THE DYNAMIC BEHAVIOR OF SLAG BASED GEOPOLYMER MORTAR UNDER VARIOUS CURING TIMES

by

Yirui Shi

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Civil Engineering
University of Toronto

© Copyright by Yirui Shi 2017
THE DYNAMIC BEHAVIOR OF SLAG BASED GEO POLYMER MORTAR UNDER VARIOUS CURING TIMES

Yirui Shi

Master of Applied Science
Graduate Department of Civil Engineering
University of Toronto
2017

Abstract

Currently, geopolymers (e.g. fly ash and slag) are excellent replacements of the traditional ordinary Portland cement (OPC) concrete due to the less production of carbon dioxide into the environment. In this thesis, a split Hopkinson pressure bar (SHPB) system is used to study the dynamic mechanical properties (i.e. dynamic compressive strength, dynamic tensile strength and dynamic fracture toughness) of slag based geopolymer mortars with two pastes and curing times (7 days, 28 days and 56 days). The results indicate that the dynamic mechanical properties of geopolymer mortars increase with the loading rates. In addition, the dynamic compressive strength, tensile strength and fracture toughness increase with the increase of curing time and decrease with the increase of water content. Some formulas are proposed to describe the trend of the dynamic compressive strength, tensile strength and fracture toughness.
Acknowledgment

The completion of this thesis also completes my career as a student. In retrospect, the joyful days in the University of Toronto not only opened my sights for advanced science and techniques, but also brought numbers of friends into my life.

Foremost, I would like to express my sincerest thanks to my advisor, Professor Kaiwen Xia, for his support, guidance and tolerance during my study at the University of Toronto.

I would also like to thank Professor Karl Peterson for providing me the materials and being my second reader. I thank Prof. Rong Chen, Dr. Sheng Huang and Dr. Wei Yao and Mr. Changyi Yu and Mr. Junchen Zhang for pleasant cooperation and insightful discussion during the course of this study and for helping me in running my experiments smoothly and efficiently. I am also lucky to have been in the company of my friends and fellows in Geotechnical laboratory in the department of Civil Engineering.

I wish to thank the organizers of the RILEM TC 247-DTA round-robin testing program, especially Anja Buchwald, Martin Cyr, Gregor Gluth, John Provis, Arie van Riessen, William Rickard, and Frank Winnefeld for the development of mix designs and coordination of materials, as well as Baumineral, ECOCEM, and BASF for donating the slag used in this study.

I would also like to thank my parents who have been always supporting me. The eternal love from the family fosters my strength to conquer the difficulties in rainy days, past, present and future.
# CONTENTS

ACKNOWLEDGMENT .................................................................................................................. iii
LIST OF FIGURES ..................................................................................................................... vi
LIST OF TABLES ........................................................................................................................ ix
Chapter 1  Introduction ............................................................................................................. 1
  1.1 Background ....................................................................................................................... 1
  1.2 Past work about Mechanical properties of geopolymer paste or mortar ....................... 2
    1.2.1 Static properties ........................................................................................................... 2
    1.2.2 Dynamic properties .................................................................................................... 12
  1.3 Research gap and research objectives ............................................................................ 15
  1.4 Summary .......................................................................................................................... 15
Chapter 2  Research methods and procedures .................................................................... 16
  2.1 Split-Hopkinson Pressure Bar system .............................................................................. 16
    2.1.1 Basic principle of SHPB ........................................................................................... 16
    2.1.2 Pulse shaping technique ........................................................................................... 17
    2.1.3 Dynamic compressive test ......................................................................................... 20
    2.1.4 Dynamic tension test ................................................................................................. 21
    2.1.5 Dynamic fracture test ............................................................................................... 22
  2.2 Sample preparation .......................................................................................................... 24
    2.2.1 Materials .................................................................................................................... 24
    2.2.2 Mixing Procedure ..................................................................................................... 27
    2.2.3 Curing Procedure ...................................................................................................... 29
Chapter 3  Compressive test results and discussions .......................................................... 30
  3.1 Introduction and Sample preparation ............................................................................... 30
  3.2 Determination of stress-strain curve ................................................................................ 31
  3.3 Determination of loading rate .......................................................................................... 34
  3.4 Results and discussion ..................................................................................................... 36
    3.4.1 Samples after test ....................................................................................................... 36
    3.4.2 Dynamic compressive strength results ..................................................................... 37
Chapter 4  Dynamic tensile test results and discussions ................................................. 40
  4.1 Introduction and Sample preparation ........................................................................ 40
  4.2 Determination of loading rate .................................................................................... 41
  4.3 Dynamic tensile test results and discussions .............................................................. 43
    4.3.1 Sample after test .................................................................................................. 43
    4.3.2 Dynamic tensile strength results ......................................................................... 44
Chapter 5  Dynamic fracture toughness of geopolymer ......................................................... 47
  5.1 Sample preparation .................................................................................................... 47
  5.2 Determination of loading rate .................................................................................... 49
  5.3 Dynamic fracture toughness results and discussion .................................................... 50
    5.3.1 Samples after test ............................................................................................... 50
    5.3.2 Dynamic fracture toughness results ..................................................................... 51
Chapter 6  Chapter 6 Conclusions and future work .............................................................. 54
  6.1 Conclusions ................................................................................................................ 54
  6.2 Future work ............................................................................................................... 55
References............................................................................................................................. 56
LIST OF FIGURES

Figure 1.1 Compressive strength development after 28 days at different temperatures (Swanepoel and Strydom 2002) .............................................................. 4

Figure 1.2 Compressive strength in long-term (Lloyd 2009) ............................................. 6

Figure 1.3 Compressive strengths of mortars at different ages (Puertas, Martínez-Ramírez et al. 2000) ................................................................................................. 7

Figure 1.4 Effects of modulus (M) and content of the mixed alkali activator on the compressive strength (Guo, Shi et al. 2010) ................................................................ 9

Figure 1.5 Compressive strength test results for different KOH concentration .................. 10

Figure 1.6 Splitting tensile strength of geopolymer concrete (Deb, Nath et al. 2014) ........ 11

Figure 1.7 The law between DIFc and average strain rate (Luo, Xu et al. 2013) ............... 13

Figure 1.8 The comparison of two typical stress–strain curves. (Xin, Jin-yu et al. 2014) .... 13

Figure 1.9 Relationships between dynamic compressive strength and strain rate (Ren, Xu et al. 2015) ........................................................................................................ 14

Figure 1.10 Dynamic compressive strength at different temperatures (Su, Xu et al. 2016) .. 14

Figure 2.1 Schematics of a split Hopkinson pressure bar (SHPB) system ......................... 17

Figure 2.2 Incident, reflected and transmitted waves captured in a typical test .................. 17

Figure 2.3 The typical incident wave (with or without shaper) ......................................... 18

Figure 2.4 Copper sheet and copper shaper ....................................................................... 19

Figure 2.5 Dynamic force balance for a typical dynamic tension test with pulse shaping .... 19

Figure 2.6 Schematics of compression test and sample .................................................... 21
Figure 4.3 Dynamic force balance (In: Incident wave, Re: Reflected wave, Tr : Transmitted wave) .................................................................42

Figure 4.4 Tensile stress history .........................................................................................................................42

Figure 4.5 Brazilian disc sample after the dynamic tensile test (a) No.1 (b) No.2 (c)No.9 (d)No.13 .................................................................................................................................43

Figure 4.6 Dynamic tensile strength at various loading rate and curing time (a) paste 1 (b) paste 2 .................................................................................................................................45

Figure 5.1 The sample set at the SHPB system ..................................................................................................48

Figure 5.2 Geopolymer based NSCB specimen .................................................................................................48

Figure 5.3 Dynamic force balance of fracture toughness test .................................................................49

Figure 5.4 Typical SIF-time curve for determining loading rate ............................................................50

Figure 5.5 Typical recovered specimens from dynamic NSCB tests .......................................................51

Figure 5.6 Dynamic fracture toughness at various loading rate and curing time (a) paste 1 (b) paste 2 .........................................................................................................................................52
LIST OF TABLES

Table 1.1 Compressive strength (mpa) in different curing time curing temperature .................. 3

Table 1.2 Compressive strengths (Mpa) of Na-PSS polymers after different ageing times (Barbosa, MacKenzie et al. 2000) ........................................................................................................ 5

Table 1.3 Effect of parameters on compressive strength (Hardjito, Wallah et al. 2004) ........... 8

Table 1.4 properties of mixes  (Pan, Sanjayan et al. 2011) ......................................................... 11

Table 2.1 Weight Percentage of each components of Slag ......................................................... 26

Table 2.2 Actual Mix Design Composition of Slag .................................................................... 26

Table 3.1 Fitting parameters for dynamic UCS ......................................................................... 39

Table 4.1 Fitting parameters for dynamic tensile strength ....................................................... 46

Table 5.1 Fitting parameters for dynamic fracture toughness .................................................... 53
Chapter 1 Introduction

1.1 Background

Nowadays, with development of the world, the demand for cement has greatly increased. Currently, Ordinary Portland Cement (OPC), is one of the most important materials used in civil industry. The world annual of Ordinary Portland Cement (OPC) consumption is about 1.56 billion tons, and the number is still rising at an approximate rate of 3 % annually (Shashank, Varad et al. 2015). According to the report done by (Mehta and Burrows 2001), OPC production in the world releases 1.35 billion tons of greenhouse gas emissions which approximately equal to 7% of the total global greenhouse gas emissions. These massive greenhouse gas emissions to the Earth’s atmosphere cause serious problems, such as air and environmental pollution. Furthermore, if a building utilized OPC as the principal material exposes in a corrosive environment, its building service life will be shortened (Mehta and Burrows 2001). Therefore, we need to find another material which is much sustainable and environmental friendly.

A new group of building material that has a high potential as the substitution of OPC is geopolymer cement. Among this group, fly ash and slag are two geoploymer cements that are consumed widely. Many industrial companies produce a lot of wastes like industrial fly ash and slag and these products, in addition, has a huge destructive impact on the environment and health; for example, the yield of fly ash in China is about 620 million tons in 2015. To deal this problem, some researchers suggest that those industrial wastes can be used as building materials to replace OPC. Moreover, geopolymer cements have many advantages comparing raditional OPC; high temperature resistant (Kong and Sanjayan 2008), and high durablility against sulfate exposure(Bakharev 2005) are among the most important advantages of geopolymer cements over OPC.

During the last decades, many studies have been conducted to examine the mechanical properties of geopolymer concrete. However, most of the previous studies focused on the
mechanical properties of geopolymer concrete under static loading, and there are few research regarding the dynamic properties of geopolymer concrete. Therefore, it is necessary to analyze the response of geopolymer concrete under dynamic load.

The potential research results can be applied in various areas. Explosion events caused by accident or terrorist attack which is unfortunately one of the biggest concerns in our society can cause high dynamic loads on civil structures. Another major source of dynamic load is seismic events. This thesis mainly focuses on the dynamic behavior of geopolymer mortar under explosion impact and seismic event in order to verify whether geopolymer can be used as construction materials for civil engineering structures.

1.2 Past work about Mechanical properties of geopolymer paste or mortar

1.2.1 Static properties

Different studies have been conducted to study the factors affected the compressive strength of geopolymer concretes. Based on these studies, the most significant factors are curing temperature, curing time and material mixing ratio. The following paragraphs explain effect of each factor on the mechanical behavior of this material in detail.

Curing temperature

Palomo, (Palomo, Grutzeck et al. 1999) studied the influence of different curing temperatures, curing times, and type of activators on compressive strength of geopolymer concretes. They use fly ash and set four types activators ratios, two temperatures (65 and 85°C) and two liquid/solid ratios (0.25 and 0.3), and curing time of 2, 5, and 24 h. as Table 1.1 clearly shows the significant effect of curing temperature on strength of this material; by increase of curing temperature from 65 to 85 °C, the strength of samples were increased.

The results show that temperature and the type of activator are two important factors affecting the mechanical strength, especially when the temperature is 85°C after curried 5h the strength could reach to 57.4 MPa.
In addition, Swanepoel (Swanepoel and Strydom 2002) found that concrete prepared by fly ash clay reaches its highest strength during curing temperature of 60 degrees for 48h compared to other samples that were cured at 40, 50, 60 and 70 °C for different time intervals (6, 24, 48 and 72 h) which show in Figure 1.1

Table 1.1 Compressive strength(MPa) in different curing times and curing temperatures

<table>
<thead>
<tr>
<th>Activator</th>
<th>Curing temperature (°C)</th>
<th>Activator/fly ash ratio of 0.25(time of curing)</th>
<th>Activator/fly ash ratio of 0.3 (time of curing)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>2h</td>
<td>5h</td>
</tr>
<tr>
<td>Solution 1</td>
<td>65</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Solution 1</td>
<td>85</td>
<td>9.3</td>
<td>22.0</td>
</tr>
<tr>
<td>Solution 2</td>
<td>65</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Solution 2</td>
<td>85</td>
<td>1.4</td>
<td>9.4</td>
</tr>
<tr>
<td>Solution 3</td>
<td>65</td>
<td>4.3</td>
<td>31.7</td>
</tr>
<tr>
<td>Solution 3</td>
<td>85</td>
<td>39.8</td>
<td>48.2</td>
</tr>
<tr>
<td>Solution 4</td>
<td>65</td>
<td>0</td>
<td>9.5</td>
</tr>
<tr>
<td>Solution 4</td>
<td>85</td>
<td>7.7</td>
<td>34.3</td>
</tr>
</tbody>
</table>
Water content

Basically, Strength decreases as water content of geopolymer increases. This trend is similar with compressive strength in OPC. (Barbosa, MacKenzie et al. 2000) analyzed the influence of water content for geopolymer binders.

First, they made 7 samples labelled: PSS1, PSS2, PSS3, PSS4, PSS5, PSS6 and PSS7. For these seven samples, PSS1, PSS3 and PSS5 have low water content while PSS2, PSS4 and PSS6 have higher water content. PSS7 was made as an anhydrous sample. Moreover, the activator ratio of PSS1 is same as PSS2. The activator ratio of PSS3 is same as PSS4, and the activator ratio of PSS5 equals to PSS6. The compressive strength of PSS1, PSS3, and PSS5 are shown in Table 1.2.

The compressive strength of Sample No2, 4 and 6 didn’t show in Table 1.2 since these samples were still too soft to be tested after three days curing. This shows that water content plays an
important role on the mechanical properties of employer binders. Too much water content will extend the curing time. In other words, high water decreases short-term strength.

Table 1.2 Compressive strengths (MPa) of Na-PSS polymers after different curing times

(Barbosa, MacKenzie et al. 2000)

<table>
<thead>
<tr>
<th>Sample</th>
<th>1 h strength</th>
<th>24 h strength</th>
<th>3 days strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na-PSS1</td>
<td>48</td>
<td>52</td>
<td>49</td>
</tr>
<tr>
<td>Na-PSS3</td>
<td>41</td>
<td>19</td>
<td>25</td>
</tr>
<tr>
<td>Na-PSS5</td>
<td>28</td>
<td>28</td>
<td>30</td>
</tr>
<tr>
<td>Na-PSS7</td>
<td>1</td>
<td>3</td>
<td>8</td>
</tr>
</tbody>
</table>

Curing time

Lloyd (Lloyd 2009) studied the change of properties of geopolymer mortar with special consideration of curing time. The result shows in Figure 1.2. Lloyd used the same curing conditions to test compressive strength of three types fly ash, slag and the mix of fly ash and slag. In the six-month curing, for most of the samples, the strengths present increasing trend as curing time increases. Slag preformed constant behavior and reacts faster than fly ash, as it reaches higher strength in short-term. FA3 shows low strength compares to other fly ash. However, when FA3 mix with slag, it gets the highest strength. Also, the mechanical strength of mixture continuously increases during the six-month period.

Puertas (Puertas, Martínez-Ramírez et al. 2000) compared the compressive strength of geopolymer concrete with various activator concentrations (NaOH 2 and 10 M), curing temperatures (25°C and 65°C), fly ash/ slag ratios (100/ 0, 70/ 30, 50/ 50, 30/ 70, and 0/ 100) and curing times (1 day, 7 days, 28 days, 90 days). The test results demonstrate that the
compressive strength for curing temperature at 65°C in one day is higher than the others. However, after one day, the compressive strength of that sample cured at 25°C exceed those treated at 65°C (Figure 1.3). Compressive strength decreased on curing at the higher temperature for long-term because exposing the sample to high temperature for long time will break microstructures of geopolymer mixture and slow the geopolymerization process.

Figure 1.2 Compressive strength in long-term (Lloyd 2009)
Solution concentration Silicate and hydroxide ratio

NaOH concentration and silicate and hydroxide ratio is one of the important factors that affect compressive strength of geopolymer. According to Hardjito (Hardjito, Wallah et al. 2004), high solution concentration or liquids ratio reinforce the strength. He set two different concentrations (8M and 14M) and two ratios (0.4 and 2.5) under the same curing conditions. The compressive strengths of these samples are shown in Table 1.3. In addition, Guo’s (Guo, Shi et al. 2010) shows that the compressive strength does not change linearly by concentration and ratio of alkali activator. Guo set three different concentration of activator (1M, 1.5M and 2M) and 6 to 15% content of Na₂O, and the results are illustrated in Figure 1.4. The highest compressive strength is obtained when the modulus is 1.5. Higher concentrations of Na₂O yielded higher compressive strength. In addition, the increasing rate of compressive strength drops when the concentration of Na₂O is higher than 10%. Cheng and Chiu 2003 shows that
the concentration of activator influenced the compression strength of Slag based geopolymer mortar. In Figure 1.5, the sample with 10N concentration of KOH has the higher strength comparing the other ones (Cheng and Chiu 2003)

Table 1.3 Effect of parameters on compressive strength of geopolymer  (Hardjito, Wallah et al. 2004)

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Concentration of NaOH liquid in molarity(M)</th>
<th>Sodium silicate/NaOH liquids ratio by mass</th>
<th>7-days compressive strength after curing at 60°C for 24h, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-1</td>
<td>8M</td>
<td>0.4</td>
<td>17.3</td>
</tr>
<tr>
<td>A-2</td>
<td>8M</td>
<td>2.5</td>
<td>56.8</td>
</tr>
<tr>
<td>A-3</td>
<td>14M</td>
<td>0.4</td>
<td>47.9</td>
</tr>
<tr>
<td>A-4</td>
<td>14M</td>
<td>2.5</td>
<td>67.6</td>
</tr>
</tbody>
</table>
Figure 1.4 Effects of modulus (M) and content of the mixed alkali activator on compressive strength of geopolymer (Guo, Shi et al. 2010)
Fracture properties and tensile splitting strength

Pan (Pan, Sanjayan et al. 2011) discussed the compressive and tensile behavior of geopolymer paste and concrete. The tensile splitting strength was measured by performing the cylinder splitting test, and three-point bending tests were used to test fracture properties. Table 1.3 shows the properties of each mixture. Mix 1 is OPC concrete, and mix 2 is geopolymer clay. The rest of samples are geopolymer concrete with the different material ratios. He found that mechanical behavior of geopolymer is better than OPC. In addition, (Deb, Nath et al. 2014) studied tensile strength of geopolymer concrete (four different ratios of material) under long term curing process. Based on their results which are shown in Figure 1.6, the tensile strength continuous increase by curing time.
Table 1.4 properties of mixes  (Pan, Sanjayan et al. 2011)

<table>
<thead>
<tr>
<th>Mix</th>
<th>Density $\text{kg/m}^3$</th>
<th>Compressive strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Modulus of elasticity (GPa)</th>
<th>Poisson’s ratio</th>
<th>Fracture energy (N/mm)</th>
<th>Characteristic length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mix1</td>
<td>1876</td>
<td>68.2</td>
<td>2.8</td>
<td>15.3</td>
<td>-</td>
<td>15.2</td>
<td>29</td>
</tr>
<tr>
<td>Mix2</td>
<td>2031</td>
<td>71.2</td>
<td>3.3</td>
<td>11.2</td>
<td>-</td>
<td>9.1</td>
<td>10</td>
</tr>
<tr>
<td>Mix3</td>
<td>2530</td>
<td>65.1</td>
<td>3.9</td>
<td>45.2</td>
<td>0.16</td>
<td>98.9</td>
<td>294</td>
</tr>
<tr>
<td>Mix4</td>
<td>2555</td>
<td>69.8</td>
<td>5.0</td>
<td>35.5</td>
<td>0.19</td>
<td>80.1</td>
<td>114</td>
</tr>
<tr>
<td>Mix5</td>
<td>2496</td>
<td>72.1</td>
<td>4.9</td>
<td>36.1</td>
<td>0.15</td>
<td>69.8</td>
<td>105</td>
</tr>
<tr>
<td>Mix6</td>
<td>2445</td>
<td>77.9</td>
<td>5.1</td>
<td>41.2</td>
<td>0.16</td>
<td>65.2</td>
<td>103</td>
</tr>
</tbody>
</table>

Figure 1.6 Splitting tensile strength of geopolymer concrete (Deb, Nath et al. 2014)
1.2.2 Dynamic properties

To understand the relationship between static compressive strength and dynamic compressive strength of geopolymer, Luo et al (2013) used a Spilt-Hopkinson pressure bar (SHPB) system. They found that the dynamic increase factor for compression (DIFC) increases approximately linearly with the logarithm of the average strain rate. With high strain rate loading, the DIFC of geopolymer concrete mixtures increases with the increasing strain rate (Luo, Xu et al. 2013).

As shown in Figure 1.7. Xin et al (2014) compared dynamic compressive strength of geopolymer concrete with two different activators. As be seen in Figure 1.8, The elastic modulus of NNSFGC is greater than that of NSSFGC under the same strain rate (Xin, Jin-yu et al. 2014).

Ren et al (2015) investigated the influence of water immersion on dynamic mechanical properties of geopolymer concrete. The quasi-static strength of GC decreases after water immersion. For the impact loading, however, water immersion exhibits a strengthening and stiffening effect on GC as confirmed by the higher dynamic strength and higher dynamic elastic modulus of GCW (Ren, Xu et al. 2015) as shown in Figure 1.9.

Su et al (2016) set five groups samples that had been thermally treated at different temperature (RT, 200, 400,600 and 800°C). The result shows that the dynamic compressive strength of the GC sample is higher at 200°C than at room temperature. After that the dynamic compressive strength didn’t drop with the temperature rise until the sample was treated at 800°C in which the strength drops significantly (Su, Xu et al. 2016). The results are shown in Figure 1.10.
Figure 1.7 The law between $DIF_c$ and average strain rate (Luo, Xu et al. 2013)

Figure 1.8 The comparison of two typical stress–strain curves. (Xin, Jin-yu et al. 2014)
Figure 1.9 Relationship between dynamic compressive strength and strain rate (Ren, Xu et al. 2015)

Figure 1.10 Dynamic compressive strength at different temperatures (Su, Xu et al. 2016)
1.3 Research gap and research objectives

Most of the research have been done so far on geopolymer have been focused on the mechanical behavior of this material under static loading regime; while the dynamic properties have not been investigated and indeed, there are very few research about the relationship between dynamic properties and different material ratio or curing time. Moreover, Out of Author of this study knowledge, almost there is no document that has studied how the dynamic properties of geopolymer changes in the long period.

In this thesis, the dynamic behavior of geopolymer mortar with two different material ratios under various curing time (7 days, 28 days and 56days) are investigated.

1.4 Summary

This chapter provide a brief background on geopolymer, and literature review about mechanical properties (static properties and dynamic properties) of geopolymer paste and concrete. This chapter also described the research gap about previous works. At the end, objectives were revealed.
Chapter 2 Research methods and procedures

2.1 Split-Hopkinson Pressure Bar system

2.1.1 Basic principle of SHPB

Dynamic test experienced over 100 years’ development. From the start, John Hopkinson (1849–1898) and his son Bertram Hopkinson (1874–1918) investigated and derived dynamic press bar (Hopkinson 1901, Hopkinson 1904). In 1949 Kolsky developed split pressure bar system (SHPB) (Kolsky 1949, Kolsky 1963). This system is constituted by two bars (incident bar and transmitted bar). Nowadays SHPB system is widely used in the world. Moreover, the use of Hopkinson Bar technique has been extended to accommodate tension, shear, torsion, bending, indentation, and combined load cases. In the beginning, SHPB is widely used for testing the dynamic compressive response of various metallic materials at high loading or strain rates. After that, researchers extended the application of SHPB to test brittle materials; such as concretes (Ross and Tedesco 1989).

The SHPB system, which shows in Figure 2.1, has three important parts: a striker bar, an incident bar (2500 mm in length) and a transmitted bar (1500 mm in length). The diameter of bars is 25 mm. All bars are made from managing steel, whose density is 8100 kg/m3, one dimensional P-wave velocity is 4970 m/s, Young’s modulus is 200 GPa and yielding strength is 2.5 GPa. Frist sample is put between the incident bar and the transmitted bar. Then the gas is injected gas into the cylinder. When the pressure of cylinder reaches a certain number, the striker will be launched and impact the incident bar. The impact generates a longitudinal compressive wave $\varepsilon_i$ which propagates along the incident bar to the sample; When wave reaches the sample, part of the wave is reflected and become reflected wave $\varepsilon_r$ and the remaining wave will pass through the sample to the transmitted bar as the transmitted wave $\varepsilon_t$. All the waves are recorded by the strain gauges. Figure 2.2 shows all three waves captured by the strain gauges.
Figure 2.1 Schematics of a split Hopkinson pressure bar (SHPB) system.

Figure 2.2 Incident, reflected and transmitted waves captured in a typical test

2.1.2 Pulse shaping technique

In plastic material such as most of metal, achieving stress equilibrium when using the SHPB apparatus is easy. However, for brittle material due to its low wave speed, it takes longer propagation time of stress wave in specimen than plastic material. In addition, the failure strain of brittle material is small, usually only parts per thousand, so before the stress achieves an equilibrium state, specimen has been damaged in the ascent stage of square wave. Hence,
stress equilibrium is a relatively big challenge. In order to realize the stress equilibrium of samples during dynamic test of brittle materials, the pulse shaping technique was induced to achieve the dynamic force balance (Dai, Huang et al. 2010).

In this thesis, the C1100 copper disc with 7.3 mm diameter and 1 mm thickness was used as the pulse shaper material which shows in Figure 2.4. During the test, the striker impacts on the pulse shaper before the incident bar, it will generate a non-dispersive ramp pulse propagating into the incident bar. This pulse with slow-rising front facilitates the dynamic force balance across the specimen (Frew, Forrestal et al. 2002).

The rise time of shaped stress pulse was up to more than 80 µs, much bigger than about 10 µs of square stress pulse, thus that can provide sufficient time for the specimen to achieve stress equilibrium state.

![Figure 2.3 The typical incident wave (with or without shaper)](image-url)
Figure 2.4 Copper sheet and copper shaper

Figure 2.5 Dynamic force balance for a typical dynamic tension test with pulse shaping.
2.1.3 Dynamic compressive test

This test is intended to measure dynamic uniaxial compressive strength of geopolymer mortar in cylindrical specimens. Normally, for the static compressive test, the slenderness ratio (ratio of length to diameter) of the sample is 2. However, this value of slenderness ratio has a major influence on the axial inertia for the dynamic tests. The suggest slenderness ratio to achieve stress equilibrium in the dynamic tests is 1. In this tests after finishing sample preparation, the sample is sandwiched between the incident and the transmitted bars which is shown in Figure 2.6. In addition, in order to minimize the friction effect, the bars and sample interfaces are fully lubricated using the vacuum grease (Dai, Huang et al. 2010).

Calculation

Based on the 1D elastic stress wave theory, the displacements and forces on the two bar-sample interfaces are:

\[ u_1 = C \int_0^t [\varepsilon_I - \varepsilon_R] d\tau \]  \hspace{1cm} (2.1)

\[ u_2 = C \int_0^t [\varepsilon_T] d\tau \]  \hspace{1cm} (2.2)

\[ P_1 = EA[\varepsilon_I + \varepsilon_R] \]  \hspace{1cm} (2.3)

\[ P_2 = EA\varepsilon_T \]  \hspace{1cm} (2.4)

Here \( u_1 \) and \( u_2 \) are the displacements, \( P_1 \) and \( P_2 \) are the forces; \( E \) is the young’s modulus of the bar; \( A \) is the cross-sectional area; \( \varepsilon_I \), \( \varepsilon_R \), \( \varepsilon_T \) are the incident strain signal, reflected strain signal and reflected strain signal, respectively. \( C \) is the wave velocity of the bar material. Using equations 2.1-2.4, the stress, strain and strain rate of specimen can be derived as:

\[ \sigma_s(t) = \frac{P_1(t) + P_2(t)}{2A_s} = \frac{EA}{2A_s} (\varepsilon_I + \varepsilon_R + \varepsilon_T) = \frac{EA}{A_s} \varepsilon_T(t) \]  \hspace{1cm} (2.5)
\[ \varepsilon_s = \frac{u_1 - u_2}{L_s} = \frac{c}{L_s} \left[ \int_0^t [\varepsilon_I(\tau) - \varepsilon_R(\tau)] d\tau - \int_0^t \varepsilon_T(\tau) d\tau \right] = -\frac{2c}{L_s} \int_0^t \varepsilon_R d\tau \]  

\[ \dot{\varepsilon}(t) = \frac{c}{L_s} \left[ [\varepsilon_I(t) - \varepsilon_R(t)] d\tau - \varepsilon_T(t) \right] = -\frac{2c}{L_s} \varepsilon_R \]

where \( \sigma_s \) and \( \varepsilon_s \) are the axial compressive stress and the strain of sample, respectively. \( L_s \) and \( A_s \) are the height and cross-section of the sample.

\[ 2.1.4 \text{ Dynamic tension test} \]

In this thesis, Brazilian Disk (BD) test is used to determine tensile strength of geopolymer mortar.

The BD test is based on the fact that the mortar is much weaker in tension comparing in compression. As the result, the diametrically loaded mortar disc specimen fails due to the tension along the loading diameter near the center. The BD specimen in the SHPB system is shown schematically in Figure 2.7 where the sample disc is sandwiched between the incident and the transmitted bars (Xia and Yao 2015).
Dynamic tensile strength is determined by the following equation (Iqbal, Mohanty et al. 2008):

\[ \sigma_t = \frac{2P_f}{\pi Dt} \] (2.8)

where \( \sigma_t \) is the tensile strength; \( P_f \) is the load when the failure occurs; and \( t \) and \( D \) are the sample disc thickness and diameter, respectively.

![Diagram of Brazilian disc and flattened Brazilian disc](image)

Figure 2.7 Schematics of Brazilian disc and flattened Brazilian disc.

2.1.5 Dynamic fracture test

This test is intended to measure the dynamic fracture toughness of geopolymer mortar using the notched semicircular bend (NSCB) specimen.

The geometry of the NSCB specimen is shown in Figure 2.8 where the sample disc is sandwiched between the incident and the transmitted bars. As can be observed in this figure, the specimen is supported by two pins mounted on the transmitted bar.
Determination of the dynamic fracture toughness

All dimensions of the geometry should be converted into dimensionless with the specimen radius $R$ and diameter $D = 2R$ as: $\alpha_a = \frac{a}{R}$, $\alpha_t = \frac{t}{R}$, $\alpha_s = \frac{s}{D}$. $a$ is the notch length, $R$ is the radius of the specimen, $t$ is the thickness of the sample, and $S$ is the distance between the two supporting pins. The history of Mode-I stress intensity factor (SIF) $K_I(t)$ of NSCB specimen can be determined by the following equation:

$$K_I(t) = \frac{P(t)S}{tR^{3/2}} Y(\alpha_a)$$ \hspace{1cm} (2.9)

where $Y(\alpha_a)$ is a dimensionless function that can be determined using the following equations.

$$Y(\alpha_a) = 0.537 + 3.4409\alpha_a - 8.0792\alpha_a^2 + 16.489\alpha_a^3(\alpha_s = 0.50)$$ \hspace{1cm} (2.10)

$$Y(\alpha_a) = 0.4670 + 3.9094\alpha_a - 8.7634\alpha_a^2 + 16.845\alpha_a^3(\alpha_s = 0.55)$$ \hspace{1cm} (2.11)

$$Y(\alpha_a) = 0.4444 + 4.2198\alpha_a - 9.1101\alpha_a^2 + 16.952\alpha_a^3(\alpha_s = 0.60)$$ \hspace{1cm} (2.12)

The dynamic fracture toughness $K_{IC}$ is obtained from the peak value of $K_I(t)$, provided that the dynamic force balance has been achieved at both ends of the sample.
2.2 Sample preparation

2.2.1 Materials

In this study, slag based geopolymer mortar were considered to investigate the dynamic behavior of mortar. Ground Granulated Blast Furnace Slag (GGBS), Figure 2.9, is obtained by quenching molten iron slag from a blast furnace which is the by-product of iron and steel making. The chemical composition of a slag varies depending on the composition of the raw materials in iron production process. The main component of blast furnace slag is CaO, SiO2, Al2O3 and MgO. In general, the increase in CaO content causes the increase of the compressive strength and basicity of the slag. Activation of slag involves low to mild alkali material containing primarily silicate and calcium and produces calcium silicate hydrate similar to that formed in OPC (Li, Pan et al. 2014).
The slag for mortars was characterized and a suitable paste formulation was designed by a company called ASCEM (AB 2014). As recommended by ASCEM, two mortars with different slag contents and composition of the pastes were considered in this study. The mixing ratio of the paste and weight of sand is 4:6 as presented in Table 2.1. In addition, the actual mix design composition of Slag based on the weight per cubic meter are set out in Table 2.2.

The Sodium silicate solution used here is called “PQ-D” (typically 29.4 % SiO₂ and 14.7 % Na₂O), and used for the mix-design Sodium hydroxide solution of nominal composition 41.7 % NaOH + 58.3 % H₂O (equivalent to 32.3 % Na₂O + 67.7 % H₂O) was prepared from NaOH pellets and deionized water.
Table 2.1 Weight Percentage of each components of Slag

<table>
<thead>
<tr>
<th>Components</th>
<th>Slag#1 (Paste A)</th>
<th>Slag #2 (Paste A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GGBFS</td>
<td>25.8%</td>
<td>25.88%</td>
</tr>
<tr>
<td>Sodium Silicate</td>
<td>0.77%</td>
<td>0.52%</td>
</tr>
<tr>
<td>Solution</td>
<td>39.04%</td>
<td>39.94%</td>
</tr>
<tr>
<td>NaOH Pellet</td>
<td>0.77%</td>
<td>0.52%</td>
</tr>
<tr>
<td>Deionized Water</td>
<td>11.69%</td>
<td>13.03%</td>
</tr>
<tr>
<td>Sand</td>
<td>60.96%</td>
<td>60.06%</td>
</tr>
</tbody>
</table>

Table 2.2 Actual Mix Design Composition of Slag

<table>
<thead>
<tr>
<th></th>
<th>Slag #1 (paste A)</th>
<th>Slag #2 (paste B)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Unit: kg/m³</td>
<td>Unit: kg/m³</td>
</tr>
<tr>
<td>Slag</td>
<td>839.2</td>
<td>827.6</td>
</tr>
<tr>
<td>Sodium Silicate</td>
<td>25.17</td>
<td>16.55</td>
</tr>
<tr>
<td>Solution</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NaOH Pellet</td>
<td>25.17</td>
<td>16.55</td>
</tr>
<tr>
<td>Deionized Water</td>
<td>380.1</td>
<td>416.6</td>
</tr>
<tr>
<td>Sand</td>
<td>1982.6</td>
<td>1920.8</td>
</tr>
</tbody>
</table>
2.2.2 Mixing Procedure

Mixing procedure consists of seven different step shown below:

(1) Place all the liquids in the bowl

(2) Add powder (slag)

(3) Mix for 30 seconds at low speed

(4) Continusely add sand while mixing in 30 seconds

(5) Mix for 30 seconds at high speed

(6) Stop for 90 seconds, scrope the mortar

(7) Mix for 60 seconds at high speed

Figure 2.10 Geopolymer after mixing process
Figure 2.11 Fresh geopolymer mortar is filled into molds

Figure 2.12 Two paste mortar after extruding from molds
2.2.3 Curing Procedure

After mixing, the geopolymer mortar is casted into the molds that are 30 cm in height and 25 cm in diameter and vibrated for 1 minutes to remove air bubbles prior to curing process. Then, sample is covered with PE sheet and placed in a curing chamber with an ambient laboratory condition (23 degrees Celsius and 80% relative humidity) for two days. After that, samples are extruded from the molds and placed in sealed zip lock bags prior to testing. We put a wet cotton ball in sealed zip lock bags to keep the relative humidity high (Figure 2.13). After 7, 28 and 56 curing days samples are ready to be tested.

Figure 2.13 Samples during the curing process.
Chapter 3 Compressive test results and discussions

This chapter focuses on the dynamic compressive test. First, the preparation procedure before each test is demonstrated and then experimental formula that are used to evaluate the data is explained. Finally, results of compressive tests are discussed as well.

3.1 Introduction and Sample preparation

In the previous chapter, materials and method of curing process were described extensively. When each sample was ready to be tested, first the sample was removed from sealed zip lock bag and after that small cylinder were drilled from it. This small cylinder had 25 mm diameter and was cut to pieces with length of 25 mm (slenderness ratio is 1). Both end of each piece were polished carefully. Figure 3.1 and Figure 3.2. shows the typical sample before the test. As mentioned before the shape of sample is cylinders and height is approximately 25mm ± 0.02mm, the diameter is approximately 25mm.

Figure 3.1 Dynamic compressive strength test sample
Therefore, the height of samples is 25mm and the radius is 25mm. The length of the UCS specimen in the loading direction is short, which facilitates the dynamic force balance in dynamic tests.

There are about 120 samples been tested under two different pastes and three different curing time (7 days, 28 days and 56 days).

After sample preparation, each sample was sandwiched between the incident and transmitted bars. For achieving the force balance, a copper shaper was placed on the end of the incident bar as shown in Figure 3.2 More than 120 samples were tested for two different pastes and three different curing time (7, 28 and 56 days).

![Sample set on the bar](image1.jpg) ![Shaper](image2.jpg)

Figure 3.2 (a) sample set on the bar (b) shaper

### 3.2 Determination of stress-strain curve

Figure 3.2 to Figure 3.4 show stress-strain curves of two pastes based geopolymer mortar in different curing times (7 days 28 days 56 days). The failure strain of all the samples is around 0.005 to 0.015. In general, according to the stress-strain curves, the characteristic of geopolymer mortar in this test are having curve steep, high elastic modulus, high stress intensity, and low failure strain; in addition, the phenomenon of brittle fracture are obvious.
Four different stages can be observed in one typical stress-strain curve of this material. First, the curve is slightly bent upward. Second, the stress rises like a straight line. Third, the curve bends down until reaches the maximum stress. Fourth, curve falls rapidly. In the first and second stage, the geopolymer is nearly elastic deformation. And then, geopolymer shows some plastic deformation.

![Stress-strain curves of 7days mortar](image)

Figure 3.2 Stress-strain curves of 7days mortar (a) paste 1 (b) paste 2
Figure 3.3 stress-strain curve of 28 days mortar (a) paste 1 (b) paste 2
Figure 3.4 stress-strain curve of 56 days mortar (a) paste 1 (b) paste 2

### 3.3 Determination of loading rate

After achieving the dynamic force balance across the specimen (Figure 3.5), the dynamic compressive strength can be calculated using Eq (2.5). Loading rate is one of the most
important parameters that describes the rate dependency of compressive strength of materials. It can be determined by the time evolution of compressive stress in the specimen. Figure 3.6 shows the dynamic loading history for a typical compressive test, in which there is an approximately linear rising of the stress versus time. According to the suggested method for determination of the dynamic compressive strength of rock-like material by ISRM, the loading rate is the slope of this region (Zhou, Xia et al. 2011). This parameter is determined by a least square fitting method and shown as a line in Figure 3.6. For all dynamic compressive tests in this study, the loading rate was determined using the same method.

![Dynamic force balance for a typical dynamic UCS test with pulse shaping.](image)

Figure 3.5 Dynamic force balance for a typical dynamic UCS test with pulse shaping.
3.4 Results and discussion

3.4.1 Samples after test

Figure 3. shows typically recovered samples of both mortars under the different loading rate after dynamic UCS test. For two mortars, the failure mode is typically splitting and the number of fragments increases with loading rate increases. Figure 3.7 (c) and (f) shows the remaining parts of the sample which has highest loading rate; hence the sample was completely broken into small pieces.
3.4.2 Dynamic compressive strength results

Figure 3.8 presents the compressive strength of different pastes under different curing times. For two mortars, the dynamic compressive strength increases with the loading rate and curing time. In both mortars, the compressive strength significantly increased after curing for 28 days. In addition, the different pastes caused different result. In this thesis, two different pastes been tested. For two pastes, the most important parameter changed is water content and activator ratio. The water content and activator ratio of paste 1 is less than the paste 2. According to these figures, the compressive strength of paste 1 is always greater than paste 2. Although the strength of pastes 2 is increasing with the increase of curing time.
Figure 3.9 Dynamic compressive strength at various loading rate and curing time (a) paste 1 (b) paste 2
To describe the complicated dependence of the UCS for both mortars on the curing time and the loading rate, the following formula is proposed \cite{Malvar, 1998 #52} \cite{Yeh, 1998 #54}:

$$\sigma_{cs} = \sigma_{cs0}\left(1 + \alpha \left(\frac{\dot{\sigma}_{cs}}{\dot{\sigma}_{cs0}}\right)^\gamma\right) \times \left(\beta \ln\left(\frac{D}{28}\right) + C\right) \quad 3.1$$

where $\sigma_{cs0}$ is the static UCS, $\dot{\sigma}_{cs0} = 0.001\text{GPa/s}$ is the reference loading rate (i.e. loading rate under static loading), $\dot{\sigma}_{cs}$ is the loading rate of the dynamic UCS test, and $D$ is curing time of geopolymer mortar based on number of curing days. $\gamma$, $\alpha$, $\beta$ and $C$ are fitting constants.

On the Eq.(3.1), the first term describes the loading rate dependence and the second term represents the curing time. For each mortar, the parameters $\gamma$, $\alpha$, $\beta$ and $C$ are determined using Genetic algorithm, which is an effective method to find the best solution based on natural selection. The values of these four parameters are given in Table 3.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha$</td>
</tr>
<tr>
<td>Paste 1</td>
<td>0.00000074</td>
</tr>
<tr>
<td>Paste 2</td>
<td>0.00000039</td>
</tr>
</tbody>
</table>
Chapter 4 Dynamic tensile test results and discussions

4.1 Introduction and Sample preparation

Brazil test was applied to determine dynamic tensile strength. As the suggestion of International Society for Rock Mechanics (ISRM) (Zhou, Xia et al. 2011), the sample diameter should be close to 50 mm, and the thickness should be approximately equal to the specimen radius (Figure 4.2). Smaller specimens are preferred to achieve the dynamic force balance and higher loading rates. In this test, the diameter and thickness of specimen are 40mm and 18mm, respectively.

More than 120 samples were tested for two pastes under three different curing times (7 days, 28 days and 56 days). During the test, for achieving the force balance, sample is sandwiched between the incident and transmitted bars, which shown in Figure 4.1.

Figure 4.1 sample set on the bar
4.2 Determination of loading rate

Same as the UCS test, after achieving the dynamic force balance across the specimen, which shown in Figure 4.3, the dynamic tensile strength can be calculated by Eq (2.8). The loading rate is computed using the time evolution of the tensile stress in the specimen (Figure 4.4 Tensile stress history. For all dynamic tension tests in this study, the loading rate was determined using the same method.
Figure 4.3 Dynamic force balance (In: Incident wave, Re: Reflected wave, Tr: Transmitted wave)

Figure 4.4 Tensile stress history
4.3 Dynamic tensile test results and discussions

4.3.1 Sample after test

Figure 4.5 Shows Brazilian disc sample after the dynamic tensile test (No.1, No.2, No.9, No13), The larger the number labeled on the sample, the higher loading rate is applied to the sample. The relatively ideal failure mode means two equal halves divided along a loading diameter with a damage zone can be observed here. It is observed that the width of damage zone increases with the increase of the loading rate. This phenomenon is consistent with the results of other rock-like materials reported in previous studies.

Figure 4.5 Brazilian disc sample after the dynamic tensile test (a) No.1 (b) No.2 (c)No.9 (d)No.13
4.3.2 Dynamic tensile strength results

For two mortars, the dynamic tensile strength increases with the loading rate and curing time. During this thesis, two different pastes been tested. For two pastes, the tensile strength is increasing with increase of curing time and decrease with increase the water content. The trend of tensile strength like the UCS, the increase of 7 days to 28 days is greater than 28 days to 56 days. The tensile strength of paste 1 is always greater than paste 2, which shows in Figure 4.6.
Figure 4.6 Dynamic tensile strength at various loading rate and curing time (a) paste 1 (b) paste 2

To fully describe the relationship of the tensile strength of two mortars at the curing days and the loading rate effect, the following formula is proposed \{Malvar, 1998 #50\} \{Yeh, 1998 #51\}:

$$\sigma_{TS} = \sigma_{T50} \left(1 + \alpha \left(\frac{\sigma_{TS}}{\sigma_{T50}}\right)^{\gamma}\right) \ast \left(\beta \ln \left(\frac{D}{28}\right) + C\right)$$

4.1

Where $\sigma_{T50}$ is the static tensile strength, $\sigma_{T50} = 0.001\text{GPa/s}$ is the reference loading rate (i.e. loading rate under static loading), $\sigma_{TS}$ is the loading rate of the dynamic tensile strength test, and D is curing days of geopolymer mortar based on number of curing days. $\gamma$, $\alpha$, $\beta$ and $C$ are fitting constants. On the Eq. (4.1), the first term describes the loading rate dependence and the second term represents the curing time. For each mortar, the parameters $\gamma$, $\alpha$, $\beta$ and $C$ are determined using Genetic algorithm, which is an effective method to find the best solution based on natural selection. The values of these four parameters are given in Table 4.1
Table 4.1 Fitting parameters for dynamic tensile strength

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter value</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>α</td>
<td>γ</td>
<td>β</td>
<td>C</td>
</tr>
<tr>
<td>Paste 1</td>
<td>0.0000053</td>
<td>0.89626</td>
<td>0.1295</td>
<td>0.9959</td>
</tr>
<tr>
<td>Paste 2</td>
<td>0.000080</td>
<td>0.68802</td>
<td>0.0904</td>
<td>0.998</td>
</tr>
</tbody>
</table>
Chapter 5 Dynamic fracture toughness of geopolymer

5.1 Sample preparation

Notched semi-circular bend (NSCB) specimen was used to measure dynamic fracture toughness in this study. As compared with other methods for determining fracture toughness of brittle materials, the NSCB specimen is advantageous because (1) NSCB specimen is core-based, (2) the length of the NSCB specimen in the loading direction is short, which facilitates the dynamic force balance in dynamic tests.

Based on the International Society for Rock Mechanics (ISRM) suggested method for measuring dynamic fracture toughness of rock-like material Geopolymer, first, mortar sample was drilled, cut and polished into thin discs, and then, each disk was cut into two halves. In next step of sample preparation, using a rotary diamond-impregnated saw, a notch with an approximately 1 mm width was machined along the direction perpendicular to the diametrical cut in the center of the disk specimen. Then the tip of the notch was sharpened with a diamond wire saw to obtain a small enough crack tip, which aims to guarantee valid and accurate measurements of the fracture toughness. In our case, the diameter and thickness of sample are 40 and 20 mm, respectively (Figure 5.1 and 5.2).

more than 120 samples were tested under for both pastes under three different curing times (7 days, 28 days and 56 days).

During the test, sample is sandwiched between the incident and transmitted bars. To achieve the force balance, a copper shaper is placed on the end of the incident bar.
Figure 5.1 The sample set at the SHPB system

Figure 5.2 Geopolymer based NSCB specimen
5.2 Determination of loading rate

Same as the UCS test, the dynamic force balance was achieved in both sides of the specimen which is shown in Figure 5.3. The history of Mode-I stress intensity factor (SIF), $K_I(t)$, is computed using Eq (2.9). The loading rate can be determined by the time evolution of the SIF in the specimen. The rock dynamic fracture toughness depends on the loading rate, and the loading rate is measured as the pre-peak slope of the SIF history curve. The loading rate for the test as shown in the Figure 5.4 is determined as 75GPa $m^{1/2}/s$. Figure 5.4 demonstrates all dynamic tests in this study, the loading rate was determined using the same method.

![Figure 5.3 Dynamic force balance of fracture toughness test](image-url)
5.3 Dynamic fracture toughness results and discussion

5.3.1 Samples after test

Figure 5.5 shows typical recovered NSCB specimens of two mortars under the different loading rates. Loading rate increases from specimen (a) to specimen (d). In all of tests, the specimens were completely split into two roughly identical halves by a damage zone enclosing the main crack along the notch. It can be seen that the width of damage zone increases with increase of the loading rate.
5.3.2 Dynamic fracture toughness results

For two mortars which shown in Figure 5.6, the dynamic fracture toughness rises as the loading rate and curing time increase. Also different paste caused a different result. During this thesis, two different pastes were tested. Depending to these figures, the fracture toughness of paste 1 is always greater than paste 2.
Figure 5.6 Dynamic fracture toughness at various loading rates and curing times (a) paste 1
(b) paste 2
Dependency of the dynamic fracture toughness of two mortars to curing time and the loading rate can be shown by following formula (Malvar, 1998 #52) (Yeh, 1998 #54):

\[ K_{IC} = K_{IC0} \left( 1 + \alpha \left( \frac{\dot{K}_1}{\dot{K}_{10}} \right)^\gamma \right) \* (\beta \ln \left( \frac{D}{28} \right) + C) \]

where \( K_{IC0} \) is the static fracture toughness, \( \dot{K}_{10} = 0.001 \, GPa/m^{1/2}/s \) is the reference loading rate (i.e. loading rate under static loading), \( \dot{K}_1 \) is the loading rate of the dynamic fracture toughness test, and \( D \) is curing days of geopolymer mortar based on number of curing days. \( \gamma, \alpha, \beta \) and \( C \) are fitting constants. On the Eq. (5.1), the first term describes the loading rate dependence and the second term represents the curing time. For each mortar, the parameters \( \gamma, \alpha, \beta \) and \( C \) are determined using Genetic algorithm, which is an effective method to find the best solution based on natural selection. The values of these four parameters are given in Table 5.1.

<table>
<thead>
<tr>
<th>Material</th>
<th>( \alpha )</th>
<th>( \gamma )</th>
<th>( \beta )</th>
<th>( C )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paste 1</td>
<td>0.0000013</td>
<td>1.14182</td>
<td>0.0619</td>
<td>0.9937</td>
</tr>
<tr>
<td>Paste 2</td>
<td>0.0000153</td>
<td>0.97985</td>
<td>0.0703</td>
<td>0.9973</td>
</tr>
</tbody>
</table>

Table 5.1 Fitting parameters for dynamic fracture toughness
Chapter 6 Conclusions and future work

6.1 Conclusions

In this thesis, using the SHPB system, the dynamic properties (dynamic compressive strength, dynamic tensile strength and dynamic fracture toughness) of slag based geopolymer mortar pastes have been studied. Samples were made with various mix designs in order to determine the influence of different water content and curing time on the dynamic properties of geopolymer mortar. Two different pastes were utilized to test the dynamic properties of geopolymer. The main difference of two pastes is water content and activator ratio. Test results demonstrate that water content, loading rate and curing time influence the dynamic strength of geopolymer mortar.

In the dynamic compressive strength test of geopolymer mortar, stress-strain curve was induced, and Loading rate determined by the stress-time curve. The strength result shows that the compressive strength of paste 1 is always greater than paste 2. The difference is caused by the various water content and activator ratio in this test; increasing water content and decreasing the activator ratio will reduce the strength of geopolymer mortar. In addition, the compressive strength rises with increase of curing time. Even after 56-day curing time, the strength is still rising.

Geopolymer mortar is a brittle material. So the characteristic of geopolymer mortar is similar to the other brittle materials. As a consequence, its tensile strength performance is poor. During the dynamic test, the tensile strength of geopolymer mortar shows the same trend with dynamic compressive test. Curing time, water content activator ratio and loading rate impact behavior of tensile strength, and the tensile strength keeps growing in long-period curing time.

The dynamic fracture toughness of two mortars was measured by means of the dynamic NSCB test with the SHPB apparatus. For two mortars, the dynamic fracture toughness increases with the loading rate, curing time and decreases with the increase the water content. decreasing the activator ratio also can decrease the strength of geopolymer. Although fracture toughness
increased during increase of curing time, fracture toughness does not change significantly. The value of fracture toughness is around 1 MPa and 3 MPa.

Above all, for the mix design paste 1 has higher strength comparing paste 2 and as a general conclusion, using geopolymer not only guarantees the requirement of dynamic strength but also reduces the emissions of carbon dioxide.

6.2 Future work

Frist, as well-known geopolymer mortar or concrete performed high short-time strength. However, it is too difficult to prepare and conduct dynamic tests on geopolymer under low curing time. This problem needed to be figured out in the future to have the chance of studying the dynamic response of this material under varieties of curing time. Secondly, since geopolymer shows acceptable performance to high-temperature resistant, it is necessary to test this material under high temperature as well. This can give more information about the performance of geopolymer cement during the emergency event such as: earthquake, gas or chemical explosions, terrorist attacks and blasting, tunnel and or building fires.
References

AB (2014). Mix approach for blast furnace slag based AAM (RILEM TC-DTA).


Hopkinson, J. (1901). Original Papers by the Late John Hopkinson, At the University Press.


