortar

Figure 4.24 reveals that fly ash-based geopolymer mortar does not show any exothermicity, as shown by metakaolin-based geopolymer paste or mortar (Davidovits 1999).

In the case of metakaolin-based geopolymer material, Davidovits (1999) observed that whenever the specimens did not show any exothermicity, the compressive strength was very low. For instance, in Figure 4.23, when the kaolinite clay was fired at 600°C for 6 hours, instead of at 750°C for 6 hours, there was no exothermicity and the geopolymer specimens made using this material reached only low strength. Fly

ash-based geopolymers did not show any such correlation between exothermicity and compressive strength. It appears that the geopolymerisation that occurs in fly ash-based geopolymers may be different to that of metakaolin-based geopolymers.

4.8 MIXTURE DESIGN PROCESS

Concrete mixture design process is vast and generally based on performance criteria. Based on the test data gathered in this research, a preliminary mixture design process for fly ash-based geopolymer concrete is proposed.

The role and influence of aggregates are considered to be the same as in the case of OPC concrete. The performance criteria depend on the application. In this illustration, the compressive strength of hardened concrete and the workability of fresh concrete are selected as the performance criteria.

The process of selecting the required mixture proportion is shown in Figure 4.25, which has been adopted from a similar approach used in the case of OPC concrete (Neville 2000).

Figure 4.25 identifies the salient parameters to meet the specified compressive strength and the workability of a low-calcium fly ash-based geopolymer concrete. The test data reported in the earlier parts of this Chapter can be used to arrive at a suitable mixture by using a trial-and-error process.

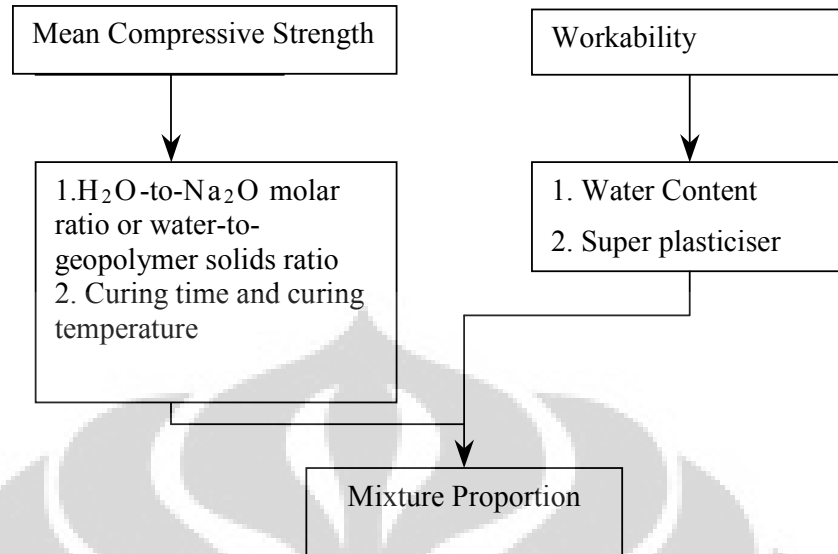


Figure 4.25: Preliminary Mixture Design Process

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 INTRODUCTION

This Chapter presents a summary of the present study, the major conclusions, and some recommendations for future research.

When this study started in 2001, the published literature contained only limited knowledge and know-how on the process of making fly ash-based geopolymer concrete. Most of the literature dealt with the use of metakaolin or calcined kaolin as the source material for making geopolymer paste and mortar. Moreover, the exact details regarding the mixture compositions and the process of making geopolymers were kept undisclosed in the patent and commercially oriented research documents.

With the generic information available on geopolymers, a rigorous trial-and-error method was adopted to develop a process of manufacturing fly ash-based geopolymer concrete using the technology currently used to manufacture OPC concrete. In order to reduce the number of variables in this trial-and-error approach, the study was restricted to low-calcium (ASTM Class F) dry fly ash obtained from Collie Power Station in Western Australia, and to the type of aggregates used locally to make OPC concrete.

After some failures in the beginning, the trial-and-error method yielded successful results with regard to manufacture of low-calcium (ASTM Class F) fly ash-based geopolymer concrete. Once this was achieved, tests were performed to quantify the effect of the salient parameters that influence the short-term properties of fresh and hardened geopolymer concrete.

In the following Sections, the outcomes of the study are summarised.

5.2 MANUFACTURING PROCESS

5.2.1 Material Preparation

Aggregates used in the manufacture the fly ash-based geopolymer concrete were in a saturated surface dry (SSD) condition. The aggregate selection and proportion were in accordance with the current practice used in making OPC concrete.

The alkaline liquid consisted of a combination of sodium silicate solution and sodium hydroxide solution. The sodium silicate solution was purchased from a local supplier. The sodium hydroxide solution was prepared by dissolving the solids, purchased from a local supplier in flakes or pellets form, in water. Both the solutions were premixed the day before use. The alkaline liquid was mixed with the super plasticiser, if any, and the extra-added water, if any, to prepare the liquid component of the geopolymer concrete mixture.

5.2.2 Mixing, Placing and Compaction

The aggregate and the fly ash were mixed dry in a pan mixer for about three minutes. The liquid component of the mixture was then added to the solids particles, and mixing continued for another four minutes in most cases.

The fresh fly ash-based geopolymer concrete remained workable up to at least two hours without any sign of setting and degradation in compressive strength. The fresh geopolymer concrete could easily be placed, compacted, and finished in moulds in that time. In all these operations, the equipment and the facilities currently used for OPC concrete were used.

For cylinder specimens of 100x200 mm, the mixture was cast in three layers. Each layer received 60 manual strokes, and vibrated for 10 seconds on a vibrating table. In some cases, the common internal needle vibrator was also utilised to successfully compact the fly ash-based geopolymer concrete.

5.2.3 Curing

After finishing, the test specimens were covered by a vacuum bagging film. Curing at an elevated temperature was achieved either in the dry curing environment in an oven, or in the steam curing chamber, for a specified period of time.

After curing, the concrete specimens were allowed to cool down in the moulds to avoid drastic change in the environment for at least six hours. After releasing from the moulds, the test specimens were left to air dry in the ambient conditions in the laboratory until the day for testing.

5.3 TEST SPECIMENS AND TEST VARIABLES

The test specimens in this study were mainly of 100x200 mm cylinders; larger size 150x300 mm cylinders were used to measure the indirect splitting tensile strength.

The concentration of sodium hydroxide solution was in the range between 8 M and 16 M. The sodium silicate solution-to-sodium hydroxide solution ratio by mass was in the range of 0.4 to 2.5; for most Mixtures, this ratio was 2.5. The solution-to-fly ash ratio by mass was approximately 0.35 in most cases, except for the Mixtures with extra-added water.

In order to study the effect of mixture composition on the compressive strength of fly ash-based geopolymer concrete, the test variables were the H_2O -to- Na_2O molar ratio in the range between 10.00 and 14.00, and the Na_2O -to- SiO_2 molar ratio between 0.095 and 0.120. These ranges of variable were selected after several trials. Outside these ranges, geopolymer concrete mixtures were either too dry for handling or too wet causing segregation of aggregates. For these ranges of variables, the water-to-geopolymer solids ratio by mass in the geopolymer paste varied from 0.17 to 0.22.

The mass of naphthalene sulphonate-based super plasticiser varied from 0% to 4% of the mass of fly ash. Workability was measured by the conventional slump test. The influence of water content on the slump value was also studied by varying the mass of extra water added to a reference mixture in the range of 0 to 26.5 kg/m³.

The range mixing time studied was between two and sixteen minutes.

For curing, temperature ranges from 30°C to 90°C were studied. The curing time ranged from four hours to four days, either in the dry curing environment in the oven or in the steam curing chamber. The influence of age at test was studied up to the age of 90 days.

5.4 CONCLUSIONS

Based on the experimental work reported in this study, the following conclusions are drawn:

1. Higher concentration (in terms of molar) of sodium hydroxide solution results in higher compressive strength of fly ash-based geopolymer concrete (Table 4.9).
2. Higher the ratio of sodium silicate-to-sodium hydroxide ratio by mass, higher is the compressive strength of fly ash-based geopolymer concrete (Table 4.9).
3. As the curing temperature in the range of 30°C to 90°C increases, the compressive strength of fly ash-based geopolymer concrete also increases (Figures 4.1 and 4.2).
4. Longer curing time, in the range of 4 to 96 hours (4 days), produces higher compressive strength of fly ash-based geopolymer concrete (Figure 4.3). However, the increase in strength beyond 24 hours is not significant.
5. The addition of naphthalene sulphonate-based super plasticiser up to approximately 4% of fly ash by mass, improves the workability of the fresh fly ash-based geopolymer concrete with very little effect on the compressive strength of hardened concrete (Figure 4.5, 4.6 and 4.7).
6. The slump value of the fresh fly-ash-based geopolymer concrete increases with the increase of extra water added to the mixture (Figure 4.13).
7. The Rest Period, defined as the time taken between casting of specimens and the commencement of curing, of up to 5 days increases the compressive strength of hardened fly ash-based geopolymer concrete. The increase in strength is substantial in the first 3 days of Rest Period (Figure 4.8 and 4.9).

8. The fresh fly ash-based geopolymer concrete is easily handled up to 120 minutes without any sign of setting and without any degradation in the compressive strength (Figure 4.4).
9. As the H_2O -to- Na_2O molar ratio increases, the compressive strength of fly ash-based geopolymer concrete decreases (Figure 4.10).
10. As the ratio of water-to-geopolymer solids by mass increases, the compressive strength of fly ash-based geopolymer concrete decreases (Figure 4.11).
11. The effect of the Na_2O -to- Si_2O molar ratio on the compressive strength of fly ash-based geopolymer concrete is not significant (Figure 4.12).
12. The compressive strength of heat-cured fly ash-based geopolymer concrete does not depend on age (Figures 4.16 and 4.17).
13. Prolonged mixing time of up to sixteen minutes increases the compressive strength of fly ash-based geopolymer concrete (Figures 4.14 and 4.15).
14. The average density of fly ash-based geopolymer concrete is similar to OPC concrete.
15. The measured values of the modulus elasticity of fly ash-based geopolymer concrete with compressive strength in the range of 40 to 90 MPa, were similar to those of OPC concrete. The measured values are at the lower end of the values calculated using the current design Standards due to the type of coarse aggregate used in the manufacture of the geopolymer concrete (Table 4.11).
16. 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 (Table 4.10). These values are similar to those of OPC concrete.
17. The stress-strain relations of fly ash-based geopolymer concrete in compression fits well with the expression developed for OPC concrete (Figures 4.19, 4.20, 4.21 and 4.22), with the strain at peak stress in the range of 0.0024 to 0.0026 (Table 4.12).
18. The indirect tensile strength of fly ash-based geopolymer concrete is only a fraction of the compressive strength, as in the case of Portland cement concrete. The measured values are higher than those recommended by the relevant Australian Standard (Table 4.13).

19. Fly ash-based geopolymer mortar does not show any exothermic action, as shown by metakaolin-based geopolymer paste or mortar (Figure 4.24). In spite of this, the fly ash-based geopolymer shows high compressive strength.

5.5 RECOMMENDATIONS FOR FUTURE RESEARCH

To date, the reaction mechanism of geopolymerisation is still not clear. Fundamental research in this area would increase the potential of the material. For example, a study is needed to identify the scientific reason for increase in strength after a longer resting period, and to investigate the role of water in geopolymerisation.

Although the present work identified many salient parameters that influence the properties of fresh and hardened fly ash-based geopolymer concrete, a large database should be built on the engineering properties of various mixtures using fly ash from different sources. Such a database may identify additional parameters, and lead to familiarise the utilisation of this material in many applications.

Further research should identify possible applications of geopolymer technology. This would lead to research areas that are specifically oriented towards applications. The geopolymer technology has the potential to go beyond making concrete; there could be possibilities in other areas of infrastructure needed by the community.



APPENDIX A

**Details of Preliminary Study:
Mixture Proportions, Curing Details, and Properties.**

Appendix A:

Details of Preliminary Mixtures: Mixture Proportions (kg/m³), Curing Details, and Properties.

| t No | Aggregate | | | Fly Ash (kg) | NaOH Solution | | Sodium Silicate (kg) | Added Water (kg) | Super- plasticiser (kg) | Curing | | | Age at Test (days) | Slump (mm) | Density (kg/m ³) | Compressive Strength (MPa) | Standard Deviation | Special Features |
|---------|---------------|--------------|-------------------|-------------------|---------------|--------------------|----------------------------|------------------------|-------------------------------|------------------------|---------------|--------|--------------------------|---------------|---------------------------------|----------------------------------|-----------------------|-----------------------------|
| | 10 mm (kg) | 7 mm (kg) | Fine Sand (kg) | | Mass (kg) | Molarity | | | | Time (hours) | Temp. (°C) | Method | | | | | | |
| P1 | 554 | 647 | 647 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | 10.3 | 6.1 | 24 | 60 | Steam | 13 | 75 | 2356 | 85 | 4.03 | Rest Period 3 days |
| P2 | 554 | 647 | 647 | 408 ^{a)} | 41 | 14M ^{*)} | 103 | 15.5 | 6.1 | 24 | 60 | Steam | 13 | 170 | 2338 | 77 | 1.35 | Rest Period 3 days |
| P3 | 554 | 647 | 647 | 408 ^{a)} | 41 | 16M ^{*)} | 103 | 18.5 | 6.1 | 24 | 60 | Steam | 14 | 170 | 2335 | 73 | 3.66 | Rest Period 3 days |
| P4 | 554 | 647 | 647 | 408 ^{a)} | 41 | 16M ^{*)} | 103 | 18.5 | 6.1 | 24 | 90 | Steam | 14 | 170 | 2332 | 84 | 1.07 | Rest Period 4 days |
| P5 | 554 | 647 | 647 | 408 ^{a)} | 41 | 14M ^{**)} | 103 | 17.6 | 6.1 | 24 | 60 | Steam | 11 | 215 | 2306 | 57 | 2.50 | Rest Period 3 days |
| P6 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 16.5 ^{x)} | 8.2 | 4 | 90 | Steam | 1 | 39 | 2378 | 29 | 2.10 | |
| P7 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 16.5 ^{x)} | 8.2 | 4 | 90 | Steam | 7 | 39 | 2367 | 30 | 0.66 | |
| P8 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 16.5 ^{x)} | 8.2 | 4 | 90 | Steam | 28 | 39 | 2340 | 33 | 0.68 | |
| P9 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 16.5 ^{x)} | 8.2 | 4 + 20 ^{+))} | 90 | Steam | 28 | 39 | 2349 | 39 | 0.50 | |
| P10 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 20.7 ^{x)} | 8.2 | 4 | 90 | Steam | 1 | 60 | 2360 | 24 | 0.52 | |
| P11 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 20.7 ^{x)} | 8.2 | 4 | 90 | Steam | 7 | 60 | 2346 | 26 | 0.88 | |
| P12 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 20.7 ^{x)} | 8.2 | 4 | 90 | Steam | 28 | 60 | 2317 | 28 | 0.16 | |
| P13 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 20.7 ^{x)} | 8.2 | 4 + 20 ^{+))} | 90 | Steam | 28 | 60 | 2322 | 33 | 1.11 | |
| P14 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 24.8 ^{x)} | 8.2 | 4 | 90 | Steam | 1 | 168 | 2366 | 17 | 0.44 | |
| P15 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 24.8 ^{x)} | 8.2 | 4 | 90 | Steam | 7 | 168 | 2347 | 18 | 0.39 | |
| P16 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 24.8 ^{x)} | 8.2 | 4 | 90 | Steam | 28 | 168 | 2313 | 19 | 1.07 | |
| P17 | - | 1309 | 561 | 408 ^{c)} | 35 | 14M ^{**)} | 88 | 24.8 ^{x)} | 8.2 | 4 + 20 ^{+))} | 90 | Steam | 28 | 168 | 2307 | 25 | 0.38 | |
| P18 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 20.7 ^{x)} | 6.1 | 3 + 21 ⁺⁺⁾ | 60 | Steam | 4 | 182 | 2319 | 36 | 0.22 | Compaction: needle vibrator |
| P19 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 20.7 ^{x)} | 6.1 | 3 + 21 ⁺⁺⁾ | 60 | Steam | 7 | 182 | 2327 | 37 | 0.49 | Compaction: needle vibrator |
| P20 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 20.7 ^{x)} | 6.1 | 3 + 21 ⁺⁺⁾ | 60 | Steam | 14 | 182 | 2298 | 38 | 1.34 | Compaction: needle vibrator |
| P21 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 20.7 ^{x)} | 6.1 | 3 + 21 ⁺⁺⁾ | 60 | Steam | 28 | 182 | 2288 | 36 | 3.96 | Compaction: needle vibrator |
| P22 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 18.6 ^{x)} | 6.1 | 3 + 21 ⁺⁺⁾ | 60 | Steam | 1 | 204 | 2282 | 15 | 2.21 | Compaction: needle vibrator |
| P23 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 18.6 ^{x)} | 6.1 | 3 + 21 ⁺⁺⁾ | 60 | Steam | 2 | 204 | 2280 | 34 | 1.59 | Compaction: needle vibrator |
| P24 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 18.6 ^{x)} | 6.1 | 4 | 90 | Steam | 4 hrs | 128 | 2338 | 21 | 1.97 | Compaction: needle vibrator |
| P25 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 18.6 ^{x)} | 6.1 | 4 + 20 ^{+))} | 90 | Steam | 12 | 128 | 2308 | 44 | 1.21 | Compaction: needle vibrator |
| P26 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 18.6 ^{x)} | 6.1 | 24 | 60 | Steam | 4 | 202 | 2295 | 36 | 2.24 | Compaction: needle vibrator |
| P27 | - | 1294 | 554 | 408 ^{c)} | 51 | 14M ^{**)} | 103 | 18.6 ^{x)} | 6.1 | 24 | 60 | Steam | 5 | 202 | 2295 | 37 | 2.24 | Compaction: needle vibrator |

^{+))} 4 hrs curing, allow to cool, de-moulded, continued curing for another 21 hrs ⁺⁺⁾ 3 hrs curing, allow to cool, de-moulded, continued curing for another 20 hrs. ^{a)} Batch I ^{b)} Batch II ^{c)} Batch III ^{*)} Tech. Grade ^{**)} Com. Grade



APPENDIX B

**Calculation of Molar Ratio of Mixtures 13 to 17 and 20 to 22, and
Water-to-Geopolymer Solids Ratio of Mixtures 20 to 22**

Calculation of the Molar Ratio of Mixtures No 13 to 17 and No 20 to 22

I. Mixture Proportion (kg/m³)

| | Mix #13 | Mix #14 | Mix#15 | Mix #16 | Mix#17 | Mix #20 | Mix #21 | Mix #22 |
|---------------------------|---------|---------|--------|---------|--------|---------|---------|---------|
| Fly Ash | 408 | 408 | 408 | 408 | 408 | 408 | 408 | 408 |
| Sodium Silicate Solution | 103 | 103 | 103 | 103 | 103 | 103 | 103 | 103 |
| NaOH solution | 41 | 41 | 41 | 41 | 41 | 41 | 41 | 41 |
| Added water | 0 | 7.476 | 14.338 | 20.648 | 26.478 | 0 | 10.64 | 21.28 |
| Molarity of NaOH solution | 8 M | 10 M | 12 M | 14 M | 16 M | 14 M | 14 M | 14 M |

II. Some Chemical Compounds of Fly Ash Batch I (% by mass)

| | % |
|--------------------------------|-------|
| SiO ₂ | 53.36 |
| Al ₂ O ₃ | 26.49 |
| Na ₂ O | 0.37 |

III. Chemical Composition of Sodium Silicate (% by mass)

| Oxides | % |
|-------------------|------|
| SiO ₂ | 29.4 |
| Na ₂ O | 14.7 |
| Water | 55.9 |

IV. % of NaOH Flakes in Various Molarity

| NaOH solution | % |
|---------------|-------|
| NaOH 8 M | 26.23 |
| NaOH 10 M | 31.37 |
| NaOH 12 M | 36.09 |
| NaOH 14 M | 40.43 |
| NaOH 16 M | 44.44 |

V. Molecular Weight of Some Oxides

| Oxides | gr |
|--------------------------------|--------|
| SiO ₂ | 60.09 |
| Al ₂ O ₃ | 101.96 |
| Na ₂ O | 61.98 |
| H ₂ O | 18.00 |
| NaOH | 39.99 |

VI. Calculation of the moles of the geopolymers constituents and the molar ratio

| Mix # | NaOH Solution | Fly Ash | | | Sodium Silicate | | | NaOH solution | | Added Water | Total Moles (per m ³) | Molar Ratio | | | | | | |
|---------|---------------|------------------|--------------------------------|-------------------|------------------|-------------------|------------------|---------------|--------|-------------|-----------------------------------|-------------------|------------------|--------------------------------|------------------|------------------------------------|--|------------------------------------|
| | | SiO ₂ | Al ₂ O ₃ | Na ₂ O | SiO ₂ | Na ₂ O | H ₂ O | Flakes | Water | | | Na ₂ O | SiO ₂ | Al ₂ O ₃ | H ₂ O | Na ₂ O/SiO ₂ | SiO ₂ /Al ₂ O ₃ | H ₂ O/Na ₂ O |
| Mix #13 | 8 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 134.46 | 134.46 | 1680.32 | 0.00 | 403.11 | 4126.99 | 1060.02 | 5013.50 | 0.098 | 3.89 | 12.44 |
| Mix #14 | 10 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 160.81 | 160.81 | 1563.24 | 415.33 | 429.46 | 4126.99 | 1060.02 | 5338.11 | 0.104 | 3.89 | 12.43 |
| Mix #15 | 12 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 185.01 | 185.01 | 1455.73 | 796.56 | 453.65 | 4126.99 | 1060.02 | 5636.01 | 0.110 | 3.89 | 12.42 |
| Mix #16 | 14 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 207.26 | 207.26 | 1356.87 | 1147.11 | 475.90 | 4126.99 | 1060.02 | 5909.96 | 0.115 | 3.89 | 12.42 |
| Mix #17 | 16 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 227.81 | 227.81 | 1265.53 | 1471.00 | 496.46 | 4126.99 | 1060.02 | 6163.07 | 0.120 | 3.89 | 12.41 |
| Mix #20 | 14 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 207.26 | 207.26 | 1356.87 | 0.00 | 475.90 | 4126.99 | 1060.02 | 4762.85 | 0.115 | 3.89 | 10.01 |
| Mix #21 | 14 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 207.26 | 207.26 | 1356.87 | 591.11 | 475.90 | 4126.99 | 1060.02 | 5353.96 | 0.115 | 3.89 | 11.25 |
| Mix #22 | 14 M | 3623.05 | 1060.02 | 24.36 | 503.94 | 244.29 | 3198.72 | 207.26 | 207.26 | 1356.87 | 1182.22 | 475.90 | 4126.99 | 1060.02 | 5945.07 | 0.115 | 3.89 | 12.49 |

| Calculation of Water-to-Geopolymer Solids Ratio for Mixtures No 20 to 22 | | | | | | | | | | |
|--|-------------|----------------------|----------------|-----------------------------|---|----------------------|--------------|---------------|----------------|---------------|
| I. Mixture Proportion (kg/m ³) | | | | | | | | | | |
| | | | | | | | | | | |
| | | | Mix #20 | Mix #21 | Mix #22 | | | | | |
| Fly Ash | | | 408 | 408 | 408 | | | | | |
| Sodium Silicate Solution | | | 103 | 103 | 103 | | | | | |
| NaOH solution | | | 41 | 41 | 41 | | | | | |
| Added water | | | 0 | 10.64 | 21.28 | | | | | |
| Molarity of NaOH solution | | | 14 M | 14 M | 14 M | | | | | |
| II. Chemical Composition of Sodium Silicate (% by mass) | | | | | III. % of NaOH Flakes in Various Molarity | | | | | |
| Oxides | % | | | | | NaOH solution | % | | | |
| SiO ₂ | 29.4 | | | | | NaOH 8 M | 26.23 | | | |
| Na ₂ O | 14.7 | | | | | NaOH 10 M | 31.37 | | | |
| Water | 55.9 | | | | | NaOH 12 M | 36.09 | | | |
| | | | | | | NaOH 14 M | 40.43 | | | |
| | | | | | | NaOH 16 M | 44.44 | | | |
| IV. Calculations of Water-to-Geopolymer Solids by mass | | | | | | | | | | |
| | | | | | | | | | | |
| | NaOH | NaOH solution | | Sodium Silicate Sol. | | Fly Ash | Added | Total | | |
| | | Solids | Water | Solids | Water | | Water | Solids | Water / | |
| | | kg | kg | kg | kg | kg | kg | kg | Solids | Solids |
| Mix #20 | 14 M | 16.58 | 24.42 | 45.42 | 57.58 | 408.00 | 0.00 | 82.00 | 470.0 | 0.174 |
| Mix #21 | 14 M | 16.58 | 24.42 | 45.42 | 57.58 | 408.00 | 10.64 | 92.64 | 470.0 | 0.197 |
| Mix #22 | 14 M | 16.58 | 24.42 | 45.42 | 57.58 | 408.00 | 21.28 | 103.28 | 470.0 | 0.220 |

ENGINEERING PROPERTIES OF MAE MOH FLY ASH GEOPOLYMER CONCRETE

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Abstract

Fly ash-based geopolymer concrete and mortar were studied in this work. Sodium hydroxide and sodium silicate solution were used as alkali activators in 7 different mix proportions. Water was added to control the concrete slump at 200 ± 25 mm. The same geopolymer pastes of concrete were mixed with sand at the ratio of 1: 2.75 to make mortar. Cube concretes 100 x 100 x 100 mm were used for compressive strength test. All specimens were cured at 2 different temperatures, viz. 25°C and 60 °C for 24 hours. The specimens were then left at 25°C until the test age. Mortar bars 25 x 25 x 300 mm were cast to study the length change after immersion in 5% sodium sulfate solution. Mortar cubes 50 x 50 x 50 mm were also used to study the change in compressive strength after immersion in 5% MgSO₄ solution. Mortars were cured at 60 °C for 24 hours and left at 25°C. The results show that high alkalis activated geopolymer can be used as cementitious material in place of Portland cement for making concrete. MIX 5 in this study with high Na₂O: SiO₂ and NaOH molarity exhibits 3 day compressive strength higher than 30 MPa and has good resistance to sulfate attack similar to Portland cement type V mortar.

1. Introduction

High alkali activated fly ash concrete gradually earns an interest from material scientists [1,2]. Fly ash is to totally replace manufactured cement to make concrete-like material. This will turn the construction material to the new era. It is an inorganic aluminosilicate polymer synthesized from predominantly silicon and aluminium material of geological origin or by-product materials such as fly ash. Sometimes, it is called geopolymer. Fly ash-based geopolymer is made by mixing fly ash with sodium silicate solution and highly caustic hydroxide solution and cured at 25°C or at higher temperature.

Geopolymer term was first introduced by Davidovits [3]. Utilization of such a material to produce the valuable-added products is of considerable commercial interest.

The exact mechanism on geopolymer setting and hardening is not fully understood. Most proposed mechanisms consist of a dissolution, transportation or poly-condensation. Chemical composition, pressure, and temperature are considered important factors affecting the polymerization. It is normal that different sources of fly ash give different geopolymer properties.

The major source of fly ash in Thailand is from Mae Moh in the northern part of the country. The ash is now used for concrete construction though out the country. Being a lignite fly ash, it contains a high percentage of CaO[4]. It can, however, be classified as type F complied with ASTM C 618. This ash has been successfully used to produce geopolymer

The purpose of this research is to study the effect of chemical composition and curing temperature on the compressive strength of concrete

2. Experimental program

2.1 Materials

Class F fly ash (FA) from Mae Moh power station, with specific surface area of 2120 cm²/g was used as the base material in this work. The chemical composition of the fly ash is given in Table 1. Commercial grade sodium hydroxide in flake form (98% purity) conformed to TIS:150-2518 and sodium silicate solution conformed to TIS: 433-2539 (Na₂O=14.7%, SiO₂=29.4%, Water = 55.9%) were used as the alkali activators.

Table 1 - Chemical composition of fly ash (%)

| SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | SO ₃ | LOI |
|------------------|--------------------------------|--------------------------------|-----|-----------------|-----|
| 45.32 | 20.92 | 10.7 | 7.6 | 1.8 | 0.2 |

Concrete proportioning was first trialed following ACI 211.1.. River sand and limestone (max size = 3/8 in.) in saturated surface dry condition were used. The mixtures were adjusted by adding water to obtain the slump of 200 ± 25 mm. Tap water was used in this test. Table 2 shows mix proportion of concrete.

The same pastes in concrete mixtures were used to make mortar with a fly ash to sand ratio of 1: 2.75. Portland cement type I and V mortars were also made for comparison. The details of mixes are shown in Table 3.

2.2 Mixing and curing

All mixtures were mixed at room temperature. The temperature of all solutions was as ambient (25 °C). The specimens were wrapped by plastic sheet to prevent loss of moisture. The samples were cured at 2 different temperatures. The first was cured at 25°C (-R suffix) and the other was cured at 60 °C (-C suffix). They were temperature-cured for 24 hours then left at 25°C until the tested date.

Table 2 – Mix proportions of concretes

| Mix ID | W/B | FA | Agg. | S | W | Na ₂ O : SiO ₂ | | NaOH |
|--------|------|-----|------|-----|-----|--------------------------------------|--|-----------|
| | | | | | | kg/m ³ | | |
| 1 | 0.40 | 514 | 1056 | 700 | 95 | 127 | | 55(15 M) |
| 2 | 0.42 | 514 | 1056 | 700 | 119 | 79 | | 79(15 M) |
| 3 | 0.41 | 514 | 1056 | 700 | 119 | 79 | | 79(20 M) |
| 4 | 0.47 | 475 | 1056 | 700 | 79 | 158 | | 79(15 M) |
| 5 | 0.46 | 475 | 1056 | 700 | 79 | 158 | | 79(20 M) |
| 6 | 0.48 | 475 | 1056 | 700 | 79 | 119 | | 119(15 M) |
| 7 | 0.46 | 475 | 1056 | 700 | 79 | 119 | | 119(20 M) |

w/b = water to binder ratio, FA = fly ash, Agg. = Aggregate, S= sand, W= water

Table 3 - Mix proportions of mortars (g)

| Mix ID | Cement | Fly Ash | Sand | Na ₂ O : SiO ₂ | NaOH | | Water | w / b |
|--------|--------|---------|------|--------------------------------------|-------|-------|--------|-------|
| | | | | | 15 M | 20 M | | |
| 1M | 0 | 486.5 | 1338 | 113.96 | 55.3 | | 90.3 | 0.40 |
| 2M | 0 | 486.5 | 1338 | 74.2 | 74.2 | | 112.7 | 0.42 |
| 3M | 0 | 486.5 | 1338 | 74.2 | | 74.2 | 113.05 | 0.41 |
| 4M | 0 | 449.4 | 1236 | 149.8 | 74.2 | | 74.2 | 0.472 |
| 5M | 0 | 449.4 | 1236 | 149.8 | | 74.2 | 74.2 | 0.46 |
| 6M | 0 | 449.4 | 1236 | 112.7 | 112.7 | | 74.2 | 0.475 |
| 7M | 0 | 449.4 | 1236 | 112.7 | | 112.7 | 74.2 | 0.457 |
| I-40 | 700 | 0 | 1925 | | | | 280 | 0.40 |
| V-40 | 700 | 0 | 1925 | | | | 280 | 0.40 |

2.3 Test procedures

Compressive strength of concretes was tested at the age of 1, 3, 7, and 28 days. The mortars immersed in water and 5% MgSO₄ solution were tested for compressive strength at 28, 60 and 90 days in accordance with ASTM C 109. Length change of mortar bars immersed in 5% Na₂SO₄ solution was measured as prescribed in ASTM C 490-96. All mortar specimens were cured in the same conditions and immersed in 5% sodium sulfate and 5% magnesium sulfate solution at the age of 2 days.

3. Results and Discussion

Compressive strength of concrete

Compressive strengths of concretes were shown in Table-4. It was found that MIXes 1, 2 and 3 exhibited very low compressive strengths and were not suitable to use as structural

concrete even though they were cured at 60 °C. MIXes 4, 5, 6, and 7 gave considerable compressive strengths. For example, MIX 5 with 60°C cured was 25.7 MPa at one day and increased to 35.8 MPa within 28 days,. It should be noted that no Portland cement involved in these mixtures. Fig.1 clearly shows that higher curing temperature significantly affects the early strength of concrete more than that of the later age. At one day, compressive strength of MIX 5 in normal room condition is 3.4 MPa and it increases to 25.7 MPa when the curing temperature is elevated to 60 °C. It is about 7 times higher than those curing at 25°C.

Table 4 - Compressive strength of concrete

| MIX ID | Compressive strength (MPa) | | | | | | | |
|--------|----------------------------|-------|-------|--------|---------------|-------|-------|--------|
| | Cured at temperature | | | | Cured at 60°C | | | |
| | 1-day | 3-day | 7-day | 28-day | 1-day | 3-day | 7-day | 28-day |
| 1 | 0.9 | 1.3 | 2.4 | 3.1 | 4.1 | 4.4 | 4.9 | 6.6 |
| 2 | 0.6 | 1.6 | 2.8 | 10.9 | 7.8 | 10.7 | 11.6 | 13.7 |
| 3 | 0.7 | 0.8 | 1.6 | 11.5 | 8.6 | 9.4 | 13.4 | 16.6 |
| 4 | 1.7 | 5.5 | 12.4 | 26.6 | 21.1 | 22.7 | 25.5 | 28.9 |
| 5 | 3.4 | 8.3 | 16.3 | 29.7 | 25.7 | 32.1 | 32.9 | 35.8 |
| 6 | 1.8 | 4.5 | 9.1 | 15.8 | 17.5 | 18.7 | 21.9 | 24.4 |
| 7 | 1.8 | 5.4 | 10.6 | 21.8 | 21.6 | 24.7 | 27.0 | 28.4 |

In order to observe the influence of chemical composition on the compressive strength of concrete, chemical ratios of paste were tabulated in Table 5. Each term is calculated from both solid and liquid parts of the paste. For example, SiO₂ was obtained from both fly ash and sodium silicate solution.

It can be observed that when the Na₂O/SiO₂ increases from 0.115 to 0.182, compressive strength increases as well. However, when this ratio reaches 0.213, compressive strength of concrete becomes lower. The Na₂O/Al₂O₃ ratios can be observed in the same way. As this term increases, the compressive strength increases as well. After the ratio reaches 0.818, compressive strength tends to drop down. It also shows that the increase of water to Na₂O ratio reduces the compressive strength of concrete. Similar result has also reported [4].

Compressive strength of mortars immersed in 5% MgSO₄ solution

Compressive strengths of mortars are slightly different to those of concretes. However, MIX 5M still gave the highest compressive strength. To compare with Portland cement type I and type V mortar with w/c = 0.4, it is clear that the compressive strength of mortar I-40 and V-40 immersed in water gave higher strength than other geopolymer mortars indicating that it can withstand MgSO₄ attack better than the other mixes. Compressive strength of MIX-5M was 19.8, 22.4 and 25.6 MPa at 28, 60 and 90 days, respectively. After they were immersed in MgSO₄, the strength slightly reduced to 17.9, 23.3 and 24.2 MPa at the same ages. MIX V-40 showed good performance as well.

Compressive strength of MIX I-40 reduced dramatically from 35.2 MPa in water cured condition to 23.0 MPa after immersed in 5% MgSO₄. Bakharev [5] has found similar results that geopolymer was able to gain compressive strength as age increased in sulphate environment.

Table 5 - Chemical composition ratios of fly ash paste versus compressive strength of concrete at 28 days

| MIX ID. | Chemical composition ratios | | | | Compressive strength at 28 days (MPa) | |
|---------|------------------------------------|--|------------------------------------|--|---------------------------------------|------|
| | Na ₂ O/SiO ₂ | SiO ₂ /Al ₂ O ₃ | H ₂ O/Na ₂ O | Na ₂ O/Al ₂ O ₃ | 25 °C | 60°C |
| 1 | 0.115 | 4.276 | 22.135 | 0.492 | 3.1 | 6.6 |
| 2 | 0.139 | 4.051 | 20.249 | 0.563 | 10.9 | 13.7 |
| 3 | 0.160 | 4.051 | 17.173 | 0.647 | 11.5 | 16.6 |
| 4 | 0.162 | 4.488 | 17.648 | 0.727 | 26.6 | 28.9 |
| 5 | 0.182 | 4.488 | 15.304 | 0.818 | 29.7 | 35.8 |
| 6 | 0.213 | 4.285 | 14.080 | 0.914 | 15.8 | 24.4 |
| 7 | 0.245 | 4.285 | 11.804 | 1.051 | 21.8 | 28.4 |

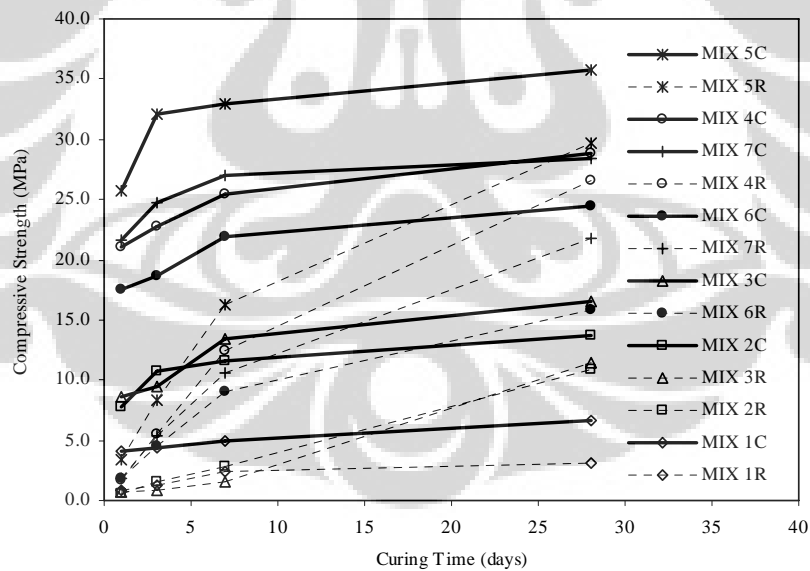


Figure 1 – Relationship between compressive strength and curing time of concrete

Length change of mortar bar exposed to Na₂SO₄

Mortar bars made by Portland cement type I and V were cast with w/c = 0.40 as control samples to compare with those of geopolymer mortars. All samples were soaked in Na₂SO₄ right after demolding. The results are shown in Fig. 2. It reveals that sample I-40 expand at highest rate among all samples. It expands about 0.1% of the original length. MIXes 5M, 6M and V-40 showed better performance. They expand in the range of 0.028 to 0.035% of the original.

Table 6 - Compressive strength of mortars

| Mix ID | Compressive strength (MPa) of mortars after immersed | | | | | |
|--------|--|-------------------|--------|-------------------|--------|-------------------|
| | 28-day | | 60-day | | 90-day | |
| | Water | MgSO ₄ | Water | MgSO ₄ | Water | MgSO ₄ |
| 1M | 15.7 | 13.2 | 17.3 | 15.3 | 17.7 | 15.4 |
| 2M | 5.8 | 5.0 | 6.3 | 4.6 | 6.6 | 2.3 |
| 3M | 4.1 | 3.9 | 5.0 | 3.7 | 6.2 | 2.6 |
| 4M | 21.2 | 20.4 | 21.5 | 20.7 | 23.2 | 14.7 |
| 5M | 19.8 | 17.9 | 22.4 | 23.3 | 25.6 | 24.2 |
| 6M | 22.0 | 13.8 | 23.8 | 15.5 | 23.4 | 15.2 |
| 7M | 11.2 | 10.9 | 12.8 | 12.0 | 14.4 | 12.6 |
| I-40 | 31.6 | 32.0 | 33.1 | 27.0 | 35.2 | 23.0 |
| V-40 | 31.5 | 31.8 | 34.0 | 31.1 | 37.0 | 29.0 |

4. Conclusions

From the test results, the following conclusions can be drawn:

1. Curing temperature at 60 °C affects early compressive strength of concretes more than those at a later age.
2. Compressive strength of geopolymer concrete seems to depend on chemical ratios of the paste.
3. Length change test of geopolymer mortars show satisfactory performance similar to Portland cement type V mortar.
4. MIX 5 in this work with high Na₂O : SiO₂ and NaOH molarity shows adequate performance in both compressive strength and resistance to sulfate attack.

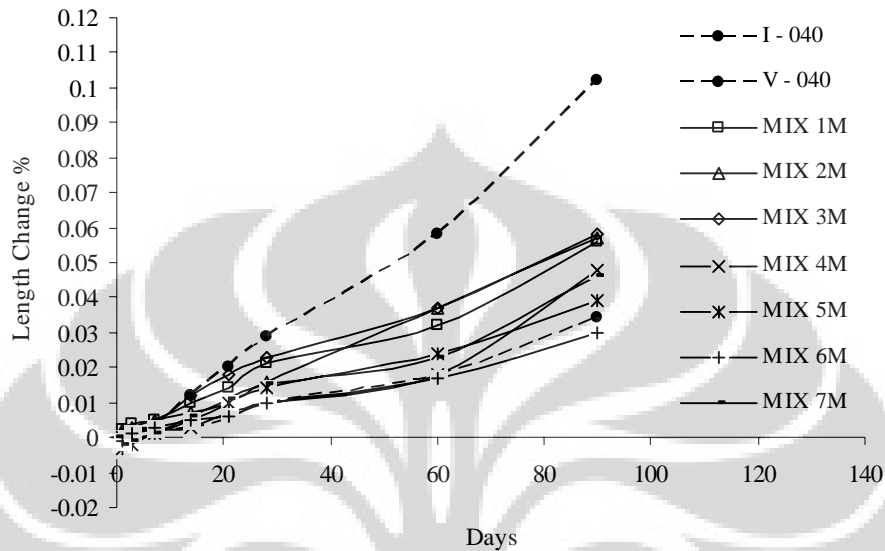


Figure 2 – Length change of mortar bars due to immersed in 5% Na₂SO₄

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Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

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ABSTRACT

This paper presents a study on water penetrability properties, namely water absorption, volume of permeable voids, permeability and sorptivity of low calcium fly ash geopolymer concrete. In this research, geopolymer concrete is made from fly ash with a combination of sodium hydroxide and sodium silicate as alkaline activator. Seven mixes were cast in 100x200mm cylinders and cured for 24 hours at 60⁰C in the steam curing chamber. After 28 days, the cylinders were cut into slices for permeability, sorptivity and volume of permeable voids tests. In addition, a microstructure characteristic of geopolymer concrete was studied using Scanning Electron Microscopy (SEM). Results indicate that geopolymer concrete has low water absorption, volume of permeable voids and sorptivity. It is found that the geopolymer concrete could be classified as a concrete with an average quality according to water permeability value. Moreover, a low water/binder ratio and a well-graded aggregate are some important factors to achieve low water penetrability of geopolymer concrete.

Keywords: *absorption, durability, geopolymer, porosity, sorptivity, water permeability*

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1. INTRODUCTION

Water penetrability, namely absorption, permeability and sorptivity are some important measurements to control concrete durability. Penetrability of liquid into the concrete consists of permeability through a porous medium, diffusion and absorption. Regarding to this, pores in concrete have an important role to allow the liquid/fluid move through the concrete. However, the tendency of concrete to absorb and transmit water by capillary action not only depends on the porosity but also on its pore diameter, distribution, continuity and tortuosity.

Geopolymer concrete is a new type of concrete that can be made from fly ash/metakaolin/slag and activated with alkaline solutions. Many studies confirmed that fly ash geopolymer concrete has good engineering properties (Hardjito, 2005; Fernandez-Jimenez, *et al.* 2006; Sofi, *et al.* 2007). Other studies also show that low calcium fly ash geopolymer concrete has good durability on acid and sulphate condition (Wallah, 2005), alkali-aggregate reaction (Garcia-Lodeiro, *et al.* 2007), corrosion (Yodmune & Yodsujai, 2006) and fire resistance (Kong, *et al.*, 2007). Despite the superior resistance of the low calcium fly ash geopolymer concrete in various severe environments, according to Kong, *et al.* (2007) and Sindhunata (2006), the fly ash geopolymer paste contains higher proportion of pores in the mesopores size. This condition may lead water to penetrate easily and will affect the durability of the material.

Limited studies made on geopolymer concrete show that metakaolin geopolymer concrete has permeability 10^{-11} m/s (Davidovits, 1994a), while Shi (1996) found that permeability of slag geopolymer concrete is more than 10^{-12} m/s. Since the water penetrability of fly ash geopolymer concrete is rarely reported, hence the aim of this investigation is to determine water penetrability of low calcium fly ash geopolymer, namely water permeability, sorptivity and water absorption.

2. GEOPOLYMER CONCRETE

Geopolymer is a mineral polymer from the geochemistry process (Davidovits, 1994b). This alumina silicate polymer is synthesised from silica and alumina in the source material. Silica and alumina are obtained from natural material and industry by-products such as fly ash, metakaolin and slag. Although different source materials are used to manufacture geopolymers, basically, the activation of the source materials using an alkaline solution results in compact well cemented composites.

The geopolymerization process consists of chemical reaction of Si-Al mineral in alkaline condition that involves the dissolution of Si-O-Al-O bond. The process is described as $Mn [-(Si - O_2)_z - Al - O]_n, wH_2O$, with Mn = alkaline element, - = bond, z = 1, 2, 3, and n = degree of polymerization. The alkaline chemicals used in geopolymerization are $Ca(OH)_2$, NaOH, Na_2SiO_3 (sodium silicate), a combination of NaOH and sodium silicate, a combination of KOH and NaOH, KOH, potassium silicate and its combination, and sodium carbonate. A combination of alkaline solution determines the final product and geopolymer strength. Research on the effects of alkaline solution on the final product of geopolymer (Fernandez-Jimenez, *et al.* 2005) showed that a combination of NaOH and Na_2SiO_3 (sodium silicate)

produced a solid material almost without pores and has a strong bond between aggregate and geopolymer matrix.

Some researchers reported a mesoporous character of geopolymer paste/concrete (Chang, *et al.* 1999; Kong, *et al.* 2007; Shindunata, *et al.* 2006). This has resulted from a fusion of fly ash highly in Si and Al elements with alkaline solution. Fernandez-Jimenez, *et al.* (2005), revealed that type of activator plays an important role to convert fly ash into mesoporous product. According to Sindhunata *et al.* (2006), the fly ash geopolymer gel is porous because evaporation of the aqueous pore solution leaving the empty voids, insufficient geopolymer gel to fill the gaps in between an unreacted fly ash, and porosity of partially reacted fly ash particles. It is found that the total pore volume of concrete increases as the curing temperature is elevated.

4. EXPERIMENTAL PROGRAM

4.1 Materials and Mixtures

Geopolymer concrete in this study was made from low calcium fly ash with a combination of sodium hydroxide (NaOH) and sodium silicate solution (Na_2SiO_3). Table 1 shows the chemical composition of fly ash from Collie power station, Western Australia.

Table 1. Chemical analysis fly ash

| Elements | Fly ash |
|-------------------------|---------|
| SiO_2 | 50.3 |
| Al_2O_3 | 26.3 |
| Fe_2O_3 | 13.6 |
| CaO | 2.27 |
| K_2O | 0.55 |
| MgO | 1.44 |
| Na_2O | 0.36 |
| P_2O_5 | 1.58 |
| SO_3 | 0.32 |
| LOI | 0.54 |

Table 2 displays the mixture proportion of fly ash geopolymer concrete in this research. The basic geopolymer mixture proportion (mix GP1) was selected from some mixtures proposed by Hardjito (2005). The mixture is primarily used to produce geopolymer concrete with properties and performance that is equivalent to OPC concrete with strength 35 MPa. Different mixes of low calcium fly ash geopolymer concrete were made by varying the water/binder ratio (0.20-0.25), aggregate/binder ratio (3.5, 3.9, 4.7) and aggregate grading (7:10mm, 7:10:20mm). Two mixes of OPC concrete were made by varying the water/cement ratio to achieve the same level of strength with geopolymer concrete.

Sodium hydroxide in a form of pellets was dissolved in the water. In this research, the concentration of sodium hydroxide used was 14M. Sodium silicate solution with SiO_2 to Na_2SiO_3 ratio approximately 2 was supplied by PQ Australia. Superplasticizer (naphthalene based) was included in the mixes to improve workability. The granite coarse aggregate used

Water Penetrability of Low Calcium Fly Ash Geopolymer Concrete

was 20mm maximum size. The aggregates were conditioned to meet SSD requirement (3-5% moisture content).

Table 2. Mixture proportion

| Mixture no | w/c | w/b | a/b | Quantity (kg/m ³) | | | | | | | | | |
|------------|------|------|-----|-------------------------------|--------|------------------|------|------|------|---------|------------|-----|-----|
| | | | | Water | Cement | Coarse Aggregate | | | Sand | Fly ash | NaOH (14M) | S.S | S.P |
| | | | | | | 7mm | 10mm | 20mm | | | | | |
| C1 | 0.53 | - | - | 205 | 386 | 621 | 562 | - | 637 | - | - | - | - |
| C2 | 0.50 | - | - | 188 | 377 | 635 | 574 | - | 642 | - | - | - | - |
| GP1 | - | 0.23 | 3.9 | 25.8 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP2 | - | 0.22 | 3.9 | 20.7 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP3 | - | 0.20 | 3.9 | 16.5 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP4 | - | 0.25 | 3.9 | 36.2 | - | 647 | 554 | - | 647 | 408 | 41 | 103 | 6.1 |
| GP5 | - | 0.22 | 3.5 | 25.8 | - | 630 | 540 | - | 630 | 444 | 44 | 111 | 6.1 |
| GP6 | - | 0.24 | 4.7 | 25.8 | - | 672 | 576 | - | 672 | 356 | 36 | 89 | 6.1 |
| GP7 | - | 0.23 | 3.9 | 25.8 | - | 645 | 370 | 277 | 554 | 408 | 41 | 103 | 6.1 |

Note: A = OPC/control mixture, B = Geopolymer mixture, S.S = Sodium Silicate; S.P = Superplasticizer

4.2 Specimens preparation and curing

OPC concrete specimens were prepared according to AS 1012.2-1983. Low calcium fly ash geopolymer concrete were made using a mixing procedure developed by Hardjito (2005). A chemical solution consists of NaOH (14M), Sodium Silicate, extra water and Superplasticizer was prepared approximately 2 hours before mixing process. In this process, firstly, the fly ash and aggregates were mixed for three minutes. Then a chemical solution was poured slowly to the dry mix. The pan mixer continued to mix all ingredients for another four minutes to achieve uniform mix.

All OPC and geopolymer concrete specimens were cast in concrete cylinders of 100mm diameter by 200mm height. Fifteen concrete cylinders from each of the nine concrete mixtures were cast. Those samples were cured using a steam curing process at temperature of 60°C for 24 hours. Then the specimens were left for air curing in a control environment with a temperature of 23-25°C until testing. Six cylinders from each mixture were used to determine compressive strength at 7 and 28 days (three specimens tested as each date). Three specimens for each mixture were prepared for water absorption and AVPV test, while other three were used for sorptivity test at 28 days age of concrete. For water permeability test, only two slices of individual specimens were used. Small samples with a thickness 5mm and area of 1cm² were taken for Scanning Electron Microscopy (SEM) analysis. These samples were coated with carbon and undergone a vacuuming process for overnight prior to SEM.

4.3 Test Procedure

Compressive strength tests were performed at 7 and 28 days using an Avery testing machine with a loading rate 16 MPa/minute.

Water absorption and volume of permeable voids determination were carried out according to ASTM C 642. For each concrete mix, three specimens were cut into slices with maximum thickness of 50mm for water absorption and AVPV test. These specimens were dried in the oven at 105°C until constant mass. Water absorption is measured by drying the specimen to

constant mass, immersing it in water and measuring the increase in mass as a percentage of dry mass. Volume of permeable voids is determined by boiling the concrete for at least 5 hours, weighing them in water, then measuring the percentage of boiled specimens with dried mass and mass in the water.

Sorptivity test was carried out according to Hall (1989). In this test, three specimens were dried in the oven at 105⁰C to constant mass. After cooling, the bottom surface of the specimen was cut and this cut surface was made to contact with water. The test was carried out by measuring the weight gain of the specimen at the set time intervals of 5 min, 10 min, 30 min, 1 h, 2 h, 3 h and 4 h. Then uptake of water per unit area of concrete surface I (g/mm) followed a linear relationship with the square root of time for the suction periods (t), hence

$$I = C + St^{0.5} \quad (4.3.1)$$

where S , the sorptivity is the slope of the I vs $t^{0.5}$ plot and can be obtained by linear regression.

Water permeability test were carried out for mixes GP1, GP2, GP4 and GP5 based on GHD Water Permeability method (previously Taywood Engineering Ltd), that modified according to DIN 1048. These specimens were dried in the oven at 105⁰C until constant mass. The specimens were coated with epoxy coating in the circular side to prevent water penetration from that side during the test. A pressure of 850 kPa was given to the samples at pressure head of 92.5 m. After the specimen saturated, then the flow rate reading was taken using burette by measuring the changing of volume of water with time. Permeability is defined using Darcy's Law,

$$k = \frac{QL}{AH} \quad (4.3.2)$$

where k = permeability coefficients (m/s), Q = flow rate (m³/s), A = area (m²), L = depth of specimen (m), H = head of water (m).

5. RESULTS AND DISCUSSIONS

5.1 Properties of fresh and hardened concrete

The slump and compressive strength of OPC and geopolymer concrete are shown in Table 3. The high slump of geopolymer mixes were achieved by addition of superplasticizer. Although the slump values are higher than 200mm for the geopolymer concrete, the compressive strength values are different for each mixture. It shows that geopolymer concrete has high workability for compressive strength than 30 MPa. It was found that an increase of amount of water will improve the workability, but decrease the strength of concrete (Hardjito, *et al.* 2004). When the water content is increased drastically, it will tend to produce bigger crystals of geopolymer and decrease the specific surface area of concrete. This will eventually lead to a decrease in strength (van Jaarsveld, *et al.* 2002).

Table 3. Properties of fresh and compressive strength of hardened concrete

| Mixture no | Slump (mm) | Compressive strength | |
|------------|------------|----------------------|---------|
| | | 7 days | 28 days |
| C1 | 200 | - | 34.09 |
| C2 | 80 | 39.68 | 47.50 |
| GP1 | 260 | 30.92 | 34.86 |
| GP2 | 230 | 38.32 | 41.36 |
| GP3 | 270 | 67.09 | 67.53 |
| GP4 | 270 | - | 25.28 |
| GP5 | 260 | 45.96 | 48.06 |
| GP6 | 240 | 24.19 | 25.44 |
| GP7 | 260 | 32.45 | 36.13 |

5.2 Water Absorption and Apparent Volume of Permeable Voids

The results of water absorption and AVPV of geopolymer concrete for mixes with different water/binder ratio is presented in Figure 1. The water absorption and AVPV increases with an increase in water content of the mix. The results indicated that the water absorption and AVPV were much affected by the extra water added into the mixture since it increases capillary porosity of concrete. As shown, water absorption and AVPV for mix GP4 with water/binder ratio 0.25 was significantly higher than those for other geopolymer mixes. Geopolymer concrete uses a very small amount of water in the mixture. The additional extra water is useful to achieve a particular strength. However, a relatively higher water/binder ratio produces a weaker and pervious matrix, leading to higher capillary porosity that is turn responsible for the increase in water absorption and AVPV of geopolymer mixes.

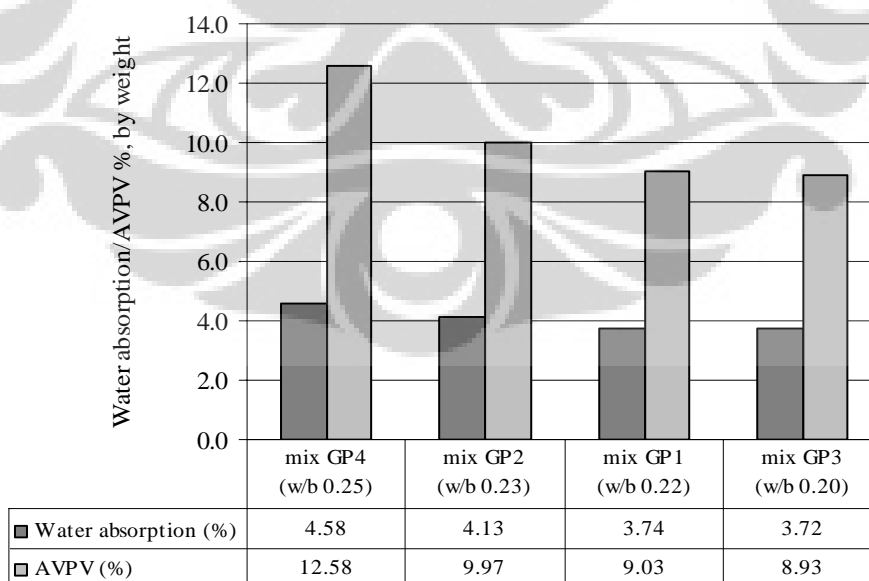


Figure 1. Water absorption and AVPV of geopolymer concrete for mixes with different water/binder ratio

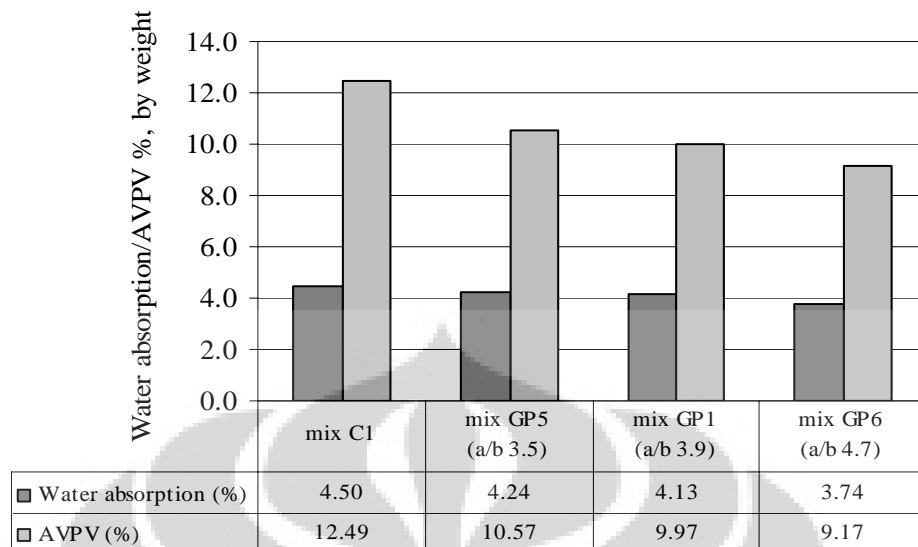


Figure 2. Water absorption and AVPV of OPC concrete and geopolymer concrete with different variation of aggregate binder ratio

Figure 2 shows water absorption and AVPV for different variation of aggregate binder ratio. Furthermore, mix GP5 resulted in higher compressive strength with high water absorption and AVPV than mix GP1. This mix represents more binder content than aggregate results on more porous concrete. Inclusion of sodium silicate addition in high amount is vulnerable to create more channels in the concrete during the steam curing process. This phenomenon confirmed the observations made by Sindhunata (2006) and Chang (1999).

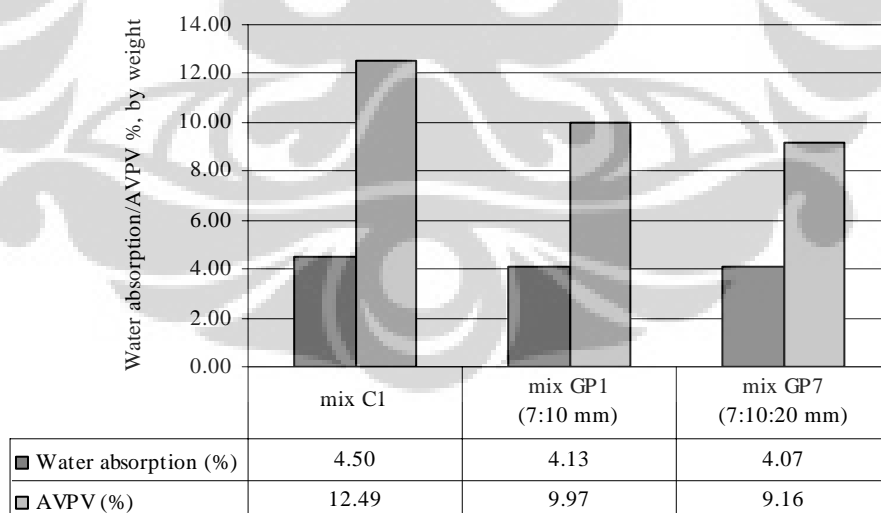


Figure 3. Water absorption and AVPV of OPC concrete and geopolymer concrete with different variation of aggregate grading

It can be seen from Figure 3 that for all mixes with the same water binder ratio, except for mix C1, a well-graded aggregate result on lower absorption and AVPV. In this case, aggregates

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composition using 7, 10, 20mm shows a lower capillary porosity compared to mix GP1 with only two different types of aggregates, which is 7 and 10mm. A better distribution of aggregate size reduces the size and continuity of concrete pores.

OPC concrete mixes (C1 and C2) that steam cured with the same strength with geopolymer concrete exhibits higher water absorption and AVPV (Figure 4). It indicates that for OPC concrete cured with steam curing resulted on high capillary porosity concrete. In this stage, there is no continuous hydration to fill and reduce the continuity of the pores. This condition results on coarser microstructure and higher porosity on the concrete. A similar increase in water absorption for steam cured OPC was reported by Ho, *et al.* (2003) and Campbell & Detwiler (1993).

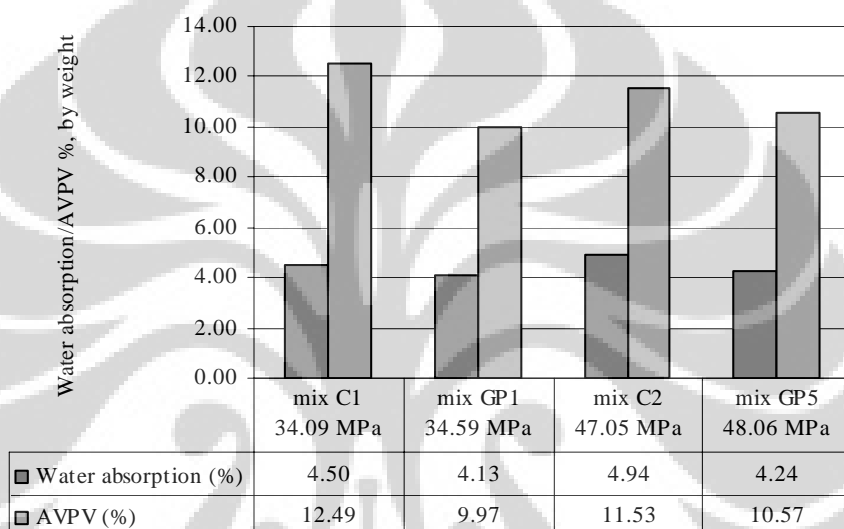


Figure 4. Water absorption and AVPV of control mixes and geopolymer concrete with the same strength

For both OPC and geopolymer mixes, a decrease in water/binder or water/cement ratios exhibits a marginal reduction of water absorption and AVPV. From the results, it can be seen that durability is more related to water/binder ratio than compressive strength. As the water content reduces, the paste content increases reducing the volume of capillary pores and thus showed a decreasing trend of water absorption and AVPV.

5.3 Sorptivity

Table 4 shows sorptivity values for control and geopolymer concrete at various water/binder ratio, aggregate binder ratio and aggregate grading. As shown, the results indicated that the sorptivity was significantly lower for all the geopolymer mixes than for the control mix with a water/cement ratio 0.50 (around 40 MPa strength level). For all geopolymer mixes, the sorptivity reduces with a decrease of water content and better grading distribution. These sorptivity values are in the range of Hall (1989) observation on concrete with water cement ratio 0.40-0.60 with sorptivity values in the range 0.094-0.170.

Table 4. Sorptivity of control and geopolymer concrete with regression coefficients

| Mixture no | Sorptivity (mm/min ^{0.5}) | R ² value |
|------------|-------------------------------------|----------------------|
| C2 | 0.2080 | 0.9971 |
| GP1 | 0.1262 | 0.9897 |
| GP2 | 0.1503 | 0.9924 |
| GP4 | 0.2038 | 0.9963 |
| GP5 | 0.1478 | 0.9912 |
| GP7 | 0.1507 | 0.9930 |

Figure 5 shows comparison of sorptivity value of geopolymer with different water/binder ratio. It is revealed that the water/binder ratio has significantly influenced the sorptivity as per water absorption and AVPV. This suggests that the increase of amount of water resulted in high porosity concrete, hence increases capillary suction.

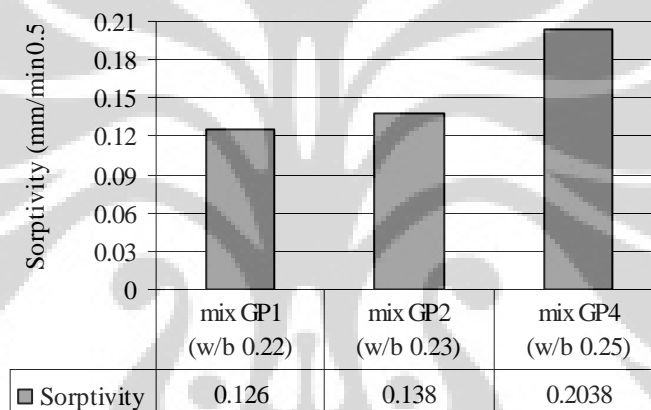


Figure 4. Sorptivity of geopolymer concrete with different water/binder ratio

Figure 5 shows comparison of sorptivity of geopolymer concrete and the corresponding control mix. A typical geopolymer concrete mix (GP2) exhibits lower sorptivity than the corresponding control mix (A2), which again illustrates the effect of binder content and thus the capillary pores on the sorptivity. Lower slope of geopolymer concrete showed reduced moisture intake as compared to the corresponding control mix. Although geopolymer concrete is known to have more pores in mesopore size, in general the results show that it has a lower capillary porosity than OPC concrete cured with steam. There is a need to investigate such a phenomenon to correlate the lower sorption characteristics with the pore structure of geopolymer concrete.

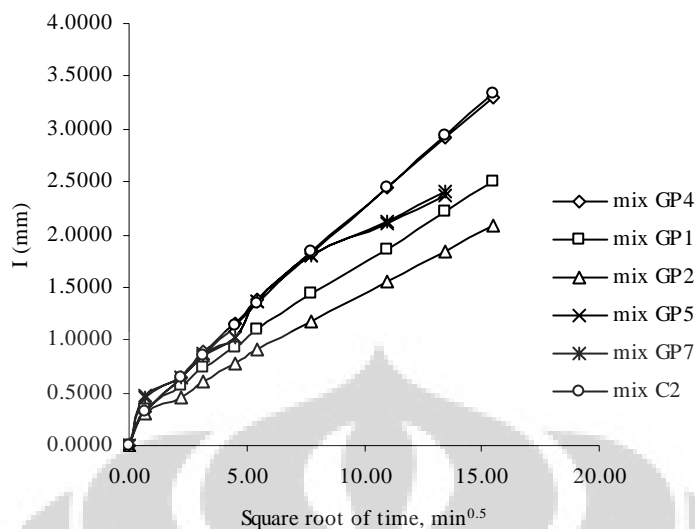


Figure 6. Comparison of capillary absorption rate of geopolymer concrete with control mix

5.4 Water Permeability

Table 5 indicates that the water permeability coefficient of geopolymer also has a tendency to increase with an increase of water/binder ratio. The permeability of high water/binder ratio concrete is greater because of the presence of larger capillary pores. However, those values are still in the range of water permeability coefficient for concrete with an average quality (10^{-11} - 10^{-12} m/s) according to Concrete Society Technical Report 54 (Rendell, *et al.* 2002).

It is also obvious that the percentage of void content might not affect the water permeability coefficient of geopolymer concrete significantly. It can be assumed that pore continuity has more contribution to higher water permeability coefficient for mix GP1. In the case of geopolymer concrete, blocking of the pores may be stopped after the accelerated steam curing process ceased. Thus, the ability to fill the pore structure depends mainly on the curing process. The increase of strength, eventually, is only a continuing effect of geopolymerization without any hydration.

Table 5. Water permeability coefficients of geopolymer concrete with different mixes

| Mixture no | Water permeability coefficient ($\times 10^{-11}$ m/s) | Void content (%) |
|------------|---|------------------|
| GP1 | 4.67 | 10.5 |
| GP2 | 3.95 | 13 |
| GP3 | 2.46 | 10.8 |
| GP5 | 2.91 | 10 |
| GP7 | 2.61 | 8.2 |

As observed from Table 5, mix GP3 with water/binder ratio 0.20 shows the lowest water permeability coefficient. It is found also that mix GP7 with aggregate grading (7, 10, 20mm)

shows low water permeability and void content. This indicates that the low water/binder ratio and a well-graded aggregate have large influences on geopolymer concrete permeability. As for OPC concrete, low water content and continuous grading contributes to lower porosity and discontinuity of concrete pores.

5.5 SEM Analysis

The microstructure of fly ash based geopolymer concrete is presented in Figures 6a and 6b. Figure 7 shows a typical SEM micrograph of mix GP2. This micrograph shows the geopolymer gel with partially or completely unreacted fly ash particles. Geopolymer product has unshaped and uniform microstructure. Some cracks were observed in the surface that might be due to mechanical damage during the sample preparation. The geopolymer microstructure from this research looks like many types of geopolymer from similar observations by Fernandez-Jimenez, *et al.* (2005) and Skvara, *et al.* (2006).

Figure 8 shows the holes in the microstructure resulted from air bubbles in the mixture. Those voids are distributed around the layer of geopolymer matrix. It is also found that there are some unreacted fly ash particles in the microstructure. Fly ash is known to have a significant proportion of particles with hollow spheres that possible to create porosity when they partially dissolved. As the result, the geopolymer matrix contains more dispersed small sized pores that can contribute to the overall porosity.

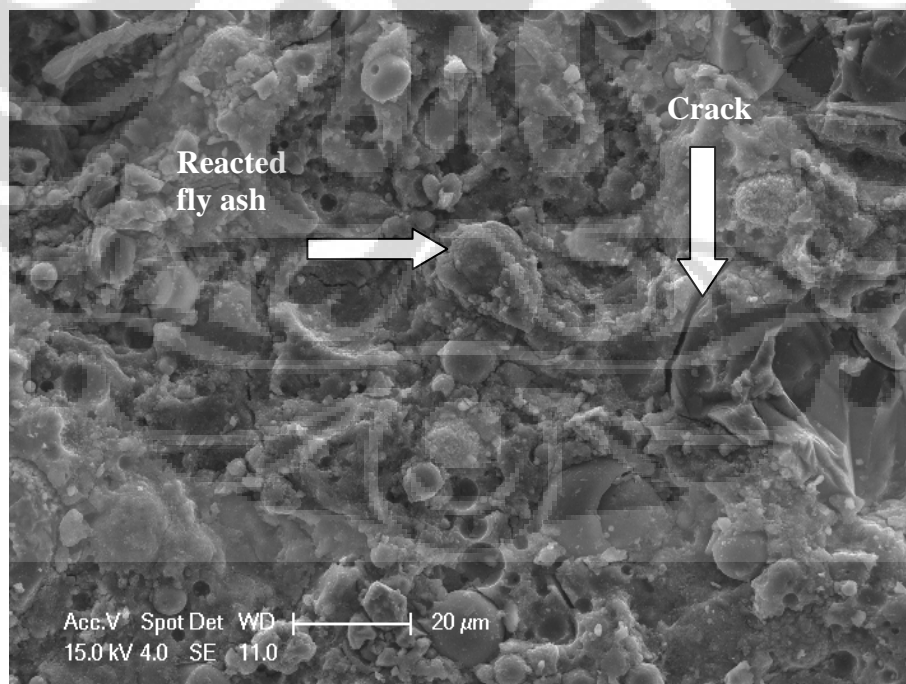


Figure 7. Typical SEM micrograph of geopolymer concrete (mix GP2)

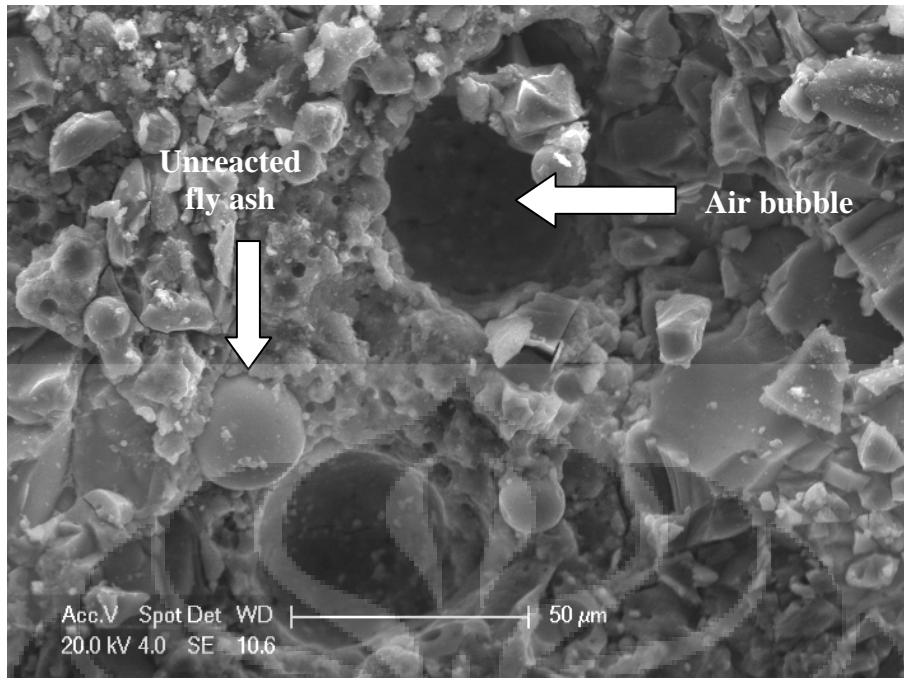


Figure 8. Air bubbles and unreacted fly ash of geopolymer concrete (mix GP2)

6. CONCLUSIONS

The following conclusions can be drawn based on the test results and discussion of the present study for measuring water penetrability of geopolymer concrete:

1. Fly ash geopolymer concrete exhibits low water absorption and sorptivity.
2. Geopolymer could be classified as a concrete with average quality according to water permeability coefficient values.
3. A water/binder ratio and well-graded aggregate are some important parameters that influence the water penetrability of low calcium fly ash geopolymer concrete. It is found that the higher water/binder ratio, then the lower water absorption and AVPV, sorptivity and water permeability. It is recommended to have low water/binder ratio and a better grading to reduce the capillary porosity and the overall porosity of geopolymer concrete.
4. Water absorption, AVPV, and sorptivity of low calcium fly ash geopolymer concrete are lower than the corresponding OPC concrete mixes. Steam cured OPC concrete shows higher capillary porosity than steam cured geopolymer concrete.
5. Geopolymer concrete with lower aggregate/binder ratio also indicates a high porous matrix. Sodium silicate inclusion to the mix might be the main cause of this finding.
6. From the microstructural analysis, the partially dissolved fly ash particles with hollow spheres mainly contribute to the porosity of the geopolymer matrix.

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