Influence Assessment of Environmental Temperature and Base Material Properties on Bond Capacity of Post-installed Bonded Anchors

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1. Introduction

When attaching a jet fan to a tunnel or constructing seismic strengthening of concrete structures, anchors are inevitable necessary. As the one of the anchoring method, there is a post-installed anchoring method which installs an anchor in a hole drilled in a hardened concrete. Post-installed anchors have been using in the field of both civil engineering and architecture because of its advantages such as ease of installation, and certainty in the securement of the mounting position of the anchor bolt. The types of post-installed anchors are roughly divided into a metallic anchor and a bonded anchor. In this study, bonded anchor, which is installed with mortar for bonding, is only focused on since the anchoring system of the bonded anchor is complicated and there are still spaces for improvement in the design bond capacity. In view of the accident of tunnel ceiling panels collapse occurred in Sasago tunnel in 2012, advancement of durability design of bonded anchors and evaluation of its durability is urgently required [1]. From the viewpoint of durability, it is expected that bond capacity decreases as time passing when considering the long-term use of bonded anchors; mortar for bonding is supposed to be damaged by influences from the characteristics of the base material or environmental factors such as temperature, creep and fatigue. In this study, therefore, influence assessment is conducted based on how the bond capacity is changed by focusing on the environmental temperature and the properties of the base material, which have not been investigated so far although these are considered to be one of the factors affecting bond capacity.

2. Experimental outline

2.1 Test method

A cylindrical concrete with a diameter of 200 mm and a height of 100 mm, including a steel pipe with a thickness of 5 mm, was casted, and a hole having a diameter of 14 mm and an effective embedment depth of 60 mm was drilled in the center of the concrete. Specimen was prepared by installing a threaded rod having a nominal diameter of M12 into the borehole with mortar for bonding as shown in Fig. 1a. For the anchor installation, the casted side was avoided and the side of formwork was used to select a smoother surface. Mortar A (vinyl urethane type) and mortar B (epoxy type) were used for bonding. In the experiments, the threaded rods were pulled out by applying the axial tensile force at a speed of 1.0 kN/sec, and the load and displacement were measured until failure with tensile testing machine as shown in Fig. 1b. In addition, since special focus is given to the mortar adhesion part in this study, confinements were used with the purpose of suppressing cone shaped failure of concrete. The inner diameter of the confinements was set as 21mm according to European Technical Approval Guidelines (ETAG) 001-5. Furthermore, cement was used as a gap filter between the confinements and the concrete to achieve uniform stress distribution.

![Figure 1 Description of specimens and testing machine](image1)

2.2 Influence of environmental exposure

Exposure tests in real environment were conducted by setting specimens at Asahikawa and Naha as shown in Fig. 2. There are two main purposes for this test. One is to obtain the temperature change of the anchor part in our country. The other purpose of the exposure tests is to clarify the influence of temperature history on bond capacity.

![Figure 2 Situation of exposure at both regions](image2)

2.3 Influence of high and low temperature

Pullout test was conducted, which is under high and low temperature conditions based on the temperature obtained in the exposure test, with the aim of knowing to what extent the bond capacity changes due to the influence of high and low temperature. Since the temperature is considered to affect the bonded anchor when the time of installing and the time of pullout test, the temperature change in these 2 stages were set as a parameter. The parameters used were two patterns, one giving a temperature change from the time of...
anchor installation to the completion of pullout test and the other giving a temperature change only during pullout test. Table 1 shows the lists of parameters.

Table 1 List of parameters
<table>
<thead>
<tr>
<th>Type</th>
<th>Concrete curing</th>
<th>Anchor installation</th>
<th>Pullout test</th>
</tr>
</thead>
<tbody>
<tr>
<td>NNN</td>
<td>20 °C</td>
<td>20 °C</td>
<td>20 °C</td>
</tr>
<tr>
<td>NNL</td>
<td>20 °C</td>
<td>20 °C</td>
<td>Low (-20 °C)</td>
</tr>
<tr>
<td>NLL</td>
<td>20 °C</td>
<td>Low (-20 °C)</td>
<td>Low (-20 °C)</td>
</tr>
<tr>
<td>NNH</td>
<td>20 °C</td>
<td>20 °C</td>
<td>High (60 °C)</td>
</tr>
<tr>
<td>NHH</td>
<td>20 °C</td>
<td>High (60 °C)</td>
<td>High (60 °C)</td>
</tr>
</tbody>
</table>

2.4 Influence of concrete compressive strength

The compressive strength of concrete is supposed to have little influence on bond capacity in this test using confinements. Therefore, pullout tests were carried out using concrete of different compressive strength, and the correlation between compressive strength and bond capacity was clarified. Table 2 shows the main values of concrete mix properties used for this experiment.

Table 2 Concrete mix properties used
<table>
<thead>
<tr>
<th>Type</th>
<th>Unit water (kg/m³)</th>
<th>W/C (%)</th>
<th>S/a (%)</th>
<th>Aggregate size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>160</td>
<td>40.0</td>
<td>47.0</td>
<td>25</td>
</tr>
<tr>
<td>Ii</td>
<td>160</td>
<td>45.0</td>
<td>47.0</td>
<td>25</td>
</tr>
<tr>
<td>Il</td>
<td>160</td>
<td>55.0</td>
<td>47.0</td>
<td>25</td>
</tr>
<tr>
<td>IV</td>
<td>160</td>
<td>65.0</td>
<td>47.0</td>
<td>25</td>
</tr>
<tr>
<td>V</td>
<td>159</td>
<td>58.0</td>
<td>45.0</td>
<td>20</td>
</tr>
</tbody>
</table>

3. Results and Discussion

3.1 Influence of environmental exposure

Figure 3 shows the change in temperature of mortar layer for successive 2 years. As reflected in the above parameters of temperature, it is found that the anchor part experiences a maximum of 55 °C and a minimum of -24.5 °C by the full year exposure for 2 years.

Figure 3 Temperature change of mortar layer

With regards to the influence of temperature history, figure 4 shows the results of the pullout test and shows the transition of bond capacity of each mortar from the initial to the second year. In Asahikawa, the bond capacity increased gradually, on the other hand, in Naha the bond capacity decreased in the second year although it did not fall below the value of initial year. Then, the cause of the transition of these bond capacity was tried to evaluate by the concept of accumulated temperature. The accumulated values are given in Table 3. Since the accumulated temperature for the first year of Naha and that of second year of Asahikawa shows close values, the corresponding bond capacity of both were compared. However, as these values show a value differs by at least 10% or more in between, it seems that the bond capacity cannot be evaluated merely by the concept of accumulated temperature. At the present stage, the reason why bond capacity changes due to actual environmental exposure is still under consideration, however it is expected that a new perspective on this issues will be found from the result of the third year of exposure obtained next year.

Figure 4 Transition of bond capacity by exposure

Table 3 Accumulated temperature
<table>
<thead>
<tr>
<th></th>
<th>Asahikawa</th>
<th>Naha</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>1897.5 °C</td>
<td>7401.9 °C</td>
</tr>
<tr>
<td>2 year</td>
<td>7661.5 °C</td>
<td>188891.3 °C</td>
</tr>
</tbody>
</table>

3.2 Influence of high and low temperature

Figure 5 shows the load displacement curves obtained by the pullout test under each temperature condition. When collectively looking at the changes in bond capacity obtained under the conditions of high and low temperature, that is in the range of environmental temperature, regarding mortar A, it was found that the temperature change during the pullout test leads to an increase in the bond capacity, while the temperature change from the anchor installation to pullout leads to a decrease. (Fig. 5 a, b) Regarding mortar B, on the other hand, it was found that the bond capacity greatly changes due to temperature change at the time of loading, and temperature change during mortar curing reaction leads to lower bond capacity. In addition, it was found that the influence by temperature is more sensitive to mortar B than mortar A. (Fig. 5 c, d) Moreover, it was also found that the amount of displacement up to failure increases at high temperature in both mortars. There are reports that concrete compressive strength increases at low temperature, while becomes low at high temperature [2][3]. It seems that the changes in bond capacity due to temperature behave similar. However, as will be described in the next section, the concrete compressive strength does not affect the bond capacity. Therefore, it is considered that the change in bond capacity was obtained by the material properties of mortars.

Figure 5 Change in bond capacity

a) High temp. with mortar A  b) Low temp. with mortar A
3.3 Influences of concrete compressive strength

Figure 6 shows concrete compressive strength and the corresponding bond capacity. The correlation coefficient shows a relatively low value of 11.6% as a whole, and it cannot be said that the correlation is high although the correlation is seemed to appear in mix properties V. Taking into account the fact that the mix properties have no big difference other than water cement ratio and the mix properties itself seem to have little influence on bond capacity, it can be said that concrete compressive strength hardly affects bond capacity in this test method using confinements.

3.4 Classification by failure interface

The results of pullout test conducted at room temperature showed variations in bond capacity. In addition, the type of interface failure also indicated different results. Therefore, the failure modes were categorized to clarify how interface affects bond capacity as shown in the Fig. 7. When consistent failure occurs at the mortar-concrete interface or failure occurs at the anchor-mortar interface up to 15 mm from the bottom end of the threaded bolt, it is categorized as failure type A as shown in Fig. 7a. In the case of when consistent failure occurs at the mortar anchor interface, it is categorized as failure type C as shown in Fig. 7c and other failure type is categorized as failure mode B as shown in Fig. 7b. The categorized bond capacity based on the classification of these failure interfaces is given at Fig. 8. From the figure, it is found that the bond capacity increases as the failure mode is shifted from A to C as an overall trend in both mortar although the mortar B shows the different trend exhibiting that failure type B shows lower value than that of failure type A. Therefore it can be said that failure surface affects the bond strength, and failure with anchor-mortar interface has the biggest capacity among 3 types of interfaces.

3.5 Consistency with existing design equation

The Japan Society of Civil Engineers (JSCE) proposes the design equation for pullout failure in bonded anchors as shown below [4].

\[
T_{bd} = \pi D_d h_{ef} \tau_{ad} \\
\tau_{ad} = 10 \sqrt{\frac{f_{cd}}{21}}
\]

Where \( T_{bd} \), \( D_d \), \( h_{ef} \), \( \tau_{ad} \), and \( f_{cd} \) are design bond capacity, diameter of threaded rod, effective embedment depth of anchor, bond strength of bonded anchor, and concrete compressive strength respectively.

The design equation is based on the assumption of the case where the confinements are not used. However, since it is enough conceivable to install an anchor with a plate in a real situation, it is important to know what extent the experimental bond capacity using confinements, which revealed concrete compressive strength does not affect bond capacity, matches the design capacity. Figure 9 indicates that comparison between design capacity and experimental capacity including the results with different temperature condition. It shows that all values of experimental capacity show higher than that of design capacity. From this result, it can be said that the design equation evaluates the experimental capacity to the safety side. However, given that the value of design capacity is expressed without safety factors, actual bond capacity is estimated to remarkably lower value by the design capacity. Considering the design bond capacity is estimated to be three times smaller than that of experimental capacity in some cases, it is considered that more suitable expression is necessary, which does not use concrete compressive strength as a parameter and is able to take different temperature conditions and different failure interfaces into consideration.
3.6 Proposal equation for bond strength

The calculation equation of bond strength is proposed that is suitable for this experiment method using confinements, taking failure interface and temperature influence into account. In the proposed equation as shown below, bond strength is supposed to be obtained by multiplying the coefficient of the temperature and the failure interface by the value obtained by dividing the experimental bond capacity by the bonding area of mortar and concrete, which is the major failure mode in experiments. With regards to the temperature coefficient represented by \( \alpha \) in the equation, it was obtained from the bond capacity ratio of bond capacity obtained at three temperature zones and bond capacity at normal temperature. The temperature coefficient was determined from the bond capacity ratio between bond capacity obtained at each temperature zone and bond capacity at normal temperature. The temperature coefficient was set to 1.0 for mortar A because the maximum bond capacity ratio was only about 15% difference and it was considered that there was no big difference, while the coefficient was obtained by the approximation by first order least squares method for mortar B. Similarly, regarding the coefficient related to the interface failure represented by \( \beta \), it was determined by the bond capacity ratio of the bond capacity at each interface failure. The calculated equations are as following.

For mortar A,

\[
\tau = \frac{T_{\text{exp}}}{\pi h_f D} \beta_i
\]

\( \beta_1 = 1.00, \ \beta_2 = 1.20, \ \beta_3 = 1.74 \)

For mortar B,

\[
\tau = \frac{T_{\text{exp}}(-0.01t + 1.18)}{\pi h_f D} \beta_i
\]

\( \beta_1 = 1.00, \ \beta_2 = 1.00, \ \beta_3 = 1.30 \)

Where \( T_{\text{exp}} \) \( D \), \( t \) and \( \beta \) are experimental capacity, diameter of borehole, temperature of mortar layer and coefficient of interface failure respectively. \( \beta_1, \ \beta_2 \) and \( \beta_3 \) indicate the coefficient of concrete-mortar interface, mixed interface and mortar anchor interface respectively, and these values \( \beta \) are supposed to be substituted for \( \beta_i \).

Figure 10 shows the relationship between experimental bond capacity used in Fig. 9 and the bond capacity calculated from the bond strength that considered the temperature and the failure interface obtained in this equation. As can be seen from the figure, the calculated bond capacity and the experimental capacity are proportional relation to each other by the proposed equation, showing a better relationship than the relationship between the design capacity and the experimental capacity. Therefore, by using the above equations, it is possible to know the bond capacity under a certain temperature within the range of environmental temperature if the bond capacity at normal temperature and the failure type are known. However, as a problem of the present situation, the failure interface cannot be predicted, and it is impossible to know the exact failure interface unless the failure behaviors are actually confirmed.

4. Conclusion

- Bond capacity tends to slightly increase from the beginning of exposure when exposed for 2 years.
- It is thought that the concrete compressive strength hardly affects bond capacity of bonded anchors in this test method.
- Sensitivity differs between mortar A (vinyl urethane) and mortar B (Epoxy), however bond capacity changes with the influence of temperature.
- As a tendency, the bond capacity is strongly related to the type of interface failure.
- JSCE design equation cannot predict the bond capacity correctly obtained by the experiments under confinements.
- Calculation equation of bond strength that is suitable for this experiment method under confinements is prepared. However, the equation cannot predict the failure mode at the present.

References