- Technical Paper -

FUNDAMENTAL STUDY ON THE EFFECT OF CURLING BEHAVIOR OF PLASTERING MORTAR DUE TO DRYING SHRINKAGE ON MORTAR-CONCRETE ADHESION SYSTEM

Peiyi ZHANG [*1], Atsushi TERAMOTO [*2], Takaaki OHKUBO [*3]

ABSTRACT

Curling deformation of the plastering mortar due to drying shrinkage may result in delamination and reduce the durability of the mortar and concrete adhesion systems. To assess the potential impact of this phenomenon on adhesion, in this study, the curling of mortar in the free drying shrinkage and restrained shrinkage states was investigated using laser sensors and digital image correlation (DIC) technique, respectively. A simple numerical simulation method is proposed to predict the stresses at the mortar-substrate adhesive interface due to curling.

Keywords: plastering mortar, curling deformation, drying shrinkage, modelling

1. INTRODUCTION

The widely used plastering mortar exterior wall coatings suffer from low durability. Low durability is mainly caused by a low adhesion efficiency between the plastering mortar and the substrate [1]. The different response of the two materials to the climatic conditions can lead to fatigue failure of the mortar-substrate adhesion system. Since mortar is more easily deformed than the concrete substrate, it is constrained by the substrate and stress is generated in and out of the plane, resulting in deterioration such as peeling and cracking.

The deformation of plastering mortars depends on many factors. Previous studies in our laboratory have mainly focused on the effects of thermal loads, that is, the decrease in adhesion caused by the mismatch between the thermal expansion of the mortar and concrete substrate [2]. Meanwhile, we discovered significant adhesive strength loss at the free edges of the mortar-concrete adherend, which parts of the specimens that were not subjected to thermal loading. Curling of mortar caused by drying shrinkage was considered as an adhesion failure mechanism.

Cracking and upward curling in the corners and edge of mortar caused by drying shrinkage are common problems. This phenomenon is mainly due to the moisture gradient within the thickness of the plastering mortar, which in turn leads to differential shrinkage between the top surface and the bottom of the plastering mortar during the drying process. In particular, the water-cement ratio of plastering mortar is usually large to provide good workability. The water content exceeding that required for cement hydration will lead to more severe drying shrinkage. Since the substrate attempts to suppress the curling deformation of the plastering mortar, restraining stress is generated in interface of substrate and the mortar.

Previous studies on deterioration of plastering mortar have focused on the in-plane stresses, researchers have characterized cracking due to the restraint of drying shrinkage [3] [4]. But the adhesion between mortar and concrete is influenced by stresses in both directions (in-plane and out-of-plane). To this end, it is necessary to predict the restraining stress generated at the adhesive interface in both directions and thus assess the potential impact of this phenomenon on the durability of the mortar-concrete adhesion systems.

The purpose of this study is to understand the curling behavior of plastering mortars, thus assessing its effect on the mortar-concrete adhesion system. For this purpose, the curling behavior of plastering mortar with and without concrete restraint was investigated separately. And a simple numerical simulation model of curling is proposed for estimating the stresses generated at the adhesive interface. The model and the experimental measurements in the state of "free" curling of the mortar was validated mutually. Under the restrained conditions, the correlation between curling and delamination was supported, based on the monitoring of the displacement field by means of digital image correlation (DIC) technique.

2. FREE CURLING OF PLASTERING MORTAR

2.1 Experimental procedure

(1) Specimen preparation

Two mortar specimens (PL & SR) were prepared to investigate the curing behavior under the non-restraint condition. The mixture proportion of PL specimens were decided according to the Japanese

*1 Ph. D student, Graduate School of Advanced Science and Engineering, Hiroshima University, JCI Student Member
*2 Assistant Professor, Graduate School of Advanced Science and Engineering, Hiroshima University, JCI Member
*3 Professor, Graduate School of Advanced Science and Engineering, Hiroshima University, JCI Member

Architectural Standard Specification — JASS15 Plastering Work. And specimen containing shrinkage reducing admixture (SRA) were also prepared who had same water to cement ratio and sand to cement ratio with PL. The mixture proportion are listed in Table 1.

SRA is widely used as an admixture to reduce the drying shrinkage of cementitious materials and has been shown to be beneficial in reducing curling [4]. As described earlier, curling is the result of the drying shrinkage gradient in the thickness of the mortar. Therefore, the thickness of specimens and the amount of drying shrinkage (with / without SRA) as two parameters to prepare multiple specimens with different curling deformations, as shown in Table 2.

The mortar specimens had dimensions of 10/20/30×100×400 mm, as shown in Fig. 1. The specimens were demolded on the third day after casting and subsequently curing in 20 ℃ for 21 days.

Table 1 Mix proportions of plastering mortar

Cement (C)	Fine aggregate	S/C (by Weight)	W/C (%)
Ordinary Portland cement	S: Crushed sand	2.5	50

Table 2 Specifications of mortar specimens

Parameter	Specimen notation					
	PL-1	PL-2	PL-3	SR-1	SR-2	SR-3
Thickness	10mm	20mm	30mm	10mm	20mm	30mm
SRA	-			1% (by weight of gross mass)		

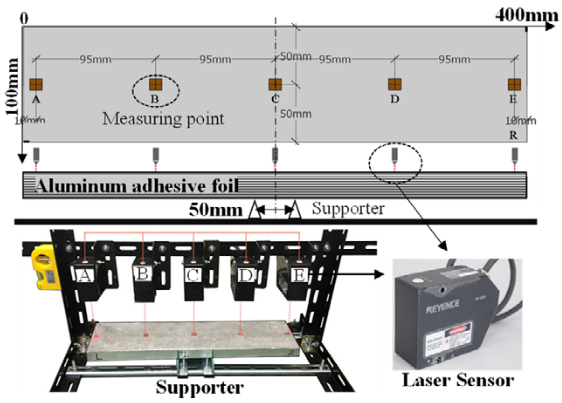


Fig. 1 Displacement measurement system

(2) Measurements with Laser Sensors

Figure 1 shown the device for measuring curling behavior, that is, the displacement of the upper surface of the mortar in the out-of-plane direction. To reproduce the curling of exterior wall mortar, the upper surface of specimens was open to air and the other sides were protected from drying by adhesive aluminum tapes. Ideally, the specimen will have a parabolic shape on the section after being curled. Five symmetrical measuring points were set on the central axis of the drying surface, a thin copper plate of 10 mm^2 is attached to each measuring point. The five laser sensors whose accuracy is 0.2 μm/m are used to measure the displacement in the vertical direction. The bottom surface supported by two steel sheets, each of which was 25 mm from the center of the specimen to limit the position of the measuring points. Therefore, specimens should only occur self-restraint caused by the drying shrinkage gradient.

To observe a more pronounced curl, the specimens were placed in an incubator at 40 ℃ and 3% of relative humidity (RH) for accelerated drying after the initial value was measured. The displacement and mass loss were then measured periodically over a period of 72 hours.

2.2 Experimental result

(1) The curling deformation

Figure 2 shown the displacement of the drying surface of the mortar specimen in the out-of-plane direction. Based on the displacement results of the five symmetrical measurement points, the specimens were considered to exhibit significant curling. At a point C corresponding to the central portion of the specimen, as the drying progresses, it is displaced downward, and the others are symmetrically displaced upward. The displacement was significantly reduced from the ends to the middle (A and E at both ends, B and D at the midpoint). Measuring points A and E, B and D are in a central symmetrical position, and the displacement of the two is in an approximately symmetrical state.

On the whole, the measurement points distributed in symmetrical positions on both sides have similar displacements. In the following results, the difference in displacement between the ends (A, E) and

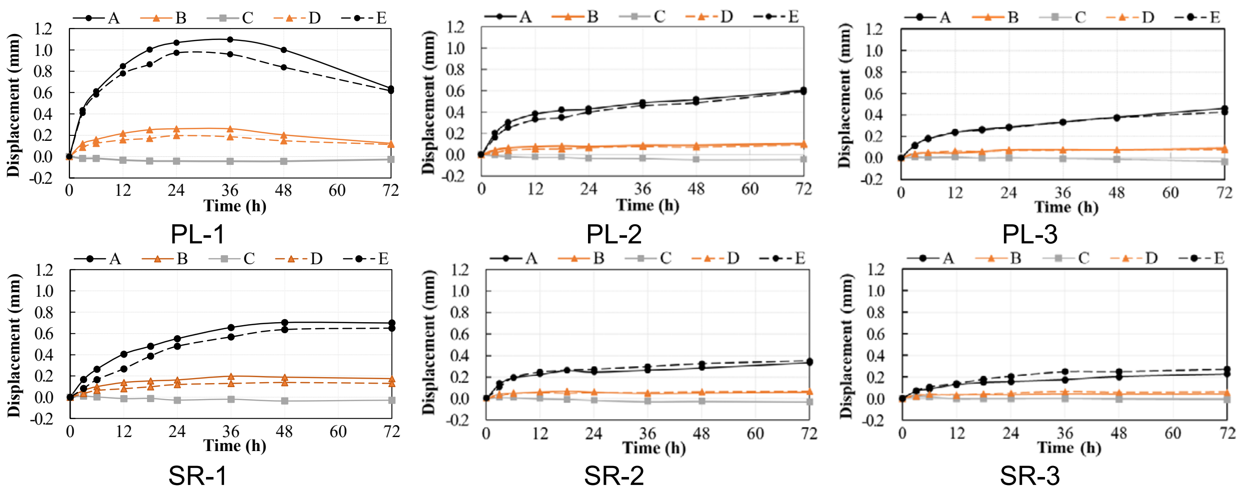


Fig. 2 The displacement of each point changes with time

the center (C) of the specimens is used to calculate the curl amount.

The curling deformation is given as follows:

$$C = (dA + dE)/2 - dC \quad (1)$$

where,

C : Curling deformation index [mm]

dA, dE and dC : Displacement at point A, E and C [mm]

Figure 3 shown the curling deformation index of each specimen over 72 hours. As the thickness increases, the curling deformation of the specimen decreases. This indicates that the thinner specimens produced a greater shrinkage gradient due to the faster drying speed, and non-dried part functions as a restraint in the thick specimens. The thinner specimen (PL-1) first reaches the maximum curl state at 36 hours, and then the deformation of the specimen begins to fall back since the drying speed inside the specimen begins to become uniform and the difference in the amount of shrinkage between the surface and the bottom surface was reduced. Compared with PL specimens, the curling deformation of mortars containing SRA was significantly reduced.

(2) Mass loss rate

The mass loss rate(water-loss) of mortars is shown in Fig. 4. Since the specimens only evaporated water through the upper surface, in the initial stage of drying, it is considered that the mass loss of the specimen dependent on the thickness. The 10mm thin specimens showed largest decrease in mass moisture content. In particular, the specimens containing SRA showed a larger mass loss rate regardless of the thickness. This result is as expected because the SRA used in this experiment is not a type that has a water retention effect, but a type that reduces capillary tension.

2.3 Verification by numerical analysis

(1) Finite element model

A simple numerical simulation method for curling is proposed, based on the 3D Finite Element Method (FEM) analyses with the program ANSYS Workbench. The results obtained by numerical analysis have been compared with the experimental results to verify mutually.

The models have the same dimensions as the specimens, three thicknesses (10mm / 20mm / 30mm) were set, as shown in Fig. 5. Corresponding to the positions of the two supporting steel sheets in the displacement measurement (each 25 mm from the center of the bottom surface of model), two lines of 100 mm length were fixed as constraints. Table 3 listed all material parameters used for numerical analysis in this paper, referring to the "Standard Specifications for Concrete Structures -2007" [5].

Since all specimens have the same drying area, that is, the same type of specimens need to simulate the same shrinkage gradient to reproduce the curl. For this purpose, we split the mortar model from 1/10 of the thickness into two elements, with the upper 1/10 as a shrinkage element. The drying shrinkage is controlled by adjusting the thermal expansion coefficient of the shrinkage element material.

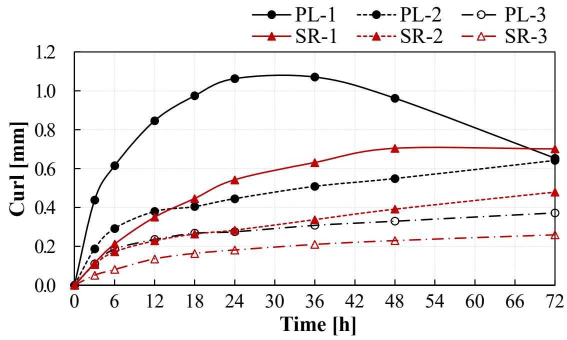


Fig. 3 Curling deformation over 72 hours

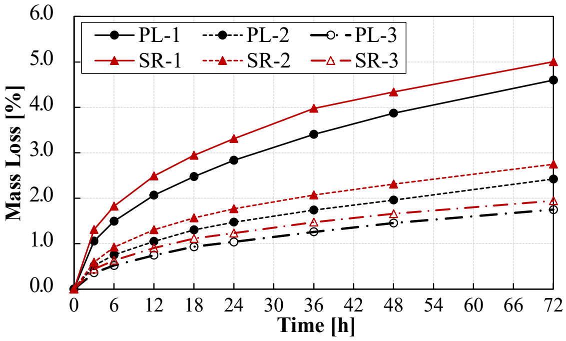


Fig. 4 Mass loss of each specimens

(2) Numerical results

According to Fig. 3, both PL-1 and SR-1 specimens reached maximum deformation in the free curling test. We applied a shrinkage strain of 1300 μ/mm and 800 μ/mm to the shrinkage element based on the displacement of the PL-1 specimen at 36 hours and the displacement of the SR-1 specimen at 72 hours, respectively.

The experimental and numerical displacement comparison results are shown in Fig. 6. Corresponding to the measurement points of displacement in the specimen, the displacement path is the long central axis of the upper surface (shrinkage surface) of the model. Fig. 6(b), (c) shows the results of the model given a shrinkage strain of 1300 μ/mm and 800 μ/mm, compared to the maximum displacement results of PL specimen and the SR specimen, respectively. The numerical results obtained for the models with different thicknesses at quantitative shrinkage strains are well agreed with the experimental results, which indicates that all specimens almost reached peak curling within 72 hours.

In this analysis, we did not give the overall distribution of drying shrinkage strain in the specimen as in reality. Just gave a shrinkage strain to some elements of the upper surface, but the results of the experiment can be reproduced by this analysis, which verified the model and supported the ability to characterize the curl using displacement measurements. In addition, when the same shrinkage strain is input, the experimental results are reproducible for specimens of different thicknesses. This indicates that the internal shrinkage gradients of the driving curling forces of the mortar are similar, which

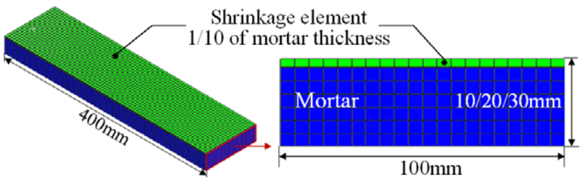
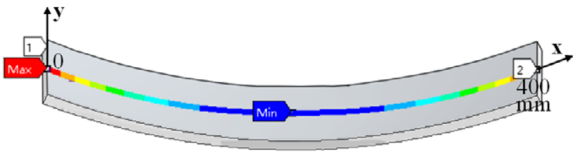
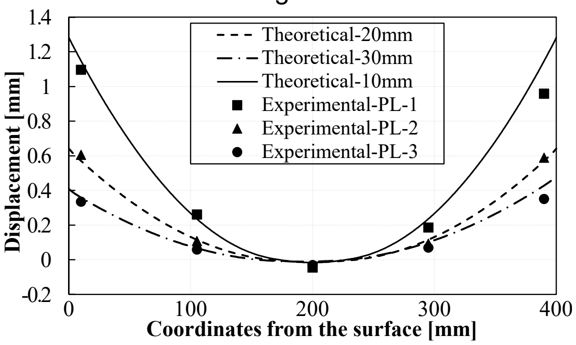


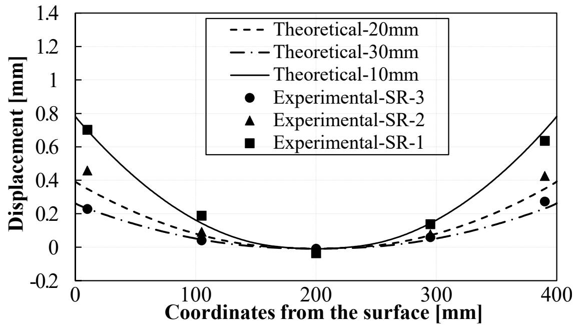
Fig. 5 Free shrinkage model



(a) Displacement of the long axes path in the shrinking surface.



(b) 1300 μ/mm shrinkage model with PL specimen



(c) 800μ /mm shrinkage model with SR specimens

Fig. 6 Comparison the displacement between experimental and numerical response.

may be due to the severe drying conditions.

3. STRESS ESTIMATION UNDER RESTRAINT CONDITIONS

In order to understand the influence of curling on the mortar-concrete adhesion system, modeling the restrained condition to estimate the stress state at the adhesion interface when the curling of the mortar is restrained by the concrete substrate. The model consists of three components, concrete with dimensions of 100×100×400 mm, mortar with dimensions of 10×100×400 mm, and the adhesion interface, the mesh adopted is shown in Fig. 7. An adhesive material based on the Cohesion Zone Model (CZM) was set up at the adhesion interface element. The maximum normal and tangential contact stresses are referenced to the average adhesive strengths obtained in previous studies, by shear test and pull-off test. The state of interfacial stresses in

Table 3 Model material parameters

Parameter	Mortar	Concrete
Density(kg/m³)	2100	2300
Young's Modulus (GPa)	20	28
Poisson's Ratio	0.2	0.2
Tensile Yield Strength (MPa)	3.50	2.78
Compressive Yield Strength (MPa)	39.6	30
Adhesive Interface		
CZM: Separation-Distance based Debonding		
Maximum Normal Stress (MPa)		1.05
Maximum Tangential Stress (MPa)		0.973
Artificial Damping Coefficient(s)		0.001

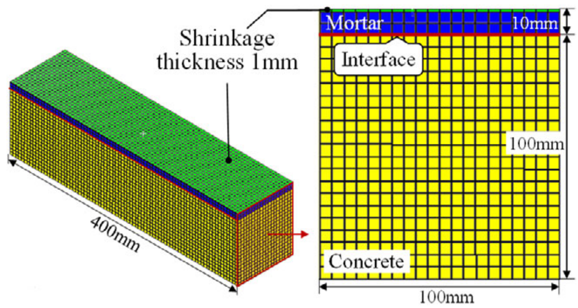


Fig. 7 Restrained shrinkage model

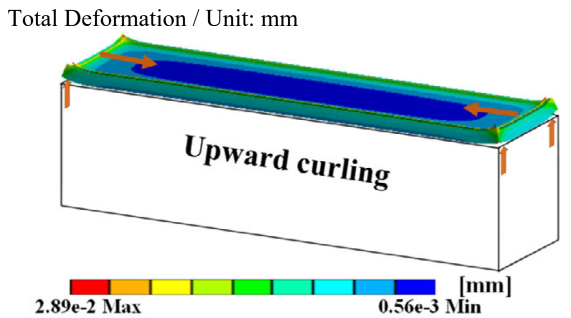
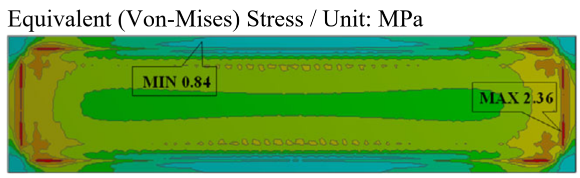
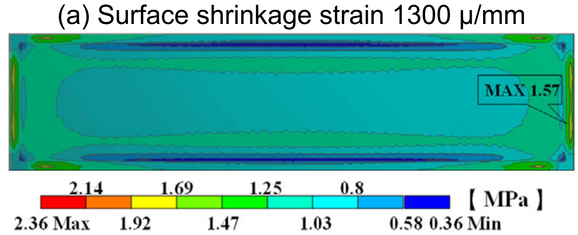


Fig. 8 Maximum deformation of mortar



(a) Surface shrinkage strain 1300 μ/mm

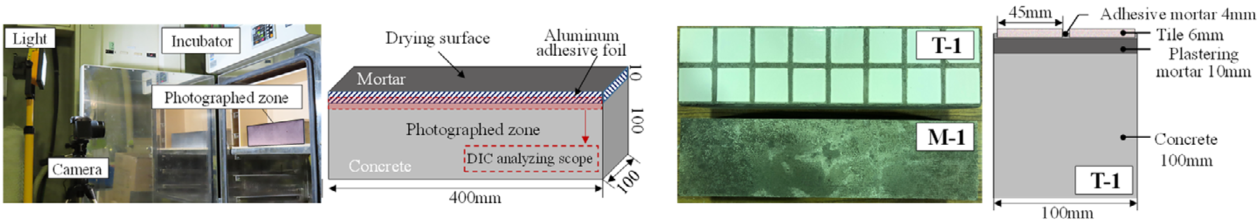


(b) Surface shrinkage strain 800 μ/mm

Fig.9 Equivalent (Von-Mises) Stress (MPa) in the interface

mortars subjected to thermal loading has been studied in our laboratory using the same model [2].

Based on the numerical results of the free curling with the same thickness (10mm), the same method was used to apply the corresponding shrinkage



(a) DIC procedure (b) Specimen

Fig. 10 Monitoring the peeling behavior at the interface between the plastering mortar and the concrete

strain to the restrained curling model. After applying a strain of 1300 μ/mm to the shrinkage element, the deformation result of the mortar Fig. 8 and the equivalent stress distribution at the adhesive interface is shown in Fig. 9(a). The stresses are concentrated at the corners and free edges of the interface. In previous studies, the correlation between the stress generation and the adhesive strength reduction mechanism has been confirmed [2]. We believe that the effect of this degree of stress generation on the mortar-concrete adhesion system is not negligible.

As described in Chap. 2.2, SRA has the effect of reducing the curling of the mortar. According to the numerical results of the SR-1 free curling model, a strain of 800 μ/mm was applied to the shrinkage element of the model and the equivalent stress distribution at the adhesive interface is shown in Fig. 9(b). The interfacial stress decreases as the curling deformation decreases. Hereby, SRA is thought to be able to suppress the reduction in adhesion of the mortar to the substrate due to curling deformation.

4. VERIFICATION OF PEELABILITY BY DIC

4.1 Experimental procedure

Although the numerical simulation results have shown the potential of curling in reducing the adhesive strength of mortar to concrete, the correlation between the interlayer peeling phenomenon and curling still needs to be supported by experimental data. To this end, we monitored the peeling of a mortar cast on a concrete substrate by Digital Image Correlation (DIC) technique, namely monitor the relative displacement between the mortar and the substrate in the out-of-plane direction.

A 100×100×400 mm concrete block was used as the substrate for the specimen. Two common Japanese exterior wall finishes were investigated, mortar coating and tile finish. The mixture proportions of the materials used in the specimens are shown in Table 4.

Table 4 Composition of the specimens

Composition of the concrete substrate

Strength (N/mm^3)	Slump (cm)	W/C (%)	Weight (kg/m^3)				
			Water	Cement	Fines	Coarse	Admixture
36	18	44	180	410	798	887	3.32

Composition of the plastering mortar

Mortar	Cement	Fine Aggregate	S/C (by Weight)	W/C (%)
Pre-mixed mortar	OPC	S: Crushed sand	2.5	50

The concrete substrate was demolded the day after casting and subsequently curing in water for more than two months. Since the restrained curling tests were performed under the same conditions to those of free curling tests, in an incubator (40 °C and R.H. 3%), the concrete was sufficiently dried in the same environment for more than one week before plastering in order to reduce the effect on curling. A mortar layer of 400 mm^2 and 10 mm thickness was then poured on these substrates. To control the thickness of the mortar layer, a suitable mold was used to plaster. After plastering, the mortar was cured in a 20 °C and R.H. 60% environment with a wet cloth covering the exposed surface for 7 days.

After seven days, the mold was removed and the four sides of the plastering mortar layer are insulated by adhesive aluminum tapes. By this time, the preparation of one specimen (M-1) was completed, and the other specimen (T-1) was coated with a tile finish on the upper surface of the plastering mortar layer using adhesive mortar. The tile had dimension of 6×45×45 mm, as shown in Fig. 10(b).

The DIC technique is based on the comparison of two images with two random gray levels recorded before and after a displacement. The first picture is called "reference" and the second "deformed" [3]. In order to ensure the accuracy and relevance of the results obtained by this method, these principles were followed when acquiring the images for post-processing:

(1) Provide a suitable light source and ensure that the light source is consistent for each shot.
(2) The relative position of the camera to the photographed object remains constant.
(3) The parameters of the camera are the same for each shot.

The photographic procedure is shown in Fig. 10(a). During the test, a LED light provides a stable light source. The camera is remotely controlled by a mobile device to ensure that there is no change in the position of the light source, the camera and the specimen. In order to improve the efficiency of image post-processing, the photographed surface of the specimen was spray painted to obtain a random ink dot pattern. From the beginning of drying, images (8278 × 6208 pixels) of the plane were recorded every 24 hours for 3 days.

4.2 Post-processing result

In this study, DIC is carried out using Vic-2D v6, a software developed by Correlated Solutions, to measure displacement fields. In the post-processing software, the AOI (Area-of-Interest) and the size of the subset for the operation are selected. Each subset is used as the smallest feature image unit to estimate the deformation by matching the "deformed" image to the subset with the same characteristics in the "reference" image. Our aim is to investigate the peeling behavior of

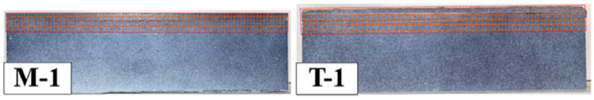


Fig. 11 AOI and subset size (40 × 40 pixels)

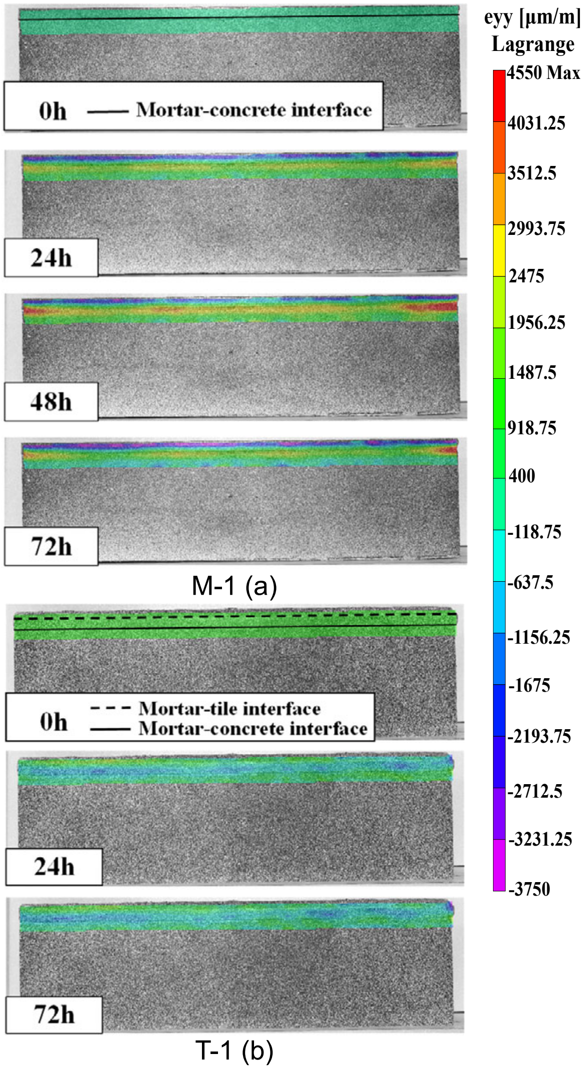


Fig. 12 Strain distributions [µm/m] (in the out-of-plane direction) exhibited by specimens M-1(a) and T-1(b) at each moment.

the mortar-concrete adhesive interface, as shown in Fig. 11, where the selected AOI contains the coating and the interface, and the subset size of 40 × 40 pixels is the result of several tests.

Figure 12 shown the strain distribution along the out-of-plane direction as calculated by the post-processing software. After 48 hours of drying, it can be observed that the M-1 specimen has a clear tendency to peel at the free edge of the adhesive interface between mortar and concrete. Compared to the M-1 specimen, no significant strain in the out-of-plane direction was observed in the AOI range of the T-1 specimen. The strain distribution at 72 hours of drying was almost identical to that at 24 hours. That is, almost no interlaminar peeling occurred in T-1 specimen. Based on the different material properties of ceramic and cementitious materials, the main object of evaporating moisture from T-1 specimens is the adhesive mortar layer, through the tile joints and thin sides, thus the strain may have occurred mainly in the in-plane direction.

5. CONCLUSIONS

Plastering mortar curls due to the drying shrinkage gradient present in the thickness, and the continuous monitoring of the displacement field by the DIC technique enables a clear observation of the mortar peeling due to curling, which can be considered as the mechanism of the adhesion between mortar and concrete decreases at the free edges.

The proposed numerical analysis method can simulate the curl simply and effectively to understand the stress state generated at the interface. It is considered that the curling deformation is an important factor to affect the adhesive unity of mortar and concrete.

Two methods to reduce the curling deformation were tried in this study, applying SRA and overlay. Based on the displacement measurements and DIC monitoring results, both methods were effective in suppressing curling. The inhibition capacity has not been investigated in detail, but we believe that the application of similar techniques that can keep the mortar uniformly dry in construction may be effective in preventing the decrease of bond strength at the free edges, and plan to develop them in the future.

In summary, this study is useful for improving the understanding of the behavior of mortar-concrete adhesion systems, thus improving the durability of mortar coating in actual RC structures. However, this study was conducted under severe dry conditions, a milder experimental environment needs to be set up to further understand the curling behavior, while monitoring the interface stress. Furthermore, in order to evaluate the effect of curling on the durability of the mortar-concrete adhesion system, mechanical properties tests in this condition are planned.

REFERENCES

[1] E. B. Zanelato, J. Alexandre, A. R. G. Azevedo, M. T. Marvila," Evaluation of roughcast on the adhesion mechanisms of mortars on ceramic substrates," Materials and Structures, April 2019, 52:53.

[2] P. Zhang, A. Teramoto, T. Ohkubo," Laboratory-scale Method to Assess the Durability of Rendering Mortar and Concrete Adhesion Systems," Journal of Advanced Concrete Technology Vol.18, 2020, pp. 521-531.

[3] T. Mauroux, F. Benboudjema, P. Turcry, A. Aït-Mokhtar, O. Deves," Study of cracking due to drying in coating mortars by digital image correlation," Cement & Concrete Research Vol.42, 2012, pp. 1014-1023.

[4] M. Chilwesa, L. Facconi, F. Minelli, A. Reggia, G. Plizzari," Shrinkage induced edge curling and debonding in slab elements reinforced with bonded overlays: Influence of fibers and SRA," Cement & Concrete Composites Vol.102, 2019, pp. 105-115.

[5] Japan Society of Civil Engineers: Standard Specifications for Concrete Structures -2007