Experimental studies on the prevention of staining in building exterior: focused on the sloped wall

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1. Introduction

1.1. Background and purpose of study

With the development of new building materials and technology, the exterior of the building is becoming increasingly complex beyond aesthetic limitations and constraints. Complex exterior attract attention in the short term, but in the long term, repeated exterior pollution and maintenance costs can lead to unexpected results. In particular, certain forms of exterior can have a profound effect on the life span of building by causing and repeating premature staining depending on weather conditions. The sloped wall, one of the certain exteriors, is a position where dust is more likely to collect than the vertical wall, and consideration of the external environment and precipitation patterns is essential. As in Figure 1, locations vulnerable to pollution, including sloped walls, can always be seen to repeat pollution after cleaning and the defects gradually increase over time. In other words, repeated staining due to physical shape causes high maintenance costs each year, and it causes abuse of resources, such as being repaired or demolished at an early stage. This situation stems from awareness lack of the exterior staining and the importance of preventing staining at the design stage. The best way to avoid pollution is to prevent problems from the beginning, and it is of paramount importance to deal seriously with the problem of exterior staining during the initial design stage of the project. If staining is considered during the design stage, it can last for a long time with economic effects without extra defect management. In other words, it is meaningful to immediately present prevention plans for various alternatives made in the initial design stage and to prevent pollution in advance based on this.

Therefore, the purpose of this study is to identify pollution phenomena and alternatives through experiments with sloped walls that are vulnerable to staining and to present basic pollution measures that can be applied to the design stage.

1.2. Study methods and procedures

In this study, a quantitative outdoor experimental study was conducted to present reasonable approach and planned plans to prevent staining of sloped walls in the design stage. The experimental site was Hapcheon-gun, Gyeongsangnam-do, and it was selected as a place for long-term experiments under the same exposure conditions during the same period. The experimental mockup was largely completed by dividing it into two aspects: Staining experiments of the sloped wall(T) and Staining prevention experiments(P). First of all, the critical angles of the six finishing materials were measured at the site for the experiment of the sloped wall(T), and the slope walls were installed sequentially at angles such as 90°, 75°, 60°, 45°, 30°, 15°, and critical angle for each material. In addition, the reverse sloped walls were additionally installed at angles such as – 75°, – 60°, – 45°, –
30°, – 15°, etc. The planning methods (P) were installed by applying Superhydrophobicity and superhydrophobicity to the critical angles of six materials to reduce dust absorption by gravity precipitation. The throating was installed at the critical angle of the painting walls and applied to the intersection of the sloped wall and the vertical wall, such as 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm. The total materials were unified into 30 cm x 48 cm to consider constructivity and to facilitate comparison of diagnosis. A total of 68 prototypes consist of a combination of sloped and vertical walls and conducted five experimental investigations over 9 months.

As a method of diagnosis of staining, a grid of 30 cm x 48 cm with 15 measuring points was made to increase mobility and accuracy of diagnosis and to determine the pollution index based on 15 average values. For quantitative diagnosis and data management of staining, CS-10 color meter satisfying KSA 0066 and YG60 glossmeter complying with ISO 2613 and jigg96 grades 1 were used. Surface roughness was measured with AMITTARI AR-131A conforming to the international standards of ISO and ASTM with auxiliary devices. The initial measurements of the entire sloped wall were diagnosed after the experimental mockup and were compared to the data measured at intervals of 2 months. Through the collected data and photographs, the pollution phenomena were compared and analyzed by angle and material to identify the measures for the staining and the characteristics of the critical angle of the sloped wall. Finally, the results

![Figure 1. Showing increasing aesthetic deficiency over time (Verhoef 1988; Parnham 1997).](image)

![Figure 2. Procedure of experiments.](image)
Defects obtained through the planning method experiment are presented according to angle, material, throating, surface control.

2. Literature review

2.1. Major previous studies

Asmone and Chew (2018) referred to the need for experience in materials and sound technical knowledge for exterior maintenance and verified the self-cleaning capacity of superhydrophobic coatings through a year-long experiment. Shim (2001) arranged cases and recurrence prevention measures from the point of view of not easily contaminated over time, and Min (1995) introduced the location, defects, inspection, diagnosis and repair methods of contamination. In addition, from the perspective of building materials and performance design, Kim (2007) described the importance of designing building materials for durable life and longevity of buildings considering various architectural needs and the global environment. Lim (2008) identified the factors behind the decline in life expectancy of the exterior of the building and identified the characteristics of change in the exterior of the building through on-site surveys of commercial buildings. Based on the above information, prior research on the persistence and pollution of the exterior of a building refers to the general causes and examples of the exterior contamination of a building, and alternative studies in the maintenance stage are the majority.

2.1.1. Defect management

The defects of a building can be defined as falling short of the quality, performance, and aesthetics levels normally expected due to the fault or omission of the parties in the design and construction stages. Therefore, defect management of a building can be classified as design defects and construction defects by managing incomplete elements of the finished object. First of all, in the design stage, premature staining occurs due to the indiscriminate planning of certain designs such as sloped walls and protruded walls, or the omission of throating, and the use of inappropriate materials. In the next construction and maintenance stage, defects such as condensation, discoloration, elimination, corrosion, cracking, and efflorescence are generated due to poor construction and supervision or insufficient material performance. Here, if defects occur during the construction and maintenance stage, actions can be taken immediately, but defects resulting from incorrectly plan in the design stage are not easy to take action. That is, the best way to avoid pollution is to prevent problems from the beginning, and it is of paramount importance to deal seriously with the problem of exterior pollution during the initial design stage of the project. Therefore, this paper proposes planning methods for defects resulting from incorrectly plan in the design stage rather than defect management in the construction and maintenance stage. It aims for buildings that live a long life by preventing staining without additional defect management by taking measures in advance during the design stage.

Table 1. Defect management by stage.

| Sortation | Design stage | Construction and maintenance stage |
|-----------|--------------|-------------------------------------|
| Defect type | Premature Staining | Peel, Rust, Efflorescence, Germ, Condensation, Leak, cracking, corrosion |
| Cause | Staining | Poor construction and supervision |
| | Specific architectural designs such as sloped wall and projected wall | Poor material performance |
| | Omitted throating | Lack of construction period |
| | Use of unsuitable materials | |
| | Insufficient design plans | |
| | Defect management | Consideration of the surrounding environment |
| | Prevention planning in design stage | Check of the material condition |
| | Apply the right coatings | Surface measures and cleaning management |
| | Prevention of | Check of joints and insulation |

Table 2. Working definition for wall concrete building.

| Researcher (year) | Working definition for wall concrete building |
|-------------------|----------------------------------------------|
| Lee (2012)        | It is a construction technology that finishes the concrete surface with the color and texture of the concrete itself without any additional finishing materials on the concrete surface. |
| Jeong, Choi, and Choi (2017) | In the form of finishing materials with the color and texture of the concrete itself, the concrete is exposed to the state of deformation after the concrete is built, emphasizing the unique beauty of the form itself. |
| Choi et al. (2019) | It is a finishing method that allows the surface of concrete to be exposed to the outside without additional finishing on the concrete surface. The surface is finished with the raw material and texture of the concrete itself, and the structure itself or by concurrently finishing the work. |
| Lim (2005)        | After constructing a reinforced concrete structure, the finishing materials are not separately constructed on the concrete surface, and the concrete surface is finished with the color and texture of the concrete itself. |
| Kim (2005)        | A building that is constructed so that the surface of concrete is exposed to the outside so that it can have a natural finishing effect on the concrete itself without using separate finishing materials. |
| Wikipedia         | Concrete wall buildings are structured and finished construction, and it is integrated process work that cannot separate the entire process from design to finish. |
Table 3. Defect of wall concrete building in design stage.

| Researcher (year) | Defect of Wall Concrete Building | Characteristics |
|-------------------|---------------------------------|------------------|
| Chew and Tan (2003a) | - Staining occurs mainly in specific designs such as new materials and complex facades. - Staining according to porosity | - Staining occurs on shelves, joints, misaligned, protruding fasteners, and louvers. - Predict and prevent exterior staining when conscientious efforts are made during the design stage. |
| Flores-Colen, de Brito, and de Freitas (2008) | - Staining is found mainly in most exterior areas of concrete. - Staining according to porosity | - Visual inspection identifies types of stains and organizes classification procedures. |
| Park et al. (2018) | - Staining caused by rainwater runoff - Contamination by the texture of the material | ● Suggest algorithms to review alternatives to materials and shapes to prevent staining during the design phase and to review rainwater runoff. |
| Blocken, Derome, and Carmeliet (2013) | - Staining caused by rainwater runoff | ● Rainwater runoff reduce design life and increase huge repair and replacement costs. ● Tendency to give up facade details essential to protecting rainwater runoff. |
| Parnham (1997) | - A number of features or elements on building facades are regularly associated with premature staining problems. | ● Definition of premature staining. ● Lack of recognition of exterior pollution. |
| Serralheiro, de Brito, and Silva (2017) | - Staining according to the surrounding environment | ● Based on visual inspection of 174 concrete surfaces. ● Buildings in dusty environments such as road-sides and coasts. ● The average life expectancy of public buildings in Seoul is 34 years. ● Presentation of pollution phenomena and prevention methods in five locations that are mainly contaminated. |
| Choi and Choi (2020) | - Shape and location aspects such as sloped wall, protruded wall, wall under window, etc. | - Cleanliness test by applying Superhydrophobicity coating. - Coating experiment for consideration in design stage. |
| Asmone and Chew (2018) | - Staining according to porosity | |

2.1.2. Wall concrete buildings

The concrete wall building is a construction technology that finishes the concrete surface with the color and texture of the concrete itself without any additional finishing materials on the concrete surface (Lee 2012). Since concrete wall buildings are exposed to the outside for 365 days, special care is needed to keep the appearance of concrete clean from external environmental pollution. In particular, planning and designing with aesthetic expectations of concrete walls is prone to major errors. Since the concrete itself is projected onto the exposed surface, it is important to understand the material of the concrete at the design stage because the repaired surface can be different from the texture of the concrete.

2.1.3. Defect of wall concrete building

Concrete walls cause defects depending on texture, porosity, shape, and surrounding environment, and mainly cause staining. The surface texture of concrete dictates the ease of holding dust on the surface of the material, the pattern of rainwater runoff, and the prominence of stains. Textured surfaces tend to have higher preservation of dust than smooth surfaces. Therefore, the textured surface may experience larger staining due to a larger amount of retained dust. Textured surfaces tend to divide and disperse the water flow above the surface. And because concrete is porous, it absorbs moisture easily during rain through capillary adsorption. Because the surface is porous, dust deposited nutrients promote biological growth and create dark spots. In addition, rainfall may cause local stains due to dust absorption, erosion and deposition due to weak cleaning effects. Third, it is the form design that should be most careful about defects. Unconsciously designed forms have fatal consequences for staining. After dust collects on the horizontal, sloped, and protruded surface, rainwater and wind spill pollution onto the external wall. And concrete buildings in dusty environments such as roadsides and coasts are more affected than those in other cities.

In order to minimize contamination of concrete wall buildings, it is necessary to consider the details of the entire process from the design stage to maintenance. A number of studies are being conducted regarding defects in concrete walls, and a total of 24 papers have been drawn. Analysis of the derived studies step by step is shown in Table 4. Most existing studies have been conducted to derive improvement measures from construction and management methods to improve the performance of finishing concrete walls, but research on staining measures at the design stage is insufficient. As a result, there is a situation in which the fundamental cause cannot be solved and repeated defects are generated. Therefore, the purpose of this study is to identify the fundamental causes and situations through appearance experiments of multiple materials and to present basic staining measures that can be applied to the design stage.
2.1.4. The Importance of Staining Concerns in the Design stage

Choi and Choi (2020) identified the pollution phenomena on the exterior of the Seoul public borough offices for reasonable access to pollution prevention and planning measures during the initial design phase. They also mentioned that it is important to consider countermeasures during the design phase for mainly contaminated locations such as sloped walls. Chew and Tan (2003a) noted that stain pollution occurs mainly in certain designs, such as new materials and complex facades, and that conscientious efforts in the initial design stage can actually predict and prevent exterior pollution. Flores-Colen, de Brito, and de Freitas (2008) identified the type of stain and organized the classification procedure through visual inspection. Park et al. (2018) proposed useful algorithms to review alternatives to materials and shapes and to review rainwater runoff to prevent pollution during the design stage. In particular, Parnham (1997) notes that it is important for the architectural design team to deal with the problem of stain pollution in the initial design stages of the project, and careful consideration in the design stage prevents expensive cleaning works and does not require fixing the building details. Initial imperfection always repeats pollution even after cleaning and the defect increases over time, so advance measures against pollution are needed.

2.1.5. Distinction from earlier studies

As the differentiation of existing research, it is proposed as stage, location, and diagnostic method. First of all, in terms of stage, research on pollution prevention is conducted mainly in the construction and maintenance stages, and there is insufficient research on planned measures to prevent pollution in the design stage. For the life and maintenance costs of a building, a fundamental study is needed to establish an anti-pollution plan immediately in various alternative measures made during the design stage. In terms of location, it is conducted the sloped wall experiment, which is the most vulnerable position to pollution. Recently, the use of sloped walls has increased sharply, but research and countermeasures for sloped walls are insufficient. Therefore, experiments and improvement measures are presented to reduce dust adsorption according to angle, material, surface tension, critical angle, water break, surface adjustment of sloped wall. Finally, in terms of diagnostic method, a new method for quantitatively diagnosing pollution of exterior surfaces can be used to compare and verify various pollution phenomena based on initial data by material.

2.2. Sloped wall and premature staining

2.2.1. Premature staining

Pollution on the exterior of building begins with physical, electronic, chemical, and biological contact factors, and causes external factors such as wind, rainwater, static electricity, ultraviolet rays, and acid gas (Shim 2001). Here, the pollution phenomenon varies depending on the defects in each stage. Defects in the design stage mainly cause staining and defects in the construction and maintenance stages cause peel, rust, efflorescence, germ. In particular, staining is one of the most common pollution phenomena found in the exterior of buildings. Dust collects mainly on horizontal and sloping surfaces and leaves stains due to rainwater and wind.

Building’s complex exterior can lead to premature staining. It is necessary to define exactly what premature staining means here. Parnham (1997) defines premature staining as a dramatic pollution of the exterior.

| Table 4. Preceding research analysis of concrete wall defect. ○: Only mention importance. |
| Researcher | Design | Procurement | Construction | Maintenance |
| Choi and Choi (2020) | | | | ○ |
| Asmone and Chew (2018) | | | ● | |
| Park et al. (2018) | | | | ○ |
| Serralheiro, de Brito, and Silva (2017) | | | | ● |
| Park, J (2015) | | | ● | ● |
| Park, W (2015) | | | ● | ● |
| Kim, S (2014) | | | ● | ● |
| Yang, H (2014) | | | ● | ● |
| Blocken, Derome, and Carmeliet (2013) | | | ● | ● |
| Lee, I (2012) | | | ● |● |
| Jung, J (2011) | | | ● |● |
| Lee, J (2009) | | | ● |● |
| Flores-Colen, de Brito, and de Freitas (2008) | | | ● |● |
| Kwon, I (2009) | | | ● |● |
| Jung, J (2007) | | | ● |● |
| Yoo, B (2007) | | | ● |● |
| Kim, B (2007) | | | ● |● |
| Chun, J (1996) | | | ● |● |
| Lim, N (2005) | | | ● |● |
| Shin, K (2005) | | | ● |● |
| Chew (2003a) | | | | ○ |
| Parnham (1997) | | | | ○ |

| Table 5. Causes and phenomena of exterior pollution by stage. |
| Stage | Pollution phenomenon | External factor | Related materials |
| Design stage | Stain | Rainwater, Wind | Painting, Tile, Metal, Stone, Concrete, Plastic, Glass |
| Construction and maintenance stage | Peel, Rust, Efflorescence, Germ | Static Rainwater, Ultraviolet, Bacteria, Birds, Plants | Brick, Stone, Concrete, Iron, PV |
2.2.2. Staining of the sloped wall

The most vulnerable position to staining is the sloped wall. The reason why sloped walls are polluted is because rainwater flows slowly compared to vertical walls. In addition, it is easy for many dusts to gather and such a high concentration of dust leaves stains without being washed away by intermittent precipitation patterns. And since sloped walls are directly exposed to rain and wind compared to vertical walls, special care is needed because they cause stain pollution from rainwater hits and extend pollution to the connected vertical wall surface by becoming the flow route of rainwater. In particular, sloped walls are heavily influenced by the climate environment, and it is necessary to identify Korea’s precipitation patterns.

The sloped wall is deposited with high concentrations of dust along the gravitational precipitation of dust and leaves stains along rainwater hits. The reverse sloped wall, on the other hand, leaves a stain by the spill of rainwater accompanied by stains or by stowed traces of rainwater falling down by gravity. Therefore, the causes of pollution are different, so measures should be different. The sloped wall should allow rainwater to flow down, avoid horizontal surfaces, and the reverse sloped wall should prevent rainwater accompanied by stains from flowing down in advance.

2.2.3. Comparison of precipitation pattern

Korea is geographically located in the temperate climate zone of the mid-latitude, with four distinct seasons of spring, summer, fall, and winter. As a continental climate, extreme climatic phenomena are occurring in hot summer and long winter. Due to the recent abnormal temperature, the average temperature is increasing year by year, and the precipitation is decreasing year by year.

Korea’s average annual precipitation is 1,278.9 mm, which is higher than the global average. However, 60–70% of annual precipitation falls in the summer and is characterized by intermittent rainfall patterns. Due to the recent abnormal temperature, precipitation is increasing in summer and fall, and the frequency of rain is decreasing in winter and spring compared to the average year (1973–2019). When comparing the precipitation patterns between England and Korea, the UK can clean itself with the average amount of rain every month. However, Korea goes beyond the limits of natural cleaning, with intermittent drops except in summer.

As a result, the exterior of the building is covered with high concentrations of dust that cannot be easily

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**Figure 3.** Staining of the sloped wall.

**Table 6.** The causes and counterplans of staining in sloped wall.

| Sortation       | Cause of staining       | Counterplan            |
|-----------------|-------------------------|------------------------|
| Sloped wall     | - Gravity sinking of dust  |
|                 | - Slow flow of rainwater  |
|                 | - Rainwater hit           |
|                 | - Preventing rainwater runoff |
|                 | - Rainwater runoff by gravity |
|                 | - Surface control         |
| Reverse sloped wall | - Sloped wall  |

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**Table 7.** Average high temperature and rainfall of the Korea.

| No.    | Average high temp (°C) | Spring (°C) | Summer (°C) | Fall (°C) | Winter (°C) | Rainfall (mm) |
|--------|------------------------|-------------|-------------|-----------|-------------|---------------|
| 1973–1975 | 17.5                  | 17.0        | 28.4        | 19.5      | 5.0         | 1,216.3       |
| 1976–1980 | 17.7                  | 17.4        | 27.9        | 20.0      | 5.2         | 1,205.6       |
| 1981–1985 | 17.6                  | 17.7        | 28.7        | 19.5      | 4.6         | 1,254.0       |
| 1986–1990 | 17.9                  | 17.7        | 28.1        | 20.0      | 6.3         | 1,314.3       |
| 1991–1995 | 18.1                  | 17.6        | 28.3        | 20.1      | 6.4         | 1,147.9       |
| 1996–2000 | 18.4                  | 18.1        | 28.3        | 20.3      | 6.6         | 1,413.1       |
| 2001–2005 | 18.2                  | 18.4        | 28.3        | 20.2      | 6.1         | 1,414.4       |
| 2006–2010 | 18.4                  | 17.9        | 28.5        | 20.6      | 6.4         | 1,302.6       |
| 2011–2015 | 18.2                  | 18.3        | 28.9        | 20.3      | 5.5         | 1,277.5       |
| 2016–2019 | 18.8                  | 19.3        | 29.6        | 20.2      | 6.7         | 1,202.9       |
| 2019     |                        |             |             |           |             |               |
cleaned and leaves ugly pollution caused by rainwater blows, so an alternative considering the reduced precipitation frequency is needed.

### 2.2.4. Surface tension and critical angle

Surface tension is the characteristic between rainwater and material. Surface tension is a type of interfacial tension that is intended to shrink itself and take as small an area as possible. In other words, there is surface tension between rainwater and exterior materials, and it draws down pollutants and contaminates the exterior walls. Lower angle and rainwater surface tension and higher surface tension of the fixture become hydrophilic. Conversely, higher angle and rainwater surface tension and lower surface tension of the fixture become hydrophobic. That is, the closer the material on the exterior is to the hydrophobic, the less contaminated it is.

The critical angle is the angle at which the water drop begins to fall and is related to the hydrophobicity of the surface. Therefore, each material has a different critical angle, and the rougher the surface, the closer the hydrophilic, the higher the critical angle. This affects the flow rate of rainwater and leaves a stain by washing down dust or staying on the surface. In other words, at angles below the critical angle, rainwater stays on the surface without flowing down and can have a profound effect on staining. Therefore, the critical angle study of sloped walls should be preceded by the situation of abnormal temperature and irregular precipitation patterns in Korea.

### 2.2.5. Superhydrophobicity and Superhydrophilicity

Superhydrophobicity refers to a surface that is not very close to water. A contact angle with a droplet of water greater than 90 degrees is hydrophobicity, and a contact angle of less than 30 degrees is hydrophilicity. Above 150 degrees is the state of superhydrophobicity with very few contact surfaces (Kwak 2010). Superhydrophobicity has a self-cleaning effect. This refers to the ability to remove dust or contaminants from the surface easily by rainwater due to the low surface tension of the fixture. This feature is called the lotus petal effect. The lotus petals observed through the microscope consist of numerous protuberances of nanoscale to 3–10 um size to prevent contamination (Park 2009).

In contrast, superhydrophilicity refers to surface conditions that are close to water. Titanium oxide, a photocatalyst, generates electrons and pores when it comes into contact with ultraviolet light. As oxygen in the air is combined with electrons and pores, an active species with resolution called superoxide ion and hydroxyl radical occurs on the surface of carbon

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**Figure 4.** Rainfall and days of the England and Korea (Choi and Choi 2020).
oxide, and the active species decomposes pollutants such as oil contained in the contaminants.

2.2.6. Static electricity
Static electricity is caused by friction between the exterior and the air, and the negative charge in the air is charged to the exterior. At this time, the principle is that the dust with positive charges is absorbed by electrostatic forces in the exterior of negative charges and leaves stain pollution (Yang 2004). Recently, the use of plastic, which is easy to charge on the exterior of buildings, has been increasing, and is the main cause of Premature staining. To reduce dust adhesion caused by electrostatic forces, the negative charge deposited in the fixture must be adjusted. Antistatic agents include conductive inorganic materials, surfactants, polymers and low molecular types, and plastic verification is required before applying the exterior of the building.

3. Experiment and methodology
3.1. Site selection and experimental setup
In this study, a quantitative outdoor experimental study was conducted to present reasonable approach and planned plans to prevent staining of sloped walls in the design stage. The experimental site was Hapcheon-gun, Gyeongsangnam-do, and it was selected as a place for long-term experiments under the same exposure conditions during the same period. The experimental mockup was largely completed by dividing it into two aspects: Staining experiments of the sloped wall(T) and Staining prevention experiments(P). The total materials were unified into 30 cm x 48 cm to consider constructivity and to facilitate comparison of diagnosis. A total of 68 prototypes consist of a combination of sloped and vertical walls and conducted five experimental investigations over 9 months.
3.1.1. Materials and critical sliding angle measurement

In this experiment, stone, concrete, painting, aluminum, glass, and polycarbonate, which are mainly used as exterior wall finishing materials, were selected and the critical angle was measured through a self-made measuring instrument at the site. Three drops of water were placed equally spaced on the surface and the angle at which all three fell was measured. The measured critical angles were 34 degrees of stone, 30 degrees of concrete, 24 degrees of paint, 23.4 degrees of aluminum, 16.5 degrees of glass and 11 degrees of polycarbonate.

3.1.2. Experimental setup of sloped wall(T) and staining prevention(P)

The sloped walls were installed at an angle of 90°, 75°, 60°, 45°, 30°, 15° for each material, and the critical angle was placed between them. In addition, the reverse sloped walls were additionally installed at angles such as – 75°, – 60°, – 45°, – 30°, – 15° for comparative analysis with the sloped walls. All sloped walls were installed in combination with vertical walls and each collected staining data. During the same period, it was placed southward under the same exposure conditions and proper pathways were
Table 8. Six materials.

| No. | Materials          | Absorption rate (%) | Critical angle (°) | Roughness (µm) | Initial brightness (L*) | Gloss rate (%) |
|-----|-------------------|---------------------|-------------------|----------------|-------------------------|----------------|
| T1  | Stone             | 40                  | 34                | 110            | 70.59                   | 50.20          |
| T2  | Painting          | 27                  | 24                | 72             | 96.54                   | 2.75           |
| T3  | Concrete          | 48                  | 30                | 75             | 75.25                   | 1.92           |
| T4  | Aluminum          | 20                  | 23.4              | 30             | 78.81                   | 29.75          |
| T5  | Polycarbonate     | 20                  | 11                | 28             | 75.07                   | 99.70          |
| T6  | Glass             | 19                  | 16.5              | 21             | 67.46                   | 123.35         |

Table 9. Experimental mockup lists.

| No. | Materials          | Angle      | Prevention experiments |
|-----|-------------------|------------|------------------------|
| T1  | Stone             | 90°, 60°, 45°, 34°, 30°, 15° | Throating 1 cm, 2 cm, 3 cm, 4 cm, 5 cm |
| T2  | Painting          | 90°, 60°, 45°, 30°, 24°, 15° | Throating 1 cm, 2 cm, 3 cm, 4 cm, 5 cm |
| T3  | Concrete          | 90°, 75°, 60°, 45°, 30°, 15° | - |
| T4  | Aluminum          | 90°, 60°, 45°, 30°, 23.4°, 15° | - |
| T5  | Polycarbonate     | 90°, 60°, 45°, 30°, 15°, 11° | - |
| T6  | Glass             | 90°, 60°, 45°, 30°, 16.5°, 15° | - |
| T7  | Painting          | −75°, −60°, −45°, −30°, −24°, −15° | - |
| P1  | Painting          | 24° Critical angle | Throating 1 cm, 2 cm, 3 cm |
| P2  | Painting          | 66°         | Antostatic agents |
| P3  | Six materials     | 15°         | Superhydrophobic coating |
| P4  | Six materials     | 15°         | Superhydrophobic coating |
| P5  | Six materials     | Critical angle by material | Superhydrophobic coating |
| P6  | Six materials     | Critical angle by material | Superhydrophilic coating |
| P7  | Painting          | −75°, −24°   | Superhydrophobic coating |
| P8  | Painting          | −75°, −24°   | Superhydrophilic coating |
| P9  | Polycarbonate     | 11° Critical angle | Antistatic agents |
| P10 | Glass             | 16.5° Critical angle | Antistatic agents |

Table 10. Experimental coatings.

| Sortation | Superhydrophobicity | Superhydrophilic | Antistatic agents |
|-----------|---------------------|------------------|------------------|
| Material name | ANSEN Sio2 ceramics | SunNuCoat – 200 | HNC – 100 |
| Main ingredient | Sio2 | TiO2 | ITO |
| Properties | Nano Water repellent coating | Photocatalyst Coating Agent | Antistatic agent |
|            | Lotus leaf effect | Self cleaning | Self cleaning effect by forming superhydrophilic membrane |
|            | Available for 4 seasons | UV protection function | Colorless and transparent |
|            | - UV protection function | - | - |
| External materials | Various materials | Variousmaterials | Plastic, glass, etc |
| Price | $ 13.03/1 L | $ 28.58/1 L | $ 100.88/1 L |

It is difficult to prevent the adsorption of dust or microdust floating in the atmosphere. To avoid gravitational precipitation of dust, the horizontal plane should be avoided as much as possible. However, since the design can be constrained, it is necessary to experiment with special coatings such as superhydrophobicity and superhydrophilicity. Special coatings at the maintenance stage are difficult to construct and may increase costs and reduce coating efficiency. However, special coating plans at the design stage can be applied to the right places depending on the material and location, reducing costs and increasing coating efficiency. Therefore, an additional critical angle and 15° were installed for each material to identify the proper utilization of special coatings during the design stage. In addition, both superhydrophobicity and superhydrophilicity were applied to each material to facilitate suitability and comparative analysis. Polycarbonate and glass were additionally applied with antistatic agents because it could cause pollution by static electricity. The throating was applied to the intersection of the sloping wall and the vertical wall with 1 cm, 2 cm, 3 cm, 4 cm, and 5 cm.

3.2. Staining diagnosis methods

3.2.1. Diagnosis meters

For quantitative diagnosis and data management of staining, a CS-10 color meter satisfying KS standard certification was used and surface roughness was measured with YG60 glossy meter and AMITARI AR-131A, which complies with ISO's international standards. All of these meters provided software, making it easier to quantitatively collect, compare, and verify data. In general, the greater the brightness difference, gloss degradation rate, and surface roughness, the greater the staining.

(1) Colormeter CIE L*a*b*

MacAdam's transformation of ANLAB color space in 1973 was one of the color spaces standardized by the International Lighting Commission in 1976, and L*a*b* colorimetric systems are the most commonly used colorimetric systems in your current day to express the color of an object. L* is used to express brightness as the basis for staining and a*, b* is used to indicate color and chromaticity (Park, Jang, Song, and Shin 2006).

3.2.2 Data analysis methods

• (1) Data measurement

The color meter is used as the main measurement of the data and the stains on the surface are measured within the range of 1–100(L*). The gloss meter and
roughness meter were used for reference and sub-use. As a method of diagnosis of staining, a grid of 30 cm x 48 cm with 15 measuring points was made to increase mobility and accuracy of diagnosis and to determine staining degree(L*) based on 15 average values. The initial measurements(IM) of the entire sloped wall were diagnosed after the experimental mockup and were compared to the staining rate (SR) measured at intervals of 2 months. Unlike the existing subjective visual inspection and digital analysis, this is a quantitative measurement method that can directly check and diagnose staining of exterior surfaces. A total of five cycles were measured every 2 months, and the changes over time were summarized into data.

- **(2) Data classification methods**

The classification of data is largely divided into two aspects: Staining experiments of the sloped wall(T) and Staining prevention experiments(P). The initial staining degree(IM) of 68 prototypes, the staining degree(L*) of each cycle, and the staining rate (SR) by comparison difference were summarized. Data diagnosed by measuring instruments such as color meter, gloss meter, and rough meter were organized by file.

- color meter(L*) = 1–100
- gloss meter(GU) = 1–1000
- rough meter(um) = 1–750

\[
L^* \text{ (Staining Degree \_1-100)} = \text{Average value of 15 points}
\]

\[
SR \text{ (Staining Rate \_%)} = \left( \frac{L^* \text{ by cycle } \div \text{ Initial } L^*}{} \right) - 1
\]

- **(3) Data analysis methods**

The data were compared and analyzed according to the staining degree by each angle, the situation of change at the critical angle, the staining degree by coating at the critical angle, and the staining degree by the length of the throating. The analyzed data present a comprehensive plan optimized for angles, coatings, and throating. 
4. Experimental results

4.1. Staining experiments of the sloped wall

4.1.1. Staining degree by angle

A total of 68 prototypes consist of a combination of sloped and vertical walls and conducted five experimental investigations over 9 months. Figure 13 shows that the closer the slope is to the horizontal plane, the higher the degree of staining. This is a natural result of the gravitational precipitation of dust and the accuracy of diagnosis has been identified. And the staining level can be seen higher on the sloped wall than on the vertical wall in the critical angle. The staining level of the critical angle was found in the order of stone (8.25), concrete (6.02), painting (5.48), aluminum (4.75), polycarbonate (4.52) and glass (4.09).

At the staining increase rate of critical angle, concrete was the highest at 30.05%, followed by stone, paint, aluminum, polycarbonate, and glass, and the staining increase rate below critical angle was also shown in proportionally. Based on the critical angle, concrete was the highest at 31.42%, followed by stone, paint, aluminum, glass, and polycarbonate. Based on the critical angle, concrete showed the highest staining rate (31.42%) between phases over time, followed by stone, paint, aluminum, glass, and polycarbonate. It can be seen that the staining increase rate and the staining rate between phases are proportional at the critical angle of the six materials, and the gap in staining level from the critical angle is widening over time. Here, the critical angle becomes the main factor of sloped wall pollution.

4.1.2. Staining degree of the sloped wall and reverse sloped wall

Comparing the staining levels of the sloped wall and reverse sloped wall, it was shown in inverse proportion as Figure 14. The closer the sloped wall to the horizontal plane, the closer the reverse sloped wall to the vertical plane, the higher the

Table 11. Diagnosis meters.

| Properties                  | CS-10 colometer | YG60 glossmeter | Amittari profile gauge |
|-----------------------------|-----------------|-----------------|------------------------|
| Aperture                    | Ø8 mm           | 9x15mm          | 1μm (0.1mils)          |
| Range                       | L*: 1–100       | 60°: 0–1000GU   | 0μm – 750μm            |
| Measurement time            | 0.5s            | 0.5s            | 1s                     |
| Price                       | $ 906.47        | $ 412.03        | $ 370.83               |

Figure 11. RGB Color Model and CIE L*a*b* Color space (Visscher 2010).
In particular, the staining rate increased at 24° for sloped wall and −75° for reverse slope wall, showing high pollution levels in the perpendicular range depending on the surface tension of the material based on the critical angle (24°).

4.1.3. Staining degree and surface roughness

The roughness of the surface was high in order of stone (110㎛), concrete (75㎛), painting (72㎛), aluminium (30㎛), polycarbonate (28㎛), and glass (21㎛), and appeared proportionally to the brightness difference measured 9 months later. In other words, the roughness of the surface was proportional to the brightness difference and inversely proportional to the gloss difference. The staining of the surface was mainly contaminated from the critical angle at the bottom of the inclined wall and at the top of the vertical wall, and staining measures are needed for the corner section where the sloped wall and vertical wall are connected.

Table 12. Efficiency comparison of coatings.

| Sortation          | Comparison of materials                                                                 |
|--------------------|----------------------------------------------------------------------------------------|
| Superhydrophobicity| Concrete > Painting > Aluminum > Stone(SC) > Polycarbonate(SC) > Glass(SC)             |
| Superhydrophilicity| Painting > Concrete(SC) > Stone > Aluminium(SC) > Polycarbonate(SC) > Glass(SC)       |
| Absorptivity (%)   | Concrete(48) > Stone(40) > Painting(27) > Aluminium(20) > Polycarbonate(20) > Glass(19) |
| Surface roughness  | Stone > Concrete > Painting > Aluminium > Polycarbonate > Glass                        |

[SC]: Surface Change

staining level. In particular, the staining rate increased at 24° for sloped wall and −75° for reverse slope wall, showing high pollution levels in the perpendicular range depending on the surface tension of the material based on the critical angle (24°).
4.2.2. Staining prevention experiments of the sloped wall

4.2.1. Coating experiments

At angles below the critical angle, the planning of special coatings is essential during the design stage because of increased pollution and repetition. In order to identify the efficacy of special coating, superhydrophobicity and superhydrophilicity were applied to the critical angle of six materials, and the staining level of all materials was reduced when compared with the staining level of critical angle. By coating, the stone became darker and the concrete became brighter in superhydrophobicity. The surfaces of glass and polycarbonate have changed. In the superhydrophilicity, the surface of stone and painting was brightened after 4 months, and concrete became yellow after 2
Figure 15. Comparison of surface roughness and staining.

|      | Stone | Concrete | Painting | Aluminum | Polycarbonate | Glass |
|------|-------|----------|----------|----------|---------------|-------|
| Roughness | 110   | 75       | 72       | 30       | 28            | 21    |
| L* (after 9 months) | 8.25  | 6.02     | 5.48     | 4.75     | 4.52          | 4.09  |

Figure 16. Application of superhydrophobicity and superhydrophilicity coatings (after 9 months).
months. The surface of aluminum has changed in superhydrophilicity. Glass and polycarbonate were both changed in special coatings and tested with additional antistatic agents.

According to the staining rate by material, concrete and aluminum were measured with low staining rates in superhydrophobicity, while stone and paint were measured with low staining rates in superhydrophilicity. In superhydrophobicity, concrete was measured at 0.78% with the lowest staining rate, followed by painting, aluminum, stone, polycarbonate and glass. In superhydrophilicity, the painting was measured at 0.12% with the lowest staining rate, followed by concrete, stone, aluminum, polycarbonate and glass. At the staining rate between phases over time, painting and aluminum gradually decreased, while stone and concrete increased. Polycarbonate and glass were the most efficient in antistatic agents compared to superhydrophobicity and superhydrophilicity, and measured at 1.28% and 1.65% staining rates, respectively. In terms of the efficiency of special coatings, concrete was the highest, while glass was the lowest. Stone was measured the highest staining rate difference between superhydrophobicity and superhydrophilicity, and painting was measured at low staining rate both in superhydrophobicity and superhydrophilicity.

The absorption rate of the surface is higher in order of concrete, stone, painting, aluminum, polycarbonate, and glass, and the roughness of the surface is higher in order of stone, concrete, painting, aluminum, polycarbonate, and glass. In other words, it is proportional to the efficiency of special coatings, and the higher the absorption rate of the material, the rougher the surface, the more efficient it is. Because the type and efficiency of coating vary depending on the properties of the material, and appropriate alternatives are presented for each material.

4.2.2. Throating experiments
The throating was installed at the intersection of the sloped wall and the vertical wall with 1 cm, 2 cm, 3 cm, 4 cm, 5 cm, etc., and applied to the sloped wall prototype (A) and the reverse sloped wall prototype (B). In the throating of the sloped wall prototype (A), it appeared different from the sloped wall and the vertical wall. The sloped wall had no effect of throating, and the vertical wall was measured at a staining rate of 3.38% at 1 cm and 1.53% at 2 cm and the staining rate remained constant at throating above 2 cm. In the throating of the reverse sloped wall prototype (B), both the sloped wall and the vertical wall were measured at a low staining rate and the staining rate remained constant at throating above 2 cm. Throating in the range of about 2 cm can be a good alternative to preventing staining because it is not good to be short or long.

4.2.3. Defect solutions
This paper aims to prevent deep and surface stains from the beginning, and we conducted experiments on how to produce the fewest stain phenomena through various coating experiments. In other words, the coating experiments of various

![Figure 17. Change of coatings between phases.](image-url)
Table 13. Solutions of surface stains by material.

| No. | Materials       | Stain phenomena                      | Proper solutions                                                                 |
|-----|-----------------|--------------------------------------|----------------------------------------------------------------------------------|
| T1  | Stone           | Surface stains                       | – Applying superhydrophilicity coating after cleaning the surface regularly       |
|     |                 | Deep stains                          | – Applying superhydrophilicity coating after removing stains by mechanical method |
| T2  | Painting        | Surface stains                       | – Applying superhydrophilicity coating after washing with water                  |
|     |                 | Deep stains                          | – Not normally cleaned. Respond with regular over-painting or touch-up            |
| T3  | Concrete        | Surface stains                       | – Removal by scaling by sand, wire brush, etc., Do not use acidic detergent       |
|     |                 | Deep stains                          | – Applying superhydrophilicity coating after removing with high pressure cleaner  |
| T4  | Aluminum        | Surface stains                       | – Applying surface protection agent after cleaning with a neutral detergent      |
|     |                 | Deep stains                          | – Applying 2 clear paints after using a razor blade to remove stains as this material is prone to damage |
| T5  | Polycarbonate   | Surface stains                       | – Repeated occurrence of staining due to charge problem                          |
|     |                 | Deep stains                          | - Applying antistatic agents after washing the surface                          |
| T6  | Glass           | Surface stains                       | – Applying antistatic agents after mixing non-polluting chemicals with water and spraying them |
|     |                 | Deep stains                          | – Applying surface protection after washing with water                           |
|     |                 |                                      | - Cleaning with Neutral Detergent and Abrasive                                   |
|     |                 |                                      | - Special staining is handled using glass clear, razor, etc.                     |

4.3. Comprehensive plans for staining prevention

By identifying the measures for staining appearing on sloped walls and the characteristics of critical angles, the comprehensive planning measures according to angle, surface control, and throating are presented according to the materials. The staining degree according to the angle of each material is expressed, and it can be seen that the staining degree increases at the critical angle. Critical aerials are slope angles to be careful when designing and suggest appropriate coatings to reduce staining in this angle range.

5. Conclusions

In this study, a quantitative experimental study was conducted to present a reasonable approach to prevention of pollution of sloped walls and a planned plan in the design stage. The staining phenomenon and the planned measures of the sloped wall identified through the experimental studies are as follows.

(1) The closer the slope to the horizontal plane, the higher the staining level in all materials. And the staining level can be seen higher on the sloped wall than on the vertical wall in the critical angle. The staining level of the critical angle was found in the order of stone (8.25), concrete (6.02), painting (5.48), aluminum (4.75), polycarbonate(4.52), and glass (4.09). It can be seen that the staining increase rate and the staining rate between phases are proportional at the critical angle of the six materials, and the gap in staining level from the critical angle is widening over time. Here, the critical angle becomes the main factor of sloped wall pollution, and careful attention is needed when planning angles below critical angle in the design stage.

Figure 18. Throating plans of the sloped wall.
Figure 19. Comprehensive plans for staining prevention.
(2) Comparing the staining levels of the sloped wall and reverse sloped wall, it was shown in inverse proportion by angle. The closer the sloped wall to the horizontal plane, the closer the reverse sloped wall to the vertical plane, the higher the staining level. If the critical angle of the sloped wall is A degrees, the reverse sloped wall is A-90 degrees and shows the characteristics of the right angle range according to the surface tension of the material, and special coatings and throating plans should be considered when planned at an angle below the critical angle.

(3) The roughness of the surface is proportional to the brightness difference and inversely proportional to the gloss difference. The roughness of the surface was high in order of stone (110μm), concrete (75μm), painting (72μm), aluminum (30μm), polycarbonate (28μm), and glass (21μm), and appeared proportionally to the staining level of surface measured 9 months later.

(4) The surface of the sloped wall appeared different depending on the special coatings. In the superhydrophobicity, the stone darkened and the concrete gradually brightened. The surfaces of glass and polycarbonate have changed. In the superhydrophilicity, the surface of stone and painting was brightened after 4 months, and concrete became yellow after 2 months. The surface of aluminum has changed in superhydrophilicity. Glass and polycarbonate were both changed in special coatings and tested with additional antistatic agents. Because the basic premise of this study is not to place restrictions on possible designs, it is important to avoid coatings that cause surface changes.

(5) The efficiency of superhydrophobicity and superhydrophilicity was measured differently for each material. Concrete and aluminum were measured at low staining rates in superhydrophobicity, while stone and painting were measured at low staining rates in superhydrophilicity. In terms of efficiency of special coating, concrete was measured the highest, while glass was measured the lowest. Stone has the highest staining rate difference between superhydrophobicity and superhydrophilicity, and painting has been measured at low staining rates both in superhydrophobicity and superhydrophilicity.

(6) Polycarbonate and glass were the most efficient in antistatic agents compared to superhydrophobicity and superhydrophilicity, and measured at 1.28% and 1.65% staining rates, respectively. Because the glass and polycarbonates with low absorption rates are difficult to apply to special coatings and are affected by static electricity, antistatic agents are considered as appropriate alternatives.

(7) The absorption rate of the surface is higher in order of concrete, stone, painting, aluminum, polycarbonate, and glass. In other words, it is proportional to the efficiency of special coatings, and the higher the absorption rate of the material, the rougher the surface, the more efficient it is.

(8) In the throating of the sloped wall prototype (A), it appeared different from the sloped wall and the vertical wall. The sloped wall had no effect of throating and the vertical wall was measured at a staining rate of 3.38% at 1 cm and 1.53% at 2 cm and the staining rate remained constant at throating above 2 cm. In planning complex forms, the combination of coating plans for the right place and throating plans in the 2 cm range can be a good alternative to preventing staining.

6. Research Contribution

It is important to consider planning measures during the initial design stage in order to maintain the cleanliness and maintenance of continuous appearance and building’s life. This research is a stage in which planning measures are presented to prevent staining of the exterior during the initial design phase and can contribute to preventing various environmental pollution such as fine dust in advance. In practice, it is expected to be used as a useful alternative for preventing staining in the initial design stage as data collected through the experiments and the multidirectional staining measures according to angle, material, throating and surface coatings. In society, the exterior of buildings considered in the design stage can last long without special defect management and can contribute to reducing social capital and resource abuse.

7. Limitation of research and future research direction

This study reveals that although the planned measures were derived through experiments, it was limited to premature staining of sloped walls for a short period of time and that there was a limit to collecting staining data over a long period of time. Therefore, it is necessary to be accompanied by long-term experimental studies and to further experiment with various locations vulnerable to staining. However, it is significant that practical research was carried out to prevent staining, focusing on the planned measures that will be applied to the design stage through experiments. Further research in the city is needed for the practicality of further research, and it is necessary to verify alpha values through comparison and verification with existing data in conjunction with this study. And recently, the use of plastic, a material that is easy to change the exterior of buildings, has been on the rise and is the main cause of premature staining. Prior to the application of the exterior of the building, it is necessary to verify the plastic, and various antistatic agents and defense experiments should be
premised in order to reduce dust adhesion caused by electrostatic force.

**Disclosure statement**

No potential conflict of interest was reported by the author(s).

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