CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 SUMMARY

In the present work, an attempt has been made to study the effect of the blend of MK and BA as source material on the performance GPC and also its potential as a paver block.

The material such as MK, BA, fine aggregate, coarse aggregate, sodium hydroxide, sodium silicate and cement have been used in the present work to make GPM, GPC and control concrete. Several trial mixes have been made to arrive at optimum mix proportion for GPM to impart maximum strength. Further, the GPC mix proportion was made based on the GPM mix with maximum strength and also the guidelines prescribed by B.V. Rangan. The specimens of GPC were cast and cured at ambient temperature. The GPC and control concrete specimens were tested for compressive, split tensile, flexural strength and modulus of elasticity. Also, XRD, SEM and EDAX studies were carried out to analyse elements/ mineral compounds present, microstructure and morphological characteristics of GPC to substantiate the strength development. Further, durability of GPC in terms of sulphate resistance, acid resistance, chloride resistance etc. has also been evaluated. Finally, an attempt has also been made to study the suitability of GPC as paver blocks.
5.2 CONCLUSIONS

The very prominent conclusions drawn from the present work are as follows.

i. The optimum liquid/binder ratio to impart maximum compressive strength to MK and BA GPM made with equal proportions of BA and MK is 0.50. At the same time, alkali activator having molarity of 8 along with SiO$_2$/Na$_2$O ratio of 2 have been used to impart maximum strength to GPM.

ii. Among all mortar mixes, the bBM50 has yielded highest compressive strength of 78.24 MPa at the age of 28 days in ambient curing. Further, compressive strength of bBM$_{50}$ mortar is about 47% higher than the mortar made with 53 grade OPC. Further, the early strength gain of GPM is remarkably higher than cement mortar.

iii. The geopolymer concrete made with equal proportion of MK-BA with 0.5 liquid to binder ratio has exhibited almost 49% higher compressive strength than control concrete at the age of 28 days. Also, the early strength gain in GPC is remarkably higher than cement concrete.

iv. The similar trend has been noticed in split tensile strength, flexural strength and modulus of elasticity of GPC. The fineness, composition, amorphous nature of source material and very intense polymerization due to high molar alkali activator has imparted higher strength as well as early strength gain to GPC than cement concrete.

v. The X Ray Diffractogram analysis of GPC at the age of 1, 3, 7, 28 and 90 days shows that progressive crystallization
of compounds/minerals such as zeolite, calcite, feldspar, dolomite, gypsum, mullite, quartz, dickite and anatase improved the strength of GPC. Further, presence of the crystalline phases at the initial stage, substantiate the early strength gain of GPC.

vi. The SEM micrographs indicate that the GPC at early age has demonstrated relatively porous microstructure. Also, it has shown the presence of macro as well as micro cracks. Further, it is evident from the micrographs that more and more geopolymeric gel has been formed in GPC with age, resulting in densification of microstructure and remarkable improvement in the strength. Moreover, the macro as well as micro cracks have been vanished with the age of GPC. The strength development has been substantiated by the presence of dominant elements such as alumina, silica, sodium and iron noticed in EDAX analysis.

vii. The GPC, in general, has exhibited relatively higher durability than control concrete. The GPC has shown significantly less sorptivity than the control concrete at all ages. The sorptivity of GPC is 10%, 4% and 12% less than control concrete at the age of 7, 28 and 90 days respectively. The low sorptivity indicate that the GPC is relatively more impervious than control concrete and also, it can resist chloride ion ingestion better than control concrete.

viii. Both GPC and control concrete are free from cracks, crumbling, softening and also dimensionally quite intact even after the exposure to magnesium sulphate, sodium chloride and sulfuric acid solution over a period of
12 months. However, both the concretes have exhibited change in mass as well as compressive strength.

ix. Further, it is evident that the GPC and control concrete have shown increase in mass on exposure to magnesium sulphate and sodium chloride solution over a period of one to 12 months. It is due to the permeation of magnesium sulphate/sodium chloride solution and subsequent precipitation of salt in pore spaces of concrete. However, the GPC has demonstrated relatively less gain in mass than the control concrete. The GPC and control concrete exhibited increase in the mass, depending on exposure environment and period of exposure, in the range of 0.5% to 3.14% and 0.97 % to 4.01% respectively. It is due to the relatively low sorptivity and permeability of GPC than control concrete.

x. Nevertheless, the mass of specimens of both the concretes decreased marginally on exposure to sulfuric acid. It is due to the leaching of calcium and sodium based compounds present in the concrete due to acid attack. However, the GPC has demonstrated relatively less loss in mass than the control concrete. The GPC and control concrete exhibited decrease in the mass, depending on period of exposure, in the range of 1.13% to 4.23% and 2.35% to 6.21% respectively. It is obviously due to the relatively low sorptivity and permeability of GPC than control concrete.

xi. Also, it is clear that the both GPC and control concrete have exhibited reduction in the compressive strength on exposure to magnesium sulphate, sodium chloride and sulfuric acid solution over a period of one to 12 months. The residual
compressive strength reduced with the increase in period of exposure. However, the GPC has demonstrated higher residual compressive strength than the control concrete. This indicates that the GPC has better durability than control concrete. It is mainly due to its relatively low porosity, permeability and sorptivity.

xii. The GPC exposed to magnesium sulphate solution has shown higher residual compressive strength than control concrete indicating that the GPC resist the sulphate attack better than control concrete. The GPC concrete has shown 2.70%, 3.34%, 1.97% and 1.91% of higher residual compressive strength than control concrete at the exposure period of 1, 3, 6 and 12 months respectively. The sulphate reacts with calcium hydroxide, C-A-S and C-S-H present in control concrete leading to the formation of ettringite and also gypsum at later stage, resulting in higher strength reduction and low durability. The GPC has demonstrated better resistance to sulphate attack as it is free from the calcium hydroxide.

xiii. Further, the higher range of residual compressive strength exhibited by GPC indicates that it is more resistant to chloride attack than control concrete. The GPC concrete has shown 2.26%, 2.40%, 1.34% and 1.11% of higher residual compressive strength than control concrete at the exposure period of 1, 3, 6 and 12 months respectively. The relatively higher residual compressive strength of GPC is primarily due to its relatively low porosity, permeability and sorptivity. Also, the absence of Ca(OH)$_2$, C-S-H in GPC has improved its performance against the act of sodium chloride.
However, the formation of expansive alkaline calcium chloride and decalcification of C-S-H reduce the residual compressive strength and also durability of control concrete. Also, the GPC has demonstrated better resistance to acid attack than control concrete by showing the higher residual compressive strength. The GPC has exhibited 2.7%, 3.5%, 1.97% and 1.9% higher residual compressive strength than control concrete at the exposure period of 1, 3, 6 and 12 months respectively. The better performance of GPC is due to the absence of calcium based cementitious compounds which are more prone for acid attack. However, the formation of expansive gypsum, ettringite, decalcification of C-S-H due to the attack of sulfuric acid reduced the strength and durability of control concrete significantly.

The characteristics of GPC paver block such as compressive strength, flexural strength, split tensile strength, water absorption and abrasion resistance are in conformity with specification prescribed by BIS 15658:2006. More so, the remarkable early strength gain of GPC facilitates the pavement to open for the traffic early.

5.3 SCOPE FOR FUTURE STUDIES

In the present work, focus has been made to produce the geopolymer concrete under ambient curing conditions and evaluate its strength and durability characteristics. Also, attempt has been made to evaluate the potential of GPC as a paver blocks. Further, there is a scope to explore following areas of geopolymer concrete in future.
i. Studying the effect of super plasticizer (SP) on the properties of GPC made with blended MK and BA.

ii. Evaluation of behaviour of MK-BA GPC in beams, columns and slabs.

iii. Study can also be extended to develop self compacting MK-BA GPC and to evaluate the characteristics of GPC.
APPENDIX 1

MIX DESIGN OF CONTROL CONCRETE

Grade designation  = M30
Type of cement  = OPC 53 Grade confirming to IS: 12269 - 2013
Fine aggregate  = Zone-II
Type of exposure  = Mild
Specific gravity of Cement = 3.14
Specific gravity of Fine aggregate = 2.63
Specific gravity of Coarse aggregate = 2.69
Minimum Cement (As per field requirement) = 310 kg /m³

Maximum water cement ratio
(As per field requirement) = 0.45 (IS: 456 – 2000)

Mix Calculation:

1. Target Mean Strength  = 30 + (5 x 1.64)
   = 38.25 MPa

2. Selection of water cement ratio:
   Assume water cement ratio  = 0.45
   Adopted water cement ratio  = 0.42
3. Calculation of water:

Approximate water content for 20 mm max. size of aggregate

\[ = 186 \text{ kg/m}^3 \text{ (As per Table 2 IS: 10262-2009)} \]

Adopted water content for 50-75 mm slump = 160 kg/m³

4. Calculation of cement content:

Water cement ratio \( = 0.42 \)

Water content per cum of concrete \( = 160 \text{ kg} \)

Cement content \( = 160/0.42 \)

\[ = 381 \text{ kg/m}^3 \]

However, adopt cement content as 381 kg/m³

(As per field requirements minimum cement content 310 kg/m³)

Hence O.K.

5. Calculation for C.A. & F.A.:

Volume of concrete \( = 1 \text{ m}^3 \)

Volume of cement \( = 381/ (3.14 \times 1000) = 0.121 \text{ m}^3 \)

Volume of water \( = 160 / (1 \times 1000) = 0.160 \text{ m}^3 \)

Total volume of all in aggregates in m³ \( = 1 - 0.281 = 0.719 \)

Mass of coarse aggregate \( = 0.719 \times 0.56 \times 2.69 \times 1000 \)

\[ = 1084 \text{ kg} \]
Mass of fine aggregate = \(0.719 \times 0.44 \times 2.63 \times 1000\) 
= 833 kg

Hence Mix details per m\(^3\)

Cement = 381 kg

Revised water content as per w/c ratio 0.35 = 160 kg

Fine aggregate = 833 kg

Coarse aggregate = 1084 kg

Water cement ratio = 0.42

Quantity of materials in kg /m\(^3\) of concrete

<table>
<thead>
<tr>
<th>Cement</th>
<th>Fine aggregate</th>
<th>Coarse aggregate</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>381</td>
<td>833</td>
<td>1084</td>
<td>162</td>
</tr>
<tr>
<td>1</td>
<td>2.18</td>
<td>2.84</td>
<td>0.42</td>
</tr>
</tbody>
</table>
APPENDIX 2

MIX DESIGN OF MK-BA GEOPOLYMER CONCRETE

Unit weight of geopolymer concrete = 2400 kg/m³

Mass of combined aggregates = 75% of unit weight
= 1800 kg/m³

Coarse aggregate = 70% of 1800
= 1260 kg/m³

Fine aggregate = 30% of 1800
= 540 kg/m³

Alkaline liquid to binder ratio by mass = 0.5

Mass of binder and liquid = 2400 – 1800
= 600 kg/m³

Mass of binder = 400 kg/m³

Percentage of metakaolin in binder = 50%

Percentage of bottom ash in binder = 50%

Quantity of metakaolin = 200 kg/m³

Quantity of bottom ash = 200 kg/m³

Mass of alkaline liquid (Na₂SiO₃+NaOH) = 600-400
143

= 200 kg/m$^3$

Ratio of sodium silicate to sodium hydroxide = 2.0

Sodium Hydroxide +2 X Sodium Hydroxide =200 kg/m$^3$

3 x Sodium Hydroxide = 200 kg/m$^3$

Sodium hydroxide =200/3

Mass of sodium hydroxide (NaOH) = 66.67 kg /m$^3$

Mass of sodium silicate solution = 200- 66.67

= 133.34 kg/m$^3$

For 8M NaOH,

320 gm of solids in 1000 ml of water =1.3 kg of solution in 1000 ml of water

NaOH solids required for 66.67kg of solution = (66.67 x 320)/ 1300

= 16.41 kg/ m$^3$

Water = 50.26 kg/ m$^3$

Quantity of materials in kg /m$^3$ of concrete

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Metakaolin (kg/m$^3$)</th>
<th>Bottom Ash (kg/m$^3$)</th>
<th>Sodium silicate solution (kg/m$^3$)</th>
<th>Sodium hydroxide solution (kg/m$^3$)</th>
<th>Fine aggregate (kg/m$^3$)</th>
<th>Coarse aggregate (kg/m$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>200</td>
<td>200</td>
<td>133.34</td>
<td>66.67</td>
<td>540</td>
<td>1260</td>
</tr>
</tbody>
</table>
APPENDIX 3

MIX DESIGN OF M30 GRADE MK-BA GEOPOLYMER CONCRETE PAVER BLOCKS

Unit weight of Geopolymer concrete \( = 2400 \text{ kg/m}^3 \)

Mass of Combined Aggregates \( = 75\% \) of unit weight
= 75 \% of 2400
= 1800 kg/m\(^3\)

Coarse aggregate \( = 70\% \) of 1800
= 1260 kg/m\(^3\)

Fine aggregate \( = 30\% \) of 1800
= 540 kg/m\(^3\)

FOR M30 GRADE

Alkaline liquid to binder ratio by mass \( = 0.5 \)

Mass of binder and Liquid \( = 2400 – 1800 \)
= 600 kg/m\(^3\)

Mass of binder \( = 400 \text{ kg/m}^3 \)

Mass of alkaline liquid \( = 600-400 \)
= 200 kg/m\(^3\)
Ratio of sodium silicate to sodium hydroxide = 2.0

Sodium Hydroxide + 2 x Sodium Hydroxide = 200 kg/m³

3 X Sodium Hydroxide = 200 kg/m³

Sodium hydroxide = 200/3

Mass of sodium hydroxide (NaOH) = 66.67 kg/m³

Mass of sodium silicate solution = 200 - 66.67

= 133.34 kg/m³

For 4M NaOH,

160 gm of solids in 1000 ml of water = 1.16 kg of solution in 1000 ml of water

NaOH solids required for 66.67kg of solution = (66.67 x 160)/ 1160

= 9.19 kg/m³

Water = 57.47 kg/m³

Quantity of materials in kg/m³ of concrete

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Metakaolin (kg/m³)</th>
<th>Bottom Ash (kg/m³)</th>
<th>Sodium silicate solution (kg/m³)</th>
<th>Sodium hydroxide solution (kg/m³)</th>
<th>Fine aggregate (kg/m³)</th>
<th>Coarse aggregate (kg/m³)</th>
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