# Comparison of Elastic Modulus between Class G Cement and Geopolymer Cement under HPHT Condition

by

Muhammad Aizat bin Mohd Zulkarnain

14910

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Petroleum Engineering)

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## CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
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(PETROLEUM)

Approved by,

__________________

(Dr. Syahrir Ridha)

UNIVERSITI TEKNOLOGI PETRONAS

BANDAR SERI ISKANDAR, PERAK

January 2015

## CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MUHAMMAD AIZAT BIN MOHD ZULKARNAIN

## ABSTRACT

Well cementing is one of the important systems in oil and gas drilling. It provides support and protection to the casing, prevent the movement of fluid through the annular space outside the casing; stop the movement of fluid into vugular or fractured formations and it also use to close an abandoned well. However, Ordinary Portland Cement (OPC) used are having issues with its strength since it take a long period of time to develop and lots of rig time losses for waiting on the OPC to set. This project introduced geopolymer cement as an alternative for Class G cement. It aims to compare the elastic modulus of both Class G cement and geopolymer cement. Cement samples are prepared which consist of basic case Class G cement and a mixture of fly ash and micro silica with ratio of 80:20 respectively as the geopolymer cement. All cement samples are cured in two conditions, where the first curing condition is temperature of 80 °C and pressure of 1500 psia and the second curing condition is temperature of 120 °C and pressure of 3000 psia. Cement samples are cured for 7 hours and 24 hours in both curing conditions. Results obtained based on the test conducted gave out the value for the cements' Poisson's ratio ranging from 0.1886 to 0.2987; shear modulus vary from the lowest, 3.95 GPa to the highest, 5.49 GPa; and Young's modulus ranging from 7.54 GPa to 14.39 GPa. The Geopolymer Cement has a higher elastic modulus compared to the Class G Cement for both curing condition. The values of elasticity coefficient also increase in line with the increment of curing time and kept stable for longer period of time.

## ACKNOWLEDGEMENT

First and foremost, all praise to the Almighty Allah S.W.T, for giving me an opportunity to complete my final year project with the topic: Comparison of Elastic Modulus between Class G Cement and Geopolymer Cement under HPHT Condition.

This project might not be able to be completed without many helps received from respected lecturers, laboratory technicians and family and friends. Here I would like to express my gratitude and appreciation to my supervisor, Dr. Syahrir Ridha, for his endless support and encouragement, also for his priceless guidance and advice throughout this final year project.

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## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| *API* | = | American Petroleum Institute |
| $CO_2$ | = | Carbon Dioxide |
| $H_2O$ | = | Water |
| *HPHT* | = | High Pressure High Temperature |
| $Na_2O$ | = | Sodium Oxide |
| $OH^-$ | = | Hydroxide Ion |
| *SiO2* | = | Silicate Dioxide |
| *UCS* | = | Uni-axial Compressive Strength |

# CHAPTER 1

# INTRODUCTION

## 1.1 BACKGROUND OF STUDY

In the Merriam-Webster's dictionary [9], cement is defined as a binding element or agency and as a substance to make objects adhere to each other. In the oil and gas industry, cement is defined as the material used to permanently seal annular spaces between borehole wall and casing wall. Cement is widely used for the cementing jobs in both gas wells and oil wells and it is one of the most important parts in the well completion. Preparing and pumping of cement into place in a wellbore is referred as the process of cementing. Cement slurry is circulated through the inside of the casing and out into the annulus through the casing shoe at the bottom of the casing string.

Cement provides support and protection to the casing, prevent the movement of fluid through the annular space outside the casing; stop the movement of fluid into vugular or fractured formations and it also use to close an abandoned well. API oil well cement, informally known as Portland cement is the type of cement used in the oil and gas wells cementing. The Portland cement exhibits far less strength than concrete used for construction due to the requirement for it to be pumped in relatively narrow annulus over long distances. In API Recommended Practice 10B, 2005, the Portland cement is divided into 9 classes, which are class A, B, C, D, E, F, G, H and J.

Table 1-1: Class of Portland cement [8]

| Class | Description |
|---|---|
| A | Intended for use from surface to 6000 ft (1830 m) depth, when special properties are not required |
| B | Intended for use from surface to 6000 ft (1830 m) depth, when conditions require moderate to high sulphate-resistance |
| C | Intended for use from surface to 6000 ft (1830 m) depth, when conditions require high early strength |
| D | Intended for use from 6000 ft to 10000 ft (1830 m to 3050 m) depth, under conditions of moderately high temperature and pressures |
| E | Intended for use from 10000 ft to 14000 ft (3050 m to 4270 m) depth, under conditions of high temperatures and pressures |
| F | Intended for use from 10000 ft to 16000 ft (3050 m to 4880 m) depth, under conditions of extremely high temperatures and pressures |

| | |
|---|---|
| G | Intended for use as basic well cement from surface to 8000 ft (2440 m) depth as manufactured or can be used with accelerators and retarders to cover a wide range of well depths and temperatures |
| H | A basic cement for use from surface to 8000 ft (2440 m) depth as manufactured. Can be used with accelerators and retarders to cover a wider range of well depths and temperatures |
| J | For use as manufactured from 12000 ft to 16000 ft (3600 m to 4880 m) depth under conditions of extremely high temperature and pressure. It can be used with accelerators and retarders to cover a range of well depths and temperatures |

This study is focusing more on comparing the elastic modulus effect of both the Portland cement, specifically Class G cement, with the geopolymer cement under the high temperature and pressures condition. Class G cement has known to be mixed with water and produce hydration and in time will reduce the strength of the cement in the wellbore thus creating problems to the well integrity. Therefore, the integrity of the wells should be made using a material which is durable, anticorrosive, chemically inert, adaptive to pressure variations, and less permeable, in order to maintain well integrity.

## 1.2 PROBLEM STATEMENT

Portland cement is used extensively in well cementing operations because of the low cost factor and the widespread availability of clay, shale and limestone. However, the strength of Portland cement has always been of interest since it develops over a long period of time and lots of rig time losses for waiting on cement to set.

Compression, traction or micro annulus is an example of cement failure. The main factor that contributes to the cement failure problem is due to the extreme temperature and pressure expose to the well. The major wellbore temperature increment resulted in the formation bounding the cement sheath has relatively high Young's modulus [10]. Confinement occurs when it is not possible for the cement to expand laterally or away from the well. Rupture compressive strength can be defined as the maximum quantity of compressive stress the cement can endure under confinement.

The geopolymer cement has been widely used in the civil engineering area. Geopolymer cement is a class of material that combine an aluminium silicate with a chemical activator such as water glass. A variety of naturally occurring clays included in aluminium silicates as well as industrial by products such as fly ash from coal combustion and blast furnace slag [13]. Study about geopolymer cement concrete has been on the move for several decades and it has been known that the geopolymer cement need to be heated at low temperatures to cure and the energy required to produce geopolymer cement is significantly less than Portland cement required for mixing and resulted up to 90% reduction of carbon emissions [3].

However, geopolymer cement has not yet being used in the oil and gas sector and this study on comparing the elastic modulus of both Class G cement and geopolymer cement under HPHT condition will help on the new development of cementing procedures in the oil and gas industry.

## 1.3 OBJECTIVES AND SCOPE OF STUDY

This project is focusing on comparing the mechanical behaviours of Class G cement and geopolymer cement, specifically the effect of the elastic modulus of both cements under the high pressure and high temperature conditions. Therefore, this project aims to:

1. To determine the effect of high pressure and high temperature on the elastic modulus between Class G cement and geopolymer cement
2. To compare the elastic modulus and strength of Class G cement with the geopolymer cement under reservoir conditions

The scope of study involves:

1. Examine the elastic modulus properties of the Class G and geopolymer cement at different curing temperature, high temperatures and high pressures condition; the Poisson's ratio, shear modulus and Young's modulus

Therefore, based on the objectives of my study on the comparison of elastic modulus between Class G cement and geopolymer cement, it is relevant due to its contribution to the industry as it helps in finding ways of improving the well integrity issue in the oil and gas industry. This project is feasible enough as the required equipments and materials needed to run the laboratory tests are all available on campus which should be helpful in finishing the project on time.

# CHAPTER 2

# LITERATURE REVIEW & THEORY

## 2.1 GEOPOLYMER CEMENT

Geopolymer cement have been studied and used for about three to four decades in the civil engineering areas for buildings [5]. However in oil and gas industry, Portland cement is still being used in the cementing process. Studies have shown that the Portland cement has some limitations when it comes to high pressure and high temperature condition affecting its mechanical behaviours due to its ceramic characteristics [1, 2].

Geopolymer is a science and technology that allows us to get geopolymer cement and geopolymer binder. Resulting from the geopolymerization process, geopolymers, the alumino-silicate materials and can be produced in an alkaline or acidic medium. Geopolymers are characterized by a number of physical characteristics such as high surface smoothness, hard surface, thermal stability, long-term durability and high adhesive property to natural stone and steel [11, 12].

Geopolymerization is a general term used to describe the chemical processes which involved in reacting alumina silicates with aqueous alkaline solutions to produce geopolymer cement. Figure 2-1 shows the simplified reaction mechanism of geopolymerization process. Davidovits [4] mentioned in his paper ‘Geopolymer Cement, a review’ that the geopolymerization chemistry requires appropriate notions and terminologies that are clearly different from the Portland cement’s chemistry used by the experts [4].

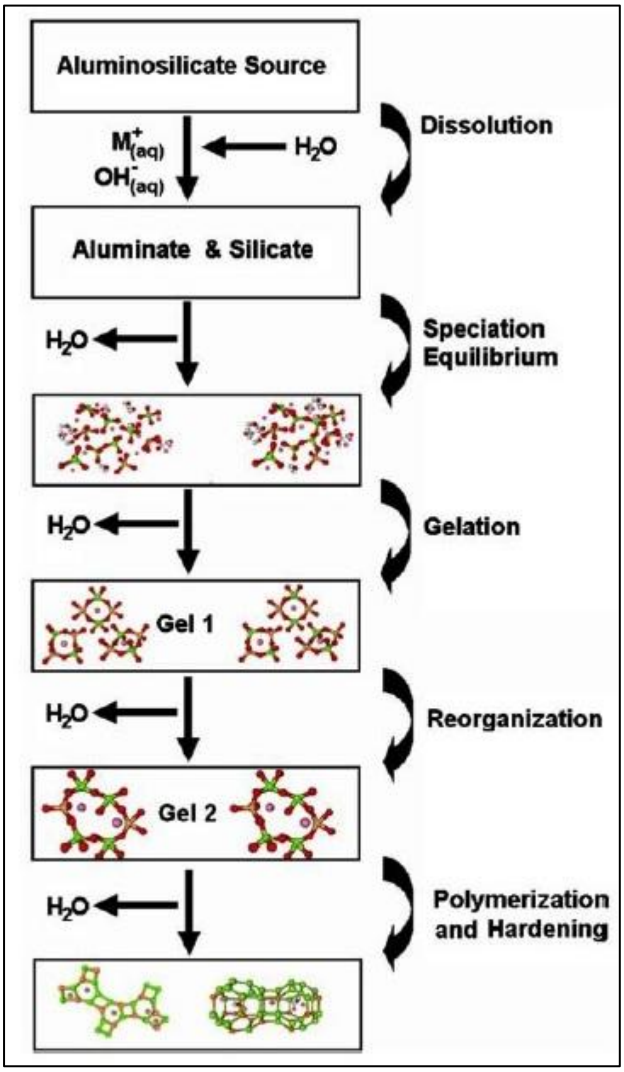


Figure 2-1: Conceptual model for geopolymerization [16]

Davidovits in 2013 [4] mentioned in his technical paper entitled 'Geopolymer, a Review' mentioned geopolymer cement is an alternative to conventional Portland cement for use in construction, transportation infrastructure and in offshore applications. Geopolymer cement is categorized into four main categories:

1. Slag-based geopolymer cement
2. Rock-based geopolymer cement
3. Fly-ash-based geopolymer cement
   i. Alkali-activated fly-ash geopolymer
   ii. Slag/fly-ash-based geopolymer cement
4. Ferro-sialate-based geopolymer cement

## 2.2 ELASTIC MODULUS

Elastic modulus, the Young's modulus, sometimes referred as effective stiffness is part of the properties of cement. Elastic modulus is a material property that describes the material's stiffness and thus it is one of the most crucial properties of solid materials, as for this study is the Class G cement and geopolymer cement [15]. During the occurrence of mechanical deformation, it gives energy to the material unintentionally. The materials somehow store the energy and it is summarized in the stress-strain curves as shown in Figure 2-2 below. Strain is the contraction or elongation of materials per unit length while stress is defined as force per unit area [15].

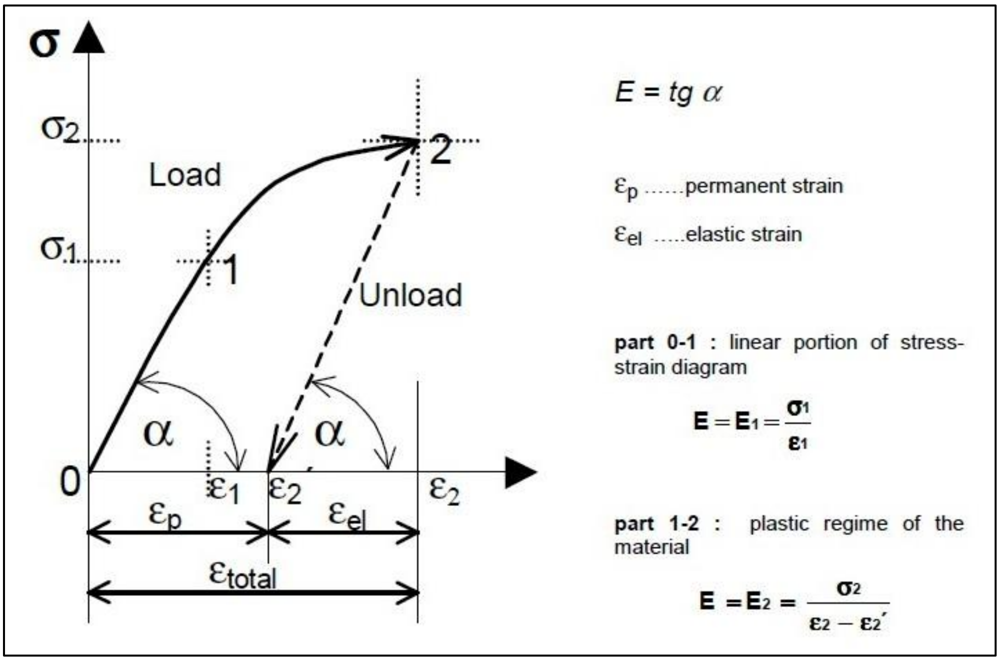


Figure 2-2: Graphical relationship between total strain, permanent strain and elastic strain [15]

The variation of Young's modulus (E) of Class G and geopolymer cement with the different curing temperatures shows that geopolymer cement possesses the highest E values at elevated temperature compared to the Class G cement which has the highest E values only at lower curing temperatures [1]. It is as predicted as the higher E value is affected by the higher UCS value at the elevated temperatures.

From the experiment done by Nasvi et al., [1] the stress-strain behaviour of both geopolymer and Class G cement is unstable at 80°C when the stress and strain reduces drastically. From the graph of the stress-strain curve, the final geopolymer matrix is highly brittle and the peak stress will be higher as the curing temperature is increased [1]. The failure stress and failure strain above 30°C of curing temperature for geopolymer are generally higher than Class G cement [1] thus the geopolymer cement will be a better alternative compared to Class G cement at elevated temperature.

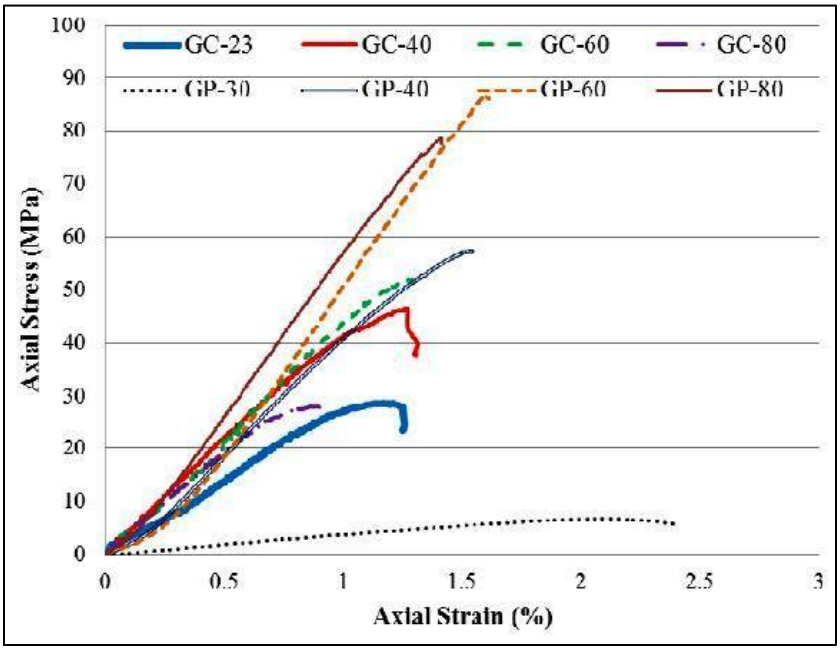


Figure 2-3: Overall stress-strain curve [1]

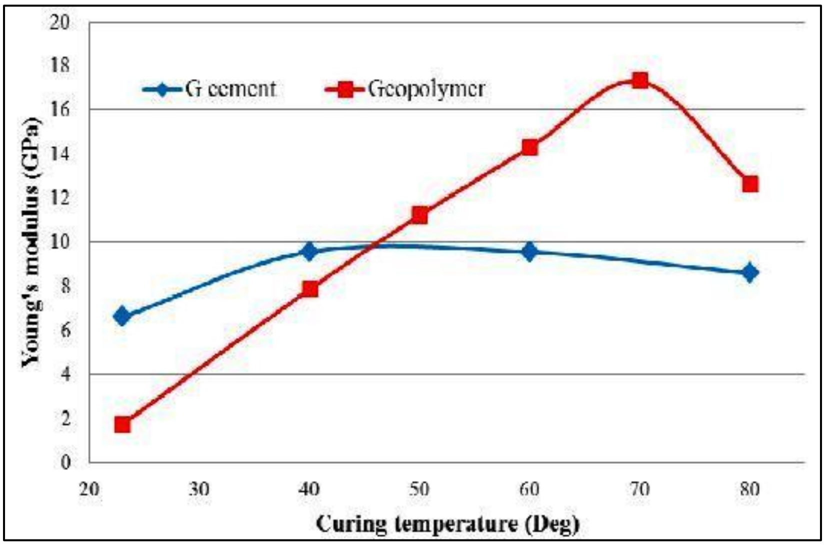


Figure 2-4: Young’s modulus vs. curing temperature [1]

# CHAPTER 3

# METHODOLOGY/PROJECT WORK

## 3.1 RESEARCH METHODOLOGY

This study has been divided into three main parts, which are preparation of cement samples, laboratory tests of cement samples and results interpretation and analysis of data.

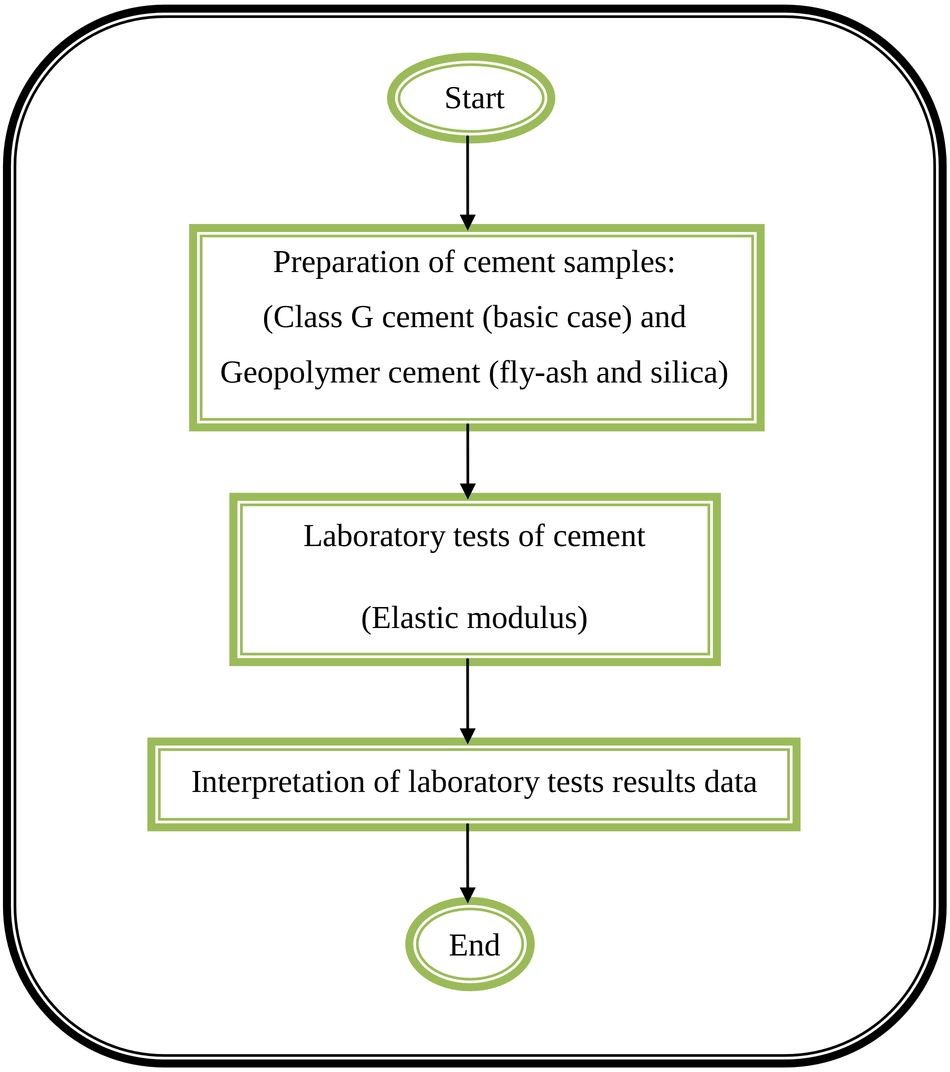


Figure 3-1: Research methodology

Details explanation of the three main parts of the research methodology can be found under the sub topic project background.

## 3.2 PROJECT ACTIVITIES

### 3.2.1 Preparation of Cement

Preparation of cement slurries are based on API RP 10-A Section 7. Two types of cement samples are prepared for Class G cement and mixture of fly ash and micro silica for geopolymer cement (Table 3-1). The mass for each material in every mix is presented in Table 3-2. No additive is added in all samples.

Table 3-1: Composition of each samples based on percentage

| Samples | Class G Cement | Fly Ash Class F | Micro Silica |
|---|---|---|---|
| Class G Cement | 100% | 0% | 0% |
| Geopolymer Cement | 0% | 80% | 20% |

Table 3-2: Mass of class G cement, fly ash, micro silica, alkaline solution in grams

| Samples | Class G Cement | Fly Ash Class F | Micro Silica | Sodium Silicate | Sodium Hydroxide | Water |
|---|---|---|---|---|---|---|
| Class G Cement | 200.00 | - | - | - | - | 88.00 |
| Geopolymer Cement | - | 160.00 | 40.00 | 57.14 | 22.86 | 41.45 |

**Water Cement Ratio and Water Geopolymer Solid Ratio**

WCR and WGS ratio = 0.44 according to water cement ratio for Class G cement. The mass method is used for WGS ratio but due to lesser specific gravity of fly ash and micro silica, the volume of fly ash and micro silica are larger compared to Class G cement. Alkaline solution to fly ash ratio is 0.5. To obtain the same ratio for WGS with WCR, 30.0g of water is added in the geopolymer cement samples.

**Alkaline Solution**

Sodium silicate and sodium hydroxide are used as alkaline activators and the ratio of sodium silicate to sodium hydroxide is 2.5 which are believed to give an effective reaction between these two solutions. Sodium silicate solution of Grade A53 which contains $Na_2O$ = 14.7%, $SiO_2$ = 29.4% and water = 55. 9% is used in this experiment. 361grams of sodium hydroxide in pellet form with 99% purity is dissolved in 1000 grams of distilled water to produce 12M sodium hydroxide solution. Both alkaline solutions are made constant for all samples.

**Mixing Procedures**

i. All materials are weighted according to Table 3-2.

ii. The mixer is turned on. Mixing container is filled with wet materials and placed on the mixer motor.

iii. Mix 1 button with rotation of 4000 r/min +-200 r/min is pressed for 15 seconds. In this moment, all the dry materials are poured into the mixing container.

iv. Mix 2 button is pushed after the 15 seconds. The rate of rotation is increase from 4000 r/min +-200 r/min to 12000 r/min +-500 r/min for 35 seconds.

v. Cement slurry is ready.

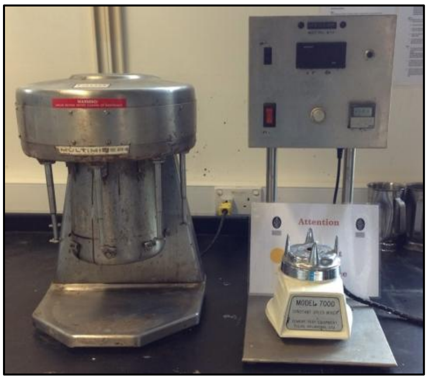

Figure 3-2: Mixing Equipment

Figure 3-3: Class G Cement

Figure 3-4: Fly Ash

Figure 3-5: Micro Silica

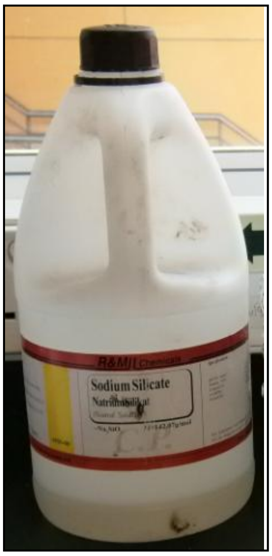


Figure 3-6: Sodium Silicate

Figure 3-7: Sodium Hydroxide pellet

**Curing Condition**

The curing conditions representing normal well condition and HPHT well respectively were as follows:

Table 3-3: Curing Condition

| Samples \ Curing Condition | Temperature: 80°C<br>Pressure: 1500 psia | | Temperature: 120°C<br>Pressure: 3000 psia | |
|---|---|---|---|---|
| Class G Cement | 7 hours | 24 hours | 7 hours | 24 hours |
| Geopolymer Cement | 7 hours | 24 hours | 7 hours | 24 hours |

**Preparation of Cured Cement Samples**

i. Curing moulds are greased on the inner surface before assemble.
ii. Prepared cement slurry is poured into the assembled moulds. The cement is poured in three layers. In every layer, cement slurry is paddled using the stirring rod to destroy the bubbles in the cement slurry. Then, all the moulds are clamped using the threaded rod.
iii. Curing chamber is switched on.
iv. The moulds are lowered into the pressure vessel. The cylinder plug thread is lubricated using grease. The cylinder plug thread is threaded

into the cylinder. Then, the set screws on top of the cylinder thread are tightened using spanner (3 different torques: 15, 30 and 40 ft-lbs).

v. A thermocouple is inserted through the hole on top of cylinder plug and is tied loosely.

vi. The air supply is opened and the flow of oil into pressure vessel is monitored through oil cylinder. The thermocouple is tightened with a spanner when the oil expelled from the thermocouple.

vii. The pump is on and off until the pressure reached the desired pressure needed for the project.

viii. The temperature is set in the program list according to the desired temperature needed for the project.

ix. The heater is on and followed by the timer.

x. Then, auto and run button is pressed to start the operation. The durations of the operation are varied in every experiment which is 7 hours and 24 hours.

Figure 3-8: HPHT Curing Chamber

Figure 3-9: Greased curing moulds

Figure 3-10: Cement slurry filled in mould

Figure 3-11: Curing moulds stack up

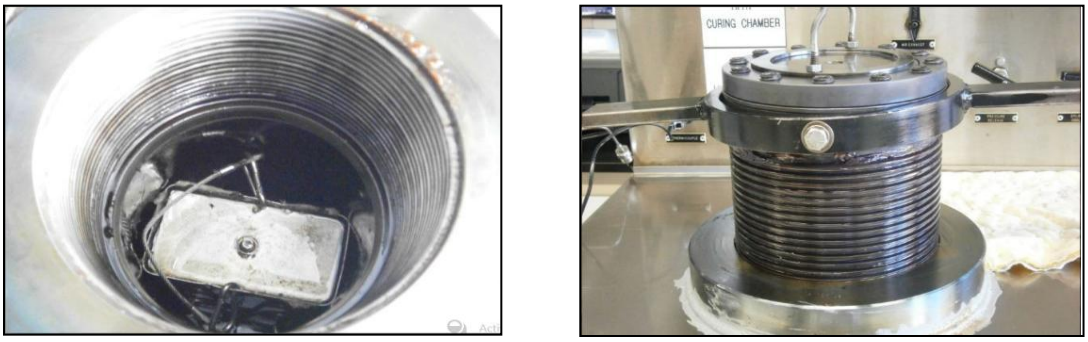


Figure 3-12: Moulds inserted into pressure vessel and cylinder plug threaded into it

### Core Cutting and Trimming of Cement Samples

The cured cement samples need to be cored using core cutting saw to be in cylinder shape. Before coring, the cured cement sample is put into the cement holder which made using class G cement as it act as a holder during the coring process.

The procedures for coring and trimming of cement samples are as follows:

i. The cement sample is placed in the core cutting saw holder
ii. The equipment is switched on
iii. The water supply is opened which act as lubricant during the coring process

iv. The rotating cutter is pulled down slowly to cut the cement sample and get a cylinder shape for cured cement with diameter of core sample set to 1 inch
v. The core cement sample is then trimmed using the core trimming saw machine
vi. The core cement sample is measured to its desired length (1.5 inch)
vii. Core cement sample is placed in the core trimming holder
viii. The equipment is switched on and water supply act as lubricant during trimming process
ix. The cement holder is pushed slowly through the saw until it finished

Figure 3-13: The cured cement sample is put into the cement holder

Figure 3-14: The cored and trimmed cement samples

### 3.2.2 Laboratory Tests of Cement Samples

**Elastic Modulus**

Elastic modulus is defined as a material property that describes the material’s stiffness and thus it is one of the most crucial properties of solid materials, as for this study is the Class G cement and geopolymer cement. Below are the equations related to the elastic modulus:

$$\frac{9}{E} = \frac{1}{K} + \frac{3}{G} \qquad \nu = \frac{(3K - 2G)}{2(3K + G)}$$

$$K = \frac{E}{3(1 - 2\nu)} \qquad G = \frac{E}{2(1 + \nu)}$$

Figure 3-15: The Young’s modulus, E, the Poisson’s ratio, v, the bulk modulus, K and the shear modulus, G

The elastic modulus can be tested using the equipment available in the laboratory. The OYO Sonic Viewer is used to measure the elastic modulus of the cement samples.

The OYO Sonic Viewer is an instrument for the ultrasonic wave velocity measurement of rock samples. It is possible to read the P and S wave propagation with high accuracy. It can calculate dynamic Poisson's ratio, dynamic elastic modulus and dynamic shear modulus by built in software.

Figure 3-16: The OYO Sonic Viewer

This equipment straight forward provided the required result for the project's objectives, which are the Poisson's ratio, v, Shear Modulus, G and the Young's modulus, E.

For each curing condition with different curing hour, 7 hours and 24 hours, both Class G cement and geopolymer cement have 4 samples respectively thus helping in acquiring the average result for both type of cement samples, especially for the Young's modulus which is the main aim of this project.

## 3.3 KEY MILESTONES

The key milestones for Final Year Project (FYP I and FYP II) are as follows:

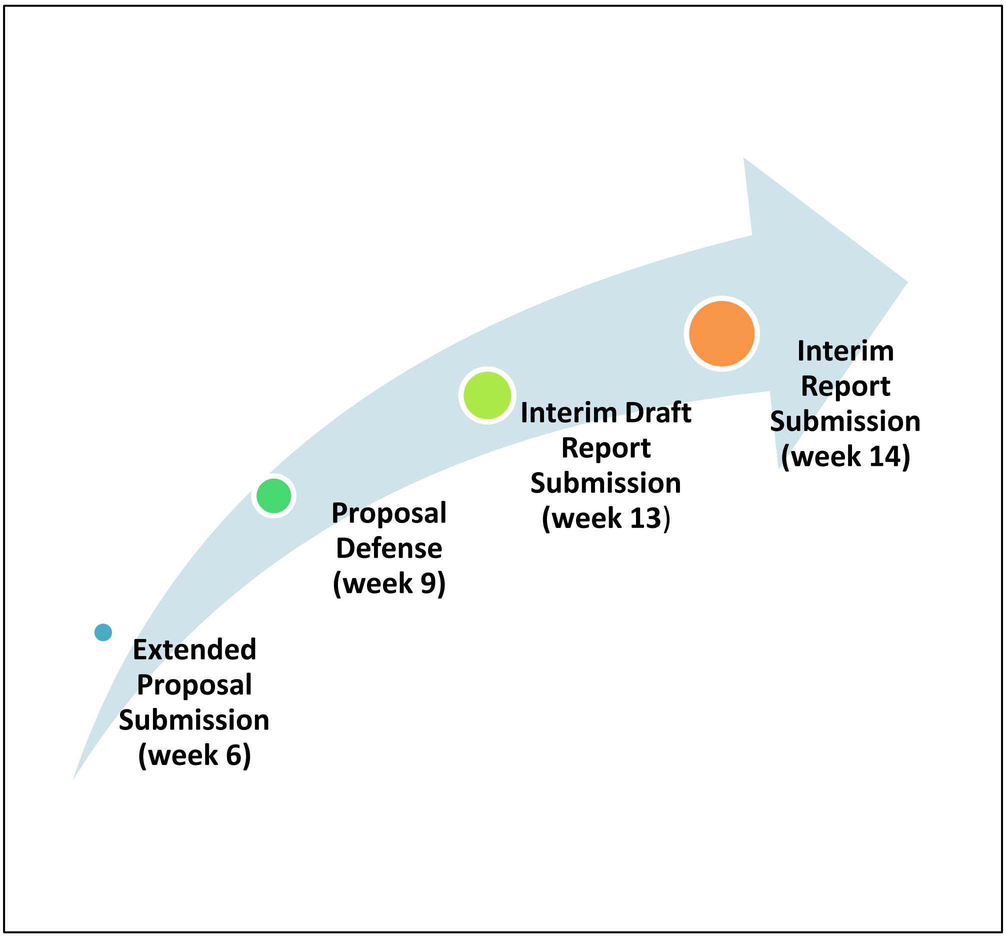


Figure 3-17: Key milestone for FYP I

FYP I covered the literature and studies about the project topic. FYP I is focusing to find out more information about any studies related to the topic to help in continuation of the project for the next phase. The key milestones for FYP I is shown clearly in Figure 3-17 above. FYP I was helpful in term of finding relevant literature for the project to be conducted in the FYP II semester.

The key milestone for FYP II is shown in Figure 3-18 below:

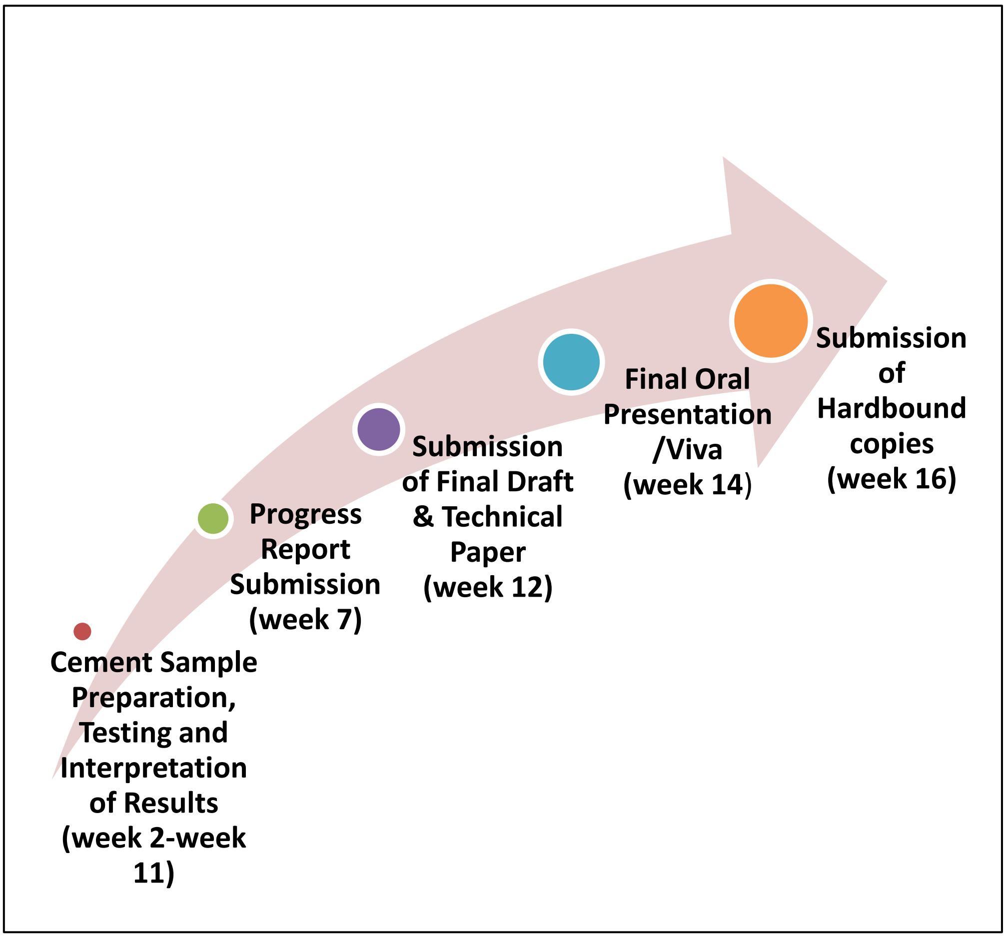


Figure 3-18: Key milestone for FYP II

## 3.4 GANTT CHART

The Gantt chart shown below is the planned project activities throughout the FYP I and FYP II.

Table 3-4: Gantt Chart for FYP I

| **Activity** | **FYP I Gantt Chart** | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Semester 7 (September 2014)** | | | | | | | | | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| Topic Overview & Title Selection | | | | | | | | | | | | | | |
| Journals findings / Literature Review | | | | | | | | | | | | | | |
| Submission of Extended Proposal | | | | | | | | | | | | | | |
| Proposal Defence | | | | | | | | | | | | | | |
| Apparatus / Tools Confirmation & Booking/Order | | | | | | | | | | | | | | |
| Data Gathering / Planning of Laboratory Work Schedule | | | | | | | | | | | | | | |
| Submission of Interim Draft Report | | | | | | | | | | | | | | |
| Submission of Interim Report | | | | | | | | | | | | | | |

Table 3-5: Gantt chart for FYP II

| Activity | FYP II Gantt Chart | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Semester 8 (January 2015) | | | | | | | | | | | | | |
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** |
| Preparation of Cement Samples (Class G Cement & Geopolymer Cement - Fly Ash+Micro Silica) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| Laboratory Tests of Cement Samples (Class G & Geopolymer Cement - Fly Ash + Silica) | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| Interpretation of Laboratory Tests Results Data & Conclusion | | | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| Submission of Progress Report | | | | | | | ■ | | | | | | | |
| Poster Presentation (Pre-SEDEX) | | | | | | | | | ■ | | | | | |
| Submission of Final Draft Report, Dissertation and Technical Paper | | | | | | | | | | | | ■ | | |
| Viva | | | | | | | | | | | | | | ■ |

# CHAPTER 4

# RESULT AND DISCUSSION

## 4.1 FIRST CURING CONDITION

The first curing condition is temperature of 80 °C and pressure of 1500 psia. The result shown below is for both curing time of 7 hours and 24 hours for Class G cement and geopolymer cement.

The result for curing time of 7 hours is as follows:

Table 4-1: Result obtained for curing condition 1 with curing time of 7 hours

| | Cement Sample | No. | Poisson's Ratio | Shear Modulus (kg/m.s^2) | Young's Modulus (Pa) |
|---|---|---|---|---|---|
| 7 HOURS | CLASS G | 1 | 0.1930 | 3.2417E+09 | 7.7350E+09 |
| | | 2 | 0.1970 | 3.1489E+09 | 7.5383E+09 |
| | | 3 | 0.1939 | 3.2166E+09 | 7.6807E+09 |
| | | 4 | 0.1964 | 3.2329E+09 | 7.7360E+09 |
| | GEOPOLYMER | 1 | 0.2713 | 4.6987E+09 | 1.1947E+10 |
| | | 2 | 0.2689 | 4.7843E+09 | 1.2142E+10 |
| | | 3 | 0.2730 | 4.6168E+09 | 1.1754E+10 |
| | | 4 | 0.2737 | 4.6475E+09 | 1.1839E+10 |

From the data obtained as shown in Table 4-1 above, the value of Poisson's ratio is in accordance with the literature where theoretical value of Poisson's ratio for cement is ranging from 0.15 to 0.2 [18] for Class G cement while for geopolymer cement indicates a higher value of Poisson's ratio compared to Class G cement. The higher the value of Poisson's ratio, the tendency for the material to return to its initial state is higher.

The most important aspect in this study is the Young's modulus of the cement sample. Provided that after the cement samples have been cured under the condition of 80 °C and 1500 psia for 7 hours, the Young's modulus values obtained for each sample is in line with the theoretical figures. The average value of the Young's modulus for both Class G and geopolymer cement shows that the accuracy of the data obtained.

Table 4-2: Average value of Young's modulus of cement samples

| | | | | |
|---|---|---|---|---|
| 7 HOURS | AVERAGE | CLASS G | 7.6725E+09 | **7.67 GPa** |
| | | GEOPOLYMER | 1.1920E+10 | **11.92 GPa** |

The average value of Young's modulus obtained for the cement samples cured under the first condition for 7 hours is shown in the Table 4-2 above. For Class G cement, the average value is 7.67 GPa and for geopolymer cement is 11.92 GPa. This clearly shows the geopolymer cement have higher elastic modulus compared to Class G cement.

The Figure 4-1 below should help in showing the values obtained for Young's modulus of the cement samples are consistent for both type of cement. The line graph also indicates clearly the geopolymer cement has higher value of elastic modulus compared to the Class G cement.

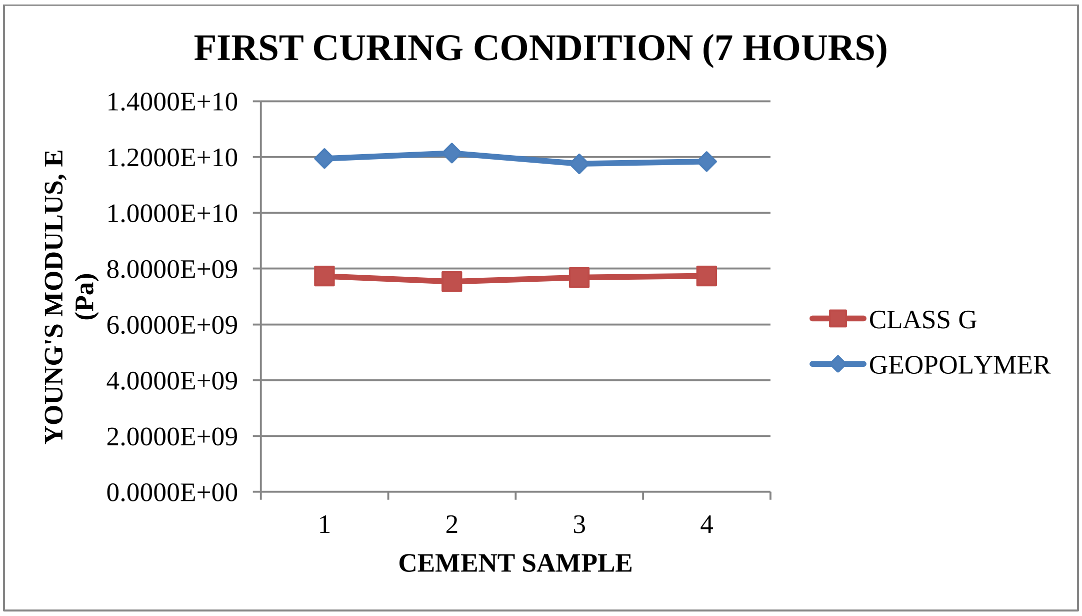


Figure 4-1: Line graph for first curing condition run for 7 hours

The other cement samples were then cured with the same condition, temperature of 80 °C and pressure of 1500 psia, but with different curing time where this time it is left in the curing chamber for 24 hours. The result for curing time of 24 hours is shown below:

Table 4-3: Result obtained for curing condition 1 with curing time of 24 hours

| | Cement Sample | No. | Poisson's Ratio | Shear Modulus (kg/m.s^2) | Young's Modulus (kg/m.s^2) |
|---|---|---|---|---|---|
| **24 HOURS** | **CLASS G** | **1** | 0.1916 | 3.7602E+09 | 8.9615E+09 |
| | | **2** | 0.1919 | 3.7184E+09 | 8.8643E+09 |
| | | **3** | 0.1900 | 3.8063E+09 | 9.0590E+09 |
| | | **4** | 0.1994 | 3.6319E+09 | 8.7123E+09 |
| | **GEOPOLYMER** | **1** | 0.2918 | 5.0122E+09 | 1.2949E+10 |
| | | **2** | 0.2906 | 5.1064E+09 | 1.3180E+10 |
| | | **3** | 0.2987 | 4.8146E+09 | 1.2505E+10 |
| | | **4** | 0.2953 | 4.9790E+09 | 1.2899E+10 |

From Table 4-3 above, the cement samples cured for 24 hours gave a significant increase for the Young’s modulus value but show only slight changes for the Poisson’s ratio. For Class G cement, the highest Poisson’s ratio value obtained is 0.1994 while the lowest value is 0.1900. This indicates the Poisson’s ratio of the 4 Class G cement samples ranging from 0.1900 to 0.1994. The Young’s modulus for Class G cement samples ranging from 8.71 GPa to 9.06 GPa.

For geopolymer cement samples, the Poisson’s ratio does not change much from geopolymer cement samples undergo the 7 hours curing time. The values range from 0.2906 to 0.2987. The Young’s modulus for this geopolymer cement cured for 24 hours is higher than the geopolymer cement cured for 7 hours. The highest value for Young’s modulus is 13.18 GPa while the lowest value is 12.51 GPa.

Table 4-4: Young’s modulus average value for samples cured 24 hours

| | | | | |
|---|---|---|---|---|
| 24 HOURS | AVERAGE | CLASS G | 8.8993E+09 | **8.90 GPa** |
| | | GEOPOLYMER | 1.2883E+10 | **12.88 GPa** |

The average value is as shown in the Table 4-4 above. For Class G samples, the average Young’s modulus value is 8.90 GPa and for geopolymer cement samples, the average value for its Young’s modulus is 12.88 GPa. Both types of cements cured for 24 hours have a higher elastic modulus compared to the cement samples cured for 7 hours. This finding indicates the longer the curing time, the higher the value of elastic modulus would be.

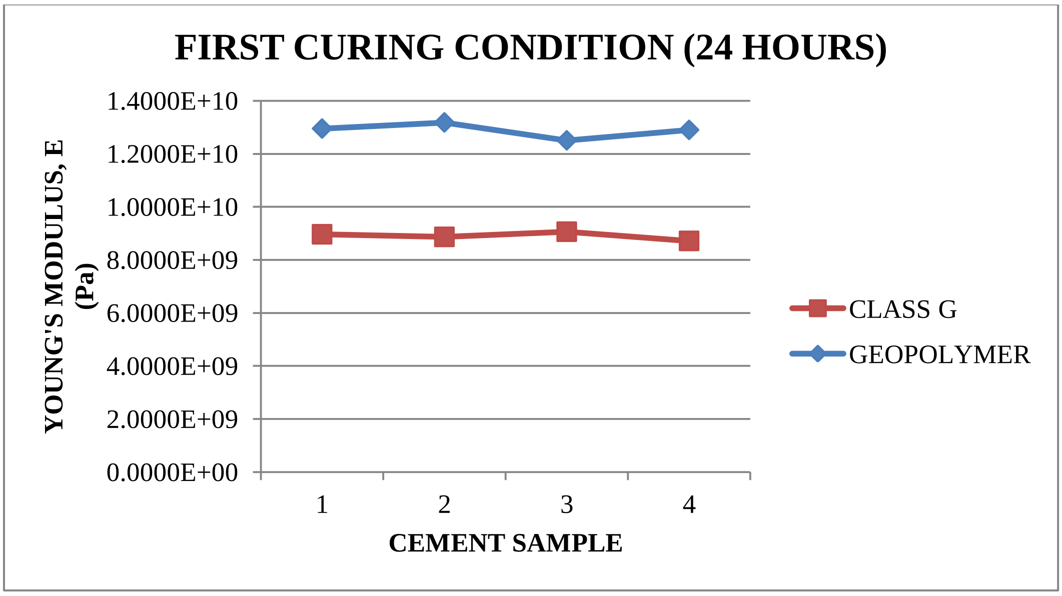


Figure 4-2: Line graph for first curing condition run for 24 hours

In Figure 4-2 above, the line graph clearly shows the geopolymer samples are having a higher value of Young's modulus compared to Class G cement samples. This finding is in accordance with the results from other studies which have been stated at the literature review section. Figure 4-3 below shows the overall results for all cements samples and its Young's modulus value.

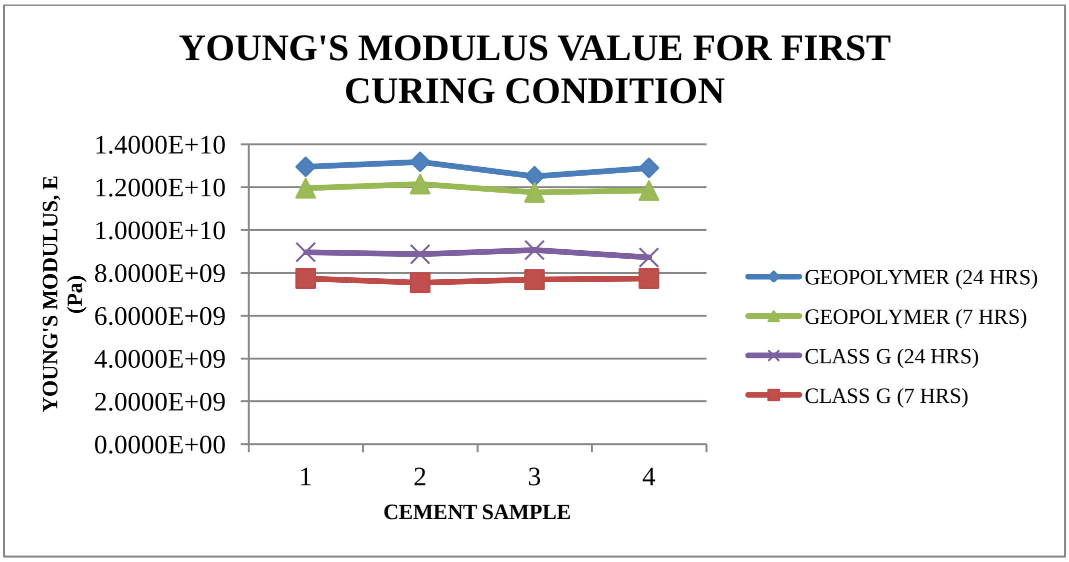


Figure 4-3: Young's modulus value for all samples in curing condition 1

As to summarize the results obtained for the first curing condition, it is clearly shows the geopolymer cements have higher elastic modulus compared to Class G cements. The line graph also clearly figured out that the longer the curing time, the higher the value of the elastic modulus.

## 4.2 SECOND CURING CONDITION

The second curing condition is set higher than the first condition. The temperature is set to 120 °C while the pressure is set to 3000 psia. This parameter is set to represent a very high temperature and pressure as in reservoir condition. For second condition, the same procedure as first condition is done which had to undergo two different curing time, 7 hours and 24 hours.

The results for the curing time of 7 hours are shown in Table 4-5 below:

Table 4-5: Results obtained for curing condition 2 with curing time of 7 hours

| | Cement Sample | No. | Poisson's Ratio | Shear Modulus (kg/m.s^2) | Young's Modulus (kg/m.s^2) |
|---|---|---|---|---|---|
| 7 HOURS | CLASS G | 1 | 0.1898 | 3.7928E+09 | 9.0258E+09 |
| | | 2 | 0.1901 | 3.7290E+09 | 8.8756E+09 |
| | | 3 | 0.1886 | 3.8439E+09 | 9.1374E+09 |
| | | 4 | 0.1902 | 3.8056E+09 | 9.0586E+09 |
| | GEOPOLYMER | 1 | 0.2468 | 5.2978E+09 | 1.3211E+10 |
| | | 2 | 0.2480 | 5.2069E+09 | 1.2997E+10 |
| | | 3 | 0.2454 | 5.3466E+09 | 1.3318E+10 |
| | | 4 | 0.2486 | 5.2066E+09 | 1.3002E+10 |

Based on Table 4-5, for Class G cement, the highest value of Poisson's ratio is 0.1902 while the lowest value is 0.1886. The value is slightly lower than the value obtained for the cement undergo first curing condition. Poisson's ratio is believed to be affected by the high temperature and pressure thus lowering the Poisson's ratio of the cement samples.

For the Young's modulus, the value ranging from 8.88 GPa to 9.14 GPa for the Class G cement samples. The value at this condition is higher than the Young's modulus from the first curing condition. This proves the literature which the elastic modulus of cement increases at elevated temperature thus having a higher strength of the cement.

The geopolymer cement samples were showing the same pattern as shown by the Class G cement where the Poisson's ratio is less than the geopolymer samples cured at first condition and its Young's modulus exhibits a higher value compared to the first curing condition. The Poisson's ratio ranging from 0.2454 to 0.2486 and the Young's modulus is from 13.00 GPa to 13.32 GPa.

The average value of the Young's modulus for both Class G and geopolymer samples cured for 7 hours is shown below:

Table 4-6: Young's modulus average value for samples cured 7 hours

| | | | | |
|---|---|---|---|---|
| 7 HOURS | AVERAGE | CLASS G | 9.0243E+09 | **9.02 GPa** |
| | | GEOPOLYMER | 1.3132E+10 | **13.13 GPa** |

The average value of Young's modulus for cement samples is calculated. For Class G cement, the average value is 9.02 GPa and for geopolymer cement, the average value is 13.13 GPa. Comparing the average value from second curing condition with the first curing condition with same curing time, it indicates the value from second curing condition is higher than the value from the first condition.

It comes to a point in agreeing on the higher temperature and pressure will result in higher value of Young's modulus of the cement. Theoretically and proven where geopolymer cement is having a higher value compared to Class G cement which also portrayed by the first curing condition with same curing time of 7 hours. Figure 4-4 below shows the Young's modulus consistently and approximately within the same range.

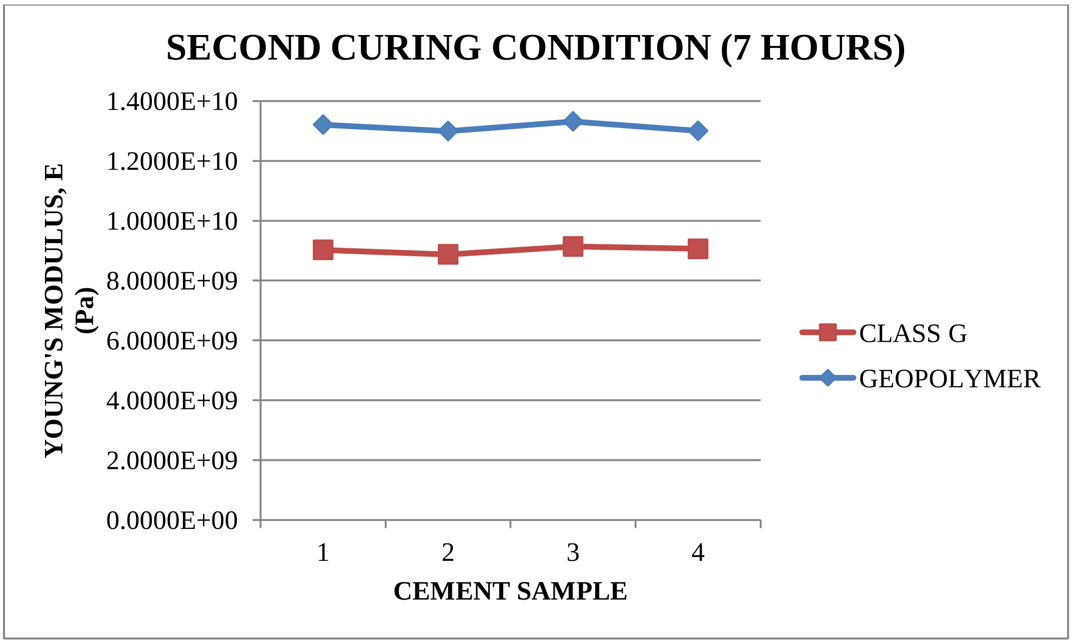


Figure 4-4: Line graph for second curing condition run for 7 hours

The other samples were cured with the same condition, temperature of 120 °C and pressure of 3000 psia, but with different curing time, which was 24 hours. The results are as follows:

Table 4-7: Results obtained for curing condition 2 with curing time of 24 hours

| | Cement Sample | No. | Poisson's Ratio | Shear Modulus (kg/m.s^2) | Young's Modulus (kg/m.s^2) |
|---|---|---|---|---|---|
| 24 HOURS | CLASS G | 1 | 0.1968 | 4.1480E+09 | 9.9288E+09 |
| | | 2 | 0.1987 | 4.0572E+09 | 9.7271E+09 |
| | | 3 | 0.1968 | 4.1938E+09 | 1.0038E+10 |
| | | 4 | 0.1956 | 4.1692E+09 | 9.9698E+09 |
| | GEOPOLYMER | 1 | 0.3049 | 5.4239E+09 | 1.4155E+10 |
| | | 2 | 0.3060 | 5.3225E+09 | 1.3902E+10 |
| | | 3 | 0.3033 | 5.4921E+09 | 1.4316E+10 |
| | | 4 | 0.3030 | 5.5233E+09 | 1.4394E+10 |

From Table 4-7 above, the Poisson’s ratio for Class G cement ranging from 0.1956 to 0.1987. Comparing the value obtained with the value from the curing condition 1, the Poisson’s ratio for samples cured in condition 2 is higher. This does not tally with the theoretical or expected findings as the longer the curing time, the Poisson's ratio value should be decreasing with time. However, the differences are not much as the values were still within the significant range of Poisson's ratio of the Class G cement.

Furthermore, the Young's modulus indicates the expected outcome where the value is higher compared to the value from the first curing condition. This is believed due to the effect of high temperature and high pressure and the longer curing time compared to the first curing condition. The Young's modulus for Class G cement cured for 24 hours in the second curing condition ranging from 9.73 GPa to 10.04 GPa.

The geopolymer cement samples also showed the same pattern of results as analyzed for Class G cement. The Poisson's ratio is higher than the Poisson's ratio from first curing condition. The Poisson's ratio for geopolymer cements ranging from 0.3030 to 0.3060. The lowest Young's modulus for geopolymer cement cured for 24 hours with the second curing condition is 13.90 GPa while the highest is 14.39 GPa.

The average Young's modulus calculated for both Class G and geopolymer cement samples are shown in Table 4-8 below:

Table 4-8: Young's modulus average value for samples cured 24 hours

| | | | | |
|---|---|---|---|---|
| 24 HOURS | AVERAGE | CLASS G | 9.9159E+09 | **9.92 GPa** |
| | | GEOPOLYMER | 1.4192E+10 | **14.19 GPa** |

The calculated value for average Young's modulus is 9.92 GPa and 14.19 GPa for Class G and geopolymer cement respectively. The values are higher than the average values from the first curing condition and higher than samples cured only for 7 hours.

Thus this proves that the longer curing time will result in higher Young's modulus of elasticity. The results obtained also portrayed the high temperature and high pressure helps in the increasing value of elastic modulus of cement samples. However, there is always limitation for the elastic modulus until it reaches its limitation point. Figure 4-5 below exhibits the values for Young's modulus obtained for each cement samples tested in curing condition 2.

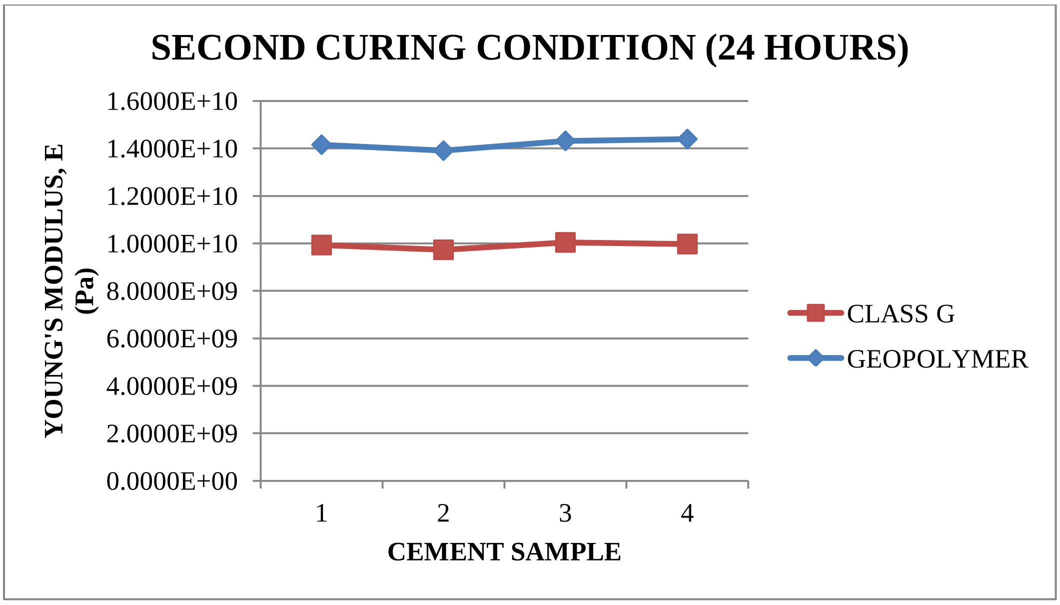


Figure 4-5: Line graph for second curing condition run for 24 hours

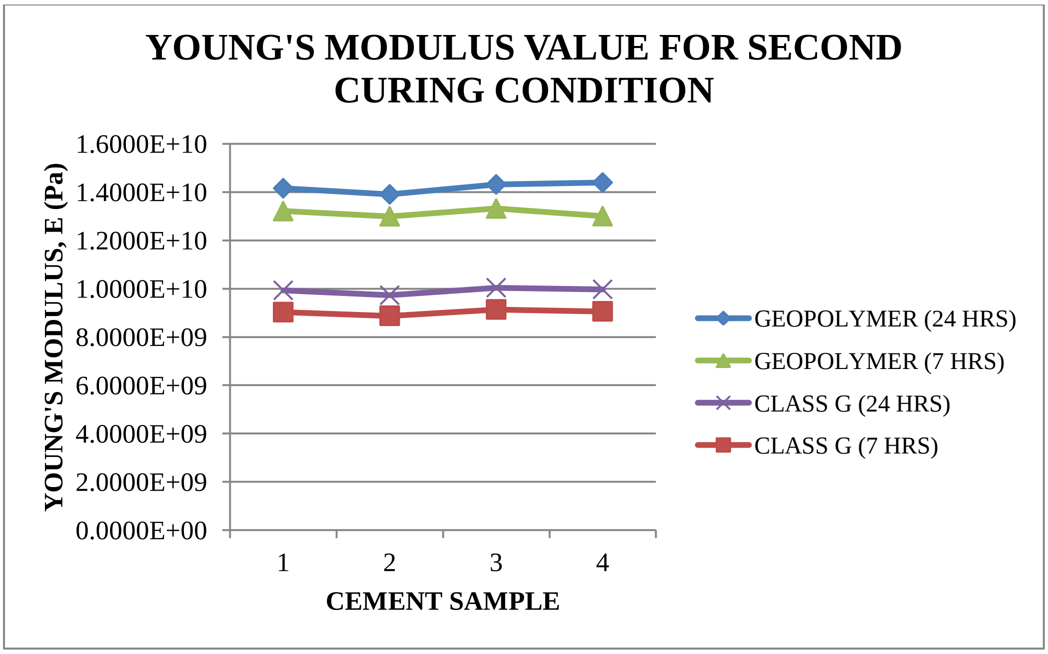


Figure 4-6: Young’s modulus value for all samples in curing condition 2

From Figure 4-5 and Figure 4-6 above, the summary of the findings are geopolymer cement showed a higher value of elastic modulus compared to Class G cement in both curing time of 7 and 24 hours. The high temperature and pressure used in curing condition 2 affecting the Young’s modulus as it is higher compared to values obtained from curing condition 1.

## 4.3 OVERALL ANALYSIS

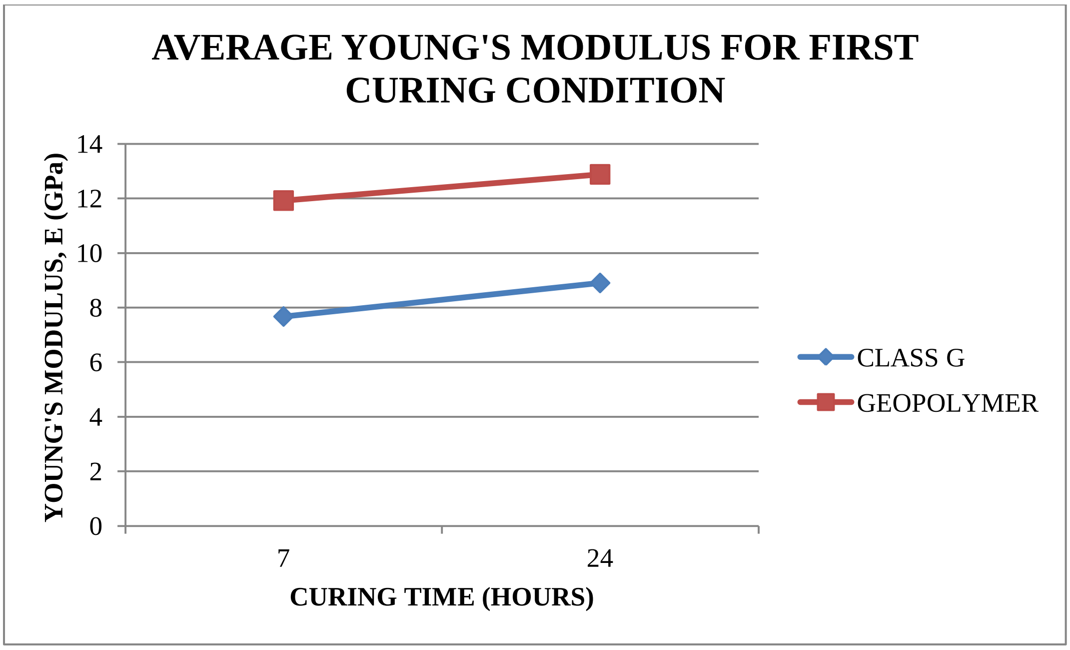


Figure 4-7: Average Young’s modulus for first curing condition with different curing time

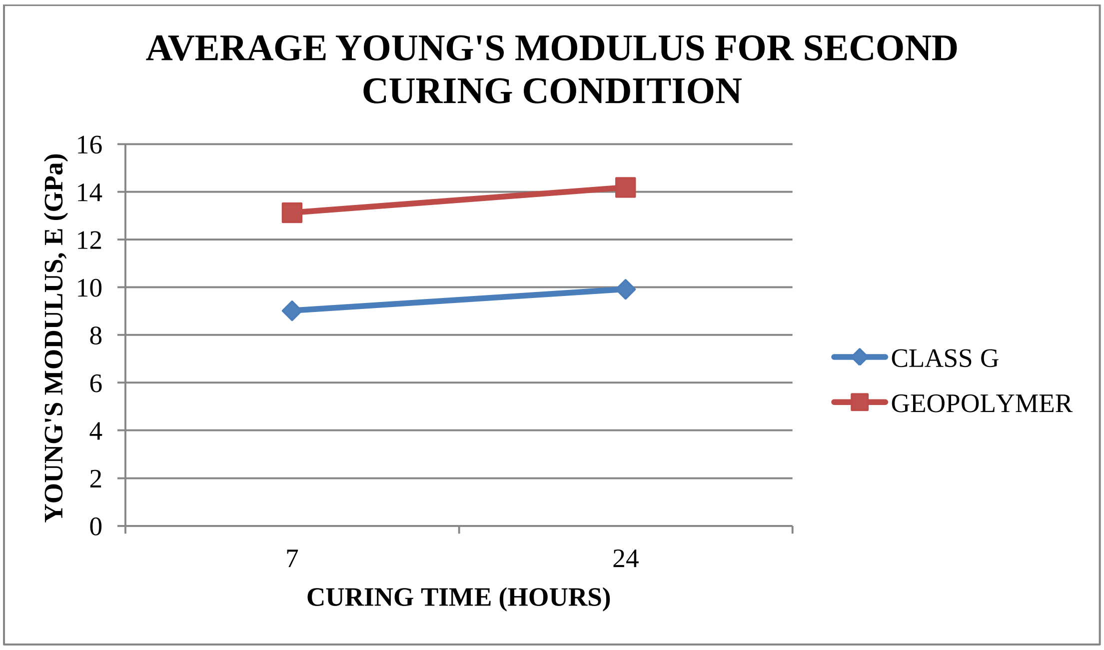


Figure 4-8: Average Young’s modulus for second curing condition with different curing time

As to summarize the findings and discussion of the results obtained in this project, Figure 4-7 and Figure 4-8 shows that the value of Young’s modulus increases with longer curing time. We can also conclude that the higher temperature and pressure, which used in second condition, 120 °C and 3000 psia, gave higher value of Young's modulus compared to the first condition of 80 °C and 1500 psia, for both Class G and geopolymer cement as shown in Figure 4-9 below.

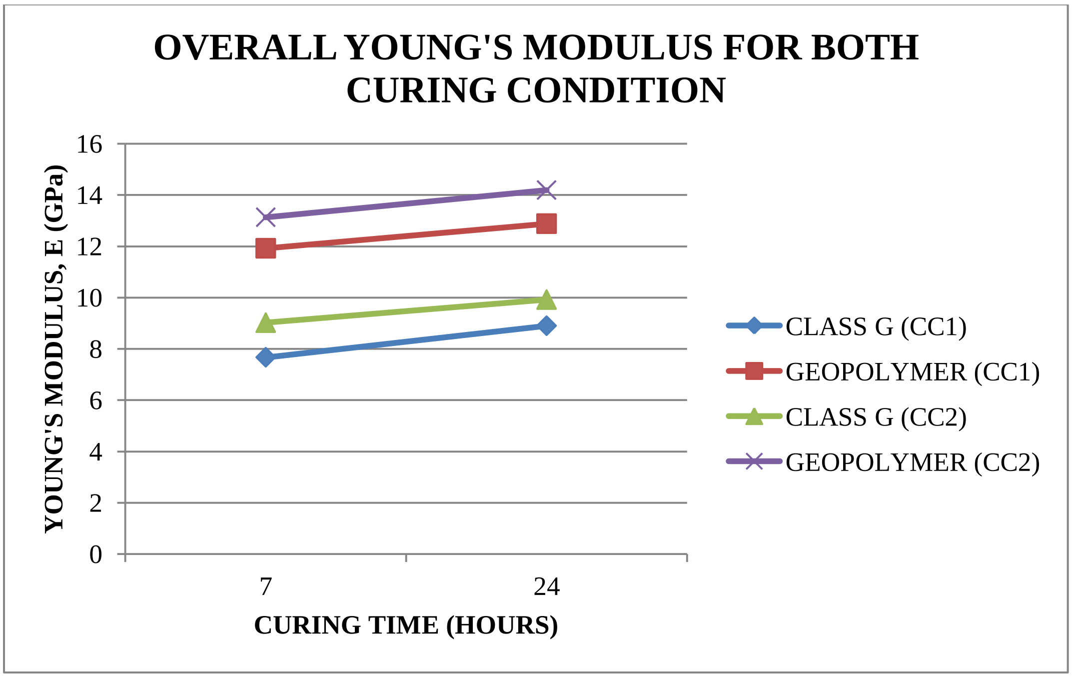


Figure 4-9: Overall Young's modulus for all samples in different curing condition

# CHAPTER 5

# CONCLUSION AND RECOMMENDATION

## 5.1 CONCLUSION

In conclusion, this project came out with numbers of conclusion regarding the elastic modulus of the cement, both Class G and geopolymer cement. In higher pressure and temperature (HPHT) condition, the Young's modulus of the cement samples is higher when compared to a lower pressure and temperature. Both high and normal represented by the two curing condition used in this project.

It also exhibit that the longer curing time will result in an increment of the Young's modulus value. This shows that the longer curing time will also increase the elastic modulus of the cement. However, the longer curing time will then stabilize the value of the Young's modulus.

Higher Young's modulus which represents the elastic modulus of the cements portrayed that the strength of the cement is also high when put in HPHT condition. The density of the cements plays a role in having a high elastic modulus of the cement. Correct ratio of water to cement ratio (WCR) and water to geopolymer solid (WGS) is crucial in order to achieve the high Young's modulus of the cements.

## 5.2 RECOMMENDATIONS

Suggested further works for continuation and expansion:

1. Use longer curing time to see clear pattern of Young’s modulus with longer curing time in HPHT condition.
2. Expand studies on geopolymer cement by using nano silica instead of micro silica and compare the performance of both against high pressure and temperature.
3. Develop studies on other properties of geopolymer cement like strength of geopolymer cement or thickening time to see its suitability to be used as oil well cement.

## REFERENCES


[1] Nasvi, M.C.M., Ranjith, P.G., Sanjayan, J., "Comparison of Mechanical Behaviors of Geopolymer and Class G Cement as Well Cement at Different Curing Temperatures for Geological Sequestration of Carbon Dioxide," in *46th U.S. Rock Mechanics/Geomechanics Symposium*, 2012.

[2] Khalifeh, M., Saasen, A., Vralstad, T., Hodne, H., "Potential Utilization of Geopolymers in Plug and Abandonment Operations," in *Society of Petroleum Engineers Bergen One Day Seminar, Norway*, 2nd April 2014.

[3] Rangan, B.V., "Geopolymer concrete for Environmental Protection," *The Indian Concrete Journal*, April issue, pp. 41-59, 2014.

[4] Davidovits, J., "Geopolymer Cement, A Review," Institut Geopolymere, January 2013.

[5] Davidovits, J., "30 Years of Successes and Failures in Geopolymer Applications. Market Trends and Potential Breakthroughs," in *Geopolymer 2002 Conference, Melbourne, Australia*, October 2002.

[6] Balaguru, P.N., Giancaspo, J., Lyon, R.E., "Recent Advances in Inorganic Polymer Composites," in *The 13th International Offshore and Polar Engineering Conference, Hawaii, U.S.A.*, May 2003.

[7] Davidovits, J., Izquierdo, M., Querol, X., Antennuci, D., Nugteren, H., Butselaar-Orthlieb, V., Fernandez-Pereira, C., and Luna, Y., "Geopolymer Cement Based on European Coal Fly Ashes," in The European Research Project GEOASH, *Technical Paper #22, Geopolymer Institute Library*, retrieved from: www.gepolymer.org, 2014.

[8] George E King Consulting Inc. Chapter 3: Cementing [Online]. Available: http://gekengineering.com/Downloads/Free_Downloads/Cementing_Chapter_3.pdf

[9] Merriam-Webster (2014). "Cement." Retrieved October 20, 2014 from http://www.merriam-webster.com/dictionary/cement.

[10] Mitchell, A.L., & Casman, E.A., "Economic Incentives and Regulatory Framework for Shale Gas Well Site Reclamation in Pennsylvania," *environmental science & technology*, 45(22), 9506-9514, 2011.

[11] Skvara, F.J., and Kopecky, T.L., "Geopolymer Materials Based on Fly Ash." *Ceramics – Silikaty*, 49 (3) 195-204, 2005.

[12] Temuujin, J.M., Rickard, A., Lee, W., Williams, M., and van Riessen, I.A., "Preparation of Metakaolin based Geopolymer Coatings on Metal Substrates as Thermal Barriers," *Applied Clay Science* 45 (2009) 265-270, 2009.

[14] Davidovits, J., "High-Alkali Cements for 21$^{st}$ Century Concretes in Concrete Technology, Past, Present and Future," *Proceedings of V. Mohan Malhotra Symposium*, Editor: P. Kumar Metha, ACI SP-144, pp. 383-397, 1994.

[15] Introduction to Concrete: Properties of Concrete. Retrieved from: www.ce.memphis.edu/1101/notes/.../concrete_properties_slides.pdf

[16] The Department of Materials Engineering and Chemistry, K123. Chapter 15, Modulus of Elasticity pp. 79-86, retrieved from: http://tpm.fsv.cvut.cz/, 2007.

[17] Duxson, P., Fernandez-Jimenez, A., Provis, J.L., Lukey, G.C., Palomo, A., and van Deventer, J.S.J., "Geopolymer Technology: The Current State of the Art," in *Advances in Geopolymer Science and Technology Book* (2007) pp. 2917-2933, 2006.

[18] Amani, M., Kosinowski, C., Schubert, J., Teodoriu, C., and Yuan, Z., "Investigation of the Mechanical Properties of Class G Cement and Their Effect on Well Integrity," in *International Journal of Engineering and Applied Sciences*, 2013.

[19] Nazmin, N., "Micro Geopolymer Cement with Enhanced Physical Properties for Well Cementing," Universiti Teknologi PETRONAS, May 2014.