2003

High-performance mortar reinforced with short carbon fibers.

Md. Safiuddin

University of Windsor

Follow this and additional works at: https://scholar.uwindsor.ca/etd

Recommended Citation
https://scholar.uwindsor.ca/etd/2304

This online database contains the full-text of PhD dissertations and Masters' theses of University of Windsor students from 1954 forward. These documents are made available for personal study and research purposes only, in accordance with the Canadian Copyright Act and the Creative Commons license—CC BY-NC-ND (Attribution, Non-Commercial, No Derivative Works). Under this license, works must always be attributed to the copyright holder (original author), cannot be used for any commercial purposes, and may not be altered. Any other use would require the permission of the copyright holder. Students may inquire about withdrawing their dissertation and/or thesis from this database. For additional inquiries, please contact the repository administrator via email (scholarship@uwindsor.ca) or by telephone at 519-253-3000 ext. 3208.
HIGH PERFORMANCE MORTAR REINFORCED WITH SHORT CARBON FIBERS

by

Md. Safiuddin

A Thesis
Submitted to the Faculty of Graduate Studies and Research through the Department of Civil and Environmental Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

Windsor, Ontario, Canada
2003

© 2003 Md. Safiuddin
The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

Canada
DECLARATION

I hereby declare that the experimental work presented in this thesis is my own and I am the sole author of the document.

I solemnly authorize the University of Windsor to reproduce this document by photocopying or by other means, in total or part, and to lend the document at the request of other institutions and individuals for the intention of scholarly research.

Md. Safiuddin
ABSTRACT

The aim of the work reported in this thesis was to evaluate the performance of carbon fiber reinforced mortar in respect of workability, strength, impact resistance, toughness, durability, and cost-effectiveness. Laboratory experiments were carried out to investigate the properties of both fresh and hardened mortars reinforced with short carbon fibers and to optimize the mix with sufficient workability, good strength, superior impact resistance, enhanced toughness, and excellent durability at reasonable cost. Experimental investigation was carried out at the Concrete Laboratory of the University of Windsor. Five different types of mortar were taken under study including the control mortar based on the results obtained from trial mixes. Four carbon fiber reinforced mortars were prepared with pitch-based short carbon fibers in the range of 1% to 4% volume content. The tests were conducted on fresh mortars to determine slump, inverted slump cone flow, unit weight and air content. It was found that the slump decreased with increasing volume content of carbon fibers. The flow time, as observed in inverted slump cone test, also increased, and therefore the mass flow and the volume flow reduced with greater volume content of carbon fibers. On the other hand, the unit weight of fresh mortar decreased due to the incorporation of carbon fibers. However, amongst carbon fiber reinforced mortar composites, the mortar with 3% fiber volume content provided the highest unit weight. The results of air content were also consistent with the unit weights. The change in air content of various mortars followed a trend reciprocal to that of unit weights.

Hardened mortars were tested for compressive, splitting tensile, first-crack and ultimate flexural strengths, first-crack toughness, first-crack and ultimate impact resistances, and water absorption. The compressive strength increased with the addition of carbon fibers up to 3% volume content and then it dropped. This observation was consistent with the results of unit weight and air content. On the contrary, the splitting tensile, first-crack and ultimate flexural strengths, and the first-crack toughness increased linearly with increase in carbon fiber volume contents. The first-crack and ultimate impact resistances also increased with greater volume content of carbon fibers. Finally, the mortars containing
carbon fibers in the range of 1% to 3% volume content resulted in reduced water absorption in hardened mortar. Fiber volume content greater than 3% induced poor workability, caused difficulties in placing and compacting the fresh mortar, and therefore provided increased water absorption.

Based on the results of slump and inverted slump cone flow tests, the slump and the flow time have been correlated. The correlation reveals that the flow test is more indicative of actual workability than the traditional slump test. However, the slump test is satisfactory for carbon fiber reinforced mortar possessing moderate to high workability. The results of splitting tension test have also been correlated with the ultimate flexural strength obtained from third-point flexure test. The correlation shows that the flexure test is more efficient than the splitting tension test in the case of carbon fiber reinforced mortar. Eventually, an approach has been derived from the results of volume flow, compressive strength, ultimate flexural strength, ultimate impact resistance and water absorption, and considering the cost of constituent materials to determine the performance to cost ratios. The performance to cost ratio of carbon fiber reinforced mortar reasonably increased for a fiber content between 1% and 3%, and over this range it decreased. Finally, it is understood from the overall results and performance to cost ratios that carbon fiber reinforced mortar with 3% fiber content has produced the most cost-effective mix with optimal properties.
DEDICATION

Dedicated To

Scientists, Engineers, and Technologists of the Era
ACKNOWLEDGEMENTS

The author wishes to express his sincere gratitude to the co-advisors Dr. George Abdel-Sayed, Professor Emeritus of the Department of Civil and Environmental Engineering, and Dr. Nataliya Hearn, Associate Professor of the Department of Civil and Environmental Engineering for their precious guidance, advice and financial support throughout the research project. Deep thanks are also due to the Committee Members for their valuable comments.

The author appreciates the sincere cooperation received from the Department of Civil and Environmental Engineering and the Faculty of Graduate Studies and Research at the University of Windsor as well as the financial support provided by the Ministry of Training, Colleges and Universities of Canada.

The author acknowledges and appreciates the excellent cooperation from Mr. Richard Clark and Mr. Patrick Seguin, Technologists and Mr. Lucian Pop, Technician of the Department of Civil and Environmental Engineering. Special thanks are also due to Ms. Alison Samson for her assistance to upgrade the quality of writing. The author is also thankful to Master Builders Technologies, Ontario, Canada for supplying silica fume and superplasticizer required for the experimental investigation.

Finally, and from heart and soul, the author is ever grateful to his family members for their devoted support and encouragement throughout the study period at the University of Windsor.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>iv</td>
</tr>
<tr>
<td>DEDICATION</td>
<td>vi</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>vii</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>viii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>xv</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>xviii</td>
</tr>
<tr>
<td>ABBREVIATIONS AND NOTATION</td>
<td>xxii</td>
</tr>
<tr>
<td>CHAPTER I: INTRODUCTION</td>
<td></td>
</tr>
<tr>
<td>1.1 General</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Objectives</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Research Significance</td>
<td>3</td>
</tr>
<tr>
<td>1.4 Research Procedure</td>
<td>4</td>
</tr>
<tr>
<td>1.5 Scope</td>
<td>5</td>
</tr>
<tr>
<td>CHAPTER II: LITERATURE REVIEW</td>
<td></td>
</tr>
<tr>
<td>2.1 General</td>
<td>7</td>
</tr>
<tr>
<td>2.2 Fiber Materials</td>
<td>7</td>
</tr>
<tr>
<td>2.2.1 Types of fiber</td>
<td>8</td>
</tr>
<tr>
<td>2.2.2 Fiber form</td>
<td>8</td>
</tr>
<tr>
<td>2.2.3 Fiber geometry</td>
<td>9</td>
</tr>
<tr>
<td>2.2.4 Fiber characteristics</td>
<td>10</td>
</tr>
<tr>
<td>2.2.5 Fiber parameters</td>
<td>10</td>
</tr>
<tr>
<td>2.2.5.1 Fiber length</td>
<td>10</td>
</tr>
<tr>
<td>2.2.5.2 Equivalent diameter</td>
<td>11</td>
</tr>
<tr>
<td>2.2.5.3 Aspect ratio</td>
<td>11</td>
</tr>
<tr>
<td>2.2.5.4 Fiber count</td>
<td>11</td>
</tr>
<tr>
<td>2.2.5.5 Fiber denier</td>
<td>11</td>
</tr>
<tr>
<td>2.2.5.6 Fiber specific surface</td>
<td>12</td>
</tr>
</tbody>
</table>

Table of Contents
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.2.5.7</td>
<td>Reinforcement area</td>
<td>12</td>
</tr>
<tr>
<td>2.2.5.8</td>
<td>Strength and toughness</td>
<td>12</td>
</tr>
<tr>
<td>2.2.6</td>
<td>Regimes of fiber content</td>
<td>13</td>
</tr>
<tr>
<td>2.2.7</td>
<td>Distribution of fibers</td>
<td>13</td>
</tr>
<tr>
<td>2.2.8</td>
<td>Alignment of fibers</td>
<td>14</td>
</tr>
<tr>
<td>2.2.9</td>
<td>Role of fibers</td>
<td>14</td>
</tr>
<tr>
<td>2.3</td>
<td>Fibers in Cement Composites</td>
<td>15</td>
</tr>
<tr>
<td>2.3.1</td>
<td>Historical perspective</td>
<td>15</td>
</tr>
<tr>
<td>2.3.2</td>
<td>Modern developments</td>
<td>16</td>
</tr>
<tr>
<td>2.3.3</td>
<td>Current practices</td>
<td>17</td>
</tr>
<tr>
<td>2.3.4</td>
<td>Classes of fiber reinforced cement composites</td>
<td>19</td>
</tr>
<tr>
<td>2.3.5</td>
<td>Stress-strain behavior of fiber reinforced composites</td>
<td>20</td>
</tr>
<tr>
<td>2.4</td>
<td>Carbon Fibers in Cement Composites</td>
<td>22</td>
</tr>
<tr>
<td>2.4.1</td>
<td>Types of carbon fiber reinforced cement composites</td>
<td>22</td>
</tr>
<tr>
<td>2.4.2</td>
<td>Background</td>
<td>22</td>
</tr>
<tr>
<td>2.4.3</td>
<td>Advantages</td>
<td>24</td>
</tr>
<tr>
<td>2.4.4</td>
<td>Applications</td>
<td>25</td>
</tr>
<tr>
<td>2.5</td>
<td>Carbon Fiber Reinforced Mortar</td>
<td>26</td>
</tr>
<tr>
<td>2.5.1</td>
<td>Production</td>
<td>26</td>
</tr>
<tr>
<td>2.5.1.1</td>
<td>Mixing</td>
<td>27</td>
</tr>
<tr>
<td>2.5.1.2</td>
<td>Compaction</td>
<td>28</td>
</tr>
<tr>
<td>2.5.1.3</td>
<td>Curing</td>
<td>30</td>
</tr>
<tr>
<td>2.5.2</td>
<td>Microstructure</td>
<td>32</td>
</tr>
<tr>
<td>2.5.3</td>
<td>Fiber-mortar bond</td>
<td>34</td>
</tr>
<tr>
<td>2.5.4</td>
<td>Fiber-mortar interaction</td>
<td>35</td>
</tr>
<tr>
<td>2.5.5</td>
<td>Major properties</td>
<td>38</td>
</tr>
<tr>
<td>2.5.5.1</td>
<td>Workability</td>
<td>38</td>
</tr>
<tr>
<td>2.5.5.2</td>
<td>Lightweight</td>
<td>40</td>
</tr>
<tr>
<td>2.5.5.3</td>
<td>Dimensional stability</td>
<td>40</td>
</tr>
<tr>
<td>2.5.5.4</td>
<td>Compressive strength</td>
<td>41</td>
</tr>
<tr>
<td>2.5.5.5</td>
<td>Tensile strength</td>
<td>43</td>
</tr>
</tbody>
</table>

Table of Contents
2.5.5.6 Flexural strength .................................................. 44
2.5.5.7 First-crack strength ............................................. 46
2.5.5.8 Toughness ........................................................... 46
2.5.5.9 Impact resistance .................................................. 46
2.5.6 Durability ............................................................... 47
  2.5.6.1 Resistance to water ............................................. 48
  2.5.6.2 Resistance to chemicals ....................................... 49
  2.5.6.3 Resistance to corrosion ........................................ 50
  2.5.6.4 Resistance to freeze-thaw ..................................... 50
  2.5.6.5 Resistance to heat ............................................... 51
2.5.7 Mix design ............................................................. 52
  2.5.7.1 Need for different mix design approach ..................... 52
  2.5.7.2 Mix design based on trial mixes ............................. 53
  2.5.7.3 Mix optimization ............................................... 54
2.5.8 Economy ............................................................... 55
2.6 Concluding Remarks .................................................. 56

CHAPTER III: EXPERIMENTAL MATERIALS

3.1 General ........................................................................... 57
3.2 Carbon Fibers .............................................................. 57
  3.2.1 Classification .......................................................... 57
    3.2.1.1 PAN-based carbon fibers .................................... 58
    3.2.1.2 Pitch-based carbon fibers .................................. 58
  3.2.2 Fabrication ............................................................. 58
  3.2.3 Structure ............................................................... 60
  3.2.4 Physical properties ............................................... 61
  3.2.5 Functions ............................................................. 61
  3.2.6 Fiber content ........................................................ 62
3.3 Sand ............................................................................. 62
  3.3.1 Physical properties ............................................... 62
  3.3.2 Functions ............................................................. 63

Table of Contents
Table of Contents

3.3.3 Gradation ................................................. 64
3.3.4 Sand content ............................................. 65

3.4 Portland Cement ............................................... 65
3.4.1 Mineralogical composition ................................. 65
3.4.2 Chemical composition ...................................... 66
3.4.3 Physical properties ......................................... 66
3.4.4 Functions .................................................. 67
3.4.5 Cement content ............................................ 68
3.4.6 Hydration of portland cement .............................. 68
   3.4.6.1 Hypothesis of hydration ............................... 69
   3.4.6.2 Hydration Process ..................................... 69

3.5 Silica Fume .................................................... 71
3.5.1 Physical properties ......................................... 71
3.5.2 Chemical composition ...................................... 72
3.5.3 Functions .................................................. 73
3.5.4 Role of silica fume in CFRM ............................... 75
3.5.5 Silica fume dosage .......................................... 75

3.6 Water .......................................................... 76
3.6.1 Physical requirements ...................................... 76
3.6.2 Chemical requirements ...................................... 77
3.6.3 Functions .................................................. 78
3.6.4 Water content .............................................. 78

3.7 Superplasticizers ............................................... 79
3.7.1 Physical requirements ...................................... 80
3.7.2 Chemical composition ...................................... 81
3.7.3 Functions .................................................. 82
3.7.4 Role of superplasticizers in CFRM .......................... 83
3.7.5 Superplasticizer dosage .................................... 84

3.8 Concluding Remarks ........................................... 85
## CHAPTER IV: EXPERIMENTAL PROCEDURES

4.1 General .................................................................................................................. 86

4.2 Materials Selection .................................................................................................. 86
4.2.1 Sand ...................................................................................................................... 86
4.2.2 Portland cement ................................................................................................. 87
4.2.3 Silica fume .......................................................................................................... 88
4.2.4 Pitch-based carbon fibers ................................................................................. 89
4.2.5 Water ................................................................................................................... 90
4.2.6 Superplasticizer ............................................................................................... 90

4.3 Design of Mixes ...................................................................................................... 91

4.4 Mix proportions ...................................................................................................... 92
4.4.1 Saturated surface dry basis mix proportions .................................................... 92
4.4.2 Water corrections ............................................................................................. 92
4.4.3 Adjusted mix proportions ................................................................................. 93

4.5 Preparation of Mortar Mixes ................................................................................ 93
4.5.1 Batching ............................................................................................................. 94
4.5.2 Mixing ............................................................................................................... 94

4.6 Testing of Fresh Mortar ........................................................................................ 94
4.6.1 Slump test ......................................................................................................... 95
4.6.2 Test for unit weight and air content ................................................................. 97
4.6.3 Inverted slump cone test ............................................................................... 99

4.7 Preparation of Test Specimens ............................................................................ 100
4.7.1 Molding ........................................................................................................... 100
4.7.2 Demolding ....................................................................................................... 103
4.7.3 Curing .............................................................................................................. 104

4.8 Testing of Hardened Mortar ................................................................................ 104
4.8.1 Compression test ............................................................................................ 105
4.8.2 Splitting tension test ...................................................................................... 106
4.8.3 Flexure test ..................................................................................................... 107
4.8.4 Impact test ....................................................................................................... 108

---

Table of Contents
4.8.5 Water absorption test ........................................ 110
4.9 Concluding Remarks ............................................. 112

CHAPTER V: RESULTS AND DISCUSSIONS
5.1 General .......................................................... 113
5.2 Test Results of Fresh Mortars and Discussions ............... 113
  5.2.1 Slump .................................................. 113
  5.2.2 Unit weight and air content ................................. 115
  5.2.3 Inverted slump cone flow ................................ 119
5.3 Test Results of Hardened Mortars and Discussions .......... 123
  5.3.1 Compressive strength ........................................ 123
  5.3.2 Splitting tensile strength .................................. 128
  5.3.3 Flexural strength and toughness ......................... 132
  5.3.4 Impact resistance .......................................... 140
  5.3.5 Water absorption ........................................... 146
5.4 Cost-effectiveness .............................................. 148
5.5 Optimum Mix ................................................... 150
5.6 Summary of Test Results ....................................... 150

CHAPTER VI: CONCLUSIONS AND RECOMMENDATIONS
6.1 Conclusions on Properties of Fresh Carbon Fiber Reinforced Mortars ........................................ 151
6.2 Conclusions on Strength, Toughness, and Impact Resistance of Fresh Carbon Fiber Reinforced Mortars ......................... 152
6.3 Conclusions on Durability and Overall Cost-effectiveness of Carbon Fiber Reinforced Mortars ......................... 152
6.4 Conclusion on Mix Optimization of Carbon Fiber Reinforced Mortars ........................................... 153
6.5 Recommendations for Further Research ....................... 153

REFERENCES  ............................................................. 154
### APPENDIX

<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Results of Experiments Conducted on Different Constituent Materials</td>
<td>168</td>
</tr>
<tr>
<td>B</td>
<td>Mix Design for Different Types of Mortar</td>
<td>179</td>
</tr>
<tr>
<td>C</td>
<td>Batch Compositions</td>
<td>185</td>
</tr>
<tr>
<td>D</td>
<td>Detailed Schedule of Test Program</td>
<td>187</td>
</tr>
<tr>
<td>E</td>
<td>Sample Calculation for Unit Weight and Air Content</td>
<td>189</td>
</tr>
<tr>
<td>F</td>
<td>Sample Calculation for Inverted Slump Cone Flow</td>
<td>191</td>
</tr>
<tr>
<td>G</td>
<td>Sample Calculation for Compressive Strength</td>
<td>193</td>
</tr>
<tr>
<td>H</td>
<td>Sample Calculation for Splitting Tensile Strength</td>
<td>194</td>
</tr>
<tr>
<td>I</td>
<td>Detailed Results of Flexure Test</td>
<td>195</td>
</tr>
<tr>
<td>J</td>
<td>Sample Calculation for First-crack and Ultimate Flexural Strengths and First-crack Toughness</td>
<td>198</td>
</tr>
<tr>
<td>K</td>
<td>Sample Calculation for First-crack and Ultimate Impact Resistances</td>
<td>200</td>
</tr>
<tr>
<td>L</td>
<td>Sample Calculation for Water Absorption</td>
<td>202</td>
</tr>
<tr>
<td>M</td>
<td>Evaluation of Performance to Cost Ratios</td>
<td>203</td>
</tr>
<tr>
<td></td>
<td><strong>VITA AUCTORIS</strong></td>
<td>209</td>
</tr>
</tbody>
</table>
**LIST OF TABLES**

<table>
<thead>
<tr>
<th>Table Reference</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Different Types of Fiber and Their Physical Properties</td>
<td>9</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Various Applications of Carbon Fiber Reinforced Cement Composites</td>
<td>26</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Effect of Different Carbon Fiber Volume Contents on Strengthening of CFRM Composite</td>
<td>44</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Effect of Fiber Volume Content on Flexural Behavior of CFRM Prepared with 6 mm Long Pitch-based Carbon Fibers</td>
<td>44</td>
</tr>
<tr>
<td>Table 2.5</td>
<td>Impact Behavior of Carbon Fiber Reinforced Cement</td>
<td>47</td>
</tr>
<tr>
<td>Table 2.6</td>
<td>Effect of Sulfuric Acid Exposure on Carbon Fiber Reinforced Cement Prepared with 40% Silica Fume</td>
<td>49</td>
</tr>
<tr>
<td>Table 2.7</td>
<td>Effect of Nitric Acid Exposure on Carbon Fiber Reinforced Cement Prepared with 40% Silica Fume</td>
<td>50</td>
</tr>
<tr>
<td>Table 2.8</td>
<td>Effect of Heat on Flexural Strength of CFRM Composite</td>
<td>52</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Physical Properties of Carbon Fibers</td>
<td>61</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Physical Properties of Natural Sand</td>
<td>63</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Requirement for Gradation of Sand</td>
<td>64</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>Mineralogical Composition of Portland Cement</td>
<td>66</td>
</tr>
<tr>
<td>Table 3.5</td>
<td>Chemical Composition of Portland Cement</td>
<td>67</td>
</tr>
<tr>
<td>Table 3.6</td>
<td>Physical Requirements for Type I Portland Cement</td>
<td>67</td>
</tr>
<tr>
<td>Table 3.7</td>
<td>Physical Properties of Silica Fume</td>
<td>71</td>
</tr>
<tr>
<td>Table 3.8</td>
<td>Chemical Requirements for Silica Fume</td>
<td>72</td>
</tr>
<tr>
<td>Table 3.9</td>
<td>Chemical Composition of a Typical Silica Fume</td>
<td>72</td>
</tr>
<tr>
<td>Table 3.10</td>
<td>Acceptance Criteria for Questionable Mixing Water</td>
<td>77</td>
</tr>
<tr>
<td>Table 3.11</td>
<td>Chemical Requirements for Questionable Mixing Water</td>
<td>78</td>
</tr>
<tr>
<td>Table 3.12</td>
<td>Specific Requirements for Physical Properties of Superplasticizers</td>
<td>80</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Physical Properties of River Sand</td>
<td>87</td>
</tr>
</tbody>
</table>
Table 4.2: Physical Properties of Lafarge Type 10 Normal Portland Cement .......................................................... 88

Table 4.3: Physical Properties of Rheomac® SF 100 Silica Fume .......................................................... 88

Table 4.4: Physical and Chemical Properties of Dialead K6611T Coal Tar Pitch-based Carbon Fibers ......................... 90

Table 4.5: Physical Properties of Tap Water ........................................................................................................... 90

Table 4.6: Physical Properties of Rheobuild® 1000 Superplasticizer .............................................................. 91

Table 4.7: Saturated Surface Dry Basis Mix Proportions ......................................................................................... 93

Table 4.8: Adjusted Mix Proportions ..................................................................................................................... 93

Table 5.1: Slump of Various Fresh Mortar Composites ......................................................................................... 114

Table 5.2: Unit Weight of Various Fresh Mortar Composites .................................................................................. 116

Table 5.3: Air Content of Various Fresh Mortar Composites .............................................................................. 116

Table 5.4: Flow Time of Various Fresh Mortar Composites .................................................................................. 119

Table 5.5: Mass Flow of Various Fresh Mortar Composites .................................................................................. 119

Table 5.6: Volume Flow of Various Fresh Mortar Composites ............................................................................. 120

Table 5.7: 7 Days Compressive Strength of Different Mortar Composites ......................................................... 124

Table 5.8: 28 Days Compressive Strength of Different Mortar Composites ......................................................... 124

Table 5.9: Strengthening Factors for Various Mortar Composites Tested in Compression .................................. 126

Table 5.10: 7 Days Splitting Tensile Strength of Different Mortar Composites .................................................... 128

Table 5.11: 28 Days Splitting Tensile Strength of Different Mortar Composites .................................................... 128

Table 5.12: Strengthening Factors for Various Mortar Composites Tested in Splitting Tension ......................... 130

Table 5.13: First-crack and Ultimate Flexural Strengthening Factors for Various Mortar Composites Tested in Flexure ......................................................................................... 135

Table 5.14: Toughening factors for First-crack Toughness of Various Mortar Composites Tested in Flexure .................. 136
Table 5.15:  Comparison of Theoretical and Experimental First-crack Deflections ................................................................. 138
Table 5.16:  7 Days Impact Test Results of Different Mortar Composites .................. 141
Table 5.17:  28 Days Impact Test Results of Different Mortar Composites ................................................................. 141
Table 5.18:  First-crack Impact Resistance of Various Mortar Composites ...................... 142
Table 5.19:  Ultimate Impact Resistance of Various Mortar Composites .................... 142
Table 5.20:  Impact Resistance Factors for Various Mortar Composites ................... 145
Table 5.21:  7 Days Water Absorption of Different Mortar Composites .................... 146
Table 5.22:  28 Days Water Absorption of Different Mortar Composites .................... 146
Table 5.23:  Water Absorption Resistance Factors for Various Mortar Composites .......... 148
# LIST OF FIGURES

| Figure 2.1: | Comparative Stress-strain Behavior Diagrams of Fiber Reinforced and Conventional Cement Composites | 21 |
| Figure 2.2: | Effect of Compaction on Strength of Cement-based Composites | 29 |
| Figure 2.3: | Effect of Different Types of Curing on Compressive Strength of Normal Portland Cement Concrete | 30 |
| Figure 2.4: | Effect of Different Types of Curing on Initial Surface Absorption of Normal Portland Cement Concrete | 31 |
| Figure 2.5: | A Fractured Surface of CFRM Component Showing Random Distribution of Carbon Fibers | 33 |
| Figure 2.6: | Schematic Representation for Inclusion-Interface-Bulk Paste Matrix Microstructure | 34 |
| Figure 2.7: | Dense Packing of Hydration Products around Carbon Fibers | 35 |
| Figure 2.8: | Schematic Representation for Fiber-Mortar Interaction | 37 |
| Figure 2.9: | Fracture of Carbon Fiber Followed by Pullout | 38 |
| Figure 2.10: | Relation between Carbon Fiber Volume Content and Workability of Fresh Carbon Fiber Reinforced Cement Composites | 39 |
| Figure 2.11: | Variation of Length Change in CFRM and Plain Mortar | 41 |
| Figure 2.12: | Effect of Carbon Fiber Volume Content on Compressive Strength of CFRM Composite | 42 |
| Figure 2.13: | Tensile Behavior of CFRM Composite Prepared with Different Carbon Fiber Volume Contents | 43 |
| Figure 2.14: | Effect of Carbon Fiber Volume Content on Flexural Behavior of CFRM Composite | 45 |
| Figure 2.15: | Water Absorption of Carbon Fiber Reinforced Cement Prepared with Different Fiber Contents | 48 |
| Figure 2.16: | Effect of Freeze-Thaw Cycles on Dynamic Modulus of Elasticity of CFRM Composite | 51 |
| Figure 3.1:  | Processes for Producing PAN-based Carbon Fibers | 59 |
| Figure 3.2:  | Processes for Producing Pitch-based Carbon Fibers | 59 |
| Figure 3.3:  | Crystal Structure of Graphite | 60 |
| Figure 3.4:  | Packing of Cement Grains without Silica Fume | 73 |
| Figure 3.5:  | Packing of Cement Grains with Silica Fume | 73 |
| Figure 3.6:  | Pore Structure in Absence of Silica Fume | 74 |
| Figure 3.7:  | Pore Structure in Presence of Silica Fume | 74 |
| Figure 3.8:  | Chemical Formula of Naphthalene Superplasticizer | 81 |
| Figure 3.9:  | Chemical Formula of Melamine Superplasticizer | 82 |
| Figure 3.10: | Cement-Water Agglomeration in Absence of Superplasticizer | 83 |
| Figure 3.11: | Dispersion of Cement in Presence of Superplasticizer | 83 |
| Figure 4.1:  | Major Component Materials Used in the Present Study | 89 |
| Figure 4.2:  | Pan-type Mixer Used for Preparing Mortar Mixes | 95 |
| Figure 4.3:  | Slump Test for CFRM with 2% Carbon Fiber Volume Content | 96 |
| Figure 4.4:  | Slump Test for CFRM with 3% Carbon Fiber Volume Content | 96 |
| Figure 4.5:  | Leveling Stage of Test for Unit Weight and Air Content of Fresh Mortars | 97 |
| Figure 4.6:  | Weighing Stage of Test for Unit Weight and Air Content of Fresh Mortars | 98 |
| Figure 4.7:  | Inverted Slump Cone Apparatus for Flow Test of Fresh Mortars | 99 |
| Figure 4.8:  | An Operating Stage of Inverted Slump Cone Flow Test for Fresh Mortars | 100 |
| Figure 4.9:  | A Molded Beam Specimen Used in Flexure Test | 101 |
| Figure 4.10: | Several Molded Cylinders Used in Compression and Splitting Tension Tests | 101 |
| Figure 4.11: | A Molded Parent Cylinder Required for Impact Test | 102 |
| Figure 4.12: | A Molded Parent Cube Required for Water Absorption Test | 102 |
| Figure 4.13: | Curing Tanks Used to Cure the Specimens by Ponding | 103 |
Figure 4.14: Triplicate Capped Cylinder Specimens Used in Compression Test ................................................................. 104
Figure 4.15: Compression Test of Hardened Mortar Using Cylinder Specimen ........................................................................ 105
Figure 4.16: Splitting Tension Test of Hardened Mortar Using Cylinder Specimen ................................................................. 106
Figure 4.17: Flexure Test of Hardened Mortar Using Beam Specimen .................................................................................... 107
Figure 4.18: Principal Components of Impact Test Apparatus in Companion with Cylinder Specimen ............................................. 108
Figure 4.19: Triplicate Cylinder Specimens Used for Impact Test ......................................................................................... 109
Figure 4.20: An Operating Stage of Impact Test for Hardened Mortars .................................................................................. 110
Figure 4.21: Several Cube Specimens Used in Water Absorption Test ..................................................................................... 111
Figure 4.22: An Operating Stage of Water Absorption Test for Hardened Mortars ...................................................................... 111
Figure 5.1: Variation of Slump with Different Carbon Fiber Volume Contents ................................................................................. 114
Figure 5.2: Variation of Unit Weight with Different Carbon Fiber Volume Contents ................................................................. 117
Figure 5.3: Variation of Air Content with Different Carbon Fiber Volume Contents ................................................................. 118
Figure 5.4: Variation of Flow Time with Different Carbon Fiber Volume Contents ........................................................................ 120
Figure 5.5: Variation of Mass Flow with Different Carbon Fiber Volume Contents ....................................................................... 121
Figure 5.6: Variation of Volume Flow with Different Carbon Fiber Volume Contents ................................................................. 121
Figure 5.7: Correlation between Slump and Flow Time of Carbon Fiber Reinforced Mortar Composite ............................................ 123
Figure 5.8: Variation of Compressive Strength with Different Carbon Fiber Volume Contents ......................................................... 125
# ABBREVIATIONS AND NOTATION

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACI</td>
<td>American Concrete Institute</td>
</tr>
<tr>
<td>AFRC</td>
<td>Asbestos Fiber Reinforced Cement</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>BOP</td>
<td>Bent Over Point</td>
</tr>
<tr>
<td>CFRC</td>
<td>Carbon Fiber Reinforced Cement Composite</td>
</tr>
<tr>
<td>CFRM</td>
<td>Carbon Fiber Reinforced Mortar</td>
</tr>
<tr>
<td>CFRM1</td>
<td>Carbon Fiber Reinforced Mortar with 1% Carbon Fibers</td>
</tr>
<tr>
<td>CFRM2</td>
<td>Carbon Fiber Reinforced Mortar with 2% Carbon Fibers</td>
</tr>
<tr>
<td>CFRM3</td>
<td>Carbon Fiber Reinforced Mortar with 3% Carbon Fibers</td>
</tr>
<tr>
<td>CFRM4</td>
<td>Carbon Fiber Reinforced Mortar with 4% Carbon Fibers</td>
</tr>
<tr>
<td>CLFRC</td>
<td>Cellulose Fiber Reinforced Cement Composite</td>
</tr>
<tr>
<td>CSA</td>
<td>Canadian Standards Association</td>
</tr>
<tr>
<td>DAC</td>
<td>Dry Air Curing</td>
</tr>
<tr>
<td>EMI</td>
<td>Electromagnetic Interference</td>
</tr>
<tr>
<td>ETS</td>
<td>Enviro Turn Systems</td>
</tr>
<tr>
<td>FB</td>
<td>Fiber Bridging</td>
</tr>
<tr>
<td>FD</td>
<td>Fiber Debonding</td>
</tr>
<tr>
<td>FP</td>
<td>Fiber Pullout</td>
</tr>
<tr>
<td>FR</td>
<td>Fiber Rupture</td>
</tr>
<tr>
<td>FRC</td>
<td>Fiber Reinforced Cement Composite</td>
</tr>
<tr>
<td>GFRC</td>
<td>Glass Fiber Reinforced Cement Composite</td>
</tr>
<tr>
<td>KCI</td>
<td>Kureha Chemical Industry</td>
</tr>
<tr>
<td>MBT</td>
<td>Master Builders Technologies</td>
</tr>
<tr>
<td>MC</td>
<td>Matrix Cracking</td>
</tr>
<tr>
<td>MCA</td>
<td>Mitsubishi Chemical America</td>
</tr>
<tr>
<td>MKC</td>
<td>Mitsubishi Kasei Corporation</td>
</tr>
<tr>
<td>MM</td>
<td>Mortar Matrix</td>
</tr>
<tr>
<td>Notation</td>
<td>Meaning</td>
</tr>
<tr>
<td>----------</td>
<td>----------------------------------------------</td>
</tr>
<tr>
<td>B</td>
<td>Binder</td>
</tr>
<tr>
<td>b</td>
<td>Width</td>
</tr>
<tr>
<td>C</td>
<td>Cement</td>
</tr>
<tr>
<td>$C_f$</td>
<td>Cost factor</td>
</tr>
<tr>
<td>$C_{sf}$</td>
<td>Compressive strength factor</td>
</tr>
<tr>
<td>CF</td>
<td>Carbon Fiber</td>
</tr>
<tr>
<td>$C_{3A}$</td>
<td>Tricalcium Aluminate</td>
</tr>
<tr>
<td>$C_{5A3}$</td>
<td>Pentacalcium Trialuminate</td>
</tr>
<tr>
<td>$C_{4AF}$</td>
<td>Tetracalcium Aluminoferrite</td>
</tr>
<tr>
<td>$C_{2S}$</td>
<td>Dicalcium Silicate</td>
</tr>
<tr>
<td>$C_{3S}$</td>
<td>Tricalcium Silicate</td>
</tr>
<tr>
<td>CSH</td>
<td>Calcium Silicate Hydrate</td>
</tr>
<tr>
<td>$CSH_2$</td>
<td>Calcium Sulfate Dihydrate</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>$d$</td>
<td>Depth</td>
</tr>
<tr>
<td>$E$</td>
<td>Elastic modulus</td>
</tr>
</tbody>
</table>

Abbreviations and Notation
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f'_c$</td>
<td>Compressive strength</td>
</tr>
<tr>
<td>$F_{sf}$</td>
<td>Ultimate flexural strength factor</td>
</tr>
<tr>
<td>H</td>
<td>Height</td>
</tr>
<tr>
<td>I</td>
<td>Moment of inertia</td>
</tr>
<tr>
<td>$I_{sf}$</td>
<td>Ultimate impact resistance factor</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>l</td>
<td>Load span</td>
</tr>
<tr>
<td>$R_{FC}$</td>
<td>First-crack load</td>
</tr>
<tr>
<td>S</td>
<td>Sand</td>
</tr>
<tr>
<td>$S_a$</td>
<td>Adjusted amount of sand</td>
</tr>
<tr>
<td>S/B</td>
<td>Sand Binder ratio</td>
</tr>
<tr>
<td>SF</td>
<td>Silica Fume</td>
</tr>
<tr>
<td>SP</td>
<td>Superplasticizer</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
</tr>
<tr>
<td>$V_{ff}$</td>
<td>Volume flow factor</td>
</tr>
<tr>
<td>W</td>
<td>Water, Width</td>
</tr>
<tr>
<td>$W_a$</td>
<td>Adjusted amount of water</td>
</tr>
<tr>
<td>$W_{arf}$</td>
<td>Water absorption resistance factor</td>
</tr>
<tr>
<td>W/B</td>
<td>Water-Binder ratio</td>
</tr>
<tr>
<td>X, Y and Z</td>
<td>Cartesian axes</td>
</tr>
<tr>
<td>$\Delta_{FC}$</td>
<td>First-crack deflection</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Strain</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Poisson’s ratio</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stress</td>
</tr>
<tr>
<td>$\sigma_n$</td>
<td>Normal stress</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

1.1 General

Mortar and concrete are composite materials based on hydraulic cement. They are widely used because of many beneficial properties including good compressive strength, fire resistance, ease of application and low cost. Unfortunately, cement mortar and concrete possess very low tensile and flexural strengths, limited ductility and little resistance to cracking. They exhibit an elastic brittle behavior under tensile stresses. The primary reason for this weakness is their inability to resist the initiation and growth of cracks due to relatively low tensile strength. Internal microcracks are inherently present in cement composites. When loaded, these microcracks propagate and open up. Due to poor tensile strength, the connectivity of microcracks increases and results in macrocracks that lead to the brittle fracture in cement composites. This inherent deficiency can be overcome by adding fibers, as they could arrest the cracks and allow much larger deformation beyond the peak stress. Incorporation of randomly distributed short fibers in cement composites increases the tensile strength and the toughness of cementitious matrix by preventing or controlling the initiation, propagation and connectivity of cracks.

The presence of fibers in cement composites substantially improves their static and dynamic properties. Recent studies have reported that the flexural strength and the toughness of cement composites can be radically improved using a limited amount of different types of short fibers (Banthia and Sheng 1991a, Pierre et al. 1999, Soroushian et al. 1992a). Fibers not only increase the tensile strength and the toughness but also improve the impact resistance (Banthia et al. 1998, Bayasi and Zeng 1993) and fatigue strength (Naaman and Hammoud 1998). Besides, they reduce shrinkage and bring forth improvement in the durability characteristics of composites (Marikunte and Soroushian 1994).
The first widely used fiber reinforced composite was asbestos cement in which asbestos fibers were incorporated (Marikunte and Shah 1995). Thereafter, wide varieties of other fibers have been used to produce cement-based composites. Amongst these, conventional fibers such as glass and steel fibers, and synthetic fibers such as polypropylene and cellulose fibers are noteworthy. The reinforcement with asbestos fibers helped the construction industries especially in thin sheet applications for many years. Unfortunately, asbestos fibers were found to cause fibrosis (asbestosis) and two other forms of lung cancer (Gilson 1972) and led to a quest for alternative fibers, which are environmentally safe and sound. Attempts were made with glass, cellulose and steel fibers but they seemed to be discouraging due to durability problems. Embrittlement and strength loss of glass fibers (Bentur 1986), moisture sensitivity of cellulose fibers (Soroushian and Marikunte 1991), and corrosion of steel fibers exposed on the surface (ACI Committee 544, 1990) have steered the construction industries to find an environmentally safe and durable fiber. Eventually, carbon fibers turned out to be very attractive for cement composites because of their superior chemical stability at ambient temperatures. They are inert, medically safe, physically as strong as steel fibers and chemically more stable than glass fibers in an alkaline environment. Besides, carbon fibers are also lighter and their strength to density ratio is higher than other fibers. Historically, polyacrylonitrile (PAN)-based carbon fibers were used first to produce fiber reinforced cement (FRC) composites (Ali et al. 1972). The drawback of this carbon fiber was its high cost but the development of short pitch-based carbon fibers has compensated this shortcoming. Through the past few years, pitch-based carbon fibers have been considered as an excellent reinforcement for cement-based composites and due to dropping prices, they have been extensively used for general applications (Akihama et al. 1988, Banthia 1992, Banthia and Genois 1995, Ohama et al. 1985, Zheng and Chung 1989). The present work has used randomly oriented short pitch-based carbon fibers in cement mortar and monitored their performance at different fiber contents. This study examines the properties of various fresh and hardened carbon fiber reinforced mortars (CFRMs). The mortars were prepared with various carbon fiber contents and tested for workability, unit weight and air content, compressive and splitting tensile strengths, first-crack and ultimate flexural strengths, first-crack toughness, impact resistance, and water
absorption. It is hoped that the outcome of this experimental study would help to produce CFRM in North America at reasonable cost and thus extend the scope of thin sheet products and encourage other applications.

1.2 Objectives

The aim of the present experimental study is to investigate the performance of cement mortar reinforced with short carbon fibers. It has focused on the workability, lightweight, strength, impact resistance and durability issues of CFRM. The major objectives of the research program are as follows:

a. Investigation of the effect of various carbon fiber volume contents on the workability in terms of slump and inverted slump cone flow, unit weight, and air content of freshly mixed CFRM.

b. Investigation of the effect of various carbon fiber volume contents on the compressive and splitting tensile strengths, the first-crack and ultimate flexural strengths, and the first-crack toughness of CFRM.

c. Assessment of the first-crack and ultimate impact resistances of CFRM incorporating different carbon fiber volume contents.

d. Examination of the role of different carbon fiber volume contents on the durability of CFRM in terms of water absorption.

e. Optimization of the mix for CFRM producing a good range of workability, strength, toughness, impact resistance, and durability at reasonable cost.

f. Evaluation of the performance to cost ratio for CFRM in order to make a decision on cost-effectiveness.

1.3 Research Significance

The use of carbon fibers in mortar rather than in paste could offer many advantages such as lower unit cost, lightweight, reduced shrinkage, and better rheological behavior in companion with satisfactory mechanical properties. The work reported herein reveals the effectiveness of short carbon fibers in enhancing the properties of CFRM. Several
important aspects of CFRM such as workability, strength, toughness, impact resistance, and durability have been addressed and experiments were conducted to examine the effect of different volume contents of carbon fibers on these properties. The reported test results specify the effective fiber content in order to produce high performance CFRM. Thus, the outcome of this study would be useful for mix optimization of mortar reinforced with carbon fibers. The present study exhibits that, if the volume content of carbon fibers is optimized, desirable properties can be achieved in CFRM at a lower expense or greater property improvements could be obtained without increasing the reinforcement cost. Merging with the existing works, the comprehensive experimental data obtained in this study will enrich the present state of knowledge and guide the construction industries to produce and commercialize CFRM at a lower cost.

1.4 Research Procedure

Carbon fiber reinforced mortar has gained extensive attention these days for its exceptional attributes and superiority over ordinary cement mortar. The state of the knowledge on CFRM is not complete yet and the researchers are still trying to understand the behavior from different perspectives. The present study also stands behind their noble efforts. The following systematic procedure was adopted to conduct the present research program successfully:

Step 1: As a first step before comprehensive literature review and laboratory investigation, the objectives of the research were determined.

Step 2: Literature of fiber materials and their essence in cement composites were reviewed, and major properties and different theoretical aspects of CFRM were emphasized.

Step 3: Proper materials were selected carefully. Thereafter, the physical properties of materials such as moisture content, specific gravity, absorption, sand gradation, etc., were determined mostly for the purpose of mix design.
Step 4: Mix proportions were worked out based on a number of trial mixes. Then the original work started. Batching, mixing, sampling, testing of fresh composites, and casting of test specimens were carried out competently.

Step 5: Test specimens were cured and prepared for testing hardened composites. Laboratory tests were carried out to determine compressive and splitting tensile strengths, first-crack and ultimate flexural strengths, first-crack toughness, impact resistance, and water absorption of CFRM.

Step 6: Test results were accumulated and analyzed prudently to draw the conclusions and to set forth several recommendations for further research.

1.5 Scope

The detailed test results are presented and discussed in this thesis after several sections for introduction, condensed review of literature, materials description and experimental procedure. The contents are dealt in six chapters with several appendices.

Chapter I introduces the innovation of carbon fibers in cement composites, defines the objectives and brings up the research significance. This chapter also describes research procedure and scope of the thesis.

Chapter II portrays the current state of knowledge on fiber materials and FRC composites, presents a brief research background and illustrates some important aspects of cement composites reinforced with carbon fibers, particularly CFRM, and highlights the major properties and foremost durability issues of CFRM.

Chapter III describes the materials used in the present research work and illustrates their functions and particular properties.

Chapter IV conveys the detailed experimental procedure including materials selection, design of mixes, casting of specimens and testing of both fresh and hardened composites.
Chapter V presents the detailed experimental results, discusses their consequences from different standpoints, and summarizes the test results.

Chapter VI draws the conclusions on the properties, durability, cost-effectiveness and mix optimization of carbon fiber reinforced mortars, and presents some recommendations for further research.

In addition to the aforementioned six chapters, this thesis also includes a number of appendices. Mix design of various mortar mixes, batch compositions, schedule of test program, and detailed results of experiments on constituent materials and both fresh and hardened composites along with necessary sample calculations, and evaluation of the performance to cost ratio for various mortars are included in the appendices.
CHAPTER II

LITERATURE REVIEW

2.1 General

Carbon fiber reinforced cement composites (CFRCs) are a relatively new development in building materials technology. The invention of comparatively low-cost pitch-based carbon fibers has made a breakthrough in the market of advanced composite materials. This chapter introduces different types of fiber with their geometry, characteristics and various parameters; clarifies several aspects of fiber materials; depicts different types, historical perspective, modern developments, and current practices of fiber reinforced cement composites (FRCs); explains the behavior diagram of FRCs; illuminates the types, background, advantages and application of CFRCs, and particularly highlights the production, microstructure, fiber-mortar interaction, major properties, durability issues, mix design, mix optimization, and economy of carbon fiber reinforced mortars (CFRMs). Above all, the maxim of this chapter is to reveal the essence of CFRMs.

2.2 Fiber Materials

Cement-based materials such as mortar and concrete are widely used owing to their manifold advantages. The shortcomings of these materials are their brittleness and low tensile strength, which can be improved by incorporating fibers. Fibers are slender and elongated filaments in the forms of bundles, networks, or strands of any natural or manufactured material that can be distributed throughout freshly mixed cement composites (ASTM C 1116-02, 2002). The addition of fibers to plain mortar or concrete forms a composite possessing greater tensile strength and toughness, and offers better serviceability. The most commonly used fibers in mortar and concrete are steel, glass and more recently polymeric fibers such as nylon, polypropylene, etc., and advanced fibers like aramid, carbon fibers, etc.
2.2.1 Types of fiber

A wide variety of fibers have been used in cement paste, mortar or concrete since the early use of asbestos fibers. In general, the fibers can be classified as follows:

a. Conventional fibers such as glass and steel fibers.
b. Low modulus fibers such as polypropylene, polyvinyl alcohol, and nylon.
c. Natural fibers, for example cellulose, sisal, and jute.
d. Advanced fibers such as carbon fiber, and aramid or Kevlar.
e. Hybrid fibers obtained by mixing more than one type of fibers.
f. Metallic fibers other than steel, for example tungsten.
g. Other fibers such as boron and silicon carbide fibers.

Some of the most commonly used fibers and their typical physical properties are shown in Table 2.1. Carbon fibers are also included in Table 2.1 for overall comparison, although they are discussed in detail in Chapter III.

2.2.2 Fiber form

There are several fiber forms for reinforcing cement composites. The fibers are mainly divided into two forms as follows:

a. Continuous form: reinforcement with continuous fibers provides the best mechanical properties. However, it cannot be adapted easily to mass production and therefore is generally confined to the applications in which the property benefits are more important than the cost penalty.

b. Discontinuous or short form: discontinuous short fibers are available in chopped and milled forms. Reinforcement of cement composites with discontinuous or short fibers could offer the property advantages as achieved in case of continuous fibers. Besides, mass production of cement composites using short fibers is possible with quite intricate shapes.

<table>
<thead>
<tr>
<th>Fiber Type</th>
<th>Diameter (μm)</th>
<th>Specific Gravity</th>
<th>Tensile Strength (GPa)</th>
<th>Elastic Modulus (GPa)</th>
<th>Strain to Failure (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acrylic</td>
<td>12.7 – 104.2</td>
<td>1.17</td>
<td>0.21 – 1.0</td>
<td>14.6 – 19.6</td>
<td>7.5 – 50.0</td>
</tr>
<tr>
<td>Aramid I</td>
<td>12</td>
<td>1.44</td>
<td>3.62</td>
<td>62</td>
<td>4.4</td>
</tr>
<tr>
<td>Aramid II</td>
<td>10</td>
<td>1.44</td>
<td>3.62</td>
<td>117</td>
<td>2.5</td>
</tr>
<tr>
<td>Asbestos</td>
<td>0.02 – 30</td>
<td>2.60</td>
<td>3.5</td>
<td>165</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Carbon (PAN-based)</td>
<td>7 – 8</td>
<td>1.75 – 1.95</td>
<td>3000 – 4000</td>
<td>250 – 400</td>
<td>0.5 – 1.5</td>
</tr>
<tr>
<td>Carbon (Pitch-based)</td>
<td>14 – 18</td>
<td>1.65 – 1.85</td>
<td>590 – 2000</td>
<td>30 – 200</td>
<td>2.0 – 2.4</td>
</tr>
<tr>
<td>Cellulose (Kraft)</td>
<td>20 – 120</td>
<td>1.54</td>
<td>0.3 – 0.5</td>
<td>24 – 40</td>
<td>---</td>
</tr>
<tr>
<td>Glass (Alkali Resistant)</td>
<td>9 – 15</td>
<td>2.60</td>
<td>2.0 – 4.0</td>
<td>70 – 80</td>
<td>2.0 – 3.5</td>
</tr>
<tr>
<td>Nylon</td>
<td>22.9</td>
<td>1.16</td>
<td>0.97</td>
<td>5.17</td>
<td>20.0</td>
</tr>
<tr>
<td>Polyester</td>
<td>19.8</td>
<td>1.34 – 1.39</td>
<td>0.9 – 1.1</td>
<td>17.5</td>
<td>---</td>
</tr>
<tr>
<td>Polyethylene</td>
<td>20 – 380</td>
<td>0.96</td>
<td>0.2 – 0.3</td>
<td>5.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Polypropylene (Fibrillated)</td>
<td>20 – 200</td>
<td>0.90</td>
<td>0.5 – 0.75</td>
<td>5 – 77</td>
<td>8.0</td>
</tr>
<tr>
<td>Polyvinyl Alcohol</td>
<td>15</td>
<td>1.30</td>
<td>0.9</td>
<td>29</td>
<td>---</td>
</tr>
<tr>
<td>Rayon</td>
<td>20 – 380</td>
<td>1.50</td>
<td>0.40 – 0.60</td>
<td>6.90</td>
<td>10 – 25</td>
</tr>
<tr>
<td>Steel</td>
<td>5 – 500</td>
<td>7.84</td>
<td>0.5 – 2</td>
<td>210</td>
<td>0.5 – 3.5</td>
</tr>
</tbody>
</table>

### 2.2.3 Fiber geometry

Fibers vary in a wide range of geometric forms. They can be prismatic, non-prismatic or collated (Zollo 1997). In prismatic fibers, the cross-section doesn’t vary with length. They are usually of round or polygonal cross-section with smooth or rough (deformed) surface throughout the length. In contrast, the cross-section of non-prismatic fibers differs along the length. Furthermore, the collated fibers consist of multifilament or monofilament networks that are generally designed to separate at the time of mixing.
2.2.4 Fiber characteristics

The fiber characteristics should be such as to induce substantial increase in strength and toughness of cement composites (Naaman 1985). The most desirable fiber characteristics are as follows:

a. Geometrical characteristics: shape, length and diameter, aspect ratio, and surface deformation.
b. Physical characteristics: weight, density or specific gravity, surface roughness, resistance to weathering, resistance to heat, and fire resistance.
c. Chemical characteristics: chemical stability and non-reactivity in aggressive environments.
d. Mechanical Characteristics: compressive, tensile, first-crack and ultimate flexural strengths, impact resistance, bond, stiffness (elastic modulus), toughness (ductility), and elongation (strain) to failure.

2.2.5 Fiber parameters

Fiber parameters relating to the geometry, weight, and some important mechanical characteristics of fibers will be discussed in this section.

2.2.5.1 Fiber length

This parameter is of greater importance for short fibers. The stress is assumed to be transmitted from the matrix to the fibers by a shear transfer mechanism when the fibers are of finite length. For a particular fiber, there is a critical length required to build up the shear stress between fiber and matrix to the tensile fracture stress of the fiber. The matrix cannot grip the fibers effectively to take the strain if the fiber length is less than the critical length. Then the fibers slip and pull out instead of being fractured in tension. Consequently, the composite exhibits lower mechanical performance under tension and flexure.
2.2.5.2 *Equivalent diameter*

This parameter is important when the fibers are not round and prismatic in cross-section. The equivalent diameter of a fiber is the diameter of the circle with an area same as that of the average cross-sectional area of an actual fiber. It has effect on the tensile strength and flexural stiffness of fibers and the fluidity of fresh FRC composites (Banthia 1992, Zollo 1997). The fiber tensile strength is inversely proportional to equivalent fiber diameter whereas the flexural stiffness of fiber is directly proportional to equivalent diameter. The fluidity of fresh mix is also directly proportional to equivalent fiber diameter. It follows that equivalent fiber diameter affects the compaction during the process of mixing and placement.

2.2.5.3 *Aspect ratio*

Aspect ratio is a convenient numerical parameter for fibers. It is defined as the fiber length divided by an equivalent fiber diameter. Aspect ratio is actually a measure of the slenderness of fibers. This parameter is also related to fiber stiffness and may affect mixing and placing of FRCs. Typical aspect ratios of fiber vary in the range of about 30 to 150 for length dimensions of 6.4 to 76 mm (ACI 544, 1990).

2.2.5.4 *Fiber count*

Fiber count is defined as the number of fibers in a unit volume of fiber composite. It can be only one single large fiber or a number of smaller individual fibers. Thus, fiber count depends upon the size of individual fiber. Fiber count influences the physical properties of fiber composites. It is also directly related to the statistical probability of cracking (Zollo 1997). In addition, it has significant effect on the post-crack behavior of fiber composites.

2.2.5.5 *Fiber denier*

This is a physical term often used to specify the weight of fibers. The gram weight of 9000 meters of a fiber is defined as its denier (Zollo 1997). It is useful to compare the
weight of different fibers, and to reveal whether a fiber is lighter or heavier than the others.

2.2.5.6 Fiber specific surface

The surface area of fibers in a unit volume of fiber composite is defined as the fiber specific surface. It depends upon the number of fibers distributed within the paste or binder phase occupied in one unit volume of composite. Like fiber count, fiber specific surface has also considerable effect on the post-crack behavior of fiber composite (Zollo 1997). It is directly related to the amount of energy absorbed during propagation of cracks.

2.2.5.7 Reinforcement area

Reinforcement area is defined as the actual cross-sectional area of fibers that cut across any plane of fiber composite containing randomly distributed fibers. It is affected by the length, number, and alignment of fibers. Smaller fiber length and greater number of fibers tend to reduce the effective reinforcement area, as they increase the fiber obliquity. Besides, fiber alignment is an important factor that controls the effectiveness of fibers. The effective reinforcement area is lowered when the fibers are aligned in inclined planes with respect to the direction of loading (Soroushian and Lee 1990). It also influences the post-crack behavior of fiber composite since the ability of fibers to transmit stress across a crack depends upon the cross-sectional area of fibers within the crack plane.

2.2.5.8 Strength and toughness

Strength and toughness of fibers are generic parameters. Strength relates stress capacity whereas toughness gives an account of energy absorption capacity. These are useful only when precisely defined and determined (Zollo 1997). Strength and toughness of fibers are dependants of fiber geometry. They influence the performance of fiber composites both prior to and after cracking.
2.2.6 Regimes of fiber content

The properties of fiber composites vary with varying fiber volume contents. Shah and Rangan (1971) showed that increasing volume of fibers increased the strength and toughness of the composites almost linearly. Increasing fiber volume content also consistently increases ductility and energy absorption capacity (Balaguru et al. 1992, Balaguru and Shah 1992). Fiber volume content is also seen to significantly affect the mixing and placement of fiber composites (Zollo 1997).

Fiber reinforced cement composites may exhibit the brittle post-peak failure pattern at low fiber volume content in presence of silica fume. This is because the presence of silica fume slightly reduces the ductility and makes the material slightly more brittle. Therefore, higher fiber volume content is advised for use in presence of silica fume. The development in processing technology has made possible the manufacture of thin-sheet products from fiber composites with as much as 15% fiber volume content (Marikunte and Shah 1995). However, it is economical to keep the fiber volume content in the moderate range. Based on the volume of entire fiber composite, the regimes of fiber volume content could be established as follows:

a. Low fiber content: fiber volume content is between 0.1% and 1%.
b. Moderate fiber content: fiber volume content is in the range of 1% to 3%.
c. High fiber content: fiber volume content lies in the range of 3% to 15%.

2.2.7 Distribution of fibers

Distribution of fibers can affect the performance of fiber composites. The direction of fiber distribution influences the resistance against crack propagation more than the tensile strength. Perpendicular fibers show no resistance after the tensile strength of the matrix is surpassed. Conversely, parallel fibers provide about 30% more toughness than the randomly distributed fibers (Shah and Rangan 1971). Hence is the importance of fiber distribution.
Fiber distribution and the bulk of fiber free areas play important roles in the initiation and advancement of cracks in fiber composites. If the fibers clump, the size of areas unsupported by fibers increases and crack initiation needs less energy. Besides, once the crack forms, it can propagate easily through the fiber free areas in the matrix. Most of the fibers are usually dispersed randomly in all three directions within the matrix. However, short fibers are likely to disperse in two dimensions because of the effects of short fiber alignment and the length of the fibers (Akihama et al. 1988). The presence of fine or fine and coarse aggregates also tends to cause the uneven dispersion of fibers and increase the fiber free areas in the total volume of composite.

2.2.8 Alignment of fibers

The fibers are efficient to provide strength and stiffness along their length. They impart greatest strength and stiffness when they are aligned parallel to the direction of stress. Otherwise, the fibers act in a less efficient manner. Therefore, a fiber composite with the fibers all aligned in one direction would offer maximum resistance to stress in that direction. However, it is very difficult to make use of this orientation property to its maximum effect in case of discontinuous short fibers. In addition, there are other variables, which may affect fiber orientation. Some of them are as follows:

a. Fiber volume fraction.
b. Fiber length, fiber diameter or aspect ratio.
c. Fiber distribution.
d. State of compaction.
e. State of workability.

2.2.9 Role of fibers

Fibers play two major roles in fiber composites. The first major role of fibers is to control the propagation of cracks under loading and thus to give an enhanced tensile strength and flexural resistance to an otherwise brittle material. The load carrying capacity and the toughness of fiber composites mostly increase with an increase in fiber volume content.
Fiber reinforced matrix can continue to carry a considerable amount of load after occurrence of cracking (Mindess 1995). This means that the low fracture toughness of plain mortar is rectified significantly in presence of fibers. Consequently, a much greater stable crack growth is induced before the cracks become unstable. Therefore, the cracks could also sustain a much wider opening before instability occurs. In fact, fibers act as stress-transfer bridges and thereby reduce the stress intensity at the crack tips.

The second major role of fibers is that they increase the interfacial bond strength in composite material (Katz et al. 1995). This is due to their inherent surface roughness or impregnation of finer cement and silica fume particles. Besides, fibers increase the impact resistance tremendously and decrease the water absorption of cement composites. They also impart greater resistance to freeze-thaw, corrosion, aggressive chemicals, heat, and fire.

2.3 Fibers in Cement Composites

Fibers are mainly used in cement composites to improve their tensile, flexural and impact behaviors with simultaneous increases in stiffness, toughness, and elongation at failure. They are usually mixed with hydraulic cement and fine or fine and coarse aggregates, water, and occasionally water reducing and/or accelerating admixtures to produce fiber reinforced cement composites (ACI 544, 1990).

2.3.1 Historical perspective

The idea of using fibers to improve the performance of building materials is old and innate. For instance, more than a century ago, addition of straw fibers to sun-dried mud bricks, horsehair in plaster, and asbestos to pottery produced composites with better performance (ACI 544, 1990). After the invention of portland cement, the use of asbestos cement in sheets and pipes represented the major application of fiber composites and asbestos cement became the most important manmade fiber reinforced cementitious material over the years (Dunstan 1987). Thereafter, mortar and concrete evolved as popular cement-based composites and attempts were taken to add fibers to them in order
to improve their performance. The patent of Joseph Lambot in 1847 (Naaman 1985) advised the use of continuous fibers in concrete in the form of wires or wire meshes, which headed the advancement of reinforced concrete and ferrocement as famous today. The usage of discontinuous short fibers to reinforce the cement-based materials was a challenge to ancient civil engineers. The production of fiber composites adding fibers to the mixer simply like adding aggregates or admixtures was a dream a century ago but today it has become true. The development of FRCs can be placed in two main periods: the first period, prior to the 1960s, corresponds to the slow pioneering stage showing almost no significant applications. Many patents were granted during this period but the patents of Alfsen and Constantinesco (Naaman 1985) deserve a special mention. Alfsen described a process in his patent to improve the tensile strength of concrete using fibers of iron, wood or other materials. On the other hand, Constantinesco recommended the use of coiled or helical type steel fibers to improve the crack resistance and energy absorption of concrete that paved the way for the development of steel fiber reinforced cement composite (SFRC). The second stage, since the early 1960s, corresponds to the stage of more rapid development with many noteworthy applications. Glass fiber reinforced cement composite (GFRC) became prominent with SFRC composites at this stage. Then the search went on without any interruption for the most suitable fiber for reinforcing cement-based materials. As a result, a number of fibers such as polypropylene and nylon, cellulose, carbon and Kevlar were examined to observe their performance. In parallel to the search for appropriate alternative fibers, there were major efforts to establish the underlying theory of fiber reinforcement in connection with mechanics of composite materials, fracture mechanics and damage mechanics. Romualdi and Batson (1963) in USA, and Aveston, Cooper and Kelly (1971) in UK did their fundamental studies on fiber reinforced composites. Later many other researchers carried forward their early works and contributed a lot to the modern developments.

2.3.2 Modern developments

The modern development of fiber composites started in the early 1960s. The research of Romualdi and Batson (1963) and Romualdi and Mandel (1964) on crack arrest in concrete and the use of closely spaced wire reinforcement are noteworthy. After 1960s, a
high level of research and development activity took place in the field of fiber reinforced cement-based materials. The Portland Cement Association (PCA) investigated the usage of fiber reinforcement in cement paste, mortar and concrete (Monfore 1968). Many experiments were conducted to verify the properties of GFRC (Majumdar and Ryder 1968, Grimer and Ali 1969). As a result, the use of GFRC in pipes is now well established. Further, GFRC sheets and panels are being used increasingly as paneling and cladding in housing and renovations (ACI 1985). Then in the late 1970s and in the early 1980s, great efforts were taken to use steel fibers as reinforcement in cement composites (Lankard 1978, Henager 1981). Consequently, steel fibers were used in various applications (Vandenbergh and Nemegeer 1985, Melamed 1985). Thereafter, in the last two decades, many researchers carried out brilliant attempts for using synthetic fibers in cement composites (Akihama et al. 1988, Banthia and Genois 1995, Bayasi and Zeng 1993, Dunstan 1987, Kim and Park 1998, Marikunte and Soroushian 1994, Ohama and Amano 1984, Soroushian et al. 1992a). Thus, the use of synthetic fibers including hybrid fibers to reinforce cement paste, mortar or concrete has progressed to the stage of commercial applications. For instance, during research work at the University of Surrey, nets of fibrillated polypropylene or polyethylene were placed in a mortar matrix in layers to develop a composite, which is now familiar as NETCEM in the market (Dunstan 1987). Still the development is going on and it is believed that the family of fiber composites will be one of the most widely used materials in the current century.

2.3.3 Current practices

At present, FRC composites are used in practice in a relatively limited range of applications. The following are noteworthy:

a. Asbestos fiber reinforced cement (AFRC): This is obtained by hardening a mix of cement, asbestos and water and being used for years. AFRC provides high strength in tension and bending, frost resistance, low heat conductivity, high resistance to attack by mineralized aqueous solution, high water-tightness and low unit weight. Unfortunately, it has been found that asbestos dust causes a disease very similar to silicosis, which results in fibrosis of the lungs called asbestosis (Rangwala 1999).
was also observed that about half of the persons suffering from asbestosis are very prone to get lung cancer. Thus, asbestos has emerged as a versatile killer and therefore AFRC is now rapidly being replaced by cellulose fiber cement.

b. Cellulose fiber reinforced cement composite (CLFRC): Cellulose fibers came out for the original purpose of replacing asbestos fibers and are being used with a limited range in reinforcing cement composites. CLFRC provides enhanced tensile, flexural, and impact properties but may warp due to changes in humidity, as cellulose fibers are very sensitive to the moisture (Soroushian and Marikunte 1991). As a result, CLFRC may lose some strength. Then the alternative to cellulose fibers was sought and polypropylene fibers came out as another type for replacing asbestos fibers.

c. Polypropylene fiber reinforced cement composite (PPFRC): Polypropylene fibers are chemically inert and very stable in the alkaline environment of cement composites and therefore suitable for reinforcing cement paste, mortar and concrete. PPFRC can be used in thin sheet applications and to prevent temperature and shrinkage cracking in absence of secondary steel reinforcement (Sanjuán and Moragues 1997). This composite is typically applied in constructing overlays and pavements, slabs, flooring systems, crash barriers, precast partition walls, precast pile shells, precast units for water tanks, and preparing shotcrete for tunnel lining, canals, and reservoirs (Krenchel and Shah 1985, Zheng and Feldman 1995). Although PPFRC offers numerous advantages, it has some drawbacks such as poor fire resistance, low modulus of elasticity, low bond strength and sensitivity to sunlight. Yet, these disadvantages are not critical and the overall performance of PPFRC is favorable for their particular uses.

d. Glass fiber reinforced cement composite (GFRC): The potential for using glass fibers in cement composites was recognized in the 1940s. Later more developments on glass fibers took place and alkali resistant glass fibers came about in the late 1960s (ACI 1985). GFRC coalesces the high compressive strength of cement mortar with significantly tensile, flexural, and impact strengths imparted by the fiber reinforcement, and thus are suitable for thin sheet applications. Suitably formulated GFRC also offers good waterproofing characteristics, resistance to
chloride penetration and high abrasion resistance, and therefore is very attractive for thin toppings on parking decks, concrete bridges, industrial concrete floors and for waterproofing of many concrete structures (Razi 1985).

e. Steel fiber reinforced cement composite (SFRC): It mainly consists of cement, fine or fine and coarse aggregates and discontinuous steel fibers. Steel fibers are generally longer and stiffer than any other types of fiber. They are more likely to offer enhanced strength, toughness, and impact resistance when used as reinforcements in cement composites. SFRC may also contain mineral and chemical admixtures commonly used with conventional cement composites (ACI 544, 1987). It is largely used in pavements of highway and airport, bridge overlays, factory floors, precast concrete pipe, tunnel linings, and in shotcrete repairs to bridge substructures (Melamed 1985, Vandenbergh and Nemegee 1985).

f. Carbon fiber reinforced cement composite (CFRC): It provides excellent mechanical properties and durability. CFRC is advantageous over polypropylene, glass, and steel fiber reinforced cement composites in respect of finishability, weatherability, mixability, thermal resistance, and long-term chemical stability in aggressive environments (Banthia 1992). Therefore, it is propitious for thin sheet applications.

2.3.4 Classes of fiber reinforced cement composites

ACI Committee 544 (1990) has categorized fiber reinforced cement composites into four classes as follows:

   a. Glass fiber reinforced cement composite (GFRC).
   b. Steel fiber reinforced cement composite (SFRC).
   c. Synthetic fiber reinforced cement composite (SNFRC).
   d. Natural fiber reinforced cement composite (NFRC).

On the other hand, ASTM (ASTM C 1116-02, 2002) has classified fiber reinforced cement composites as follows:
a. Type I steel fiber reinforced cement composite (SFRC), which contains steel, alloy steel, or carbon steel fibers.
b. Type II glass fiber reinforced cement composite (GFRC) that contains alkali-resistant glass fibers.
c. Type III synthetic fiber-reinforced cement composite (SNFRC), which includes polypropylene or other synthetic fibers but excludes carbon fibers.

The ACI classification includes CFRC in the class of SNFRC whereas ASTM classifies it in a group of fiber composites incorporating other fibers such as natural fibers, metallic fibers other than steel, etc.

2.3.5 Stress-strain behavior of fiber reinforced composites

The behavior diagram of fiber reinforced cement composites is quite different from that of conventional cement based composites. The presence of fibers fundamentally alters the behavior of cement composites. Thus, the mechanical behavior of FRCs differs with that of conventional cement-based composites. The inherent stress-strain capacity of the matrix itself is enhanced in FRCs. The typical stress-strain behavior diagram of FRC under tension is shown in Figure 2.1. The curve showing the behavior of FRC can be divided into four stages. The first stage (OA) is similar to that of conventional cement composite. Initiation of internal cracking is negligible at this stage. The material behaves elastically and strain varies linearly with stress. The second stage (AB) lies between point A and the peak stress point B known as bent-over point (BOP). At this stage, strain primarily varies almost linearly with stress but the linearity deviates as the stress increases. Stress reaches its peak level and increasing stress level initiates cracks, which are primarily few and widely dispersed. The cracks begin to localize at peak stress level (BOP). The third stage (BC) is characterized with further straining with sharp reduction in stress. The localized bands of cracks move closer at this stage. The fourth stage (CD) occurs between point C and the point of high strain level, D. The process of straining with further reduction in stress continues at this stage and eventually leads to the homogenization of microcracks. Beyond point D, the network of microcracks is extremely extended and eventually the material fails with the formation of macrocracks.
The overall behavior diagram reveals that the toughening of FRC includes the suppression of localization phenomenon, which leads to the increased tensile strength at BOP, and the homogenous distribution of cracks at very high strain level occurring at point D, which results in the enhanced toughness (ductility) in the composite. The behavior diagram of FRC also reveals the following attributes:

a. The microcracking is stabilized and homogeneously distributed even at very high strain levels.

b. The stress-strain curve remains almost linear up to the initiation of cracking in the matrix of composite but deviate in the region of peak stress level.

c. The ascending part of the stress-strain curve for FRC is steeper than that of conventional cement composite.

![Stress-strain diagram](image)

Figure 2.1: Comparative Stress-strain Behavior Diagrams of Fiber Reinforced and Conventional Cement Composites (Adapted from Betterman et al. 1995).
d. The peak stress of FRC is much higher than that of conventional cement composite.
e. The post-peak branch of stress-strain curve first comes down sharply then becomes much flatter in FRC and the strain continues to increase until failure.
f. The toughness of FRC is much higher than that of conventional cement composite.

2.4 Carbon Fibers in Cement Composites

The Japanese started the use of short carbon fibers in cement composites in a form known as carbon fiber reinforced cement composite (CFRC). At the first stage of development, typically, 3% to 5% short carbon fibers were incorporated in cement paste or mortar to produce CFRC but there was no use of coarse aggregates. Although PAN-based carbon fibers induce superior performance, mostly pitch-based carbon fibers were used in Japan in the production of CFRC. The following sections will illuminate the types, background, advantages and applications of CFRC containing pitch-based carbon fibers.

2.4.1 Types of carbon fiber reinforced cement composites

Carbon fiber reinforced cement composites (CFRCs) can be classified as follows based on the nature of matrix:

a. Carbon fiber reinforced cement paste
b. Carbon fiber reinforced mortar
c. Carbon fiber reinforced concrete

2.4.2 Background

Much research on CFRCs was conducted in the early 1970s by Ali et al. (1972), Waller (1974) and Sarkar and Bailey (1975). However, they carried out their research using PAN-based carbon fibers. As PAN-based carbon fibers are very expensive, their widespread commercial usage in CFRCs did not occur. Thereafter, pitch-based carbon fibers appeared in Japan in 1980 (Akihama et al. 1988), and became prominent owing to their low cost. In the following two decades, significant research was carried out to judge
the potential of pitch-based carbon fibers (Akihama et al. 1986, Akihama et al. 1988, Banthia and Sheng 1991a, Banthia and Sheng 1991b, Banthia and Dubeau 1994, Banthia and Genois 1995, Banthia et al. 1993, Banthia et al. 1995, Ohama and Amano 1984, Ohama et al. 1985, Park et al. 1991). In particular, mass production and industrialization of CFRCs went on in Japan in the form of curtain walls for high-rise buildings (Akihama et al. 1986, Akihama et al. 1988, Ohama and Amano 1984, Ohama et al. 1985). As a result, construction industries now know much more about CFRCs and are extending their uses in different sectors. Carbon fibers were used first in large scale in the form of lightweight cladding tile panels for Al-Shaheed Monument in Iraq in 1982 (Akihama et al. 1988). After this successful application, CFRC was used structurally in the exterior curtain wall of the 37-storey Ark-Mori Building in Japan in 1986 (Akihama et al. 1988). In the following few years, CFRCs were applied successfully in Japan to construct the curtain walls of Suidobashi Building of the Tokyo Dental College, Shinagawa-Ku Building, Hitachi Civic Center, Nihonbashi-Honcho Building, Sea Fort Square, Edo-Tokyo Museum, and the United Nations University (Banthia and Genois 1995, Morgan et al. 1992). They were also used successfully in Japan to construct parapet and partition walls.

Japan has also developed very high performance CFRC using a high strength pitch-based carbon fiber possessing a tensile strength of 2350 MPa and an elastic modulus of 140 GPa (Akihama et al. 1988). This high strength pitch-based carbon fiber exhibits almost the same performance as PAN-based carbon fibers in cement-based fiber composites. Experiments have revealed that the flexural strength of CFRC prepared with high strength pitch-based carbon fibers is nearly doubled over CFRC having conventional pitch-based carbon fibers. This outstanding achievement has paved a path to develop various high performance building elements from CFRCs. Subsequently, in many countries other than Japan, considerable efforts were taken to use CFRCs in different sectors. That course has also touched North America. Although USA and Canada are far behind in the advancement of CFRCs compared to Japan, the development is growing especially in the automobile and construction industries.
2.4.3 Advantages

Carbon fiber reinforced cement composites offer a great potential to the construction industries due to their outstanding mechanical properties. The advantages that they offer can be listed as follows:

a. The most obvious advantage of CFRCs is the substantial increase in tensile, first-crack and ultimate flexural strengths, stiffness, and toughness or energy absorption capacity.

b. CFRCs also impart improved impact resistance, corrosion resistance, fatigue endurance, dimensional stability, resistance to earthquake damage, wind resistance, water-tightness, and durability under heat, light, cyclic load, and freeze-thaw, and therefore are attractive for successful use in thin precast products.

c. CFRCs provide magnificent resistance to cracking, possess increased fracture energy, and pertain to the increased tensile ductility and reduced drying shrinkage.

d. CFRCs offer better finishability, thermal resistance, weather resistance, mixability at high volume fractions, and long-term chemical stability against alkaline and other aggressive environments compared to steel, polypropylene or glass fiber reinforced cement composites.

e. CFRCs are found to be better conductors due to the extremely fine size of carbon fibers, which provide a more effective inter-fiber continuity.

f. CFRCs offer decreased electrical resistivity and therefore are useful as smart structural materials that allow nondestructive flaw detection by electrical probing.

g. CFRCs provide excellent dimensional stability compared to conventional cement-based composites due to reduced drying shrinkage.

h. CFRC products are much lighter than conventional cement-based products and therefore are very attractive for use.

i. CFRCs offer greater flexibility in design, excellent formability and easement in casting and molding of complex architectural forms, and therefore are conducive to complicated designs.

j. CFRCs result in an increase in electromagnetic interference (EMI) shielding effectiveness due to their low electrical resistivity.
2.4.4 Applications

Carbon fiber reinforced cement composites have proved their merits for producing many types of structural and non-structural elements required in constructions. The life expectancy of CFRC products is very high. As well, they provide increased design flexibility. Hence, one may expect a high need of CFRC products in the present millennium. The noteworthy applications of CFRCs are as follows:

a. CFRCs are successfully being used in Japan and elsewhere to fabricate thin precast products such as tiles, curtain walls, decorative frames, roofing sheets, cladding panels, ferrocements, and permanent forms for concrete (Banthia and Sheng 1996).

b. They could be used significantly as a material for external walls especially for structures in seismic regions, for small machinery foundation (Banthia 1992), and for repair and protective coating of structural elements constructed in severe environments (Soroushian et al. 1992b).

c. CFRCs can be used to refurbish deteriorated concrete surfaces most often occurring in parking or bridge structures and industrial floors, and in repairs and waterproofing of concrete structures such as water storage and treatment tanks, swimming pools and fish hatcheries (Razi 1985).

d. They are very useful for conductive floor panel system, cathodic protection, and lightning arrester due to their excellent electrical conductivity (Banthia et al. 1995).

e. CFRCs can be used as a stress, strain or temperature sensor for self-monitoring of concrete structures based on its piezo-resistance and Seebeck effects (Chung 2000).

f. They are also suggested for uses in the electrical and electronic industries due to their low electrical resistivity and improved EMI shielding effectiveness (Chung 2000, Banthia 1992).

g. CFRCs can also be applied in automobile industries; for instance, Kanno et al. (1989) attempted the usage of carbon fiber reinforced paste in the cylinder head of the motorcycle engine.

Table 2.2 presents the novel applications of CFRCs in various civil engineering constructions in Japan.
Table 2.2: Various Applications of Carbon Fiber Reinforced Cement Composites (Morgan et al. 1992).

<table>
<thead>
<tr>
<th>Structure</th>
<th>Installation Date</th>
<th>Installation Area (m²)</th>
<th>Type of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higashi – Murayama Purification Plant</td>
<td>Sep. 1988</td>
<td>80</td>
<td>Partition Panel</td>
</tr>
<tr>
<td>Suidobashi Building of Tokyo Dental College</td>
<td>Aug. 1989</td>
<td>4,138</td>
<td>Curtain Wall and Parapet Panels</td>
</tr>
<tr>
<td>Nihonbashi – Honcho Building</td>
<td>Sep. 1989</td>
<td>1,380</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Shinjuku District Heating Center</td>
<td>Dec. 1989</td>
<td>5,650</td>
<td>Curtain Wall and Louver</td>
</tr>
<tr>
<td>Toshin 24 Omori Building</td>
<td>Aug. 1990</td>
<td>3,000</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Hitachi Civic Center</td>
<td>Sep. 1990</td>
<td>2,000</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Shibaura Heights</td>
<td>Sep. 1990</td>
<td>3,700</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>World Business Garden</td>
<td>Mar. 1991</td>
<td>6,600</td>
<td>Dome</td>
</tr>
<tr>
<td>Sea Fort Square</td>
<td>Mar. 1991</td>
<td>6,700</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>The United Nations University</td>
<td>Oct. 1991</td>
<td>9,800</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Toranomon 3–Chome Building</td>
<td>Oct. 1991</td>
<td>6,200</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Tokyo East 21</td>
<td>Oct. 1991</td>
<td>11,400</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Edo-Tokyo Museum</td>
<td>Dec. 1991</td>
<td>12,000</td>
<td>Curtain Wall</td>
</tr>
<tr>
<td>Hamaoka Atomic Power Plant</td>
<td>Jan. 1992</td>
<td>2,900</td>
<td>Formwork of Walls</td>
</tr>
</tbody>
</table>

2.5 Carbon Fiber Reinforced Mortar

The following sections will highlight different aspects of carbon fiber reinforced mortar (CFRM) with especial attention to its microstructure, fiber-mortar interaction, major properties and durability issues. Mix design and optimization of CFRM mixes will also be addressed.

2.5.1 Production

Carbon fiber reinforced mortar is produced by mixing carbon fibers with cement mortar. The entire production process is generally comprised of three phases, which will be discussed hereafter:
2.5.1.1 Mixing

Conventional mixing technique is not suitable for CFRM due to high specific surface area of carbon fibers. About 1% carbon fibers by volume can be mixed evenly with mortar using a conventional mortar mixer. Further, carbon fibers might be used up to 3% volume contents by conventional means if finer cement is used with substantial amount of high range water reducers or superplasticizer (Banthia 1992). Beyond this volume content, it is very difficult to mix the carbon fibers in conventional ways since carbon fibers become prone to ball and disperse non-uniformly. Therefore, special mixing technique and/or the use of dispersing agent could help improving the dispersion of carbon fibers in cementitious matrix. A suitable dispersing agent like carboxyl methyl-cellulose, silica fume or ground granulated blast furnace slag and appropriate amount of high range water reducer such as superplasticizer should be used when high volume contents of carbon fibers are intended to be used in CFRM. The researchers have recommended 20% or more silica fume and a minimum 2% superplasticizer by weight of cement for CFRM mixes (Ohama and Amano 1984).

The mixing of CFRM mortar is different from that of conventional mortar mixing. Conventional transit mixer or revolving drum mixer should be used with extra care. However, an OMNI mixer is preferable for mixing of CFRM. The distinct feature of this mixer is that it does not bring any shear forces on the mixed material (Obla and Li 1995). An OMNI mixer facilitates uniform mixing and dispersion of carbon fibers even at high volume contents (Banthia 1992, Banthia and Genois 1995). It also can work with random motion. Consequently, it will not cause damage to the fibers while mixing and disperse the fibers evenly throughout the mix.

Carbon fibers should be added to a fluid mix in order to obtain good dispersion of the fibers and to avoid fiber clumping. In fresh state, CFRM mixes are not highly flowable but proper proportioning and mixing could make them having appreciable moldability and finishability. Sound mixing comes with the well dispersion of carbon fibers. It is better to mix fine aggregates and cement or cement plus dispersant such as silica fume first followed by the addition of half of the mixing water. It is recommended that
superplasticizer should not be added with the first half of mixing water to avoid the loss of superplasticizer through absorption by aggregates (Price 1994). It is a good practice to mix superplasticizer and a portion of the mixing water together in a separate container by simple stirring and add in the mixer at the later stage of mixing operation. Silica fume could also be mixed separately with water and superplasticizer in order to reduce its stickiness and to avoid creating excessive dust during mixing operation. It will also minimize the risk of health hazards due to silica fume. Carbon fiber is generally added at the later stage of mixing operation. The total mixing time can be 5 to 7 minutes but it should be kept in mind that excessive mixing could damage the fibers and can cause loss of workability.

2.5.1.2 Compaction

In the process of mixing and placing of any cement-based composite, air is likely to get entrapped within the composite. If this air is not fully removed, the hardened composite will not attain its desirable properties and therefore could be deteriorated in the long run. Compaction is the process adopted for expelling this entrapped air from the freshly mixed composite (Shetty 2000). It attempts to remove the additional void spaces filled with entrapped air and thus reduces the porosity in hardened composite and results in increased impermeability and durability. It also increases the closeness between constituent particles and results in greater surface area for enhanced bonding. How compaction together with water-binder ratio affects the compressive strength of cement-based materials has been shown in Figure 2.2.

Carbon fiber reinforced mortar has to be well compacted at the time of placing. The purpose is to maintain the unit weight of CFRM at a sufficiently high level in order to enhance the major engineering properties and durability. The unit weight of hardened CFRM will be lower than expected if compaction is neglected or partially effective. Consequently, compressive strength, ultimate tensile and flexural strengths, and other matrix dependant properties will be affected permanently over the life span of CFRM components.
Vibration is the proper way of compacting CFRM. However, internal vibration is not beneficial to CFRM, as it could damage carbon fibers and disturbs the distribution and orientation of carbon fibers. Indeed, external vibration is convenient to achieve good compaction and to minimize the extent of entrapped air within the cast components. Thus, a vibrating table should be used to compact CFRM mixes by vibration.

![Graph showing effect of compaction on strength of cement-based composites](image)

*Water-Binder Ratio*

Figure 2.2: Effect of Compaction on Strength of Cement-based Composites (Adapted from Juvas 1994).

While vibrating CFRM mixes, vibration time is another parameter that can affect the workability of fresh composite. The duration of vibration depends upon the workability of CFRM and the effectiveness of vibrating body. In general, CFRM mixes require longer vibration time than ordinary mixes. Nevertheless, excessive vibration may cause reaccommodation of solid constituents and liquid phase to flow resulting in separation of phases (Betancourt 1988). Therefore, vibration should be associated carefully to CFRM mixes to prevent phase separation.

Literature Review
2.5.1.3 Curing

The hydration of cement is relatively slow at ambient environments and therefore any cement-based material should be allowed to hydrate or cure for several weeks after casting to achieve full strength development. The aim of curing is to keep cement composites fully saturated or as nearly saturated as possible until the water-filled spaces in fresh composite are substantially reduced by hydration products (Gowripalan et al. 1992). In other words, curing is essential to maintain suitably warm and moist environment for development of hydration products and thereby to reduce porosity and decrease the average propinquity of cement grains. This is because the moisture movement and the surrounding temperature significantly affect the properties of cement-based materials (Tan and Gjørv 1996).

![Graph showing compressive strength vs. age of test for different curing methods.]

Figure 2.3: Effect of Different Types of Curing on Compressive Strength of Normal Portland Cement Concrete (Zain et al. 1999a, Zain et al. 2000a).

Hydration products extend from grain surfaces and grain-to-grain bonds are established due to proper curing under appropriate temperature and moisture (Hover 1998). If the cement-based materials are not well cured, especially at the early stage, they will suffer from irreparable loss (Ramezanianpour and Malhotra 1995, Safiuddin et al. 2001,
Safiuiddin et al. 1999, Zain et al. 1999a, Zain et al. 2000a). Inefficient curing will result in permanently low-grade properties over the life of cementitious materials. Figure 2.3 and Figure 2.4 reveal how the curing could affect the strength and durability of cement-based composites.

![Graph showing the effect of curing on water absorption]

Figure 2.4: Effect of Different Types of Curing on Initial Surface Absorption of Normal Portland Cement Concrete (Safiuiddin et al. 2001, Safiuiddin et al. 1999).

As CFRM components are usually of thin sections and manufactured with a lower water-binder ratio than conventional concrete, they are very vulnerable to rapid drying. In addition, the presence of silica fume enhances rapid drying. If CFRM products suffer from rapid drying, the hydration will not complete and the cement will never achieve its full strength. As a result, the properties of CFRM will be affected adversely and so much attention must be paid to the proper curing of CFRM components.
Carbon fiber reinforced mortar components should essentially be kept in moist environment immediately after manufacture (casting) and during the period of curing to ensure optimum hydration. There are several curing methods currently in use such as sealing in airtight polyethylene bag, storage in oven with controlled temperature, or total immersion in water (Safiuddin 1998, Safiuddin et al. 1999, Zain et al. 1999a, Zain et al. 2000a).

The curing for CFRM components can be divided into three phases as follows: a) A predemolding curing to provide sufficient strength to the mortar components for demolding. This is carried out by covering the components carefully with the lids of molds (if available) or polythene sheets to minimize airflow across the open surfaces thus preventing as much water as possible from evaporation. b) Main curing for optimum cement hydration as mentioned earlier. c) Post-curing to normalize the components prior to storage, usage or testing by simply keeping them at ambient conditions.

The hydration rate will be different in each of these phases, but CFRM components should have been brought up to the final stage of strength requirements at the end of the curing cycle. An ideal curing regime for CFRM is to cover the components in the molds immediately after manufacture or casting with a polythene sheet until demolding and then store it preferably in a humid environment at more than 95% RH and 20° C to 25° C for additional 7 days.

2.5.2 Microstructure

Carbon fiber reinforced mortar consists of carbon fibers mixed in cement mortar matrix with some amounts of entrapped and/or entrained air pores. Mostly pitch-based carbon fibers 3 to 10 mm in length and 0.015 to 0.02 mm in diameter are used at 2% to 5% by volume as fiber inclusions in CFRM mixes. Carbon fibers are dispersed in the cementitious matrix in a three dimensional random fashion based on the technique of mixing. Random distribution of carbon fibers can be noticed in Figure 2.5. At the micro-level and like other cement-based composites, CFRM can be considered as a three-phase system: cement paste, inclusions, and the interface between cement paste and inclusions.
Fine aggregate (sand) and carbon fibers can be considered as the inclusions in CFRM. As in other cement-based composites, the cement paste and the interface between cement paste and inclusion play important roles to control the porosity and the bond strength in CFRM.

Figure 2.5: A Fractured Surface of CFRM Component Showing Random Distribution of Carbon Fibers (Banthia 1992).

The porosity of cement paste is comprised of gel pores (1.5 to 2.0 nm) and capillary pores (10 nm to 5 µm) (Hearn et al. 1994). Compared to the cement paste, the interface is more porous and therefore regarded as the weak link relating to the properties of any cement-based composite. The interface mainly consists of a water film, a calcium hydroxide layer on the inclusion side, and a porous paste matrix layer between calcium hydroxide layer and bulk paste matrix (Hearn et al. 1997). This is shown in Figure 2.6. The interface is more porous mainly due the presence of water film surrounding the inclusion. At the time of mixing, water film usually surrounds the inclusion and results in effectively higher water-binder ratio in the proximity of interface. The porosity of interface is also supplemented by entrapped bleed water.
2.5.3 Fiber-mortar bond

The bond between fibers and mortar is very important although the mechanical properties of fiber reinforced mortar mainly depend upon the volume content, distribution, orientation, and size of fibers and the composition of mortar matrix. Loads are usually transferred to the fibers from the matrix and therefore a strong fiber-matrix bond is desirable. This can be achieved in CFRM by anchorage mechanism and by applying surface treatment and sizing to carbon fibers.

Carbon fibers are dispersed in the matrix and bonded with the cementitious materials. The higher amount of pores in CFRM can affect the bond between fibers and matrix. When pores contact with the carbon fibers present in matrix, they can lead to a lack of
bond between fibers and matrix. Therefore, a dense packing of hydration products around carbon fibers is crucial for a good fiber-matrix bond. This could be achieved using cements having particle size below 45 μm and low water-binder ratio mixes with an appropriate fiber dispersing agent like silica fume or ground granulated blast furnace slag (Banthia and Genois 1995). The cement with lower particle size and the dispersant reduce the porosity of matrix and thus give the fibers better chance of bonding to the matrix. Dense packing resulting from dispersant addition reduces the distance between carbon fibers and the matrix (Park et al. 1991). Thus, the interfacial area increases and the interfacial bonding between carbon fibers and the matrix is enhanced. This can be seen in Figure 2.7. Furthermore, the roughness of fiber surface and the impregnation of finer cement and silica fume particles on the surface of fibers enhance the interfacial bonding (Ostertag et al. 2001).

![Image of dense packing of hydration products around carbon fibers](image)

Figure 2.7: Dense Packing of Hydration Products around Carbon Fibers (Banthia 1992).

### 2.5.4 Fiber-mortar interaction

The interaction between fibers and mortar could influence the performance of CFRM products. Plain mortar is commonly a composite of cement, water, and fine aggregate (sand); sometimes admixtures are added in mortar for different purposes. There are
numerous incipient microcracks at the surface layer of mortar due to the autogenous (hydration) shrinkage. As the mortar is stressed under various loading conditions, the microcracks extend, propagate and result in larger macrocracks. When carbon fibers are mixed, they become randomly aligned in the mortar matrix. The matrix thus becomes a composite mixture reinforced by carbon fibers. In CFRM component, the tensile stress level required for a crack to initiate through it is increased depending on the number and effectiveness of the fibers aligned in the crack tip zone. At about the failure stress of plain mortar, cracks propagate around the carbon fibers and the subsequent behavior depends on whether the fibers bridging the cracks are sufficient to carry the load or not. Beyond the failure stress of plain mortar, carbon fibers act as reinforcing agents in CFRM. As the crack tip progresses through the mortar matrix, the relative separation of two points each side of the propagating crack increases. For carbon fibers passing through the crack and resisting the microcrack widening, the development of the required stress in fibers is provided by both surface bond effects between mortar and fibers and mechanical anchorage mechanisms due to fiber shape. Under the increasing stress caused by crack propagation, the carbon fibers progressively lose surface bond and then bridge the developed crack over the length of the debonded fiber. When the stress exceeds the balanced condition, the end anchorage is lost and the fiber ends either slide through the voids present in mortar in straightening mode or slip by local crushing of mortar matrix as the ends pull out. The researchers urge that this is the preferred failure mechanism in CFRM component. However, at higher bond levels, the fiber may fail by fracture instead of pullout (Bentur 2000) or by fracture and pullout (Banthia 1992). Different phases of fiber-mortar interaction are schematically shown in Figure 2.8.

The criterion for fiber failure by pullout or fracture depends upon the fiber length embedded in the mortar matrix and bond strength. There is a critical embedded length of fibers that depends upon their geometrical characteristics and tensile strength, and on fiber-mortar bond. When the embedded length is more than critical, it will break if the fracture plane lies at the mid-point of the fiber. Conversely, the fiber will always pull out if the embedded length of fiber on either side of the fracture plane is shorter than the half of the critical length. Nevertheless, as the energy consumed in fiber fracture is negligible compared to that expended in pullout, the fiber failure by fracture will result in improved
strength efficiency with reduced energy consumption. It is also suggested that the carbon fibers may have been progressively cut by the sharp edges of sand particles during pullout and thus the failure pattern of the fibers near to the sand particles can occasionally be a brittle type.

Figure 2.8: Schematic Representation for Fiber-Mortar Interaction (Adapted from Anderson 1994).

In summary, the intricate nature of the microstructural features implies the complexities involved in the toughening and strengthening mechanisms. However, fiber pullout, fiber fracture or even a combination of the two modes as shown in Figure 2.9 (Banthia 1992) appears to be the operative failure mechanisms during fiber-mortar interaction in case of CFRM composite.
2.5.5 Major properties

The major properties of CFRM such as workability, lightweight, dimensional stability, different kinds of strength, toughness, and impact resistance will be discussed briefly in the following sections. Some of these properties are physical whereas the others are mechanical in nature. Most of the properties mentioned hereafter have been taken under experimental investigation in the present study.

2.5.5.1 Workability

The workability of cement composite is considered as that property, which specifies the aptitude of composite to be mixed, handled, transported, and most importantly placed with a minimal loss of homogeneity. It is vital that the fresh cement composite has satisfactory workability to ease mixing, transport, placement, and compaction. To ignore workability is to ignore one of the strongest driving forces that maintain the quality of cement-based composites (Hover 1998). Any cement-based composite without adequate workability will suffer in its hardened state due to poor compaction. Poor workability
would increase the porosity in the composite and it will in turn adversely affect the mechanical performance of hardened composite.

![Graph showing the relation between Carbon Fiber Volume Content and Workability of Fresh Carbon Fiber Reinforced Cement Composites](image.png)

**Figure 2.10:** Relation between Carbon Fiber Volume Content and Workability of Fresh Carbon Fiber Reinforced Cement Composites (Park et al. 1991).

The workability of cement composites is influenced by a host of factors but water-binder ratio plays the major role compared to others. Water-binder ratio is intimately related to the workability of fresh composite. This ratio should be kept as minimum as possible simultaneously with sufficient workability in fresh composite in order to avoid the reduction in strength. A water-binder ratio of 0.50 has been advised as the higher limit for CFRM to get sufficient fluidity along with adequate strength (Chung 1994). The workability of CFRM composites having low water-binder ratios can be increased using ordinary or high range water reducers (Chung 1994). Water reducers increase the fluidity of fresh composite. The demand of water reducer in CFRM increases with the higher content of carbon fibers, as the carbon fibers reduce the fluidity of fresh mixes.
The workability of CFRM composite largely varies with fiber diameter, specific surface area and fiber volume content (Ohama et al. 1985). When the other parameters remain unchanged, the workability is found to be directly proportional to the fiber diameter and inversely proportional to the specific surface area. The workability is also inversely proportional to the fiber volume content. This can be seen in Figure 2.10. Large specific surface area available in high fiber volume content tends to restrain the flowability and mobility of the mix (Bayasi and Soroushian 1992). Interlocking of fibers and formation of fiber balls during mixing cause to entrap relatively large amounts of air voids, which might be very detrimental to the material properties of hardened CFRM. In addition, inter-particle friction within fibers and between fibers and sand particles can be another factor reducing the workability of fresh CFRM mix.

2.5.5.2 Lightweight

Carbon fiber reinforced mortar produces much lighter structures than conventional mortar and concrete. It can make the structure lighter by up to 60% (KCI 1990). For instance, a CFRM curtain wall with the same capacity as a curtain wall of conventional concrete is above 50% lighter than the reinforced concrete curtain wall (MKC 1992). This is because CFRM composite allows using much thinner cross section due to its high tensile and flexural strengths. Besides, the unit weight of CFRM is less than that of conventional mortar and reinforced concrete, as it includes lighter carbon fibers but excludes any reinforcing bars for most of the structural applications.

2.5.5.3 Dimensional stability

Dimensional stability is of great importance since excessive length change due to drying shrinkage and thermal effects would cause cracking and lower the air tightness and resistance to water penetration. The dimensional stability of CFRM is superior to that of plain mortar or concrete. There is almost no risk of material cracking owing to drying shrinkage in precast members produced from CFRM. This is because the rate of drying shrinkage can be kept as low as 0.02% to 0.05% in CFRM components using autoclave
(high pressure steam) curing. Figure 2.11 shows the excellent dimensional stability of the CFRM composite.

![Graph showing rate of length change over drying age](image)

Figure 2.11: Variation of Length Change in CFRM and Plain Mortar (MKC 1992).

### 2.5.5.4 Compressive strength

The effect of carbon fibers on the compressive strength of CFRM is not well defined. Some researchers reported that there is no substantial increase in the compressive strength and sometimes it might decrease (Banthia and Genois 1995, Banthia et al. 1994). Exceptionally, Ohama et al. (1985) showed that the compressive strength could increase for a certain range of fiber contents. Although they observed the increase in compressive strength for carbon fiber reinforced cement, the similar effect can be expected in case of CFRM depending on the state of workability and compaction. However, the increase or decrease in compressive strength depends upon carbon fiber volume content as shown in Figure 2.12. In fact, the decrease in compressive strength is related to the increased air...
voids in mixes containing carbon fibers and also due to the deficiencies encountered in compacting stiffer mixes having high volume fraction of carbon fibers. The extent of air voids is usually 1% for plain mortar, which might be increased to 6% to 9% and even more in CFRM composite (Chung 1994).

The adverse effect of carbon fibers on compressive strength is further associated with the foam created by the dispersants. However, the decrease in compressive strength can be more than compensated for by using a silica fume as a dispersant and a superplasticizer as a high range water reducer (Chung 1994). This is because the microstructure is densified with reduced porosity in presence of silica fume and superplasticizer. Besides, superplasticizer takes the entrapped air out of the mix and induces some microscopic air spheres (entrained air) even in absence of air entraining admixture. The entrained air spheres act like ball bearings in a fresh composite. Consequently, the workability of the fresh CFRM mixes improves and allows good compaction, thus resulting in good strength in hardened components.

![Graph showing the effect of carbon fiber volume content on compressive strength of CFRM composite.](image)

Figure 2.12: Effect of Carbon Fiber Volume Content on Compressive Strength of CFRM Composite (Banthia et al. 1994, Ohama et al. 1985).
2.5.5.5 Tensile strength

In CFRM component, the tensile strength and the elongation at failure increase with the fiber volume content. Park et al. (1991) reported that the tensile strength of CFRM composite at 5% carbon fiber volume content is about 3 to 4 times greater than that of the plain cement-based composite. The tensile strength of CFRM is primarily influenced by the length of carbon fibers. It is also inversely proportional to the fiber diameter. Other factors such as matrix strength, fiber modulus, fiber-matrix bond, fiber dispersion, etc., have also considerable effects on the tensile strength of CFRM composite (Banthia and Genois 1995).

![Graph showing tensile stress-strain behavior](image)

**Figure 2.13:** Tensile Behavior of CFRM Composite Prepared with Different Carbon Fiber Volume Contents (Banthia et al. 1994).

Banthia et al. (1994) conducted uniaxial tensile tests on CFRM composite using 3 mm long pitch-based carbon fibers having a diameter of 18 µm, a tensile strength of 590 MPa and a modulus of elasticity of 30 GPa. They evaluated the effect of different volume...
contents of carbon fibers in terms of strengthening factors. The results obtained by them are shown in Figure 2.13 and Table 2.3. It is noted from Figure 2.13 that a substantial increase in tensile strength has been brought about by the addition of carbon fibers. In addition, Table 2.3 shows the level of strengthening with the increase in carbon fiber volume content.

Table 2.3: Effect of Different Carbon Fiber Volume Contents on Strengthening of CFRM Composite (Banthia et al. 1994).

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Carbon Fiber Volume Content (%)</th>
<th>Strengthening Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plain Mortar</td>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.38</td>
</tr>
<tr>
<td>CFRM</td>
<td>2</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>2.06</td>
</tr>
</tbody>
</table>

2.5.5.6 Flexural strength

The flexural strength of CFRM is influenced by the characteristics of fibers and other factors as mentioned previously in case of tensile strength. CFRM products provide greatly increased flexural strength due to the presence of carbon fibers. In general, the flexural strength of CFRM component increases steadily with fiber volume content. It has been reported that addition of 1% carbon fiber volume content could produce flexural strength as high as 15 MPa in cement paste. The flexural strength of cement paste could reach 30 MPa with 5% carbon fiber volume content (Banthia and Genois 1995).

Table 2.4: Effect of Fiber Volume Content on Flexural Behavior of CFRM Prepared with 6 mm Long Pitch-based Carbon Fibers (Banthia and Genois 1995).

<table>
<thead>
<tr>
<th>CF (% V)</th>
<th>Ultimate Flexural Strength (MPa)</th>
<th>Specific Fracture Energy (x 10^3 N-mm/mm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.08</td>
<td>1.57</td>
</tr>
<tr>
<td>1</td>
<td>5.97</td>
<td>13.07</td>
</tr>
<tr>
<td>2</td>
<td>7.96</td>
<td>38.34</td>
</tr>
<tr>
<td>3</td>
<td>10.47</td>
<td>64.18</td>
</tr>
</tbody>
</table>
Conversely, it has been found by experiments that CFRM provides lower flexural strength than carbon fiber reinforced paste. Seemingly, the flexural strength of CFRM is increased by approximately the same amount as the fiber volume content (Morgan et al. 1992). This follows that the flexural strength becomes almost double at 2% fiber volume content, and about 4 times greater at 4% fiber volume content. Banthia and Genois (1995) determined the flexural strength of CFRM composite in their research. The results obtained by them are shown in Table 2.4 and Figure 2.14.

![Figure 2.14: Effect of Carbon Fiber Volume Content on Flexural Behavior of CFRM Composite (Banthia and Genois 1995).](image)

Table 2.4 shows that ultimate flexural strength and the fracture energy increase considerably with an increase in fiber volume content, except that there is a slight decrease in ultimate flexural strength in the case of 1% carbon fiber volume content. The modulus of rupture is almost doubled at 3% volume content. The increase in fracture energy is also noteworthy. At 3% volume content, fracture energy increased almost 41
times that of plain mortar. Hence, it is evident that the fracture energy improves significantly in presence of carbon fibers.

2.5.5.7 First-crack strength

The first crack strength of CFRM subjected to direct tension or flexure is much higher than that of conventional mortar. In general, the first crack strength depends upon the composition of mortar matrix and the volume content of fibers. In CFRM composite with the same matrix composition, the first crack strength increases with the increase in the volume content of carbon fibers (Banthia and Sheng 1996). This can be seen from Figures 2.13 and 2.14.

2.5.5.8 Toughness

Toughness is a measure of the capacity of a material to absorb energy. It is closely related to the ductility. The higher the toughness, the greater is the ductility. Toughness is usually assessed as the area under a load-deflection curve (ACI 544, 1988). Toughness is determined to help defining the performance requirements of fiber reinforced cement composites. It indicates the extent of energy absorption or resistance to failure after cracking in fiber reinforced cement composites.

The toughness of CFRM is greatly influenced by the geometrical characteristics and volume contents of carbon fibers. An increase in the volume of carbon fiber addition usually improves the toughness of CFRM composites (Banthia and Sheng 1996). This can be seen in Figure 2.14.

2.5.5.9 Impact resistance

The impact resistance of a material relates the quantity of work required per unit volume to cause failure. It is a complex characteristic of a material that takes into account both the toughness and strength of a material. CFRM components are highly resistant to impact loads due to their superior strain capacity and toughness. Indeed, fracture energy absorption increases under impact owing to carbon fiber reinforcement (Banthia and
Genois 1995, Banthia and Ohama 1989). Experiment shows that impact loads generally impose damage over a localized area of CFRM component containing higher volume content of carbon fibers. This is because the presence of carbon fibers tends to prevent the propagation of cracks outside the zone of impact. In addition, the impact resistance of CFRM is high when most of the fibers fail by being pulled out of the matrix, as this process absorbs a greater amount of energy than fiber fracture. In contrast, the impact resistance is lowered if few fibers fail by pullout.

Ohama et al. (1985) determined the impact resistance of carbon fiber reinforced cement using a drop-weight test different from that of ACI Committee (1988). Due to the presence of carbon fibers, they noticed a remarkable increase in the number of blows causing a failure of the specimen. Their results are shown in Table 2.5. It is evident from Table 2.5 that the impact resistance increased about 200 times for carbon fibers at or above 3% volume content. A similar trend of impact resistance is expected in the case of CFRM.

Table 2.5: Impact Behavior of Carbon Fiber Reinforced Cement (Ohama et al. 1985).

<table>
<thead>
<tr>
<th>Experimental Information</th>
<th>Carbon Fiber Length: 3 mm and 10 mm Specimen: 100L x 100W x 10H mm plates Drop Weight: 80 g Steel Ball, 20 cm Fall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Fiber Volume Content (%)</td>
<td>0</td>
</tr>
<tr>
<td>Number of Blows</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

2.5.6 Durability

The property of a material to resist the combined action of environmental and other factors is known as its durability. CFRM composite is more durable than conventional mortar (KCI 1990). The carbon fibers that are generally used in CFRM consist of more than 90% elemental carbon, which is chemically very stable. The superior chemical inertness of carbon fibers makes CFRM products highly durable in aggressive
environments. The following sections will examine the resistance of CFRM components to water, aggressive chemicals, corrosion, freeze-thaw, and heat.

2.5.6.1 Resistance to water

The resistance of a material to water is measured by its ability to absorb and retain water—the higher the resistance, the lower the amount of absorbed water. Like other engineering properties, water absorption of cementitious composites is directly influenced or controlled by the porosity (Hearn et al. 1994). The porosity, depending on the relative quantities of pores of various types and sizes, dominantly controls the microstructure and thus the other properties of cement-based materials (Hearn et al. 1997). If the total porosity is less, the water absorption is comparatively low. Further, the microstructure of composite’s surface layer is more porous than that of inner core due to so-called ‘wall effect’, so water absorption is relatively high in the surface layer (Safiuddin 1999).

Figure 2.15: Water Absorption of Carbon Fiber Reinforced Cement Prepared with Different Fiber Contents (Ohama et al. 1985).
Water absorption of CFRM is significantly lower than that of plain mortar or concrete. This is because the porosity, both in surface layer and inner core, is reduced in CFRM possessing good workability in presence of superplasticizer. Besides, water absorption is lowered due to the restriction of shrinkage and any other cracks. Ohama et al. (1985) experimentally determined the extent of water absorption in carbon fiber reinforced cement and their results are given in Figure 2.15. It is evident from Figure 2.15 that the extent of water absorption in carbon fiber reinforced cement decreases with the increase in carbon fiber volume content. A similar trend of water absorption is expected in CFRMs with various carbon fiber volume contents.

2.5.6.2 Resistance to chemicals

The resistance of cementitious materials to chemicals largely depends on the extent to which the reactive elements of cement paste are exposed to the aggressive agents. This is a function of water absorption in the surface layer of any cement-based composite. The water absorption of CFRM is lower than that of plain mortar and concrete and therefore it shows good resistance to aggressive chemicals.

Table 2.6: Effect of Sulfuric Acid Exposure on Carbon Fiber Reinforced Cement Prepared with 40% Silica Fume (Banthia and Sheng 1991c).

<table>
<thead>
<tr>
<th>Carbon Fiber Volume Content (%)</th>
<th>Peak Load (N)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Prior to Acid Exposure</td>
<td>After 30 Day Acid Exposure</td>
<td>After 60 Day Acid Exposure</td>
<td>After 90 Day Acid Exposure</td>
</tr>
<tr>
<td>1</td>
<td>180</td>
<td>300</td>
<td>220</td>
<td>200</td>
</tr>
<tr>
<td>3</td>
<td>400</td>
<td>425</td>
<td>315</td>
<td>500</td>
</tr>
<tr>
<td>5</td>
<td>600</td>
<td>615</td>
<td>500</td>
<td>550</td>
</tr>
</tbody>
</table>

Carbon fiber reinforced mortar is very attractive due to superior chemical inertness of carbon fibers compared to glass and several polymer fibers. The chemical stability of CFRM is high since carbon fibers are not corroded in the alkaline cementitious environment. Although strong oxidizing agents such as nitric and sulfuric acids could
attack carbon fibers, their composites have been found to have no appreciable degradation either in the strength or in the toughness due to cyclic exposure to a weak acid (Banthia and Sheng 1991c). Tables 2.6 and 2.7 show that acid exposure doesn’t cause any significant effect on the load carrying capacity of a carbon fiber reinforced cement. Similar performance could be expected in the case of a CFRM composite.

Table 2.7: Effect of Nitric Acid Exposure on Carbon Fiber Reinforced Cement Prepared with 40% Silica Fume (Banthia and Sheng 1991c).

<table>
<thead>
<tr>
<th>Carbon Fiber Volume Content (%)</th>
<th>Peak Load (N)</th>
<th>Prior to Acid Exposure</th>
<th>After 30 Day Acid Exposure</th>
<th>After 60 Day Acid Exposure</th>
<th>After 90 Day Acid Exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>180</td>
<td>240</td>
<td>255</td>
<td>275</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>390</td>
<td>540</td>
<td>490</td>
<td>420</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>600</td>
<td>490</td>
<td>495</td>
<td>560</td>
</tr>
</tbody>
</table>

2.5.6.3 Resistance to corrosion

Carbon fiber reinforced mortar is protected itself against corrosion due to the alkaline cementitious environments as observed in GFRC composites (Bentur and Mindess 1990). It is neither affected by chloride solutions, which can cause corrosion in case of steel fibers (Ohama 1987). Besides, it is more resistant to water absorption as well as water permeation. Hence, if steel reinforcements (bars) were used in CFRM, there would be little chance for corrosion to occur in chloride environment.

2.5.6.4 Resistance to freeze-thaw

In certain climates such as in Canada and some states of USA, cementitious materials undergo long period of exposure at sub-zero temperatures and to freeze-thaw conditions. Therefore, cement-based materials must be sufficiently durable so that they can withstand such severe atmospheric conditions. CFRM composites provide improved freeze-thaw durability (Soroushian et al. 1992c). Limited data regarding the freeze-thaw resistance of
CFRM composite are available. Akihama et al. (1988) studied the freeze-thaw resistance of CFRM in accordance with ASTM C666 (1999) over 300 cycles of freezing and thawing. Their results, in Figure 2.16, indicate that the diminution of dynamic modulus of elasticity is insignificant. The relative dynamic modulus of all CFRM components was above 95%. It reveals that the overall durability of CFRM against freeze-thaw is excellent.

![Graph showing the effect of freeze-thaw cycles on dynamic modulus of elasticity of CFRM composite](image)

Figure 2.16: Effect of Freeze-Thaw Cycles on Dynamic Modulus of Elasticity of CFRM Composite (Akihama et al. 1988).

2.5.6.5 Resistance to heat

The resistance of cement-based materials to heat depends on their density and moisture content. For dry materials, it increases with the increase in density. Although CFRM is a lightweight material, it is greatly resistant to high temperatures. It doesn’t induce any durability problem due to extreme heat. Akihama et al. (1988) prepared small beam...
specimens by CFRM having 2% carbon fiber volume content and immersed them in hot water at 75°C for up to five months, then tested for flexural strength in order to confirm the durability of CFRM against heat. The first-crack and ultimate flexural strengths of CFRM specimens obtained after 5 months immersion in hot water are shown in Table 2.8. It is obvious from Table 2.8 that the flexural strength of CFRM increased instead of diminution due to hot water immersion. Thus, it reveals that there is no durability problem at high temperatures.

Table 2.8: Effect of Heat on Flexural Strength of CFRM Composite (Akihama et al. 1988).

<table>
<thead>
<tr>
<th>Curing Method Used before Immersion in 75°C Hot Water for 5 Months</th>
<th>First Crack Flexural Strength (MPa)</th>
<th>Ultimate Flexural Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before Immersion</td>
<td>After Immersion</td>
</tr>
<tr>
<td>Dry Air Curing</td>
<td>3.45</td>
<td>4.25</td>
</tr>
<tr>
<td>Autoclaving</td>
<td>3.45</td>
<td>4.50</td>
</tr>
</tbody>
</table>

2.5.7 Mix design

Good mix design of any cementitious composite comes down to combining the various components that go into the composite to obtain the required strength while ensuring that the mixture maintains adequate workability until final setting. Mix design for CFRM composites vary from those of conventional cement-based composites. There is no established mix design method so far for CFRM composites. Schrader and Munch (1976) established a mix design procedure for SFRC. The similar concept could be followed to establish a mix design method for CFRM. However, the researchers have used mostly trial-and-error methods in designing CFRM mixes.

2.5.7.1 Need for different mix design approach

The process of mix design for conventional cement-based materials is not applicable to CFRM. The reasons are as follows:
a. Established relationships between average and characteristic strengths could be unacceptable for CF RM.

b. Traditional curves showing the relation between water-binder ratio and strength could be misleading for CF RM possessing adequately high workability.

c. None of the traditional curves for water-binder ratio and strength relationship accounts for the effect of the mineral admixture, which is usually added to disperse the carbon fibers uniformly in CF RM mixes.

d. Coarse aggregates are not included as a mix component in CF RM.

e. Water content required for CF RM depends upon the effectiveness of silica fume and superplasticizer and on the content of carbon fibers.

f. Reference sand gradation used for conventional cement composites could not give good results if applied to CF RM.

In summary, since the fiber characteristics, the amount of fibers, and the dosages of superplasticizer and silica fume may have greater effects on the strength characteristics, workability and durability performance, a different approach is needed instead of traditional method to design the CF RM mixes.

### 2.5.7.2 Mix design based on trial mixes

In general, strength is the primary criterion for designing the mixes of cement-based materials. In designing CF RM mixes, however, workability must be given equal importance with strength. Since CF RM mixes contain relatively high cement contents, good strength is intrinsic. Yet, better strength can be gained by maintaining a good workability. So much attention should be paid on workability rather than strength. Further, durability is an important issue to improve the serviceability of CF RM components. By balancing workability and strength in CF RM products, good durability will be achieved is seeded in the same ground. Nevertheless, balancing the requirements for workability and strength is often problematic. The situation is rendered even more complex when fibers need to be dispersed and mixed very competently.
Material selection is equally important in mix design of CFRM. Fiber characteristics and type of cement influence the properties of CFRM. Besides, sand type, characteristics, and gradation could negatively affect the properties of CFRM. Thus, the key to success in designing a high performance CFRM mix is to find the appropriate materials to meet the performance requirements.

In preparing the trial CFRM mixes, consideration should be given to the amount of water and sand to be used with binder. Therefore, selection of water-binder ratio in company with sand-binder ratio is paramount. CFRM mixes should normally be designed with a water-binder ratio in the order of 0.35. If water-binder ratio is allowed to be too high, the unit weight of CFRM will decrease with consequent effects on the mechanical properties. For this reason, the maximum water-binder ratio suggested to use is 0.50 (Chung 1994). On the other hand, the sand-binder ratio should be chosen at 0.50 or higher values. If the sand-binder ratio is kept below 0.50, the matrix related properties will improve but it may induce considerable shrinkage, moisture movement and creep in CFRM components. Furthermore, at sand-binder ratios greater than 0.50, the properties of CFRM are relatively unaffected by the changes in sand-binder ratio, given that the necessary workability is maintained in the resulting mix without significantly increasing the water-binder ratio. It should also be borne in mind that very high sand-binder ratio will not be conducive to achieve good strength. Therefore, sand-binder ratios in the range of 0.50 to 2.0 should be used in preparing the trial CFRM mixes.

2.5.7.3 Mix optimization

Carbon fibers are costlier than any other material components of CFRM. Therefore, optimization of CFRM mix is desirable to make it cost-effective. The performance of CFRM and the cost of mortar can be taken into consideration to evaluate the overall cost-effectiveness. The idea introduced by Nehdi et al. (1996) could be used to examine the cost-effectiveness of CFRMs and to obtain an optimal mix. Volume flow as a measure of workability performance, compressive strength, ultimate flexural strength and ultimate impact resistance as the measures of mechanical performance, and water absorption as a measure of durability performance of mortars might be compared with cost to determine
the cost-effectiveness with respect to the overall performance. As a basis for comparison between CFRM and plain mortar, a parameter called performance to cost ratio (PCR) can be introduced as follows.

\[
PCR = \frac{V_{\text{ff}} + (C_{\text{sf}} \times F_{\text{sf}} \times I_{\text{ef}} \times W_{\text{arf}})}{C_f} \times 100
\] (2-1)

Where,

\(PCR\) = Performance to cost ratio
\(C_f\) = Cost factor
\(C_{\text{sf}}\) = Compressive strength factor
\(F_{\text{sf}}\) = Ultimate flexural strength factor
\(I_{\text{ef}}\) = Ultimate impact resistance factor
\(W_{\text{arf}}\) = Water absorption resistance factor
\(V_{\text{ff}}\) = Volume flow factor

The values of \(C_f, C_{\text{sf}}, F_{\text{sf}}, I_{\text{ef}}, W_{\text{arf}},\) and \(V_{\text{ff}}\) for CFRMs can be worked out knowing their unit cost, compressive strength, ultimate flexural strength, ultimate impact resistance, water absorption, and volume flow with respect to the unit cost and the comparable properties of the control mortar (NPCM). Then, the performance to cost ratios (PCRs) can be determined and the cost-effectiveness can be evaluated from the obtained PCRs. The higher the PCR, the more cost-effective is the mortar with respect to the performance it could provide. Eventually, the optimum mix can be defined based on the properties and the PCRs of various CFRMs.

2.5.8 Economy

The precast products made of CFRM are generally lighter. Further, thin sheet applications are possible using CFRM composite. Therefore, savings can be attained through thinner lightweight application of CFRM although the material cost is notably higher than that of conventional precast units. CFRM products offer superior mechanical performance. They provide greater tensile and flexural strengths, toughness, impact
resistance, and water-tightness than plain mortar. Thus, the overall mechanical performance of CFRM makes it acceptable over the cost. Besides, CFRM products would provide enhanced durability, and hence, better service life. Then, the cost-effectiveness of CFRM components in construction industries will be apparent if the cost analysis is conducted based on the lifecycle costing.

2.6 Concluding Remarks

The improvements in strength and durability of cement composites by incorporating pitch-based carbon fibers are promising. The future of CFRM composites in structural as well as non-structural areas is very vivid. Especially, CFRM products could be used extensively in different sectors of construction. However, wide research endeavors are vital to take over the existing knowledge gaps and to bridge different issues for the bright prospect of CFRM composite.
CHAPTER III

EXPERIMENTAL MATERIALS

3.1 General

Production of cement-based composites places stringent requirements on materials selection if excellent performance is sought in respect of workability, strength, toughness, impact resistance, and durability. Quality component materials must be selected along with the specifications in order to achieve the high performance of composites. This is because the performance of composites depends upon the properties of constituent materials and the roles they play when combined. The following sections will depict the constituent materials necessary for producing carbon fiber reinforced mortar (CFRM).

3.2 Carbon Fibers

Carbon fibers are a key constituent in advanced composite material. These extraordinary fibers were once confined to a limited number of high-priced applications in the aerospace arena but now are growing to take a good position among the basic raw materials for construction industries. Carbon fibers are high strength and high stiffness synthetic fibers that possess more than 90% carbon in composition (Chung 1994). They are appealing for producing high quality fiber composites, which could be used in a variety of structural and electrical applications. Carbon fibers provide amazing structural properties in CFRM and make it attractive to entertain the growing demands in construction industries. In fact, the family of carbon fibers now serves a large segment of the market for advanced composite materials.

3.2.1 Classification

There are mainly two different types of carbon fibers presently being used in the production of carbon fiber reinforced composites. These are polyacrylonitrile (PAN)-based and pitch-based carbon fibers.
3.2.1.1 PAN-based carbon fibers

PAN-based carbon fibers are produced from polyacrylonitrile polymer fibers in presence of a solvent and a catalyst followed by additional chemical and surface treatments. PAN-based carbon fibers offer much higher tensile strength and modulus of elasticity than pitch-based carbon fibers. They, however, impart less ductility in fiber composites than pitch-based carbon fibers and break at a lower elongation. PAN-based carbon fibers are mostly used in composites for the aircraft and aerospace industries and in sports and recreation equipment. PAN-based carbon fibers are considerably more expensive than pitch-based carbon fibers. Therefore, they are not attractive for producing CFRM to be used in civil engineering applications.

3.2.1.2 Pitch-based carbon fibers

Pitch-based carbon fibers are made from petroleum, coal tar, and other types of pitches. They are superior to PAN-based fibers in imparting flexibility, ductility, and wear resistance in fiber composites but inferior in respect of tensile strength, and modulus of elasticity. Still pitch-based carbon fibers are superior to many other synthetic fibers and suitable for cement paste, mortar and concrete. Besides, they are much cheaper, and therefore offer better cost-performance. Thus, pitch-based carbon fibers are more attractive than PAN-based carbon fibers to produce CFRM for civil engineering construction.

3.2.2 Fabrication

Carbon fibers are commercially fabricated from polymers such as polyacrylonitrile and pitch, for instance petroleum and coal tar pitches.

There are two main processes involved in the fabrication of carbon fibers from pitch or polymers. Both processes utilize pyrolysis, which is performed by heating. Various grades of carbon fibers can be obtained in each process depending on the extent of heat treatment, stretching, oxidation, and carbonization. The processes producing PAN-based and pitch-based carbon fibers are shown in Figures 3.1 and 3.2, respectively.
Figure 3.1: Processes for Producing PAN-based Carbon Fibers (Adapted from Chung 1994).

Figure 3.2: Processes for Producing Pitch-based Carbon Fibers (Adapted from Chung 1994).
3.2.3 Structure

Carbon fibers consist of small crystallites of ‘turbostratic’ graphite, which is one of the allotropic forms of carbon (Hull and Clyne 1996). Turbostratic graphite is closely similar to graphite crystals. In graphite crystal, carbon atoms are arranged two dimensionally like a honeycomb structure lying in a plane. Carbon atoms within a plane are bonded by covalent and metallic bonds (Chung 1994). The planes are stacked one over another and weaker Vander Walls forces hold them together. The crystal structure of graphite is shown in Figure 3.3.

![Graphite Crystal Structure Diagram](image)

Figure 3.3: Crystal Structure of Graphite (Chung 1994).
3.2.4 Physical properties

The performance of carbon fibers in CFRM largely depends upon their physical properties, which are governed by the structure of fibers. The major physical properties of PAN-based and pitch-based carbon fibers are given in Table 3.1.


<table>
<thead>
<tr>
<th>Property</th>
<th>PAN-based Carbon Fiber</th>
<th>Pitch-based Carbon Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament Diameter (µm)</td>
<td>7 – 8</td>
<td>14 – 18</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>1.75 – 1.95</td>
<td>1.65 – 1.85</td>
</tr>
<tr>
<td>Tensile Strength (MPa)</td>
<td>3000 – 4000</td>
<td>590 – 2000</td>
</tr>
<tr>
<td>Modulus of Elasticity (GPa)</td>
<td>250 – 400</td>
<td>30 – 200</td>
</tr>
<tr>
<td>Elongation at Break (%)</td>
<td>0.5 – 1.5</td>
<td>2.0 – 2.4</td>
</tr>
</tbody>
</table>

3.2.5 Functions

Carbon fibers have two main functions in CFRM: as a crack arrester (Banthia et al. 1995, and as a bonding enhancer (Banthia et al. 1995, Katz et al. 1995, Soroushian et al. 1992b). Carbon fibers can be used with large volume contents and dispersed uniformly in the matrix because of their very fine sizes. Thus, the number of fibers in the matrix increases and the fiber-fiber spacing is reduced. This increases the effectiveness of carbon fibers to arrest and deflect microcracking. As a result, fracture energy, tensile and flexural strengths, and toughness of CFRM are greatly increased.

Closely spaced carbon fibers also induce greater bond strength. A very strong bond between carbon fibers and matrix is developed because of increased number of fibers, reduced fiber spacing and densification of the transition zone surrounding the fibers (Katz et al. 1995, Obla and Li 1995). Consequently, the mechanical behavior of CFRM is significantly improved. Furthermore, carbon fibers impart greater resistance in CFRM against impact, freeze-thaw, corrosion, and aggressive chemicals.
3.2.6 Fiber content

The fiber content is usually expressed in terms of volume or weight. The major properties of CFRM such as tensile and flexural strengths, toughness and impact resistance are proportional to fiber content. Relatively, a very high content of carbon fibers can be used in CFRM. However, processing problems such as breakage, segregation, non-preferred orientation, and non-uniform distribution of fibers could arise with high fiber contents. Besides, very high fiber content would cause difficulties in placing and compacting the fresh composite because of reduced workability. Consequently, the fiber content is seen to significantly affect the performance of hardened composites. In practice, it is useful to classify CFRM based on fiber content. Volume fiber content in CFRM can be considered high if it is above 3%, moderate if in the range of 1% to 3%, and low if in the range of 0.1% to 1%, based on the total volume of the fiber composite. However, 1% to 5% carbon fibers by volume have been used in most of the research work on carbon fiber reinforced composites (Akihama et al. 1988, Banthia 1992, Banthia and Dubeau 1994, Banthia and Sheng 1991b, Kim and Park 1998, Ohama et al. 1985, Soroushian et al. 1992a).

3.3 Sand

Sand acts as fine aggregate and forms an important ingredient of mortar and concrete. According to ASTM, sand is defined as fine aggregate passing the 9.5 mm sieve and almost entirely passing the 4.75 mm (No. 4) sieve and predominantly retained on the 75 μm (No. 200) sieve (ASTM C125-00a, 2002). Sand particles consist of small grains of silica. It is formed by the natural disintegration and abrasion of rocks or processing of completely friable sandstones. Sand can be obtained from pit, river, sea, and lake. It can be fine, medium, coarse or gravelly depending on the size of grains.

3.3.1 Physical properties

The physical properties of sand should be such that those can enhance the performance of mortar or other cement based composites. Sand should be sound, damp free, low
absorbent, and free from deleterious materials such as clay, silt, organic matter, shells, and salts to produce high-quality cement based composites. It should be clean, chemically inert, and well graded. Sand grains ought to be sharp, angular, coarse and durable. Some important physical properties of natural sand are shown in Table 3.2.

Table 3.2: Physical Properties of Natural Sand (ASTM C 33-02a, 2002; Safiuddin 1998; Shetty 2000).

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Volume (%)</td>
<td>60 – 70</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.6 – 2.8</td>
</tr>
<tr>
<td>Absorption (%)</td>
<td>1 – 2</td>
</tr>
<tr>
<td>Fineness Modulus</td>
<td>2 – 3</td>
</tr>
<tr>
<td>Maximum Size (mm)</td>
<td>4.75 – 9.5</td>
</tr>
<tr>
<td>Minimum Clay Content (%)</td>
<td>3 – 5</td>
</tr>
</tbody>
</table>

3.3.2 Functions

Sand is frequently used as a major constituent of mortar in order to serve the following purposes:

a. It acts as an adulterant and contributes the greater volume of mortar resulting in reduction of cost.

b. It subdivides the cement paste and thus offers more surface area for dispersion and adhesion.

c. It prevents excessive shrinkage and cracking in mortar during setting.

d. It helps in the adjustment of strength of mortar varying its proportion with cement.

e. It, if well graded, adds to the density of mortar.

f. It is also believed that some chemical reactions take place between silica of sand particles and the constituents of cement to form hardened mass in mortar.
3.3.3 Gradation

Gradation of sand represents the size distribution of sand particles. In general, gradation has an important effect on the workability of freshly mixed mortar or concrete and thereby on the properties of hardened composites. It affects porosity, shrinkage, and durability of mortar and concrete. Sand should contain particles of uniformly varying sizes or it should be well graded in order to get a dense mortar with sufficient workability. Besides, well-graded sand lessens the quantity of paste, which is the weak link in a mass of cement-based composite material. It also results in increased economy as the quantity of cement is lowered for a given consistency.

Sand gradation is usually determined by sieve analysis. It introduces a parameter known as ‘fineness modulus’ for arriving at satisfactory sand grading. Fineness modulus is a ready index of the coarseness or fineness of sand. The larger the index, the coarser is the sand. Based on sieve analysis, ASTM has defined the requirement for grading of sand for use in cement composites (ASTM C33-02a, 2002). It has been shown in Table 3.3.

Table 3.3: Requirement for Gradation of Sand (ASTM C 33-02a, 2002).

<table>
<thead>
<tr>
<th>Sieve</th>
<th>Percent Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5 mm</td>
<td>100</td>
</tr>
<tr>
<td>4.74 mm (No.4)</td>
<td>95 – 100</td>
</tr>
<tr>
<td>2.36 mm (No.8)</td>
<td>80 – 100</td>
</tr>
<tr>
<td>1.18 mm (No.16)</td>
<td>50 – 85</td>
</tr>
<tr>
<td>600 μm (No.30)</td>
<td>25 – 60</td>
</tr>
<tr>
<td>300 μm (No.50)</td>
<td>5 – 30</td>
</tr>
<tr>
<td>150 μm (No.100)</td>
<td>0 – 10</td>
</tr>
</tbody>
</table>

Sand grading is not an important parameter with regard to the mechanical properties of microfiber reinforced mortars (Pierre et al. 1999). Carbon fiber reinforced mortar typically contains such a high content of fine cementitious materials that the sand grading is relatively unimportant compared to plain mortar. Banthia and Genois (2000)
particularly studied the propagation of cracks in microfiber reinforced cement composites and tried to quantify the influence of sand grading. They observed that sand gradation has no effect on crack growth in CFRM.

3.3.4 Sand content

Sand content is important for CFRM as it gives the bulk volume of mortar and makes it economical. It can be quantified relatively with the amount of binder in terms of sand-binder ratio. Usually, the sand-binder ratio of plain mortar is in the range of 2.5 to 3.5 based on the weight of binder (cement); but it becomes lower for CFRM as the reduced sand content is beneficial to control the extension of smaller cracks (Banthia and Genois 2000). Researchers mostly have used the sand-binder ratios in the range of 0.5 to 2.0 for CFRM (Banthia 1992, Banthia and Genois 1995, Banthia et al. 1993, Banthia et al. 1995, Pigeon et al. 1996).

3.4 Portland Cement

Portland cement is a hydraulic cement produced by pulverizing the clinker consisting essentially of hydraulic calcium silicates and usually containing one or more of the forms of calcium sulfate as an interground addition (ASTM C 150-02, 2002). It hardens by interacting with water and forms water resisting compound. Portland cement is most widely used to produce mortar, concrete, and other cement based composite materials. It is also a major component for CFRM.

3.4.1 Mineralogical composition

Portland cement is manufactured from calcareous materials such as limestone or chalk, and from argillaceous materials such as clay and shale. The raw materials are ground, mixed intimately in certain proportions and burnt at high temperature to manufacture the portland cement. During the process of cement manufacture, the oxides present in raw materials interact with one another at high clinkering temperature and form a series of
more complex mineral compounds. The mineralogical composition of portland cement is given in Table 3.4.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Mass Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemical Name</strong></td>
<td><strong>Abbreviated Name</strong></td>
</tr>
<tr>
<td>Tricalcium Silicate (C₃S)</td>
<td>Alite</td>
</tr>
<tr>
<td>Dicalcium Silicate (C₂S)</td>
<td>Belite</td>
</tr>
<tr>
<td>Tricalcium Aluminate (C₃A)</td>
<td>---</td>
</tr>
<tr>
<td>Tetracalcium Aluminoferite (C₄AF)</td>
<td>Celite</td>
</tr>
<tr>
<td>Pentacalcium Trialuminate (C₅A₃)</td>
<td>---</td>
</tr>
<tr>
<td>Calcium Sulfate Dihydrate (CSH₂)</td>
<td>Gypsum</td>
</tr>
</tbody>
</table>

### 3.4.2 Chemical composition

Chemical analysis of portland cement has revealed that it mainly consists of oxide compounds. The major oxide compounds are lime, silica, alumina, and iron. In addition to these four compounds, there are some other minor compounds. Two minor compounds namely sodium and potassium oxides are of some importance. They are referred to as alkalis in cement. Besides, magnesia and sulfuric anhydrite can be mentioned although they are not very much beneficial constituents of cement. The chemical composition of portland cement is shown in Table 3.5.

### 3.4.3 Physical properties

The physical properties of cement significantly influence the characteristics of cement-based materials. Therefore, most specifications for portland cement place limits on its
physical properties. The requirements for major physical properties of normal portland cement are presented in Table 3.6.

Table 3.5: Chemical Composition of Portland Cement (Brandt 1995).

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mass Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical Name</td>
<td>Abbreviated Name</td>
</tr>
<tr>
<td>Calcium Oxide</td>
<td>Lime</td>
</tr>
<tr>
<td>Silicon Dioxide</td>
<td>Silica</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>Alumina</td>
</tr>
<tr>
<td>Ferric Oxides</td>
<td>Iron</td>
</tr>
<tr>
<td>Magnesium Oxide</td>
<td>Magnesia</td>
</tr>
<tr>
<td>Sulfur Trioxide</td>
<td>Sulfuric Anhydrite</td>
</tr>
<tr>
<td>Alkaline Oxides</td>
<td>Alkalis</td>
</tr>
</tbody>
</table>

Table 3.6: Physical Requirements for Type I Portland Cement (ASTM C 150-02, 2002).

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness (Specific Surface)</td>
<td>Minimum 160 m²/kg if Measured by Turbidimeter Test&lt;br&gt;Minimum 280 m²/kg if Measured by Air Permeability Test</td>
</tr>
<tr>
<td>Air Content Induced in Mortar</td>
<td>Maximum 12%</td>
</tr>
<tr>
<td>Autoclave Expansion</td>
<td>Maximum 0.80%</td>
</tr>
<tr>
<td>Compressive Strength</td>
<td>Not Less than 12 MPa at 3 Days&lt;br&gt;Not Less than 19 MPa at 7 Days&lt;br&gt;Not Less than 28 MPa at 28 Days</td>
</tr>
<tr>
<td>Initial Setting Time</td>
<td>Not Less than 60 Minutes if Measured by Gillmore Test&lt;br&gt;Not Less than 45 Minutes if Measured by Vicat Test</td>
</tr>
<tr>
<td>Final Setting Time</td>
<td>Not More than 600 Minutes if Measured by Gillmore Test&lt;br&gt;Not More than 375 Minutes if Measured by Vicat Test</td>
</tr>
<tr>
<td>False Set (Final Penetration)</td>
<td>Minimum 50%</td>
</tr>
</tbody>
</table>

3.4.4 Functions

Cement is a key component for any cement-based composite material. It is an excellent binding material. Cement possesses good plasticity and assists to produce workable fresh
composites. In hardened state, it offers strength and hardness to mortar, concrete, and other cement based composites. It also provides water tightness in cement-based materials and makes them durable.

3.4.5 Cement content

The performance of any cement-based composite is a function of cement content. Fiber composites are generally characterized by higher cement content. They contain more cement than conventional cement-based composites. Usually, the minimum cement content for conventional concrete used in flatwork varies from 282 kg/m$^3$ to 366 kg/m$^3$ depending on the maximum size of aggregate (Kosmatka et al. 1995). On the other hand, the cement content more often ranges from 392 kg/m$^3$ to 557 kg/m$^3$ in high strength concrete (ACI Committee 363, 1988). It is advisable to use the cement content below 500 kg/m$^3$ in high strength and high performance concretes (Gutiérrez and Cánovas 1996). This will avoid excessive increase in brittleness and result in reduced material cost. Cement contents in the range of 450 kg/m$^3$ to 500 kg/m$^3$ are likely to be appropriate in high strength concrete (Taylor et al. 1996). Compared to conventional and high strength cement composites, the cement content is exceptionally very high in carbon fiber reinforced cement composites. A literature survey on carbon fiber reinforced mortar and concrete was carried out in the present study. It reveals that most of the works used cement content ranging between 500 kg/m$^3$ and 1500 kg/m$^3$ (Banthia et al. 1995, Katz et al. 1995, Kim and Park 1998, Obla and Li 1995, Ohama et al. 1985, Park et al. 1991, Pigeon et al. 1996, Sun et al. 2000, Zheng and Chung 1989).

3.4.6 Hydration of portland cement

Hydration refers to the chemical reaction between hydraulic cement and water forming new compounds most of which have strength producing properties (ASTM C 219-01a, 2002). In other words, the silicates and aluminates of portland cement react with water and form bonding products, which in time produce a firm and hard mass known as the hydrated cement paste.
3.4.6.1 Hypothesis of hydration

The hydration of cement can occur in two ways: by ‘through solution’ and ‘solid state’ mechanisms. At first, the direct addition of some water molecules takes place. This is known as the ‘through solution’ mechanism. In this mechanism, the cement compounds dissolve to produce a super-saturated solution from which different hydrated products are precipitated. The second way is the ‘solid state’ mechanism. In this mechanism, the water molecules attack cement compounds and convert them into hydrated products beginning from the surface and progressing to the interior of the compounds with time. It is likely that both ‘through solution’ and ‘solid state’ mechanisms might occur during the course of hydration reactions (Shetty 2000). However, the ‘through solution’ mechanism predominates at the early stages of hydration whereas the ‘solid state’ mechanism operates at the later stages of hydration.

3.4.6.2 Hydration process

The hydration process does not occur instantaneously. When portland cement is mixed with water, the resulting paste begins to stiffen after a period, undergoes initial and final sets with development of strength, and achieves hardness. Minute crystals of calcium and gel form during hydration process. These hydration products tend to consolidate the matrix of composite and hold its components together. The total hydration process goes under three phases as described below:

Silicate phase: In this phase, tricalcium silicate (3CaO.SiO₂) and dicalcium silicate (2CaO.SiO₂) react with water (H₂O). The whole process undergoes in five steps (Dodson 1990). Nevertheless, the main reaction products are calcium silicate hydrate [3CaO.2SiO₂.3H₂O] and calcium hydroxide [Ca(OH)₂]. According to Lea (1971), the entire reactions of silicate compounds can be illustrated as follows:

\[
2(3\text{CaO}.\text{SiO}_2) + 6\text{H}_2\text{O} \rightarrow 3\text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + 3\text{Ca(OH)}_2 \quad (3-1)
\]

\[
2(2\text{CaO}.\text{SiO}_2) + 4\text{H}_2\text{O} \rightarrow 3\text{CaO}.2\text{SiO}_2.3\text{H}_2\text{O} + \text{Ca(OH)}_2 \quad (3-2)
\]
It can be found from the above equations that both silicates require approximately the same amount of water for their hydration, but tricalcium silicate produces comparatively low quantity of calcium silicate hydrate and more quantity of Ca(OH)\textsubscript{2} than that formed in the hydration of dicalcium silicate. However, both silicates contribute to the development of strength.

**Aluminate phase**: According to Dodson (1990), this phase is comprised of two steps. In the first step, tricalcium aluminate (3CaO.Al\textsubscript{2}O\textsubscript{3}) immediately reacts with water and gypsum (CaSO\textsubscript{4}.2H\textsubscript{2}O) to form an insoluble compound known as the ettringite (3CaO.Al\textsubscript{2}O\textsubscript{3}.3CaSO\textsubscript{4}.32H\textsubscript{2}O). In the second step, the ettringite reacts with the remainder of tricalcium aluminate (3CaO.Al\textsubscript{2}O\textsubscript{3}) and additional water (H\textsubscript{2}O) to form a low sulfate ettringite (CaO.Al\textsubscript{2}O\textsubscript{3}.CaSO\textsubscript{4}.12H\textsubscript{2}O). This is an unstable compound, which is eventually converted into tricalcium aluminate hydrate (3CaO.Al\textsubscript{2}O\textsubscript{3}.6H\textsubscript{2}O). The chemical reactions involved in this phase are as follows:

\[
3\text{CaO.Al}_2\text{O}_3 + 3(\text{CaSO}_4.2\text{H}_2\text{O}) + 26\text{H}_2\text{O} \rightarrow 3\text{CaO.Al}_2\text{O}_3.3\text{CaSO}_4.32\text{H}_2\text{O} \tag{3-3}
\]

\[
3\text{CaO.Al}_2\text{O}_3.3\text{CaSO}_4.32\text{H}_2\text{O} + 2(3\text{CaO.Al}_2\text{O}_3) + 4\text{H}_2\text{O} \rightarrow 3(3\text{CaO.Al}_2\text{O}_3.\text{CaSO}_4.12\text{H}_2\text{O}) \tag{3-5}
\]

\[
3\text{CaO.Al}_2\text{O}_3.\text{CaSO}_4.12\text{H}_2\text{O} \rightarrow 3\text{CaO.Al}_2\text{O}_3.6\text{H}_2\text{O} \tag{3-6}
\]

In absence of gypsum, tricalcium aluminate directly reacts with water and forms tricalcium aluminate hydrate, [3CaO.Al\textsubscript{2}O\textsubscript{3}.6H\textsubscript{2}O]. This reaction is very rapid and therefore leads to the quick hardening of cement known as ‘flash set’.

**Aluminoferrite phase**: This phase is not as clear-cut as the aluminate phase because of the complexity of chemical reactions. Researchers believe that, in presence of gypsum, compounds analogous to ettringite and its low sulfate form are produced in which the aluminum ions are partially replaced by ferric ions (Fukuhsara et al. 1981). In absence of gypsum, tri- and hexahydrates of aluminoferrite are thought to form, but their formation rate is slow compared to the tricalcium aluminate hydrates.
3.5 Silica Fume

Silica fume is a very fine pozzolan material, composed mostly of amorphous silica produced by electric arc furnaces as a byproduct of the production of elemental silicon or ferrosilicon alloys (ASTM C 1240-01, 2002). From physical point of view, silica fume is an extremely fine powder having particles with diameters ranging from less than 0.1 μm to about 1 or 2 μm (Aftcin 1998). In relative terms, silica fume particles are 100 times smaller than cement particles and almost of the same fineness as cigarette smoke.

3.5.1 Physical properties

Silica fume is usually used as an addition to or as a partial replacement of cement. It is available in undensified, densified, and slurry forms and varies in color from white to pale grey to black.


<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Particle Size</td>
<td>0.1 – 0.3 μm</td>
</tr>
<tr>
<td>Fineness (Specific Surface)</td>
<td>15000 – 25000 m²/kg (by Nitrogen Adsorption)</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.1 – 2.3</td>
</tr>
<tr>
<td>Percent Retained on 45-μm Sieve</td>
<td>Maximum 10%</td>
</tr>
<tr>
<td>Bulk Density (Undensified)</td>
<td>200 – 300 kg/m³</td>
</tr>
<tr>
<td>Bulk Density (Densified)</td>
<td>500 – 700 kg/m³</td>
</tr>
</tbody>
</table>

As silica fume particles are finer than cement, they should usually be regarded as a part of the cement paste matrix in determining the percentages of fine and coarse aggregates (ACI Committee 212, 1986). Therefore, some of the physical properties of silica fume are very useful for the mix design of cement composites. The principal physical properties of silica fume are listed in Table 3.7.
3.5.2 Chemical composition

Silica fume is mostly composed of amorphous silica. The silica content of silica fume varies depending on the type of alloy fabricated - the higher the silicon content of alloy, the higher the silica content of silica fume. Silica fume produced during the production of silicon metal usually contains more than 90% silica whereas it may possess less than 90% silica if produced during the manufacture of ferrosilicon alloys.

According to ASTM Standard C 1240-01 (2002), silica fume should conform the requirements for chemical composition prescribed in Table 3.8. The chemical composition of a typical silica fume has been illustrated in Table 3.9.

<table>
<thead>
<tr>
<th>Chemical Component</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>Minimum 85%</td>
</tr>
<tr>
<td>Moisture Content</td>
<td>Maximum 3%</td>
</tr>
<tr>
<td>Igneous Loss</td>
<td>Maximum 6%</td>
</tr>
<tr>
<td>Available Alkalis as Na₂O</td>
<td>Maximum 1.5%</td>
</tr>
</tbody>
</table>

Table 3.8: Chemical Requirements for Silica Fume (ASTM C 1240-01, 2002).

<table>
<thead>
<tr>
<th>Chemical Component</th>
<th>Mass Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>90.6</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>1.2</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.1</td>
</tr>
<tr>
<td>CaO</td>
<td>0.3</td>
</tr>
<tr>
<td>MgO</td>
<td>0.8</td>
</tr>
<tr>
<td>Na₂O</td>
<td>0.45</td>
</tr>
<tr>
<td>K₂O</td>
<td>1.97</td>
</tr>
<tr>
<td>Igneous Loss</td>
<td>3.0</td>
</tr>
<tr>
<td>Total</td>
<td>99.4</td>
</tr>
</tbody>
</table>

Table 3.9: Chemical Composition of a Typical Silica Fume (Brandt 1995).
3.5.3 Functions

In cement-based composites, silica fume mainly serves on two levels: as a microfiller and as a pozzolanic material (Babu and Prakash 1995, Detwiler and Mehta 1989). Silica fume particles can fill the voids between the larger cement grains because of their extreme fineness. This function, called particle packing, refines the microstructure of cement composites creating a much denser pore structure. As a result, the number and the size of capillaries are reduced, the impermeability is dramatically increased, and the entire matrix becomes more resistant to aggressive environments. This effect has been illustrated in Figures 3.4 and 3.5.

![Figure 3.4: Packing of Cement Grains without Silica Fume.](image)

![Figure 3.5: Packing of Cement Grains with Silica Fume.](image)

The microfiller effect of silica fume is also said to be responsible for the increase in fluidity of cement composites with a very low water-binder ratio. It is believed that the ultrafine silica fume spheres act like small ball bearings in fresh composite and thereby improve the fluidity (Zain and Safiuddin 1999). Besides, silica fume particles displace some of the water present between flocculated cement grains and thus increase the quantity of water available to enhance the fluidity of a fresh composite.
The second function that silica fume performs, as a pozzolanic material, is chemical in nature. Silica fume is a very efficient pozzolanic material because of its extreme fineness and high glass content (Malhotra 1993). It chemically reacts with calcium hydroxide liberated during the hardening process of cement and produces additional calcium silicate hydrate (Zain et al. 2000b). The pore channels in cement composites are blocked by this pozzolanic reaction product. Consequently, the porosity is greatly reduced and the composite’s matrix becomes much denser and impervious. The pozzolanic effect of silica fume is portrayed in Figures 3.6 and 3.7.

Figure 3.6: Pore Structure in Absence of Silica Fume.

Figure 3.7: Pore Structure in Presence of Silica Fume.
Some researchers (Cheng-yi and Feldman 1985) also believe that silica fume results in an improved bond between hydrated cement and sand. Though sand is stronger than hardened cement paste, the strength of mortar is lower than that of paste partly because of weak sand-cement bonding. The incorporation of silica fume in mortar appears to strengthen that weak bonding.

3.5.4 Role of silica fume in CFRM

Silica fume, in addition to its general benefits, further improves the performance of CFRM. It facilitates the dispersion of carbon fibers in fresh mortar mixes (Banthia 1992, Chung 2000, Park et al. 1991, Soroushian et al. 1992b). It has been shown experimentally that silica fume results in more effective dispersion of carbon fibers, and induces greater workability, homogeneity, formability and fluidity in fresh CFRM (Park et al. 1991). This is obviously due to the larger specific surface area of silica fume. If silica fume is not added, the larger amount of carbon fibers causes fiber-balls to form.

Silica fume is also used to enhance the fiber-matrix bond. A dense packing of hydration products around the fibers is vital for a good fiber-matrix bond. This can be achieved by using silica fume with a low water-binder ratio (Banthia and Genois 1995, Katz et al. 1995, Park et al. 1991). In CFRM, silica fume results in the increased densification of the matrix surrounding the carbon fibers. This leads to the enhanced contact between carbon fibers and the matrix increasing the interfacial area. As a result, the higher interfacial bond between carbon fibers and the matrix is achieved.

3.5.5 Silica fume dosage

Theoretically, silica fume dosage should be 25% to 30% by weight of total binder to fix all the potential lime liberated during the hydration of calcium silicates (Altinçin 1998). Such high dosage of silica fume needs greater amount of superplasticizer, which may cause segregation and bleeding problems in fresh composite. In practice, silica fume has been used mostly at a dosage between 5% and 10% for significant strength gains in high performance concrete. However, the silica fume dosage can be increased in CFRM, as
the tendency of segregation and bleeding due to greater amount of superplasticizer is greatly reduced in presence of fibers. The dosage of silica fume should also be increased to facilitate the dispersion of carbon fibers. A silica fume dosage of 20% or more has been suggested for CFRM (Ohama and Amano 1984). Nevertheless, the cost of silica fume must be taken into consideration while choosing the dosage since silica fume is much costlier than cement. Most of the research works on carbon fiber reinforced cement composites have used silica fume dosage in the range of 10% to 20% (Banthia et al. 1994, Katz and Li 1995, Obla and Li 1995, Soroushian et al. 1992c), and very few above 30% (Ohama et al. 1985, Park et al. 1991). Considering the cost and effectiveness of silica fume, the practical and economic optimum dosage for CFRM should be between 15% and 20% by weight of total binder.

3.6 Water

Water is the least expensive but most important component of cement-based composites. The quality of water to be used in mixing and curing of cement composites is important since water having harmful impurities such as sediment, oil, sugar or chemicals is destructive to the strength and setting properties of cement. If water containing harmful impurities is used, it could disrupt the affinity between aggregate and cement paste and can adversely affect the workability of fresh composite (Nawy 1996). The impurities of water may also cause staining on the surface of hardened composite and lead to the corrosion of reinforcement. Therefore, the suitability of water for mixing and curing purposes must be examined before use. In general, any drinkable natural water having no test and odor is suitable to be used as mixing and curing water for cement-based composites.

3.6.1 Physical requirements

The mixing water should preferably be potable or clean, fresh and free of obvious contaminants. If water contains quantities of substances, which cause unusual color and objectionable smell or taste, it should not be used unless service records indicate that it is not injurious to the quality of cement composite. However, although the use of potable
water is generally safe, the criterion of potability is not absolute. Water not fit for drinking may also be used satisfactorily in making cement-based composites. As a rule, any water with a pH of 6.0 to 8.0 and silt content below 2000 parts per million (ppm) is suitable for use in cement-based composites (Neville and Brooks 1987). When the suitability of water is questionable, the mixing water should be subject to the acceptance criteria given in Table 3.10 prior to use in preparing cement-based composites such as mortar and concrete.

Table 3.10: Acceptance Criteria for Questionable Mixing Water (ASTM C 94/C 94M-00, 2002).

<table>
<thead>
<tr>
<th>Property</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 Days Compressive Strength Observed in Mortar or Concrete</td>
<td>At Least 90% of Control</td>
</tr>
<tr>
<td>Setting Time of Cement when Used with Questionable Water</td>
<td>Initial: Maximum Deviation from Control is 1 Hour</td>
</tr>
<tr>
<td></td>
<td>Final: Maximum Deviation from Control is 1.5 Hour</td>
</tr>
</tbody>
</table>

3.6.2 Chemical requirements

Mixing water should not contain high amount of solids, chlorides, alkalis, carbonates and bicarbonates, sulfates, and other salts, which are inferior to the quality of cement composites. Water containing dissolved solids below 2000 ppm can generally be used satisfactorily for making cement-based composites. Although dissolved solids exceeding 2000 ppm are not always harmful, they can affect the hydration of certain cement adversely. Therefore, water having more than 2000 ppm of dissolved solids should be tested for its effect on strength and setting time. Water containing organic acids may also adversely affect the hardening of cement. Therefore, further testing is necessary in case of such water. In general, before use, the questionable mixing water is required to comply with the chemical requirements listed in Table 3.11.
Table 3.11: Chemical Requirements for Questionable Mixing Water (ASTM C 94/C 94M-00, 2002; Shetty 2000).

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Tolerable Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chloride as Cl⁻</td>
<td>Prestressed Concrete: 500 Other Reinforced Concrete: 1000</td>
</tr>
<tr>
<td>Sulfate as SO₄²⁻</td>
<td>3000</td>
</tr>
<tr>
<td>Alkalies as Na₂O and K₂O</td>
<td>600</td>
</tr>
<tr>
<td>Sodium and Potassium Carbonates and Bicarbonates</td>
<td>1000</td>
</tr>
<tr>
<td>Sodium Sulfide</td>
<td>100</td>
</tr>
<tr>
<td>Total Solids</td>
<td>50000</td>
</tr>
<tr>
<td>Organic Acids</td>
<td>3000</td>
</tr>
</tbody>
</table>

3.6.3 Functions

Water is an essential component of cement-based composites. It performs two functions: one is physical and the other is chemical. In physical function, water wets the aggregate and lubricates the fresh mix for easy workability whereas in chemical function it contributes to the development of hydration reaction. Sufficient water is required for the optimum hydration of cement and to maintain the workability for easy placement (Owens 1992). Hydration of cement can take place only in presence of water. Reacting with water, cement paste hardens and binds the aggregates, and thus provides sufficient strength and hardness to the cement composites. Water is also used in the curing of newly placed cement-based composites. It maintains the required moisture condition and vapor pressure for cement hydration during the period of curing (Zain et al. 1999a, Zain et al. 2000a). Applying water for curing of cement composites is alike to wholesome feeding given to the newborn babies.

3.6.4 Water content

Water content should be sufficient to complete the chemical reactions with cement or binder and to fill up the gel-pores. It has been estimated that 23% water by weight of binder is required for chemical reactions and another 15% water is necessary to occupy
the space within gel-pores. Therefore, at least 38% water by weight of binder is essential for full hydration in any cement-based composite (Shetty 2000). However, this amount can be reduced to 20% and even to 16% using high range water reducers or superplasticizers (Pliskin 1992). Usually, 20% to 40% water by weight of binder is used for high performance cement-based composites (Aïtcin 1997). In case of CFRM, most aforementioned research works recommend 25% to 50% water by weight of binder to be used in preparing the fresh composite.

It is crucial to optimize the amount of water as water quantity is closely related to the workability and strength of cement composites; but it is not an easy task to determine the amount of water to be used to achieve high performance in respect of workability, strength, impact resistance, and durability. In general, the minimum water content varies in the range of 120 to 165 l/m³ for high performance cement-based composites without fiber (Aïtcin 1998). In contrast, this range becomes almost double and even more for CFRM due to the high content of cementitious particles. Besides, CFRM demands more water since the presence of fibers usually tends to reduce the workability of fresh composite. Therefore, as a whole, higher water content is needed for CFRM mixes.

3.7 Superplasticizers

Superplasticizers are high range water reducing admixture, which usually provide a far greater degree of water reduction without causing excessive retardation of setting time and without large amount of entrapped air. They can reduce the water requirement at least for 12% and substantially increases the strength at the same cement content (ASTM C 494/C 494M-99a, 2002). Superplasticizers could also permit an increase in the workability of cement composites without increasing the water-binder ratio, thus maintaining the strength level (ACI Committee 212, 1987). They can easily change the zero slump cement composite to a composite with a slump greater than 20 cm (Zain and Safiuddin 1999, Zain et al. 1999b, Safiuddin et al. 2000); but they must be compatible with the cement for their optimum efficiency. There are mainly four families of superplasticizers: polynaphthalene sulfonates, polymelamine sulfonates, lignosulfonates and polyacrylates. At present, the first two are most widely used in construction.
industries. Polynaphthalene sulfonates are sold as dark brown liquid with a solid content generally between 40% and 42%. They are also available in solid form as a brownish powder. On the other hand, polymelamine sulfonates are sold as a clear liquid with 22% solid content.

3.7.1 Physical requirements

Superplasticizers are formulated to produce high plasticity, normal-setting characteristics, and accelerated strengths in cement-based composites. They possess a pH between 7.5 and 8.5, and a viscosity in the range of 60 to 80 centipoises but differ in solid contents depending on the types (Aïtcin 1998). No chlorides are used in their formulation. They are usually compatible with air entraining agents, waterproofing agents and many other admixtures. A particular brand of superplasticizer can be used as a singular admixture or as a component in an admixture system but it must fulfill some physical requirements for superior performance. In general, superplasticizers should conform to the specific physical requirements as listed in Table 3.12 for optimum performance in cement-based composites.

Table 3.12: Specific Requirements for Physical Properties of Superplasticizers (ASTM C 494/C 494M-99a, 2002).

<table>
<thead>
<tr>
<th>Property</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content in Presence of Superplasticizer</td>
<td>Maximum 88% of Control</td>
</tr>
<tr>
<td>Setting Time of Cement when Used with Superplasticizer</td>
<td>Initial: Maximum Deviation from Control: 1 Hour Final: Maximum Deviation from Control: 1.5 Hour</td>
</tr>
<tr>
<td>28 Days Compressive Strength of Mortar or Concrete when Prepared with Superplasticizer</td>
<td>Minimum 110% of Control</td>
</tr>
<tr>
<td>Length Change in Mortar Containing Superplasticizer</td>
<td>Maximum 135% of Control when Length Change of Control Is 0.030% or Greater Maximum 1% Increase over Control when Length Change of Control Is below 0.030%</td>
</tr>
<tr>
<td>Relative Durability Factor of Concrete with Superplasticizer</td>
<td>80</td>
</tr>
</tbody>
</table>
3.7.2 Chemical composition

Polynaphthalene sulfonate and polymelamine sulfonate superplasticizers are mostly used in the production of high performance cement-based composites. They are commonly known as naphthalene and melamine superplasticizers. Naphthalene superplasticizers are the sulfonated salts of polycondensate of naphthalene and formaldehyde. The raw materials for naphthalene superplasticizers are naphthalene, sulfuric acid and formaldehyde. On the contrary, melamine superplasticizers are the sulfonated salts of polycondensate of melamine and formaldehyde and they are produced from the raw materials melamine, sulfuric acid and formaldehyde. In both cases, the raw materials are chemically combined through sulfonation and polymerization. The chemical formulas are shown in Figures 3.8 and 3.9, respectively.

![Chemical formula of naphthalene superplasticizer](image)

Figure 3.8: Chemical Formula of Naphthalene Superplasticizer (Aïtcin 1992).
Figure 3.9: Chemical Formula of Melamine Superplasticizer (Aitcin 1992).

3.7.3 Functions

Superplasticizers physically interact with cement and reduce the mixing water requirement by deflocculation of cement grains (Aitcin et al. 1994, Hover 1998). The cement grains in suspension can recover their initial grain size by this process. Superplasticizers exert their action by decreasing the surface tension of water and by equidirectional charging of the cement grains. When a superplasticizer is added to cement composites, the cement particles disperse in the aqueous phase of fresh composite and therefore cement-water agglomerates cannot form (Dodson 1990).

The dispersion mechanism is driven by the adsorption of superplasticizer molecules on the cement grains. Adsorbed superplasticizer molecules bring about repulsion forces between cement particles due to their negative electrical charges. Consequently, flocculation is prevented and the cement particles are dispersed homogeneously in the fresh composite (Erdogdu 2000). This in turn results in an appreciable reduction in the quantity of mixing water, since water molecules, which were previously entrapped in
cement grain flakes become free. How superplasticizers function to reduce the mixing water demand and improve the rheology of fresh cement-based composite has been illustrated in Figures 3.10 and 3.11.

Figure 3.10: Cement-Water Agglomeration in Absence of Superplasticizer.

Figure 3.11: Dispersion of Cement in Presence of Superplasticizer.

Superplasticizers could also chemically interact with cement particles. They can react with the hydration products of cement. It has been reported earlier (Odler and Becker 1980) that some of the superplasticizers react with tricalcium aluminate and lower the initial hydration rate while the others could delay the hydration reaction of tricalcium silicate component during hydration of cement particles.

3.7.4 Role of superplasticizers in CFRM

Superplasticizers have proven to be very useful in producing high quality cement-based fibrous composites with a low water-binder ratio and high workability (ACI Committee...
A superplasticizer is generally added in CFRM to reduce plastic viscosity and thus to maintain sufficient workability in fresh state. In presence of superplasticizers, the inter-particle friction and the flow resistance decrease and thereby result in the improvement of workability. The effectiveness of superplasticizers on workability improvement largely depends on the water-binder ratio. For a constant dosage, the lower the water-binder ratio, the more effective is the superplasticizer. Superplasticizers become ineffective for water-binder ratios greater than 40% by weight of binder (Faroug et al. 1999).

Superplasticizers also disperse the silica fume particles and the fibers more evenly throughout the fresh mix of CFRM, so assuring better workability and enhanced bond strength (Zheng and Chung 1989). Thorough dispersion of silica fume particles and fibers also tends to release the entrapped air and the superplasticizer takes this entrapped air out of the mix. As a result, the capillary porosity is greatly reduced and this increases the strength.

### 3.7.5 Superplasticizer dosage

The superplasticizer dosage generally varies in the range of 5 to 20 l/m³ in high performance cement-based materials without fibers (Aifcin et al. 1994). In CFRM, superplasticizer dosage is much higher and it mainly depends on the contents of silica fume and carbon fibers. For a given silica fume content and workability, the dosage increases with the increase in fiber content. This is because higher fiber content increases the water demand to maintain a particular workability. However, a minimum superplasticizer dosage of 2% by weight of binder has been recommended for CFRM (Ohama and Amano 1984). In carbon fiber reinforced cement composites, the superplasticizer dosage can be as high as 5% to 6% by weight of binder (Ohama et al. 1985, Park et al. 1991). A very high dosage of superplasticizer might cause segregation and bleeding in a fresh composite and thus a reduced adhesion between the fibers and the cement paste. Therefore, the superplasticizer dosage should be chosen carefully. However, there is no straightforward way to do that; it can only be fixed based on the rheology of trial mixes.
3.8 Concluding Remarks

Selection of materials is very vital to obtain a CFRM with sufficient workability, good strength and toughness, excellent impact resistance, and enhanced durability. The availability, cost, and properties of constituent materials are the defining factors to judge the suitability of materials, and to evaluate the benefits expected from CFRM. Quality constituent materials must be sought before producing CFRM products for commercial applications. Therefore, a guideline for materials selection is essential in order to optimize the production of CFRM.
CHAPTER IV

EXPERIMENTAL PROCEDURES

4.1 General

Experimental study was carried out to determine some physical properties of the constituent materials, and to investigate the major attributes of both fresh and hardened carbon fiber reinforced mortars (CFRMs). The aim of experimental investigation was to examine the suitability of constituent materials and to explore the performance of CFRM in respect of workability, strength, toughness, impact resistance, and durability. This chapter will deal with materials selection, design of mixes, mix proportions, preparation of mortar mixes, testing of fresh mortars, preparation of test specimens, and testing of hardened mortars.

4.2 Materials Selection

For the entire research work, sand, portland cement, silica fume, pitch-based carbon fibers, water and superplasticizer have been used. The materials were selected complied with the requirements. The following sections will address the component materials used in the present study.

4.2.1 Sand

Locally available natural sand (river sand) as shown in Figure 4.1 has been used as fine aggregate in the present study. The sand was purchased from R-Lessard Trucking Ltd., Windsor. It was clean and free from deleterious materials. The maximum particle size of the sand has been found as 2.36 mm during sieve analysis. The important physical properties of the sand selected for the present study were experimentally determined at the Concrete Laboratory of the University of Windsor. The detailed experimental results are given in Appendix A. A summary of results is given in Table 4.1.
Table 4.1: Physical Properties of River Sand.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Evaporable Moisture Content</td>
<td>0.5%</td>
</tr>
<tr>
<td>Saturated Surface Dry Basis</td>
<td>2.60</td>
</tr>
<tr>
<td>Bulk Specific Gravity</td>
<td></td>
</tr>
<tr>
<td>Absorption</td>
<td>1.6%</td>
</tr>
<tr>
<td>Surface Moisture</td>
<td>0%</td>
</tr>
<tr>
<td>Fineness Modulus</td>
<td>1.97</td>
</tr>
</tbody>
</table>

It is evident from the results of sieve analysis that the sand failed to meet the grading requirements given by ASTM (ASTM C33-02a, 2002). The fineness modulus was less than 2.30, and the percents passing 1.18 mm and 2.36 mm sieves were greater than the maximum limits. However, it did not cause any workability problem in the present study. As the CFRM mixes contained cement at an amount twice the amount of sand, the grading of sand had no significant effect on the workability. Besides, the dosage of superplasticizer was chosen in such a way so that it can prevail over the effect of sand with gap grading.

4.2.2 Portland cement

CAN/CSA A5 Type 10 Lafarge normal portland cement as shown in Figure 4.1 has been used in the present study. It complied with ASTM Type I Portland cement according to ASTM standard specification (ASTM C150-02, 2002). The amount of cement required for this project was purchased from AZAX Builders Supplies, Windsor. Some of the physical properties of Lafarge Type 10 normal portland cement are given in Table 4.2. Amongst these properties, the moisture content and the specific gravity were determined experimentally at the Concrete Laboratory of the University of Windsor. The rest of the physical properties have been gathered from the material safety data sheet prepared by Lafarge North America, Inc. (2002). The test results of the moisture content and specific gravity of normal portland cement are detailed in Appendix A.
Table 4.2: Physical Properties of Lafarge Type 10 Normal Portland Cement.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Evaporable Moisture Content</td>
<td>0.5%</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>3.15</td>
</tr>
<tr>
<td>pH</td>
<td>12 – 13</td>
</tr>
<tr>
<td>Solubility in Water</td>
<td>Slight (0.1 – 1.0%)</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>&gt; 1000°C</td>
</tr>
<tr>
<td>Freezing Point</td>
<td>None, Solid</td>
</tr>
<tr>
<td>Viscosity</td>
<td>None, Solid</td>
</tr>
</tbody>
</table>

4.2.3 Silica fume

Grey granular Rheomac® SF 100 compacted silica fume as shown in Figure 4.1 has been used in the present study. It complied with the ASTM standard specification for silica fume (ASTM C 1240-01, 2002). Silica fume was used as a 15% by weight partial replacement of portland cement. The required amount of silica fume was supplied by Master Builders Technologies (MBT), Ltd., Canada. Table 4.3 presents some of the physical properties of Rheomac® SF 100 silica fume. Among these properties, the moisture content and the specific gravity were determined at the Concrete Laboratory of the University of Windsor and are detailed in Appendix A. The other physical properties have been collected from the material safety data sheet prepared by Master Builders Technologies, Ltd. (2001).

Table 4.3: Physical Properties of Rheomac® SF 100 Silica Fume.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Evaporable Moisture Content</td>
<td>1.1 %</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.20</td>
</tr>
<tr>
<td>Percent VOC (w/w)</td>
<td>0</td>
</tr>
<tr>
<td>Solubility in Water</td>
<td>Slight</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>&gt; Air</td>
</tr>
<tr>
<td>Odor</td>
<td>Odorless</td>
</tr>
</tbody>
</table>
4.2.4 Pitch-based carbon fibers

Dialead K6611T coal tar pitch-based short carbon fibers as shown in Figure 4.1 have been used in the present study. They are available in black chopped strand of multifilaments sized with water-soluble resin by 1% to 2%. The fibers are 10 mm long and have a filament diameter 17 μm. The fibers are insoluble in water and their elemental carbon content is about 98% to 99%. The fibers were incorporated as a volume content in the range of 1% to 4%. The required amount of carbon fibers was purchased from Mitsubishi Chemical America (MCA), Inc. Some of the physical and chemical properties of Dialead K6611T are given in Table 4.4. Among these properties, the specific gravity was determined at the Concrete Laboratory of the University of Windsor and the detailed results are given in Appendix A. The tensile strength and the tensile modulus have been noted from the technical bulletin of Mitsubshi Kasei Corporation (1992). The other properties have been taken from the material safety data sheet supplied by Mitsubishi Chemical America, Inc. (1999).
Table 4.4: Physical and Chemical Properties of Dialead K6611T Coal Tar Pitch-based Carbon Fibers.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.85</td>
</tr>
<tr>
<td>Tensile Strength</td>
<td>1770 MPa</td>
</tr>
<tr>
<td>Tensile Modulus</td>
<td>180 GPa</td>
</tr>
<tr>
<td>Solubility in Water</td>
<td>None</td>
</tr>
<tr>
<td>Odor</td>
<td>Odorless</td>
</tr>
<tr>
<td>pH</td>
<td>7.0</td>
</tr>
<tr>
<td>Oxidization</td>
<td>None</td>
</tr>
</tbody>
</table>

4.2.5 Water

Normal tap water has been used in the present study for mixing and curing purposes. The quality of this water conformed to the requirements indicated in ASTM standard specification for ready mixed concrete (ASTM C 94/C 94M-00, 2002). In general, the water quality was excellent for use in producing fresh CFRM. It didn’t contain any objectionable substances causing color or odor. The density of this water has been taken as 1000 kg/m³. Table 4.5 presents some of the other physical properties of tap water given by Enviro Turn Systems (ETS), British Columbia, Canada (2002).

Table 4.5: Physical Properties of Tap Water.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbidity</td>
<td>2.07 NTU</td>
</tr>
<tr>
<td>pH</td>
<td>7.0</td>
</tr>
<tr>
<td>Color</td>
<td>&lt; 5.00 TCU</td>
</tr>
<tr>
<td>Odor</td>
<td>None</td>
</tr>
<tr>
<td>Total Dissolved Solids</td>
<td>18.00 mg/l</td>
</tr>
</tbody>
</table>

4.2.6 Superplasticizer

A naphthalene superplasticizer, Rheobuild® 1000 as shown in Figure 4.1, has been used in the present study. It is a dark brown liquid cement-dispersing agent. It does not
contain any chloride. According to ASTM standard specification for chemical admixtures (ASTM C 494/C 494M-99a, 2002), it complies with Type F high range water reducing admixture. The required amount of superplasticizer was supplied by Master Builders Technologies (MBT), Canada. Table 4.6 gives some of the physical properties of Rheobuild® 1000 superplasticizer. The specific gravity and the solid content of superplasticizer were determined at the Concrete Laboratory of the University of Windsor and the results are detailed in Appendix A. The other properties have been taken from the material safety data sheet prepared by Master Builders Technologies, Ltd. (2000).

Table 4.6: Physical Properties of Rheobuild® 1000 Superplasticizer.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value or Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity</td>
<td>1.20</td>
</tr>
<tr>
<td>Solid Content</td>
<td>40%</td>
</tr>
<tr>
<td>Percent VOC (w/w)</td>
<td>0</td>
</tr>
<tr>
<td>pH</td>
<td>8.0</td>
</tr>
<tr>
<td>Solubility in Water</td>
<td>100%</td>
</tr>
<tr>
<td>Vapor Density</td>
<td>&lt; Air</td>
</tr>
<tr>
<td>Odor</td>
<td>Musty</td>
</tr>
<tr>
<td>Boiling Point</td>
<td>100°C</td>
</tr>
<tr>
<td>Freezing Point</td>
<td>0°C</td>
</tr>
</tbody>
</table>

4.3 Design of Mixes

In total, one control mortar and four different types of CFRM mixes were designed with a water-binder ratio of 0.35 and a sand-binder ratio of 0.50. The control mix was normal portland cement mortar and coded as NPCM whereas the mortars reinforced with different carbon fiber volume contents were coded as CFRM1, CFRM2, CFRM3, and CFRM4, respectively. In each mix, silica fume was used as a 15% by weight partial replacement of cement. In these four CFRMs, the carbon fibers were added to the mixes with a volume content of 1%, 2%, 3%, and 4%, respectively. The final proportions of constituent materials including the dosages of superplasticizer were fixed based on the trial mixes. The weight basis amounts of the materials for a unit volume of mortar have been worked out based on the absolute volumes of the constituent materials but the
proportions of materials obtained thereby were applicable only in saturated surface dry condition. However, the component materials were batched in ambient condition and therefore water corrections were made to get the adjusted mix proportions.

4.4 Mix Proportions

The mix proportions were settled monitoring the performance of the trial mixes. The acceptability of trial mixes was examined by observing the workability and by determining the tensile strength at 7 days. The workability of trial mixes was maintained in such a way so that the inverted slump cone flow time of fresh composite stayed below 30 seconds. In determining the mix proportions, cement together with silica fume has been considered as the binder and the amounts of silica fume and superplasticizer were measured based on the total amount of binder.

4.4.1 Saturated surface dry basis mix proportions

The proportions of different constituent materials were worked out by absolute volume method. The absolute volumes of sand, cement, silica fume, water, and carbon fibers and air voids were taken under consideration during computation. In contrast, the content of superplasticizer was not considered while computing the saturated surface dry basis mix proportions, as it was incorporated in the mix as an additive. As a rule of thumb, 1% air content was considered for control plain mortar whereas 4% air content was assumed for mortar with 1% carbon fibers (CFRM1). In CFRMs other than CFRM1, the increased in air content was assumed by the increase in volume content of carbon fibers. The detailed computation for saturated surface dry basis mix proportioning is given in Appendix B. The saturated surface dry basis mix proportions of various component materials are summarized in Table 4.7.

4.4.2 Water corrections

Water corrections were made considering the water contributed by the superplasticizer and the water absorbed by the sand. In this context, it was assumed that the moisture
contents of cement and silica fume in someway compensated for the loss of water due to evaporation and handling at the time of mixing. The detailed computation of water corrections for various mixes has been presented in Appendix B.

<table>
<thead>
<tr>
<th>Type of Mix</th>
<th>C (kg/m³)</th>
<th>S (kg/m³)</th>
<th>SF (kg/m³)</th>
<th>CF (%V)</th>
<th>W (kg/m³)</th>
<th>SP (%B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>955.9</td>
<td>562.3</td>
<td>168.7</td>
<td>0</td>
<td>393.6</td>
<td>1</td>
</tr>
<tr>
<td>CFRM1</td>
<td>917.2</td>
<td>539.6</td>
<td>161.9</td>
<td>1</td>
<td>377.7</td>
<td>2</td>
</tr>
<tr>
<td>CFRM2</td>
<td>898.0</td>
<td>528.2</td>
<td>158.5</td>
<td>2</td>
<td>369.8</td>
<td>3</td>
</tr>
<tr>
<td>CFRM3</td>
<td>878.6</td>
<td>516.9</td>
<td>155.1</td>
<td>3</td>
<td>361.8</td>
<td>4</td>
</tr>
<tr>
<td>CFRM4</td>
<td>859.4</td>
<td>505.5</td>
<td>151.7</td>
<td>4</td>
<td>353.9</td>
<td>5</td>
</tr>
</tbody>
</table>

### 4.4.3 Adjusted mix proportions

The proportions of sand and water were adjusted based on the water corrections. The detailed computation for adjusted mix proportions of different mixes is given in Appendix B. The adjusted mix proportions are summarized in Table 4.8.

<table>
<thead>
<tr>
<th>Type of Mix</th>
<th>C (kg/m³)</th>
<th>Sₐ (kg/m³)</th>
<th>SF (kg/m³)</th>
<th>CF (%V)</th>
<th>Wₐ (kg/m³)</th>
<th>SP (%B)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>955.9</td>
<td>556.2</td>
<td>168.7</td>
<td>0</td>
<td>394.1</td>
<td>1</td>
</tr>
<tr>
<td>CFRM1</td>
<td>917.2</td>
<td>533.7</td>
<td>161.9</td>
<td>1</td>
<td>372.8</td>
<td>2</td>
</tr>
<tr>
<td>CFRM2</td>
<td>898.0</td>
<td>522.4</td>
<td>158.5</td>
<td>2</td>
<td>359.8</td>
<td>3</td>
</tr>
<tr>
<td>CFRM3</td>
<td>878.6</td>
<td>511.3</td>
<td>155.1</td>
<td>3</td>
<td>346.7</td>
<td>4</td>
</tr>
<tr>
<td>CFRM4</td>
<td>859.4</td>
<td>500.0</td>
<td>151.7</td>
<td>4</td>
<td>334.1</td>
<td>5</td>
</tr>
</tbody>
</table>

### 4.5 Preparation of Mortar Mixes

The mortar mixes were prepared based on the adjusted mix proportions. The component materials were batched at ambient conditions and mixed accordingly to prepare the fresh mortars.
4.5.1 Batching

The total volume of each fresh mortar was divided into two batches. Therefore, there were 10 batches in total for five different types of mortar mix. The batch volumes were computed for each mortar. The quantity of fresh mortar was taken to be at least 15% more than required. Then, the amounts of component materials required for each batch were worked out based on the adjusted mix proportions. The detailed batch compositions are presented in Appendix C.

4.5.2 Mixing

The constituent materials were mixed in a pan-type mixer having a capacity of 0.1 m$^3$. The mixer, which was used for mixing is shown in Figure 4.2. The overall mixing time was six minutes. The mixing procedure was established monitoring the behavior of trial mixes. Based on the observations for the trial mixes, the following mixing sequence was used in preparing the fresh mortars:

a. Sand, cement, and silica fume were charged first into the mixer and then mixed with half of the mixing water for one minute.

b. Superplasticizer was mixed with the remaining half of the water in a separate container simply by stirring and the entire liquid mixture of water and admixture was then added gradually into the running mixer within one minute.

c. The mixing was continued for additional one minute.

d. The carbon fibers were hand-sprinkled in the running mixer gradually within two minutes in case of CFRMs.

e. Lastly, the mixing of all component materials was continued for additional one minute.

4.6 Testing of Fresh Mortar

The fresh mortars were sampled for slump test, inverted slump cone flow test and for the test of unit weight and air content. The sampling was conducted in accordance with
ASTM standard practice (ASTM C 172-99, 2002). The schedule of the test program for freshly mixed mortars is given in Table D1 of Appendix D.

![Pan-type Mixer Used for Preparing Mortar Mixes.](image)

Figure 4.2: Pan-type Mixer Used for Preparing Mortar Mixes.

### 4.6.1 Slump test

The slump of fresh mortar was measured according to ASTM standard (ASTM C 143/C 143M-00, 2002). A sample of freshly mixed mortar was placed in the slump cone. In case of control NPCM, the slump cone was filled at one time and no compaction was required, as it was at highly fluid state.
Figure 4.3: Slump Test for CFRM with 2% Carbon Fiber Volume Content.

Figure 4.4: Slump Test for CFRM with 3% Carbon Fiber Volume Content.
In case of CFRMs, the fresh mortar was poured into the cone in three layers and each layer was compacted by rodding in a specified manner. The slump cone was then lifted up vertically without any disturbance and the mortar was allowed to subside. The distance between the centers of the original and subsided top surfaces was measured and reported as the slump of the mortar. Figures 4.3 and 4.4 show the slump test for two different CFRMs.

4.6.2 Test for unit weight and air content

The unit weight and the air content of freshly mixed mortar were determined in accordance with ASTM standard (ASTM C 138/C 138M-01a, 2002). A cylindrical measure complied with ASTM standard (ASTM C 29/C 29M-97, 2002) was used in this test. The measure was calibrated before using in the test in order to know its volume capacity. The empty measure was also weighed before starting the test.

![Figure 4.5: Leveling Stage of Test for Unit Weight and Air Content of Fresh Mortars.](image-url)
A sample of freshly mixed mortar was poured into the cylindrical measure in three layers. Each layer was compacted by vibration using a vibration table. The measure was filled at in one layer and no vibration was used in the case of NPCM, as the composite was self-compacting. The top surface of the composite was leveled and the measure including the sample was then weighed. Figures 4.5 and 4.6 show two stages of the test for determining unit weight and air content of fresh mortar.

Figure 4.6: Weighing Stage of Test for Unit Weight and Air Content of Fresh Mortars.
4.6.3 Inverted slump cone test

The flow of fresh mortar was measured by inverted slump cone test according to ASTM standard (ASTM C 995-01, 2002). The apparatus for this test is shown in Figure 4.7. A square bucket instead of a circular one was used to ease the placement of a metal plate just below the lower end of the inverted slump cone.

![Inverted Slump Cone Apparatus for Flow Test of Fresh Mortars.](image)

The inverted slump cone was loosely filled with fresh mortar putting the bottom plate underneath the cone. No means of compaction was used at the time of filling operation. The bottom plate was then slid off. Immediately, the vibrator was started and positioned on the center of the cone, and then allowed to fall freely up to the bucket's bottom. The vibrator was then held vertically with the end resting on the bottom of the bucket. The stopwatch was started from initial immersion of the vibrator and the time required for emptying the inverted slump cone was recorded as the flow time. The aforementioned procedure was used for all CFRMs. In case of the control NPCM, no vibrator was used, as it was self-flowing. Figure 4.8 shows an operating stage of inverted slump cone test.
4.7 Preparation of Test Specimens

The fresh mixes were used to prepare the test specimens. Beam, cylinder, and cube specimens were prepared for testing the hardened mortar. The types and the sizes of test specimens are shown in detail in Table D2 of Appendix D. The shorter cylinders for impact test and the smaller cubes for water absorption test were not cast directly. At first, 150D x 300H mm parent cylinders were cast to obtain the test cylinders for the impact testing. On the other hand, 150 mm parent cubes were cast to obtain the test cubes for water absorption test. The followings steps were pursued in order to obtain the specimens for testing of the hardened mortar.

4.7.1 Molding

Beam and cube specimens were molded in reusable cast iron molds whereas cylinder specimens were molded in single-use plastic molds. ASTM standard practice (ASTM C 192/C 192M-00, 2002) was followed for molding the test specimens in the laboratory.
Figure 4.9: A Molded Beam Specimen Used in Flexure Test.

Figure 4.10: Several Molded Cylinders Used in Compression and Splitting Tension Tests.
Figure 4.11: A Molded Parent Cylinder Required for Impact Test.

Figure 4.12: A Molded Parent Cube Required for Water Absorption Test.
Three layers of filling were used for cube and cylinder specimens whereas two layers were used in case of beam specimens. A vibrating table was used for compaction. Each layer was vibrated until a thin layer of bleed water appeared on the surface. Figures 4.9 to 4.12 show the different types of molded specimens.

4.7.2 Demolding

The beam and the cube specimens were covered with wax papers and polyethylene sheets 30 to 45 minutes after casting and left in their molds for 24 hours. Conversely, the cylinder specimens were sealed immediately using the lids and left undisturbed for 24 hours. All the specimens were removed from their molds at an age of 24 hours. The big pores in surface layer, if any, were filled by a neat cement paste. Then, the specimens were marked and transferred for curing.

Figure 4.13: Curing Tanks Used to Cure the Specimens by Ponding.
4.7.3  Curing

The demolded specimens were placed inside the curing tanks as shown in Figure 4.13. Water curing by ponding was used to cure the specimens until the time of testing at 7 and 28 days, respectively. The curing temperature was between 21° C and 25° C. ASTM standard practice (ASTM C 192/C 192M-00, 2002) was followed in curing the specimens.

4.8  Testing of Hardened Mortar

Standard methods were followed to test the hardened mortars. The specified tests were carried out at the Concrete Laboratory of the University of Windsor to determine the compressive, splitting tensile, first-crack and ultimate flexural strengths, first-crack toughness, first-crack and ultimate impact resistances, and water absorption at the age of 7 and 28 days. The following sections briefly describe the test methods used.

Figure 4.14: TriPLICATE CAPPED CYLINDER SPECIMENS USED IN COMPRESSION TEST.
4.8.1 Compression test

The compressive strength of hardened mortar was determined according to ASTM standard (ASTM C 39/C 39M-01, 2002). Three 100D x 200H mm cylinders were used in this test at each testing age. Prior to the compression test, the cylinders were dried at room temperature and capped by sulfur mortar in accordance with ASTM standard practice (ASTM C 617-98, 2002). Figure 4.14 shows the triplicate capped specimens prepared for compression testing.

Figure 4.15: Compression Test of Hardened Mortar Using Cylinder Specimen.

In testing each specimen, the test cylinder was placed in the center position of the lower platen of the compression-testing machine as shown in Figure 4.15. The upper platen was then driven downward so that its flexible head just touched the top face of the specimen. Uniaxial loading was applied steadily to increase the stress at a rate of 0.14 to 0.34
MPa/s. The maximum load to fail the specimen was indicated in the load scale. It was noted and used to compute the compressive strength.

4.8.2 Splitting tension test

The splitting tensile strength of hardened mortar was determined in accordance with ASTM standard (ASTM C 496-96, 2002). The testing machine conformed to the requirements as in the compression test. Triplicate 100D x 200H mm cylinders were used in this test at each testing age. In testing each specimen, the cylinder was placed horizontally in the center position of the lower platen of the testing machine as shown in Figure 4.16.

![Figure 4.16: Splitting Tension Test of Hardened Mortar Using Cylinder Specimen.](image)

Two light wooden blocks were used to keep the specimen in central position. The upper platen was then driven downward so that its flexible head just touched the diametrical
surface along the length of the specimen. The load was applied continuously and without shock to induce the stress at a constant rate within the range of 689 to 1380 kPa/min. The loading was continued until failure of the specimen. The maximum applied load indicated by the testing machine at failure was recorded and used to calculate the splitting tensile strength.

4.8.3 Flexure test

The first-crack and ultimate flexural strengths, and the first-crack toughness of hardened mortars were determined according to ASTM standard (ASTM C 1018-97, 2002). Three 400L x 75W x 100H mm beam specimens were used in this test at each testing age. They were tested immediately after removal from the curing tank. In each test case, the beam specimen was turned on its side with respect to its position as molded and was centered in the supporting block. The load-applying block was brought in contact with the surface of the specimen at the third points. The complete test set-up is shown in Figure 4.17.

Figure 4.17: Flexure Test of Hardened Mortar Using Beam Specimen.
The load was applied continuously and without shock by means of a hydraulic jack. The loading system included a load-cell of 111.2 kN (25 kips) capacity. It was connected to the data acquisition system. Two transducers were also used touching the central bottom of the specimen to measure the mid-point deflection. They were also connected to the data acquisition system. Both the load-cell and the transducers were calibrated before using in the test.

4.8.4 Impact test

The first-crack and ultimate impact resistances of hardened mortars were determined in accordance with the test method recommended by ACI Committee 544 (1988). This test measures the amount of impact energy required to start a visible first crack in fiber composites, and then to continue opening that crack until failure.

Figure 4.18: Principal Components of Impact Test Apparatus in Companion with Cylinder Specimen.
The test set-up consists of a standard 4.5 kg (10 lb) compaction hammer with a 457 mm (18 in) drop conforming ASTM specification for compacting hammer for use in laboratory (ASTM D 1557-00, 2002), a 63.5 mm (2.5 in) diameter steel ball, and a positioning fixture. The simplified positioning fixture was manufactured at the Concrete Laboratory of the University of Windsor. The principal components of impact test apparatus are shown in Figure 4.18.

Three 150D x 62.5H mm cylinders as shown in Figure 4.19 were used in the test at each testing age. Each parent 150D x 300H mm cylinder was cut and triplicate 150D x 62.5H mm cylinders were prepared for the test. The impact test was conducted by dropping the hammer repeatedly on the steel ball supported by the specimen, while observing the formation of cracks and failure of the specimen. Figure 4.20 shows an operational stage of the impact test. The number of blows required causing the first visible crack on the top and for the ultimate failure of the specimen were recorded and used to compute the impact resistance at first crack and failure, respectively.

Figure 4.19: Triplicate Cylinder Specimens Used in Impact Test.
Figure 4.20: An Operating Stage of Impact Test for Hardened Mortars.

4.8.5 Water absorption test

The water absorption of hardened mortar was determined according to Method A specified in ASTM standard (ASTM C 1195-91, 1999). Three 50 mm cube specimens were used in this test at each testing age. Each 150 mm parent cube was cut and six 50 mm smaller cubes were prepared as shown in Figure 4.21. The cube specimens were used for testing at 7 and 28 days.

Before starting the test, the specimens were oven-dried at a temperature of 100\(^{\circ}\)C to 110\(^{\circ}\)C for 24 hours and then allowed to cool to room temperature for 30 minutes. Triplicate specimens were weighed separately and then immersed in distilled water at 21\(^{\circ}\)C to 25\(^{\circ}\)C for 48 hours. Thereafter, the specimens were removed from the water and weighed in saturated surface dry condition to determine the amount of absorbed water. Figure 4.22 shows an operational stage of water absorption test.
Figure 4.21: Several Cube Specimens Used in Water Absorption Test.

Figure 4.22: An Operating Stage of Water Absorption Test for Hardened Mortars.
4.9 Concluding Remarks

Constituent materials have been selected carefully and testing of both fresh and hardened mortars has been conducted in accordance with ASTM standards. Although the flexure test set-up could not monitor the post-crack behavior of CFRMs, the first-crack load, the first-crack deflection and the ultimate load were easily observed. The overall experimental data obtained from the present laboratory investigation provide useful database for construction industries dealing with carbon fiber reinforced cement composites.
CHAPTER V

RESULTS AND DISCUSSIONS

5.1 General

A number of tests were conducted on both fresh and hardened carbon fiber reinforced mortars. This chapter presents all the results in detail after analyzing the experimental data and discusses their significance, accuracy and any discrepancies.

5.2 Test Results of Fresh Mortars and Discussions

The slump and the inverted slump cone flow tests, and the test for unit weight and air content were performed on fresh mortars. The test results of fresh mortars are shown and discussed below.

5.2.1 Slump

The slump test was conducted for each batch of different types of freshly mixed carbon fiber reinforced mortar. The detailed test results are shown in Table 5.1 and Figure 5.1. From Figure 5.1 it can be seen that the slump decreases linearly with increase in carbon fiber volume content.

The slump of cement-based fiber composite is inversely proportional to the fiber volume content. In CFRM, the slump has diminished linearly with increasing volume content of carbon fibers for a constant aspect ratio. A similar effect was observed by Bayasi and Soroushian (1992) dealing with fibers other than carbon fibers. The volume content is a vital fiber parameter, which significantly influences the level of damage to the workability of the fiber reinforced cement composite. In general, the increase in fiber volume content drastically reduces the workability of a fresh composite. The large surface area of carbon fibers tends to restrain the mobility of fresh composite causing interlocking of fibers. However, a uniform dispersion of carbon fibers in the presence of silica fume and superplasticizer resulted in an adequate slump in the fresh CFRM and
thus made the casting operation much easier under external vibration. In particular, the superplasticizer modified the fresh composite in a positive manner by altering the rheology. It reduced the inter-particle friction in fresh mixes and thus improved the workability.

Table 5.1: Slump of Various Fresh Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Slump (cm)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch 1</td>
<td>Batch 2</td>
<td>Average</td>
<td></td>
</tr>
<tr>
<td>NPCM*</td>
<td>27</td>
<td>26</td>
<td>26.5</td>
<td></td>
</tr>
<tr>
<td>CFRM1</td>
<td>19</td>
<td>19</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>CFRM2</td>
<td>13</td>
<td>12</td>
<td>12.5</td>
<td></td>
</tr>
<tr>
<td>CFRM3</td>
<td>6</td>
<td>7</td>
<td>6.5</td>
<td></td>
</tr>
<tr>
<td>CFRM4</td>
<td>3</td>
<td>2</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.1: Variation of Slump with Different Carbon Fiber Volume Contents.

* Self-compactable

Results and Discussions 114
The slump results indicate that less workability is obtained in the mix having 4% carbon fiber volume content compared to those with 1% and 2% volume contents due to the greater amount of carbon fibers. As a result, a higher dosage of superplasticizer was used to make it workable. The mixes with 1% and 2% carbon fiber contents received 2% and 3% superplasticizer (by weight of binder), respectively. In contrast, the mixes with 3% and 4% carbon fiber contents consumed 4% and 5% superplasticizer, respectively. The increased amount of superplasticizer in CFRM with greater fiber content helped the compaction, resulting in a good fiber-matrix interfacial bond and mechanical anchorage of the short carbon fibers.

The slump test is the most widely used single-point test. Unfortunately, it is not a good test to measure the relative workability of all cement-based composites. Especially, the slump is often misleading when applied to cement-based fiber composites. For stiff mixes of a fiber composite, this test doesn’t provide an accurate indication of workability. For instance, in the present study, the slump test on CFRM with 3% fiber content resulted in a low slump but actually the composite was adequately workable as indicated by the inverted slump cone test. Therefore, the slump test is not recommended for very low-slump cement-based composites (Domone 1998). In cement-based fiber composites, the workability judged on the basis of slump may appear too low for placement, as the fibers impart substantial stability to the slump sample (Johnston 1992). For this reason, the slump test is not an ideal test to measure the workability of carbon fiber reinforced composites. However, it can be used in addition to the flow test, or alone, when the correlation between slump and flow time is known.

5.2.2 Unit weight and air content

The test for unit weight and air content was carried out for each batch of different types of freshly mixed carbon fiber reinforced mortar. The detailed test results are given in Tables 5.2 and 5.3. A sample calculation has been shown in Appendix E. The average results for unit weight are shown in Figure 5.2 and the average results for air content are presented in Figure 5.3. It is evident from Figure 5.2 that the unit weight dropped due to the inclusion of carbon fibers. However, within the carbon fiber reinforced mortars, both
a decrease and increase in unit weight were observed depending on fiber content, workability, and degree of compaction. On the other hand, it is obvious from Figure 5.3 that the air content increased greatly when carbon fibers were incorporated into the plain mortar. It is also notable from Figure 5.3 that the air content varied with fall and rise in different carbon fiber reinforced mortars for the range of fiber contents used in the present study. Nevertheless, carbon fiber reinforced mortar with 3% fiber volume content contained a comparatively low amount of air content.

Table 5.2: Unit Weight of Various Fresh Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Unit Weight (kg/m³)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch 1</td>
<td>Batch 2</td>
</tr>
<tr>
<td>NPCM*</td>
<td>2067.22</td>
<td>2074.25</td>
</tr>
<tr>
<td>CFRM1</td>
<td>1968.78</td>
<td>1968.78</td>
</tr>
<tr>
<td>CFRM2</td>
<td>1954.72</td>
<td>1940.66</td>
</tr>
<tr>
<td>CFRM3</td>
<td>1982.84</td>
<td>1996.91</td>
</tr>
<tr>
<td>CFRM4</td>
<td>1898.47</td>
<td>1912.53</td>
</tr>
</tbody>
</table>

Table 5.3: Air Content of Various Fresh Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Air Content (%)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch 1</td>
<td>Batch 2</td>
</tr>
<tr>
<td>NPCM*</td>
<td>1.1</td>
<td>0.8</td>
</tr>
<tr>
<td>CFRM1</td>
<td>4.9</td>
<td>5.5</td>
</tr>
<tr>
<td>CFRM2</td>
<td>6.0</td>
<td>6.8</td>
</tr>
<tr>
<td>CFRM3</td>
<td>4.5</td>
<td>3.9</td>
</tr>
<tr>
<td>CFRM4</td>
<td>8.3</td>
<td>7.5</td>
</tr>
</tbody>
</table>

The unit weight of fresh mortar decreased when carbon fibers were incorporated mainly due to the drastic reduction in workability. Similar results were obtained by Akihama et al. (1986) and Park et al. (1991). It was expected before starting the experiment that the unit weight of carbon fiber reinforced mortar would be reduced for all mixes with

* Self-compactable
increased fiber contents because of the difference in relative density between the matrix and fibers. However, a carbon fiber reinforced mortar with 3% fiber volume provided relatively high unit weight. This is probably due to reduced heterogeneity resulting from a more uniform distribution of carbon fibers throughout the mix, and sufficient compaction received by the fresh composite.

![Graph showing variation of unit weight with different carbon fiber volume contents.]

Figure 5.2: Variation of Unit Weight with Different Carbon Fiber Volume Contents.

The sand particles usually tend to prevent the air bubbles from rising to the surface during casting and compacting. The presence of short carbon fibers is likely to amplify this phenomenon (Pigeon et al. 1996). However, the excellent dispersion of fibers obtained by the addition of silica fume and superplasticizer results in reduced amount of air bubbles entrapped in the mix. In particular, the liquefying and the dispersing effects of superplasticizer assist the entrapped air bubbles to exit the fresh mix. The degree of liquidation and the dispersion obviously depend upon the dosage of the superplasticizer. Perhaps, these effects combined with effective compaction resulted in relatively low air content in the carbon fiber reinforced mortar with 3% fiber content. The largest air
content was found in the carbon fiber reinforced mortar containing 4% fiber content. This is mainly due to reduced workability and poor compaction. As excessive amount of superplasticizer is not conducive to cement hydration; more than 5% superplasticizer could not be used to make the mix with 4% fiber content sufficiently workable. Consequently, the mix was too stiff for good compaction. So, the degree of compaction was poor and therefore greater amount of air bubbles was left in the mix.

![Graph showing variation of air content with carbon fiber volume content](image)

Figure 5.3: Variation of Air Content with Different Carbon Fiber Volume Contents.

In general, the unit weight and the air content are inter-related. The unit weight reduced considerably owing to air content introduced into the fresh mix at the time of mixing. It is notable from Figure 5.2 and Figure 5.3 that the variations of unit weight and air content are somehow reciprocal. The greater the air content, the lower the unit weight. As carbon fiber reinforced mortar at 3% fiber content had lower air content, it resulted in a higher unit weight.
5.2.3 Inverted slump cone flow

The inverted slump cone flow test was conducted for each batch of different types of freshly mixed carbon fiber reinforced mortar. The detailed test results are given in Tables 5.4 to 5.6. A sample calculation is shown in Appendix F. The results of flow test are given in Figure 5.4. It can be seen in Figure 5.4 that the flow time of the fresh composite increases exponentially with increase in carbon fiber volume content. It indicates that the flow time of CFRM tends to diminish significantly with increasing carbon fiber contents.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Flow Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch 1</td>
</tr>
<tr>
<td>NPCM*</td>
<td>4</td>
</tr>
<tr>
<td>CFRM1</td>
<td>6</td>
</tr>
<tr>
<td>CFRM2</td>
<td>7</td>
</tr>
<tr>
<td>CFRM3</td>
<td>9</td>
</tr>
<tr>
<td>CFRM4</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 5.4: Flow Time of Various Fresh Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Mass Flow (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch 1</td>
</tr>
<tr>
<td>NPCM*</td>
<td>2.843</td>
</tr>
<tr>
<td>CFRM1</td>
<td>1.805</td>
</tr>
<tr>
<td>CFRM2</td>
<td>1.536</td>
</tr>
<tr>
<td>CFRM3</td>
<td>1.212</td>
</tr>
<tr>
<td>CFRM4</td>
<td>0.614</td>
</tr>
</tbody>
</table>

Table 5.5: Mass Flow of Various Fresh Mortar Composites.

* Self-compactable
Table 5.6: Volume Flow of Various Fresh Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Volume Flow (l/s)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Batch 1</td>
<td>Batch 2</td>
<td>Average</td>
</tr>
<tr>
<td>NPCM*</td>
<td>1.375</td>
<td>1.375</td>
<td>1.375</td>
</tr>
<tr>
<td>CFRM1</td>
<td>0.917</td>
<td>1.100</td>
<td>1.009</td>
</tr>
<tr>
<td>CFRM2</td>
<td>0.786</td>
<td>0.786</td>
<td>0.786</td>
</tr>
<tr>
<td>CFRM3</td>
<td>0.611</td>
<td>0.688</td>
<td>0.650</td>
</tr>
<tr>
<td>CFRM4</td>
<td>0.324</td>
<td>0.367</td>
<td>0.346</td>
</tr>
</tbody>
</table>

Figure 5.4: Variation of Flow Time with Different Carbon Fiber Volume Contents.

\[ y = 3.8274e^{0.3269x}, \; R^2 = 0.9446 \]
Figure 5.5: Variation of Mass Flow with Different Carbon Fiber Volume Contents.

Figure 5.6: Variation of Volume Flow with Different Carbon Fiber Volume Contents.

Results and Discussions
The mass flow of carbon fiber reinforced mortar has been computed using the unit weight, flow time, and corresponding volume of fresh mortar, which is equal to the volume of the inverted slump cone. The variation of mass flow with increasing fiber content is shown in Figure 5.5. Also, the volume flow of carbon fiber reinforced mortar has been calculated from flow time and corresponding volume of fresh composite. The variation of volume flow with the increase in fiber content is shown in Figure 5.6. It is evident from Figures 5.5 and 5.6 that the flow deceased almost linearly as the fiber volume increased. Similar trends were observed by Akihama et al. (1986), Park et al. (1991), and Banthia et al. (1994).

The presence of carbon fibers tends to reduce the flow drastically. However, the liquefying action of superplasticizer and the dispersing role of both silica fume and superplasticizer, maintained good workability, homogeneity, formability and fluidity in the mixes. Usually, a flow time between 8 and 30 seconds indicates that the fresh composite is suitable for placement by vibration (Johnston 1992). In the present study, the flow times were in the range of 4 to 17 seconds. Thus, the mobility, or ability of fresh composite to flow under vibration, was excellent. It also indicates that the workability remained adequate over a wide range of fiber volume contents, even though the corresponding slump was quite low.

The slump and the flow time can be correlated. A correlation between slump and flow time obtained from the present study is shown in Figure 5.7. It can be seen from Figure 5.7 that CFRM flows well under vibration when the standard slump is greater than 10 cm. It also shows that the variation of flow time is not significant above this slump. So, the results of slump test can be accepted for a moderately to highly workable CFRM.

The inverted slump cone test is appropriate for fieldwork. It is portable and easier than other flow tests such as the Vebe test. However, this test is generally not suitable for cement-based fiber composites having a slump of more than 10 cm because the composite will flow through the cone very quickly (Balaguru and Shah 1992). This drawback has been eliminated in the present study by modifying the shape of the bucket and introducing a metal plate underneath the inverted slump cone so that it can retain the fresh composite.
during placement. Finally, it is also understood from the present study that the simple slump test can be conducted in the field if the correlation between slump and flow time is known for a given mix of CFRM.

![Graph showing correlation between slump and flow time for different batches.](image)

**Figure 5.7**: Correlation between Slump and Flow Time of Carbon Fiber Reinforced Mortar Composite.

### 5.3 Test Results of Hardened Mortars and Discussions

The compression, tension, flexure, impact and water absorption tests were carried out on hardened carbon fiber reinforced mortars. The following sub-sections present and discuss the results of these tests.

#### 5.3.1 Compressive strength

The water cured hardened cylinder specimens were tested for compressive strength at ages of 7 and 28 days. The complete test results are given in Tables 5.7 and 5.8. A sample calculation is shown in Appendix G. The average results are shown in Figure 5.8. It is evident from Figure 5.8 that the compressive strength increased almost linearly with
the addition of fibers up to 3% fiber volume and then dropped sharply. Ohama et al. (1985) obtained a similar trend of results in their study on carbon fiber reinforced cement composites. The compressive strength, as shown in Figure 2.12, also dropped beyond 3% fiber content in their studies.

Table 5.7: 7 Days Compressive Strength of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specimen 1</td>
</tr>
<tr>
<td>NPCM</td>
<td>35.13</td>
</tr>
<tr>
<td>CFRM1</td>
<td>38.81</td>
</tr>
<tr>
<td>CFRM2</td>
<td>45.89</td>
</tr>
<tr>
<td>CFRM3</td>
<td>48.16</td>
</tr>
<tr>
<td>CFRM4</td>
<td>34.56</td>
</tr>
</tbody>
</table>

Table 5.8: 28 Days Compressive Strength of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Compressive Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specimen 1</td>
</tr>
<tr>
<td>NPCM</td>
<td>38.67</td>
</tr>
<tr>
<td>CFRM1</td>
<td>49.01</td>
</tr>
<tr>
<td>CFRM2</td>
<td>55.24</td>
</tr>
<tr>
<td>CFRM3</td>
<td>62.61</td>
</tr>
<tr>
<td>CFRM4</td>
<td>47.06</td>
</tr>
</tbody>
</table>

The effect of fiber content in carbon fiber reinforced mortar is not always conducive to the compressive strength as recognized in case of tensile and flexural strengths. It largely depends on workability, degree of compaction and air content. Even if the fibers increase the compressive strength, it is low when compared to the increases in tensile and flexural strengths. This is because the fibers cannot provide good reinforcement in compression as they do in tension and flexure. The strengthening factors have been calculated and are shown in Table 5.9. It can be seen from Table 5.9 that 3% carbon fiber volume content provides the maximum increase in compressive strength and the extent of strengthening is
61% at an age of 28 days. The results for unit weight and air content of the carbon fiber reinforced mortar with 3% fiber volume support the increased compressive strength obtained in the present study. In general, the rise in unit weight and the reduction in air content tend to increase the compressive strength. Table 5.9 also shows that carbon fiber reinforced mortar with 4% fiber content has a very low compressive strength. The main reason is that the fresh mix could not be compacted effectively because of poor workability. Therefore, an excessive amount of air bubbles remained entrapped in the mix and caused a negative effect on the compressive strength. This could also be due in part to the retarding effect of superplasticizer as observed by Pigeon et al. (1996). Since relatively a high dosage of superplasticizer was used in the mix with 4% carbon fiber volume content, it could alter the composition of CSH phase and retard the hydration significantly. Thus, the carbon fibers can improve compressive strength if used at volumes that do not cause any adverse effect on workability.

![Graph](image)

Figure 5.8: Variation of Compressive Strength with Different Carbon Fiber Volume Contents.
Table 5.9: Strengthening Factors for Various Mortar Composites Tested in Compression.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>NPCM</th>
<th>CFRM1</th>
<th>CFRM2</th>
<th>CFRM3</th>
<th>CFRM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengthening Factor for 7 Days Compressive Strength</td>
<td>1</td>
<td>1.15</td>
<td>1.30</td>
<td>1.43</td>
<td>1.02</td>
</tr>
<tr>
<td>Strengthening Factor for 28 Days Compressive Strength</td>
<td>1</td>
<td>1.28</td>
<td>1.45</td>
<td>1.61</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Figure 5.9: Failure Pattern of the Specimen in Compression Test in the Case of Normal Portland Cement Mortar.

The failure pattern of the specimens in compression testing shows that the ductility was much increased by the carbon fibers. Normal portland cement mortar exhibited a brittle failure as shown in Figure 5.9. On the other hand, carbon fiber reinforced mortar at first
yielded and then progressively crushed as shown in Figure 5.10. The standard compression test under uniaxial loading produced a combination of shear failure near the ends with lateral swelling and cracking in the central portion of the specimen. It follows that the fibers could have some sort of reinforcing effect in the lateral direction. However, this effect was predominant in carbon fiber reinforced mortars with 3% and 4% fiber content. It indicates that fiber volume content has a significant effect on the lateral strain capacity and thereby on the toughness or ductility of carbon fiber reinforced mortar.

![Figure 5.10: Failure Pattern of the Specimen in Compression Test in the Case of Carbon Fiber Reinforced Mortar.](image)

The increase in ductility as observed in compression test was largely due to the increased resistance against crack growth. The resistance to crack propagation increased with greater fiber volume contents. Therefore, the improvement in ductility was significant with greater fiber contents. Shah and Chandra (1968) showed that the volume of compressed concrete starts to dilate and this dilation is related to slow growth of
microcracks within cement composite. The addition of carbon fibers in plain mortar delayed and reduced the volume dilation. As a result, improved ductility behavior was noticed in the specimens under compression testing.

5.3.2 Splitting tensile strength

The water cured hardened cylinder specimens were tested for splitting tensile strengths at ages of 7 and 28 days. The detailed test results are given in Tables 5.10 and 5.11. A sample calculation has been shown in Appendix H. The average results are presented Figure 5.11. It is obvious from Figure 5.11 that the splitting tensile strength of carbon fiber reinforced mortars increases linearly with increase in fiber volume content. A similar trend of increase in tensile strength has been reported in several other studies (Akihama et al. 1986, Kim and Park 1998, Zheng and Chung 1989).

Table 5.10: 7 Days Splitting Tensile Strength of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specimen 1</td>
</tr>
<tr>
<td>NPCM</td>
<td>3.36</td>
</tr>
<tr>
<td>CFRM1</td>
<td>4.29</td>
</tr>
<tr>
<td>CFRM2</td>
<td>4.71</td>
</tr>
<tr>
<td>CFRM3</td>
<td>5.88</td>
</tr>
<tr>
<td>CFRM4</td>
<td>6.45</td>
</tr>
</tbody>
</table>

Table 5.11: 28 Days Splitting Tensile Strength of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Tensile Strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Specimen 1</td>
</tr>
<tr>
<td>NPCM</td>
<td>4.25</td>
</tr>
<tr>
<td>CFRM1</td>
<td>5.14</td>
</tr>
<tr>
<td>CFRM2</td>
<td>5.74</td>
</tr>
<tr>
<td>CFRM3</td>
<td>6.45</td>
</tr>
<tr>
<td>CFRM4</td>
<td>6.78</td>
</tr>
</tbody>
</table>
Figure 5.11: Variation of Splitting Tensile Strength with Different Carbon Fiber Volume Contents.

It is understood from Figure 5.11 that the increase in splitting tensile strength of carbon fiber reinforced mortars was directly related to the volume content of carbon fibers. The strengthening factors for various carbon fiber reinforced mortars have been calculated and are shown in Table 5.12. It is evident from Table 5.12 that the splitting tensile strength of CFRM at 4% carbon fibers is 1.5 to 2 times greater than that of NPCM. This increase in tensile strength is low when compared to the findings of other researchers who conducted direct tension test using dumbbell specimens (Akihama et al. 1986, Park et al. 1991). The splitting tension test has been conducted in the present study to determine the tensile strength of carbon fiber reinforced mortar. Neville (1996) mentioned that the splitting tension test yields a lower value of tensile strength in the case of mortar. This is perhaps due to the absence of large particles such as coarse aggregates near the surface to which
the load is applied. Also, it can be seen from Table 5.12 that the rate of increase in splitting tensile strength was greater at the age of 7 days although the maximum tensile strength was obtained at 28 days. This is because the gain in tensile strength is usually high at low strength whereas it slows down at higher strengths.

Table 5.12: Strengthening Factors for Various Mortar Composites Tested in Splitting Tension.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>NPCM</th>
<th>CFRM1</th>
<th>CFRM2</th>
<th>CFRM3</th>
<th>CFRM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengthening Factor for 7 Days Splitting Tensile Strength</td>
<td>1</td>
<td>1.33</td>
<td>1.46</td>
<td>1.79</td>
<td>1.90</td>
</tr>
<tr>
<td>Strengthening Factor for 28 Days Splitting Tensile Strength</td>
<td>1</td>
<td>1.21</td>
<td>1.34</td>
<td>1.49</td>
<td>1.59</td>
</tr>
</tbody>
</table>

The increase in tensile strength is not attributed to the addition of carbon fibers alone. It is not only dependent on the relative volume content of carbon fibers but also on the strength of the bond between the constituents. Katz et al. (1995) and Park et al. (1991) reported that the densification of the matrix surrounding the fibers plays an important role in increasing the interfacial bond strength and enhancing the pullout behavior of the carbon fibers. The presence of silica fume in the carbon fiber reinforced mortar results in a densification of the matrix around the fibers and therefore the contact area between fibers and adjacent materials is enhanced and a stronger bond is established. The interfacial bond is also strengthened by the newly formed CSH from the pozzolanic reaction between silica fume and Ca(OH)$_2$. The fiber-sand particle interlock can also improve the interfacial bond. Subsequently, the tensile strength increases due to the improved bond strength. Furthermore, fine cement grains and finer silica fume particles might penetrate into the holes or surface grooves of the carbon fibers. Consequently, the surface roughness of fibers would increase and therefore the bond between the fibers and the matrix could be enhanced. Also, the roughness of the fiber surface would increase the

Results and Discussions

130
interfacial shear stress. Both of these effects might eventually lead to a greater improvement in tensile strength.

Ductile behavior was also observed in the carbon fiber reinforced mortar while testing the specimens under splitting tension. The failure patterns for NPCM and CFRM are shown in Figures 5.12 and 5.13, respectively. The cylinder specimens used in the splitting tension test of NPCM failed suddenly. The failure was of brittle type and the cylinders were completely split as shown in Figure 5.12. Conversely, the failure pattern for the cylinders used in splitting tension test of CFRM was ductile under the applied load. This was evidenced by the increased ability of the cylinders more heavily reinforced with carbon fibers to deform markedly under the applied load without actually collapsing. The specimens failed showing a visible vertical crack throughout the axis but did not fall apart. This is evident in Figure 5.13.

![Figure 5.12: Failure Pattern of the Specimen in Splitting Tension Test in the Case of Normal Portland Cement Mortar.](image-url)
Figure 5.13: Failure Pattern of the Cylinder Specimen in Splitting Tension Test in the Case of Carbon Fiber Reinforced Mortar.

5.3.3 Flexure strength and toughness

The water cured hardened beam specimens were tested to determine the first-crack and ultimate flexural strengths, and the first-crack toughness at ages of 7 and 28 days. The full test results are given in Appendix I. The flexural load-deflection plots for various mortars are given in Figure II and Figure I2. A sample calculation has been shown in Appendix J. The average test results are presented in Figures 5.14 to 5.16. It is obvious from Figures 5.14 to 5.16 that the first-crack and ultimate flexural strengths and the first-crack toughness of carbon fiber reinforced mortar increased linearly with increase in fiber content. Akihama et al. (1986), Banthia and Sheng (1991a), and Kim and Park (1998) have observed a similar trend.
Figure 5.14: Variation of First-crack Flexural Strength with Different Carbon Fiber Volume Contents.

The flexure test was conducted by third-point loading arrangement as shown in Figure 5.17. The third-point loading test usually gives more reliable results. This is because the probability of a weak element being subjected to the critical stress is considerably greater under two third-point loads (Neville 1995). In third-point loading, the middle-third of the length of extreme fiber in the beam is subjected to the maximum bending stress. Therefore, the critical crack may appear at any section within the middle third where the bending stress is maximum or within one of the two end-thirds of the beam. In the present study, all specimens failed with fracture occurring within the middle third of the
beams, as indicated in Figure 5.17. This shows that the bottom fibers in the middle third of the beam experienced the maximum bending stress.

The first-crack and the ultimate flexural strengthening factors have been computed and are presented in Table 5.13. Furthermore, the first-crack toughening factors have been calculated and are shown in Table 5.14. The addition of carbon fibers has significantly increased the resistance of the mortar to crack propagation as evidenced by increased first-crack and ultimate flexural strengths and considerably greater first-crack toughness. It is also obvious from Table 5.13 that the strengthening factors were slightly greater at 7 days, although the higher strengths were obtained at the age of 28 days. The mortar containing a carbon fiber volume content of 4% provided the overall maximum first-crack and ultimate flexural strengths as well as first-crack toughness at both testing ages.

![Graph showing variation of ultimate flexural strength with carbon fiber volume content](image)

Figure 5.15: Variation of Ultimate Flexural Strength with Different Carbon Fiber Volume Contents.
Table 5.13: First-crack and Ultimate Flexural Strengthening Factors for Various Mortar Composites Tested in Flexure.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>NPCM</th>
<th>CFRM1</th>
<th>CFRM2</th>
<th>CFRM3</th>
<th>CFRM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strengthening Factor for 7 Days First-crack Flexural Strength</td>
<td>1</td>
<td>1.18</td>
<td>1.32</td>
<td>1.38</td>
<td>1.48</td>
</tr>
<tr>
<td>Strengthening Factor for 28 Days First-crack Flexural Strength</td>
<td>1</td>
<td>1.13</td>
<td>1.20</td>
<td>1.27</td>
<td>1.38</td>
</tr>
<tr>
<td>Strengthening Factor for 7 Days Ultimate Flexural Strength</td>
<td>1</td>
<td>1.58</td>
<td>1.83</td>
<td>2.02</td>
<td>2.13</td>
</tr>
<tr>
<td>Strengthening Factor for 28 Days Ultimate Flexural Strength</td>
<td>1</td>
<td>1.38</td>
<td>1.54</td>
<td>1.70</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Figure 5.16: Variation of First-crack Toughness with Different Carbon Fiber Volume Contents.
Figure 5.17: Failure Pattern of the Beam Specimen in Flexure Test.

Table 5.14: Toughening Factors for First-crack Toughness of Various Mortar Composites Tested in Flexure.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>NPCM</th>
<th>CFRM1</th>
<th>CFRM2</th>
<th>CFRM3</th>
<th>CFRM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toughening Factor for 7 Days First-crack Toughness</td>
<td>1</td>
<td>1.10</td>
<td>1.24</td>
<td>1.46</td>
<td>1.84</td>
</tr>
<tr>
<td>Toughening Factor for 28 Days First-crack Toughness</td>
<td>1</td>
<td>1.11</td>
<td>1.28</td>
<td>1.45</td>
<td>1.60</td>
</tr>
</tbody>
</table>

In general, a two-fold increase in ultimate flexural strength and first-crack toughness strength has been brought about by fibers at 4% volume content. The corresponding first-crack strength has also been increased by nearly 50%. The increase in first-crack and ultimate flexural strengths, and first-crack toughness with the addition of carbon fibers is mainly due to the increased reinforcing and bonding effects of fibers resulting from the

Results and Discussions 136
improved densification of microstructure in the presence of silica fume and superplasticizer.

The peak load and the ductility are clearly increased by the addition of carbon fibers as indicated by the load-deflection plots shown in Appendix I. It is evident from Figures 11 and 12 that the mortar with 4% carbon fibers provided the clear indication of enhanced ductile behavior compared to other mortars with lower fiber contents. This is mainly because of increased fiber content. Usually, the addition of silica fume produces a slightly increased brittleness in mortar. This was easily overcome by higher fiber content present in the mortar with 4% carbon fibers. The greater first-crack toughness produced by 4% carbon fiber also indicate that the composite was considerably tough.

The first-crack deflections obtained from the flexure test are tabulated in Appendix I. The first-crack deflections at the mid-span were also calculated theoretically using Equation (5-1) (Morgan et al. 1995) and Equation (5-2) (ACI Committee 363, 1988) given below, and then compared with the experimental deflections.

\[ \Delta_{R_c} = \frac{23R_{fc}t^3}{1296EI} \left[ 1 + \frac{216d^2(1 + \mu)}{115t^2} \right] \]  

\[ E = 3320\sqrt{f_c} + 6900 \]  

Where,

\( E = \) Modulus of elasticity (MPa)

\( I = \) Moment of inertia (\( mm^4 \)) = \( \frac{bd^3}{12} \)

\( b = \) Width of specimen = 75 mm

\( d = \) Depth of specimen = 100 mm

\( l = \) Load span of beam = 300 mm

\( 21 \text{ MPa} < f_c' = \) Compressive strength of mortar < 83 MPa

\( \Delta_{Rc} = \) First-crack deflection (mm)

\( \mu = \) Poisson’s ratio (assumed to be 0.25)

\( R_{fc} = \) First-crack load (N)
For ease of comparison the computed and experimental first-crack deflections are shown together in Table 5.15. In general, the experimental first-crack deflections are about 17% to 51% greater than the theoretical first-crack deflections. The error in the experimental deflections is due to inefficient seating and twisting of the specimen on its supports, or deformation of the supporting system. The downward movement of the beam specimen as a rigid body and the settlement of supports induce extraneous deflections. Due to these extraneous effects, the measure deflections can be as much as an order of magnitude larger (Morgan et al. 1995). However, the measurement of deflections on both sides at the mid-span of the specimen, as followed in the present study, has reduced the extraneous effects. The deflections can be measured more accurately by using a Japanese ‘Yoke’ or a similar device (Morgan et al. 1995).

Table 5.15: Comparison of Theoretical and Experimental First-crack Deflections.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Theoretical First-crack Deflection (mm)</th>
<th>Experimental First-crack Deflection (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 Days</td>
<td>28 Days</td>
</tr>
<tr>
<td>NPCM</td>
<td>0.039</td>
<td>0.051</td>
</tr>
<tr>
<td>CFRM1</td>
<td>0.043</td>
<td>0.052</td>
</tr>
<tr>
<td>CFRM2</td>
<td>0.046</td>
<td>0.053</td>
</tr>
<tr>
<td>CFRM3</td>
<td>0.047</td>
<td>0.054</td>
</tr>
<tr>
<td>CFRM4</td>
<td>0.057</td>
<td>0.066</td>
</tr>
</tbody>
</table>

The first-crack and ultimate flexural strengths and the first-crack toughness have been determined according to ASTM C 1018-97 (2002). The onset of first-crack must be identified in load-deflection plot in order to calculate the first-crack flexural strength and to determine the first-crack deflection as necessary for toughness measurement. ASTM C 1018 (2002) specifies that the first-crack start at the point where the curvature first increases sharply and the slope of the curve show a definite change. Unfortunately, locating this point is not so simple and may involve subjectivity. Banthia and Trottier (1995) has shown that the precise determination of the location of first-crack is still difficult even if all errors in measurement of first-crack deflection due to extraneous
deformations are eliminated. This is because, in practice, the location of first-crack on load-deflection plot is quite ambiguous and depends on, except other factors, the resolution of the recording device and the judgment of the operator.

The ultimate flexural strength can be correlated with the tensile strength obtained from the present study. The correlation is shown in Figure 5.18. It is evident from Figure 5.18 that the flexural strength was much higher than the tensile strength. The difference between flexural and tensile strengths increased with the increase in fiber content. This is perhaps due to the orientation of the fibers and the nonlinear stress distribution in the specimens.

![Graph showing the correlation between splitting tensile strength and ultimate flexural strength of carbon fiber reinforced mortar composite.](image)

**Figure 5.18:** Correlation between Splitting Tensile and Ultimate Flexural Strengths of Carbon Fiber Reinforced Mortar Composite.

Sakai et al. (1994) reported that carbon fibers tend to be oriented at right angles to the vibrational direction of the vibrator. This tendency is also expected to be affected by the
dimensions of the specimen. The compaction by vibration induced a degree of preferential 2D-fiber orientation parallel to the length of the specimen in beam specimens, which were used for the flexure test. This is also evidenced by the broken carbon fibers oriented at right angles with the fractured face of the beam. Thus, the fiber orientation coincided with the direction of the major tensile stress and resulted in greater ultimate flexural strength. On the other hand, the carbon fibers were oriented in a 3D-random fashion in the cylinder specimens used for splitting tension test. This was confirmed by observing the carbon fibers lying at the fracture face of the cylinder. Perhaps, the lower dimension lying in the horizontal plane hindered the orientation of carbon fibers in a direction perpendicular to the pathway of vibration. Consequently, the reinforcing effectiveness in cylinder specimens was comparatively low towards the direction of the major tensile stress and therefore resulted in a lower tensile strength.

Furthermore, the ultimate flexural strength has been calculated based on the elastic beam theory, in which the stress-strain relation is assumed to be linear. It follows that the ultimate flexural stress in the beam is supposed to be proportional to the distance from its neutral axis. In fact, the linear stress-strain relation is no longer valid when the first-crack appears. Therefore, the actual stress block between first-crack and maximum loads becomes parabolic instead of being triangular. Thus, the ultimate flexural strength is overestimated. Besides, the maximum fiber stress reached in flexure test may be higher than in splitting tension test because the fibers and other less-stressed materials near to the neutral axis block the propagation of cracks. In particular, the carbon fibers aligned in the direction of the major tensile stress effectively slow down the formation of the first-crack, impede the propagation of cracks, and thus delay the failure. As a result, the ultimate flexural strength becomes greater than the splitting tensile strength.

5.3.4 Impact resistance

The water cured hardened cylinder specimens were tested to determine the first-crack and the ultimate impact resistances at ages of 7 and 28 days. The complete test results are given in Tables 5.16 to 5.19. A sample calculation has been shown in Appendix K. The average test results are presented in Figures 5.19 and 5.20.
Table 5.16: 7 Days Impact Test Results of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CFRM1</td>
<td>23</td>
<td>20</td>
<td>21</td>
</tr>
<tr>
<td>CFRM2</td>
<td>27</td>
<td>31</td>
<td>29</td>
</tr>
<tr>
<td>CFRM3</td>
<td>35</td>
<td>38</td>
<td>34</td>
</tr>
<tr>
<td>CFRM4</td>
<td>44</td>
<td>48</td>
<td>45</td>
</tr>
</tbody>
</table>

Number of Blows Required for Ultimate Failure

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>CFRM1</td>
<td>29</td>
<td>25</td>
<td>28</td>
</tr>
<tr>
<td>CFRM2</td>
<td>38</td>
<td>40</td>
<td>42</td>
</tr>
<tr>
<td>CFRM3</td>
<td>57</td>
<td>61</td>
<td>59</td>
</tr>
<tr>
<td>CFRM4</td>
<td>85</td>
<td>90</td>
<td>84</td>
</tr>
</tbody>
</table>

Table 5.17: 28 Days Impact Test Results of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>CFRM1</td>
<td>27</td>
<td>24</td>
<td>26</td>
</tr>
<tr>
<td>CFRM2</td>
<td>36</td>
<td>40</td>
<td>38</td>
</tr>
<tr>
<td>CFRM3</td>
<td>45</td>
<td>49</td>
<td>42</td>
</tr>
<tr>
<td>CFRM4</td>
<td>56</td>
<td>61</td>
<td>53</td>
</tr>
</tbody>
</table>

Number of Blows Required for Ultimate Failure

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>4</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>CFRM1</td>
<td>34</td>
<td>30</td>
<td>32</td>
</tr>
<tr>
<td>CFRM2</td>
<td>45</td>
<td>51</td>
<td>47</td>
</tr>
<tr>
<td>CFRM3</td>
<td>70</td>
<td>65</td>
<td>68</td>
</tr>
<tr>
<td>CFRM4</td>
<td>140</td>
<td>148</td>
<td>130</td>
</tr>
</tbody>
</table>
Table 5.18: First-crack Impact Resistance of Various Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRM1</td>
<td>464.002</td>
<td>403.480</td>
<td>423.654</td>
<td>430.379</td>
</tr>
<tr>
<td>CFRM2</td>
<td>544.698</td>
<td>625.394</td>
<td>585.046</td>
<td>585.046</td>
</tr>
<tr>
<td>CFRM3</td>
<td>706.090</td>
<td>766.612</td>
<td>685.916</td>
<td>719.539</td>
</tr>
<tr>
<td>CFRM4</td>
<td>887.656</td>
<td>968.352</td>
<td>907.830</td>
<td>921.279</td>
</tr>
</tbody>
</table>

First-crack Impact Resistance (J)
Testing Age: 28 Days

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>40.348</td>
<td>40.348</td>
<td>60.522</td>
<td>47.073</td>
</tr>
<tr>
<td>CFRM1</td>
<td>544.698</td>
<td>484.176</td>
<td>524.524</td>
<td>517.799</td>
</tr>
<tr>
<td>CFRM2</td>
<td>726.264</td>
<td>806.960</td>
<td>766.612</td>
<td>766.612</td>
</tr>
<tr>
<td>CFRM3</td>
<td>907.83</td>
<td>988.526</td>
<td>847.308</td>
<td>914.555</td>
</tr>
<tr>
<td>CFRM4</td>
<td>1129.744</td>
<td>1230.614</td>
<td>1069.222</td>
<td>1143.193</td>
</tr>
</tbody>
</table>

Table 5.19: Ultimate Impact Resistance of Various Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>40.348</td>
<td>60.522</td>
<td>40.348</td>
<td>47.073</td>
</tr>
<tr>
<td>CFRM1</td>
<td>585.046</td>
<td>504.350</td>
<td>564.872</td>
<td>551.423</td>
</tr>
<tr>
<td>CFRM2</td>
<td>766.612</td>
<td>806.960</td>
<td>847.308</td>
<td>806.960</td>
</tr>
<tr>
<td>CFRM3</td>
<td>1149.918</td>
<td>1230.614</td>
<td>1190.266</td>
<td>1190.266</td>
</tr>
<tr>
<td>CFRM4</td>
<td>1714.790</td>
<td>1815.660</td>
<td>1694.616</td>
<td>1741.689</td>
</tr>
</tbody>
</table>

Ultimate Impact Resistance (J)
Testing Age: 28 Days

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>80.696</td>
<td>100.870</td>
<td>100.870</td>
<td>94.145</td>
</tr>
<tr>
<td>CFRM1</td>
<td>685.916</td>
<td>605.220</td>
<td>645.568</td>
<td>645.568</td>
</tr>
<tr>
<td>CFRM2</td>
<td>907.830</td>
<td>1028.874</td>
<td>948.178</td>
<td>961.627</td>
</tr>
<tr>
<td>CFRM3</td>
<td>1452.528</td>
<td>1311.310</td>
<td>1371.832</td>
<td>1378.557</td>
</tr>
<tr>
<td>CFRM4</td>
<td>2824.360</td>
<td>2985.752</td>
<td>2622.620</td>
<td>2810.911</td>
</tr>
</tbody>
</table>
It is obvious from Figures 5.19 and 5.20 that the first-crack and the ultimate impact resistances have been increased significantly with increasing fiber content. Limited studies have been reported on the impact resistance of carbon fiber reinforced mortar using the ACI drop-weight test. Ohama et al. (1985) investigated the impact resistance of carbon fiber reinforced cement operating a similar device and obtained comparable trends. In the recent past, Soroushian et al. (1992b) carried out the ACI drop-weight test on carbon fiber reinforced composite containing lightweight aggregates and obtained important gains in impact resistance with increase in fiber content as observed in the present study.

![Diagram showing variation of first-crack impact resistance with different carbon fiber volume contents.]

Figure 5.19: Variation of First-crack Impact Resistance with Different Carbon Fiber Volume Contents.

Plain mortar took a very small number of blows for a visible first-crack. It also did not show any considerable impact resistance beyond the first crack. Once the first crack appeared on the surface, the specimen failed with only few addition blows. In contrast,
the mortars with increasing carbon fiber content provided improved impact resistance against first crack and ultimate failure. From Figures 5.19 and 5.20, it is obvious that carbon fiber reinforced mortar offered the maximum first-crack and ultimate impact resistances at 4% fiber content. For this mortar, a large number of blows were required to produce a visible first-crack and then ultimate failure of the specimens.

![Graph showing variation of Ultimate Impact Resistance with Carbon Fiber Volume Content](image)

Figure 5.20: Variation of Ultimate Impact Resistance with Different Carbon Fiber Volume Contents.

The impact resistance factors due to various carbon fiber volume contents have been computed and are shown in Table 5.20. It is noticeable from Table 5.20 that the impact resistance of carbon fiber reinforced mortar increased markedly with increasing fiber content. The superior improvement in impact resistance is chiefly attributed to the increased anchorage of the carbon fibers and to the enhanced interfacial bonding between fibers and matrix in the presence of silica fume.
The impact resistance is also related to the toughness. The impact resistance increased as the toughness increased with the addition of carbon fibers. The cracking patterns of the specimens as shown in Figure 5.21 also suggest that the toughness as well as the impact resistance increased predominantly with the increase in carbon fiber volume content. Indeed, the number of cracks at failure increased with greater fiber contents indicating the increase of impact resistance in the specimens.

Table 5.20: Impact Resistance Factors for Various Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>First-crack Impact Resistance Factor</th>
<th>Ultimate Impact Resistance Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At 7 Days</td>
<td>At 28 Days</td>
</tr>
<tr>
<td>NPCM</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CFRM1</td>
<td>21.33</td>
<td>11.00</td>
</tr>
<tr>
<td>CFRM2</td>
<td>29.00</td>
<td>16.29</td>
</tr>
<tr>
<td>CFRM3</td>
<td>35.67</td>
<td>19.43</td>
</tr>
<tr>
<td>CFRM4</td>
<td>45.67</td>
<td>24.29</td>
</tr>
</tbody>
</table>

Figure 5.21: Cracking Patterns in Impact Test Specimens with Different Carbon Fiber Volume Contents.
5.3.5 Water absorption

The water absorptions of various mortars were determined at ages of 7 and 28 days using smaller cube specimens. The detailed test results are given in Tables 5.21 and 5.22. A sample calculation is also shown in Appendix L. The average test results are shown in Figure 5.22. It can be seen from Figure 5.22 that the water absorption decreased with the addition of carbon fibers up to 3% fiber content, and then increased at 4% fiber content. Very few studies on the water absorption of carbon fiber reinforced mortars are available in the literature. Ohama et al. (1985) performed water absorption tests for carbon fiber reinforced cement and found that the water absorption tends to decrease with increasing carbon fiber content up to 5%. A similar trend of reduction in water absorption capacity has been observed in the present study for carbon fiber contents in the range of 1% to 3%.

Table 5.21: 7 Days Water Absorption of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFRM1</td>
<td>14.47</td>
<td>14.23</td>
<td>14.30</td>
<td>14.33</td>
</tr>
<tr>
<td>CFRM2</td>
<td>13.48</td>
<td>13.99</td>
<td>13.54</td>
<td>13.67</td>
</tr>
<tr>
<td>CFRM3</td>
<td>12.69</td>
<td>12.56</td>
<td>12.09</td>
<td>12.45</td>
</tr>
<tr>
<td>CFRM4</td>
<td>14.14</td>
<td>16.93</td>
<td>15.17</td>
<td>15.41</td>
</tr>
</tbody>
</table>

Table 5.22: 28 Days Water Absorption of Different Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar Composite</th>
<th>Specimen 1</th>
<th>Specimen 2</th>
<th>Specimen 3</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>13.61</td>
<td>13.57</td>
<td>14.22</td>
<td>13.80</td>
</tr>
<tr>
<td>CFRM1</td>
<td>13.38</td>
<td>13.44</td>
<td>13.60</td>
<td>13.47</td>
</tr>
<tr>
<td>CFRM2</td>
<td>12.94</td>
<td>12.42</td>
<td>12.67</td>
<td>12.68</td>
</tr>
<tr>
<td>CFRM3</td>
<td>11.10</td>
<td>11.57</td>
<td>11.02</td>
<td>11.23</td>
</tr>
<tr>
<td>CFRM4</td>
<td>15.64</td>
<td>15.08</td>
<td>15.98</td>
<td>15.56</td>
</tr>
</tbody>
</table>
Figure 5.22: Variation of Water Absorption with Different Carbon Fiber Volume Contents.

The water resistance factors due to various carbon fiber volume contents have been calculated and are shown in Table 5.23. It is evident from Table 5.23 that the resistance to water absorption increased considerably at 3% carbon fiber content whereas it decreased for 4% fiber content. This could be ascribed to the amount of pores and voids as evidenced in the test of unit weight and air content. The total porosity and the pore size largely affect the water absorption capacity. The larger the total porosity and the pore size, the greater the water absorption. The mortar with 3% carbon fiber content received a higher degree of compaction due to sufficient workability. Therefore it had low amount of air voids. It is also likely that the pore size has been reduced in the presence of silica fume and superplasticizer. Accordingly, its water absorption capacity decreased.
Table 5.23: Water Absorption Resistance Factors for Various Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>NPCM</th>
<th>CFRM1</th>
<th>CFRM2</th>
<th>CFRM3</th>
<th>CFRM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Absorption Resistance</td>
<td>1</td>
<td>1.01</td>
<td>1.06</td>
<td>1.16</td>
<td>0.94</td>
</tr>
<tr>
<td>Factor at 7 Days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water Absorption Resistance</td>
<td>1</td>
<td>1.03</td>
<td>1.09</td>
<td>1.23</td>
<td>0.89</td>
</tr>
<tr>
<td>Factor at 28 Days</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The usage of superplasticizer and silica fume in carbon fiber reinforced mortar decreases the capillary porosity of the matrix. The superplasticizer allows for a substantial reduction in mixing water and thus reduces the overall porosity of the mortar. It also reduces bleeding and so assures a better adhesion among sand particles, carbon fibers and binding paste. Moreover, silica fume provides additional improvement to the porosity. It also improves the interfaces with sand particles and carbon fibers. However, all these improvements largely depend upon workability and degree of compaction. Workability and compaction play important roles in the formation of pores and voids in composite. As the mortar with 3% carbon fiber content possessed adequate workability, the fresh mortar became well compacted under vibration. Accordingly, its water absorption capacity has been reduced. Conversely, excessive pores and voids are likely in carbon fiber reinforced mortar with 4% fiber content as the workability was poor and the fresh composites were too stiff for easy placing and sufficient compaction. As a result, it shows the maximum water absorption capacity. The results of the compressive strength test also support the observed trend of water absorption in the present study.

5.4 Cost-effectiveness

The cost-effectiveness of carbon fiber reinforced mortars has been assessed based on the performance to cost ratios. The performance to cost ratios have been calculated comparing the performance of mortars with respect to volume flow as a measure of workability, compressive strength, flexural strength and impact resistance to appraise the
mechanical behavior, and water absorption as an indicator of durability with reference to unit cost. The detailed computation is given in Appendix M.

![Bar Graph](image)

**Performance to Cost Ratio (FCR)**

**Carbon Fiber Volume Content (%)**

Figure 5.23: Variation of Performance to Cost Ratio with Different Carbon Fiber Volume Contents.

The performance to cost ratios have been plotted for different carbon fiber volume contents and are shown in Figure 5.23. It can be seen from Figure 5.23 that the performance to cost ratio is increased up to 3% carbon fiber volume content. Beyond the 3% fiber content, it decreases. In particular, the mortar with 3% carbon fibers has provided the highest performance to cost ratio.

The workability, strength, impact resistance, and durability issues are most vital for any cement-based composites if they are intended to provide high performance during service life. At the same time, cost is equally important. The optimum benefits are always
desirable at a reasonable cost. In the context of present study, carbon fiber reinforced mortar at 3% fiber content offers the maximum benefits, and therefore is proven to be the most cost-effective. It should also be mentioned that the lifetimes of plain and carbon fiber reinforced mortars were not considered in the computation of performance to cost ratios. If the lifetimes had been included, the performance to cost ratio of carbon fiber reinforced mortar with 3% fiber content would definitely be much higher.

5.5 Optimum Mix

The optimal mix has been defined based on the overall performance with regard to workability, strength, impact resistance and durability, and also by considering the performance to cost ratios of various carbon fiber reinforced mortars. From these perspectives, the mortar with 3% carbon fiber content is the optimal mix since it provided adequate slump and flow for placing and compaction by vibration; produced good compressive, tensile and flexural strengths; offered excellent impact resistance and reduced water absorption; and finally proved its cost-effectiveness giving the highest performance to cost ratio.

5.6 Summary of Test Results

In general, the compressive, tensile, first-crack and flexural strengths, the first-crack toughness, the first-crack and ultimate impact resistances, and the air content increased whereas the slump, the mass or volume flow, the unit weight, and the water absorption decreased as the volume content of carbon fibers increased. The mortar with 3% carbon fibers provided sufficient workability, good strength, superior impact resistance, and exhibited the potential of excellent durability having low water absorption. It also produced the highest performance to cost ratio. Therefore, it can be considered as the optimal mix in the context of present study.
6.1 Conclusions on Properties of Fresh Carbon Fiber Reinforced Mortars

The following conclusions are based on the properties of freshly mixed carbon fiber reinforced mortars:

a. The slump of carbon fiber reinforced mortar decreases linearly with increase in carbon fiber volume content.

b. Carbon fiber reinforced mortar with moderate fiber content provides sufficient slump for easy placing and good compaction of fresh composite.

c. The unit weight of carbon fiber reinforced mortar is lower than that of normal portland cement mortar.

d. The unit weight of carbon fiber reinforced mortar varies with fiber volume content, and depends largely on workability and compaction.

e. The air content in carbon fiber reinforced mortar is greater than that of normal portland cement mortar.

f. The air content of carbon fiber reinforced mortar depends upon fiber volume content as well as workability and degree of compaction.

g. The flow time of carbon fiber reinforced mortar increases predominantly with the increase in fiber volume content.

h. The mass flow and the volume flow of carbon fiber reinforced mortar reduce linearly with increasing fiber contents.

i. The slump test is not always a satisfactory test for carbon fiber reinforced mortars.

j. The slump test can be used for carbon fiber reinforced mortar when the correlation between slump and flow time is known.
6.2 Conclusions on Strength, Toughness, and Impact Resistance of Carbon Fiber Reinforced Mortars

The following conclusions are based on the static and dynamic properties of carbon fiber reinforced mortars:

a. Considerable strengthening and toughening is possible by reinforcing a cement mortar matrix with pitch-based short carbon fibers.
b. The compressive strength of carbon fiber reinforced mortar increases with the addition of carbon fibers provided the fresh composite is sufficiently workable and well compacted.
c. The tensile strength of carbon fiber reinforced mortar increases linearly with the increase in fiber volume content.
d. The first-crack and flexural strengths of carbon fiber reinforced mortar increase linearly with increasing fiber volume contents.
e. The first-crack toughness of carbon fiber reinforced mortar increases linearly with the increase in fiber volume content.
f. Pitch-based short carbon fibers are very effective for improving the impact resistance of cement-based matrices.
g. The first-crack and the ultimate impact resistances of carbon fiber reinforced mortar increase considerably with increasing carbon fiber volume contents.

6.3 Conclusions on Durability and Overall Cost-effectiveness of Carbon Fiber Reinforced Mortars

The following conclusions are on the durability and overall cost-effectiveness of carbon fiber reinforced mortars:

a. The addition of carbon fibers diminishes the water absorption and thus enhances the durability of cement-based matrices provided the fresh composites possess sufficient workability and receive well compaction.
b. Adequately workable carbon fiber reinforced mortar is cost-effective and offers excellent performance prevailing over the high material cost.
6.4 Conclusion on Mix Optimization of Carbon Fiber Reinforced Mortars

The mix for carbon fiber reinforced mortar with 3% fiber content is proven to be the optimum mix based on its performance in respect of slump, flow, unit weight, air content, compressive, tensile, first-crack and flexural strengths, first-crack toughness, first-crack and ultimate impact resistances, water absorption, and cost-effectiveness.

6.5 Recommendations for Further Research

The following recommendations can be made for further research and development in related fields:

a. The effect of different carbon fiber volume contents should be investigated by varying fiber parameters, water-binder ratios and sand contents, and by using low to medium size coarse aggregates.

b. The combined effect of carbon and other micro- or macro-fibers on the properties and the durability of resulting fiber composite should be investigated.

c. The properties and the durability of carbon fiber reinforced mortars should be investigated at sub-normal temperature to examine the suitability and sustainability of carbon fiber reinforced mortars in Canadian climatic conditions.

d. The use of carbon fibers in conjunction with continuous steel or FRP bars in truly structural applications should be examined with a view to producing far superior static and dynamic properties.

e. A standard mix proportioning method needs to be developed for cement-based carbon fiber reinforced cement composites.

f. Further developments of the modified inverted slump cone flow test apparatus and the modified impact test apparatus could be done in order to increase their efficiency.

g. The present techniques of characterizing flexural toughness and first-crack strength need improvement.
REFERENCES

ACI Committee 212. (1987). “Guide for Use of Admixtures in Concrete”, *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, Detroit, USA.

ACI Committee 363. (1988). “High Strength Concrete”, *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, Detroit, USA.

ACI Committee 544. (1987). “Guide for Specifying, Mixing, Placing, and Finishing Steel Fiber Reinforced Concrete”, *ACI Manual of Concrete Practice*, Part 5, American Concrete Institute, Detroit, USA.


ACI Committee 544. (1990). “State-of-the-Art Report on Fiber Reinforced Concrete”, *ACI Manual of Concrete Practice*, Part 5, American Concrete Institute, Detroit, USA.


References


References


References


References


Lankard, D.R. (1978). “Steel fiber Reinforced Refractory Concrete”, *Refractory Concrete*, ACI SP-57, American Concrete Institute, Detroit, USA, pp.241-263.

References


References 163


References


APPENDIX A

Results of Experiments Conducted on Different Constituent Materials

Total Evaporable Moisture Content of Sand:

The total evaporable moisture content of river sand has been determined at the Concrete Laboratory of the University of Windsor according to the standard ASTM C 566-97 (2002). The detailed computation and the experimental result are as follows:

Weight of container, \( W_c = 580.04 \text{ g} \)
Weight of container and original sample, \( W_{c+s} = 1080.04 \text{ g} \)
Thus, the weight of original sample, \( W_s = (1080.04 - 580.04) \text{ g} = 500 \text{ g} \)

Again, weight of container and dried sample, \( W_{c+ds} = 1077.43 \text{ g} \)
Thus, the weight of dried sample, \( W_{ds} = (1077.43 - 580.04) \text{ g} = 497.39 \text{ g} \)

Now, the total evaporable moisture content of sand,

\[
M_s = \frac{W_c - W_{ds}}{W_{ds}} \times 100 \quad (A-1)
\]

\[
= \frac{500 - 497.39}{497.39} \times 100
\]

\[
= 0.525 \%
\approx 0.5 \%
\]

Bulk Specific Gravity and Absorption of Sand:

The bulk specific gravity and the absorption of river sand have been determined in accordance with the standard ASTM C 128-97 (1999). Figures A1 and A2 show the operational stages of the experiment. The detailed computation and the experimental results are as follows:

Weight of pan, \( P = 579.73 \text{ g} \)
Weight of pan and saturated surface-dry specimen, \( (P+S) = 1079.73 \text{ g} \)
Weight of pan and oven dried specimen, \( (P+A) = 1071.90 \text{ g} \)
Weight of pycnometer filled with water up to the calibration mark, \( B = 663.30 \text{ g} \)
Weight of pycnometer with sand sample and water up to the calibration mark, \( C = 970.04 \text{ g} \)
Thus, the weight of saturated surface-dry specimen, \( S = (1079.73 - 579.73) \text{ g} = 500 \text{ g} \)

Weight of oven dried specimen, \( A = (1071.90 - 579.73) \text{ g} = 492.17 \text{ g} \)

Now,

Saturated surface-dry basis bulk specific gravity of sand,

\[
G_s = \frac{S}{B + S - C} \tag{A-2}
\]

\[
= \frac{500}{663.30 + 500 - 970.04}
\]

\[
= 2.587
\]

\approx 2.60

---

Figure A1: An Operational Stage to Get the River Sand Sample in Saturated Surface-dry Condition.
Again, absorption of sand,

\[ A_s = \frac{S - A}{A} \times 100 \]  

\[ = \frac{500 - 492.17}{492.17} \times 100 \]

\[ = 1.59\% \]

\[ \approx 1.6\% \]

Figure A2: An Operational Stage to Determine the Specific Gravity of River Sand.

**Surface Moisture in Sand:**

The amount of surface moisture in river sand has been determined at the Concrete Laboratory of the University of Windsor according to the standard ASTM C 70-94 (2002). The experimental results and the detailed computation are as follows:

- Weight of empty flask, \( W_f = 401.21 \) g
- Weight of flask filled with water up to the calibration mark, \( W_{f+w} = 799.37 \) g
- Weight of flask, sample, and water filled up to the calibration mark, \( W_{f+w+s} = 922.0 \) g
Weight of sand sample in air, $W_s = 200$ g
Thus, the weight of water displaced by the sample,
$V_s = (799.37 + 200 - 922.0)$ g = 77.37 g
Now, the amount of surface moisture in terms of saturated surface-dry sand,

$$M_{ss} = \frac{V_s - V_g}{W_s - V_s} \times 100$$  \hspace{1cm} \text{(A-4)}$$

Where,
$V_g =$ Weight of the sample divided by the bulk specific gravity of sand
$= (200 + 2.587)$ g = 76.92 g

Thus, from Equation (A-4), $M_{ss} = \frac{77.37 - 77.31}{200 - 77.37} \times 100 = 0.049\% \approx 0\%$

**Sieve Analysis of Sand:**

The sieve analysis of river sand was conducted at the Concrete Laboratory of the University of Windsor in accordance with the standard ASTM C 136-01 (2002). The set-up for sieve analysis is shown in Figure A3. The detailed results are shown in Table A1.

![Figure A3: Experimental Set-up for Sieve Analysis of River Sand.](image-url)
Table A1: Sieve Analysis of River Sand.

<table>
<thead>
<tr>
<th>Sieve Size</th>
<th>Weight of Material Retained (g)</th>
<th>Percentage of Material Retained</th>
<th>Cumulative Percentage Retained</th>
<th>Total Percentage of Material Passing</th>
</tr>
</thead>
<tbody>
<tr>
<td>9.5-mm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>4.75-mm</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>2.36-mm</td>
<td>1.4</td>
<td>0.3</td>
<td>0.3</td>
<td>99.7</td>
</tr>
<tr>
<td>1.18-mm</td>
<td>16.5</td>
<td>3.3</td>
<td>3.6</td>
<td>96.4</td>
</tr>
<tr>
<td>600-μm</td>
<td>109.4</td>
<td>21.9</td>
<td>25.5</td>
<td>74.5</td>
</tr>
<tr>
<td>300-μm</td>
<td>231.1</td>
<td>46.2</td>
<td>71.7</td>
<td>28.3</td>
</tr>
<tr>
<td>150-μm</td>
<td>122.2</td>
<td>24.5</td>
<td>96.2</td>
<td>3.8</td>
</tr>
<tr>
<td>Pan</td>
<td>19.4</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

Weight of sand sample = 500 g

Fineness modulus, $FM = \frac{0.3 + 3.6 + 25.5 + 71.7 + 96.2}{100} = 1.973 \approx 1.97$

Total Evaporable Moisture Content of Portland Cement:

The total evaporable moisture content of Lafarge Type 10 portland cement has been determined at the Concrete Laboratory of the University of Windsor following the method used for fly ash or natural pozzolans (ASTM C 311-00, 2002). The detailed results are given in Table A2.

Table A2: Total Evaporable Moisture Content of Lafarge Type 10 Portland Cement.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Weight of Sample in Air (g)</th>
<th>Weight of Oven-dried Sample (g)</th>
<th>Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>50</td>
<td>49.73</td>
<td>0.54</td>
</tr>
<tr>
<td>Sample 2</td>
<td>50</td>
<td>49.73</td>
<td>0.54</td>
</tr>
<tr>
<td>Sample 3</td>
<td>50</td>
<td>49.75</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Average moisture content of cement, $M_c = \frac{0.54 + 0.54 + 0.50}{3} = 0.527\% \approx 0.5\%$

Specific Gravity of Portland Cement:

The specific gravity of Lafarge Type 10 portland cement was determined at the Concrete Laboratory of the University of Windsor in accordance with the standard ASTM C 188-95 (2002). The experimental set-up is shown in Figure A4. The detailed computation and the results are as follows:
Mass of cement in air, $M_{ca} = 64$ g
Initial volume after filling with kerosene, $V_{ic} = 400$ ml
Final Volume after pouring cement in kerosene, $V_{fc} = 420.5$ ml

Thus, the density of cement,

$$D_c = \frac{M_{ca}}{V_{fc} - V_{ic}} = \frac{64}{420.5 - 400} = 3.1527 \text{ g/cm}^3$$  \hspace{1cm} (A-5)

Figure A4: Experimental Set-up to Determine the Specific Gravity of Lafarge Type 10 Portland Cement.

Now,
Room temperature = $23^0C$
Density of water at $4^0C$, $D_{w4} = 1$ g/cm$^3$
Density of water at $23^0C$, $D_{w23} = 0.99754$ g/cm$^3$
Thus, the specific gravity of cement,

$$G_c = \frac{D_c}{D_{w4}} \times D_{w23}$$

$$= \frac{3.1527}{1} \times 0.99754 = 3.1449 \approx 3.15$$

**Total Evaporable Moisture Content of Silica Fume:**

The total evaporable moisture content of Rheomac® SF 100 silica fume was determined at the Concrete Laboratory of the University of Windsor complied with the procedure mentioned in the standard specification for silica fume (ASTM C 1240-01, 2002). The detailed results are given in Table A3.

**Table A3: Total Evaporable Moisture Content of Rheomac® SF 100 Silica Fume.**

<table>
<thead>
<tr>
<th>Designation</th>
<th>Weight of Sample in Air (g)</th>
<th>Weight of Oven-dried Sample (g)</th>
<th>Moisture Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>50</td>
<td>49.44</td>
<td>1.12</td>
</tr>
<tr>
<td>Sample 2</td>
<td>50</td>
<td>49.44</td>
<td>1.12</td>
</tr>
<tr>
<td>Sample 3</td>
<td>50</td>
<td>49.42</td>
<td>1.16</td>
</tr>
</tbody>
</table>

Average moisture content of silica fume,

$$M_{sf} = \frac{1.12 + 1.12 + 1.16}{3} = 1.13\% \approx 1.1\%$$

**Specific Gravity of Silica Fume:**

The specific gravity of Rheomac® SF 100 silica fume was determined in the Concrete Laboratory of the University of Windsor complied with the procedure used for portland cement (ASTM C 188-95, 2002). The experimental set-up is shown in Figure A5. The detailed computation and the results are as follows:

Mass of silica fume in air, $$M_{sf_{a}} = 50 \text{ g}$$
Initial volume after filling with kerosene, $$V_{sf} = 400 \text{ ml}$$
Final Volume after pouring cement in kerosene, $$V_{sf_{f}} = 422.6 \text{ ml}$$

Appendix A 174
Thus, the density of silica fume,

\[ D_q = \frac{M_{sf}}{V_{sf} - V_{lsf}} = \frac{50}{422.6 - 400} = 2.212 \text{ g/cm}^3 \]  

(A-7)

Now,
Room temperature = 23\(^\circ\)C
Density of water at 4\(^\circ\)C, \(D_{w4} = 1 \text{ g/cm}^3\)
Density of water at 23\(^\circ\)C, \(D_{w23} = 0.99754 \text{ g/cm}^3\)

Figure A5: Experimental Set-up to Determine the Specific Gravity of Rheomac\textsuperscript{®} SF 100 Silica Fume.
Thus, the specific gravity of silica fume,

\[ G_f = \frac{D_{sf}}{D_{w4}} \times D_{w23} \quad (A-8) \]

\[ = \frac{2.212}{1} \times 0.99754 \]

\[ = 2.206 \approx 2.2 \]

**Specific Gravity of Carbon Fibers:**

The specific gravity of Dialead K6611T pitch-based carbon fibers was determined at the Concrete Laboratory of the University of Windsor following the procedure used for sand (ASTM C 128-97, 1999). Figure A6 reveals an operational stage of the experiment. The detailed computation and the result are as follows:

![Image of measurement equipment]

*Figure A6: An Operational Stage to Determine the Specific Gravity of Dialead K6611T Pitch-based Carbon Fibers.*
Weight of carbon fibers in air, $W_{cf} = 25$ g
Weight of pycnometer filled with water up to calibration mark, $W_{p+w} = 1125.15$ g
Weight of pycnometer with fiber sample and water up to the calibration mark, $W_{p+w+cf} = 1136.60$ g

Thus, the specific gravity of carbon fibers,

$$G_{cf} = \frac{W_{cf}}{W_{cf} + W_{p+w} - W_{p+w+cf}}$$

$$= \frac{25}{25 + 1125.15 - 1136.60}$$

$$= 1.845 \approx 1.85$$

**Specific Gravity of Superplasticizer:**

The specific gravity of superplasticizer, Rheobuild® 1000, was determined at the Concrete Laboratory of the University of Windsor using a graduated cylinder. The experimental results and the detailed computation are as follows:

Capacity of graduated cylinder, $V_c = 100$ ml
Weight of graduated cylinder, $W_c = 133.51$ g
Weight of cylinder filled with water up to the calibration mark, $W_{c+w} = 232.61$ g
Weight of cylinder filled with superplasticizer up to the calibration mark, $W_{c+sp} = 252.78$ g
Room temperature = $20^0C$
Specific gravity of water at $20^0C$, $G_{w20} = 0.99819$

Thus, the specific gravity of superplasticizer,

$$G_{sp} = \frac{W_{c+sp} - W_c}{W_{c+w} - W_c} \times G_{w20}$$

$$= \frac{252.78 - 133.51}{232.61 - 133.51} \times 0.99819$$

$$= 1.201 \approx 1.2$$
Solid Content of Superplasticizer:

The solid content of superplasticizer, Rheobuild® 1000, was determined at the Concrete Laboratory of the University of Windsor complied with the procedure given in the standard specification for chemical admixtures required for concrete (ASTM C 494/C 494M-99a, 2002). The detailed results are given in Table A4.

Table A4: Solid Content in Rheobuild® 1000 Superplasticizer.

<table>
<thead>
<tr>
<th>Designation</th>
<th>Weight of Sample in Air (g)</th>
<th>Weight of Oven-dried Residue (g)</th>
<th>Solid Content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample 1</td>
<td>4.38</td>
<td>1.76</td>
<td>40.18</td>
</tr>
<tr>
<td>Sample 2</td>
<td>4.45</td>
<td>1.79</td>
<td>40.22</td>
</tr>
<tr>
<td>Sample 3</td>
<td>4.40</td>
<td>1.77</td>
<td>40.23</td>
</tr>
</tbody>
</table>

Average solid content of superplasticizer, 

\[ S_c = \frac{40.18 + 40.22 + 40.23}{3} = 40.21\% \approx 40\% \]
APPENDIX B

Mix Design for Different Types of Mortar

Background Data:

Specific gravity of cement, $G_c = 3.15$
Moisture content of cement, $M_c = 0.5\%$
Specific gravity of silica fume, $G_{sf} = 2.20$
Moisture content of silica fume, $M_{sf} = 1.1\%$
Bulk specific gravity of sand, $G_s = 2.60$
Absorption of sand, $A_s = 1.6\%$
Moisture content of sand, $M_s = 0.5\%$
Specific gravity of superplasticizer, $G_{sp} = 1.20$
Solid content of superplasticizer, $S_c = 40\%$ by volume
Specific gravity of carbon fibers, $G_{cf} = 1.85$
Density of water, $\rho_w = 1000$ kg/m$^3$

Background Design Information:

Volume of mortar composite, $V = 1$ m$^3$
Water ($W$) = 35% of Binder ($B$) by weight i.e., water-binder ratio ($W/B$) = 0.35
Sand ($S$) = 50% of $B$ by weight i.e., sand-binder ratio ($S/B$) = 0.50
Silica fume ($SF$) = 15% of $B$ by weight, used as a partial cement replacement material
Cement ($C$) = 85% of $B$
Superplasticizer ($SP$) = 1% to 5% of $B$ by weight, used as an addition
Volume content of carbon fibers, $V_{cf} = 1\%$ to 4% of $V$

Assumptions:

a. The loss of water during mixing operation owing to evaporation and workmanship is compensated by the moisture contents of cement and silica fume.
b. Air content of normal portland cement mortar is approximately 1% whereas it varies from 4% to 7% by volume for various carbon fiber reinforced mortars.

Basic Equations:

$$\frac{1}{\rho_w}\left(\frac{C}{G_c} + \frac{SF}{G_{sf}} + \frac{S}{G_s} + W\right) + V_{cf} + A_c = 1$$

(B-1)
\[ W_{as} = S \left( \frac{A_s - M_s}{100 + A_s + M_s} \right) \]  \hspace{1cm} (B-2)

\[ W_{sp} = V_{sp} \left( \frac{100 - S_c}{100} \right) \]  \hspace{1cm} (B-3)

\[ S_a = S - W_{as} \]  \hspace{1cm} (B-4)

\[ W_a = W + W_{as} - W_{sp} \]  \hspace{1cm} (B-5)

Where,
- \( A_c \) = Air content
- \( W_a \) = Adjusted water
- \( W_{as} \) = Water absorbed by sand
- \( W_{sp} \) = Water contributed by superplasticizer
- \( V_{sp} \) = Volume of superplasticizer
- \( S_a \) = Adjusted sand
- \( A_s, C, G_c, G_s, M_s, S, SF, S_c, V_{cf}, W, \) and \( \rho_\alpha \) have been explained previously.

**Mix Design for NPCM:**

**SSD basis mix proportions**

Assumed \( A_c = 1\% \) of mortar volume, \( V \); \( V_{cf} = 0\% \) of \( V \)

From Equation \( (B-1) \),

\[
\frac{1}{1000} \left( \frac{0.85B}{3.15} + \frac{0.15B}{2.20} + \frac{0.50B}{2.60} + \frac{0.35B}{0.01} \right) = 1
\]

By solving and interpreting:
- \( B = 1124.6 \) kg
- \( C = 955.9 \) kg
- \( SF = 168.7 \) kg
- \( S = 562.3 \) kg
- \( W = 393.6 \) kg
- \( SP = 1\% \) of \( B = 11.246 \) kg = 9372 ml

**Water corrections**

From Equation \( (B-2) \), \( W_{as} = 562.3 \times \{(1.60-0.50)+(100+1.60-0.50)\} = 6.1 \) kg

From Equation \( (B-3) \), \( W_{sp} = 9372 \times \{(100-40)+100\} = 5623 \) ml = 5.6 kg
Adjusted mix proportions

\[ C = 955.9 \text{ kg} \]
\[ SF = 168.7 \text{ kg} \]
From Equation (B-4), \( S_a = 562.3 - 6.1 = 556.2 \text{ kg} \)
From Equation (B-5), \( W_a = 393.6 + 6.1 - 5.6 = 394.1 \text{ kg} \)
\( SP = 9372 \text{ ml} \)

Mix Design for CFRM1:

SSD basis mix proportions

Assumed \( A_c = 4\% \) of mortar volume, \( V \); \( V_{cf} = 1\% \) of \( V \)
From Equation (B-1),

\[
\frac{1}{1000} \left( \frac{0.85B}{3.15} + \frac{0.15B}{2.20} + \frac{0.50B}{2.60} + 0.35B \right) + 0.04 + 0.01 = 1
\]

By solving and interpreting:
\( B = 1079.1 \text{ kg} \)
\( C = 917.2 \text{ kg} \)
\( SF = 161.9 \text{ kg} \)
\( S = 539.6 \text{ kg} \)
\( W = 377.7 \text{ kg} \)
\( CF = 1\% \) of \( V = 0.01 \text{ m}^3 = 18.5 \text{ kg} \)
\( SP = 2\% \) of \( B = 21.582 \text{ kg} = 17985 \text{ ml} \)

Water corrections

From Equation (B-2), \( W_{ad} = 539.6 \times \{(1.60-0.50)+(100+1.6-0.50)} \) = 5.9 \text{ kg} \)
From Equation (B-3), \( W_{sp} = 17985 \times \{(100-40)+100} \) = 10791 ml = 10.8 \text{ kg} \)

Adjusted mix proportions

\[ C = 917.2 \text{ kg} \]
\[ SF = 161.9 \text{ kg} \]
From Equation (B-4), \( S_a = 539.6 - 5.9 = 533.7 \text{ kg} \)
From Equation (B-5), \( W_a = 377.7 + 5.9 - 10.8 = 372.8 \text{ kg} \)
\( CF = 18.5 \text{ kg} \)
\( SP = 17985 \text{ ml} \)
Mix Design for CFRM2:

SSD basis mix proportions

Assumed $A_e = 5\%$ of mortar volume, $V$; $V_{cf} = 2\%$ of $V$
From Equation (B-1),

$$\frac{1}{1000} \left( \frac{0.85B}{3.15} + \frac{0.15B}{2.20} + \frac{0.50B}{2.60} + \frac{0.35B}{2.00} \right) + 0.05 + 0.02 = 1$$

By solving and interpreting:
$B = 1056.4$ kg
$C = 898.0$ kg
$SF = 158.5$ kg
$S = 528.2$ kg
$W = 369.8$ kg
$CF = 2\%$ of $V = 0.02$ m$^3 = 37.0$ kg
$SP = 3\%$ of $B = 31.692$ kg = 26410 ml

Water corrections

From Equation (B-2), $W_{as} = 528.2 \times \{(1.60-0.50) / (100+1.60-0.50)\} = 5.8$ kg
From Equation (B-3), $W_{sp} = 26410 \times \{(100-40) / 100\} = 15846$ ml = 15.8 kg

Adjusted mix proportions

$C = 898.0$ kg
$SF = 158.5$ kg
From Equation (B-4), $S_a = 528.2 - 5.8 = 522.4$ kg
From Equation (B-5), $W_a = 369.8 + 5.8 - 15.8 = 359.8$ kg
$CF = 37.0$ kg
$SP = 26410$ ml

Mix Design for CFRM3:

SSD basis mix proportions

Assumed $A_e = 6\%$ of mortar volume, $V$; $V_{cf} = 3\%$ of $V$
From Equation (B-1),

$$\frac{1}{1000} \left( \frac{0.85B}{3.15} + \frac{0.15B}{2.20} + \frac{0.50B}{2.60} + \frac{0.35B}{2.00} \right) + 0.06 + 0.03 = 1$$
By solving and interpreting:
\( B = 1033.7 \text{ kg} \)
\( C = 878.6 \text{ kg} \)
\( SF = 155.1 \text{ kg} \)
\( S = 516.9 \text{ kg} \)
\( W = 361.8 \text{ kg} \)
\( CF = 3\% \text{ of } V = 0.03 \text{ m}^3 = 55.5 \text{ kg} \)
\( SP = 4\% \text{ of } B = 41.348 \text{ kg} = 34457 \text{ ml} \)

**Water corrections**

From Equation (B-2), \( W_{aw} = 516.9 \times \{(1.60-0.50)+(100+1.60-0.50)\} = 5.6 \text{ kg} \)
From Equation (B-3), \( W_{sp} = 34457 \times \{(100-40)/100\} = 20674 \text{ ml} = 20.7 \text{ kg} \)

**Adjusted mix proportions**

\( C = 878.6 \text{ kg} \)
\( SF = 155.1 \text{ kg} \)
From Equation (B-4), \( S_o = 516.9 - 5.6 = 511.3 \text{ kg} \)
From Equation (B-5), \( W_a = 361.8 + 5.6 - 20.7 = 346.7 \text{ kg} \)
\( CF = 55.5 \text{ kg} \)
\( SP = 34457 \text{ ml} \)

**Mix Design for CFRM4:**

**SSD basis mix proportions**

Assumed \( A_e = 7\% \text{ of mortar volume, } V; \ V_e = 4\% \text{ of } V \)
From Equation (B-1),

\[
\frac{1}{1000} \left( \frac{0.85B}{3.15} + \frac{0.15B}{2.20} + \frac{0.50B}{2.60} + \frac{0.35B}{2.00} \right) + 0.07 + 0.04 = 1
\]

By solving and interpreting:
\( B = 1011.0 \text{ kg} \)
\( C = 859.4 \text{ kg} \)
\( SF = 151.7 \text{ kg} \)
\( S = 505.5 \text{ kg} \)
\( W = 353.9 \text{ kg} \)
\( CF = 4\% \text{ of } V = 0.04 \text{ m}^3 = 74 \text{ kg} \)
\( SP = 5\% \text{ of } B = 50.550 \text{ kg} = 42125 \text{ ml} \)
Water corrections

From Equation (B-2), $W_{as} = 505.5 \times \{(1.60-0.50)+(100+1.60-0.50)\} = 5.5$ kg
From Equation (B-3), $W_{sp} = 42125 \times \{(100-40)/100\} = 25275$ ml = 25.3 kg

Adjusted mix proportions

$C = 859.4$ kg
$SF = 151.7$ kg
From Equation (B-4), $S_{a} = 505.5 - 5.5 = 500.0$ kg
From Equation (B-5), $W_{o} = 353.9 + 5.5 - 25.3 = 334.1$ kg
$CF = 74.0$ kg
$SP = 42125$ ml
APPENDIX C

Batch Compositions

Background Information:

Size of beam specimen = 400L x 75W x 100H mm
Size of parent cylinder specimen = 150D x 300H mm
Size of small cylinder specimen = 100D x 200H mm
Size of parent cube specimen = 150L x 150W x 150H mm

Basic Equation:

\[ P_b = V_b \times P_{am} \]  \hspace{1cm} (C-1)

Where,
\[ P_b = \text{Batch weight of any material (kg)} \]
\[ P_{am} = \text{Adjusted mix proportion of the same material (kg/m}^3) \]
\[ V_b = \text{Batch volume (m}^3) \]

Batch 1 Compositions:

Batch volume

Number of beam specimens = 3
Number of parent cylinder specimens = 1
Number of small cylinder specimens = 6
Number of parent cube specimens = 1

Volume of 3 beam specimens = 0.009439 m\(^3\)
Volume of 1 parent cylinder specimen = 0.005302 m\(^3\)
Volume of 6 small cylinder specimens = 0.009426 m\(^3\)
Volume of 1 parent cube specimen = 0.00354 m\(^3\)

Thus, batch volume, \( V_b = 1.15 (0.009439+0.005302+0.009426+0.00354) = 0.03186 \text{ m}^3 \)

Using Equation (C-1), the compositions of batch 1 for different mortar mixes have been determined based on the adjusted mix proportions, which were worked out previously in Appendix B. The detailed batch 1 compositions are given in Table C1.
Table C1: Batch 1 Compositions of Different Mortar Mixes.

<table>
<thead>
<tr>
<th>Type of Mix</th>
<th>Cement (kg)</th>
<th>Sand (kg)</th>
<th>Silica Fume (kg)</th>
<th>Carbon Fiber (g)</th>
<th>Water (kg)</th>
<th>Superplasticizer (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>30.5</td>
<td>17.7</td>
<td>5.4</td>
<td>---</td>
<td>12.6</td>
<td>299</td>
</tr>
<tr>
<td>CFRM1</td>
<td>29.2</td>
<td>17.0</td>
<td>5.2</td>
<td>589</td>
<td>11.9</td>
<td>573</td>
</tr>
<tr>
<td>CFRM2</td>
<td>28.6</td>
<td>16.6</td>
<td>5.0</td>
<td>1179</td>
<td>11.5</td>
<td>842</td>
</tr>
<tr>
<td>CFRM3</td>
<td>28.0</td>
<td>16.3</td>
<td>4.9</td>
<td>1768</td>
<td>11.1</td>
<td>1098</td>
</tr>
<tr>
<td>CFRM4</td>
<td>27.4</td>
<td>15.9</td>
<td>4.8</td>
<td>2358</td>
<td>10.7</td>
<td>1342</td>
</tr>
</tbody>
</table>

Batch 2 Compositions:

Batch volume
Number of beam specimens = 3
Number of parent cylinder specimens = 1
Number of small cylinder specimens = 6

Volume of 3 beam specimens = 0.009439 m³
Volume of 1 parent cylinder specimen = 0.005302 m³
Volume of 6 small cylinder specimens = 0.009426 m³

Thus, batch volume, \( V_b = 1.15 (0.009439+0.005302+0.009426) = 0.02779 \text{ m}³ \)

Using Equation (C-1), the compositions of batch 2 for various mortar mixes have been determined based on the adjusted mix proportions, which were worked out previously in Appendix B. The detailed batch 2 compositions are given in Table C2.

Table C2: Batch 2 Compositions of Different Mortar Mixes.

<table>
<thead>
<tr>
<th>Type of Mix</th>
<th>Cement (kg)</th>
<th>Sand (kg)</th>
<th>Silica Fume (kg)</th>
<th>Carbon Fiber (kg)</th>
<th>Water (kg)</th>
<th>Superplasticizer (ml)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>26.6</td>
<td>15.5</td>
<td>4.7</td>
<td>---</td>
<td>11.0</td>
<td>260</td>
</tr>
<tr>
<td>CFRM1</td>
<td>25.5</td>
<td>14.8</td>
<td>4.5</td>
<td>0.514</td>
<td>10.4</td>
<td>500</td>
</tr>
<tr>
<td>CFRM2</td>
<td>25.0</td>
<td>14.5</td>
<td>4.4</td>
<td>1.028</td>
<td>10.0</td>
<td>734</td>
</tr>
<tr>
<td>CFRM3</td>
<td>24.4</td>
<td>14.2</td>
<td>4.3</td>
<td>1.542</td>
<td>9.6</td>
<td>958</td>
</tr>
<tr>
<td>CFRM4</td>
<td>23.9</td>
<td>13.9</td>
<td>4.2</td>
<td>2.056</td>
<td>9.3</td>
<td>1171</td>
</tr>
</tbody>
</table>
# APPENDIX D

## Detailed Schedule of Test Program

Table D1: Test Program for Various Fresh Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Number of Batches</th>
<th>Type of Test</th>
<th>Number of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>2</td>
<td>Slump Test</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test for Unit Weight and Air Content</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverted Slump Cone Test</td>
<td>2</td>
</tr>
<tr>
<td>CFRM1</td>
<td>2</td>
<td>Slump Test</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test for Unit Weight and Air Content</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverted Slump Cone Test</td>
<td>2</td>
</tr>
<tr>
<td>CFRM2</td>
<td>2</td>
<td>Slump Test</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test for Unit Weight and Air Content</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverted Slump Cone Test</td>
<td>2</td>
</tr>
<tr>
<td>CFRM3</td>
<td>2</td>
<td>Slump Test</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test for Unit Weight and Air Content</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverted Slump Cone Test</td>
<td>2</td>
</tr>
<tr>
<td>CFRM4</td>
<td>2</td>
<td>Slump Test</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Test for Unit Weight and Air Content</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inverted Slump Cone Test</td>
<td>2</td>
</tr>
</tbody>
</table>
Table D2: Test Program for Various Hardened Mortar Composites.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>Type of Test</th>
<th>Type and Size of Specimen</th>
<th>Number of Specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>7-day Test</td>
</tr>
<tr>
<td>NPCM</td>
<td>Flexural</td>
<td>400L x 75W x 100H mm Beam</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Impact</td>
<td>150D x 62.5H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Absorption</td>
<td>50 mm Cube</td>
<td>3</td>
</tr>
<tr>
<td>CFRM1</td>
<td>Flexural</td>
<td>400L x 75W x 100H mm Beam</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Impact</td>
<td>150D x 62.5H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Absorption</td>
<td>50 mm Cube</td>
<td>3</td>
</tr>
<tr>
<td>CFRM2</td>
<td>Flexural</td>
<td>400L x 75W x 100H mm Beam</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Impact</td>
<td>150D x 62.5H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Absorption</td>
<td>50 mm Cube</td>
<td>3</td>
</tr>
<tr>
<td>CFRM3</td>
<td>Flexural</td>
<td>400L x 75W x 100H mm Beam</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Impact</td>
<td>150D x 62.5H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Absorption</td>
<td>50 mm Cube</td>
<td>3</td>
</tr>
<tr>
<td>CFRM4</td>
<td>Flexural</td>
<td>400L x 75W x 100H mm Beam</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Compression</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Tension</td>
<td>100D x 200H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Impact</td>
<td>150D x 62.5H mm Cylinder</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Absorption</td>
<td>50 mm Cube</td>
<td>3</td>
</tr>
</tbody>
</table>
APPENDIX E

Sample Calculation for Unit Weight and Air Content

Background Information:

Weight of empty measure = 2.5 kg  
Volume of empty measure = 7.111 x 10⁻³ m³ (by calibration)

Basic Equations:

\[ \gamma_{fm} = \frac{W_{fm}}{V_{fm}} \]  \hspace{1cm} (E-1)

\[ V_b = \frac{W_b}{\gamma_{fm}} \]  \hspace{1cm} (E-2)

\[ A_c = \frac{V_b - V_{lab}}{V_b} \times 100 \]  \hspace{1cm} (E-3)

Where,

\( A_c \) = Air content (%)  
\( V_b \) = Batch volume of fresh mortar  
\( V_{fm} \) = Volume of fresh mortar placed in cylindrical measure  
\( V_{lab} \) = Total absolute volume of component materials  
\( W_b \) = Total weight of batched materials  
\( W_{fm} \) = Weight of fresh mortar placed in cylindrical measure  
\( \gamma_{fm} \) = Unit weight of fresh mortar

Unit Weight of Freshly Mixed NPCM:

Batch 1  
Weight of fresh mortar and empty measure = 17.2 kg  
Weight of fresh mortar = (17.2 - 2.5) kg = 14.7 kg

Thus, from Equation (E-1),  
Unit weight of NPCM = (14.7)/(7.111 x 10⁻³) = 2067.22 kg/m³
Batch 2
Weight of fresh mortar and empty measure = 17.3 kg
Weight of fresh mortar = (17.25 – 2.5) kg = 14.75 kg

Thus, from Equation (E-1),
Unit weight of NPCM = (14.75)÷(7.111 x 10⁻³) = 2074.25 kg/m³

Air Content of Freshly Mixed NPCM:

Batch 1
Total weight of batched materials, \( W_b = (30.5+17.7+12.6+5.4+0.359) = 66.559 \) kg
Unit weight of fresh mortar, \( \gamma_{fm} = 2067.22 \) kg/m³

Thus, from Equation (E-2),
Volume of mortar produced in first batch, \( V_b = (66.559)÷(2067.22) = 0.032197 \) m³
Total absolute volume of the component materials in the batch, \( V_{tab} = 0.031844 \) m³

Thus, from Equation (E-3),
Air content, \( A_c = [(0.032197-0.031844)÷(0.032197)] \times 100 = 1.096% \approx 1.1% \)

Batch 2
Total weight of batched materials, \( W_b = (26.6+15.5+11+4.7+0.313) = 58.113 \) kg
Unit weight of fresh mortar, \( \gamma_{fm} = 2074.25 \) kg/m³

Thus, from Equation (E-2),
Volume of mortar produced in second batch, \( V_b = (58.113)÷(2074.25) = 0.028016 \) m³
Total absolute volume of the component materials in the batch, \( V_{tab} = 0.027803 \) m³

Thus, from Equation (E-3),
Air content, \( A_c = [(0.028016-0.027803)÷(0.028016)] \times 100 = 0.760% \approx 0.8\% \)
APPENDIX F

Sample Calculation for Inverted Slump Cone Flow

Background Information:

Volume of inverted slump cone = 0.0055 m³
Mass flow = Inverted slump cone flow with respect to mass
Volume flow = Inverted slump cone flow with respect to volume

Basic Equations:

\[
M_{fm} = \frac{V_{sc} \times \gamma_{fm}}{T_f}
\]  \hspace{1cm} (F-1)

\[
V_{fm} = \frac{V_{sc}}{T_f} \times \left(\frac{1000 \text{ l}}{m^3}\right)
\]  \hspace{1cm} (F-2)

Where,
\[M_{fm}\] = Mass flow of fresh mortar (kg/s)
\[T_f\] = Time of flow (s)
\[V_{fm}\] = Volume flow of fresh mortar (l/s)
\[V_{sc}\] = Volume of mortar poured in inverted slump cone (m³)
\[\gamma_{fm}\] = Unit weight of fresh mortar (kg/m³)

Mass Flow of Freshly Mixed NPCM:

Batch 1
Unit weight of NPCM, \[\gamma_{fm} = 2067.22\text{ kg/m}^3\]
Volume of mortar poured in inverted slump cone, \[V_{sc} = 0.0055\text{ m}^3\]
Time of flow, \[T_f = 4\text{ s}\]

Thus, from Equation (F-1),
Mass flow of freshly mixed NPCM = \[(0.0055 \times 2067.22) + 4\] = 2.843 kg/s

Batch 2
Unit weight of NPCM, \[\gamma_{fm} = 2074.25\text{ kg/m}^3\]
Volume of mortar poured in inverted slump cone, \[V_{sc} = 0.0055\text{ m}^3\]
Time of flow, \[T_f = 4\text{ s}\]

Thus, from Equation (F-1),
Mass flow of freshly mixed NPCM = \[(0.0055 \times 2074.25) + 4\] = 2.852 kg/s
Volume Flow of Freshly Mixed NPCM:

Batch 1
Volume of mortar poured in inverted slump cone $V_{sc} = 0.0055 \text{ m}^3$
Time of flow, $T_f = 4 \text{ s}$

Thus, from Equation (F-2),
Volume flow of freshly mixed NPCM $= \{(0.0055 / 4) \times 1000\} = 1.375 \text{ l/s}$

Batch 2
Volume of mortar poured in inverted slump cone $V_{sc} = 0.0055 \text{ m}^3$
Time of flow, $T_f = 4 \text{ s}$

Thus, from Equation (F-2),
Volume flow of freshly mixed NPCM $= \{(0.0055 / 4) \times 1000\} = 1.375 \text{ l/s}$
APPENDIX G

Sample Calculation for Compressive Strength

Background Information:

Diameter of cylinder specimen, \( D = 100 \text{ mm} \)
Area of the loaded face of the cylinder specimen = \((\pi 100^2 \times 0.25) = 7853.98 \text{ mm}^2\).

Basic Equation:

\[
C_s = \frac{F_i}{A_s} \times \left( 4.45 \frac{N}{lb \text{- wt}} \right)
\]  
\((G-1)\)

Where,
\( C_s \) = Compressive strength (MPa)
\( F_i \) = Failure load for the specimen tested (lb-wt)
\( A_s \) = Area of the loaded face

Compressive Strength of Hardened NPCM:

Testing age = 7 days
Failure load, \( F_i \) for specimen 1 = 62000 lb-wt
\( A_s = 7853.98 \text{ mm}^2 \)

Thus, applying Equation (G-1),
7-day compressive strength of specimen 1,
\( C_{s1} = \{(62000 \div 7853.98) \times 4.45\} = 35.13 \text{ MPa} \)
Similarly, for specimen 2, \( C_{s2} = 34.28 \text{ MPa} \) and for specimen 3, \( C_{s3} = 33.71 \text{ MPa} \)

Thus, the average compressive strength,
\( C_{sa} = \{(35.13 + 34.28 + 33.71) \div 3\} = 34.37 \text{ MPa} \)
APPENDIX H

Sample Calculation for Splitting Tensile Strength

Background Information:

Diameter of cylinder specimen, \( D = 100 \) mm
Length of the loaded cylinder specimen, \( L = 200 \) mm

Basic Equation:

\[
T_s = \frac{2F_i}{\pi DL} \times \left( 4.45 \frac{N}{lb - wt} \right)
\]  

\( (H-1) \)

Where,

\( T_s \) = Compressive strength (MPa)
\( F_i \) = Failure load for the specimen tested (lb-wt)
\( D \) = Diameter of the cylinder specimen (mm)
\( L \) = Length of the cylinder specimen (mm)

Tensile Strength of Hardened NPCM:

Testing age = 7 days
Failure load, \( F_i \) for specimen 1 = 23750 lb-wt
The diameter and the length of cylinder specimen are as mentioned above.

Thus, applying Equation \((H-1)\),
7-day tensile strength of specimen 1,
\( T_{s1} = \left\{ (2 \times 23750) + (\pi \times 100 \times 200) \right\} \times 4.45 \) = 3.36 MPa
Similarly, for specimen 2, \( T_{s2} = 3.29 \) MPa and for specimen 3, \( T_{s3} = 3.22 \) MPa

Thus, the average tensile strength,
\( T_{sa} = \{(3.36 + 3.29 + 3.22) \div 3\} = 3.29 \) MPa
APPENDIX I

Detailed Results of Flexure Test

![Graph showing Load-Deflection relationship for various mortars at 7 days of test age.]

*Figure 11: Flexural Load-Deflection Plots for 7 Days Older Mortars with Various Carbon Fiber Volume Contents.*

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>First-crack Load (N)</th>
<th>First-crack Deflection (mm)</th>
<th>Maximum Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>10545</td>
<td>0.0591</td>
<td>10545</td>
</tr>
<tr>
<td>CFRM1</td>
<td>12465</td>
<td>0.0548</td>
<td>16691</td>
</tr>
<tr>
<td>CFRM2</td>
<td>13876</td>
<td>0.0557</td>
<td>19350</td>
</tr>
<tr>
<td>CFRM3</td>
<td>14584</td>
<td>0.0624</td>
<td>21250</td>
</tr>
<tr>
<td>CFRM4</td>
<td>15586</td>
<td>0.0737</td>
<td>22478</td>
</tr>
</tbody>
</table>

*Table 11: Flexural First-crack and Maximum Loads and First-crack Deflections for Various Mortars Tested at the Age of 7 Days.*
Figure I2: Flexural Load-Deflection Plots for 28 Days Older Mortars with Various Carbon Fiber Volume Contents.

Table I2: Flexural First-crack and Maximum Loads and First-crack Deflections for Various Mortars Tested at the Age of 28 Days.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>First-crack Load (N)</th>
<th>First-crack Deflection (mm)</th>
<th>Maximum Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>14615</td>
<td>0.0664</td>
<td>14615</td>
</tr>
<tr>
<td>CFRM1</td>
<td>16450</td>
<td>0.0651</td>
<td>20111</td>
</tr>
<tr>
<td>CFRM2</td>
<td>17506</td>
<td>0.0707</td>
<td>22524</td>
</tr>
<tr>
<td>CFRM3</td>
<td>18500</td>
<td>0.0760</td>
<td>24813</td>
</tr>
<tr>
<td>CFRM4</td>
<td>20210</td>
<td>0.0766</td>
<td>26010</td>
</tr>
</tbody>
</table>
Table I3: First-crack and Ultimate Flexural Strengths and First-crack Toughness for Various Mortars Tested at the Age of 7 Days.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>First-crack Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>First-crack Toughness (N-mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>4.22</td>
<td>4.22</td>
<td>311.60</td>
</tr>
<tr>
<td>CFRM1</td>
<td>4.99</td>
<td>6.68</td>
<td>341.54</td>
</tr>
<tr>
<td>CFRM2</td>
<td>5.55</td>
<td>7.74</td>
<td>386.45</td>
</tr>
<tr>
<td>CFRM3</td>
<td>5.83</td>
<td>8.50</td>
<td>455.02</td>
</tr>
<tr>
<td>CFRM4</td>
<td>6.23</td>
<td>8.99</td>
<td>574.34</td>
</tr>
</tbody>
</table>

Table I4: First-crack and Ultimate Flexural Strengths and First-crack Toughness for Various Mortars Tested at the Age of 28 Days.

<table>
<thead>
<tr>
<th>Type of Mortar</th>
<th>First-crack Strength (MPa)</th>
<th>Flexural Strength (MPa)</th>
<th>First-crack Toughness (N-mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPCM</td>
<td>5.85</td>
<td>5.85</td>
<td>485.22</td>
</tr>
<tr>
<td>CFRM1</td>
<td>6.58</td>
<td>8.04</td>
<td>535.45</td>
</tr>
<tr>
<td>CFRM2</td>
<td>7.00</td>
<td>9.01</td>
<td>618.84</td>
</tr>
<tr>
<td>CFRM3</td>
<td>7.40</td>
<td>9.93</td>
<td>703.00</td>
</tr>
<tr>
<td>CFRM4</td>
<td>8.08</td>
<td>10.41</td>
<td>774.04</td>
</tr>
</tbody>
</table>
APPENDIX J

Sample Calculation for First-crack and Ultimate Flexural Strengths and First-crack Toughness

Background Information:

Length of specimen, \( L = 400 \text{ mm} \)
Width of specimen, \( W = 75 \text{ mm} \)
Height of specimen, \( H = 100 \text{ mm} \)

Basic Equations:

\[
FC_S = \frac{R_{FC} \times l}{bd^2} \quad (J-1)
\]

\[
F_S = \frac{R \times l}{bd^2} \quad (J-2)
\]

\[
T_{FC} = \frac{R_{FC} \times \Delta_{FC}}{2} \quad (J-3)
\]

Where,
\( b = W = 75 \text{ mm} \)
\( d = H = 100 \text{ mm} \)
\( l = \) Load span = 300 mm
\( R = \) Maximum load (N)
\( F_S = \) Ultimate flexural strength (MPa)
\( FC_S = \) First-crack flexural strength (MPa)
\( T_{FC} = \) First-crack toughness (N-mm)
\( R_{FC} = \) First-crack load (N)
\( \Delta_{FC} = \) First-crack deflection (mm)
First-crack Flexural Strength of NPCM:

Testing age = 7 days
First-crack load, \( R_{FC} = 10545 \text{ N} \)

Thus, from Equation (J-1), first-crack flexural strength,
\[
F_{CS} = \frac{10545 \times 300}{75(100)^2} = 4.22 \text{ MPa}
\]

Ultimate Flexural Strength of NPCM:

Testing age = 7 days
Maximum load, \( R = 10545 \text{ N} \)

Thus, from Equation (J-2), ultimate flexural strength,
\[
F_s = \frac{10545 \times 300}{75(100)^2} = 4.22 \text{ MPa}
\]

First-crack Toughness of NPCM:

Testing age = 7 days
First-crack load, \( R_{FC} = 10545 \text{ N} \)
First-crack deflection, \( \Delta_{FC} = 0.0591 \text{ mm} \)

Thus, from Equation (J-3), first-crack toughness,
\[
T_{FC} = \frac{10545 \times 0.0591}{2} = 311.60 \text{ N-mm}
\]
APPENDIX K

Sample Calculation for First-crack and Ultimate Impact Resistances

Background Information:

Mass of dropping hammer, $M = 4.5$ kg (10 lb)
Drop height, $H = 457$ mm $= 0.457$ m (18 in.)
Acceleration due to gravity, $g = 9.81$ m/s$^2$

Basic Equation:

$$I_r = MgHN$$  \hspace{3cm} (K-1)

Where,
$I_r$ = Impact resistance (N-m or J)
$N$ = Number of blows required for fracture
$M$ = Mass of dropping hammer (kg)
$g$ = Acceleration due to gravity (m/s$^2$)
$H$ = Drop height (m)

First-crack Impact Resistance of NPCM:

Testing age = 7 days
The mass of dropping hammer ($M$), the drop height ($H$) and the acceleration due to gravity ($g$) are as mentioned above.
For specimen 1, $N = 1$

Thus, from Equation (K-1), $I_{r1} = 20.174$ J
Similarly, for specimen 2, $I_{r2} = 20.174$ J, and for specimen 3, $I_{r3} = 20.174$ J
Therefore, the average first-crack impact resistance,
$I_{fra} = \{ (20.174+20.174+20.174)+3 \} J = 20.174$ J
Ultimate Impact Resistance of NPCM:

Testing age = 7 days
The mass of dropping hammer (M), the drop height (H) and the acceleration due to gravity (g) are same as before.
For specimen 1, N = 2

Thus, from Equation (K-1), \( I_{11} = 40.348 \) J
Similarly, for specimen 2, \( I_{12} = 60.522 \) J, and for specimen 3, \( I_{13} = 40.348 \) J
Therefore, the average ultimate impact resistance,
\( I_{ura} = \{ (40.348 + 60.522 + 40.348) / 3 \} \) J = 47.073 J
APPENDIX L

Sample Calculation for Water Absorption

Background Information:

Oven temperature for drying the specimens = 100° C to 110° C
Water temperature = 23 ± 1.7° C
Immersion period = 48 h

Basic Equation:

\[ W_a = \frac{B - A}{A} \times 100 \]  \hspace{1cm} (L-1)

Where,
\( W_a \) = Water absorption (mass %)
\( A \) = Mass of the dried specimen
\( B \) = Mass of the specimen after immersion in cool water for 48 h

Water Absorption for NPCM:

Testing age = 7 days
For specimen 1, \( B = 290.15 \) g, and \( A = 253.30 \) g
So, from Equation (L-1), \( W_{a1} = \frac{\{(290.15 - 253.30) \times 100\}}{253.30} \approx 14.55\% \)
Similarly for specimen 2, \( W_{a2} = 14.42\% \), and for specimen 3, \( W_{a3} = 14.34\% \)
Therefore, the average water absorption,
\( W_{aa} = \frac{(14.55\% + 14.42\% + 14.34\%) + 3}{3} = 14.44\% \)
APPENDIX M

Evaluation of Performance to Cost Ratios

Cost of Component Materials:

Cost of river sand = CAD$ 16.30/ton ≈ CAD$ 0.02/kg
Cost of Lafarge Type 10 normal portland cement = CAD$ 10.4/sack = CAD$ 0.26/kg
Cost of Rheomac® SF 100 silica fume = CAD$ 0.70/kg
Cost of tap water = CAD$ 0.62/m³ = CAD$ 0.00062/kg
Cost of Rheobuild® 1000 superplasticizer = CAD$ 2.50/l = CAD$ 0.0025/ml
Cost of Dialead K6611T pitch-based carbon fibers = CAD $60.17/kg

Basic Equation:

\[
PCR = \left( \frac{V_{fm}}{V_{fc}} + \frac{C_{sm}}{C_{sc}} \times \frac{F_{sm}}{F_{sc}} \times \frac{I_{rm}}{I_{rc}} \times \frac{W_{ac}}{W_{am}} \right) \times 100
\]  

(M-1)

Where,

\( PCR \) = Performance to cost ratio
\( C_m \) = Cost of 1 m³ of any mortar
\( C_c \) = Cost of 1 m³ of control mortar (NPCM)
\( V_{fm} \) = Volume flow factor of any mortar
\( V_{fc} \) = Volume flow factor of control mortar
\( C_{sm} \) = 28 days compressive strength of any mortar
\( C_{sc} \) = 28 days compressive strength of control mortar
\( F_{sm} \) = 28 days ultimate flexural strength of any mortar
\( F_{sc} \) = 28 days ultimate flexural strength of control mortar
\( I_{rm} \) = 28 days ultimate impact resistance of any mortar
\( I_{rc} \) = 28 days ultimate impact resistance of control mortar
\( W_{am} \) = 28 days water absorption of any mortar
\( W_{ac} \) = 28 days water absorption of control mortar
Performance to Cost Ratio of Control Mortar NPCM:

Cost of 1 m³ of mortar,
\[
C_m = 955.9 \times 0.26 + 168.7 \times 0.70 + 556.2 \times 0.02 + 394.1 \times 0.00062 + 9372 \times 0.0025 \\
\approx \text{CAD } 401.42
\]
\[C_c = C_m = \text{CAD } 401.42\]

\[
V_{fm} = 1.375 \text{ l/s} \\
V_{fc} = V_{fm} = 1.375 \text{ l/s}
\]

\[
C_{sm} = 39.05 \text{ MPa} \\
C_{sc} = C_{sm} = 39.05 \text{ MPa}
\]

\[
F_{sm} = 5.66 \text{ MPa} \\
F_{sc} = F_{sm} = 5.66 \text{ MPa}
\]

\[
I_{rm} = 94.145 \text{ J} \\
I_{rc} = I_{rm} = 94.145 \text{ J}
\]

\[
W_{am} = 13.80 \% \\
W_{ac} = W_{am} = 13.80 \%
\]

Now, from Equation (M-1),

\[
PCR = \frac{1.375 + \left( \frac{39.05 \times 5.85 \times 94.145 \times 13.8}{401.42} \right)}{401.42 \times 100} = 200
\]
Performance to Cost Ratio of CFRM 1:

Cost of 1 m³ of mortar,
\[ C_m = 917.2 \times 0.26 + 161.9 \times 0.70 + 533.7 \times 0.02 + 372.8 \times 0.00062 + 17985 \times 0.0025 \]
\[ + 18.5 \times 60.17 \approx CAD \$1520.82 \]
\[ C_c = CAD \$401.42 \]

\[ V_{fm} = 1.009 \text{ l/s} \]
\[ V_{fc} = 1.375 \text{ l/s} \]

\[ C_{sm} = 49.77 \text{ MPa} \]
\[ C_{sc} = 39.05 \text{ MPa} \]

\[ F_{sm} = 7.91 \text{ MPa} \]
\[ F_{sc} = 5.66 \text{ MPa} \]

\[ I_{rm} = 645.568 \text{ J} \]
\[ I_{rc} = 94.145 \text{ J} \]

\[ W_{am} = 13.47 \% \]
\[ W_{ac} = 13.80 \% \]

Now, from Equation (M-1),

\[
PCR = \frac{1.009 + \left( \frac{49.77}{39.05} \times \frac{8.04}{5.85} \times \frac{645.568}{94.145} \times \frac{13.80}{13.47} \right)}{1520.82} \times 100 \approx 344
\]
Performance to Cost Ratio of CFRM2:

Cost of 1 m³ of mortar,
\[ C_m = 898.0 \times 0.26 + 158.5 \times 0.70 + 522.4 \times 0.02 + 359.8 \times 0.00062 + 26410 \times 0.0025 + 37.0 \times 60.17 \approx \text{CAD } 2647.42 \]
\[ C_c = \text{CAD } 401.42 \]

\[ V_{fm} = 0.786 \text{ l/s} \]
\[ V_{fc} = 1.375 \text{ l/s} \]

\[ C_{sm} = 56.75 \text{ MPa} \]
\[ C_{sc} = 39.05 \text{ MPa} \]

\[ F_{sm} = 8.47 \text{ MPa} \]
\[ F_{sc} = 5.66 \text{ MPa} \]

\[ I_{rm} = 961.627 \text{ J} \]
\[ I_{rc} = 94.145 \text{ J} \]

\[ W_{am} = 12.68 \% \]
\[ W_{ac} = 13.80 \% \]

Now, from Equation (M-1),

\[
PCR = \frac{0.786 + \left( \frac{56.75 \times 9.01 \times 961.627 \times 13.80}{39.05 \times 5.85 \times 94.145 \times 12.68} \right)}{2647.42 \times 100} \approx 386
\]

\[
= \frac{401.42}{401.42}
\]
Performance to Cost Ratio of CFRM3:

Cost of 1 m$^3$ of mortar,

\[ C_m = 878.6 \times 0.26 + 155.1 \times 0.70 + 511.3 \times 0.02 + 346.7 \times 0.00062 + 34457 \times 0.0025 \\
+ 55.5 \times 60.17 \approx \text{CAD} \$3773.03 \]

\[ C_c = \text{CAD} \$401.42 \]

\[ V_{fm} = 0.650 \text{ l/s} \]
\[ V_{fc} = 1.375 \text{ l/s} \]

\[ C_{sm} = 62.99 \text{ MPa} \]
\[ C_{sc} = 39.05 \text{ MPa} \]

\[ F_{sm} = 9.70 \text{ MPa} \]
\[ F_{sc} = 5.66 \text{ MPa} \]

\[ I_{rm} = 1378.557 \text{ J} \]
\[ I_{rc} = 94.145 \text{ J} \]

\[ W_{am} = 11.23 \% \]
\[ W_{ac} = 13.80 \% \]

Now, from Equation (M-1),

\[
PCR = \frac{0.650}{1.375} + \frac{(62.99 \times 9.93 \times 1378.557 \times 13.80)}{(39.05 \times 5.85 \times 94.145 \times 11.23)} \times 100 \approx 529
\]

\[
\frac{3773.03}{401.42}
\]
Performance to Cost Ratio of CFRM4:

Cost of 1 m³ of mortar,
\[ C_m = 859.4 \times 0.26 + 151.7 \times 0.70 + 500 \times 0.02 + 334.1 \times 0.00062 + 42125 \times 0.0025 \\
+ 74.0 \times 60.17 \approx CAD \$4897.73 \]
\[ C_c = CAD \$401.42 \]

\[ V_{fm} = 0.346 \text{ l/s} \]
\[ V_{fc} = 1.375 \text{ l/s} \]

\[ C_{sm} = 47.72 \text{ MPa} \]
\[ C_{sc} = 39.05 \text{ MPa} \]

\[ F_{sm} = 9.84 \text{ MPa} \]
\[ F_{sc} = 5.66 \text{ MPa} \]

\[ I_{rm} = 2810.911 \text{ J} \]
\[ I_{rc} = 94.145 \text{ J} \]

\[ W_{am} = 15.56 \% \]
\[ W_{ac} = 13.80 \% \]

Now, from Equation (M-1),

\[
PCR = \frac{0.346 + \left( \frac{47.72 \times 10.41 \times 2810.911 \times 13.80}{39.05 \times 5.85 \times 94.145 \times 15.56} \right) \times 100}{4897.73} \approx 474
\]
\[
401.42
\]
NAME: Md. Saﬁuddin

PLACE OF BIRTH: Dhaka, Bangladesh

YEAR OF BIRTH: 1969

EDUCATION:
Sher-e-Bangla Nagor Govt. Boys High School
Dhaka, Bangladesh
Secondary School Certificate, 1984

Dhaka College
Dhaka, Bangladesh
Higher Secondary Certificate, 1986

Bangladesh University of Engineering and Technology
Dhaka, Bangladesh
Bachelor of Science in Civil Engineering, 1995

The National University of Malaysia
Selangor Darul Ehsan, Malaysia
Master of Science in Civil and Structural Engineering, 1998