Research on the Bond Anchorage Properties of Alkali-Activated Slag Cementitious Material

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Abstract. By bond-anchorage property tests at 20°C ~500°C, the distribution of shear stress between carbon fiber sheets and concrete at all levels of loading and anchorage lengths were measured, which means the bond lengths during CFRP sheets are pulled off at the same time when the concrete is torn and stripped were gotten. The failure modes were obtained. In addition, the failure loads were measured, and the calculated formulas of anchorage lengths were identified by fitting at high temperature. It can be seen that the anchorage lengths of carbon fiber sheets increase with increasing temperature at 20°C ~100°C, the anchorage lengths of carbon fiber sheets decrease with increasing temperature at 100°C ~500°C. Tests prove that AASCM has favorable high-temperature resistant and bond anchorage properties.

1. Introduction
With the rapid development of China's steel industry, slag has become a huge industrial by-product. It is known that China produces about 240 million tonnes of slag per year[1-3], which accounts for 50 per cent of global production. Alkali-activated slag cementitious material (AASCM) is based on industrial by-products - slag as raw material, with sodium silicate, NaOH as the main alkaline activators, with or without a certain cold heat history of aluminate natural minerals containing silicon or industrial waste residue (e.g. metakaolin, phosphorus slag, steel slag, coal gangue, fly ash, red mud, etc) and alkaline activators (such as alkali metal hydroxide, alkali metal carbonate, alkali metal sulfate, etc). Thus, AASCM is obtained by chemical reactions[4-6]. It is known that the compressive strength of AASCM is not less than 50 MPa. On the other hand, organic epoxy matrices are commercially available and have been extensively used to the FRP reinforcing technique. Nevertheless, the major disadvantages of organic matrices are their lack of heat and fire resistance, low glass transition temperature Tg (60°C to 82°C), susceptibility to UV radiation, and impossibility of application on humid surfaces. On the contrary, the compressive strength of AASCM after 600 °C is not reduced, which means AASCM has excellent high-temperature resistant[7-10], Although Taljsten studies and defines anchor lengths of steel and CFRP plates bonded to concrete with epoxy[11], the bond anchorage properties of the inorganic adhesives still have been published very few, and the guide specifications and standards on the bond anchorage properties of AASCM are rarely seen at home and abroad. Moreover, the lack of detailed and reliable technical indicators greatly hinders its popularization and application. Therefore, this essay studies on the bond anchorage properties of
AASCM at room temperature, at high temperature, and after high temperature. The failure modes and failure loads were obtained. In addition, this essay can be used as the main basis for determining the parameters of various engineering designs.

2. Materials and formulation

2.1. Raw materials and mix proportion
S95 slag (Quality grade is S95, which means specific surface area of slag is 400m²/kg) is proposed by mass fraction of 36.9% SiO₂, mass fraction of 15.66% Al₂O₃, mass fraction of 37.57% CaO, mass fraction of 9.3% MgO, mass fraction of 0.36% Fe₂O₃. The activity indexes of slag (Which means the compressive strength ratio of the test samples and comparison samples of the same age (%) are mainly: the quality coefficient 1.69, the alkaline coefficient 0.97, and the activity coefficient 0.42. The main parameters of potassium silicate solution are shown in Table 1. The mass fraction of sodium hydroxide is not less than 96.0%.

| Table 1. Parameters of potassium silicate solution |
|---------------------------------|--------|--------|--------|
| Baume degree | Density | Modulus | mass fraction, % |
|                |        |        | K₂O | SiO₂ |
| 46.3           | 1.465  | 2.76   | 15.98 | 28.15 |

Test uses one relatively optimal matching ratio W42 of AASCM, and main parameters are shown in Table 2.

| Table 2. The proportion parameters used for test |
|-----------------------------------------------|--------|--------|--------|--------|--------|
| Matching ratio | Slag | Modulus of potassium silicate | Potassium silicate amount, % | Sodium hydroxide, % | Water amount % |
| W42            | 1    | 1.0    | 12    | 5.35   | 42     |

2.2. CFRP sheets and concrete
Two commercially available types of CFRP sheets (UT70-20 and UT70-30, Toray, Japan) and C30 concrete with a water/binder ratio 0.40 were used for bond tests. The tensile strengths of CFRP sheets were determined according to JG/T 167-2004 on the basis of the nominal thicknesses. The nominal thicknesses were also used to all other calculations of the present study. The CFRP sheet (UT70-30) has tensile strength of 4125 MPa, an ultimate tensile strain of 1.71%, and a modulus of elasticity of 244 GPa. The nominal thickness of UT70-30 is 0.167 mm and fiber weight is 300 g/m². On the other hand, the CFRP sheet (UT70-20) has tensile strength of 4114 MPa, nominal thickness of 0.111 mm and fiber weight of 200 g/m².

3. The bond anchorage properties of AASCM

3.1. The bond anchorage properties of AASCM at room temperature
In order to achieve CFRP sheets and concrete working together, the CFRP-adhesive-concrete interfaces bonding strengths should be satisfactory; For the CFRP sheets giving full play to their strengthening effects, the interface of adhesive should have sufficient bond anchorage strength to transfer shear stress. If the anchorage length of CFRP sheets is insufficient, there is comparatively large stress concentration at the CFRP end, which will lead to debonding of the CFRP strip from the concrete, so CFRP sheets are difficult to give full play to their strengthening effects; By contrast, if the
The anchorage length of CFRP sheets is too long, the unnecessary materials will be wasted. Therefore, identifying appropriate anchorage lengths are very important to practical engineering.

The two types of anchorage failure modes summarized from twenty specimens were:

- **Anchorage failure (AF).** Sixteen specimens were failed by peeling of the concrete cover adjacent to the CFRP sheets. The failure process started with visible concrete cracks near the loading end of the concrete prism along the longitudinal axis of the CFRP sheets. As the load increased, visible cracking in the concrete initiated interfacial debonding of the CFRP strip from the loading end, and the majority of debonding occurred at the middle part of the test specimen along its longitudinal axis; A thin layer of concrete was peeled off and attached to the CFRP strip accompanied by a loud popping sound. When the anchorage length was insufficient, the anchorage failure would happen as shown in Figure 1(a).

- **Tensile failure of CFRP sheets (TF).** Four specimens were failed by CFRP rupture. When the applied load \( P \) increased to about 80% of the ultimate load \( P_u \), a crisp sound was heard due to some extent of debonding in concrete adjacent to the adhesive-concrete surface, which indicated that the CFRP sheets were pulled uniformly; Then a sharp crackling sound might be heard due to CFRP rupture. The fracture surface of the CFRP sheets generally presented zigzag shapes, and the location of the fracture surface was in the non-anchorage zone of CFRP sheets. When the anchorage length was sufficient, the tensile failure of the CFRP sheets would happen as shown in Figure 1(b).

![Figure 1](image1.png)

**Figure 1** Schematic diagram of two types of anchorage failure modes

Therefore, the anchorage length of CFRP sheets can be identified more clearly using the test results as shown in Table 3. Which explains precisely the concept of anchorage length: the stress is transferred along the length of CFRP sheets, and the strain is not zero along the length of the CFRP sheets. The typical strain distribution and development for specimens T-10 and T-20 along the CFRP strip are as shown in Figure 2, where \( P \) is the applied load; \( P_u \) is the ultimate load; \( s \) is the slip at the loaded end.
The anchorage length $L_a$ increases almost linearly with the increase of the applied load $P$, but the average shear strength $\tau$ decreases with the increase of the anchorage length $L_a$ (as shown in Table 3). By observing the strain development along the length of the CFRP sheets (Figure 2), it is clear that the CFRP sheets do not attain their fracture strain. Consequently, a difference in the length of the high stress area reveals a difference in the anchorage length value: the higher the length of the high stress area, the smaller the basic anchorage length.

Table 3 Test results of the anchorage lengths of CFRP sheets

| Type          | No. | $L_a$(mm) | $P$(kN) | Anchorage failure modes | $R$(%) | $\bar{P}$(kN) | $\tau$(MPa) |
|---------------|-----|-----------|---------|-------------------------|--------|---------------|-------------|
| UT70-20 CFRP sheets | T-1 | 120       | 16.9    | AF                      | 95%    | 17.20         | 1.02        |
|               | T-2 | 140       | 17.5    | AF                      | 80%    | 18.25         | 0.93        |
|               | T-3 | 160       | 18.4    | AF                      | 80%    | 19.01         | 0.85        |
|               | T-4 | 180       | 18.1    | AF                      | 85%    | 19.55         | 0.78        |
|               | T-5 | 19.2      | 18.8    | AF                      | 55%    | 19.20         | 0.71        |
|               | T-6 | 19.7      | 19.4    | AF                      | 45%    | 19.15         | 0.70        |

| UT70-30 CFRP sheets | T-7           | 200       | 19.8 | TF                      | —      | 19.95         | 0.71        |
|                     | T-8           | 20.1      | 20.1 | —                       | —      |               |             |
|                     | T-9           | 220       | 20.8 | AF                      | 80%    | 21.05         | 0.68        |
|                     | T-10          | 220       | 21.3 | AF                      | 75%    | 22.20         | 0.66        |
|                     | T-11          | 240       | 21.9 | AF                      | 80%    | 23.65         | 0.65        |
|                     | T-12          | 24.2      | 22.5 | AF                      | 65%    | 24.00         | 0.61        |
|                     | T-13          | 260       | 23.4 | AF                      | 45%    | 24.85         | 0.71        |
|                     | T-14          | 260       | 23.9 | AF                      | 35%    | 25.40         | 0.70        |
|                     | T-15          | 280       | 24.2 | AF                      | 45%    | 26.00         | 0.65        |
|                     | T-16          | 280       | 24.2 | AF                      | 30%    | 26.65         | 0.61        |
|                     | T-17          | 300       | 24.0 | AF                      | 35%    | 27.20         | 0.60        |
|                     | T-18          | 300       | 24.7 | TF                      | —      | 24.35         | 0.58        |

(a) Typical strain distribution for T-10 (b) Typical strain distribution for T-20

Figure 2 Strain development along the length of CFRP sheets

3.2. The bond anchorage properties of AASCM at high temperature
In order to identify the constant temperature time, thermocouples were embedded in AASCM specimen surface center to 4 mm, and the heating curve of furnace and measuring point temperature are shown in Figure 3 and Figure 4. Lastly, the constant temperature time is identified as 30min.
The heating rate was chosen 4 °C /min and target temperatures were 100°C, 200°C, 300°C, 400°C, 500°C. The test phenomenon is shown as Figure 5.

(a) Anchorage failure  (b) Tensile failure of CFRP sheets

Figure 5 Schematic diagram of two types of anchorage failure modes at high temperature

When target temperatures are 100°C, 200°C, 300°C, 400°C, 500°C, anchorage lengths are measured with 387.5 mm, 337.5 mm, 312.5 mm, 300 mm and 300 mm, respectively. The anchorage length of the measured values can be relatively high temperature CFRP anchor length (L_a/T/L_a) with temperature change law of unified use Type (1) express, fitting curve and test curve are as shown in Figure 6.

\[
\frac{L_{a,T}}{L_a} = \begin{cases} 
0.91+4.80 \left( \frac{T}{1000} \right) & 20°C \leq T \leq 100°C, \ R^2 = 0.999 \\
1.73-4.53 \left( \frac{T}{1000} \right) +11.65 \left( \frac{T}{1000} \right)^2 -11.17 \left( \frac{T}{1000} \right) & 100°C < T \leq 500°C, \ R^2 = 0.997 
\end{cases}
\]

(1)

In the formula,
L_{a,T} —— the anchor length of CFRP at temperature T (mm);
L_a —— the anchor length of CFRP at room temperature (20 °C) (mm);
T —— experience temperature (°C);
R^2 —— the correlation coefficient of the fitting accuracy
Figure 6 Relative anchorage length at high temperature

As shown in Figure 6, it is seen that the anchorage lengths of CFRP sheets increase with increasing temperature at 20°C ~100°C, but the anchorage lengths of CFRP sheets decrease with increasing temperature at 100°C ~500°C. In short, the basic anchorage lengths at high temperature were higher than those at room temperature.

3.3. The bond anchorage properties of AASCM after high temperature

When target temperatures are 100°C, 200°C, 300°C, 400°C, 500°C after high temperature, anchorage lengths are measured with 487.5 mm, 475 mm and 450 mm, 437.5 mm and 400 mm, respectively. Comparative analysis shows that the damage form of double shear specimens after high temperature are the same with room temperature damage form, but AASCM and concrete color becomes shallow, and concrete stripping areas after high temperature are bigger than that at room temperature. Compared with the double shear specimens under high temperature failure pattern, at the same temperature, the stripping areas of the concrete after high temperature are bigger than that at high temperature. From Figure 1 and Figure 5, it can be seen that AASCM provides the anaerobic protection for CFRP after high temperature and at high temperature, and AASCM avoids the CFRP wire from being oxidized. The anchorage length of the measured values after high temperature can be relatively CFRP anchor length at high temperature, which can be expressed by Type (2) express, and fitting curve and test curve are as shown in Figure 7.

\[
\frac{L_{aT}}{L_a} = \begin{cases} 
0.82 + 9.26 \left( \frac{T}{1000} \right) & 20^\circ C \leq T \leq 100^\circ C, \quad R^2 = 0.999 \\
1.83 - 1.09 \left( \frac{T}{1000} \right) & 100^\circ C < T \leq 500^\circ C, \quad R^2 = 0.988
\end{cases}
\]

In the formula,
\( L_{aT} \)——the anchor length of CFRP after temperature T (mm).
As shown in Figure 7, it is seen that the relative anchorage lengths of CFRP sheets grow linearly after 20°C ~100°C, but the relative anchorage lengths of CFRP sheets decline gradually at 100°C ~500°C. In short, the basic anchorage lengths after high temperature were higher than those at room temperature and those at high temperature. Figure 7 shows that the fitting curve fits well with the test curve.

4. Conclusions
By bond-anchorage property tests at 20°C ~500°C, the all levels of loading and anchorage lengths were measured. It can be seen that the anchorage lengths of carbon fiber sheets increase with increasing temperature at 20°C ~100°C, and the anchorage lengths of carbon fiber sheets decrease with increasing temperature at 100°C ~500°C.

- It is identified that the basic anchorage length at room temperature, at high temperature and after high temperature meet expectations. Tests prove that AASCM has favorable high-temperature resistant and excellent bond anchorage properties.
- The two types of anchorage failure modes summarized from twenty specimens were anchorage failure and tensile failure of CFRP sheets. AASCM provides the anaerobic protection for CFRP after high temperature and at high temperature, and AASCM avoids the CFRP wire from being oxidized.
- The failure loads and anchorage lengths were measured at high temperature and after high temperature, and the calculated formulas of anchorage length were obtained by fitting. The fitting curve fits well with the test curve.

Acknowledgements
This work was financially supported by the National Natural Science Foundation of China (NO. 51508140).

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