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ABSTRACT

Roofs with high-reflectance (solar reflectance) coating, commonly known as cool roofs, can stay cool in the sun, thereby reducing building energy consumption and mitigating the urban heat island. However, chemical-physical degradation and biological growth can decrease their solar reflectance and the ability to save energy. In this study, the solar spectral reflectance of 12 different roofing products with an initial albedo of 0.56–0.90 was measured before exposure and once every three months over 32 months. Specimens were exposed on the roofs of dormitory buildings in Xiamen and Chengdu, each major urban areas with hot summers. The albedos of high and medium-lightness coatings stabilized in the ranges 0.45–0.62 and 0.36–0.59 in both cities, respectively. This study yielded albedo loss exceeded those reported in the latest Chinese standard by 0.08-0.15. Finally, DesignBuilder (EnergyPlus) simulations estimate that a new cool roof with albedo 0.78 on a six-story dormitory building will yield annual site energy savings (heating and cooling) for the top floor, which are 8.01 kWh/m^2 (24.2%) and 9.12 kWh/m^2 (26.3%) per unit floor area in Xiamen and Chengdu, respectively; while an aged cool roof with albedo 0.45 and 0.56 will yield the annual savings by 5.12 kWh/m^2 (15.4%) and 2.47 kWh/m^2 (10.5%) in these two cities.

Key Words

High-reflectance coating; Cool roof; Dormitory; Solar reflectance; Energy savings.

1. Introduction

The building sector consumed 40% of global energy and led to considerable carbon emission, consequently it is imperative to improving the energy performance of the building and concurrently ensuring a desirable indoor environment [1]. In China, the energy consumption caused by roof heat transfer accounts for 35% of the total consumption for top floor areas [2]. High-reflectance building roof surfaces with high albedo (solar reflectance), known as “cool roofs”, have been used to prevent overheating of buildings by solar radiation control, reduce the cooling energy need and peak loads of buildings, mitigate heat island effect, and reduce carbon emissions [3][4][5]. Cool roofs have been credited or prescribed in building energy efficiency standards for China [6], especially in hot summer climate areas (hot summer/cold winter and hot summer/warm winter zones).

The albedo of high-reflectance coatings has been found to decrease shortly after installation, which is known as natural aging. Many experimental studies have been performed on the impacts of natural aging, and some of them found that the albedo loss had certain characteristics. Dornelles et al. [7] researched the natural aging of 12 roofs with standard paint and 8 roofs with high-reflectance paint in São Paulo, Brazil, and found that the albedo sharply decreased to 0.50 from 0.74 within the first 6 months. Additionally, Paolini et al. [8] exposed white and beige finish coats for four years in Milan, and found the solar reflectance of the white finish coats dropped to 0.55 from 0.75 in four years, and to 0.38 from 0.46 for the beige coats, while the thermal emittance was unchanged. Sleiman et al. [9] observed changes to the albedos of hundreds roof products at three sites in the United States after three years outdoor exposure, and found that the albedo of some initially bright-white field-applied coatings (initial value of 0.90) fell to about 0.60 in Phoenix (Arizona), to about 0.40 in Cleveland (Ohio), and to about 0.30 in Miami (Florida), respectively.

The progressively lowering of their thermal performance and energy savings were convinced being impacted by natural aging [9]. Paolini et al. [10] tested the albedo of 12 roofs (initial albedo above 0.80) of commercial buildings in Roma and Milan, Italy for a period of two years and found that the albedo decreased by 0.14 and 0.22 respectively; and each time the albedo decreased by 0.10, the cooling load of buildings increased by 4.1-7.1 MJ/(m^2·y). In order to study the cool roof effect at different height of occupants' body, Pisello, A. L et al. [11] compared the indoor thermal comfort conditions generated within the vertical cross section of the attic between the cool and traditional roof configurations in Italy, and they found 2.79 K and 1.54 K air temperature difference in summer and winter, respectively. Mastrapostoli et al. [12] found that the surface temperature of aged cool roofs (albedo 0.50–0.55) was 7-12 K higher than those with new cool roofs (albedo 0.71–0.74), and the school building simulations in Kaisariani, Greece included an application of new cool roof coating, which could decrease the energy demand for cooling by 72%, as compared to the aged cool roof.

The changes to solar reflectance result primarily from retention of deposited soiling matter, such as soot, dust, and salt, and biological growth when high reflectance coatings are exposed to environmental conditions (wind, sunlight, rain, hail, snow, and atmospheric pollution) [13][14][15][16]. This retention (deposition minus removal) depends on local air quality and local weather (e.g., rain), and is therefore tied to the city. For instance, Aoyama [17] considered black carbon particles as the main component of soil disposition in Japan, while Gao et al. [3] affirmed fog and haze (i.e., $PM_{2.5}$ and O_3) soiled the cool roof surface and caused its albedo loss in Chongqing, China. The natural aging of cool roofs is mainly due to the retention of deposited soiling, such as soot, dust, salt, and biological growth when exposed to the outdoor environment. Since different exposure conditions led to special degradation results; hence, it is necessary to conduct local research on natural aging of cool roofs in China.

To maintain maximum cooling energy savings throughout the service lifetime, cool roofs should be cleaned regularly in some cases. Levinson et al. [18] investigated the albedo of 15 single-ply roofing membranes before and after cleaning, and compared the albedo of these after natural aging with those of new membranes; the ratios were 0.41–0.89, those after scrubbing were 0.53–0.95, those after washing were 0.74–0.98, those after cleaning were 0.79–1.00, and those after bleaching were 0.94–1.02. Although cleaning can maintain the albedo of cool-roof, the energy cost savings cannot cover the labor cost [19]. In addition, further research works involve some self-cleaning high reflectance coating, consisting of a photocatalyst system with titanium oxide, or an alkyl silicate system; solar reflectance decreased by 5–10% (to 77–82% from 87%) with self-cleaning coating and by 20–23% (to 64–67% from 87%) with common cool-roof coating in 3-6 months. However, the self-cleaning coating has become somewhat expensive recently [17][20][21].

Various evaluation methods, outdoor-exposure trials and laboratory aging practice (ASTM D7897 Standard Practice for Laboratory Soiling and Weathering of Roofing Materials to Simulate Effects of Natural Exposure on Solar Reflectance and Thermal Emittance), for the aging of the cool roof have been studied. Researchers at Lawrence Berkeley National Library (LBNL) have developed a calibrated laboratory aging practice that replicates in less than three days the changes in solar reflectance and thermal emittance that roof surfacing materials experience after three years of natural exposure in various U.S. climates [22][23][24]. Nevertheless, it is challenging to reproduce and match the natural aging of cool-roof coatings in actual soiling (deposition of soot, dust, and salt, and biological growth) and weathering (meteorological conditions) conditions in the laboratory. Therefore, this study will provide the method and engineering case for natural soiling and weathering on high reflectance coatings and standard promotion, especially in Chinese cities with hot summers, where high-reflectance cool roofs are most effective [6]. Meanwhile, natural aging of the high-reflectance coatings can be used to calibrate a laboratory aging practice.

Energy Star (ES) and the Cool Roof Rating Council (CRRC) in the US have established perfect product labeling and rating programs for high reflectance coatings [25][26]. To qualify for the ENERGY STAR label issued by the U.S. Environmental Protection Agency's ENERGY STAR program, a low-slope roofing product must demonstrate an albedo of at least 0.65 when new, and an albedo of at least 0.50 three years after installation. The Cool Roof Rating Council (CRRC) establishes a practice for rating the initial and aged solar reflectance and thermal emittance of roofing products [27], and provides a directory of product ratings [25]. However, it does not set performance requirements for cool roofing products [28]. These test methods and product ratings are also recognized by the Green Globes, the Leadership in Energy and Environmental Design (LEED), California Energy Commission (CEC), and ASHRAE [29][30][31][32]. Nevertheless, the latest Chinese standard, *Building Reflective Thermal-insulating Coatings (JG/T 235-2014),* just stipulates the initial albedo of the following three types of coatings: low lightness (solar reflectance $\rho \leq 0.40$), medium lightness ($0.40 < \rho < 0.80$), and high lightness ($\rho \geq 0.80$), whereas it does not specify the albedo of high reflectance coatings after natural aging.

In general, although the cool roofs have been widely used in Chinese cities with hot summers, some problems are not fully addressed including 1) the natural aging characteristics of high-reflective coatings in conditions of specific climate and air quality in China; 2) the impacts of albedo decrease and occupant heating usage habits on energy consumption in dormitory buildings. This study therefore investigates the natural aging characteristics of 12 roofing products, and analyzes the aging effects on energy consumption of the top-floor in a prototype dormitory building in two representative cities (Chengdu and Xiamen), located in hot summer climate regions in China.

2. Natural exposure trials

The following section represents the natural exposure trials in Xiamen and Chengdu by describing the selected materials (Section 2.1), detailing the exposure procedure and climate zone (Section 2.2), and outlining the measurement method (Section 2.3).

2.1 Selected materials

As per *Building Reflective Thermal-insulating Coatings (JG/T 235-2014)*, seven high-reflectance roof coatings of two lightness types (high and medium lightness) are available in the market, with initial solar reflectance (R_{i}) ranging between 0.56 and 0.90. Two of these roofing products, C6 (WC, high lightness) and C7 (BC, medium lightness), were exposed and measured in Xiamen, and other products (C1-C5) were exposed and measured in Chengdu (Table 1).

Twelve roofing products were coated on smoothly polished concrete tiles and aluminum substrates (both with the configuration of 100 mm × 100 mm × 10 mm). These two types of samples (i.e. tiles and substrates) stand for the commonly-used roofs in residential buildings (with a dry-film thickness around 500 μm) and industrial buildings (with a dry-film thickness around 25 μm), respectively. The initial solar reflectance was measured using a Perkin-Elmer Lambda 950 UV-vis-NIR spectrometer, operated in accordance with ASTM E903-12: Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres [33], and thermal emittance was measured with a portable emissometer emittance, those of selected roofing products were listed in Figure 1. In addition, we included only flat products whose radiative properties could be readily measured using ASTM methods. The selected roofing products comprise with different spectral reflectance and open porosity.

Table 1. Selected high-reflectance roof coatings for the natural exposure trails in Xiamen and Chengdu.

Figure 1. Roofing products labeled with initial values of solar reflectance (ρ), thermal emittance (ε), lightness color coordinate (L), red/green color coordinate (a), and yellow/blue color coordinate (b).

2.2 Natural (outdoor) exposure procedure, local climate zone, and building prototype

Selected coatings were brushed or sprayed on prototype specimens, which were applied on a concrete tile or aluminum substrate (Figure 2a, b), and they were measured in two experiment sites for comparison purposes. As shown in Figure 2c, d, and Figure 4, the specimens with the same coating were placed on a specimen stand with the configuration of 1,410×1,180mm.

Figure 2. (a) Concrete tiles, (b) aluminum substrate specimens, (c) side view of the specimen holder; (d) top view of the specimen holder.

Since WR can significantly reduce the building energy consumption in hot summer climate zone in China [35], the practical applications of cool roofs have been highly promoted by the government. However, the actual energy savings are determined by the actual performance of the cool coatings (i.e., the aged albedo of the coating). In this study, two representative cities, Xiamen and Chengdu, located in the hot summer regions, are selected to explore the natural aging characteristics of coatings and its effects on building energy consumption. The specimens painted with different coatings were exposed at rooftops in two sites: Xiamen (24.48 °N, 118.08 °E, 23 m height, hot summer and warm winter region) and Chengdu (30.67 °N, 104.07 °E, 19 m height, hot summer and cold winter region), as shown in Figure 3. As highlighted in Section 1, the main causes of roof soiling and albedo loss are from pollution and weathering. The values of several parameters, including wind velocity, air dry-bulb temperature, relative humidity, air quality index and precipitation, are well-recorded in the smart weather station in exposure site (first three parameters) and local weather station (last two parameters).

Figure 3. Chinese climate zones, Chengdu and Xiamen cities location.

Each experiment sites were located in a residential area and at a distance from the primary source of pollution (i.e., power plant). One set of specimens was exposed at the low slope (2%, corresponding to a 1.1° tilt), while a duplicate set was exposed at the high slope (20%, corresponding to a 36.4° tilt). Specimens were exposed facing south with 1.5m away from the parapet to prevent being shaded (Figure 5).

The solar reflectance of the C1-C5 specimens was measured with an interval of three months from December 2014 to June 2016 in Chengdu (Figure 1). The solar reflectance of these specimens was also measured before exposure (i.e. 0 month) for the purpose of comparison. Similarly, between January 2015 and July 2016, an exposure test was also conducted in Xiamen (Figure 1) to assess the variation of solar reflectance caused by different aging conditions. The two cities are both in hot summer regions. As the test in Xiamen was interrupted due to the typhoon in July 2016, the solar reflectance of C6 and C7 specimens was measured every three months until the 18 months (i.e. June 2016). Although some research works have found the emittance of high reflectance coatings did not decrease after natural aging [9][17], the hemispherical emittance of selected coatings was also measured every three months after exposure. It was ensured that the sampling day and a few days before were not rainy in case of contamination cleaning. One specimen of each category was taken to the laboratory for further measurement every week, while the other specimens were still exposed outdoor. Three different spots on each specimen were selected for solar reflectance measurement while the mean values of the measured solar reflectance were used for analysis. It should be noted that the measured specimens were stored and no longer used for exposure test.

Figure 4. Natural outdoor-exposure of specimens (a) specimens location, and (b) exposure site.

2.3 Measurement method

This study includes the following steps for each specimen:

• Measurement of spectral reflectance over the solar spectrum 300–2,500 nm at an interval of 5.0 nm.

• Calculation of solar reflectance.

• Measurement of the hemispherical thermal emittance.

The near normal-hemispherical solar spectral reflectance of prototype specimens (300 nm-2500 nm) was measured with a Perkin-Elmer Lambda 950 UV-vis-NIR Spectrometer. The machine was equipped with a 150 mm integrating sphere and operated in accordance with ASTM E903-12:

Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres [33] and JG/T 235-2014: Architectural reflective thermal insulation coating [34]. Solar reflectance was calculated by averaging over solar spectral reflectance weighted with solar spectral irradiation.

Hemispheric thermal emittance ϵ was measured with a Devices & Services model AE1 portable emissometer, operated in accordance with ASTM C1371-15: Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers [35].

3. Case study of dormitory building energy simulation

3.1 Simulation tool, modelling, and parameters setting

The change to the solar reflectance over time after outdoor exposure provides an indication of the possible variation in the surface heat transfer of the building roof, thereby providing a deeper insight into the impact of albedo changes on the top floor area cooling and heating loads. Previous works [7][8][9] indicate that the service life of a cool roof is expected to last for 20 years, the albedo of cool roof sharply decreases only within the first 6 months and then stabilizes in 2 to 3 years. Therefore, considering the whole service life of cool roofs, it is reasonable to simulate the energy savings neglecting the changes of solar reflectance at the first 2 to 3 years.

In this study, a representative six-story dormitory building model was constructed in DesignBuilder v5.3. Designbuilder was selected as the tool for the case study as it is relatively accurate for energy simulation [36][37]. Crawley et al. [38] consider it as a mature product which offers flexible geometry input and extensive material libraries and load profiles. EnergyPlus is integrated within Designbuilder's environment which allows it to carry out complete simulations without leaving the interface. Designbuilder has quality control procedures which assure the accuracy of the results in comparison with the standalone EnergyPlus engine [39].

The building model was based on prototype of a concrete-slab (foundation, walls, and roof) dormitory building in Xiamen, which was modelled measuring 626.3 m^2 conditioned floor area and north-south oriented with windows on the south and north facades. The envelope characteristics, ventilation and infiltration rates, internal loads, operating schedules, and cooling and heating set points to comply with the prescriptive requirements or recommended design values in current Chinese building energy efficiency standards (see parameters in Table 3, Table 4, and Figure 5)

[41], and were made to reflect the typical details in hot summer climates, as shown in Table 2 and Table 3. The exterior climate data were defined by hourly typical meteorological year (TMY) from the Chinese Standard Weather Data (CSWD) [42].

Figure 5 (a) Axonometric rendering projection and (b) plan of the top floor of the representative dormitory building simulated.

Table 2. Characteristics of the top floor of the representative office building simulated.

Table 3. Roof and wall construction (listed outside to inside) of a representative dormitory building in each city [34].

The HVAC system was designed based on the Chinese building energy efficiency standards and detailed in Table 2. The setpoint temperature was 26 °C in summer and 16 °C in winter. Space cooling and heating were provided by split direct expansion air-source heat pumps, which are commonly used in China [6]. The cooling and heating COPs of the air conditioning system are 3.0 and 2.5, respectively. In the simulation, the indoor air temperature was set to maintain the room in a comfortable temperature range (cooling setpoint of 26°C; heating setpoint of 16°C, Table 2), and indoor temperature and humidity were assumed evenly distributed.

3.2 Case study

In order to estimate the impact of natural aging of high-reflectance coatings on the energy savings of cool roofs in Chinese cities with hot summer climates, six case studies were considered in this paper: the building model with a grey roof (with an aged albedo of 0.20) was simulated in Chengdu and Xiamen and used as the reference buildings. The building models with an aged cool roof and a new cool roof in Xiamen and Chengdu, respectively. In addition, the case in Xiamen comprised two scenarios, including space heating and no space heating, because Xiamen is located in hot summer/warm winter zone and does not take into account heating. Zhuang investigated the air conditioning service in Xiamen and found about 40 % of households use air-conditioned heating in winter [40]. In these cases, the albedo before and after aging was selected according to measured data, the building with a new high-reflectance coating was modelled as

0.68 and 0.80 in Xiamen and Chengdu (median values of new high-reflectance coatings in two cities), respectively, and the values of aged cool roof simulation corresponded with the median values of outdoor exposure measurement data after 30 month in Xiamen and Chengdu.

Space heating load and space cooling load savings were computed as the load of the building with the reference (grey) roof minus that of the building retrofitted with the aged cool roof. The site cooling/heating energy savings can be estimated by dividing the cooling/heating load savings with the corresponding COPs, respectively.

4. Natural exposure trials results and discussion

4.1. Natural exposure trials

Figure 6. The solar reflectance of selected roofing products (aged - initial solar reflectance), (a)-(e) shows the ten specimens exposed in Chengdu, while (f) shows the two specimens exposed in Xiamen.

The initial albedo ρ_{i} of each high-lightness coating (C1, C3, or C5; $\rho_{\mathrm{i}} \geq 0.80$) applied to a concrete substrate was about 0.02 higher than that of the same coating applied to an aluminum substrate (Figure 6 a-e), while medium-lightness coatings ($\rho_{\mathrm{i}} < 0.80$) yielded the same initial albedos over concrete and aluminum.

Figure 6 shows the evolution of albedo over the 30-month natural exposure trials conducted in Chengdu from January 2015 to June 2017 (Figure 6 a-e), and over the 18-month test performed in Xiamen from December 2014 to June 2016 (Figure 6f). In Chengdu, the albedos of selected specimens (C1-C5) decreased by 0.20 between months 0 and 3 (January 2015 to April 2015), and another wide range of albedo losses by 0.03-0.16 occurred in the heating season (i.e., November 2016 to February 2017). Paolini found similar results for roofing and walling membranes in Roma and Milano [9][7] as the heating season yielded the main value loss during the exposure (Figure 6). After one year of exposure, no remarkable albedo loss was measured in C3 and C4, while the albedos of C1 and C2 increased by 0.05 between months 3 and 9. The albedos of C1, C2, and C5 did not decrease monotonically, and they increased sharply by 0.07-0.12 between months 15 and 18 and between months 24 and 31, corresponding to the rainy seasons (March through July) in years 2016 and 2017 (Figure 7). After 30 months of natural aging, the mean albedo loss of the C1, C2, and C5 specimens was 0.23. Meanwhile, the albedos of C3 and C4 remained stable until the end, as no remarkable loss or increase in heating seasons or rainy season between months 15 and 24, and the value loss of C3 and C4 measured between 0.36–0.41 and 0.36–0.37 in month 30, respectively.

For the high-lightness coatings in Xiamen, C6 with albedo greater than 0.56 remarkably lost 0.23 between months 0 and 10 (i.e., December 2014 to September 2015), which yielded 74.2% of the total value lost. Meanwhile, the most substantial decrease of 0.13 occurring between months 0 and 3 during the first heating season (i.e., December 2014 to February 2015), and there was no albedo decrease of the same magnitude in the next winter. Between months 11 and 18 (i.e., Oct 2015 to Jun 2016), significant reductions were not measured. During the initial drop period between months 0 and 10, the pace of albedo decrease of C6 slowed gradually, and stability was achieved for most of the exposed products.

Figure 7. Daily mean wind velocity, monthly mean air temperature, relative humidity and average precipitation in Chengdu and Xiamen.

Different trends of coating albedo between these two cities are due to 1) Xiamen is warmer (average 16.5°C) than Chengdu (average 9°C) during winter; 2) average wind speed in Xiamen was higher than that in Chengdu (3.0 m/s versus 0.9 m/s as shown in Figure 7). Therefore, more building heating and dust deposition and weaker cleaning mechanism (low wind speed and less rainfall) resulted in severer air pollution concentration in Chengdu, especially in winter. Accordingly, Figure 8 shows the severe air pollution occurring between months 11 and 14 (114.7-172.3 μg PM2.5/m^3), and between months 22 and 26 (89.6-123.5 μg PM2.5/m^3) in Chengdu, corresponding to the sharp albedo losses in panels a, b, and e of Figure 6.

Figure 8. The monthly average Air Quality Index (AQI) in Chengdu and Xiamen (Dec 2014 or Jan 2015). AQI presents the daily mean concentration of areal PM 2.5. Higher daily mean concentration indicates higher the index level (i.e., I is excellent; II is good; III is light pollution; Ⅳ is moderate

pollution)[41]. AQI data were provided by local weather stations with short distance to the exposure site.

Additionally, different albedo changes were caused by differences between the air quality and rainy conditions in two cities. For C1-C5 in Chengdu, with distinct dry and rainy seasons (Figure 7), the loss of the albedo was even due to the retention of dust and airborne particulate (e.g., between month 3 and 9). While in the rainy seasons (e.g., between month 15 and 18, or after month 24), when air quality was good, the albedos increased due to rain wash. However, for C6-C7 in Xiamen with much more annual rainfall and high relative humidity (Figure 7), due to the high air quality, the albedo of coatings was decreased slowly in Xiamen (Figure. 6f).

Medium-lightness coating C7 had the lowest initial albedo (0.56). After 18 months, its albedo fell by 0.19 (33%). The albedo variation of C7 stabilized earlier than that of C6; C7 lost 0.12 in albedo between months 0 and 7 (i.e., initial to May 2015), which yields 63.5% of its total value lost. In the following 8 months (i.e., May 2015 to January 2016), the albedo showed a downward fluctuation over time, sometimes exceeding the albedo measured in the earlier three months between months 11 and 13 (i.e., measured 0.43 in Feb 2016). Due to the decrease of precipitation intensity in these months (Figure 4), soot deposits on the specimens resulted in albedos fluctuations. Similar fluctuations were also shown in low-reflectivity membranes (ρ=0.20–0.30) and glossy single-ply membranes in some cases [9][42]. Different from C6 with 2.0% slope, the most substantial decreases occurring during the rainy season (i.e., February to June in 2015, Figure 7), albedo of the C7 dropped by approximately 0.02, and in the next rainy season (i.e., February to June in 2016, Figure 7), the precipitation intensity increased again, thereby cleaning the deposited soot resulting from the substantial decreases.

The coatings exposed and tilted by 20% (pitched roof) in Xiamen and Chengdu showed similar tendency as the same coatings at 2% slope (Figure 6a-f). All selected coatings finished on concrete tile and aluminum substrate showed root mean deviation of less than 0.034 (average of 0.024) and 0.023 (average of 0.018) after 30 months of exposure respectively. In addition, the selected coatings finished with a field-applied coating on concrete tile and factory-applied coating on aluminum substrate exhibited similar trends, excluding C3 in Figure 6c (i.e., March to December 2016). All other selected coatings finished on concrete tile compared to aluminum substrate showed root mean deviation of less than 0.024 (average of 0.020) after 30 months exposure in Chengdu. Therefore, the intensity of the effects does not seem to be highly influenced by slope and substrate in the four categories of selected coatings, except C3.

Figure 9. Spectral reflectance within ranged 300nm–2500nm after every 3 months with 2%-sloped exposure for coating(a) C6 (high lightness, cement-based) and (b) C7 (medium lightness, cement-based) in Xiamen, (c) C3 (high lightness, cement-based),(d) C4 (medium lightness, cement-based), (e) C7 (high lightness, aluminum-based), and (f) C8 (medium lightness, aluminum-based) in Chengdu.

Focusing on the spectral reflectance variation after outdoor exposure (Figure 9), C6 and C3 (for the high-lightness coatings with similar spectra), and C4 and C7 (for the medium-lightness coatings with similar spectra), were exposed outdoors in Xiamen and Chengdu. Spectral reflectance changes were smallest in the UV spectrum (300 – 400 nm) and at the tail end of the NIR spectrum (2,200 – 2,500 nm), which had little significance for the surface energy balance [9]. The obvious variation of aged spectra is evident mainly in the VIS and the first portion of NIR (420nm to 2200nm), similar to what was observed by Paolini et al.[7][9]. The inflection points in the aged spectra ranged 420–600 nm is compatible with the early physical degradation of the binder of the finish coat due to UV irradiation, weathering, and soot [9], blue wavelength irradiation are also determined (Figure 9) [43]. Furthermore, the shape of aged spectra, ranging between 420 nm and 600 nm, is altered as a result of physical degradation. The reflectance of aged spectra between 420 nm and 825 nm attenuated faster so that the shape nearby 825 nm altered after one year; an obvious leap (near 0.02) occurred in all coatings exposed in Xiamen and Chengdu.

Additionally, C1 and C2 showed the appearance of cracks after exposure (Figure 10a), which could result from either substrate contraction in winter and expansion in summer, or strong UV irradiation which breaks the chains of macromolecules to create free radicals and form molecular chains, thereby results in chemical-structure changes in their binder, resins, and generate internal stress [44]. After all, it was suggested by pulverization, blistering, cracks noticed after a few months of outdoor exposure, reflectance reduction, shape alteration, and leap in this spectra portion were symptoms of this degradation. There is visual evidence of significant physical disintegration after one year of exposure (Figure 10).

Figure 10. A feature of aged specimens in months 12 (a) cracks (b) blistering (c) mildew growth.

For field-applied C3 (high lightness) and C4 (medium lightness) exposed in Chengdu (Figure 9c, e), the shape changed considerably, especially between 420 nm and 600 nm wherein the portions and intensity of the impacts and effects on C3 and C4 in Chengdu are higher than C6 and C7 in Xiamen (Figure 9a, b). The reflectance fell in extreme fashion with the impact of acid rain in Chengdu, as it contained a lot of contaminants, including humic acid and dust surrogates those were determined to drive the albedo loss in the visible and ultraviolet regions [45][46].

The spectrum of C7 was almost unchanged between 400 nm and 500 nm (Figure 9b), while for C4, which had higher reflectance (400–750 nm), the average relative loss was higher. The same reflectance recovery is suggested by slight spectra enhancement (i.e., January to July 2016, Figure 9c, d), recovery was produced by more rain-wash (Figure 4), and the carbonation and efflorescence of cement-based specimens are transient in effect and highly soluble [46]; therefore, the trend of albedo, in fact, fluctuated for some time.

The increase over time of the 1,300–2,300 nm reflectance of C7 in Xiamen may have resulted from the carbonation of concrete tile (i.e., March 2015); the phenomena observed is actually compatible with a residual of calcium carbonate [7]. However, this increase occurred only in the case of C7; therefore, it is not certain that the increase in solar reflectance is prevalent. In addition, C7 suffered the least absolute loss (near 0.20), because the absorption coefficient of soot decreases with wavelength [47][48].

4.2. Discussion

After 6 to 12 months of exposure, albedo of high-reflectance coatings decreased rapidly, with albedo losses of 0.25–0.41 and 0.14–0.27 in Chengdu and Xiamen, respectively. The loss in Chengdu was severer than that measured in Chongqing (29.18°N, 106.16°E, close to Chengdu), where an exposure trials of high-reflectance coatings (ρi=0.82) on an office building were conducted from July 2014 to July 2015 and the albedo decreased 0.20 after one year of exposure [42].

Thereafter, the albedo of C1, C2, and C5 fluctuated sharply, and albedo of high-lightness coatings stabilized approximately four months earlier than that of medium-lightness coatings. Considering the severer air pollution in the selected cities in China (shown in Figure 8), After 30 months of exposure, the albedo of high and medium-lightness coatings stabilized in the range between 0.45–0.62 and 0.36–0.59, respectively, and the aged values were smaller than the values (near 0.60) measured by Sleiman et al. [49][50]. Additionally, the measured albedo would stabilize in 2 years, which is shorter than the results in the USA. As is shown in Table 4, the latest Chinese standard addresses the albedo loss of high and medium lightness coatings by 0.20 and 0.15, respectively, but the actual albedo loss of C1-C7 exposed in Xiamen and Chengdu exceeded the values addressed by 0.08-0.15, which indicates the standard data according to lab practice is not consistent with exposure trails.

Table 4. High-reflectance roof standards in China.

Although the main causes of natural aging of high-reflectance coatings are almost the same (i.e., deposition of carbon emitted by vehicles or particles from heating furnaces), the trend of albedo value changes was different in Xiamen and Chengdu. This is due to the intensity of the deposition, physical and chemical degradation and biological growth are different in the two cities, as they are affected by local weather conditions (i.e., solar irradiation, precipitation, and air circulation) and air quality. However, the emittance values fluctuated with small changes and maintained stability after exposure in both cities.

5. The impact of aging on the energy performance of the buildings

In order to estimate the impact of the natural aging of high-reflectance coatings on the cooling and heating site energy consumption of dormitory buildings in the hot summer climate of China. The annual simulations of reference buildings with an aged grey roof (albedo of 0.20), new cool roof, and aged cool roof were performed in Xiamen and Chengdu. The boundary conditions used are presented in Tables 2 and 3 (Section 3). In some energy consumption simulation research works, the cool roof simulation used consisted of an aged albedo of 0.60 [51], but the albedo of aged high-reflectance coatings was below this value in the hot climate of China (Section 4.1). Therefore, as the solar reflectance of the aged cool roof stabilized after 2 years in both Chengdu and Xiamen, the albedo of aged cool roof simulation corresponded with the median values of outdoor exposure measurement results in Xiamen and Chengdu, respectively, and the values are shown in Table 5.

Table 5. Solar reflectance and median values of selected roofing products after outdoor exposure in Xiamen and Chengdu.

The previous simulation results indicate that the energy savings scale of the cool roof scale linearly with the change in roof albedo [4]. Figure 11 and 12 depict the annual cooling and heating loads and energy consumptions for the dormitory buildings in Xiamen and Chengdu.

Figure 11. Annual heating and cooling loads and site energy consumption for dormitory building in Xiamen with scenarios of the new or aged grey roof (albedo 0.20), aged cool roof (albedo 0.45), and new cool roof (albedo 0.78).

For the dormitory building in Xiamen, raising the roof albedo to 0.78 (for a new cool roof) from 0.20 (for an aged grey roof) decreases the annual cooling load by 24.56 kWh/m^2, and annual cooling site energy use by 8.18 kWh/m^2, respectively. It also increases the annual heating load by 0.51kWh/m^2 and annual heating site energy use by 0.17 kWh/m^2, respectively. The new cool roof can reduce energy consumption for the top floor areas by 24.2% (8.01 kWh/m^2). However, a mean albedo loss of 0.33 caused by natural aging increases the specific annual cooling needs by 5.22 kWh/m^2, and it decreases the heating penalty by 0.10 kWh/m^2, respectively, which is 10.5% energy savings of initial energy savings. Zhuang [40] measured the cooling energy use of an existing dormitory building retrofitted with an aged cool roof (albedo of 0.44) in 2014, and found the energy savings ranged between 4.42–11.44 kWh/m^2; it was determined that high-reflectance coatings had more energy savings potential in existing buildings. Additionally, when excluding space heating in winter (the second scenario in Section 3), the winter heating penalty of cool roof does not exist, the aged cool roof can reduce 9.0% energy consumption (2.92 kWh/m^2) in the end.

Figure 12. Annual heating and cooling loads and site energy consumption for dormitory building in Chengdu with scenarios of the grey roof (0.20), aged cool roof (0.56), and new cool roof (0.83).

For the dormitory building in Chengdu, annual heating and cooling loads and site energy consumption of the building model applied with a grey roof (0.20), aged cool roof (0.56), and new cool roof (0.83) were simulated (Figure 12). For a new cool roof, the results of the annual energy consumption presented a decrease of 9.12 kWh/m^2 (26.3%), while a decrease of 6.65 kWh/m^2 (15.8%) was recorded for an aged cool roof. The simulation results indicated that natural aging reduced the energy savings of high-reflectance coatings by 2.47 kWh/m^2 (10.5%). Natural aging can reduce the annual heating penalty of 1.37 kWh/m^2 (35.0%), although the energy savings for cooling with aged cool roof lost 8.64 kWh/m^2 (20.1%).

We computed, instead, a small reduction in the heating penalty after natural aging in both Xiamen (0.10 kWh/m^2) and Chengdu (0.46 kWh/m^2). The variations we computed are relatively small, but they contribute to increasing the uncertainty in building energy simulation. Thus, aged values for the solar reflectance of walls shall be considered.

6. Summary

This paper conducted an outdoor exposure experiment of 12 available high-reflectance coatings classified by high/medium lightness, flat/pitched roof, and field/factory-applied, with initial solar reflectance between 0.56 and 0.90. Each specimen was exposed on the natural rooftop racks in Xiamen and Chengdu, large Chinese cities with hot summers. During exposure, no obvious differences were noticed between the coatings substrates exposed or specimens tilted by high or low slopes in both Xiamen and Chengdu; after 30 months, the albedos (solar reflectance) of high and medium-lightness coatings stabilized in the range between 0.45–0.62 and 0.36–0.59 respectively. The albedos of C1, C2, and C5 fluctuated sharply, and the albedos of high-lightness coatings tended to stabilize four months earlier than those of medium-lightness coatings. The shapes of the spectral reflectance of exposed coatings varied by city. The shapes of the reflectance spectra of the factory-applied coatings differed from those of field-applied coatings before exposure. In addition, the exposure results in Xiamen and Chengdu after exposure trials exceeded the values addressed the latest Chinese standard by 0.08-0.15; this indicates the lab aging data is not consistent with the natural aging measurement.

The natural aging of high-reflectance coatings affects the energy savings of dormitory buildings subject to the hot summer climate of China; the representative dormitory building models with grey roof, aged cool roof, and new cool roof were built to simulate the annual heating and cooling loads and site energy consumption in Xiamen and Chengdu. Consider the heating penalty and cooling energy savings, it is shown that the application of new heat reflective roof coating can decrease the annual site energy use for the top floor areas by 8.01 kWh/m^2 (24.2%) in Xiamen and 9.12 kWh/m^2 (26.3%) in Chengdu. Albedo decreases following aging reduced these savings to 5.12 kWh/m^2 (15.4%) in Xiamen and 2.47 kWh/m^2 (10.5%) in Chengdu, respectively.

In this study, the energy consumption simulation was used to reflect the effects of albedo reduction on the energy savings of cool roof. The building prototype model was set based on a prototype of a concrete-slab (foundation, walls, and roof) dormitory building in Xiamen. The parameters, including envelope characteristics, ventilation and infiltration rates, internal loads, operating schedules, and cooling and heating setpoints, comply with the prescriptive requirements or recommended design values in current Chinese building energy efficiency standards. Therefore, the prototype can represent the current dormitory buildings in China. It is also worth noting that the validation is not fully explored in this paper, and the parametrical analysis is needed to be further investigated, to evaluate the energy savings under different building insulation (i.e., high or no thermal insulation).

Acknowledgments

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Figure captions

Figure 1. Roofing products labeled with initial values of solar reflectance (ρ), thermal emittance (ε), lightness color coordinate (L), red/green color coordinate (a), and yellow/blue color coordinate (b).

Figure 2. (a) Concrete tiles, (b) aluminum substrate specimens, (c) side view of the specimen holder; (d) top view of the specimen holder.

Figure 3. Chinese climate zones, Chengdu and Xiamen cities location.

Figure 4. Natural outdoor-exposure of specimens (a) specimens location, and (b) exposure site.

Figure 5. (a) Axonometric rendering projection and (b) plan of the top floor of the representative dormitory building simulated.

Figure 6. The solar reflectance of selected roofing products (aged - initial solar reflectance), (a)-(e) shows the ten specimens exposed in Chengdu, while (f) shows the two specimens exposed in Xiamen.

Figure 7. Daily mean wind velocity, monthly mean air temperature, relative humidity and average precipitation in Chengdu and Xiamen.

Figure 8. The monthly average Air Quality Index (AQI) in Chengdu and Xiamen (Dec 2014 or Jan 2015). AQI presents the daily mean concentration of areal PM 2.5. Higher daily mean concentration indicates higher the index level (i.e., I is excellent; II is good; III is light pollution; Ⅳ is moderate pollution)[41]. AQI data were provided by local weather stations with short distance to the exposure site.

Figure 9. Spectral reflectance within ranged 300nm–2500nm after every 3 months with 2%-sloped exposure for coating(a) C6 (high lightness, cement-based) and (b) C7 (medium lightness, cement-based) in Xiamen, (c) C3 (high lightness, cement-based),(d) C4 (medium lightness, cement-based), (e) C7 (high lightness, aluminum-based), and (f) C8 (medium lightness, aluminum-based) in Chengdu.

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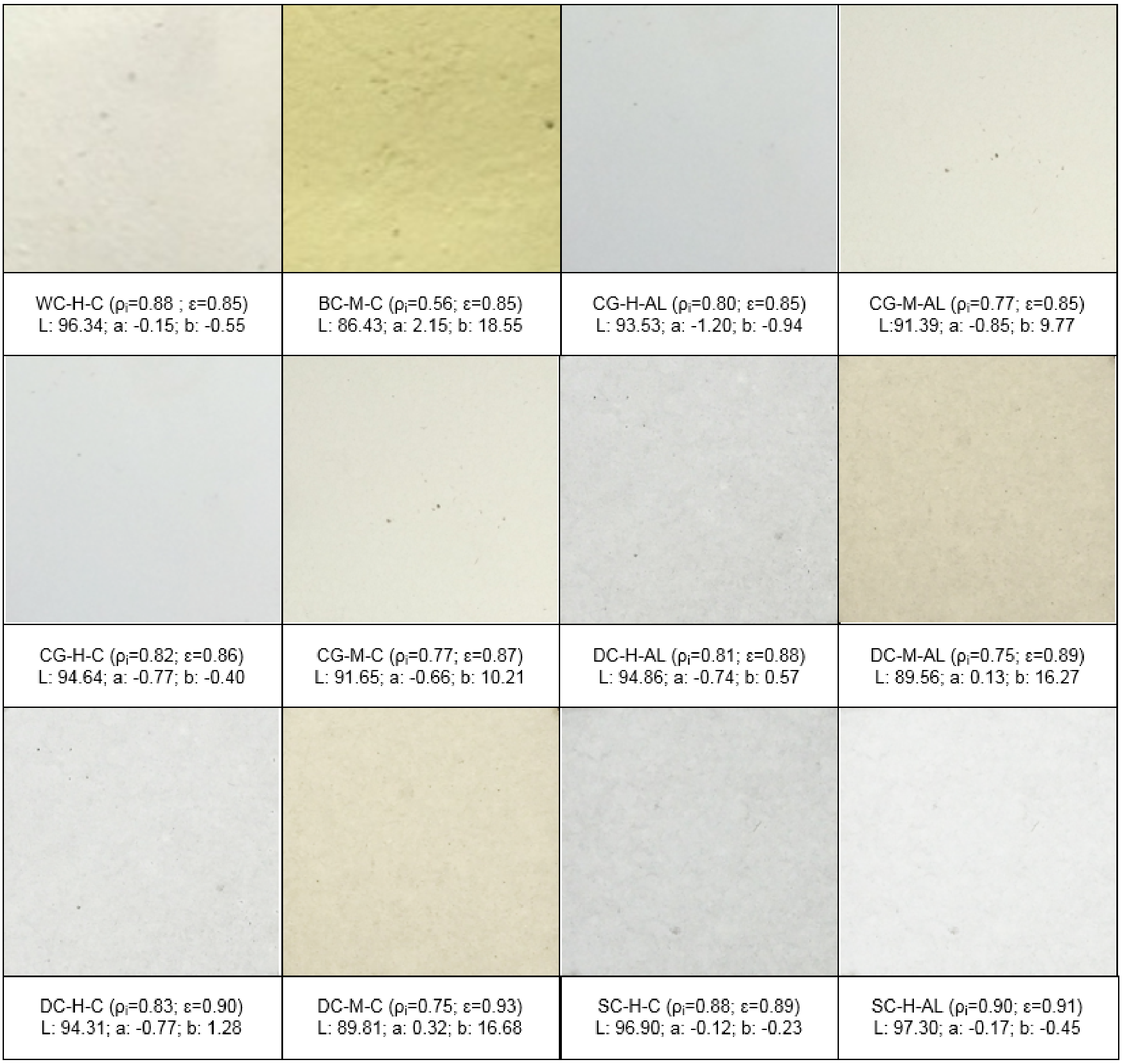

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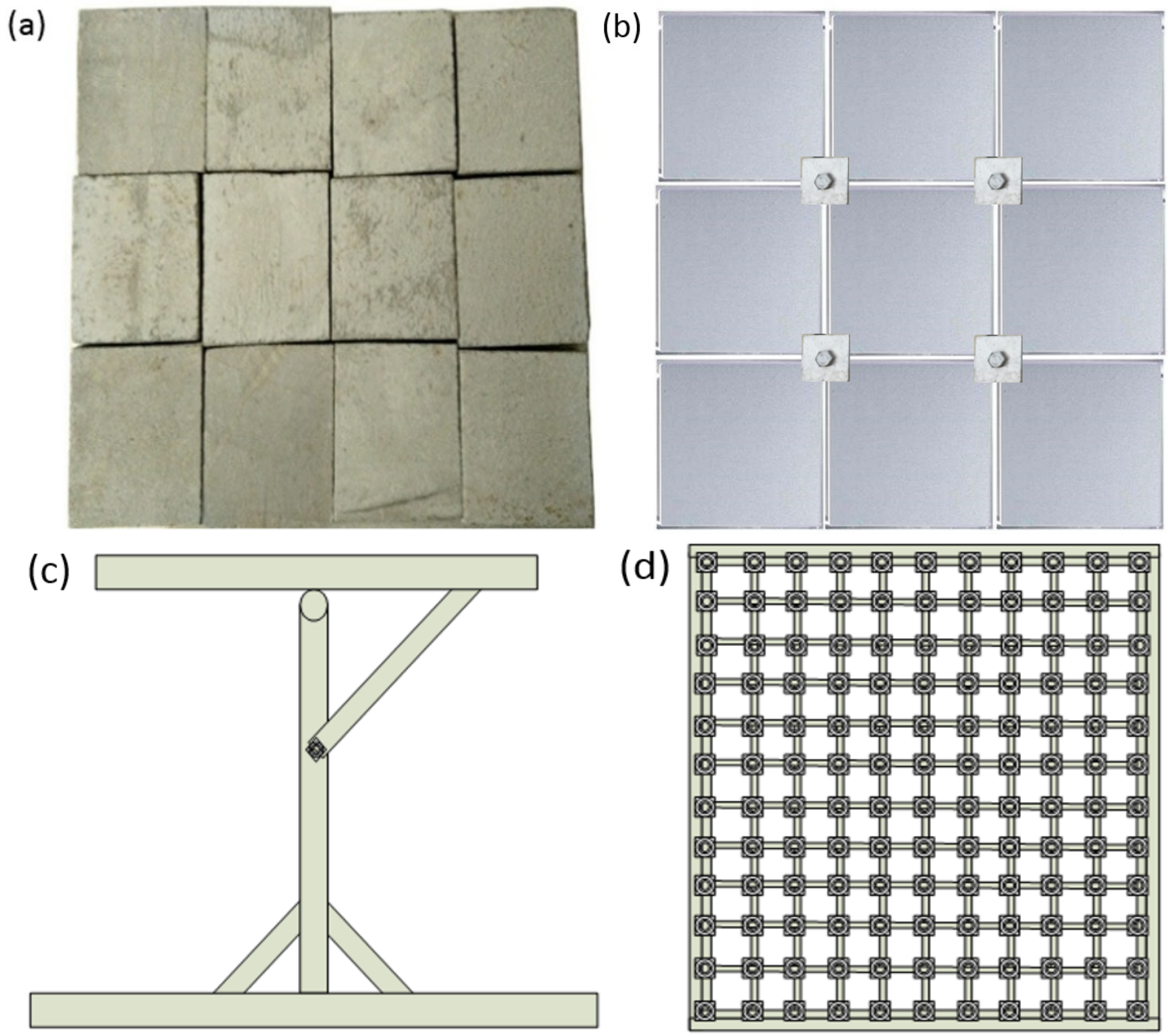

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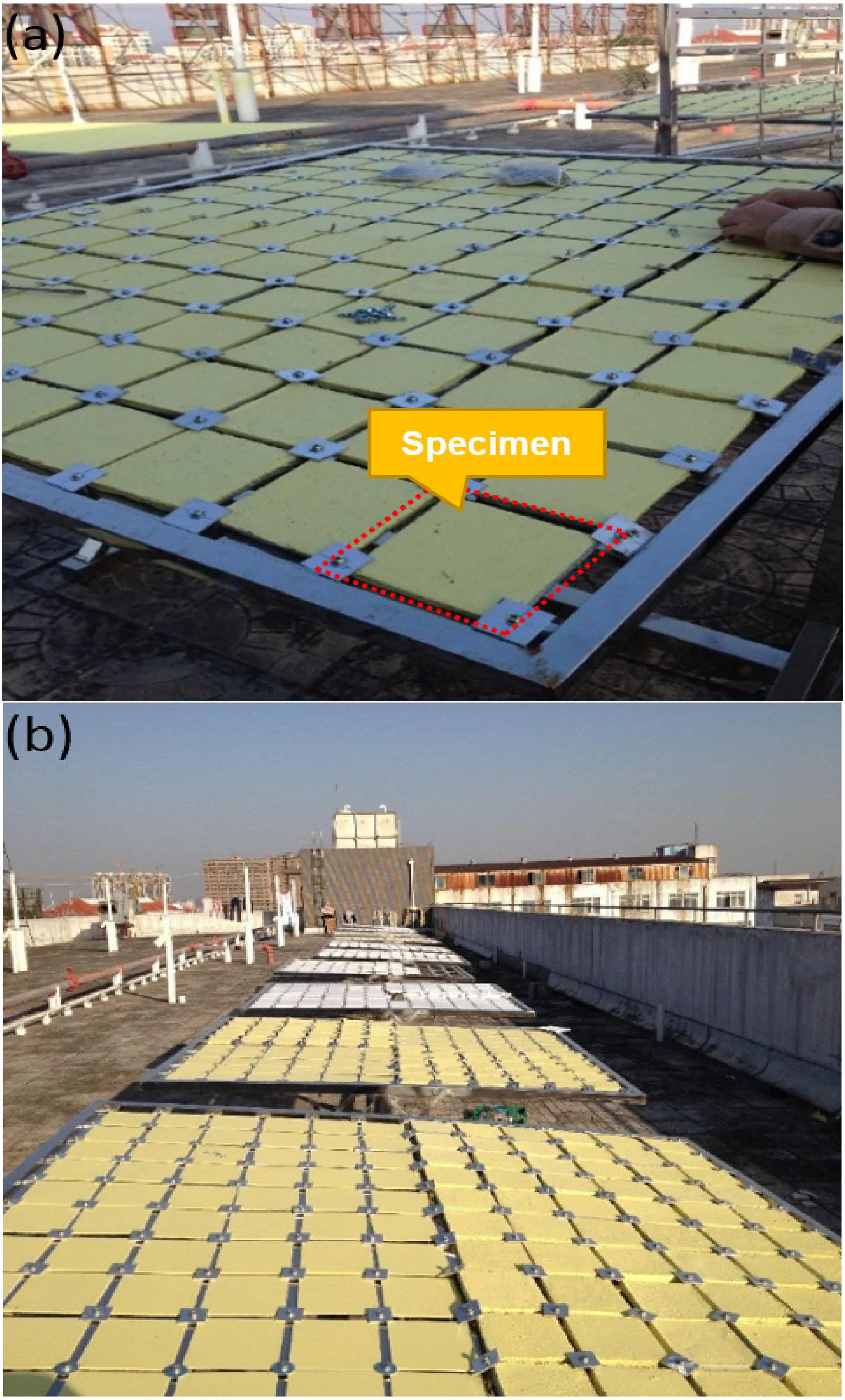

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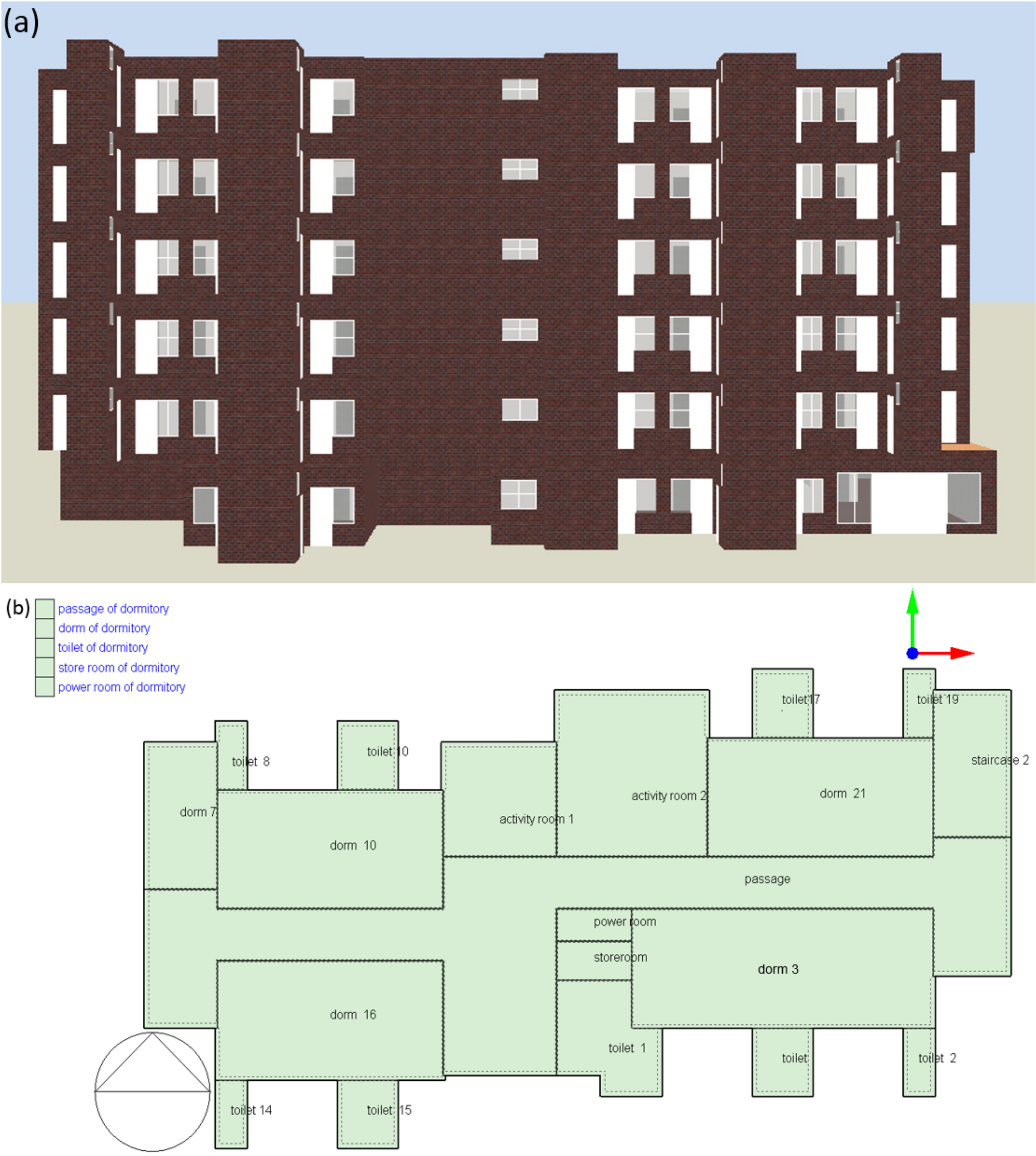

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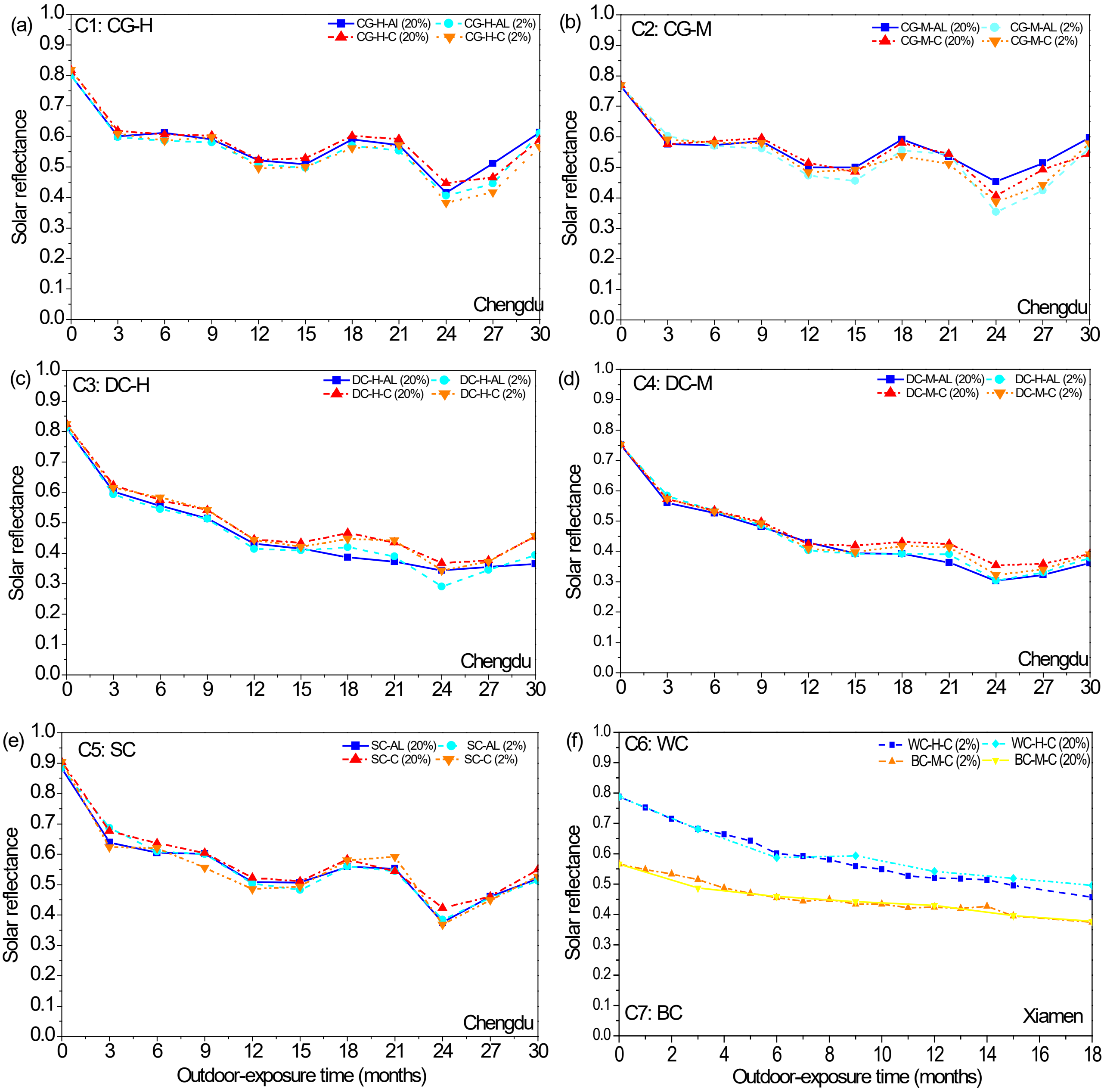

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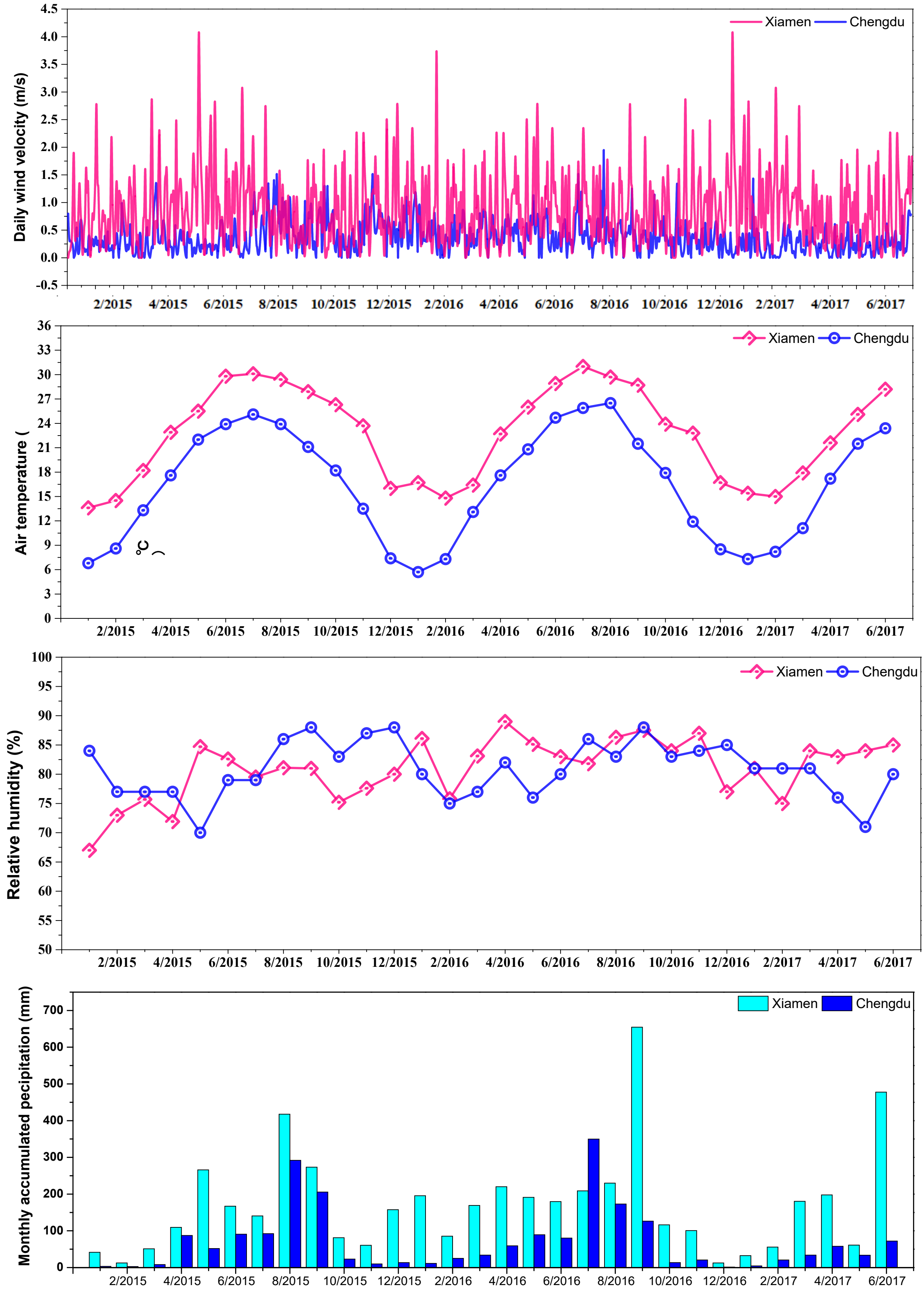

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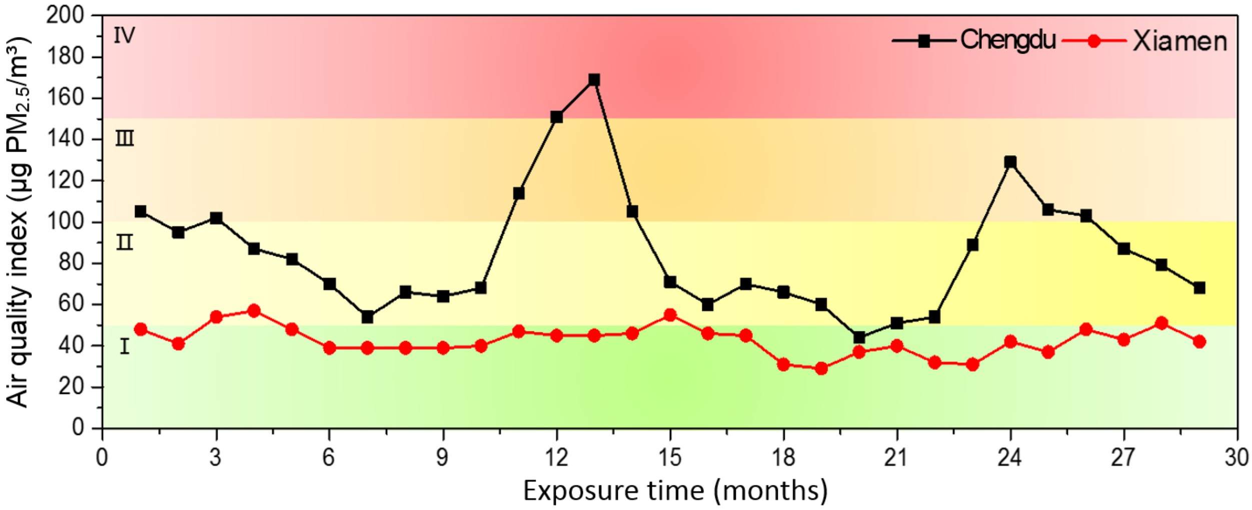

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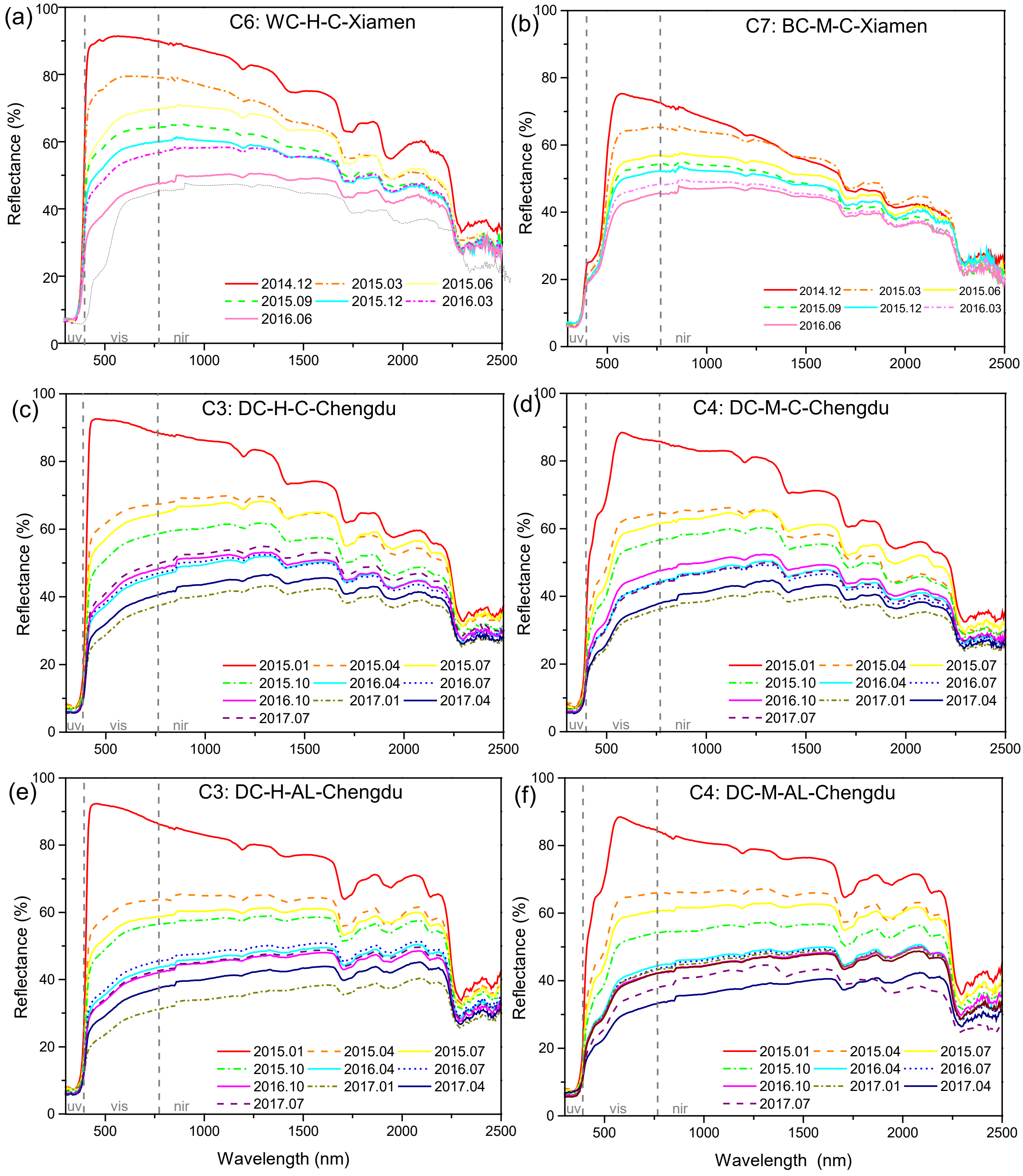

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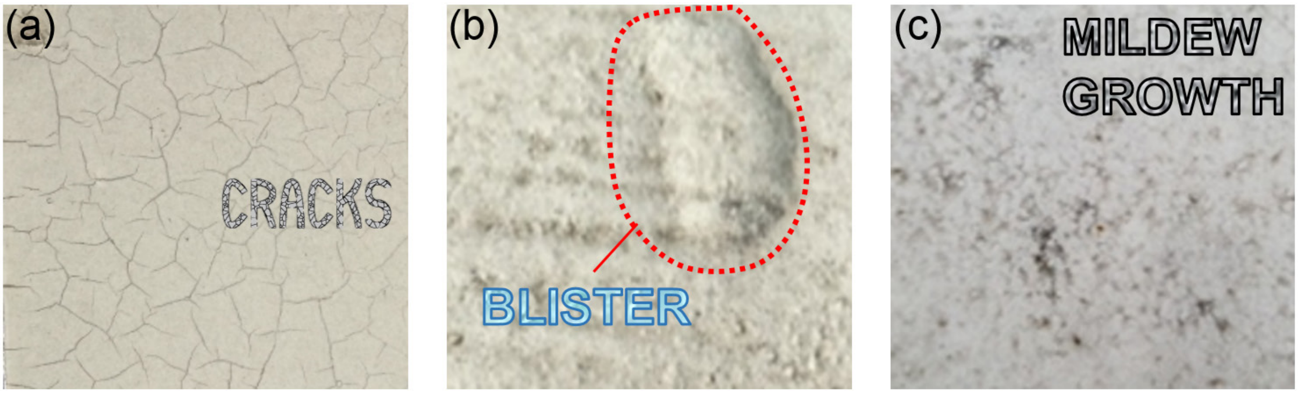

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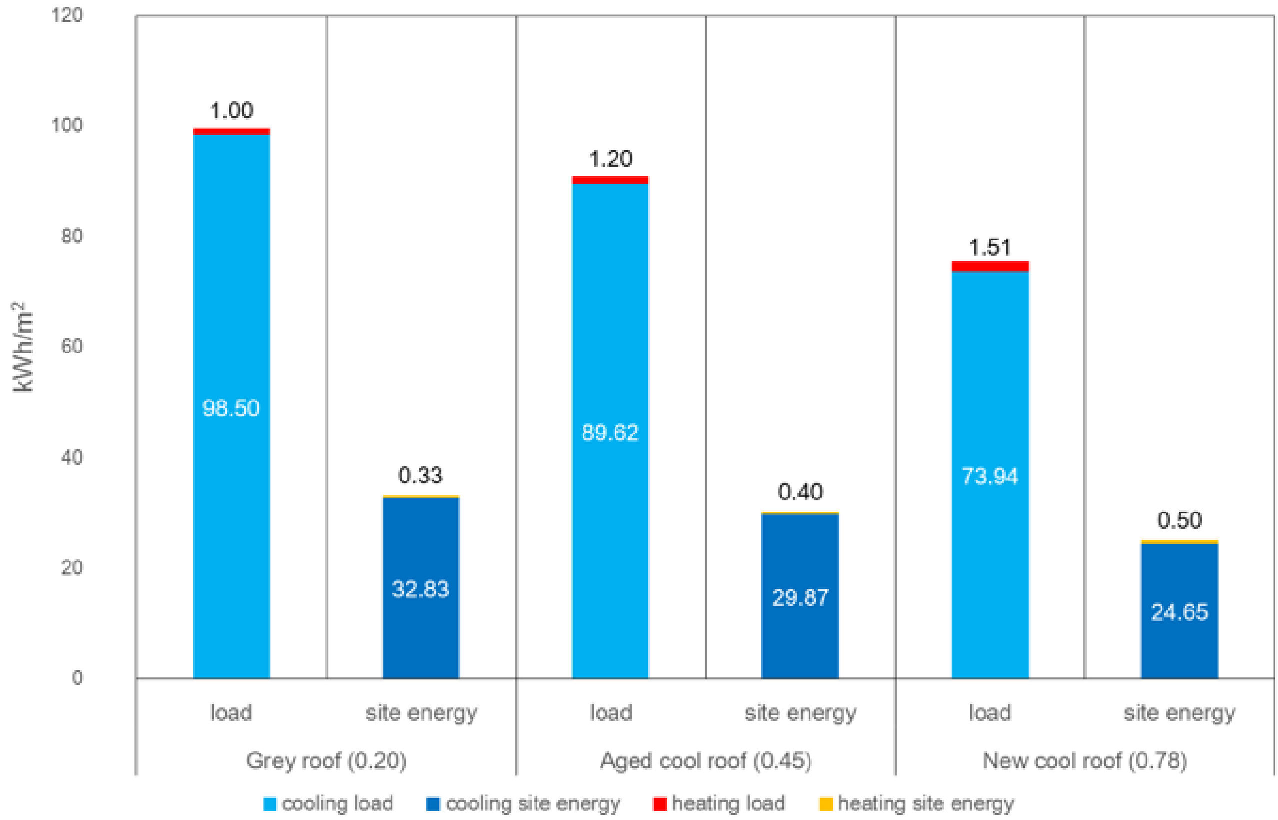

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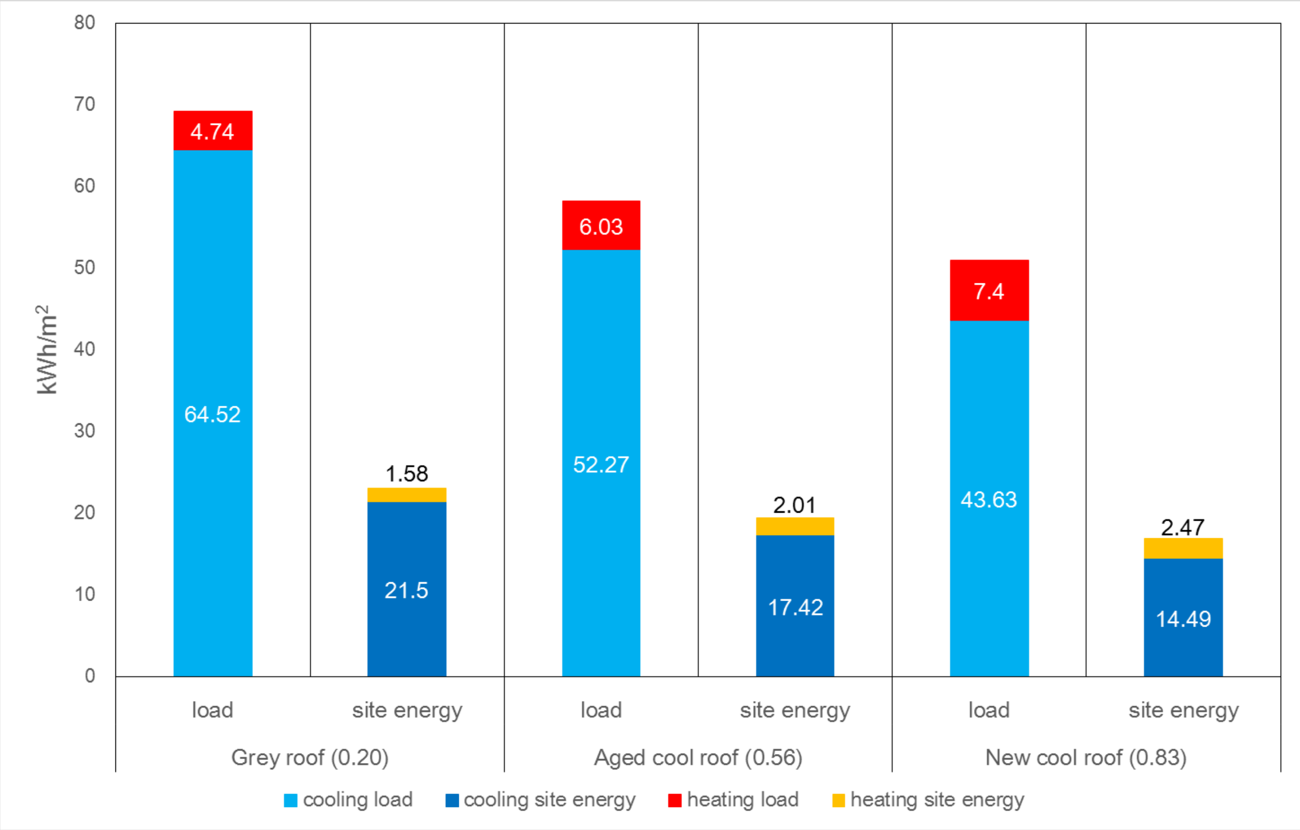

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Table captions

Table 1. Selected high-reflectance roof coatings for the natural exposure trails in Xiamen and Chengdu.

Table 2. Characteristics of the top floor of the representative office building simulated.

Table 3. Roof and wall construction (listed outside to inside) of a representative office building in each city.

Table 4. High-reflectance roof standards in China.

Table 5. Solar reflectance and median values of selected roofing products after outdoor exposure in Xiamen and Chengdu.

Table 1. Selected high-reflectance roof coatings for the natural exposure trails in Xiamen and Chengdu.

Experiment site	Code	Type[a]	Lightness	Substrate
Chengdu	C1	CG-H-AL/C	High	Aluminum/ Concrete Tile
	C2	CG-M-AL/C	Medium	Aluminum/ Concrete Tile
	C3	DC-H-AL/C	High	Aluminum/ Concrete Tile
	C4	DC-M-AL/C	Medium	Aluminum/ Concrete Tile
	C5	SC-H-AL/C	High	Aluminum/ Concrete Tile
Xiamen	C6	WC-H-C	High	Concrete Tile
	C7	BC-M-C	Medium	Concrete Tile

[a]In type X-Y-Z, X codes the manufacturer, Y codes the initial solar reflectance (H for high lightness or M for medium lightness), and Z codes the substrate (C for concrete tile or AL for aluminum).

Table 2. Characteristics of the top floor of the representative dormitory building simulated.

Layout	
Conditioned floor area, conditioned roof area (m^2)	626.3
Story height (m)	3.0
The ratio of window area to wall area	0.43 (south) 0.21 (north)
Building shape coefficient (surface-to-volume ratio) (m^{-1}) [a]	0.26
Roof, wall, window thermal transmittance (W m^{-2} K^{-1})	0.9, 1.5, 4.0[a]
Roof construction	See Table 3
Wall construction	See Table 3
Occupant density (person/m^2)	0.23 (room) [b] 0.1 (corridors) [b]
Occupancy hours (local standard time)	18:00–7:00 the next day (workdays) 00:00-24:00 (rest days and holidays)
Equipment load (W/m^2)	10 (bedroom), 3(toilet)[b]
Lighting load (W/m^2)	15 (room)[b] 5 (corridors) [b]
Cooling setpoint (°C)	26, with the setup to 28[b]
Cooling schedule	18:00–7:00 the next day (workdays); 00:00-24:00 (rest days and holidays)[c]
Heating set point (°C)	16, with the setup to 12[b]
Heating schedule	18:00–7:00 the next day (workdays) 00:00-24:00 (rest days and holidays)
Minimum fresh air via mechanical + natural ventilation (L/s-person)	8.33 [b]
Infiltration (ac/h)	1.0[a]

[a]Set based on JGJ 75-2012 Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone [37].
[b]Recommended values for dormitory buildings in the DesignBuilder V5.3.

Table 3. Roof and wall construction (listed outside to inside) of a representative office building in each city [34].

City	Construction	Description	Thickness (mm)	Density (kg/m^3)	Specific heat per unit mass(kJ/kg·K)	Thermal conductivity W/(m·K)
Chengdu	Roof	Cement mortar	25	1800	1.051	0.930
		Polyurethane hard foam plastics	14	40	1.380	0.025
		Cement mortar	20	1800	1.051	0.930
		Lightweight aggregate concrete	80	1600	0.600	0.890
		Reinforced concrete	120	2500	1.220	0.590
	Wall	High elastic coatings	10	1200	1.000	0.930
		Polymer mortar	3	1800	1.050	0.930
		XPS extruded polystyrene board	11	28	2.100	0.030
		adhesive	20	1200	1.051	0.930
		Cement mortar	20	1800	1.051	0.930
		Clay porous brick	240	1400	1.051	0.580
		Mixed mortar	20	1700	1.051	0.870
Xiamen	Roof	Fine stone concrete	40	2500	0.920	1.740
		Extruded polystyrene board	30	30	1.386	0.030
		Coil waterproof layer	2	600	1.465	0.175
		Cement mortar	20	1800	1.050	0.930
		Reinforced concrete	110	2500	0.920	1.740
		Lime, cement, sand and mortar	25	1700	1.050	0.870
	Wall	Facing outside	5	1	0.001	1.000
		Concrete hollow block	190	1300	1.050	1.166
		Cement mortar	10	1800	1.050	0.930
		AC microcrystalline inorganic insulation mortar	25	350	1.050	0.090
		Interior surface	5	1	0.001	1.000

Table 4. High-reflectance roof standards in China.

Standard	ρ_i		Accelerated aging[a] albedo variation	ρ variation after soiling
Building Reflective Thermal-insulating Coatings (JG/T 235-2014)	Low lightness	≥0.25	≤0.05	-
	Medium lightness	≥0.40		0.15
	High lightness	≥0.65		0.20

[a]Accelerated aging, water-based (400h), solvent-type (500h).

Table 5. Solar reflectance and median values of selected roofing products after outdoor exposure in Xiamen and Chengdu.

	Albedos of selected coatings		
	Initial	Month 30	Median values at month 30
Xiamen	0.57-0.78	0.37-0.50	0.45
Chengdu	0.75-0.90	0.36-0.62	0.56