Application of Alkaline-resistant Glass Fiber in Road Concrete: Corrosivity and Applicability

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ABSTRACT: The main technical requirements of road concrete are high flexural strength and fatigue durability because shear failure is the major failure mode for road concrete. Adding glass fiber into concrete could greatly increase flexural strength and wearing resistance of concrete. However, glass fiber has the great potential of corrosion in the alkaline environment formed during the cement hydration, which will directly affect the long-term performance and strength stability. Systematic researches have been launched on the corrosion mechanism, surface treatment and anti-corrosion methods of fiber, however, few works have been made in the application and design method of alkaline-resistant glass fiber in road concrete. In this paper, the corrosion mechanism and property of alkaline-resistant glass fiber in cement paste were analyzed firstly, and the corrosion inhibition of active admixture on alkaline-resistant glass fiber was discussed. The practicability and applicability of alkaline-resistant glass fiber in road concrete were illustrated though the discussion of changing trend of flexural strength of cement paste mixed with different proportion of fly ash based on the experimental results, and the appropriate amount of activated additive of fly ash was also confirmed. The results suggested a prosperous application prospect for the application of alkaline-resistant glass fiber concrete with fly ash in road projects.

INTRODUCTION

Existing researches indicated that glass fiber, with the advantages of high tensile, high elastic modulus, no combustion and low cost, can significantly improve the deformability, toughness and impact resistance of cement-based materials mixed into the cement-based materials by chopped way. Because the major failure mode of road concrete is shear failure, the main technical requirements of road concrete are high flexural strength and fatigue durability. Fibers mixed into concrete could block the expansion of micro cracks and delay the development of new cracks in the matrix, and greatly increase flexural strength and wearing resistance of concrete. Therefore adding glass fiber into concrete could well resolve the above problems and improve pavement service performance. As a new kind of artificial inorganic material, glass fiber has the advantages of wide raw material sources, convenient mass production as well as low weight, heat and sound insulation. Therefore, replacing steel fiber, glass fiber has showed a prefect application future as the concrete admixture.

For the glass fiber composite cement matrix, the alkaline-resistant glass fiber has the great potential of corrosion in the alkaline environment formed in the cement hydration process, which will directly affect the long-term performance and strength stability of the
composites. Systematic researches have been launched on the corrosion mechanism, surface treatment and anti-corrosion methods of fiber, however, few works have been made in the application and design method of alkaline-resistant glass fiber in road concrete. In this paper, the corrosion mechanism and method of alkaline-resistant glass fiber in cement paste were analyzed first, and the practicability and applicability of alkaline-resistant glass fiber in road concrete were illustrated though the discussion of the change of flexural strength. The appropriate amount of activated additive of fly ash were confirmed by experiment to inhibit the corrosion of alkaline-resistant glass fiber in cement hydration paste, which could make road concrete have high and green performance.

MATERIALS

The materials used in the experiment in this paper were as follows:
Alkaline-resistant glass fiber: Alkaline-resistant glass fiber with the length of 12mm, density of 2.70g/cm³, tensile strength 2480MPa, elastic modulus of 80.0GPa, breaking elongation of 3.6% and the ZrO₂content of 16.7%, produced in Beijing Saint Gobain Vetrotex Company.
Fly ash: Fly ash of II levels, produced in Harbin Power Plant, in line with the provisions of GB1596-2006.
Water reducing agent: FDN highly active water reducing agent.

Considering the sands used in concrete with good gradation have high density and small specific surface area to ensure the fresh concrete high workability and the hardened concrete certain strength and durability, so this experiment adopted the river sands with the rain size between 0.16mm~5mm.

EXPERIMENTAL METHODS

In order to solve the corrosion problem of alkaline-resistant glass fiber in the concrete, we start with a simple corrosion of alkaline-resistant glass fiber in cement paste to predict the corrosion by changes of flexural strength. It was supposed that alkaline-resistant glass fiber was dispersed in cement paste evenly by proper mixing method, which could reflect the real distribution and corrosion of the glass fiber in concrete road pavement, and also eliminates the possibility that glass fiber was etched because of the directional arrange of Ca(OH)₂ crystals in glass fiber bundle which results in the loss of its improvement in cement concrete.

Accelerated corrosion experiment of the alkaline-resistant glass fiber cement paste specimens was made through 80°C hot water accelerating curing, and the useful life was concluded in terms of Arrhenius equation of the effect of temperature on cement paste strength. Then the corrosion of alkaline-resistant glass fiber in cement hydration environment was studied based on the change of macro mechanical properties.

\[
K_T = A \cdot \exp \left( \frac{-E_a}{R \cdot T} \right)
\]

(1)
$K_T$—Strength development speed rate constant when curing temperature is $T$ (d$^{-1}$)

$A$—Constant (d$^{-1}$), $E_a$—Activation energy (J/mol),

$R$—Gas constant (8.314J/K·mol), $T$—Kelvin Temperature (T)

At the same time of glass fiber cement paste specimens making, equal amount of cement paste specimens without glass fiber were made to reduce the influence in the experimental results of alkaline-resistant glass fiber reinforced cement paste by the strength change of cement itself. In the experimental results, the net flexural load was calculated by flexural strength of specimens with glass fibers minus that of specimens without glass fiber. The net flexural load in every age was supposed equal if glass fiber was not corroded, otherwise, the net creased flexural load dropped. The more severely glass fiber was corroded, the greatly the net flexural load dropped, even becoming negative. Therefore, the corrosion of glass fiber can be estimated in terms of the retention rate of net flexural load in every age and the stability of strength in later age. It is also proved that active fly ash was effective to inhabit the corrosion of glass fiber and add fly ash to cement can reduce the heat of hydration, permeability and porosity, which are important to durability of cement.

RESULTS AND DISCUSSIONS

The Mechanical Property of Alkaline-resistant Glass Fiber in 32.5 Cement Paste

Weighed 1350g sands (grain size between 0.16mm~5mm), 540g 32.5 cement, 20g alkaline-resistant glass fiber, 238ml water, 8g highly active water reducing agent. The standard of shaping and curing of the specimens without glass fiber were the same with that with glass fiber except not adding highly active water reducing agent. The experimental results were as follows:

As Figure 1 shown: The flexural strength of specimens with alkaline-resistant glass fiber reached the maximum when heated to the first day, and dropped down to the minimum when heated to the third day, then the strength continue raised; While the strength of specimens without glass fiber raised up gradually and fallen down in the end. It can be seen in Figure 2, net flexural load raised to the maximum in the first day and fallen gradually down then hold the line from the third day on, which illustrated that alkaline-resistant glass fiber began to suffer corrosion from the first day and finished on the third day. The growing of strength in later age depended on the further hydration of cement paste and final flexural strength of specimens with glass fiber was still higher than that without glass fiber though glass fiber suffered corrosion. That because the concentration of Zr$^{4+}$ attaching the surface of glass fiber correspondingly became high after the reaction of alkaline-resistant glass fiber with cement. The bond of Zr-O which had been suffered the corrosion of OH$^-$ generated the colloid substance of Zr(OH) and formed a tight layer on glass fiber surface which inhabited the corrosion of alkaline to glass fiber. That suggested that the alkaline-resistant glass fiber developed the ability of immune form alkaline environment of cement paste, which proved the applicability of the application of alkaline-resistant glass fiber with uniform distribution in road concrete.
Table 1. Flexural strength of cement paste.

<table>
<thead>
<tr>
<th>Experimental specimens</th>
<th>Hot curing age (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Without glass fiber (MPa)</td>
<td>7.30</td>
</tr>
<tr>
<td>With glass fiber (MPa)</td>
<td>10.36</td>
</tr>
<tr>
<td>Net flexural strength (MPa)</td>
<td>3.06</td>
</tr>
</tbody>
</table>

Figure 1. Relationship of curing age with flexural strength

The strength of specimens without glass fiber began to come down when heated to the eighth day because temperature was the key dynamic factor affecting in cement hydration. Aft in cement paste was destroyed under the curing temperature of 70°C ~ 100°C. The increasing of curing temperature also changed lime-silicate ratio of hydrous product C-S-H. The amount of bond water of C₃S hydrous product reduced from 35% to 25% when hydrous temperature raised from 25°C to 95°C. The reason of the amount reduction of bond water under high temperature was the loss of interlaminar water in hydrous product C-S-H lessens and ettringite changed into other products to cause strength to drop down. Generally, to improve hydrous temperature could fasten cement hydration and the hydrous degree and strength in later age would reduce, so the reduction of the flexural strength in later age of the experiment was due to high temperature curing.

It was obvious that the strength of concrete with alkaline-resistant glass fiber fallen down inevitably and lost the flexible function from fiber when adding alkaline-resistant glass fiber into concrete directly without any treating. So how to resolve the problems of the strength reduction of glass fiber concrete became the main concern.

Changing Trend of Flexural Strength of Cement Paste Mixed with Different Proportion of Fly Ash

Weighed 1350g sands (grain size between 0.16mm~5mm), 540g 32.5 cement, 20g alkaline-resisant glass fiber, 238ml water, 8g highly active water reducing agent. Cement paste specimen mixed with 30% fly ash needed and cement paste specimen mixed with 40% fly ash needed 378g cement and 162g fly ash.

The standard of shaping and curing of the specimens without glass fiber were the same with that with glass fiber except not adding highly active water reducing agent. The experimental results were as follows:
Table 2. Flexural strength of cement paste with different amount of fly ash.

<table>
<thead>
<tr>
<th>Curing age (days)</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>11</th>
</tr>
</thead>
<tbody>
<tr>
<td>With 30% fly ash</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without glass fiber (MPa)</td>
<td>7.30</td>
<td>7.72</td>
<td>7.83</td>
<td>8.27</td>
</tr>
<tr>
<td>With glass fiber (MPa)</td>
<td>9.47</td>
<td>8.54</td>
<td>8.75</td>
<td>9.26</td>
</tr>
<tr>
<td>Net flexural strength (MPa)</td>
<td>2.17</td>
<td>0.82</td>
<td>0.92</td>
<td>0.99</td>
</tr>
<tr>
<td>With 40% fly ash</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Without glass fiber (MPa)</td>
<td>6.57</td>
<td>7.36</td>
<td>7.69</td>
<td>7.84</td>
</tr>
<tr>
<td>With glass fiber (MPa)</td>
<td>8.52</td>
<td>8.77</td>
<td>9.07</td>
<td>9.19</td>
</tr>
<tr>
<td>Net flexural strength (MPa)</td>
<td>1.95</td>
<td>1.41</td>
<td>1.38</td>
<td>1.35</td>
</tr>
</tbody>
</table>

Figure 3. Relationship of curing age with flexural strength with 30% fly ash

Figure 4. Relationship of curing age with net flexural strength.

As Figure 3 showed: The flexural strength of glass fiber specimens with 30% fly ash reached the maximum in the first day, and fallen down gradually then began to raise up from the third day and got to the top on the eleventh day. It could be seen in Figure 4 that alkaline-resistant glass fiber began to suffer corrosion from the first day, and finished that on the third day then basically stayed the same. Based on one day’s curing in 80℃ hot water equaling to 4.6 years’ curing in British atmosphere, the durability of alkaline-resistant glass fiber had met the demands of road concrete service life no matter how to change the strength of alkaline-resistant glass fiber.

It could be seen in Figure 5 that flexural strength of glass fiber specimens with 40% fly ash went up persistently with the hydration of cement and fly ash and kept the tendency till the eleventh day. That because the closer contact between interfaces of glass fiber and cement stones made the toughening action of glass fiber play further. In Figure 6 glass fiber began to be corroded from the first day but the corrosion slowed down in the later age. The reason was that large amounts of fly ash reacted with hydrous product Ca(OH)₂ in cement which resulted in low content of calcium in the solution and protect the corrosion.
A trend could be drawn from the net flexural strength change of cement paste with 30% and 40% fly ash: In the early age of accelerated corrosion, glass fiber was corroded quickly and kept the line for some certain period then went down afterwards. The reason of that was as follow: Large amounts of hydrous products created in cement hydration and Ca(OH)$_2$ accumulated around glass fiber formed a high PH value liquid zone and reacted with glass fiber. The glass fabric of fly ash was broken and hydrolyzed in the alkali solution with the age growing. With the depolymerization of glass fabric, low molecular weight polymers like silicates and aluminates went into pore solution and created hydrous products like C-S-H CAH and CASH, which consumed Ca(OH)$_2$ and reduced the alkalinity around glass fiber. In addition, hydrous products of deposited around glass fiber slowly with the hydration of cement and fly ash, which slimed the chances of contact between alkali solution and glass fiber and reduced the corrosion of glass fiber greatly.

In conclusion, to add active admixture could inhibit the corrosion of cement hydrous paste to alkaline-resistant glass fiber effectively and improve the flexural strength. The durability of alkaline-resistant glass fiber had met the demands of design year for road concrete when the amount of fly ash reached 30%, and flexural strength of specimens with 30% fly ash dropped to the minimum on the third day then went up afterwards. While flexural strength of specimens with 40% fly ash raised up all the time though glass fiber also suffered corrosion, which indicated that large amounts of fly ash consumed most of CH and reduced the alkalinity of cement base body to improve the density of base body and increase the binding power of interfaces. Accordingly, to add fly ash to road concrete could not only keep the increasing tendency of flexural strength but also reduce the corrosion of cement hydrous paste to glass fiber greatly which contributed a lot to the durability of road concrete.

The Optimum Amount of Alkaline-resistant Glass Fiber

The amount of alkaline-resistant glass fiber could affect not only flexural and compressive strength of concrete but also fragility, wearing resistance and freeze-thaw durability. Six groups of specimens of 100×100×100 mm were made and the mixture ratio of all the components except glass fiber was kept the same. That was: added different amounts of glass fiber to every group and tested the compressive strength of 3 days and 7 days under the same condition, then made a comparison to determine the optimum amount. The amount of glass fiber was chosen from 0.8 g/L to 1.2 g/L in the experiment in terms of the references of some researches. The testing results were as follows:
### Table 3. Flexural strength of concrete with different amount of glass fiber.

<table>
<thead>
<tr>
<th>Glass fiber ratio (Kg/m$^3$)</th>
<th>0.9</th>
<th>0.95</th>
<th>1.00</th>
<th>1.05</th>
<th>1.10</th>
<th>1.20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strength of 3 days (MPa)</strong></td>
<td>22.1</td>
<td>24.0</td>
<td>24.7</td>
<td>23.6</td>
<td>22.6</td>
<td>22.1</td>
</tr>
<tr>
<td><strong>Strength of 7 days (MPa)</strong></td>
<td>36.7</td>
<td>37.6</td>
<td>38.0</td>
<td>36.3</td>
<td>35.6</td>
<td>34.3</td>
</tr>
</tbody>
</table>

![Figure 7](image.png)

**Figure 7. Relationship of the mount of glass fiber with compression strength.**

As showed in Figure 7, compressive strength of concrete went up gradually with more adding of alkaline-resistant glass fiber. Compressive strength reached maximum when the amount of glass fiber was 1.0 kg/m$^3$, then began to go down gradually with the adding of alkaline-resistant glass fiber. The reasons of this were concluded as follows: Firstly, the more glass fiber were added, the greater the service behavior of concrete reduced and the more difficult mixing became, which caused more harmful air gaps to reduce the strength. Secondly, the more alkaline-resistant glass fiber were added, the severer glass fiber clustered, which increased the weak points of specimens and could not ensure the uniformity of mixing. Thirdly, the tensile strength that was created when specimen suffered pressure could form stress concentration easily on the top of tiny cracks with wedge shape, and with the increasing of tensile strength, the tiny cracks would stretch, merge, develop and became visible cracks in the end which destroyed the specimens. Alkaline-resistant glass fiber paralleling with the direction of inner tensile force in the specimens formed natural gaps instead. The more glass fiber was added, the more the gaps formed, which resulted in the reduction of compressive strength. Therefore, to ensure the compressive strength, the amount of alkaline-resistant glass fiber wouldn’t be excessive. The optimum amount of alkaline-resistant glass fiber is 1.0 kg/m$^3$.

### CONCLUSION

(1) When alkaline-resistant glass fiber was added to cement paste under the condition of accelerated corrosion, alkaline-resistant glass fiber began to be corroded by cement paste on the first day and finished on the third day. The increasing of strength of specimens with glass fiber in later age depended on the further hydration of cement paste and kept higher than that without glass fiber, though alkaline-resistant glass fiber was corroded by cement paste quickly. (2) Active admixture fly ash could inhibit the corrosion of cement hydrous paste to alkaline-resistant glass fiber effectively and improve the flexural strength. Flexural strength of specimens with 30% fly ash dropped down in early age then went up in later age. While flexural strength of specimens with
40% fly ash raised up all the time though glass fiber also suffered corrosion (3) The optimum amount of alkaline-resistant glass fiber is 1.0 kg/m³. The durability of glass fiber concrete with 30%~40% fly ash could meet the demands of road projects. (4) The growth rate of strength improved a great deal for the specimens with active admixture compared that without admixture. And their growth rate of tensile strength was higher than that of compressive strength, which met the durability demand of road concrete. (5) The wearing resistance and freeze-thaw durability of concrete improved greatly and dry shrinkage reduced after mixing with fly ash. There was a prosperous application prospect for alkaline-resistant glass fiber concrete with fly ash in road projects.

REFERENCES


