Housing Authority Research Fund

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Developing Performance Specifications and Testing and Acceptance Criteria of External Wall Finishes in High-rise Residential Buildings
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Summary of Report

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1. **Background**

Conditions of existing wall finishes in high-rise residential buildings are doubtful after a number of failure cases. The failure cases did not only have a negative impact on the aesthetic appearance of the buildings affected, but they also undoubtedly posed a safety hazard to the general public. Types of finishes included applied finishes such as mosaic tiles, ceramic wall tiles, sprayed-on finishes, painting over applied screeding or cladding, etc.

It was noted that building external wall finishes not only fell off from older buildings, but also from some newly completed buildings just a couple of years after their completion. Apparently, reasons for some failures included the poor quality of tiles, inadequate bonding (between wall/substrate/screeding/tiles), the alkaline reaction of cement, vibrations, lack of joints, poor workmanship, etc.

The research team, after completing its literature reviews, considered that wind loading and weathering were two possible reasons for the failures, in addition to poor workmanship. Hence, this research project investigated the current practices of the application of external wall finishes against weathering effects and wind loading.

The research team also explored the practicality of using performance specifications in the design of external wall tile finishes. The reason is that workmanship levels specified in some standards and specifications, for example, BS 5385, are rigid and difficult to achieve. Some, on the other hand, are too ambiguous. Since requirements specified in the standards and specifications depend on environmental factors that are different among countries, a performance specification sets a level of workmanship that gives designers more flexibility to choose the construction methods that they think can achieve it rather than following working procedures rigidly.

2. **Results and findings**

2.1 **The Artificial Weathering Test**

An artificial weathering test was carried out on tiled concrete samples. The concrete samples were 300mm (L) x 150mm (W) x 100mm thick and tiled on the
300mm x 150mm surface. The tiling work was carried out by instructors of the Construction Industry Training Authority (CITA) at the CITA Management Training and Trade Testing Centre in a controlled indoor environment. Variations in weather conditions related to casting of these samples were eliminated. The samples were divided into four groups: (1) Ceramic tiles fixed with 1:3 cement mortar; (2) Ceramic tiles fixed with tile adhesive; (3) Mosaic tiles fixed in accordance with the Hong Kong Housing Authority’s specifications; and (4) Unglazed ceramic tiles fixed with 1:3 cement mortar.

Some of the samples were put into a specially designed artificial weathering device in the Heavy Structure Testing Laboratory at the City University of Hong Kong for tests. The laboratory was air-conditioned and the room temperature during the tests was 24ºC. To simulate the weathering cycle, the samples were heated by a radiator to 45ºC and cooled down to room temperature by a mechanical fan. 50, 100, or 200 weathering cycles were assigned to the samples to investigate the effect of weathering on the shear strength of the external wall finishes. Each weathering cycle consisted of 30 minutes of heating, 10 minutes of cooling, 20 minutes of wetting, and finally 10 minutes of drying.

The remaining samples were assigned 50, 100, or 200 winter cycles, and then put into the freezers of three domestic refrigerators for the weathering process to determine the shear strength of external wall finishes against a cooling effect. Each winter cycle consisted of 40 minutes of cooling followed by 40 minutes of warming.

After the completion of the weathering cycles, the residual shear strengths of the finishes on the samples were determined by a specially designed setup. The setup consisted of an actuator and a set of steel fixtures for keeping the concrete samples in position during the shearing process. The shear strengths of the tile/rendering and rendering/concrete interfaces were determined in the tests.

Results of the shear strength tests are shown in the following graphs:
**Set 1 - Sample specifications:**

Tile Type: 95 mm × 45 mm × 7 mm glazed ceramic tile

Formwork: Timber

Spatterdash: 3 mm (Cement/sand = 1:2)

Rendering: 20 mm (Cement/sand = 1:3)

Cement slurry: 3 mm

According to the test results from Set 1, the plots of the shear bond strength–weathering cycles–temperature difference ($\tau_b - N - \Delta T$) were obtained:
Set 2 - Sample specifications:

Tile Type:  95 mm × 45 mm × 7 mm glazed ceramic tile  
Formwork:  Timber  
Spatterdash:  3 mm (Cement/sand = 1:2)  
Rendering:  20 mm (Cement/sand = 1:3)  
Adhesive:  3 mm (Tile adhesive)

According to the test results from Set 2, the plot of the shear bond strength–weathering cycles–temperature difference ($\tau_b - N - \Delta T$) was obtained:
Set 3 - Sample description:

Tile Type: 20 mm × 20 mm glass mosaic tile
Formwork: Steel
Adhesive: 3 mm (Tile adhesive)

According to the test results from Set 3, the plot of the shear bond
strength–weathering cycles–temperature difference \( (\tau_h - N - \Delta T) \) was obtained:

**Set 4 - Sample specifications:**

Tile Type: 95 mm × 45 mm × 7 mm unglazed ceramic tile  
Formwork: Timber  
Spatterdash: 3 mm (Cement/sand = 1:2)  
Rendering: 20 mm (Cement/sand = 1:3)  
Cement slurry: 3 mm

According to the test results from Set 4, the plot of the shear bond strength–weathering cycles–temperature difference \( (\tau_h - N - \Delta T) \) was obtained:
The results showed that the shear strengths of the external wall finishes dropped after the weathering cycles. The percentage drop was as high as 67 percent of the original un-weathered values. The rendering/concrete interface was generally weaker than that of tile/rendering interface. This observation was in line with the findings from the concrete panel test in the next section.
It can be observed from the graphs that the shear strengths of the four sets of samples increased as they approached 200 weather cycles. One possible reason for that is the variation in the workmanship among batches of samples. In this experiment, the workmanship factor was assumed to be constant, as the aim of the experiment was to determine the variation of shear strength under different weathering conditions. The concrete samples were constructed in different batches. Although the same worker was responsible for the construction of all batches of samples, there might have been variations in workmanship due to human factor.

This experiment successfully developed a set of equipment to perform an artificial weathering test in a laboratory environment, and also developed a setup to perform a shear test to determine the ultimate shear strength of external wall finishes on concrete samples. The researcher suggested that the shear strength of the tile finishes gives better indication of the performance of the tile finishes than traditional pull-off tests, as loading applied on a wall of a building causes the deflection of the wall and induces shear force between various layers in the external wall finishes. This shear force and the effect of weathering on the tile finishes are believed to be the causes of external wall tile failures. Hence, the determination of the shear strength of the tile finishes gives a direct measurement of the strength of adhesion between layers of the finishes.
With the help of the artificial weathering test setup, the weathering of the samples could be accelerated. By determining the shear strength of tile finishes after they have undergone different amounts of weathering cycles, a design curve of the shear strength of the specific tile finishes could be found. This design curve could help designers plan for maintenance works by specifying a minimum acceptable shear strength of the tile finishes.

Due to the limited number of test samples in this project, its test results are not recommended for practical use. Nevertheless, some recommendations for future investigations in order to obtain a set of design values with sufficient accuracy for use in practice in Hong Kong are included in the last chapter of this report.

2.2 The Concrete Panel Tests

The aim of the concrete panel test is to investigate the effects of static wind loads on different specifications of external wall finishes in high-rise residential buildings in Hong Kong. Concrete panels installed with different specifications of external wall finishes and subjected to static loads were tested. The test was carried out from 3rd
June, 2005 to 17th June, 2005 at the Heavy Structure Testing Laboratory of the City University of Hong Kong.

The concrete panels were 3m (L) x 1m (W) x 0.1m thick cast with either timber or steel formworks in Shenzhen, with the panels lying horizontally on the ground for safety reasons. The panels, after curing for 28 days, were transported to Hong Kong for the application of finishes. The finishes were also applied with the panels lying horizontally on the ground due to safety reasons. Sixteen panels were cast, and a total of 16 specifications were tested under the project (Table 1). Strain gauges were installed on each layer to measure the changes in strain during the test. The completed panels were mounted on a steel frame, and the load was applied by an actuator at the mid-span, as shown in Figure 2:

![Figure 2: Setup of the concrete panel test](image)

The test was carried out according to the following procedures:

a) Install the concrete panel on the test frame with 4 nos. of fixing steel bolts.
b) Check the verticality of the concrete panel.
c) Set up the actuator with a steel rod installed at the front.
d) Check the horizontal level of the actuator.
e) Set up the transducers at the back of the concrete panel.
f) Connect the actuator, transducers, and strain gauges to the data logger and set up the data logger for data processing.

g) Set at zero for all channels of the data logger before the start of the test.

h) Apply the load using a displacement control method and increase the displacement by 0.01 mm at one-second intervals.

i) Take note of the positions of cracks, if any, and record the load, displacement, and location of cracks immediately.

j) Apply the load continuously until damage to the tile finishes is observed.

k) Release the load using a displacement control method until the load is fully released.

l) Stop the test when the load is fully released and store the test data in a computer disk.

For all 16 concrete panels tested, shear failures only occurred beyond the design wind load and curvature. It was observed that during the tests, flexural cracks appeared at the mid-span of the concrete panel at the back before any shear failures were observed. These confirmed that the 16 different specifications of fixing external wall tile finishes on concrete are suitable under Hong Kong’s current wind loading requirements. The design wind load based on the Code of Practice on Wind Effects in Hong Kong 2004 was 12.8 kN, and no failure was observed from the 16 concrete panels below this loading.

For the five panels that failed in shear (Panel nos. 3, 7, 8, 14, and 15), all of the shear failures occurred at the interface between the rendering and concrete substrates. This observation showed that the bonding between the rendering and concrete substrates was the weakest among all the interfaces in the external wall finishes. One possible reason for this could be the spatterdash applied. The strength and quality of adhesion relies heavily on the judgement of the one who apply the spatterdash, which may differ among each worker.
Table 1: Specifications of tile finishes for concrete panels and a summary of test results

<table>
<thead>
<tr>
<th>Panel no.</th>
<th>Type of tile</th>
<th>Formwork</th>
<th>Spatterdash/ Bonding agent</th>
<th>Rendering</th>
<th>Cement slurry/ Adhesive</th>
<th>Max. loading</th>
<th>Max. displacement</th>
<th>Tile finishes failed? (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>20mm (1:3)</td>
<td>3mm</td>
<td>43kN</td>
<td>10mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Timber</td>
<td>Bond Coat Admix</td>
<td>20mm (1:3)</td>
<td>3mm</td>
<td>30kN</td>
<td>11mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>10mm (1:3)</td>
<td>3mm</td>
<td>28kN</td>
<td>15mm</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>30mm (1:3)</td>
<td>3mm</td>
<td>58kN</td>
<td>19mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>20mm (1:2)</td>
<td>3mm</td>
<td>60kN</td>
<td>26mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>20mm (1:4)</td>
<td>3mm</td>
<td>55kN</td>
<td>24mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>20mm (1:3)</td>
<td>3mm + MIX Bond Coat Admix</td>
<td>48kN</td>
<td>22mm</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Timber</td>
<td>3mm (1:2)</td>
<td>20mm (1:3)</td>
<td>Adhesive</td>
<td>44kN</td>
<td>31mm</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Timber</td>
<td></td>
<td></td>
<td>Adhesive</td>
<td>43kN</td>
<td>51mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Steel</td>
<td></td>
<td></td>
<td>Adhesive</td>
<td>42kN</td>
<td>50mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Timber</td>
<td></td>
<td></td>
<td>Adhesive</td>
<td>45kN</td>
<td>43mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Steel</td>
<td></td>
<td></td>
<td>Adhesive</td>
<td>45kN</td>
<td>48mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Steel</td>
<td></td>
<td></td>
<td>Bond Coat Admix</td>
<td>41kN</td>
<td>50mm</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Steel</td>
<td>3mm (1:2)</td>
<td>20mm (1:3)</td>
<td>3mm</td>
<td>40kN</td>
<td>22mm</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Steel</td>
<td>3mm (1:2)</td>
<td>10mm (1:3)</td>
<td>3mm</td>
<td>32kN</td>
<td>32mm</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td>Steel</td>
<td>3mm (1:2)</td>
<td>30mm (1:3)</td>
<td>3mm</td>
<td>60kN</td>
<td>21mm</td>
<td>N</td>
<td></td>
</tr>
</tbody>
</table>
As this test mainly focused on the effect of static wind loading on the performance of external wall finishes, further investigation should be carried out to determine the effect of dynamic wind loading and the fatigue effect of the repeated application of wind loading.

3. Conclusions and Recommendations for Further Studies

This research study investigated the effect of static lateral wind loading and weathering on the performance of external wall finishes by the concrete panel and artificial weathering tests.

Results from the concrete panel tests indicated that the existing specifications by the HKHA and the most commonly adopted specifications in Hong Kong for the application of external wall tile finishes using cement sand mortar and tile adhesive were adequate under the static lateral wind loading situation in Hong Kong. Further studies are recommended to investigate the effect of dynamic wind loading and fatigue on the performance of external wall finishes.

The artificial weathering and shear bond strength tests in this project were a good start for investigating the effects of temperature and moisture on the performance of the external wall finishes. The test results provided a basis for the development of guidelines in the design, selection, and installation of external wall finishes for high-rise residential buildings in Hong Kong. The method of artificial weathering and the proposed shear bond strength test could be further developed for future investigation and the development of an in-situ testing method. However, due to the limited number of test samples in this project, the test results are not recommended for practical use. In view of this, there are some recommendations for future investigations in order to obtain a set of design values with sufficient accuracy for use in Hong Kong:

(1) The ultimate shear bond strength for each external wall specification and specified weathering cycle should be obtained from an average of at least 20 concrete samples from the same batch in order to minimize the variations in shear bond strength due to the heterogeneous properties of external wall
finishes.

(2) The number of weathering cycles should increase further to 300, 400, 500, or even up to 1,000 in order to investigate the long-term effects of weathering on the performance of external wall finishes. This is very important towards establishing a series of design curves for designers in their design and selection of external wall finishes. The curves so obtained could also be used to determine the expected life spans of each type of external wall finish from which building owners can work out a systemic maintenance plane according to the strength degradation given by the set of design curves.

(3) The summer cycles of the artificial weathering process included both the heating and wetting processes, and the test results so obtained included the combined effects of temperature and moisture. Therefore, it was proposed that the process of heating and wetting could be carried out separately in order to investigate the effects of either the heating or wetting process on the performance of external wall finishes individually.

(4) The weakest bond between the render and concrete interfaces could be an area for in-depth study.

The research team also explored the possibility of using performance specifications in external wall tile finishes. The proposed performance specification approach provides flexibility for designers to choose construction methods and materials to be used for external wall tile finishes, unlike the current prescriptive specifications, in which flexibility is limited. Designers can propose specifications to cater to specific needs on-site.

Practically, there are three stages if the proposed performance specification approach is adopted. First, the designer will carry out design for external wall finishes. Then mock-up units will be constructed according to the design. Finally, the units will be tested against the design requirements, like shear strength or durability, to verify whether these requirements are met.

Further investigation should be carried out to determine the design parameters to be considered and tested, and tests should be carried out on the mock-up units. The
artificial weathering test, shear test, and concrete panel test performed in this project could be used or modified for use in the verification tests on the mock-up units. These tests could provide information on the static wind loading the effects of weathering on the shear strength of the tile finishes.

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