Laboratory-scale Method to Assess the Durability of Rendering Mortar and Concrete Adhesion Systems

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Abstract

The adhesion failure of the interface between concrete and rendering mortars often leads to the degradation of the reinforced concrete building envelopes. Although several methods to improve the adhesion properties between concrete and rendering mortar have been proposed, there is no system to evaluate the effectiveness of these methods from the perspective of durability. To this end, this study proposed an experimental method to evaluate the durability of rendering mortar and concrete adhesion systems at the laboratory level. In this technique, a cyclic thermal load is applied to a part of the rendering mortar surface to accelerate the degradation; this part represents an external wall subjected to solar radiation. Subsequently, appropriate constraints are applied to the loaded part of the mortar to reproduce the actual degradation mechanism. Numerical simulation and experimental results support the effectiveness of the proposed accelerated degradation method. Considering the rate of decrease in the bond strength as a criterion to evaluate the durability, the influence of several known factors on the durability can be explicitly ranked. The durability assessment method can facilitate the comparison of novel solutions during the development stage.

1. Introduction

Building envelopes are valuable tools to provide aesthetic expression and protect the building elements against climatic and environmental conditions, thereby expanding the service life of buildings in normal operation. Rendering mortar is a widely used material to construct reinforced concrete (RC) building envelopes in Japan. Specifically, this mortar is commonly used as an adhesive for the finishing material and concrete substrates, thereby providing a strong surface for exterior walls and ensuring the excellent adhesion of all finishing coatings. However, the deterioration of the rendering mortars in the form of cracking and debonding during the buildings’ life accelerates the degradation process of the RC element and reduces its durability. Moreover, the exterior wall finishes may fall off from the building owing to the delamination of the rendering mortar, posing a risk to pedestrians and properties.

Adhesion failure between the rendering mortar and concrete is a result of the fatigue that occurs owing to the different responses of various materials to the climate conditions. Although this degradation is a natural process, several factors affect its progress, such as the bonding quality of the rendering mortar and concrete, environmental exposure, conditions of use, and frequency of maintenance (Rodrigues et al. 2011; Souza et al. 2018). The existing research on the peeling problem is focused on the adhesion behavior of mortar to the substrate, because weak adhesion can significantly accelerate the degradation process (Chew 1992; Mahaboonpachai et al. 2008; Stolz et al. 2016; Liao et al. 2019). Furthermore, adherence, which is the result of the interaction between two materials, is influenced by the characteristics and properties of the substrate, characteristics of the mortar and its constituent materials, and mortar application technique, along with the climatic conditions during the application of the mortar, and the time span after application (Carasek et al. 2014).

Several researchers have proposed methods to improve the adhesion of the rendering mortar. Novel mortars have been developed by replacing the constituent compounds to the products to induce specific material properties according to the customer requirements. In general, rendering mortars must exhibit suitable fresh-state properties such as high cohesion, surface adherence, water retention, and rheology-plasticity, and hard-state properties, such as high strength, stiffness, energy damping, permeability, and durability (Aragón et al. 2019). The improvement of the mortar application workmanship is also an effective approach to enhance the material properties. Such aspects include the amount of mortar per unit area, plastering pressure (Zhao and Zhang 1997), curing method of the mortar (Thamboo and

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Dhanasekar 2015), texture of the substrate (Júlio et al. 2004; Stolz et al. 2016) and adherence extension (Carasek et al. 2014).

Although a high-adhesion mortar-concrete system can be obtained using the abovementioned techniques, it is necessary to evaluate the resistance of the resulting systems prior to their applications in building finishes. Moreover, it is necessary to balance the adhesion quality and resistance to degradation of the system according to the environmental exposure conditions. In other words, a reliable durability assessment system is required to determine the suitable treatment methods to be applied to the susceptible and relatively robust parts.

In recent years, the demand for economic and environmental sustainability in the construction industry has encouraged research on the durability of buildings, and several researchers have attempted to develop tools to evaluate the durability of buildings and building components (Yiu et al. 2007; Souza et al. 2018; Maia et al. 2019). However, the current approaches primarily focus on the adhesion quality of the rendering mortar in the early stage. Moreover, the durability assessment of such mortars has not been extensively examined, and there is no reference document in Japan to evaluate the durability of the mortar in the finishing systems. This knowledge gap makes it difficult to improve the performance of the rendering mortars applied as exterior finishing systems for buildings in practical engineering.

To address this gap, in this work, a laboratory-scale durability assessment method was established considering the application of rendering mortar in exterior finishing systems.

According to Lewry and Crewdson (1994), the critical steps in durability assessment include: 1) factors affecting durability; 2) defining the key degradation factors for accelerated testing, and the mechanism of that degradation; 3) evaluation of the significant causes of degradation in the proposed end use environment; and 4) construction of models and damage functions for the material's response to the environment based on the accelerated test results and the environmental measurements. It can thus be considered that the durability assessment must involve the two key steps of simulating the degradation mechanism and accelerating the degradation cycles. Although the degradation mechanism of the rendering mortar and concrete adhesion system has not been fully understood, the deformation mismatch between different materials under changes in the temperature and relative humidity is considered to be a key factor influencing the degradation (Chew 1999; Maranhão et al. 2011; Rumbayan et al. 2006). In particular, the mismatch between the thermal expansion of the mortar and concrete substrate under daily solar radiation, leads to a large stress accumulation, eventually causing fatigue damage. In such cases, the cracks and peeling primarily occur owing to the in-plane stress and stresses in both the directions (in-plane and out-of-plane), respectively, as shown in Fig. 1.

2. Proposed laboratory-scale durability assessment method

2.1 Accelerated degradation testing

Under normal use conditions, building components usually do not fail or considerably degrade within a reasonable testing time. Therefore, accelerated testing methods (ATs) are used in the laboratory to promptly assess or demonstrate the component or subsystem reliability. Specifically, AT experiments are performed to accelerate the failure mechanisms to ensure that the product can reach the aging state within a reasonable test period (Escobar and Meeker 2006). To assess the durability of rendering mortar in exterior finishing systems, the existing laboratory-scale ATs usually employ wet-dry and heat-cool cycles as the degradation conditions to cause relative movement between the mortar and substrate. For example, the standardized AT method described in the Japan Society for Finishings Technology Standard M-101 on water absorption modifiers for cement mortar coatings (JSFT 2015) involves irradiating the specimen surface through an infrared lamp for 105 minutes until the surface temperature increases to 70°C and subsequently sprinkling water on the surface for 15 minutes. This cycle is performed 300 times.

This experiment was originally performed to evaluate the quality of the adhesion promoters used in plastering...
mortars by testing the adhesive strength between the mortar and concrete. Nevertheless, similar AT methods share the same types of limitations. Specifically, the entire specimen is subjected to a high-temperature history and water supply, and the hydration of the plastering mortar can enhance the adhesive strength at the interface. Moreover, the cooperative mode in which the temperature and humidity can degrade the system cannot be reproduced. In the actual environment, the adhesion strength of the mortar to the substrate both increase and decrease with age (Sugo et al. 2007). However, in the existing approach, the constraints of the mortar pertain only to the substrate concrete, which makes it difficult to reproduce the actual degradation mechanism.

To avoid these limitations, in the proposed laboratory-scale AT method, solar radiation is considered as a key degradation factor to realize accelerated testing, and the degradation mechanism of the external walls subjected to solar radiation is simulated through thermal cycling. According to Rumbayan et al. (2006), the orientation of the building facing is closely related to the degree of damage, and it may help dissipate the thermal stress. Nevertheless, considering the situation of actual RC exterior walls, it is necessary to provide an appropriate restraint for the rendering mortar subjected to thermal load. As shown in Fig. 2, the uneven heating due to solarization will cause a temperature difference in the wall. The temperature difference not only exists between the different layers, but also exists in the in-plane direction of each layer. The temperature difference combined with physical difference of various materials to occur the differential movement between layers. The rendering mortar in a real structure is restrained not only by the substrate, columns and beams, but also by the mortar in the surrounding unheated area. To reproduce this state, in the proposed approach, a thermal load is applied only in the central part of the mortar, and consequently, the unheated surrounding mortar provides restraint.

2.1.1 Numerical simulation
As discussed, the adhesion failure between the rendering mortar and concrete is a result of the interlayer stress accumulation. Therefore, the rationality of the partial thermal load conditions applied in the proposed approach was verified, by performing a numerical simulation, to compare the stress state of the mortar-concrete adhesion system when heating the whole and part of the mortar. The analysis was performed using ANSYS Workbench, which is a 3D finite element method (FEM) program.

In the buildings in Japan, the rendering mortar is usually in direct contact with the concrete structure in the exterior finishing systems. As shown in Fig. 3, the 3D-FEM model consists of three components, concrete with dimensions of 100 × 100 × 400 mm, mortar with dimensions of 40 × 10 × 400 mm, and the adhesion interface. One thermal load cycle was applied to the entire and central part of the mortar surface with a load length of 400 mm and 160 mm, respectively. Figure 4 shows the temperature history of the mortar surface and the adhesion interface below the thermal load zone. It can be noted that after the peak temperature load of 70°C was maintained for 30 minutes, the temperature increased only around the loaded portion owing to the low thermal conductivity of the concrete.

The model was evaluated by performing transient thermal and structural analyses. The concrete bottom surface in the model was set as a fixed constraint, similar to that in the actual conditions. The material parameters of the concrete and mortar components were set according to the recommendations of the Japan Society of...
Civil Engineers (JSCE 2017), and are summarized in Table 1. The maximum normal and tangential contact stresses of the adhesive material at the adhesion interface were set considering the bond strength test results obtained under identical conditions in the laboratory. The purpose is to obtain the stress distribution of the adhesion interface at high temperature to verify the rationality of the proposed partial thermal load method, the dry shrinkage effect and decrease in the adhesive strength owing to the cyclic thermal loads was not considered.

Figure 5 shows the equivalent stress at the interface of the FEM model under thermal load lengths of 160 mm and 400 mm, at the 120th minute of a cycle (after heating at 70°C for 30 minutes). It can be noted that in the case of the model subjected to a partial thermal load, the stress is concentrated at the center of the mortar; in contrast, in the model subjected to the whole load, the stress is concentrated at the ends, in accordance with the movement trend of the mortar. Figure 6 shows the maximum deformation of the mortar under one thermal loading cycle, the red arrow represents the direction of the maximum principal stress of the adhesion interface at that moment. The maximum principal stress of the heated part of the interface is directed in the out-of-plane direction, and the mortar and concrete have a tendency to be delamination. However, the maximum principal stress of the interface subjected to the whole thermal load is located at the end and the direction is almost parallel with the interface.

From the deformation results, the expansion caused by the heating of the mortar constrained by the surrounding area tends to deform the material in the vertical direction, and thus, the stress is concentrated on the loaded part. In contrast, the mortar not constrained by the surroundings tends to deform toward both the ends, and the stress is concentrated at the ends.

The FEM analysis results indicate that the deformation of the mortar subjected to partial thermal load is consistent with that of the actual rendering mortar for external

| Parameter                        | Concrete | Mortar | Interface |
|----------------------------------|----------|--------|-----------|
| Density (kg/m³)                  | 2300     | 2100   | -         |
| CTE (1/°C)                       | 1.10E-05 | 1.50E-05 | -         |
| Young's Modulus (GPa)            | 28       | 20     | -         |
| Poisson's Ratio                  | 0.2      | 0.2    | -         |
| Tensile Yield Strength (Pa)      | 2.78E+06 | 3.50E+06 | -         |
| Compressive Yield Strength (Pa)  | 3.00E+07 | 3.96E+07 | -         |
| Isotropic Thermal Conductivity (W/m·°C) | 1.6 | 1.5 | -         |
| Specific Heat (kJ/kg·°C)         | 0.7      | 0.6    | -         |
| Maximum Normal Stress (Pa)       | -        | -      | 1.05E+06  |
| Maximum Tangential Stress (Pa)   | -        | -      | 9.73E+05  |
| Artificial Damping Coefficient (s)| -       | -      | 0.001     |

Table 1 Model material parameters.
walls. The complete heating method cannot reproduce the degradation mechanism of the actual walls owing to the thermal expansion of the mortar not being sufficiently constrained. Therefore, it is considered that providing thermal load at the center, which can degrade the target location by realizing an appropriate constraint for the heated part, is a superior accelerated deterioration approach compared to the complete heating approach.

2.1.2 Proposed laboratory-scale AT method
Applying a thermal load to the specimen in a non-contact manner often results in an uncontrollable temperature, and the distance between the specimen and the heat-source is thus a key parameter. Ideally, the heat should be transferred from the surface of the mortar to the concrete substrate, creating a temperature gradient across the thickness of the specimen, which is similar to the condition of an actual building facing exposed to solarization. To realize this, silicone rubber heaters with wire-wound elements can be placed directly in contact with the mortar to provide thermal loading. Such heaters exhibit excellent physical strength and can withstand repeated flexing without considerable deterioration in the service life and performance. Consequently, such heaters can be placed in close contact with the specimen and cut into any shape. In this work, high temperature-resistant double-sided tape was used to attach the rubber heater to the mortar’s surface to avoid gaps. The setup was connected to the control equipment to control the temperature, heating time, and number of cycles, as shown in Fig. 7(a).

2.2 Adhesion testing of rendering mortars
After several heat-cool cycles, the adherence of the interface between the concrete and mortar was measured, and the durability was evaluated considering the decrease in adhesion. The adhesion is generally determined by testing the maximum vertical and tangential peeling failure strength of the adhesion interface. Pull-out tests (out-of-plane) and shear strength tests (in-plane) are usually conducted to investigate the adhesive strength of the mortar-concrete interface. Specifically, pull-out tests are usually performed to realize in-site testing and correctly diagnose the cause of degradation of the exterior wall façades. In contrast, direct shear tests are only performed at the laboratory level owing to the uncontrollable reaction force.

The peeling of the mortar is caused by the restraint stresses that act both in-plane and out-of-plane; consequently, strength tests in both the directions should be performed. However, previous studies have questioned the reliability of pull-off tests. In particular, several factors influence the variability of the results of pull-out tests, such as the use of manual equipment that renders the control of the load rate application challenging, thickness of the adhesive used to fix the attachment to the mortar surface (Flores-Colen et al. 2009), and specimen geometry and dimensions (Ramos et al. 2012). The correlation between these factors and the variability remains unclear. These challenges are also encountered under in situ conditions, and Ramos et al. (2012) demonstrated that the coefficient of variation of the pull-out test results is underestimated under laboratory conditions.

Considering this background, some researchers proposed the use of shear strength testing to investigate the adhesive strength (Chew 1999; Stolz et al. 2016). Under solar radiation, although the interface in the structure undergoes a mixed mode involving tensile and shear stress, the shear stress is more dominant than the normal
stress. Rumbayan et al. (2006), who examined a wall tile structure, reported that for a tile surface temperature of 50°C, the shear stress was 2.6 MPa, whereas the normal stress was 0.008 MPa.

In this study, the pull-out test and direct shear test were conducted to evaluate the degradation effect of the partial cyclic thermal load method on the adhesive strength of mortar and concrete. Moreover, the superior test method to be used in the durability evaluation system was attempted to be clarified. The test machine, which is shown in Fig. 7(b), was in accordance with the requirements of the Japan Society for Finishing Technology standard M-101 (JSFT 2015), as shown in Fig. 7(b).

3. Experimental program

The experimental analysis was performed in two stages. In the first stage, the actual degradation effect of the proposed partial thermal cycle loading method was validated. In the second stage, the effectiveness of the laboratory-scale durability assessment method was evaluated. By adjusting certain parameters affecting the adhesion of mortar and concrete, different specimens were prepared, and their durability was compared. In both the stages, identical specimens, materials, equipment, and experimental environment were employed.

### 3.1 Specimen preparation

The specimen dimensions are shown in Fig. 8. The concrete substrate and rendering mortar had dimensions of 100 × 100 × 400 mm and 40 × 10 × 400 mm, respectively. The mixture proportions of the concrete substrate and rendering mortar are listed in Tables 2 and 3, respectively.

The concrete substrate for all the specimens was prepared by demolding the concrete the day after casting, and subsequently curing in 20°C water for more than two months. The concrete was sufficiently dried to reduce the errors caused by drying shrinkage. Specifically, before plastering, the substrates were dried for more than one week at 40°C.

Next, three parameters in the plastering process, specifically, the mortar water-cement ratio (W/C), amount of shrinkage reducing admixture (SRA), and mortar thickness, were tuned to prepare specimens, having different adhesions between the mortar and concrete. These parameters were selected as they influence the bond strength of the mortar and concrete, as specified in the Japanese Architectural Standard Specification JASS 15 for Plastering Work (AIJ 2019). Specimen SV was used as the control group, and it was prepared to have a high adhesive strength, according to the method recommended by the above specification. On this basis, the other three groups of specimens, each with one modified parameter, theoretically exhibited a lower adhesive strength. The experimental parameters of the four types of specimens are listed in Table 4. The preparation process is described in the following text.

Generally, to achieve a higher adhesive strength, a series of pretreatments such as polishing, cleaning, and adhesive application are performed on the plastered surface. In this work, sandpaper was used to clean up the substances generated during curing and the residual release agent on the substrate surface, and acetone was...
used to remove dust and grease, which improves the adhesion of the mortar. Finally, ethylene-vinyl acetate (EVA), which is an adhesion promoter, was applied to the surface two hours prior to plastering. This step is necessary to prevent the movement of water from the mortar to the concrete. In previous research, an equal volume of water was often applied to the adhesion interface to replace the EVA. In this case, after curing, the adhesion of the mortar was extremely low, and it could be easily peeled from the concrete. Lukovic and Ye (2015) stated that the absorption of the substrate influenced the voids formation on the interface. Specifically, dry substrates resulted in a larger number of voids on the interface, because the water loss by the substrate reduced the effective W/C and degree of hydration of the applied material.

The rendering mortar used in this work is a commercial ready-mixed mortar developed to plaster and repair fracture surfaces. This type of mortar is usually described in terms of the strength grade and is reasonably stable. In contrast from that of the SV specimens, the W/C of the L-1 specimens is 0.6, which is higher than the W/C of 0.5 recommended by the manufacture. The mortar thickness of the L-2 specimens was set as 15 mm instead of 10 mm (increase of 50%). In addition, because dry shrinkage influences the adhesion strength, the amount of SRA was set as a parameter, and the mortar of the L-3 specimens was mixed with 1% SRA. Because rendering mortar is fragile in the early stage of curing, it was maintained in a stationary state for two days after pouring and then moved to an environment with a temperature of 20°C and relative humidity of 60% for 28 days until the degradation experiment was performed.

3.2 Accelerated degradation
The same thermal load as that in the FEM analysis described in Section 2.1 was used in the experiment. One cycle was divided into four temperature steps for a total of three hours in the following order: 25°C for 30 minutes, then 25°C to 70°C in 60 minutes, followed by 70°C for 30 minutes and finally, 70°C to 25°C in 60 minutes. During the heating experiment, the surface temperature of the rubber heater and mortar was monitored in real time by using thermocouples. The laboratory temperature was maintained at 20°C because the rubber heater could only be operated when the set temperature was higher than the room temperature. The peak temperature of 70°C was determined based on the most severe load conditions that an exterior wall may be subjected to in summer. The number of cycles was set to 50 based on the tolerance of the weakest part. In particular, it was necessary to ensure that the specimen with the weakest adhesion strength in the degradation experiment did not peel. Figure 9 shows the temperature history of the mortar surface of a specimen under 50 thermal loading cycles. It was confirmed that the desired temperature could be applied to the mortar surface by the rubber heater.

To validate that the partial heating method could degrade the adhesion, the entire specimen was heated using the same rubber heater, and the temperature history was recorded. As shown in Fig. 10, the two thermal load lengths (160 mm and 400 mm) as in the FEM analysis were applied to the SV specimens by controlling the length of the rubber heater. Except for the SV specimens, all the other specimens were subjected to a partial thermal load.

3.3 Adhesive strength test
After the specimen was cured (after 50 load cycles) and cooled to the room temperature, the mortar was evenly cut into 10 parts with dimensions of 40 × 40 × 10 mm using a grinder and tested sequentially before testing. The adhesive strength was defined as the ratio between the failure load and the test area:

\[ a = N / A_s \]  

where \( a \) is the adhesion strength, \( N \) is the maximum shear/tensile failure force, and \( A_s \) is the test area (16 mm²).

Owing to the symmetry of the specimen, the average value of the strength at a location equidistant from the heated part was used. For example, the average of \( a \) and \( a' \) was considered as the adhesive strength of the

![Fig. 9 Temperature history of the mortar surface during 50 cycles.](image)

![Fig. 10 Thermal loading lengths.](image)
middle part A, and the adhesive strength of the specimen was divided into five parts (A to E in Fig. 11) from the center to the end for the evaluation. Because the adhesive strength test was destructive, at least two specimens were prepared (not heated after curing) to obtain the initial values for each group, and the average value was considered as the experimental result.

4. Results and discussion

4.1 Degradation effect of partial thermal cycling load on adhesion

Figure 12 shows the adhesion of the specimens in the tension and shear tests after degradation over 50 cycles of thermal loading compared to the initial value. It can be noted that the adhesive strength of the central part (A, B) of the specimens subjected to the thermal load is significantly reduced, whereas that of the unloaded part (C, D, and E) remains nearly constant. The decrease in the adhesive strength of the loaded boundary area B is slightly larger than that for the load center A in both the shear and tensile tests. Mahaboonpachai et al. (2008) reported that under a temperature gradient and thermal expansion mismatch, shear stress occurs along the interface between the concrete and adhesive mortar. In particular, a high shear stress occurs at the two edges of the specimen along the interface between the concrete and adhesive mortar. In addition, the stress state of the adhesive interface subjected to high temperatures, as shown in Fig. 4, can also explain the large decrease in the adhesive strength of region B. The stress concentration occurs not only in the central part of the load, but also in the edge region. Moreover, it can be speculated that as the adhesive strength of the central part gradually decreases with the increase of the number in thermal cycles, the stress concentration part moves from the load center to the load edge.

It can be considered that regardless of the employed strength test method, it is possible to evaluate whether the adhesive strength of the specimen decreases after the specimen is subjected to accelerated deterioration through the thermal cycle loading method. However, during the pull-off test, it was observed that the attachment attached to the mortar (used to connect the tester) peeled off from the specimen before the adhesion failure. Thus, in the proposed durability evaluation system, the direct shear test was selected to evaluate the adhesion. In both the tests and especially in the tensile test, the adhesive strength of the end of specimen E was lower than that of other parts. According to Georgin et al. (2008), mortar can undergo curled deformation owing to drying shrinkage. The moisture gradient present in the rendering mortar thickness during the curing process thus likely caused a differential shrinkage in the thickness.

4.2 Degradation effect of the thermal load lengths

To verify the degradation effect of the partial thermal loading experiment on the adhesion, the complete thermal loading experiment was performed as a control group. Figure 13 shows the shear test result and change rate of the SV specimens before and after degradation, induced by the change in the thermal loading lengths (160 mm and 400 mm). The results indicate that the partial heating method can significantly degrade the adhesion of the target location. The adhesion of the middle part (A, B) of the specimens subjected to a partial thermal load significantly decreased, whereas that of the other parts only decreased slightly. In contrast, the complete load specimens exhibited more obvious damage only at the end.

The experimental and FEM analysis results indicate that the proposed partial thermal load method can simulate the actual degradation mechanism and is a reasonable and effective means to realize accelerated degradation. A high correlation exists between the stress gen-
eration and the mechanism of reduction in the adhesive strength. It is necessary to monitor the interfacial stress in future experiments.

4.3 Durability evaluation

Figure 14 shows the shear strength results for the four groups of specimens before and after being subjected to 50 partial thermal load cycles. The strength without heating decreases in the following order: L-3 (mortar mixed with SRA) > SV (standard value) > L-1 (mortar W/C is 60%) > L-2 (mortar thickness is 15 mm).

As mentioned previously, the SV specimen was expected to have the highest initial shear strength. The recommendation in JASS 15 (AIJ 2019) on improving the adhesion does not mention the use of the admixture; therefore, we assumed that the L-3 specimens mixed with SRA exhibited a lower initial strength. However, the L-3 specimens exhibited a higher adhesion strength than that of the SV specimen. As mentioned in Section 4.1, the mortar produces a moisture gradient in the thickness during the curing. Because the moisture loss at the top of the mortar is higher than that at the bottom, the shrinkage at the surface is greater, and an upward curl deformation occurs at the edge (Ytterberg 1987). This aspect also explains the lower adhesive strength of the specimens with a thicker mortar (L-2), especially at both ends. This result demonstrates the notable effect of dry shrinkage on the mortar-concrete adhesion system. Thus, dry shrinkage should be considered a key factor influencing the failure mechanism.

Figure 15 shows the rate-of-change of the shear strength of the four specimen groups after 50 partial thermal load cycles. All the specimens exhibit a higher reduction in the adhesion strength in part B that in part A. This finding is consistent with the phenomenon described in Section 4.1, pertaining to the occurrence of the maximum adhesive strength failure at the edge of the thermal load rather than at the center. During the thermal loading, the moisture loss on the surface of the mortar is accelerated, resulting in a decrease in the adhesive strength of the ends to varying degrees.

In this work, the criterion to evaluate the durability of the rendering mortar-concrete adhesion system was as follows: A lower decrease rate of the thermal loaded parts (A and B) was considered to correspond to a higher durability of the specimen. Table 5 presents the decrease rate of the shear strength at the heated parts (A and, B). The durability was noted to decrease in the following order: L-3 > L-2 > SV > L-1. The average decrease ratio of the shear strength of the specimens (L-1) with a 10% increase in water-cement ratio was 1.13 times that for the SV group. In contrast, the decrease ratio of the L-3 specimens (mixed SRA) was 0.67 times that of the SV group.

![Figure 13 Shear strength of SV specimens under different thermal load lengths.](image1)

![Figure 14 Shear strength of the four types of specimens.](image2)

![Figure 15 Change rate of shear strength of specimens after degradation.](image3)
Table 5 Rate of decrease of the adhesion at the heated parts (A and B).

| Specimen notation | Rate of decrease of shear strength (%) |
|-------------------|---------------------------------------|
| SV                | 35.5 A 56.4 B                         |
| L-1               | 41.6 A 62.4 B                         |
| L-2               | 32.5 A 51.0 B                         |
| L-3               | 23.9 A 37.8 B                         |

The initial results of comparison of the adhesion strengths of the specimens and evaluation of their durability indicate that although the construction methods for the exterior wall plastering recommended by the existing codes can effectively improve the adhesion between the mortar and concrete, the durability of the system cannot be ensured. Consequently, it is necessary to evaluate the durability of the materials when evaluating or developing new plastering mortar materials, rendering mortar materials or workmanship techniques.

5. Conclusions

The objective of this research was to establish a laboratory-scale durability assessment method for rendering mortar and concrete adhesion systems, consisting of a partial cyclic thermal load accelerated degradation experiment and a direct shear test. The effectiveness of the method was verified by determining the decrease ratio of the adhesiveness between the mortar and concrete, the durability of the system cannot be ensured. Consequently, it is necessary to evaluate the durability of the materials when evaluating or developing new plastering mortar materials, rendering mortar materials or workmanship techniques.

The following conclusions were derived:

1. The durability assessment method can be used to compare the durability of mortar-concrete adhesion systems made using different methods and to understand the influence of various factors on the durability to a certain extent.

2. The effectiveness of the partial thermal load conditions was demonstrated, and it was noted that the restraints provided by the surrounding parts of the mortar must be considered to reproduce the real degradation environment in the laboratory.

3. The adhesive strength between the mortar and the substrate changed considerably in both the pull-off test and direct shear test. It is considered that the thermal load will cause stress in both the in-plane and out-of-plane directions at the adhesion interface between the mortar and concrete.

4. Results of the numerical analysis performed using a 3D-FEM model confirmed that the in-plane and out-of-plane stresses were concentrated in the area in which the adhesive strength was reduced by the partial heating method, and the stress generation and mechanism of the adhesion failure were reasonably correlated.

5. The stress concentration occurred at the edge of the load portion at which the joint strength decreased most during the experiment. Presumably, the weakest areas for plastering the mortar correspond to the junctions subjected to both sunlight and darkness, instead of those subjected only to direct sunlight.

At present, the proposed durability assessment method is suitable only for comparing the durability of several mortar-concrete adhesion systems at the laboratory level, thereby making it valuable to realize evaluation in the early stages of product and system development. In addition to temperature, other factors such as repeated wet and dry conditions contribute to the delamination of the actual walls. However, it is currently unable to determine which factor has the greatest influence. This study presents this durability assessment method under the premise that temperature is the most influential factor. However, the influence of other factors such as humidity will also be studied in the future.

In the context of the partial thermal load cycle AT method, the ratio of the thermal load length to the mortar length, number of thermal load cycles, and temperature setting influence the results of the adhesion strength. However, the evaluation results of the durability of different specimens are not notably influenced. Future research will be aimed at evaluating these influencing factors and optimizing the experimental program by adjusting the specimen specifications and thermal load approach.

Furthermore, in this study, the relevance of the number of cycles was not examined, and the correspondence between the number of cycles and the actual service life was not clarified. To enhance improve the rationality of the experimental results to be used as a reference for actual engineering design, the optimal aging cycle must be determined in future work through investigation and outdoor exposure testing of the actual structure.

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