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An investigation of superhydrophobic self-cleaning applications on external building façade systems in the tropics

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ABSTRACT

On-site surface applications of superhydrophobic paint and coating products were investigated for their self-cleaning effectiveness in this study. This paper presents findings from the ensuing visual assessments using a novel method based on digital image processing. Findings confirm the self-cleaning ability of the superhydrophobic surface applications, which has sustained effects over a period of one year. This paper discusses how these findings contribute to the domain of facilities management (FM) to increases the ease of façade maintenance and the maintainability of the superhydrophobic façade coating systems.

1. Introduction

The building façade faces a myriad of external stresses in tropical cities such as Singapore, which increases its vulnerability to develop common surface defects such as façade staining [1–3]. It is well established that façade cleaning is an expensive exercise due to its high use of resources (i.e. energy, water, and chemicals) and associated safety risks [4]. Meanwhile, rising building-user expectations demand more frequent cleaning and paint cycles [5], when building maintenance budgets are shrinking [3,6]. Maintainability considerations made during façade design is hence critical to minimize cleaning, repair, and replacement over its lifetime [7].

One proactive approach to reducing the number of cleaning cycles is by incorporating strategies such as self-cleaning façade. Studies [8–10] have shown that a superhydrophobic[1] surface applications can yield a surface to have such self-cleaning properties. Superhydrophobic self-cleaning technologies are increasingly used in commercial products due to its aesthetic, economic and environmental benefits [11], including water repellency [12,13], breathability, prevention of façade blisters [14], UV protection [15,16], resistance to biological agents [17,18], reduction of cleaning resource usage, corrosion and pollutant resistance.

Effective façade maintenance necessitates maintenance needs to be identified, correct remedial actions to be specified and conducted properly. This requires necessary experience and sound technical knowledge of the material and its properties [19]. Ease of façade maintenance is expressed in terms of maintenance frequency, resource requirements for maintenance and notice of possible ways of removing stains, graffiti, etc. [20]. Therefore, in-use performance information relating to novel superhydrophobic surface applications is imperative to improve the maintainability of such applications. As a first step, this study is conducted with the objective of investigating the effectiveness of superhydrophobic surface applications for its self-cleaning prowess and studies the in-service performance under the tropical conditions. No previous studies were found on long-term durability attributes or quantitative assessment techniques on superhydrophobic self-cleaning façade coating systems. The following section provides an overview of related studies referring to analysing façade surface defects and maintenance interventions.

1.1. Related work

García and Malaga [21] conducted various laboratory tests to determine cleaning efficiency of hydrophobicity of anti-graffiti treatments after weathering. Bams and Dewaele [22] developed a method to quantitatively measure staining of natural stone tiles using microscopic techniques using different parameters to identify discoloured stone surfaces from non-discoloured areas. Moropoulou et al. [23] used scanning-electron-microscopy images digitally processed by dedicated computer programs to assess the effectiveness of façade cleaning interventions based on proposed microstructure evaluation indexes.

Paulo et al. [24] developed a photographic façade inspection module in their building management software platform which uses orthophoto façade images to identify and measure defects. González-Jorge et al. [25] proposed a low-cost technique for façade inspection using photogrammetric techniques. They used information from

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[1] A superhydrophobic surface is where the contact angle between the material and a droplet of liquid is greater than 150 degrees (contact angle is only greater than 90 degrees in a hydrophobic surface).

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Table 1
Physical and chemical properties of the superhydrophobic products.

No	Criterion	Superhydrophobic white paint	Superhydrophobic building coating	Superhydrophobic glass coating	Superhydrophobic coating 1	Superhydrophobic coating 2
1	Properties	Superhydrophobic; self-cleaning with rain from low adhesion properties of dirt particles (the lotus-effect); very high CO_2 and H_2O vapour permeability; reduced wettability with water; natural protection against algae and fungi	Superhydrophobic; stain resistant; UV protection	Superhydrophobic; water repellent effect	Superhydrophobic; repels water, oil and dirt	Superhydrophobic effect; withstand heat up to 750 °C; disperse heat instantly
2	Areas of application	Mineral and organic, non-elastic substrates	Limestone, ceramic, painted wall, marble, metal and stones	Glass	Paint, metal, plastic, ceramics, glass	Glass, steel, metal, electronic boards, and automotive parts
3	Ingredients	5-chloro – 2-methyl – 4-isothiazolin – 3-one; 2-methyl-2H-isothiazol – 3-one; 1,2-benzisothiazol – 3-one; 2-methyl-2H-isothiazol – 3-one	Nano Silicone	Not advised	Sol-gel synthesized gels with a particle size less than 100 nm.	Not advised
4	Appearance	white	transparent	transparent	transparent	transparent
5	Density	1.45 – 1.55 g/cm^3, 20 °C	0.81 – 0.83 g/cm^3, 25 °C	not advised	0.80 g/cm^3, 25 °C	not advised
6	Grain size	< 100 µm	not advised	not advised	100 nm.	not advised
7	Solvent	None/ water	Isopropanol (IPA)	none	typical solvent	not advised
8	Surface coats	2 coats	2 coats	1 coat	2 coats	2 – 3 coats
9	Curing period	28 days	2 days	not advised	2 days	not advised
10	Consumption	0.34 – 0.40 L/m^2	0.33 L/m^2	not advised	not advised	not advised
11	Price	S$ 15 /L	S$ 95 /L	not advised	not advised	S$ 2000 /L

geometric and thermal imaging and digital processing (single image rectification) in their methodology. Umegaki et al. [26] used image-based classification of dust particles based on colour information to quantify suspended dust accumulation at steel plants. Thornbush [27] proposed a simple and inexpensive method to assess weathering of stone façade surfaces using an outdoor integrated digital photography and image processing method. This involved taking digital photographs on site and histogram based quantification during image processing. They used colour charts at sample points for calibration of lighting conditions.

2. Materials and method

2.1. Self-cleaning superhydrophobic products

Samples of 5 types of superhydrophobic paint and coating products available in the market were procured for this study. Table 1 refers to their relevant product information as advised by the manufacturers. Certain fields are noted as "not advised" where the information was not disclosed by the suppliers.

2.2. Site selection and experimental setup

An external façade attached to SDE 2 building (1°17'49.4"N 103°46'15.3"E) of the National University of Singapore was selected as the site to conduct this study. The rationale behind this selection was to have all surface applications in a close proximity to maintain the same exposure conditions throughout all study surfaces, viz. concrete, glass and aluminium cladding façade substrates. These surfaces receive direct sunlight to up to three hours each day and receive diffused sunlight all day.

Prevailing weather conditions and rainfall is very important for photocatalytic-coated facades. The amount of monthly mean rain days and mean thunderstorm days' amounts to almost half of the year with Singapore's tropical weather. Except for the dry spell observed during the Northeast monsoon in February and March, Singapore has routine rain days making its weather favourable for the self-cleaning coating systems that rely on rainwater to clean the façade.

The application of each superhydrophobic product on each substrate is shown in Table 2 below. The control surface for each application is also shown therein.

Fig. 1 illustrates the experimental setup as arranged on-site. The control and experimental surfaces are located side-by-side to ensure that both surfaces have the same exposure conditions. The surface preparation, application, and curing of superhydrophobic paint/coating were done as per manufacturers recommendations.

Data collection in this study was done by visual observations. Similar studies on photocatalytic coatings have used similar photogrammetric data collection methods for their merits as a precise, quick,

Table 2
Experimental Specimen/sample table.

Name	Substrate	Coating	Orientation
Coating A	Concrete	Superhydrophobic white paint	East facing
Control 1	Concrete	Generic white paint	East facing
Coating B	Concrete	Superhydrophobic building coating	East facing
Control 2	Concrete	–	East facing
Coating C	Glass	Superhydrophobic glass coating	South facing
Control 3	Glass	–	South facing
Coating D	Aluminium cladding	Superhydrophobic coating 1	South facing
Coating E	Aluminium cladding	Superhydrophobic coating 2	South facing
Control 4	Aluminium cladding	–	South facing

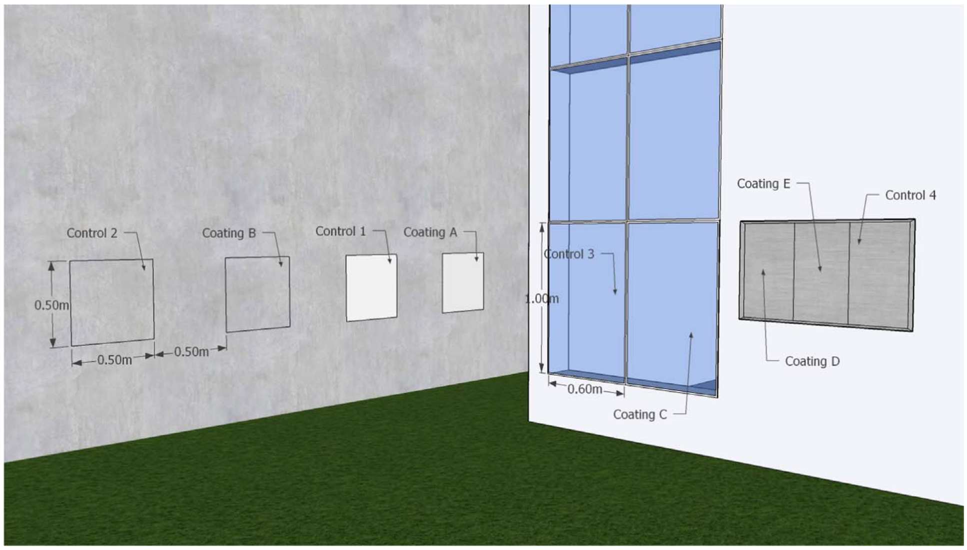

Fig. 1. Location set-up for superhydrophobic applications.

and non-contact survey technique [28]. Staining patterns on façade surfaces were captured using a digital camera with manual exposure settings to maintain consistency of the data collected. The photos were taken from the same viewpoint, from the same distance of 1 m from the façade surface on all instances.

2.3. Image processing method

Based on the experimental setup, each superhydrophobic surface and its respective control surfaces are exposed to same environmental conditions over a same period. Therefore, it was hypothesized that any difference in the accumulation of dirt stains on the two surfaces should be due to the self-cleaning ability of the superhydrophobic applications. Digital photography was used to observe these visual differences and a quantitative visual assessment was carried out by means of image processing. A novel image processing procedure is developed to achieve this, which is illustrated in Fig. 2.

Thoroughly cleaned control and experiment surfaces and photographed to document the base surface conditions (i.e. the surface with no dirt stains, Day 0). Subsequent photographs of the surfaces were taken (e.g. Day 1) to monitor the effects of staining by comparing to the conditions of Day 0. It is assumed that any difference of the surface from the base surface is due to dirt accumulated on the façade surface and any changes in illumination at the time of photo taking. Since the subsequent photographs of the control and experimental surfaces are taken at the same time, it is assumed that the two photographs have no significant change in their illumination conditions.

2.3.1. Image processing operations

As the first step in image processing, images were converted to greyscale *(Step 1)*. This controls the colour distribution and improves the programming efficiency while not affecting the objectives of the study. Then, the absolute difference between the grey-scaled images with dust and the grey-scaled base surface image is taken *(Step 2)*. This highlights the dust particles from the surface area where there is no dust. This also results in the removal of any surface deformities that may inhibit the calculations.

It is assumed that in the *difference image*, illumination component is uniformly distributed within neighbouring pixels and a Sobel operator is applied to the difference images *(Step 3)* to cancel out the illumination components from both the control and experimental surfaces. It is further assumed that the distribution of the dust component is not uniform and what remains after this operation are the stains rendered by the dust component (the *gradient image*, I_g).

2.3.2. Classification

Classification is used herein to identify occurrences of dust stains on the superhydrophobic self-cleaning material coated and control surfaces. It identifies if a given pixel location in image (I_1) is occupied by dust. This is carried out by using the corresponding pixel values of the original (I_0), the difference (I_d) and the gradient images (I_g) as inputs for the rule-based classifier to determine whether each pixel location is

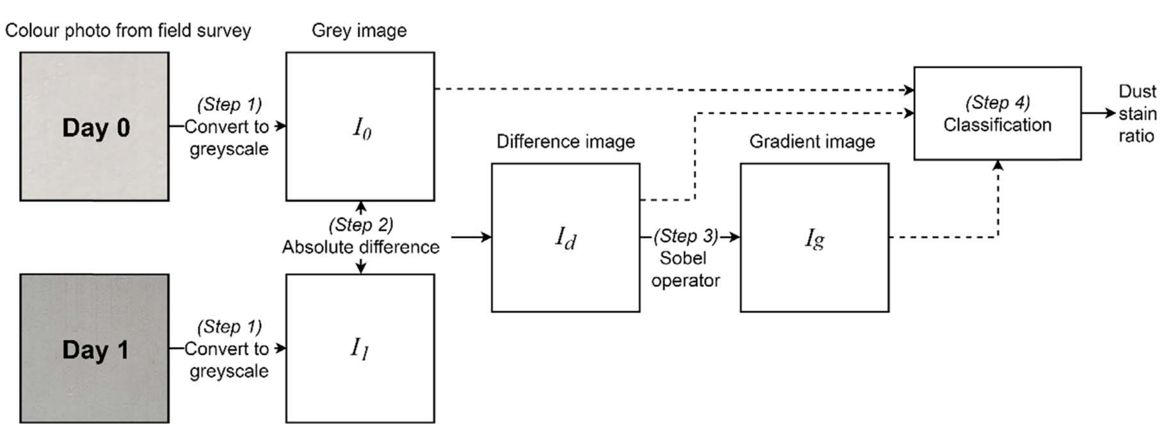

Fig. 2. Digital image processing procedure to derive dust stain ratio.

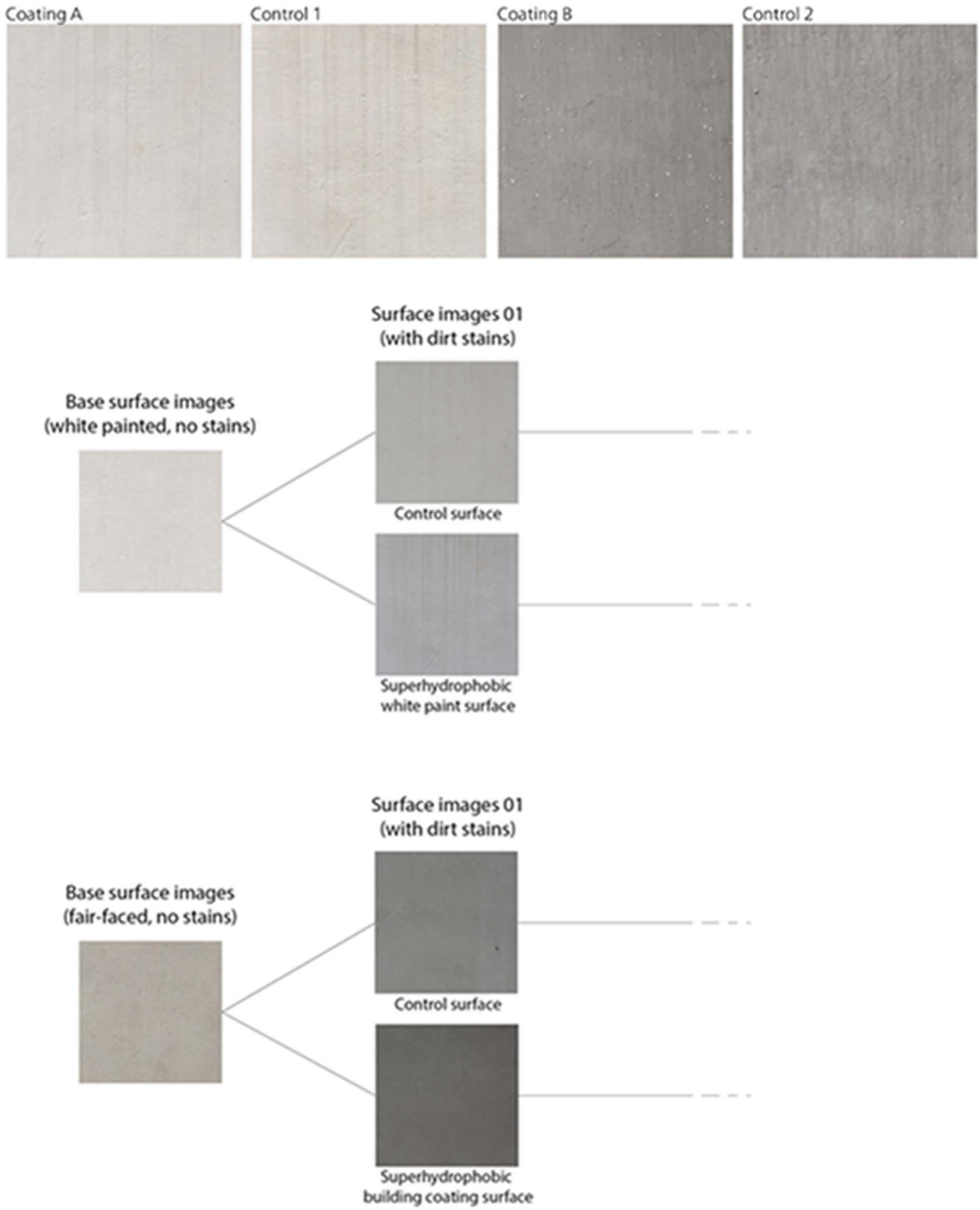

Fig. 3. Illustration of surface images used for visual analysis after one year.

dust or not.

Due to the characteristics of staining, there may be either streaks or patches of dust on the surface making it impossible to be identified using only the gradient operator. As pixels inside the edge of a large dust stain can also be dust. Therefore, the gradient and grey values are also considered in classifying stains on the surface. This classification calculates the amount of dust on the surface as the pixel ratio of dust on the surface with the base surface. This process is repeated for all data sets (i.e. each monthly observations) to compare the staining characteristics of the superhydrophobic applications with its control surfaces over time.

The current study is a conducted as a proof of concept of the innovative method by analysing staining behaviours of concrete substrates. To that effect, dust stains on concrete substrate applications Coatings A and B and Control surfaces 1 and 2 (see Fig. 3) were evaluated for a period of 4 months. The current study did not analyse surface staining behaviour for glass and aluminium substrates due to certain practical challenges which persisted due to their surface properties. However, it is feasible to expand the current method in further studies to overcome these challenges.

3. Results and discussion

Rule based classification is used with a union function to calculate

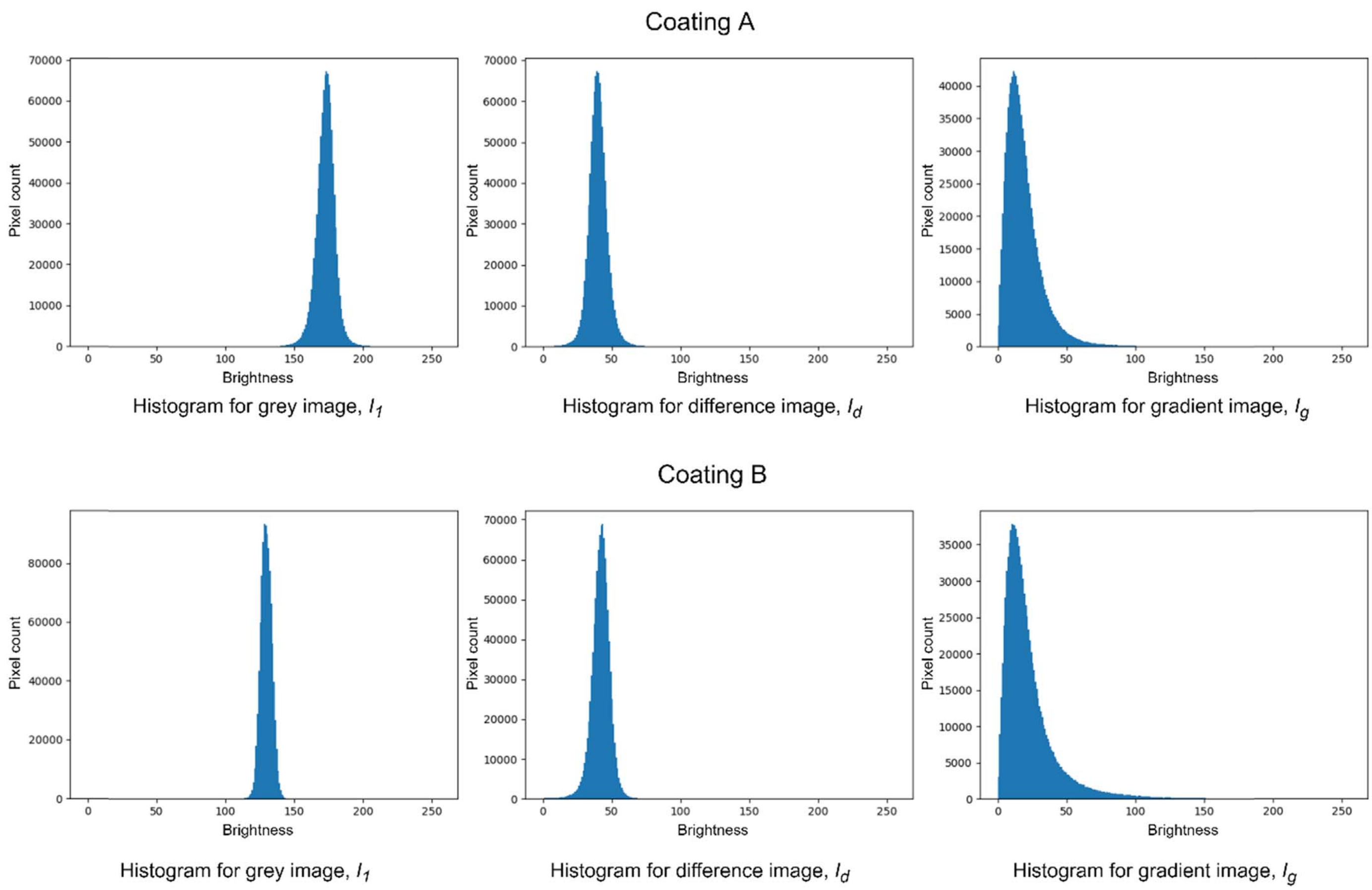

Fig. 4. Histograms used for rule based classification of coatings A and B in the first month.

the total amount of dust accumulated on a surface against a base surface condition. Fig. 4 show histograms from each stage of image processing (I_1, I_d, I_g) which are used for this classification for superhydrophobic white paint (Coating A) and superhydrophobic building coating (Coating B) respectively. These histograms are the basis for setting the classification rules based on their colour thresholding values.

Fig. 5 below is plotted using the results of the rule based classification which compares the different quantities of dust accumulated over each surface over the period of 4 months.

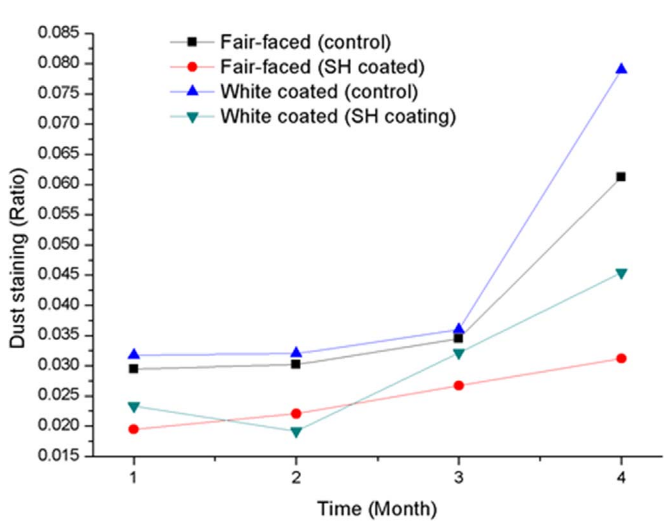

Fig. 5. Results of quantification of visual observations of staining of surfaces.

The results show that the two superhydrophobic (SH) surfaces have an overall lower count of dust stains as opposing to their respective control surfaces. This confirms that superhydrophobic façade coating products considered in this analysis are self-cleaning and requires less cleaning than a conventional façade surface. The drop in the accumulated dust on the white superhydrophobic painted surface can be attributed to the self-cleaning effects rendered by the torrential rain during that month. The sharp rises and falls displayed on the two white surfaces can be because dust stains are easily noticed on the white surfaces than the fair-faced concrete surfaces. Even so, changes of surface dust amounts on the fair-faced surfaces also show similar patterns of distribution over time. The difference in the exact amounts of dust accumulation can be different due to the varying superhydrophobicity of the two types of coatings. Also, the sharp rise of dust on the surface at the last month can be due to recent construction activities in the near vicinity of the experimental setup.

3.1. Facilities management (FM) knowledge enhancement

The current study is carried out to investigate the self-cleaning effectiveness of superhydrophobic paint and coatings commercially available on common types of façade substrates. The findings of the study affirmed that under the tropical climate conditions of Singapore, the surface applications have a positive effect on keeping the surfaces cleaner than conventional façade surfaces. This study is conducted as part of an on-going research in enhancing knowledge on building maintainability and these findings are updated to a material manual and a defect library (accessible from https://www.hpbc.bdg.nus.edu.sg/).

However, it should be noted that superhydrophobic façade coating product may have undesired effects on façade performance as well, e.g.

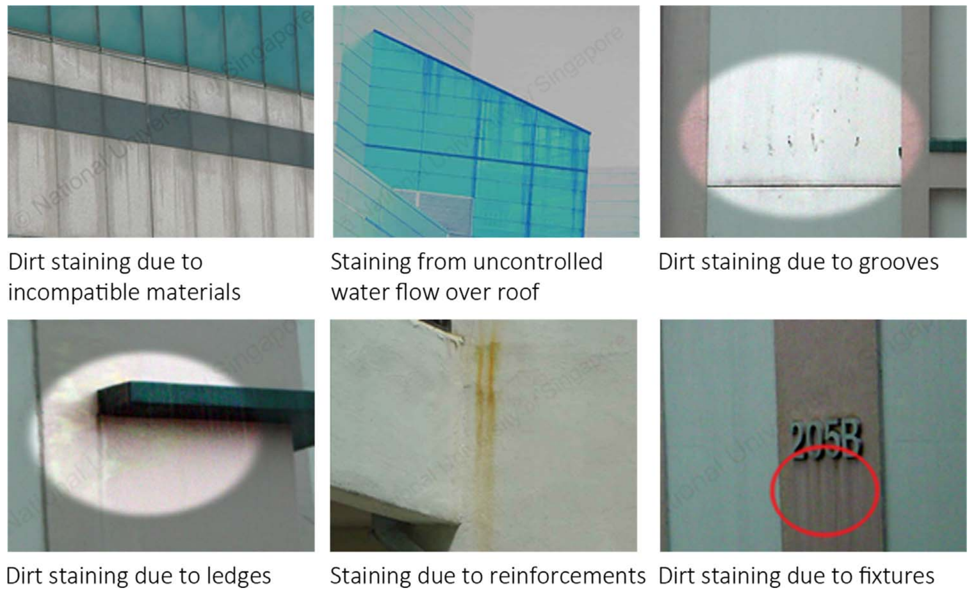

Fig. 6. Common examples of frequently staining façade areas.

impede water vapour permeability of porous substrates. This study only considered the self-cleaning effects of superhydrophobic coatings and it is noteworthy to research into the various other considerations that go into taking decisions on such applications. This can lead to the development of multicriteria decision making models for building professionals. The rate of staining of superhydrophobic façade surfaces can be modelled by building upon the current study. Future work will ensue the development of such models which can compel the FM staff to revisit their assumptions about cleaning frequencies.

In-service performance information on façade systems is useful in determining proactive maintenance interventions and realistic operational budget estimates [29]. It is apparent that self-cleaning superhydrophobic façade coating systems may require a lesser frequency of maintenance interventions which may, in turn, be favourable on a facility's operating costs. Even so, the prohibitive cost associated with superhydrophobic coating applications impedes its wide-spread usage.

However, FM can optimize the maintenance costs in a favourable manner by using superhydrophobic products in well-engineered use cases. Cost-effectiveness of superhydrophobic applications can be improved by considering such applications for important or vulnerable locations of a façade (i.e. areas difficult to clean and maintain). Examples are hard to reach areas and areas not near ground level where cleaning can be done relatively easily or locations which are more susceptible to staining defects (see Fig. 6).

The assessment method used herein can also be developed to assess the effectiveness of various façade cleaning practices. This will pave way for further optimization strategies to improve the cost-effectiveness of the FM operation. To the best knowledge of the authors, no such work is carried out on attempting to quantify the impact of such products on façade maintenance cost using in-service performance. These aspects will be explored further as such studies are pivotal in understanding the performance of superhydrophobic paints and coatings in a real-world setting.

The method proposed in this paper for comparing façade surfaces over time is innovative and it looks to standardise the façade inspection process. It is a low-cost technique that is useful in routine data collection with relative ease. Such continuous data is used to identify patterns of façade surface degradation which can then be used to prevent defects and better plan maintenance activities. Documentations of in-service performance of façade coatings can also be useful in interpreting and validating findings from façade coating related modelling and experiments.

4. Conclusions

Major contributions of this study include the introduction of a novel method to assess staining of surfaces and the knowledge generated on the self-cleaning effectiveness of superhydrophobic applications. The study finds that superhydrophobic paint or coating can reduce the façade maintenance frequency and resources needs while improving the process of stain removal. This essentially improves the ease of façade maintenance. Ultimately, these findings can be translated into improving FM knowledge on the in-service performance of self-cleaning coating materials, assisting decision makers in façade related design and maintenance applications.

The proposed innovative method is effective in comparing different façade surfaces over time and can be used in various scenarios; e.g. to assess the effectiveness of different coatings systems, to assess effects of any surface treatments, and to assess effects of cleaning using different cleaning methods. The proposed method classifies each pixel of the image as dust or not. This classification can be further optimized to identify dust or stain particles by either running the classification to coarse granularity or utilising object detection algorithms. Optimization and further expansion of the method to other surface types are proposed as future work along with modelling maintainability of superhydrophobic facade applications for the tropics.

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