6.1 GENERAL

This chapter shows the results of the various tests conducted on both reinforced and unreinforced ASTM Class F fly ash based Geopolymer concrete elements as described in chapter 5. This research was kicked off with choosing the alkaline solution to be used throughout the study. This was done by determining the strength and feasibility of Geopolymer mortar cubes manufactured with four different combinations of alkaline solution. Based on this, mixture proportion of normal strength concrete and high strength concrete was fixed. The compressive strength was obtained by both destructive and non-destructive testing of cubes made of various mix proportions. Parallel to this results, microstructural analyses were also observed and investigated.

Observations on the behaviour of reinforced short columns and slender columns and response factors such as failure modes, ductility and crack patterns are presented. A brief summary of test results including cracking load, ultimate loads, load-deflection characteristics is also given.

6.2 COMpressive STRENGTH TEST ON GEOPOLYMER MORTAR CUBES

The average compressive strength of all the four combinations of Geopolymer mortar cubes are given below. For each identity, 3 cubes were tested and the average is given in Table 6.1 and Figure 6.1.
Table 6.1 Compressive Strength of Geopolymer Mortar Cubes

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Mix identity</th>
<th>Ultimate load in kN</th>
<th>Average ultimate load in kN</th>
<th>Compressive Strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. N1</td>
<td>192.20</td>
<td>186.32</td>
<td>37.38</td>
<td></td>
</tr>
<tr>
<td></td>
<td>184.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>182.25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. N2</td>
<td>186.25</td>
<td>175.25</td>
<td>35.16</td>
<td></td>
</tr>
<tr>
<td></td>
<td>172.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>167.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. K1</td>
<td>200.75</td>
<td>193.20</td>
<td>38.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td>192.50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>186.35</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. K2</td>
<td>167.50</td>
<td>145.60</td>
<td>29.21</td>
<td></td>
</tr>
<tr>
<td></td>
<td>135.75</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>133.55</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.1 Compressive Strength of Geopolymer Mortar Cubes
6.2.1 SEM and EDAX Analyses

The results of micro analyses of Geopolymer mortar specimen done by SEM and EDAX apparatus are given in Figures 6.2 to 6.4.

Figure 6.2 SEM Report of Potassium Based K1 Specimens
Figure 6.3 SEM report of Sodium Based N1 Specimens

Figure 6.4 EDAX Report of N1 Specimen (Typical)
6.2.2 Discussions on Result

A total number of 12 Geopolymer mortar specimens were cast and tested and their strengths are shown in Table 6.1. The results indicated that out of all the four combinations, the K1 mixture (mixture of silicates and hydroxides of Potassium) yielded higher compressive strength than the other three combinations. Even though the compressive strength of K1 mixture was 3.69% higher than N1 mixture, N1 (mixture of Silicates and hydroxides of Sodium) had been selected for the whole research work. Silicates and hydroxides of Sodium were cheaper than Potassium. So the former was selected.

Moreover, Geopolymer mortar specimens prepared with Potassium salts showed multiporous structure which would cause reduction in impermeability to some extent. In addition to this, though potassium is a highly reactive salt, all the salts were not fully activated leaving unreacted white crystals deposited. It behaved similar to what Rangan BV had established that Potassium salts alter the polymerization process. From Figure 6.3, it is well exhibited that only very few number of discontinuous pores were seen imparting high range of impermeability to sodium based Geopolymer paste or mortar. From EDAX spectrum shown for N1 specimen, it shall be noted that the percentage of silica and alumina originally existed in fly ash was fully utilized and the same percentage was seen as reactant product. Therefore, from microstructural analyses, sodium based salts were once again confirmed their suitability for further works.
6.3 COMPRESSIVE STRENGTH TEST ON CONCRETE CUBES

The results of compressive strength of both OPC concrete cubes and Geopolymer Concrete cubes are presented in Table 6.2. The compressive strength of many cubes were evaluated by non-destructive testing methods initially to minimize the labour involved in casting and to decide and fix the mixture proportions for Geopolymer concretes. The OPC concrete cubes were tested after 28 days of curing, whereas Geopolymer Concrete cubes were tested on the third day. A total number of 24 Concrete cube specimens were cast inclusive of OPC concrete cubes and tested. The specimens undergoing test are shown in Figures 6.5 and 6.6. A plot of unconfined compressive strength of concrete mixtures versus Mixture of Concretes are also presented in Figure 6.7.

Figure 6.5 Compressive Strength Test on OPC Concrete Cube (Typical)
**Table 6.2 Compressive Strength of Concrete Cubes**

<table>
<thead>
<tr>
<th>Nomenclature of specimen</th>
<th>No. of Cubes tested</th>
<th>Ultimate load in kN</th>
<th>Comp. Strength in N/mm$^2$</th>
<th>Average Compressive Strength in N/mm$^2$</th>
<th>Density of Concrete (Kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G 30 (14M-NaOH)</td>
<td>3</td>
<td>939</td>
<td>41.73</td>
<td>39.96</td>
<td>2408.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>871</td>
<td>38.72</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>887</td>
<td>39.43</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 30 (12M-NaOH)</td>
<td>3</td>
<td>778</td>
<td>34.59</td>
<td>35.85</td>
<td>2390.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>832</td>
<td>36.96</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>810</td>
<td>36.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 30</td>
<td>3</td>
<td>740</td>
<td>32.90</td>
<td>31.04</td>
<td>2418.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>698</td>
<td>31.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>657</td>
<td>29.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nomenclature of specimen</td>
<td>No. of Cubes tested</td>
<td>Ultimate load in kN</td>
<td>Comp. Strength in N/mm²</td>
<td>Average Compressive Strength in N/mm²</td>
<td>Density of Concrete (Kg/m³)</td>
</tr>
<tr>
<td>--------------------------</td>
<td>--------------------</td>
<td>---------------------</td>
<td>-------------------------</td>
<td>--------------------------------------</td>
<td>---------------------------</td>
</tr>
<tr>
<td>G 50 (14M-NaOH)</td>
<td>3</td>
<td>1331</td>
<td>59.15</td>
<td>58.42</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>1312</td>
<td>58.32</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1300</td>
<td>57.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 50 (12M-NaOH)</td>
<td>3</td>
<td>1219</td>
<td>54.20</td>
<td>53.50</td>
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<td></td>
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<td>1200</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>1191</td>
<td>52.95</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 50</td>
<td>3</td>
<td>1187</td>
<td>52.77</td>
<td>55.68</td>
<td>2414.81</td>
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<td></td>
</tr>
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<td></td>
<td></td>
<td>1301</td>
<td>57.82</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 40 (14M-NaOH)</td>
<td>3</td>
<td>939</td>
<td>42.58</td>
<td>43.50</td>
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<td>871</td>
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<td></td>
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<td></td>
<td>887</td>
<td>44.77</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 40 (12M-NaOH)</td>
<td>3</td>
<td>778</td>
<td>41.55</td>
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<td>2320.00</td>
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<td></td>
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<td>832</td>
<td>43.25</td>
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<td>810</td>
<td>41.20</td>
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<td></td>
</tr>
<tr>
<td>M 40</td>
<td>3</td>
<td>740</td>
<td>43.50</td>
<td>44.50</td>
<td>2432.85</td>
</tr>
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<td>698</td>
<td>44.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>657</td>
<td>46.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 60 (14M-NaOH)</td>
<td>3</td>
<td>1331</td>
<td>59.00</td>
<td>57.85</td>
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<td>1312</td>
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<td></td>
<td></td>
<td>1300</td>
<td>56.65</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 60 (12M-NaOH)</td>
<td>3</td>
<td>1219</td>
<td>55.85</td>
<td>55.12</td>
<td>2492.00</td>
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<td></td>
<td></td>
<td>1200</td>
<td>54.98</td>
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<td></td>
<td></td>
<td>1191</td>
<td>54.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 60</td>
<td>3</td>
<td>1187</td>
<td>56.55</td>
<td>58.30</td>
<td>2486.45</td>
</tr>
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<td></td>
<td></td>
<td>1270</td>
<td>59.28</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>1301</td>
<td>59.07</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.3.1 Discussions on Results

From the observed test results, the compressive strength of G30, 14M cubes is higher than G30, 12M cubes by 11.5%. Similarly G40, G50 and G60 cubes with 14M concentration have higher compressive strength than their 12M Geopolymer counterparts by 3.6%, 9.2% and 4.6% respectively.

6.4 SPLIT TENSILE STRENGTH

Three numbers of 150mm x 300mm size cylinders were cast each for M30, M50, G30(12M), G30(14M), G50(12M) and G50(14M). Geopolymer specimens were tested for tensile strength at an age of three days after casting while OPC concrete specimens were tested after 28 days of curing. Totally 18 cylinders were tested inclusive of OPC concrete cylinders. The average test results are presented in Table 6.3.
6.4.1 Discussions on Results

From the test result, the tensile strength of Geopolymer concrete G30 specimens manufactured with 14 M Concentration of NaOH was 18.27% greater than the OPC concrete specimens and the same is 3.37% for G30, 12 M concentration. Similarly, G50 14M specimens recorded higher tensile strength than M50 specimens by 5.71% and it was 3.34% for G50 12M specimens. Split tensile strength of G30(14 M), G30(12 M) and M30 specimens was 12.3%, 11.9% and 13.4% of their corresponding compressive strength and the same for G50(14 M), G50(12 M) and M50 was 12.99%, 13.87% and 12.89% respectively. The failure of typical G50 cylinder is shown in Figure 6.8.

![Image](image.png)

**Figure 6.8** Splitting failure of Typical G50 Cylinder
### Table 6.3 Average Split Tensile Strength of Cylinder Specimens

<table>
<thead>
<tr>
<th>Nomenclature of specimen</th>
<th>No. of Cylinders tested</th>
<th>Ultimate load in kN</th>
<th>Split tensile Strength in N/mm²</th>
<th>Average Split tensile Strength in N/mm²²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>G 30 (14M-NaOH)</strong></td>
<td>3</td>
<td>362.43</td>
<td>5.13</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>333.47</td>
<td>4.72</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>346.89</td>
<td>4.91</td>
<td></td>
</tr>
<tr>
<td><strong>G 30 (12M-NaOH)</strong></td>
<td>3</td>
<td>312.98</td>
<td>4.43</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>307.33</td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>291.08</td>
<td>4.12</td>
<td></td>
</tr>
<tr>
<td><strong>M 30</strong></td>
<td>3</td>
<td>296.73</td>
<td>4.20</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>293.19</td>
<td>4.15</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>291.78</td>
<td>4.13</td>
<td></td>
</tr>
<tr>
<td><strong>G 50 (14M-NaOH)</strong></td>
<td>3</td>
<td>538.35</td>
<td>7.62</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>541.89</td>
<td>7.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>528.46</td>
<td>7.48</td>
<td></td>
</tr>
<tr>
<td><strong>G 50 (12M-NaOH)</strong></td>
<td>3</td>
<td>541.88</td>
<td>7.67</td>
<td></td>
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<td></td>
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<td></td>
</tr>
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<td></td>
<td></td>
<td>520.69</td>
<td>7.37</td>
<td></td>
</tr>
<tr>
<td><strong>M 50</strong></td>
<td>3</td>
<td>505.85</td>
<td>7.16</td>
<td></td>
</tr>
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<td></td>
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<td>503.73</td>
<td>7.13</td>
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<tr>
<td></td>
<td></td>
<td>512.21</td>
<td>7.25</td>
<td></td>
</tr>
</tbody>
</table>
6.5 WATER ABSORPTION TEST

Water absorption of G30 specimens after 28 days of immersion was 6.5% lower than M30 grade OPC specimens whereas it was 24% decrease for G50 specimens. These results are obvious from Figure 6.9. This shows the decrease in water absorption in Geopolymer concrete when the grade of concrete was increased. Figure 6.9 shows the variation of water absorption in percentage.

![Figure 6.9 Water Absorption in %](image)

6.5.1 Discussions on Results

Figure 6.9 shows the results of water absorption tests after 28 days of immersion in water. From the test result, the impermeability of Geopolymer concrete G30 specimens had increased by 6.5% when compared with OPC concrete M30 specimens. The same for G50 concrete was 24%
more than M50 concrete. The impermeability increased with increase in compressive strength of Geopolymer concrete due to the well gradation of aggregates used and the inherent property of Geopolymer paste. It is also in good agreement with Anurag Mishra (2008).

6.6 MODULUS OF RUPTURE OF CONCRETE

The Modulus of rupture of concrete was calculated using the following formula given in ASTM C293-02 and the results are presented in Table 6.4.

\[ R = \frac{3PL}{2bd^2} \]  

(6.1)

Where

\( R \) = modulus of rupture in MPa

\( P \) = maximum applied load indicated by the testing machine in N

\( L \) = span length in mm

\( b \) = average width of specimen, at the fracture in mm

\( d \) = average depth of specimen, at the fracture in mm.
Table 6.4 Modulus of Rupture of Concrete

<table>
<thead>
<tr>
<th>Beam ID</th>
<th>No. of specimens</th>
<th>Failure Load in kN</th>
<th>Average Failure load in kN</th>
<th>Modulus of rupture in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30 (14M)</td>
<td>3</td>
<td>9.14</td>
<td>9.07</td>
<td>5.43</td>
</tr>
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<td></td>
<td></td>
<td>9.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.98</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G30 (12M)</td>
<td>3</td>
<td>8.67</td>
<td>8.53</td>
<td>5.11</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>8.47</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M30</td>
<td>3</td>
<td>6.75</td>
<td>6.58</td>
<td>3.94</td>
</tr>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>6.37</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G50 (14 M)</td>
<td>3</td>
<td>10.12</td>
<td>10.04</td>
<td>6.01</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>10.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G50 (12M)</td>
<td>3</td>
<td>9.94</td>
<td>9.80</td>
<td>5.87</td>
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</tr>
<tr>
<td></td>
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<td>9.62</td>
<td></td>
<td></td>
</tr>
<tr>
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<td>3</td>
<td>8.2</td>
<td>7.80</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>7.55</td>
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</tr>
</tbody>
</table>
It is obvious from test results shown in Table 6.4 that the modulus of rupture of Geopolymer concrete respective to their grade and NaOH concentration is much higher than the OPC concrete specimens. Modulus of rupture of G30, 12M concrete is higher than M30 by 29.6% whereas G30, 14M is higher than G30, 12M by 6.3% which is due to the larger concentration of sodium hydroxide that enhanced the compressive strength and in turn modulus of rupture. These results very well coincide with the established results of Table 4.9 of Research report GC-1. Similarly, modulus of rupture of G50, 12M concrete is higher than M50 by 25.7% whereas G50, 14M is higher than G50, 12M by 2.4%. The graphical representation is illustrated in Figure 6.10.

\[ \text{Figure 6.10 Modulus of Rupture} \]
6.7 PULLOUT TEST RESULTS

From the test results, the bond strength for CTD and TMT bars are presented in Table 6.5.

Table 6.5 Comparison of Bond Strength of Various Rebars with Geopolymer Concrete

<table>
<thead>
<tr>
<th>Type of bar</th>
<th>Load at 0.25mm slip (kN)</th>
<th>Bond strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTD</td>
<td>41.0</td>
<td>5.838</td>
</tr>
<tr>
<td>TMT</td>
<td>71.5</td>
<td>9.475</td>
</tr>
</tbody>
</table>

6.7.1 Discussions on Results

From the outcome of the results of pull-out test, the bond between TMT bar and G30 Geopolymer concrete was excellent due to the roughness of steel and the average bond strength of G30(14M) concrete with TMT bar was 23.71% of its average compressive strength whereas it was 14.61% for CTD bar.

6.8 THERMAL STABILITY TEST RESULTS

6.8.1 Change in Compressive Strengths

Test results confirmed the excellent fire resistance of Geopolymer concrete when exposed to temperature of 500°C for six hours. This indicates that the Geopolymerisation process still continued when Geopolymer mortar was exposed to high temperature up to 500°C. It also resulted in drastic strength gain. Also the alteration of plastic deformation of Geopolymers had
made the strength higher. It is also observed that Geopolymer concrete specimens exposed to 500°C yielded the highest compressive strength of 42.5MPa for G30 and 78MPa for G50 type of mixture. The compressive strength increased about 13.15% for G30 type mixture and 25.8% for G50 type mixture. Unlike OPC concrete specimens, Geopolymer concrete gained strength with increase in temperature. As such, this heat-friendly quality of Geopolymers could be well utilized in furnace wall linings in refractories, go-downs/production units of crackers etc. The experimental results are shown in Figure 6.11.

OPC specimens, when exposed to elevated temperature show downward trend in compressive strength. The OPC M30 grade concrete specimens show about 56.75% decrease in compressive strength. Similarly, OPC M50 grade concrete specimens demonstrate 35.94% decrease in compressive strength.

![Figure 6.11 Effect of Temperature on Compressive Strength of Concrete](image)

**Figure 6.11 Effect of Temperature on Compressive Strength of Concrete**
Comparing the strength gained by Geopolymer concretes, 30MPa grade Geopolymer cubes achieved a strength which is 168.75% more than OPC counterparts and 50MPa grade Geopolymer cubes achieved 90.25% more than the counterparts. It is obvious from the above facts that the thermal behavior of Geopolymer concrete is far superior to OPC concrete.

Previous work by Krivenko and Kovalchuk (2002) investigated heat resistant Geopolymer materials manufactured using Class F fly ash, which had good thermal resistance properties up to 800°C. Bakharev (2006) experimented the thermal behavior of Geopolymer specimens prepared using Na-containing activator exposed to fire at 1200°C for 4 hours. He found that all specimens had a tendency of gaining strength in the heat resisting experiment up to 800°C and have showed deterioration in strength rapidly beyond 800°C temperature. Also incomplete polymerization of Geopolymers and presence of high iron content in the fly ash were the prime factors for strength degradation at elevated temperature. The ferric oxide Fe$_2$O$_3$ content in the fly ash used for this study was only 3.67%, which in turn, had reduced subsequent quantum of crystallization of Na-feldspars on firing, a degradation factor in Geopolymers. Daniel Kong and Jay Sanjayan (2010) have found that the strength of Geopolymer paste specimens of 50 MPa grade had an increase in strength of 27.27% at 500°C. Similar results were noted for G30 and G50 concrete as 28.78% and 22.77% respectively in this research. In addition to this, even after exposure to 800°C, Geopolymer paste specimens showed 5.4% improvement over the strength of the reference OPC specimens.

Under prolonged thermal exposure at 500°C for 6 hours, the increase in strength was generally attributed to the sintering process of unreacted aluminosilicate gels in the concrete which was the indicator of the continuance of polymerization. Moreover, under sustained temperature, the
thermal gradient existing between the outer surfaces and core of concrete cubes was minimal which lead to enhancement of strength.

6.8.2 Change in Visual Appearances

OPC concretes show thermal cracks after exposure to fire whereas Geopolymer concretes withstand high temperature and show no cracks. The patches of dark colour are found on the surface of OPC concrete but no such colour change could be seen on the Geopolymer concrete specimens. Spalling of top layer of OPC concrete got started when exposed to fire due to its higher thermal conductivity. As a result, the hot surface of top layers tend to peel off from the cooler core part of the specimen.

6.8.3 Change in Thermogravity

Figure 6.12 presents the test results on the change in mass of Geopolymer concrete specimens after exposure to fire. It can be seen that reduction in the mass of the OPC concrete specimens was slightly more than that of Geopolymer concrete specimens. The mass of OPC concrete specimens after 28 days of moist curing was compared with the mass of the same specimen after exposing it to fire. The average percentage decrease in mass is approximately 3.6%. In the case of Geopolymer concrete specimens, there was no such reduction in mass as that of OPC concrete. Due to evaporation loss that took place while heat curing, the average mass loss had come around 1.12% only. Moreover, the weight of water used in the manufacture of GP concrete was very minimal and subsequently reduction in evaporational loss. In addition to this, invariable of mixture proportion and compressive strength of Geopolymer concrete increased when the trapped water inside Geopolymers escaped.
6.8.4 Discussions on Thermal Stability

- Geopolymer concretes G30 and G50 exhibited high strength when exposed to high temperature. This strength gain is attributed to further polymerization that took place at higher temperatures.

- Under prolonged thermal exposure at 500 °C for 6 hours, the increase in strength was generally attributed to the sintering process of unreacted aluminosilicate gels in the concrete taking place, which was the indicator of the continuation of polymerization.

- Under sustained temperature, the thermal gradient existing between the outer surfaces and core of concrete cubes was very minimal which lead to enhancement of strength.
The ferric oxide \( \text{Fe}_2\text{O}_3 \) content in the fly ash used for this study was only 3.67%, which in turn, had reduced subsequent quantum of crystallization of Na-feldspars on firing, a strength degradation factor in Geopolymers.

Geopolymer concrete of both G30 and G50 mixes showed very low thermal conductivity and thus exhibited excellent resistance to heat and fire.

Variations in temperature have no influence in the weight reduction of Geopolymer concretes. Small reduction in mass is encountered due to evaporation of residual water during heat curing.

No thermal cracks were noticed on the surfaces of Geopolymer concretes up to 500°C. Curing at high temperatures, above 500°C, Geopolymers resulted in cracking and thus had a negative effect on physical properties of surfaces.

6.9 TEST RESULTS OF PROMINENT PARAMETERS ON STRENGTH

6.9.1 Ratio of Alkaline Liquid to Fly Ash

When the ratio of alkaline liquid to fly ash increased, high strength concrete was attained. Considering this prime factor while mixture proportioning, concrete of desired target strength was achieved. From Table 6.6, it was noted that an incremental increase of 1% of alkaline liquid to fly ash had augmented compressive strength by 5.17 MPa. Increase of the same by 2% had boosted up the strength by 13.21 MPa. It was difficult to rise up the
strength beyond reaching the target strength of 50 MPa. It needed an increase of 6% in this ratio to lift up mean compressive strength by 0.54 MPa.

**Table 6.6 Effect of Alkaline Liquid to Fly ash Ratio**

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Ratio of alkaline liquid to fly ash</th>
<th>Mean compressive strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>0.46</td>
<td>37.92</td>
</tr>
<tr>
<td>G40</td>
<td>0.47</td>
<td>42.75</td>
</tr>
<tr>
<td>G50</td>
<td>0.49</td>
<td>55.96</td>
</tr>
<tr>
<td>G60</td>
<td>0.55</td>
<td>56.50</td>
</tr>
</tbody>
</table>

Monita Olivia (2011) found out that the compressive strength of Geopolymer deteriorated due to the increase in fly ash content in the mixture. Lesser alkaline activator to activate large amount of fly ash had resulted in the formation of an aluminosilicate covering with a lot of unreacted fly ash which necessitated higher ratio of alkaline solution to fly ash to achieve higher strength.

A M Mustafa Al Bakri et al (2011) demonstrated that varying alkaline activator/fly ash ratio from 0.30 to 0.35, an increase in compressive strength by 4.63 MPa was observed and it was 0.285 MPa when the ratio was increased from 0.35 to 0.40. This was possible due to the change in the alkaline activator content which had affected the quantity of Si species.

6.9.2 **Concentration of Sodium Hydroxide (NaOH) Solution**

The effect of concentration of NaOH solution on compressive strength of concrete was studied and results are shown in Table 6.7.
Table 6.7 Effect of Concentration of NaOH Solution

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH liquid (molars)</th>
<th>Mean compressive strength at 7th day (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>8M</td>
<td>32.44</td>
</tr>
<tr>
<td>G30</td>
<td>10M</td>
<td>33.78</td>
</tr>
<tr>
<td></td>
<td>12M</td>
<td>35.85</td>
</tr>
<tr>
<td></td>
<td>14M</td>
<td>39.96</td>
</tr>
<tr>
<td></td>
<td>8M</td>
<td>41.88</td>
</tr>
<tr>
<td>G40</td>
<td>10M</td>
<td>42.82</td>
</tr>
<tr>
<td></td>
<td>12M</td>
<td>42.00</td>
</tr>
<tr>
<td></td>
<td>14M</td>
<td>43.85</td>
</tr>
<tr>
<td></td>
<td>8M</td>
<td>52.24</td>
</tr>
<tr>
<td>G50</td>
<td>10M</td>
<td>52.85</td>
</tr>
<tr>
<td></td>
<td>12M</td>
<td>53.50</td>
</tr>
<tr>
<td></td>
<td>14M</td>
<td>58.42</td>
</tr>
<tr>
<td></td>
<td>8M</td>
<td>54.11</td>
</tr>
<tr>
<td>G60</td>
<td>10M</td>
<td>54.35</td>
</tr>
<tr>
<td></td>
<td>12M</td>
<td>55.12</td>
</tr>
<tr>
<td></td>
<td>14M</td>
<td>57.85</td>
</tr>
</tbody>
</table>

Compressive strength increased with the increase in concentration of sodium hydroxide solution in terms of molarity at particular temperature under dry heat curing after 24 hours. These results very well coincide with the established results of Table 4.9 of Research report GC-1. Keeping the ratio of Na₂SiO₃ to NaOH as 0.4 and increasing the concentration of NaOH liquid from 8M to 14M, they had obtained an enhanced compressive strength of
48MPa from 17MPa and when the ratio of Na$_2$SiO$_3$ to NaOH was fixed as 2.5, the strength gained from 57MPa to 67MPa with the change in NaOH concentration from 8M to 14M.

6.9.3 Ratio of Sodium Silicate Solution to Sodium Hydroxide Solution

The effect of ratio of sodium silicate solution to sodium hydroxide solution was studied and tabulated in Table 6.8.

Table 6.8 Effect of Ratio of Na$_2$SiO$_3$ to NaOH

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Ratio of Na$_2$SiO$_3$ to NaOH by mass</th>
<th>Mean compressive strength in N/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>8M</td>
<td>0.5</td>
<td>15.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>18.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>22.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>25.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>32.44</td>
</tr>
<tr>
<td>G30</td>
<td>14M</td>
<td>0.5</td>
<td>17.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>19.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>22.75</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>30.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>39.96</td>
</tr>
<tr>
<td>G50</td>
<td>8M</td>
<td>0.5</td>
<td>22.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>27.98</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>33.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>39.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>52.24</td>
</tr>
<tr>
<td>G50</td>
<td>14M</td>
<td>0.5</td>
<td>23.58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>29.85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.5</td>
<td>39.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>45.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.5</td>
<td>57.42</td>
</tr>
</tbody>
</table>
Invariably, for all the concentration of NaOH tested, the strength increased with the increase in the ratio of Na$_2$SiO$_3$ to NaOH.

6.9.4 Curing Temperature

The results of the parametric study on the effect of curing temperature are tabulated in Table 6.9.

**Table 6.9 Effect of Curing Temperature**

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Mean compressive strength in N/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>8M</td>
<td>60°C</td>
<td>32.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70°C</td>
<td>33.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80°C</td>
<td>34.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90°C</td>
<td>34.98</td>
</tr>
<tr>
<td>G50</td>
<td>8M</td>
<td>60°C</td>
<td>49.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70°C</td>
<td>51.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td>80°C</td>
<td>52.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90°C</td>
<td>59.54</td>
</tr>
</tbody>
</table>

Interestingly, as the temperature increased, Geopolymer concrete gave higher compressive strength. In G50 concrete, for the same mixture proportions of materials, a rise in 30°C temperature showed a steep increase in strength by 10.20 MPa. Unlike G50, in G30 concrete, for the same 30°C the strength gain was not so sharp, but only 2.64 MPa. Consideration of this criterion could help in achieving higher strength concrete without altering the quantity of constituents. Instead, for the manufacture of G30 concrete, less
heat is sufficient to attain its target strength. Pozzolanic reactions were accelerated by temperature increase from 60°C to 90°C which in turn improved the compressive strength. Brooks JJ (2002) had established that viscosity of the mixture increased 5 times when the increase in temperature was from 45°C to 65°C and when the temperature got increased further from 65°C to 85°C the viscosity increased 10 times. Viscosity of mixture was an influencing property in strength enhancement.

6.9.5 Curing Time

The results of the parametric study on the effect of curing time are tabulated in Table 6.10. This study was done in order to optimize the curing time and subsequently, savings in electric power and cost of manufacturing.

Table 6.10 Effect of Curing Time

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molar</th>
<th>Curing temperature</th>
<th>Curing time in hours</th>
<th>Mean compressive strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>12M</td>
<td>60°C</td>
<td>4</td>
<td>16.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>28.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>32.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>36.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td>37.45</td>
</tr>
<tr>
<td>G50</td>
<td>12M</td>
<td>60°C</td>
<td>4</td>
<td>31.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8</td>
<td>42.34</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>16</td>
<td>51.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>24</td>
<td>53.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36</td>
<td>58.34</td>
</tr>
</tbody>
</table>
From the results, it is observed that invariable of grade of Geopolymer concrete, the target compressive strength was achieved after 16 hours of curing. Strength gain was noticed in both G30 and G50 concretes until 36 hours of curing without showing any downward trend which was due to the fact that prolonged curing time improved the polymerization process and thereby the compressive strength as claimed by Hardjito D et al (2005).

6.9.6 Rest Period

The results of the parametric study on the effect of rest period are tabulated in Table 6.11. This study was done to test the applicability of Geopolymer concrete in RMC plants.

Table 6.11 Effect of Rest Period

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Curing time in hours</th>
<th>Rest period in days</th>
<th>Mean compressive strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G50</td>
<td>12M</td>
<td>60°C</td>
<td>24</td>
<td>0</td>
<td>52.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.5</td>
<td>52.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>53.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2</td>
<td>53.23</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>54.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>56.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>57.43</td>
</tr>
</tbody>
</table>
It is interesting to note that Geopolymer concrete shall be well utilized until 5 days after removal from Pan mixer. Unlike, OPC concrete, this concrete allows for time before handling as well as curing. No appreciable increase in strength was seen up to 2 days. But beyond 2 days, strength gradually increased to considerable value.

6.9.7 Handling Time

The results of the study on the effect of handling time are tabulated in Table 6.12. It was observed from the results that Geopolymer concrete could be handled up to 210 minutes after removal from Pan mixer without any indication of setting and degradation in strength. This result firms up the handling time beyond the established time of 120 minutes as claimed by Hardjito D et al (2005).

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Curing time in hours</th>
<th>Handling time in minutes</th>
<th>Mean compressive strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>8M</td>
<td>60°C</td>
<td>24</td>
<td>0</td>
<td>32.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>32.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>45</td>
<td>32.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60</td>
<td>33.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>33.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>105</td>
<td>34.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>120</td>
<td>35.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150</td>
<td>35.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>180</td>
<td>34.55</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>210</td>
<td>34.25</td>
</tr>
</tbody>
</table>
6.9.8 Mixing Time

The results of the study on effect of mixing time on compressive strength of concrete are tabulated in Table 6.13. Hardjito D et al (2005) had found that the mixing time when prolonged to 16 minutes yielded higher compressive strength and it was 38 MPa for 2 minutes and 52 MPa for 16 minutes. Longer mixing time facilitates the dissolution of silica in the raw materials. In addition, the viscosity of the material increased with the dissolved solids content. Brooks JJ (2002) had declared that viscosity of mixture was an influencing property in strength enhancement.

Table 6.13 Effect of Mixing Time on Strength

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Curing time in hours</th>
<th>Mixing time in minutes</th>
<th>Mean compressive strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G50</td>
<td>12M</td>
<td>60°C</td>
<td>24</td>
<td>3</td>
<td>42.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>45.36</td>
</tr>
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<td></td>
<td>7</td>
<td>49.23</td>
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<td>9</td>
<td>51.11</td>
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<td></td>
<td></td>
<td>12</td>
<td>53.11</td>
</tr>
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<td></td>
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<td>15</td>
<td>57.34</td>
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<td></td>
<td></td>
<td>18</td>
<td>58.25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20</td>
<td>59.15</td>
</tr>
</tbody>
</table>
6.9.9 Time of Preparation of Alkaline Solution

The results of the parametric study on the effect of time of preparation of alkaline solution are tabulated in Table 6.14. This study was done to test the applicability of Geopolymer concrete in RMC plants. Davidovits (2002) suggested to mix sodium silicate solution and sodium hydroxide solution together at least for 24 hours before adding to solids. Mustafa Al Bakri AM et al (2011) had demonstrated that mixing the solutions just before mixing with fly ash achieved a compressive strength of 55MPa. Nath P and Sarker PK (2012) had demonstrated that mixing the solution 30 minutes before adding with dry solids and cured in ambient condition for 28 days had obtained a strength of 55MPa.

Table 6.14 Effect of time of preparation of alkaline solution on strength

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Curing time in hours</th>
<th>Time of preparation of alkaline solution</th>
<th>Mean compressive strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G50</td>
<td>12M</td>
<td>60°C</td>
<td>24</td>
<td>10 minutes</td>
<td>58.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 hour</td>
<td>58.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2 hours</td>
<td>57.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6 hours</td>
<td>57.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>12 hours</td>
<td>56.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>24 hours</td>
<td>56.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>48 hours</td>
<td>52.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>72 hours</td>
<td>50.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>168 hours</td>
<td>49.67</td>
</tr>
</tbody>
</table>
However, in this research work the highest strength was achieved with alkaline solution prepared and used within 10 minutes and using the alkaline solution even after 7 days, the target strength of concrete was not altered appreciably.

Unlike data given in CG-1 report, high strength was achieved by immediate mixing of alkaline solution into pan mixer after preparation of the same. It was also noted that the alkaline solution could be used upto 7 days, without degradation in the target strength.

**6.9.10 Age of Concrete**

The effect of the age of concrete on compressive strength was studied, from 3 days to 365 days. The results obtained are tabulated in Table 6.15. This test was done to study the property of hardened concrete rather than the behavior of fresh concrete mentioned in earlier tests. The results were substantiated in Figure 6.13.

Hadjito D et al (2005) had tested the hardened concrete after 90 days and found the strength increasing from 48MPa to 52MPa and this is similar to the results of current research which depicted an increase from 48.22MPa to 55.33MPa at the age of 90 days.
Table 6.15  Effect of Age of Concrete on Strength

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Age of concrete in days</th>
<th>Mean compressive strength in N/mm$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>12M</td>
<td>60°C</td>
<td>3</td>
<td>30.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>30.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>31.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>33.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>34.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>34.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>365</td>
<td>36.45</td>
</tr>
<tr>
<td>G50</td>
<td>12M</td>
<td>60°C</td>
<td>3</td>
<td>48.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7</td>
<td>47.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>51.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>53.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>53.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>55.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>365</td>
<td>58.34</td>
</tr>
</tbody>
</table>
Figure 6.13 Effect of Age of Concrete on Strength

6.9.11 Mode of Curing

The comparison of results of ambient temperature curing and dry heat curing of concrete on compressive strength was studied. The results are tabulated in Table 6.16. The Geopolymer concrete cubes were cured under
Table 6.16 Effect of Mode of Curing on Strength

<table>
<thead>
<tr>
<th>Mix identity</th>
<th>Concentration of NaOH in Molars</th>
<th>Curing temperature</th>
<th>Mode of curing</th>
<th>Age of concrete in days</th>
<th>Mean compressive strength in N/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>12M</td>
<td>60°C</td>
<td>Dry-heat curing</td>
<td>7</td>
<td>30.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>31.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>33.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>34.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>34.54</td>
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<td>365</td>
<td>36.45</td>
</tr>
<tr>
<td>G50</td>
<td>12M</td>
<td>60°C</td>
<td>Dry-heat curing</td>
<td>7</td>
<td>47.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>51.22</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>53.24</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
<td>56</td>
<td>53.65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>55.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>365</td>
<td>58.34</td>
</tr>
<tr>
<td>G30</td>
<td>12M (average)</td>
<td>32°C</td>
<td>Ambient temperature curing</td>
<td>7</td>
<td>15.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>19.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>28.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>32.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>37.33</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>365</td>
<td>41.56</td>
</tr>
<tr>
<td>G50</td>
<td>12M (average)</td>
<td>32°C</td>
<td>Ambient temperature curing</td>
<td>7</td>
<td>32.43</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>14</td>
<td>37.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>28</td>
<td>49.11</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>56</td>
<td>51.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>91</td>
<td>58.77</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>365</td>
<td>62.45</td>
</tr>
</tbody>
</table>
dry-heat curing mode for 24 hours and tested after 3, 7, 14, 28, 56, 91, 365 days, to match with the other mode of curing observations. Figure 6.14 shows the comparison graph of G30 and G50 concrete at two different modes of curing.

In the ambient temperature curing the target strength of concrete could be achieved only after 45 days as against the established result of 28 days. G50 concrete at the age of 7 days gave a compressive strength of 32.43MPa and at 28 days yielded 43.11MPa. Nath P and Sarker PK (2012) had revealed that they achieved a compressive strength of 42MPa at 7 days and 55MPa at 28 days.
6.10 **ELASTIC CONSTANT**

As expected modulus of elasticity increased as the compressive strength of concrete increased. It can be seen from Table 6.17 that the measured values were consistently lesser than the values calculated using equation in IS 456: 2000.

<table>
<thead>
<tr>
<th>Mixture Identity</th>
<th>$E_c$ from test (MPa)</th>
<th>$E_c$ from IS 456:2000 $E_c = 5000 \sqrt{f_{ck}}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G30</td>
<td>24290</td>
<td>27386</td>
</tr>
<tr>
<td>M30</td>
<td>25060</td>
<td>27386</td>
</tr>
<tr>
<td>G60</td>
<td>36570</td>
<td>38729</td>
</tr>
<tr>
<td>M60</td>
<td>37810</td>
<td>38729</td>
</tr>
</tbody>
</table>

Duxson et al (2007) reported that the elastic modulus of Geopolymer concrete depended on the SiO$_2$/Al$_2$O$_3$ ratio and Sofi et al (2007) found that the elastic modulus of Geopolymer concrete depended not only on SiO$_2$/Al$_2$O$_3$ ratio but also on mix design and curing method. Hardjito D and Rangan BV (2005) experimented and gave results of modulus of elasticity for Geopolymer concrete of 44MPa strength as 23GPa and the same for Geopolymer concrete of 55MPa strength as 26.1GPa. Comparatively, the observed results in this research work yielded higher modulus of elasticity reading 24.29 GPa for G30 concrete and 36.57GPa for G60 concrete. Also the Modulus of Elasticity of Geopolymer Concretes was marginally lower than that of Ordinary Cement Concretes due to lesser density of Geopolymer concrete, at similar strength levels.
6.11 REINFORCED CONCRETE SHORT COLUMNS

6.11.1 Series-A Columns

Figure 6.15 Typical Crack Pattern and Failure Mode of G40 Columns

All the columns failed at the ends, exhibiting shear failure. In all cases, cracks initiated at the ends of columns and as the load increased, the existing cracks propagated and new cracks formed along the length of columns. The width of cracks varied depending on the location. Some typical failure modes of tested columns are shown in Figure 6.15.

6.11.1.1 Load-Deflection Relationship

The load versus deflection graphs of tested columns are presented in Figures 6.16 to 6.18. As expected, the deflection of columns at failure increased as the load increased.
Figure 6.16 Load Vs Mid-height Deflection Curve of G40-1

Figure 6.17 Load Vs Mid-height Deflection Curve of G40-2
6.11.1.2 Correlation of Test and Calculated Results

The failure loads of reinforced Geopolymer columns are compared with the calculated values by using Indian standard codes. Experimental ultimate load was compared with that of GC-3 report data and been presented in Table 6.18.

Table 6.18 Correlation of Test Results

<table>
<thead>
<tr>
<th>Column Identity</th>
<th>Longitudinal Reinforcement</th>
<th>Experimental Failure Load (kN)</th>
<th>GC-3 report data (kN)</th>
<th>Correlation ratio (r)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G40-1</td>
<td>4N12 mm</td>
<td>1.47</td>
<td>902</td>
<td>940</td>
</tr>
<tr>
<td>G40-2</td>
<td>4N12 mm</td>
<td>1.47</td>
<td>890</td>
<td>940</td>
</tr>
<tr>
<td>G40-3</td>
<td>4N12 mm</td>
<td>1.47</td>
<td>922</td>
<td>940</td>
</tr>
</tbody>
</table>
It was observed from the correlation ratio that all the G40 columns took ultimate load equal to that of GCI-1 columns.

6.11.2 Series-B columns

6.11.2.1 Load Carrying Capacity

As expected, the load carrying capacity of the columns increased with the increase in compressive strength of concrete. The failure loads of reinforced Geopolymer concrete short columns are compared with the calculated values using Indian Standard codes. Ultimate load is calculated using the formula $0.4 \cdot f_{ck} \cdot A_c + 0.6 \cdot f_y \cdot A_{sc}$. The load capacity of test columns are calculated using the design provisions contained in Section 39.3 of IS 456: 2000. Comparison of tested and calculated failure loads are tabulated in Table 6.19. It is established that all the columns according to the Grade behaved similarly which is obvious from the test results. All the G30 Grade columns have shown exemplary results in load carrying capacity than M 30 Grade Concrete Columns by around 41% and G50 Grade Columns are stronger than M50 Grade concrete columns by 5% which might be due to the rigidity of higher grade Geopolymeric materials.
Table 6.19  Details of Series-B Columns and their Results

<table>
<thead>
<tr>
<th>Nomen-Clature</th>
<th>No. of columns cast</th>
<th>Details of Companion Concrete</th>
<th>Failure load (kN)</th>
<th>Calculated Failure load (kN)</th>
<th>Correlation ratio</th>
<th>Compressive Strength of Column (MPa)</th>
<th>Ductility Index (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>specimen</td>
<td></td>
<td>No. of cubes cast</td>
<td>Cube Comp. Strength (MPa)</td>
<td>Split tensile strength (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RGPCC I</td>
<td>3</td>
<td>3</td>
<td>34.59</td>
<td>4.42</td>
<td>542</td>
<td>307.85</td>
<td>34.68</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35.85</td>
<td>4.58</td>
<td>578</td>
<td>307.85</td>
<td>36.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36.00</td>
<td>4.89</td>
<td>581</td>
<td>307.85</td>
<td>37.184</td>
</tr>
<tr>
<td>RCCC I</td>
<td>3</td>
<td>3</td>
<td>32.90</td>
<td>4.21</td>
<td>402</td>
<td>307.85</td>
<td>25.73</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>31.04</td>
<td>4.03</td>
<td>410</td>
<td>307.85</td>
<td>26.24</td>
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<td></td>
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<td></td>
<td>30.67</td>
<td>4.09</td>
<td>413</td>
<td>307.85</td>
<td>26.43</td>
</tr>
<tr>
<td>RGPCC II</td>
<td>3</td>
<td>3</td>
<td>54.20</td>
<td>7.35</td>
<td>524</td>
<td>489.93</td>
<td>33.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>53.35</td>
<td>7.05</td>
<td>537</td>
<td>489.93</td>
<td>34.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>52.95</td>
<td>7.47</td>
<td>539</td>
<td>489.93</td>
<td>34.49</td>
</tr>
<tr>
<td>RCCC II</td>
<td>3</td>
<td>3</td>
<td>52.77</td>
<td>7.03</td>
<td>507</td>
<td>489.93</td>
<td>32.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>56.44</td>
<td>7.11</td>
<td>511</td>
<td>489.93</td>
<td>32.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>57.82</td>
<td>7.24</td>
<td>514</td>
<td>489.93</td>
<td>32.89</td>
</tr>
</tbody>
</table>

* RGPCC-I: Reinforced Geopolymer concrete column (G30)
RGPCC-II: Reinforced Geopolymer concrete column (G50)
RCCC-I: Reinforced Cement concrete column (M30)
RCCC-II: Reinforced Cement concrete column (M50)

6.11.2.2 Ductility

Regardless of Material, all the M30 Grade concrete columns possess high ductility index, which is appreciable for structural elements. But
having lesser ductility index, M50 Grade concrete columns exhibited
undesirable brittle failure. Due to this factor, M50 Grade concrete columns
have broken suddenly with a loud sound. The Ductility index (μ) of column is
the area of the load-deformation curve under peak load to the area of load-
deformation curve under the elastic load level, which shall be evaluated from
the ratio of compressive strength of reinforced column to the compressive
strength of plain concrete cube.

Figure 6.19 Failure Mode of G30 Grade Column (Typical)
Figure 6.20 Failure Mode of G50 Grade Column (Typical)

6.11.2.3 Ductility, Crack Patterns and Failure Modes

The initiation of cracks is seen at the mid-height of all Columns
except G50. The cracks get propagated with increase in applied load allowing
new cracks. The width of cracks at mid-height opened gradually, as the load increased until failure. The zone of failure is around 175mm above and below the mid-height of G30 columns. The mode of failure shall be seen in Figure 6.19. Invariably, in all G50 grade concrete columns, cracks initiated at the head of the column. The crack propagated upto 300mm below the top end of column. The mode of failure is seen in Figure 6.20. The reason for such failure may be due to rigidity of concrete with increase in compressive strength.

6.11.2.4 Load Vs Mid Height Deflection

The Load Vs mid-height deflection curves of M30 grade Geopolymer concrete columns and its counterparts are illustrated in Figure 6.21 and the same for M50 grade concretes are shown in Figure 6.22.

![Load vs Deflection Curves](image)

**Figure 6.21 Load Vs Mid-height Deflection-Comparison Graph (M 30 and G 30)**
From the graphs shown in Figures 6.19 and 6.20, it can be noted that the behaviour of Geopolymer concrete and reference concrete is similar to one another.

6.11.3 Series-C Columns

6.11.3.1 Load Carrying Capacity

As expected, the load carrying capacity of the columns increased with the increase in compressive strength of concrete. The failure loads of reinforced Geopolymer concrete set-A short columns are compared with the calculated values by using Indian Standard codes. Ultimate load of set-A column was calculated by using the formula $0.4 f_{ck} A_c + 0.6 f_y A_{sc}$. The load capacity of Set-B columns is calculated using the design provisions contained in Clause 38.0 of IS 456: 2000, based on “Bresler’s Load Contour Method”. It is established that all the columns according to the Grade behaved similarly.
which is obvious from the test results shown in the Table 6.20. All the G30 Grade Set-A columns have shown exemplary results in load carrying capacity than M30 Grade Concrete Columns by around 44%. All the G30 Grade Set-B columns have shown exemplary results in load carrying capacity than M30 Grade Concrete Columns by around 38%.

Table 6.20  Details of Series-C Columns and their Results

<table>
<thead>
<tr>
<th>Nomenclature of specimen</th>
<th>Column ID</th>
<th>Number of columns Cast</th>
<th>Details of Companion concrete</th>
<th>Failure load (kN)</th>
<th>Correlation ratio</th>
<th>Compressive Strength of Column (MPa)</th>
<th>Ductility Index (µ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Cube Comp. Strength (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Split tensile strength (MPa)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Set-A</td>
<td>G30</td>
<td>3</td>
<td>34.20</td>
<td>4.35</td>
<td>328</td>
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<td></td>
</tr>
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<td></td>
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<td>36.20</td>
<td>4.56</td>
<td>356</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34.35</td>
<td>4.42</td>
<td>316</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>M30</td>
<td>3</td>
<td>32.77</td>
<td>4.23</td>
<td>234</td>
<td>1.44</td>
<td>41.75 1.22</td>
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<td></td>
<td></td>
<td>36.44</td>
<td>4.41</td>
<td>246</td>
<td></td>
<td>45.34 1.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>32.95</td>
<td>4.27</td>
<td>212</td>
<td></td>
<td>40.19 1.17</td>
</tr>
<tr>
<td></td>
<td>G30</td>
<td>3</td>
<td>34.59</td>
<td>4.42</td>
<td>318</td>
<td></td>
<td></td>
</tr>
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<td>35.85</td>
<td>4.58</td>
<td>301</td>
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<td>36.00</td>
<td>4.89</td>
<td>308</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>M30</td>
<td>3</td>
<td>32.90</td>
<td>4.21</td>
<td>238</td>
<td>1.38</td>
<td>40.47 1.17</td>
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<td></td>
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<td>31.04</td>
<td>4.03</td>
<td>229</td>
<td></td>
<td>38.35 1.05</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>30.67</td>
<td>4.09</td>
<td>205</td>
<td></td>
<td>39.24 1.09</td>
</tr>
</tbody>
</table>

6.11.3.2 Ductility

Regardless of material, all the G30 Grade concrete columns possess high ductility index, which is appreciable for structural elements. But having lesser ductility index than G30 columns, M30 Grade concrete columns
exhibited a little undesirable brittle failure. Due to this factor, M30 Grade concrete columns have broken suddenly. From the ductility index, it could be seen that G30 columns, irrespective of loading, showed slight ductility before failure. But, the ductility index of M30 columns being less than 1, the failure was sudden without warning. The Ductility index (μ) of column is the area of the load-deformation curve under peak load to the area of load-deformation curve under the elastic load level, which shall be evaluated from the ratio of compressive strength of reinforced column to the compressive strength of plain concrete cube.

6.11.3.3 Crack Patterns and Failure Modes

The initiation of cracks is seen at the mid-height of all Set-A and Set-B Columns. The cracks, then, get propagated with increase in applied load allowing new cracks. The width of cracks at mid-height opened gradually, as the load increased until failure. The zone of failure is around 125mm above and below the mid-height of G30 columns.

Figure 6.23 Failure Mode of Set-A G30 Grade Columns
The mode of failure shall be seen in Figures 6.23 and 6.24. The crack propagated upto 200mm below the top end of all M30 columns. Lesser ductility could be seen in all M30 columns from Figures 6.25 and 6.26.

Figure 6.24  Failure Mode of Set-B G 30 Grade Columns

Figure 6.25  Failure Mode of Set-A M 30 Grade columns
6.11.3.4 Load Vs Mid-height Deflection

The Load Vs mid-height deflection curves of Set-A Geopolymer concrete columns and its counterparts are illustrated in the Figure 6.27 and the same for Set-B columns are shown in Figure 6.28.
From the graphs, it could be well understood that the behaviour of Geopolymer Concretes and reference concretes are similar to one another.

![Load Vs Mid-height Deflection curves of set-B columns](image)

Figure 6.28 Load Vs Mid-height Deflection – Comparison Curves of Set-B Columns

6.11.4 Slender Columns

6.11.4.1 Series-D Columns

Load Carrying Capacity

All columns are tested under monotonically increasing axial compressive load. As expected, the load carrying capacity of the columns increased with the increase in compressive strength of concrete. The failure loads of reinforced Geopolymer long columns are compared with its counterpart concrete columns. Comparison of failure loads of Geopolymer Concrete Columns and Ordinary Portland Cement Concrete Columns is
tabulated in Table 6.21. It is established that all the columns according to their corresponding Grade behaved similarly, which is obvious from the test results shown in the Table 6.21. All the G30 Grade columns have shown exemplary results in load carrying capacity than M30 Grade concrete columns by 34.2%. G50 Grade Columns are stronger than M50 Grade concrete columns by 27% which was due to the rigidity of higher grade Geopolymeric materials. This shows that the higher strength concrete columns have shown a sudden drop in load after peak is reached. This observed phenomenon reveals that there may be a possibility of stability failure to occur in higher strength concrete columns. The load vs mid-height deflection curves of Geopolymer Concrete columns (typical) and OPC Concrete Columns are shown in Figure 6.29.

![Load Vs Mid-height deflection curves of series-D columns](image)

**Figure 6.29** Load – mid Height Deflection Curves of Typical Geopolymer Concrete Columns and Typical OPC Concrete Columns
Table 6.21 Details of series-D columns and their results

<table>
<thead>
<tr>
<th>Specimen Id</th>
<th>Details of Companion Concrete elements</th>
<th>Ultimate Load Tested $P_{ut}$ (kN)</th>
<th>Calculated Ultimate Load $P_{uc}$ (kN)</th>
<th>Correlation Ratio $P_{ut}/P_{uc}$</th>
<th>Compressive Strength of Column (MPa)</th>
<th>Ductility Index ($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G 30-I</td>
<td></td>
<td>34.59</td>
<td>296</td>
<td>1.47</td>
<td>37.77</td>
<td>1.09</td>
</tr>
<tr>
<td>G 30-II</td>
<td></td>
<td>35.85</td>
<td>276</td>
<td>1.37</td>
<td>35.16</td>
<td>0.98</td>
</tr>
<tr>
<td>G 30-III</td>
<td></td>
<td>36.00</td>
<td>302</td>
<td>1.50</td>
<td>38.47</td>
<td>1.07</td>
</tr>
<tr>
<td>M 30-I</td>
<td></td>
<td>32.90</td>
<td>244</td>
<td>1.21</td>
<td>31.08</td>
<td>0.94</td>
</tr>
<tr>
<td>M 30-II</td>
<td></td>
<td>31.04</td>
<td>196</td>
<td>0.97</td>
<td>24.96</td>
<td>0.80</td>
</tr>
<tr>
<td>M 30-III</td>
<td></td>
<td>30.67</td>
<td>222</td>
<td>1.09</td>
<td>28.22</td>
<td>0.92</td>
</tr>
<tr>
<td>G 50-I</td>
<td></td>
<td>54.20</td>
<td>393</td>
<td>1.02</td>
<td>50.06</td>
<td>0.93</td>
</tr>
<tr>
<td>G 50-II</td>
<td></td>
<td>53.35</td>
<td>444</td>
<td>1.43</td>
<td>56.56</td>
<td>1.06</td>
</tr>
<tr>
<td>G 50-III</td>
<td></td>
<td>52.95</td>
<td>348</td>
<td>1.12</td>
<td>44.33</td>
<td>0.84</td>
</tr>
<tr>
<td>M 50-I</td>
<td></td>
<td>52.77</td>
<td>278</td>
<td>0.89</td>
<td>28.19</td>
<td>0.53</td>
</tr>
<tr>
<td>M 50-II</td>
<td></td>
<td>56.44</td>
<td>243</td>
<td>0.79</td>
<td>30.86</td>
<td>0.55</td>
</tr>
<tr>
<td>M 50-III</td>
<td></td>
<td>57.82</td>
<td>313</td>
<td>1.01</td>
<td>29.72</td>
<td>0.51</td>
</tr>
</tbody>
</table>

Ductility

The concept of ductility is related to the ability to sustain inelastic deformations without substantial decrease in the load carrying capacity. From the experimental results, it is inferred that, regardless of material properties, all the 30MPa Grade concrete columns possess high ductility Index, which is appreciable for structural elements. All G50 Grade concrete columns exhibited more ductility than M50 concrete columns. It is well established
that whenever the grade of concrete increases, the material tends to result in lower ductility. When Geopolymer concrete columns are used for earthquake resistance structures, a ductile type behavior is recommended and is essential to form plastic hinges and to enhance their capacity to absorb and dissipated energy without significant loss in strength. From this point of view, it is observed that Geopolymer concrete possesses superior quality.

Crack Patterns and Failure Modes

The initiation of cracks is seen at the mid-height of all Columns, invariable of Grade of concrete and type of materials. The cracks get propagated with increase in applied load allowing new cracks to form. All the G30 Grade columns showed buckling of reinforcement, as witnessed from Figure 6.30, as the load increased until failure. The zone of failure is around 175mm above and below the mid-height of RGPCC I columns. The mode of failure shall be seen in Figure 6.30. Invariably, in all M50 grade concrete columns, cracks initiated near the head of the column and the crack propagated at the circumference of column 450mm below the top end of column. The mode of failure is seen in Figure 6.31. The reason for such failure may be due to rigidity of concrete with increase in compressive strength.
Figure 6.30 Failure Pattern of G30 Concrete Column (Typical)

Figure 6.31 Failure Pattern of G50 Concrete Column (Typical)
Ultimate Loads

The ultimate loads concrete can withstand without failure are given in Figure 6.32.

![Comparison of Ultimate loads](image)

**Figure 6.32 Comparison of Ultimate Loads for G30 and G50 Concrete Columns**

It is inferred from the bar charts that both G30 and G50 grade concrete columns took higher loads when compared with calculated and its corresponding counterparts.

6.11.4.2 Series-E Columns

Load Carrying Capacity

All columns are tested under monotonically increasing compressive load at biaxial eccentricity of 15mm. As expected, the load carrying capacity of the columns increased with the increase in compressive strength of
concrete. The failure loads of reinforced Geopolymer concrete long columns are compared with the results of its counterpart concrete columns. Comparison of failure loads of tested Geopolymer concrete columns and Ordinary Portland Cement concrete columns is tabulated in Table 6.22. It is established that all the columns according to their corresponding Grade behaved similarly, which is obvious from the test results shown in the Table 6.22.

All the G 30 Grade columns have shown exemplary results in load carrying capacity than M 30 Grade concrete columns by 20.1% and G50 Grade Columns are stronger than M50 Grade concrete columns by 23.87% which is due to the rigidity of higher grade Geopolymeric materials. The load vs mid-height deflection curves of Geopolymer Concrete columns (typical) and OPC Concrete Columns are shown in Figure 6.33.

![Load Vs Mid-height deflection curves of Series-E columns](image)

Figure 6.33 Load–mid Height Deflection Curves of Typical Geopolymer Concrete Columns and Typical OPC Concrete Columns
Ductility

Table 6.22 Details of Series-E Columns and their Results

<table>
<thead>
<tr>
<th>Specimen Id</th>
<th>No. of cubes Cast</th>
<th>Details of Companion Concrete elements</th>
<th>Ultimate Load Tested $P_{ut}$ (kN)</th>
<th>Compressive Strength of Column (MPa)</th>
<th>Ductility Index ($\mu$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G 30-I</td>
<td>3</td>
<td>Cube Comp. Strength (MPa)</td>
<td>34.59</td>
<td>4.42</td>
<td>277</td>
</tr>
<tr>
<td>G 30-II</td>
<td></td>
<td>Split tensile strength (MPa)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 30-III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 30-I</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 30-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 30-III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 50-I</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 50-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G 50-III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 50-I</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 50-II</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M 50-III</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The concept of ductility is related to the ability to sustain inelastic deformations without substantial decrease in the load carrying capacity.
From the experimental results, it is inferred that, regardless of material properties, all the 30MPa Grade concrete columns possess high ductility Index, which is appreciable for structural elements. All G50 Grade concrete columns exhibited more ductility than M50 concrete columns. It is well established that whenever the grade of concrete increases, the material tends to result in lower ductility. When Geopolymer concrete columns are used for earthquake resistance structures, a ductile type behavior is recommended and is essential to form plastic hinges and to enhance their capacity to absorb and dissipate energy without significant loss in strength. From this point of view, it is inferred that Geopolymer concrete possesses superior quality than its counterparts.

**Crack Patterns and Failure Modes**

The initiation of cracks is seen at the mid-height of all columns, invariable of Grade of concrete and materials type. The cracks get propagated with increase in applied load allowing new cracks to appear. All the G30 Grade columns showed buckling of reinforcement, as witnessed from Figure 6.34, as the load increased until failure. The zone of failure is around 180mm above and below the mid-height of G30 columns. The mode of failure shall be seen in Figure 6.34. Invariably, in all M50 grade concrete columns, cracks initiated near the head of the column and the crack propagated at the circumference of column 575mm below the top end of column. The mode of failure is seen in Figure 6.35. The reason for such failure is due to the rigidity of concrete with an increase in compressive strength. All the columns buckled before failure.
Figure 6.34  Failure Pattern of G30 Concrete Column (Typical)
Figure 6.35 Failure Pattern of G50 Concrete Column (Typical)
6.12 MICROANALYSIS OF CONCRETE

6.12.1 Scanning Electron Microscopy and EDAX

Samples for scanning electron microscopy (SEM) analysis and EDAX were taken from near the surface of specimen.

Figure 6.36 SEM Image of G30 Specimen and its Corresponding EDAX Spectrum
Figure 6.37 SEM Image of G50 Specimen and its Corresponding EDAX Spectrum
SEM micrographs along with EDAX spectrum showing the images of G30 and G50 grade Geopolymer concrete are illustrated in Figures 6.36 and 6.37. In G30 and G50 specimens, unreacted fly ash particles could not be noticed rendering it a high denser microstructure of concrete. From EDAX spectrum of Geopolymer concrete, it shall be noted that iron oxide content was 3.7%. It also revealed the presence of Si, Al, K, Na and C as the main elements. The iron oxide content originally presented in source material had not increased. This shows that the metal did not undergo any chemical reaction.

6.12.2 X-Ray Diffraction Analysis

XRD patterns of the G30 and G50 samples are illustrated in Figures 6.38 and 6.39. From the spectrum of G30 and G50 concrete, it could be inferred that peaks for Zeolitic phases have arisen from aluminosilicate gel formed between 20° and 21° 2θ, which contributed amorphous structure to Geopolymers. XRD analyses also showed the presence of quartz, mullite and anorthite. The presence of anorthite phase indicates that even small portion of calcium present in fly ash has reacted with Na-polysialate-siloxo. The degree of crystallinity was caused by quartz and mullite phases present in the source material.
Figure 6.38  XRD Pattern of G 30 Concrete (Typical)

Figure 6.39  XRD pattern of G 50 Specimen
Metal compounds, originally present in the source material, did not react with alkaline solution which was revealed by noting no remarkable change in the crystalline part of spectra. XRD patterns suggested that polysialates consisted of short-range order materials with structures similar to crystalline Zeolites. In the synthesized Geopolymers, the quartz peaks have become higher in the relative intensities and the mullite peaks almost remained unchanged. All the above factors have contributed to the improvement in the compressive strength of Geopolymer concrete.