Adhesion Strength Change Analysis Based on the Application Surface Area Ratio of Spot-Bonded Tiles on Vertical Walls of High Humidity Facilities

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Abstract: Facility walls with high relative humidity, such as bathrooms or kitchens installed with tiles by spot-bonding methods, become far more prone to defect or adhesion failure when using large or heavy tiles and insufficient application area of adhesive but is still continued to be practiced due to their low costs in the material. Most importantly, if this practice is to be continued, the changes in adhesion strength of the tiles based on different adhesive application areas of adhesives must be clarified such that the very least secure application can be achieved even by using spot-bonding methods. In this regard, an experiment was conducted in this study where tile-adhered specimens with different adhesive-applied area ratios (AR) of 60 ± 2%, 80 ± 2%, and 100% were prepared. Tile adhesion strength was subsequently measured, after sectioning the entire surface of the tile into 40 pieces. Experimental results showed that the adhesion strength above the standard criteria could be achieved for about 75% of the entire tile with AR 100% conditioning, followed by 30% of the entire tile with AR 80 ± 2% conditioning, and 20% of the entire tile for AR 60 ± 2% conditioning. Further analysis showed that with AR 80 ± 2% and AR 60 ± 2% conditions, the overall adhesion strength decreased by the range of about 59–67% compared to the AR 100% application conditions. The results of the study intended to provide an analytical basis of guidelines and risks with the potential usage of spot-bonding and should only be used if AR 100% application is planned.

Keywords: spot-bonding; mortar; tile adhesion method; degradation

1. Introduction

Recent trends indicate that larger sizes and shapes of tiles are more commonly used in architecture [1,2]. Related to this, adhesion-related defects in tiles, particularly in facilities such as bathrooms, living rooms, utility rooms, balconies, kitchens, and entrances of apartment houses (as shown in Figure 1), where humidity is generally higher, are becoming more common in the tile industry [3,4]. The review of general defects showed that the rate of “indoor tile adhesion failure” occupied about 10% of the total number of defects found in residential buildings [5], and the rate of tile-adhesion failure in bathrooms was the highest [6].
The cause of these issues was found to be due to an un-regulated usage of a spot-bonding technique, where the adhesive application area ratio was low with only three or four globs of adhesive being applied to the negative side of the tile, leading to the majority of the negative-side being comprised of the cavity [7]. While spot-bonding is clearly less used than the ANSI Specifications method (Section A108.5-2.2.2; hereby called ‘troweled method’), where the adhesion must be at least 80% of the tile surface and adhesion strength must be 0.5 N/mm² or above. However, there are still parts of the world, particularly in East Asia, South East Asia, South America, and Eastern Europe, where spot-bonding methods and related low-quality material and construction methods persist due to construction work time and budget constraints [7,8]. In light of this situation, this study proposed that if the spot-bonding method was inevitably used, a proper evaluation or verification in the field should be conducted to shed light on the risks of the spot-bonding method and provide an optimal adhesive application area ratio. Accordingly, for the countries that still use spot-bonding methods for tile installation, this study offered an analysis of the change in overall tile adhesion strength according to the changes of the total adhesive application surface area for spot-bonding methods.

The application of this proposed study is foremost intended to be a demonstration and is limited and compliant to materials and applications commonly found in Korea. However, the evaluation methodology and theoretical principles are designed to be applicable to any nations where the results of this study would be beneficial. The following sections include details on the theoretical reasoning on the design of the proposed new evaluation method by a comparison of the existing ISO (International Standard Organization) 13007-2 to an experimental evaluation method involving a total surface attachment method for adhesive strength testing of spot-bonded tiles. The results showed that a complete sectioned tile testing was required for fully shedding light on the adhesion stability of spot-bonded tiles.

The following sections discuss the planning, execution, and demonstration of a new evaluation method for spot-bonded tiles. The method consisted of sectioning the entire tile (250 × 400 mm) into 50 × 50 mm tile specimen pieces with adhesive application surface ratio conditions in intervals of 60 ± 2%, 80 ± 2%, and 100%. The individual pieces underwent adhesion strength testing, whereby the adhesion stability of the respective specimens of different adhesive application ratios was compared.

2. Theoretical Discussion

2.1. Background Research

Tile installation methods are generally classified into two categories: troweled adhesion (as prescribed by the ANSI specification) and spot-bonding methods. The troweled adhesion method is widely used in Europe, the United States, and Canada. Polymer-based or acrylic-based adhesives are commonly initially applied to the wall surface, followed by the tile installation. The troweled adhesion method has systemized adhesive quality standards, construction methods, and on-site quality control methods. On the other hand, the spot-bonding method involves the method of first applying an unspecified amount or number of ‘globs’ of cementitious-based adhesive on the negative side of the tile, followed
by the wall installation. There is no clear technical standard for the proper adhesion surface area ratio of the base and tiles with this method [9]. The current status of indoor wall tile construction standards by country is shown in Table 1 below.

**Table 1.** International tile installation methods and related standards.

| Items                  | Europe                                  | U.S.                               | Asia (Korea and China) |
|------------------------|-----------------------------------------|-------------------------------------|------------------------|
| Installation Method    | Troweled adhesion method                | Troweled adhesion method            | Troweled adhesion and spot-bonding method (both) |
| Adhesive Material      | Polymer                                 | Polymer                             | Cement mortar, polymer (both) |
| Wall Type              | Achieved smoothness from board, plastering, etc., and set tile | Achieve smoothness from 1st plastering and set tile | Apartment: board, plywood finish Wall type: after brick, masonry cement mortar tile bond setting on 1st plastered side |
| Related Standard       | ISO 13007, EN 12004                     | ANSI 108, EN 1204                   | Requires more development to meet troweled-adhesion-method quality standard |
| Evaluation Standard    | Bonding strength C1:0.5 N/mm², C2:1.0 N/mm² | Shearing strength 28d:1.03–2.76 MPa | Bonding strength 0.39–0.5 N/mm² |

2.2. Tile Application Methods Comparison

Spot-bonding is a method that commonly comprised of applying spots of adhesive at few large sections on the rear side of the tile. The type of materials used is usually a cement-based adhesive with a significant portion taken up by cement mortar with an unregulated W/C ratio. It is a commonly known problem that spot-bonding leaves substantial voids behind the tile (as shown in Figure 2). Based on the survey review, approximately 3–4 globs (generally in the corner sections) are applied, and the mortar is dispersed due to the pressing force of the worker to form a larger adhesion area. The need to conduct an individual application of adhesive on the tiles results in slower workability (7–10 m²/day) with usually higher adhesive thickness than the troweled adhesion method (20–40 kg/m², 10–25 mm thickness.) This typically results in an adhesion contact that is substantially less than the requirements of having at least 80% evenly distributed tile-to-adhesive support at the edges and corners [10]. As adhesive dispersion is generally dependent on the skills and strength of the worker, there is a limit in quality consistency for sections higher than the worker’s height [11,12]. In cases where workers are installing larger sized tiles, the weight of the tile and the cementitious adhesive increase the risk of adhesion failure [9].

![Figure 2. Common spot-bonding method procedure: (a) mortar preparation for spot-bonding; (b) mortar setting (wall) for spot-bonding; (c) tile installation; (d) notched line and surface treatment.](image-url)
the construction work time. Refer to Figure 3 for sample images of how tile sizes have increased in recent years.

![Figure 3. Facilities installed with tiles: (a) 1980s case; (b) 1990s case; (c) recent case.](image)

On the other hand, the troweled adhesion method consists of initially applying the polymerized/cementitious adhesive on the substrate wall surface (as shown in Figure 4), followed by applying a notched lining of the adhesive on the surface for securing a stable tile adhesion.

![Figure 4. Notched trowel application method procedure: (a) adhesive preparation; (b) application on substrate surface and creation of 5–7 mm deep channels; (c) tile installation; (d) securing adhesion with tile and adhesive.](image)

The adhesion strength depends greatly on the type of polymer and admixture that are mixed into the adhesive material [14,15]. As opposed to the spot-bonding method, the troweled adhesion method has obvious advantages in the sense that there are no voids forming between the tile and the bonding material and, on average, uses less amount of adhesive (3–7 kg/m², 2–7 mm thickness), and has faster workability (20–30 m²/day). [16,17]. However, as the adhesive must first be applied to the entire wall sections, tile application must follow directly after to ensure that the adhesive does not dry or cure. When compared in terms of worker convenience, the troweled adhesion method is less preferred, which leads to countries without strict regulations of tile quality assurances allowing the usage of spot-bonding more freely. A comparison of typical differences between the spot-bonding method and trowel adhesion method is summarized in Table 2 below.

| Item                        | Spot-Bonding Method | Troweled Adhesion Method |
|-----------------------------|---------------------|--------------------------|
| Adhesive/Bonding Material   | Cementitious adhesive (cement/mortar-based bonding material) | Dry mortar/adhesive application (polymer, acrylic, epoxy, etc.) |
| Installation Method         | Mortar adhesive is applied to the rear side of the tile and, subsequently, installed on the wall 20–40 kg/m² | Adhesive is first applied to the wall, followed by the tile installation 3–7 kg/m² |
| Weight and Adhesive Thickness | 10–25 mm 7–10 m²/day | 2–7 mm 20–30 m²/day |
| Workability                 | Experienced workers (technicians) required | Generalized work level sufficient |
Table 2. Cont.

| Item                  | Spot-Bonding Method | Troweled Adhesion Method |
|-----------------------|---------------------|--------------------------|
| Adhesion Strength     | 0.4–0.6 N/mm²       | 1.5–4.0 N/mm²            |
| Concept Illustration  |                     |                          |
| Relevant Nations      | Korea, China, Southeast Asian Countries | Europe, U.S., etc. |

3. Experimental Regime

3.1. Experimental Scope

For the evaluation method for measuring the adhesion strength, the principle regimes of pull-off testing were conducted in compliance with the ISO standards [18,19], and the adhesive application area ratio was divided into 60 ± 2% and 80 ± 2% and 100% respectively. For the ambient conditions of the experiment, the specimens, finished with the adhesive application, were cured for 28 days under the standard conditions with a temperature of 23 ± 2 °C and humidity 50 ± 5% according to ISO 13007-2 [18] (Shown in Table 3).

Table 3. Experimental scope summary.

| Criteria                  | Detailed Content                                | Standard       |
|---------------------------|-------------------------------------------------|----------------|
| Materials                 | Adhesive for spot-bonding                        | General cementsitious adhesive (ready-made) OPC  |
|                           | 20%, sand 80%, additive 0.5%                   | ISO 13007-1    |
|                           | Ceramic tile (250 × 400 mm)                     |                |
| Tile                      | Absorptivity 13.2%                              | ISO 10545-2    |
|                           | Firing temperature: 1000–1200 °C                | ISO 13007-2    |
|                           | Flexural strength 103.7 N/cm                    |                |
| Concrete substrate        | Concrete 400 × 400 mm                           | ISO 13007-2    |
| Specimen tile size        | 250 × 400 mm                                    | N/A            |
| Evaluation                | Adhesion strength                               | Plate (metallic disc) square (50 ± 1) mm side |
|                           | Test speed (250 ± 50) N/s                       | ISO 13007-2    |
|                           | Glue epoxide                                    |                |
| Spot-bonding interface    | 100%, 80 ± 2%, 60 ± 2%                          | N/A            |
| surface area              | Cured for 28 days under standard ambient        |                |
|                           | conditions (temperature 23 ± 2 °C, humidity 50 ± 5%) | ISO 13007-2    |

As this experimental methodology’s principal purpose was to compare the changing adhesion strength stability of the entire tile surface area based on the amount of adhesive used, common factors for causing adhesion failures such as filling rate (adhesion area), adhesive material type, water absorption rate, construction environment (temperature, humidity, etc.), and structural deformation movement [10–12] were made as consistent and simple as possible for this demonstration, and the scope of the experiment of this study was limited to the effect of the adhesion area using one type of cementitious adhesive and ceramic tile in compliance to the KS L 1001:2020 standard.

3.2. Experimental Plan

3.2.1. Base Load Derivation

In general, the amount of pressing (installation) load required for tiles is difficult to exactly quantify in construction sites. In this regard, the ISO standard test method (ISO
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In general, the amount of pressing (installation) load required for tiles is difficult to standardize, and the load and time exerted by the worker when constructing a tile in the actual site are calculated, and the average working load is calculated through this, and this force is standardized. It was intended to prepare the attached specimen using a pressing load.

In order to derive an applicable evaluation methodology for assessing the ratio of the stable adhesion area for spot-bonded tiles, first, an applicable load was derived based on the estimated amount of force applied by the average worker. To this end, a separate experiment was conducted where each of the upper, middle, and lower sections based on the height of the bathroom wall of the house (2300 mm) was installed with tiles by four adult males in their 20 s and 40 s. For the tile application, a single 250 × 400 mm tile was applied to a wall structure. The force and time of pressing while attaching the tile were measured and presented as the basis for the weight when making the specimen. Refer to Table 4 for details.

Table 4. Tile application pressure derivation testing results.

| Criteria | Age | Height | Weight | Load (N)/(Pressure Applied Time (sec)) |
|----------|-----|--------|--------|---------------------------------------|
| Male A   | 20 s| 170 cm | 85 kg  | 56/(6 sec) 67/(5 sec) 61/(6 sec) 74/(6 sec) 64.5/(5.5 sec) |
| Male B   | 40 s| 174 cm | 70 kg  | 115/(8 sec) 107/(8 sec) 118/(9 sec) 127/(9 sec) 116.8/(8.5 sec) |
| Male C   | 30 s| 183 cm | 70 kg  | 75/(7 sec) 84/(6 sec) 91/(7 sec) 83/(7 sec) 83.3/(6.8 sec) |
| Male D   | 20 s| 175 cm | 78 kg  | 900-2,300 300-1,050 |
| Average  | 20 s|        |        | 1.650-2,300 |

As a result of the specimen preparation procedure, the average of the four was found to be 64.5 N (5.5 s) in the upper part, 116.8 N (8.5 s) in the middle part, and 83.3 N (6.8 s) in the lower part, and the overall average was 88.2 N (6.9 s). Based on the average of the average results, it was decided to apply a pressure load of up to 7 s using a 100 N weight on the top of the tile when manufacturing the specimen. It must be kept in mind that for the replicability of evaluation in the future, results might vary as the above testing would need to be rechecked in accordance with different national standards or circumstances.

3.2.2. Method of Estimating the Adhesion Area of the Spot-Bonded Mortar

In order to verify the adhered area of the back of the tile of the specimens, the spot-bonding area was converted by overlapping the captured image in the Autocad program.
after photographing them with a thermal imaging camera. The measurement principle of the thermal imaging camera is that the area where the immobilized mortar is applied and the empty area show a difference due to heat conduction, which can be distinguished by the spectral area of the heated area.

After attaching the spot-bonding mortar test specimen (Figure 5a) to the concrete base surface (Figure 5b), the image taken with the thermal imaging camera (Figure 5c) was formed in a grid in the Autocad program (as shown in Figure 5d) and the area was calculated. The area was set in the range of 100%, 80 ± 2%, and 60 ± 2% as in the experimental regime.

**Adhesive-Application Area Ratio (AR)**

60 ± 2%

80 ± 2%

100%

Rear side application state

Figure 5. Spot-bonded mortar adhesion surface area determination process: (a) spot-bonded mortar; (b) adhesion on to concrete surface; (c) thermal emission imaging; (d) digital mapping.

3.3. **Adhesion Testing Method Preparation**

The ISO standard evaluation was conducted according to the adhesion strength test method compliant to ISO 13007-2. A total of four separate pull-off apparatus plates (attachment pieces) were applied to the tile surface using an epoxy bond on a tile specimen of 50 × 50 mm size, two on the center sections (labeled Number 2 and 3), and two at the...
outer sections (labeled Number 1 and 4), as shown in Figure 6. The adhesion attachment strength for each installed tile piece was measured by applying a pull-off load at a speed of 250 ± 50 N/s using a UTM apparatus (Kyungsung Testing Machine Co., Ansan, Korea). This testing was repeated with five separate such specimens in order to confirm the change in the adhesion strength of the cementitious adhesive according to the applied area.

Figure 6. Specimen and test method illustrated for the ISO (International Standard Organization) standard pull-off test.

The results of adhesion strength evaluation conducted according to the adhesion strength test method of ISO 13007-2 are as shown in Table 5 and Figure 7 below, and the results showed that the strength was less than the ISO standard (0.5 N/mm²), and the specimen number 4 (70%) showed about 175% adhesion compared to the ISO standard.

Table 5. Adhesion strength result of the specimens based on ISO standard evaluation.

| Specimen Number | No. 1  | No. 2  | No. 3  | No. 4  | No. 5  | Avg.  |
|-----------------|--------|--------|--------|--------|--------|-------|
| 1               | 0.76   | 1.06   | 0.21   | 0.61   | 0.31   | 0.59  |
| 2               | 1.43   | 1.44   | 1.32   | 1.48   | 1.19   | 1.372 |
| 3               | 0.93   | 1.51   | 1.27   | 1.31   | 1.25   | 1.254 |
| 4               | 0.14   | 0.14   | 0.24   | 0.50   | 0.39   | 0.282 |
| Average         | 0.82   | 1.04   | 0.76   | 0.98   | 0.79   | 0.878 |

Figure 7. ISO standard adhesion strength evaluation results.

Figure 7 shows that the adhesion strength results varied in accordance with the location numbers, where light blue (1) and purple (4) were on the edges, and orange (2) and gray (3) were in the center sections. The results confirmed that the edge sections of all specimens (No. 1 to 5) had lower tensile strength than in the center. As a result of this analysis, the difference between the adhesive strength (average 1.31 N/mm²) of the central part (specimen No. 2 and 3) of the tile and the adhesion strength (average 0.44 N/mm²) of the edge part (No. 1 and 4) was about 0.87 N/mm². As a result of examining the negative
side of the tile after the test (shown in Figure 8), it was found that the edges of the No.1
and 4 pieces had a lower adhesion surface than the central parts of the No. 2 and No. 3
pieces. This result was similar to A. Wetzel’s (2010) previous study [1], and it was judged
that the adhesion of the edge portion was formed lower than that of the central portion.
As expected, the results of this precursory experiment indicated that the dispersion of the
adhesive on the negative side interface of the tile did not reach the edge sections of the
tile, and there was about three times the difference of achieved adhesion strength between
the center sections (Number 2 and 3 tile pieces) and the edge sections (Number 1 and 4
tile pieces).

Figure 8. Tile adhesion state after ISO standard adhesion testing.

In this regard, it was confirmed through this precursory testing that served to validate
that the normal ISO standard evaluation procedure was not sufficient to provide a concise
evaluation of the overall adhesion stability of spot-bonded tiles and that a new evaluation
method must be designed. Using the ISO standard evaluation method alone was difficult to
comprehensively determine the adhesion strength of the spot-bonded tile as the difference
in adhesion strength varied to a significant degree, depending on which part of the adhesion
attachment piece (pull-off plate) was attached to the specimen. In real sites, this type of
defect could be common with the glob-type application for spot-bonding and could result
in fractures or cracks occurring on the tile if left unattended.

Subsequently, a specially manufactured metal disc with a size of 250 × 400 mm was
used, and a tension jig was installed in the center of the tile as shown in Figure 9 (shown in
a,b), at a speed of 250 ± 50 N/s using a standard UTM specification testing apparatus.

Figure 9. Entire tile-pull-off testing attempt: (a) testing plan (unit: mm); (b) testing site; (c) testing results (fracture at the
derge sections of the tiles).

As can be seen in Figure 9c, the result of the fracturing of time was expected to having
been caused due to a bending phenomenon, in which the concentrated stress of the tension
pulled the attachment on the specimen body (concrete plate). The cavities under the edge
sections, due to the lack of adhesive dispersion, allowed the tile to crack before a proper
measurement of the entire tile’s adhesive strength could be taken.
Accordingly, a new evaluation method was derived to determine the comprehensive adhesion strength of the total surface area of the tile by sectioning the entire tile into individual pieces, whereby the adhesion strength testing (pull-off testing) was conducted, where applicable, and the adhesion strength concentration areas could be quantified and mapped. The new evaluation method derived, based on the results of the ISO standard evaluation method, consisted of sectioning the entire surface of the tile. As shown in Figure 10, a 250 × 400 mm ceramic tile (compliant to the specifications in Table 3, designed for the new evaluation) was used, and the entire surface of the tile was sectioned into 50 × 50 mm pieces (total of 40 pieces), where 8 pieces were lined up along the width and 5 pieces along the length of the tile. This process was deemed necessary for the evaluation to be able to (1) objectively and completely compare and assess the degree of adhesive dispersion ratio after pressing between the specimens of different ARs (to be able to determine how many pieces would end up with results similar to the one found in Figure 8, number 4 tile piece), and (2) if the sectioned pieces were in accordance with the specifications of the ISO evaluation standard. The process was repeated for tiles where the cementitious adhesive application surface ratio differed by the following intervals: 60 ± 2%, 80 ± 2%, and 100% surface area.

![Figure 10](image)

**Figure 10.** Tile total surface area sectioning into pieces for pull-off testing (unit: mm).

### 3.4. Specimen Preparation Method

For the specimen assembly, a tile was placed on a scale, and the cementitious adhesive was evenly distributed (about 400 g per 1 spot) and applied on the negative side of the tile (Figure 11a) parallel to the cross-section of the length of the tile. The amount at this time was about 3 to 4 spots for each adhered area, identified through the previous section ‘3.2.2 Method of estimating the surface area of spot-bonding mortar’, based on the initial total of 2000 g of cementitious adhesive. After that, 100 N weight was placed on the tile, with the ends of the tile held while applying a load for 7 s (Figure 11b), and the thickness of 10 to 15 mm (Figure 11) from the base surface was made sure to be consistent throughout the different specimens (Figure 11c). Three such specimens were prepared for each adhered area ratio conditioning, and the adhesion strength was evaluated shown in the following Figure 12.

![Figure 11](image)

**Figure 11.** Specimen preparation method: (a) mortar setting for spot-bonding; (b) 100 N weight placement; (c) mortar thickness measurement.
3.5. Adhesive Dispersion Based on Different AR Conditions

As a result of this experiment, it was confirmed that the smaller the adhered area, the higher the proportion of the adhesion strength of the center to the tile adhesion. Based on these results, the areas where it was possible to measure adhesion strength that was consistently the same for all three test specimens under the three conditions adhesive application area ratio (hereby labeled AR) of 60 ± 2%, 80 ± 2%, and 100% set in this study, are shown in Figures 13a–c. The schematic analysis (mapping) was performed as follows, based on the averaged results of the testing: in the case of specimens with cementitious AR 60 ± 2%, the area where the adhesion strength could be measured was mainly located near the center of the tile, and the peripheral parts of these sections were mostly without any adherence (cavities with no bonding due to absence of adhesive support), as shown in Figure 13a. In the case of specimens with cementitious AR 80 ± 2%, adhesion was again evidently concentrated in the center section and some in the peripheral parts, as shown in Figure 13b. In the case of specimens with AR 100%, while there were few pieces with cavities near the edge sections of the entire tile, successful adhesion was apparent throughout the entire specimen (shown in Figure 13c).

The figures below show a mapping of tile pieces where the adhesion was apparent, overlapped with the results of all three specimens. Red color indicates pieces where the adhesion was common for all 3 specimens, pink color indicates pieces where adhesion was common for 2 specimens, and light-yellow color indicates pieces where adhesion was found for one specimen.

Figure 12. Sectioned pieces adhesion strength (pull-off) evaluation method: (a) 60 ± 2% specimen (units: mm); (b) 80 ± 2% specimen (units: mm); (c) 100% specimen (units: mm).
near the center of the tile, and the peripheral parts of these sections were mostly without any adherence (cavities with no bonding due to absence of adhesive support), as shown in Figure 13a. In the case of specimens with cementitious AR 80 ± 2%, adhesion was again evidently concentrated in the center section and some in the peripheral parts, as shown in Figure 13b. In the case of specimens with AR 100%, while there were few pieces with cavities near the edge sections of the entire tile, successful adhesion was apparent throughout the entire specimen (shown in Figure 13c).

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Based on the analysis of the tile pieces where the adhesion strength could be measured, it was found that adhesion strength increased relative to the increased concentration of the adhesive-applied area ratio (AR), but the adhesion strength was much lower at the corner and edge sections. In particular, it was confirmed that even if the bonded area formed over 100% of the entire area, the cavity sections where adhesion strength could not be measured were mostly shown to be forming at the edge sections. The AR of the adhered pieces and pieces with cavity (no adherence) are shown in Table 6 below.

Based on the distribution of the adhered pieces for specimens with AR 60 ± 2%, the area in which cementitious adhesive bonding was successful reached an average of 47.5% (difference of 12.5% from the AR ratio), and for specimens with AR 80 ± 2%, the adhered piece ratio was 77.5% (difference of 2.5% from the AR ratio).

This is an important point as workers or contractors were using spot-bonding with few applications of globs, mostly only on the corner sections of the tiles. The assumption followed that pressing the tiles would spread the adhesive, resulting in an evenly distributed adhesive throughout the negative side of the tile, but the results in Table 6 show that the adhesive distribution was far less than intended, and the mapped-out tiles with

![Figure 13. Adhesion ratio distribution map of specimens based on measurable adhesion strength pieces: (a) AR (adhesive-applied area ratios) 60 ± 2%; (b) AR 80 ± 2%; (c) AR 100%.](image-url)

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secure adhesion and measurable adhesion strength was an indication of the risks of using only globs of adhesive for the spot-bonding method.

Table 6. Overall adhesion analysis report for specimens of respective AR.

| Tile Piece Adhesion Conditions | Adhesion Surface Ratio (AR) (%) |
|-------------------------------|--------------------------------|
|                               | 60 ± 2 | 80 ± 2 | 100 |
| Number of adhered tiles pieces (measurement is possible) | 19 (47.5%) | 31 (77.5%) | 40 (100%) |
| All 3 specimens with the same tile pieces | 9 (22.5%) | 14 (35%) | 34 (85%) |
| 2 specimens with the same tile pieces | 7 (17.5%) | 6 (15%) | 4 (10%) |
| Individual specimen tile pieces | 3 (7.5%) | 11 (27.5%) | 2 (5%) |
| Above standard (0.5) | Adhesion ratio 57.9% | Adhesion ratio 41.9% | 31 (77.5%) |

3.6. Analysis of Adhesion Strength by Adhesion Area

3.6.1. AR 60 ± 2% Specimen Results

For the AR 60 ± 2% specimens, out of the 40 tile pieces of the specimen, 14 (35% of the entire tile surface) of No.1 specimen showed stable adhesion, and the pieces that satisfied the ISO standard requirement (0.5 N/mm²) was 7 (50% of the stable attached pieces). For the No. 2 specimens, 14 (35% of the entire tile surface) showed stable adhesion, and 13 (92.9% of the stable attached pieces) satisfied the ISO standard requirement. For the No. 3 specimens, 16 pieces (40% of the entire tile surface) showed stable adhesion, and the pieces that satisfied the ISO standard requirement were 10 (62.5% of the stable attached pieces). The overall average adhesion strength of the No.1, No. 2, and No. 3 specimens were, respectively, 0.21 N/mm², 0.28 N/mm², and 0.26 N/mm², resulting in a comprehensive average of 0.25 N/mm². When considering the average of only the pieces with stable adhesion, the average was, respectively, 0.59 N/mm², 0.81 N/mm², and 0.66 N/mm², resulting in a comprehensive average of 0.69 N/mm². Refer to Table 7 and Figure 14 below (sections marked with 0.00 represent tiles with cavities where there was no cementitious adhesive support for the tile or cases where measurement was not impossible).

Table 7. AR 60 ± 2% specimen result.

| Specimen Number | Coordinates | x1  | x2  | x3  | x4  | x5  | x6  | x7  | x8  | Avg.  | Results |
|-----------------|-------------|-----|-----|-----|-----|-----|-----|-----|-----|-------|---------|
| 1st Specimen    | y1          | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00  | Total Avg. 0.21 N/mm²<br>Pieces measured 14 |
|                 | y2          | 0.00| 0.23| 0.16| 0.36| 0.95| 0.43| 0.71| 0.00| 0.36  |          |
|                 | y3          | 0.00| 0.27| 1.02| 0.40| 0.97| 0.92| 0.52| 0.00| 0.51  |          |
|                 | y4          | 0.00| 0.00| 0.38| 0.00| 0.89| 0.00| 0.00| 0.00| 0.16  |          |
|                 | y5          | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00  |          |
|                 | Avg.        | 0.00| 0.10| 0.31| 0.15| 0.56| 0.27| 0.25| 0.00| 0.21  |          |
| 2nd Specimen    | y1          | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00  | Total Avg. 0.28 N/mm²<br>Pieces measured 14 |
|                 | y2          | 0.00| 0.00| 0.86| 0.00| 0.90| 0.51| 0.68| 0.00| 0.37  |          |
|                 | y3          | 0.00| 0.00| 1.07| 1.01| 1.00| 1.00| 0.74| 0.00| 0.60  |          |
|                 | y4          | 0.00| 0.00| 0.94| 0.40| 0.95| 0.68| 0.63| 0.00| 0.45  |          |
|                 | y5          | 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00| 0.00  |          |
|                 | Avg.        | 0.00| 0.00| 0.57| 0.28| 0.57| 0.44| 0.41| 0.00| 0.28  |          |
| 3rd Specimen    | y1          | 0.00| 0.00| 0.00| 0.00| 0.21| 0.00| 0.00| 0.00| 0.00  | Total Avg. 0.26 N/mm²<br>Pieces measured 16 |
|                 | y2          | 0.00| 0.18| 0.47| 0.65| 0.00| 0.00| 0.85| 0.00| 0.27  |          |
|                 | y3          | 0.00| 0.41| 1.21| 0.94| 0.97| 0.78| 0.75| 0.00| 0.63  |          |
|                 | y4          | 0.00| 0.00| 0.77| 0.47| 0.87| 0.81| 0.00| 0.00| 0.37  |          |
|                 | y5          | 0.00| 0.00| 0.00| 0.21| 0.00| 0.00| 0.00| 0.00| 0.03  |          |
|                 | Avg.        | 0.00| 0.12| 0.49| 0.45| 0.41| 0.32| 0.32| 0.00| 0.26  |          |
3.6.2. AR 80 ± 2% Specimen Results

For the AR 80 ± 2% specimens, out of the 40 tile pieces of the specimen, 26 (65% of the entire tile surface) of No.1 specimens showed stable adhesion, and the pieces that satisfied the ISO standard requirement (0.5 N/mm²) were eleven (42.3% of the stable attached pieces). For the No. 2 specimens, 15 (37.5% of the entire tile surface) showed stable adhesion, and 13 (54.2% of the stable attached pieces) satisfied the ISO standard requirement. For the No. 3 specimens, 24 pieces (60% of the entire tile surface) showed stable adhesion, and the pieces that satisfied the ISO standard requirement were 13 (54.2% of the stable attached pieces). The overall average adhesion strength of No.1, No. 2, and No. 3 specimens were, respectively, 0.32 N/mm², 0.32 N/mm², and 0.29 N/mm², resulting in a comprehensive average of 0.31 N/mm². When considering the average of only the pieces with stable adhesion, the average was, respectively, 0.49 N/mm², 0.88 N/mm², and 0.48 N/mm², resulting in a comprehensive average of 0.61 N/mm². Refer to Table 8 and Figure 15 below.

Table 8. AR 80 ± 2% specimen result.

| Specimen Number | Coordinates | x1   | x2   | x3   | x4   | x5   | x6   | x7   | x8   | Avg.   | Results  |
|-----------------|-------------|------|------|------|------|------|------|------|------|--------|----------|
| 1st Specimen    | y1          | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.13 | 0.00 | 0.02   | Total Avg. 0.32 N/mm² 26 Pieces measured |
|                 | y2          | 0.00 | 0.20 | 0.19 | 0.16 | 0.40 | 0.17 | 0.99 | 0.13 | 0.28   | 0.32 N/mm² 26 Pieces measured |
|                 | y3          | 0.00 | 0.71 | 1.06 | 1.14 | 0.99 | 0.69 | 1.19 | 0.00 | 0.72   | 0.32 N/mm² 26 Pieces measured |
|                 | y4          | 0.14 | 0.81 | 0.45 | 0.78 | 0.25 | 0.57 | 0.07 | 0.32 | 0.07   | 0.32 N/mm² 26 Pieces measured |
|                 | y5          | 0.14 | 0.15 | 0.00 | 0.14 | 0.00 | 0.16 | 0.00 | 0.00 | 0.07   | 0.32 N/mm² 26 Pieces measured |
|                 | Avg.        | 0.06 | 0.37 | 0.34 | 0.45 | 0.25 | 0.62 | 0.05 | 0.32 | 0.05   | 0.32 N/mm² 26 Pieces measured |
|                 | y1          | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00   | Total Avg. 0.32 N/mm² 26 Pieces measured |
|                 | y2          | 0.00 | 0.00 | 0.85 | 1.53 | 1.29 | 0.57 | 0.00 | 0.00 | 0.53   | 0.32 N/mm² 26 Pieces measured |
| 2nd Specimen    | y3          | 0.00 | 0.00 | 0.98 | 1.12 | 1.44 | 0.75 | 0.24 | 0.00 | 0.57   | 0.32 N/mm² 15 Pieces Measured |
|                 | y4          | 0.00 | 0.00 | 0.41 | 0.74 | 1.19 | 0.90 | 0.22 | 0.00 | 0.43   | 0.32 N/mm² 15 Pieces Measured |
|                 | y5          | 0.00 | 0.00 | 0.00 | 0.52 | 0.00 | 0.00 | 0.00 | 0.00 | 0.07   | 0.32 N/mm² 15 Pieces Measured |
|                 | Avg.        | 0.12 | 0.23 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 | 0.05   | 0.32 N/mm² 15 Pieces Measured |
|                 | y1          | 0.00 | 0.34 | 0.17 | 0.16 | 0.77 | 0.35 | 0.71 | 0.00 | 0.31   | Total Avg. 0.29 N/mm² 24 Pieces Measured |
|                 | y2          | 0.00 | 0.65 | 0.81 | 0.88 | 0.44 | 0.54 | 0.65 | 0.00 | 0.50   | 0.29 N/mm² 24 Pieces Measured |
| 3rd Specimen    | y3          | 0.28 | 0.74 | 0.55 | 0.97 | 0.71 | 0.77 | 0.59 | 0.00 | 0.57   | Total Avg. 0.29 N/mm² 24 Pieces Measured |
|                 | y4          | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.08 | 0.02   | 0.29 N/mm² 24 Pieces Measured |
|                 | y5          | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.06 | 0.00 | 0.08 | 0.02   | 0.29 N/mm² 24 Pieces Measured |
|                 | Avg.        | 0.07 | 0.39 | 0.31 | 0.40 | 0.38 | 0.34 | 0.40 | 0.02 | 0.29   | 0.29 N/mm² 24 Pieces Measured |

Figure 14. AR 60 ± 2% specimen adhesion strength per piece coordinate (average).
3.6.3. AR 100% Specimen Results

For the AR 100% specimens, out of the 40 tile pieces of the specimen, 40 (100% of the entire tile surface) of No.1 specimens showed stable adhesion, and the pieces that satisfied the ISO standard requirement (0.5 N/mm$^2$) were 30 (75% of the stable attached pieces). For the No. 2 specimens, 36 (90% of the entire tile surface) showed stable adhesion, and 28 (77.8% of the stable attached pieces) satisfied the ISO standard requirement. For the No. 3 specimens, 36 pieces (90% of the entire tile surface) showed stable adhesion, and the pieces that satisfied the ISO standard requirement were 32 (88.9% of the stable attached pieces). The overall average adhesion strength of No.1, No. 2, and No. 3 specimens were, respectively, 0.78 N/mm$^2$, 0.73 N/mm$^2$, and 0.76 N/mm$^2$, resulting in a comprehensive average of 0.76 N/mm$^2$. When considering the average of only the pieces with stable adhesion, the average was, respectively, 0.78 N/mm$^2$, 0.85 N/mm$^2$, and 0.85 N/mm$^2$, resulting in a comprehensive average of 0.83 N/mm$^2$. Refer to Table 9 and Figure 16 below.

Table 9. AR 100% specimen result.

| Specimen Number | Coordinates | x1   | x2   | x3   | x4   | x5   | x6   | x7   | x8   | Avg.   | Result       |
|-----------------|-------------|------|------|------|------|------|------|------|------|--------|--------------|
| 1st Specimen    |             |      |      |      |      |      |      |      |      |        |              |
| y1              |             | 0.32 | 0.74 | 0.79 | 0.93 | 0.76 | 0.66 | 0.71 | 0.23 | 0.64   | Total Avg.   |
| y2              |             | 0.36 | 0.94 | 0.80 | 0.89 | 1.09 | 0.70 | 1.16 | 0.41 | 0.79   | 0.78 N/mm$^2$ |
| y3              |             | 0.42 | 1.11 | 1.05 | 1.18 | 1.07 | 0.89 | 0.97 | 0.43 | 0.89   | 0.73 N/mm$^2$ |
| y4              |             | 0.32 | 1.01 | 0.70 | 0.72 | 0.64 | 0.85 | 0.64 | 0.33 | 0.67   | 0.76 N/mm$^2$ |
| y5              | Avg.        | 0.38 | 1.02 | 0.86 | 1.01 | 0.96 | 0.79 | 0.90 | 0.34 | 0.78   | 0.83 N/mm$^2$ |
| y1              |             | 0.53 | 0.73 | 0.40 | 0.81 | 0.82 | 0.81 | 1.00 | 0.60 | 0.71   | 0.78 N/mm$^2$ |
| y2              |             | 0.41 | 1.04 | 0.00 | 1.00 | 1.08 | 0.99 | 0.98 | 0.48 | 0.75   | 0.75 N/mm$^2$ |
| 2nd Specimen    |             |      |      |      |      |      |      |      |      |        |              |
| y3              |             | 0.19 | 1.16 | 1.20 | 1.07 | 1.12 | 1.12 | 1.02 | 0.46 | 0.92   | Total Avg.   |
| y4              |             | 0.00 | 0.84 | 1.22 | 0.78 | 0.83 | 1.25 | 0.96 | 0.30 | 0.77   | 0.73 N/mm$^2$ |
| y5              | Avg.        | 0.23 | 0.92 | 0.73 | 0.79 | 0.82 | 0.95 | 1.01 | 0.37 | 0.73   | 0.76 N/mm$^2$ |
| y1              |             | 0.00 | 0.81 | 0.79 | 0.88 | 0.81 | 0.74 | 0.85 | 0.57 | 0.68   | 0.69 N/mm$^2$ |
| y2              |             | 0.32 | 1.01 | 0.89 | 1.02 | 1.11 | 0.87 | 1.04 | 0.69 | 0.87   | 0.67 N/mm$^2$ |
| 3rd Specimen    |             |      |      |      |      |      |      |      |      |        |              |
| y3              |             | 0.46 | 1.18 | 1.09 | 1.16 | 1.05 | 1.03 | 1.01 | 0.34 | 0.92   | Total Avg.   |
| y4              |             | 0.24 | 1.04 | 0.92 | 1.05 | 1.15 | 0.92 | 0.9  | 0.00 | 0.78   | 0.76 N/mm$^2$ |
| y5              | Avg.        | 0.20 | 0.97 | 0.89 | 0.98 | 0.96 | 0.87 | 0.90 | 0.32 | 0.76   | 0.75 N/mm$^2$ |

Figure 15. AR 80 ± 2% specimen adhesion strength per piece coordinate (average).
4. Experimental and Analysis Result

Table 10 displays the summary of the adhesive strength measurements of the different AR conditioned specimens. For each specimen number of the respective AR conditioning, first, the overall average tile (including the non-measurable pieces with cavities) adhesion strength is given. This is followed by the number of tiles with stable adhesion per specimen of the respective AR conditioning and the percentage ratio relative to the entire tile surface (out of 40 total pieces). Next, the average adhesion strength of the total number of pieces with stable adhesion is given. Among those, the number of pieces and ratio of those that passed the ISO standard regulation are outlined, respectively. Based on these results, a comprehensive report was drafted in the form of a graph where the total number of pieces (120 for each AR conditioning) and their adhesion strength results were plotted on a graph for easier visual comparison. Refer to Table 10 and Figure 17 for details.

Table 10. Tile specimen evaluation analysis result.

| AR Conditions | AR 60 ± 2% | AR 80 ± 2% | AR 100% |
|---------------|------------|------------|---------|
|               | No. 1      | No. 2      | No. 3   | No. 1      | No. 2      | No. 3   | No. 1      | No. 2      | No. 3   |
| Overall average adhesion strength (N/mm²) | 0.21 | 0.28 | 0.26 | 0.32 | 0.32 | 0.29 | 0.78 | 0.73 | 0.76 |
| Stable adhesion pieces (Numbers (%)) | 14 (35%) | 14 (35%) | 16 (40%) | 26 (65%) | 15 (37.5%) | 24 (60%) | 40 (100%) | 36 (90%) | 36 (90%) |
| Avg. adhesion strength of the stable adhesion pieces | 0.59 | 0.81 | 0.66 | 0.49 | 0.88 | 0.48 | 0.78 | 0.85 | 0.85 |
| Pieces that meet the ISO standard (0.5) or above | 7 (17.5%) | 13 (32.5%) | 10 (25%) | 11 (27%) | 12 (30%) | 13 (32.5%) | 30 (75%) | 28 (70%) | 32 (80%) |
| Entire tile/stable adhesion pieces ratio (%) | 50% | 92.9% | 62.5% | 42.3% | 80% | 54.2% | 75% | 77.8% | 88.9% |

As evidenced by the results shown in Figure 17, the majority of the sectioned tile pieces of AR 100% specimens were able to not only achieve stable adhesion (few with non-measurable tile pieces) but also met the requirements of the ISO standard evaluation criteria. However, in contrast, the results of AR 80 ± 2% showed significantly more varied results ranging from non-measurable tile pieces to pieces that meet the ISO standard criteria requirement. For the AR 60 ± 2%, there were very few pieces that passed the ISO standard criteria, with the majority of the samples having non-measurable adhesive strength. This result was a reflection of the potential unexpected results of the spot-bonding installation method of tiles, as the averaged pressure load during installation was not sufficient to achieve a stable adhesion dispersed throughout the negative side of the tiles of glob-based spot-bonded tiles. While it was expected that AR 80 ± 2% should at least achieve similar
results to that of AR 100%, the trends of adhesion strength variation throughout the tile surface were closer to that of AR 60 ± 2%.

![Graph showing adhesion strength variation](image)

**Figure 17.** Comprehensive comparison of different AR-conditioned tile pieces.

Next, the averaged values of all of the parameters in Table 10 were derived and shown in Table 11, and trend lines were provided in Figure 18. As shown below, the overall average adhesion strength of AR 60 ± 2% was 0.25 N/mm², and AR 80 ± 2% was 0.31 N/mm², and AR 100% was 0.76 N/mm², accordingly. Excluding AR 100% conditioned specimens, AR 60 ± 2% and AR 80 ± 2% specimens were both on average found not to be able to meet the ISO standard adhesion strength requirement of 0.5 N/mm², and it was confirmed that there was a difference of overall adhesion strength by a range of 59–67% across all conditions of AR 60 ± 2% to AR 100%. Refer to Table 11 and Figure 18 for details.

| AR Conditions | Results (Average) |
|---------------|-------------------|
|               | 60 ± 2%           | 80 ± 2%           | 100%           |
| 40 tile pieces adhesion strength average | 0.25 N/mm² | 0.31 N/mm² | 0.76 N/mm² |
| Fully adhered pieces | 14.7 (36.7%) | 21.7 (54.2%) | 37.3 (93.3%) |
| Average adhesion strength of the fully adhered pieces | 0.69 N/mm² | 0.61 N/mm² | 0.83 N/mm² |
| ISO standard (0.5) above | 10 (25%) | 12 (30%) | 30 (75%) |
| Entire tile/stable adhesion pieces ratio (%) | 68.5% | 58.8% | 80.6% |

**Table 11.** Overall adhesion strength result per spot-bonding surface area condition.

Figure 19 compares the strength reduction rate for the overall average adhesion strength (entire tile) and the average adhesion strength of the individually sectioned tiles (with measurable adhesion strength) based on changing AR conditions. As a result of analyzing the pieces with secure bonding, the adhesion strength of the AR 60 ± 2% condition was an average of 0.69 N/mm², AR 80 ± 2% was an average of 0.61 N/mm², and AR 100% was an average of 0.83 N/mm². In the case of AR 100%, all of the specimens showed an adhesion strength performance that met the ISO standard requirement.
Figure 18. Average adhesion strength change linear regression based on the spot-bonding surface area.

Figure 19. Adhesion strength difference between the averaged and individual adhered pieces relative to the common adhered points.

As can be seen in Figure 19, both AR 60 ± 2% and AR 80 ± 2% had a significant variation of the comparison (an indication that a majority of the surface area was a cavity), whereas, in contrast, AR 100% had a minimal difference of adhesion strength when comparing the values of the entire tile to those with stable adhesion. Through these results, it was shown that if AR 100% was secured, it was possible to secure the standard adhesion strength for about 80% of the entire tile surface, and when the adhesion area (AR) was around 80%, it was possible to secure the standard adhesion strength with only about 30% of the entire surface, and when AR was around 60%, only 25% of the entire tile could achieve stable adhesion.

The experimental demonstration conducted in this study was performed using a commonly used adhesive material and tile base in Korea, compliant with the material specifications and regulations of both the ISO standards and KS (Korean standard). However, further investigation of different tile bases and adhesives must be conducted using the evaluation regime and guideline of this study to propose an installation guideline and standard for the spot-bonding method of tiles. While the quantitative results of this experiment are not yet expected to be used as a reference for other countries, it is hoped that
the methodology is replicable and highly recommended to be conducted in other nations for a better understanding of their respective situations on the spot-bonding installation of tiles.

5. Conclusions

In this study, the change in adhesion strength according to the reduction of the adhesion area of the stubborn mortar in relation to the detachment defects of the indoor wall tiles was analyzed, and the following conclusions were drawn:

(1) Through the ISO standard adhesion strength evaluation method it was confirmed that the spot-bonding method is also able to secure stable adhesion, but only in sections where the spot-bonding mortar was securely installed, leading to the hypothesis that, as long as a higher surface area application of the cementitious adhesive is achieved, a stable installation of the tile by spot-bonding can also be achieved.

(2) By using a new evaluation method consisting of sectioning the tile into individual pieces across the entire tile surface, an adhesion strength evaluation in the spot-bonding method using large tiles was made possible by schematic mapping of the tile with high and concentrated adhesion strength. Through this schematic analysis of adhesion strength throughout the tile surface, the results confirmed that the adhesion strength of the tile cementitious adhesive surface ratio should be 100% in order to achieve adhesion strength of the tile above the standard regulation for approximately 80% of the tile area. Further investigation is required to assess different material types, different load conditions during tile pressing, and ambient conditions need to be conducted in the near future to establish a reliable data set on the tile spot-bonding installation method, but it is hoped, nonetheless, that the evaluation methodology proposed in this study is viable for continuous studies on this topic.

Based on the results of this study, the following conclusions can be offered; the spot-bonding installation method for tiles is still effective, but only when having secured an AR of 100% (by which only about 75% of the tile surface would achieve stable adhesion). It is evident that the practice of spot-bonding will not be completely discontinued any time soon, as the economic advantages of spot-bonding for contractors are too high. If such is the case, what should at the very least happen is, the results of this study should be referenced to understand the exact risks of poorly conducted spot-bonding tile installation. The results of the evaluation method demonstration have experimentally proven that if spot-bonding is to be used, then few glob applications (AR 60–80%) should not be conducted. When evaluating the adhesion stability to large-sized tiles in the future, a test method of splitting and measuring the entire surface of the tile can be applied, and a study on the standard test method for this is required.

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Abbreviations

AR     Adhesive-application area ratio
ISO    International Standard Organization
USP    Upper substrate part
UTM    Universal testing machine

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