Energy Research and Development Division

FINAL PROJECT REPORT

Solar-Reflective "Cool" Walls: Benefits, Technologies, and Implementation

Appendix J: Natural Exposure of Wall Products (Task 4.2 Report)

California Energy Commission
Gavin Newsom, Governor

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Appendix J:
Natural exposure of wall products (Task 4.2 report)

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Abstract

High albedo ("cool") walls that stay cool in the sun can help decrease building cooling demand and mitigate the urban heat island effect in hot and sunny climates. The magnitude of these potential benefits (or penalties) are expected to vary over time as walls weather and soil. To investigate the trend and magnitude of these changes as a function of climate, season and exposure duration, this study tracked the evolution of solar reflectance in 77 wall materials deployed for two or five years across six exposure locations in two parallel campaigns. In a two-year campaign, 69 wall materials were exposed at three California sites—Berkeley, Los Angeles, and Fresno—from spring 2016 to spring 2018, with solar reflectance tracked quarterly. In a parallel five-year campaign, 55 products are being exposed at three sites across the United States— New River, AZ (near Phoenix); Miami, FL; and Medina, OH (near Cleveland)—from summer 2016 to summer 2021, with solar reflectance tracked yearly. As of the 2-year mark in the California campaign and the 1-year mark in the U.S. campaign, observed albedo (solar reflectance) losses spanned from modest to negligible, and no material exhibited a loss exceeding 0.10. High albedo retention was categorically observed in wall products incorporating fluoropolymers or employing self-cleaning technologies.

1 Introduction

The main goal of this task was to assess the performance of commercially-available and prototype cool wall technologies. This was achieved by tracking, for a broad variety of wall products, changes in solar reflectance as a function of time exposed in the natural environment. Protocols developed for the evaluation of these radiative properties have been described in the Task 4.1 report: *Metrics and methods to assess cool wall performance*. Specimens used in these measurements were subjected to natural exposure at three locations in California: Berkeley, Los Angeles, and Fresno. These sites represent the three most populated regions of the state and different climate zones: the San Francisco Bay Area, the South Coast Basin and the Central Valley. In addition to the three California sites, the scope of the project was later expanded in consultation with the California Energy Commission (CEC) to expose specimens at the three sites used nationally for roofing product rating: Florida, Arizona and Ohio.

This study intended to cover all the main types of wall materials and coatings typically used in residential and commercial construction in the United States. For that purpose, our team has built a strong industrial collaborative consortium comprising 11 companies that have signed CRADA agreements with LBNL and have supported the activities described below. Samples received from industrial partners are being exposed outside for 2 years at California sites and 5 years in U.S. sites to obtain a good description of initial aging processes and their effect on solar reflectance. The sample set includes products with high, medium and low initial albedos. They also include conventional products alongside advanced and innovative materials, some of which are still research prototypes.

One of the advanced technologies represented in the study's sample set is the use of dirt pick-up resistant and/or self-cleaning additives in coating formulations. Dirt-resistant coatings are formulated with fluorinated polymers or other alternatives that minimize interactions with atmospheric deposition. High surface hydrophobicity leads to water beading and runoff (also known as the "lotus effect"), which further contributes to the removal of deposited particles and chemicals.

Photocatalytic self-cleaning products can remove soiling from their surface by catalyzing the elimination of deposited soiling in the presence of sunlight. Photoactive building envelope materials represent a growing sector of the construction market, with $740M in sales in 2009, doubling by 2014 (Gagliardi, 2010). These products are used in new construction and in retrofits, and include cementitious coatings such as mortar, plaster and paint; coated metal siding; architectural fabrics; tiles; precast panels; and roofing.

The "stay-clean" properties of dirt-resistant and photoactive self-cleaning surfaces have been documented mainly in laboratory tests, and need to be quantified under real-world conditions to assess potential energy savings. A key barrier to the development of dirt-resistant and self-cleaning products has been the lack of metrics and methods to evaluate their performance.

This project applied metrics and processes to facilitate the evaluation of soiling-resistant building envelope products, by quantitatively comparing the evolution of the solar reflectance and water contact angle of "stay-clean" materials with that of baseline conventional products through natural exposure. This approach could serve as the basis of a rating method for these materials.

2 Methodology

2.1 Selection of exposed materials

Eleven industrial partners participated in this study. In the initial phase of the project, partners were invited to submit specimens of products of interest. These products were evaluated by the LBNL team to down-select a subset of products to be exposed in the field. The selection criteria used to develop a balanced portfolio of samples sought to include

a) as many product categories as possible;

b) as many substrates for field-applied coatings (paints) as possible;

c) a wide palette of colors;

d) a variety of white and light-colored products with high initial solar reflectance (since reflective surfaces are prone to soiling); and

e) as many manufacturers as possible.

Table 1 summarizes the materials used in this study, which are also illustrated in Figure 1. The main characteristics of each material are presented in Table 2. To clarify our nomenclature:

a) We apply the term "product" as it is used by manufacturers—to identify a unique item available for purchase, or a unique prototype of an item being developed for sale.

b) A product may require a substrate for exposure and measurement ("testing"). We use the term "material" to describe a wall product in testable form. A product that does not require a substrate, such as a factory-painted metal cladding or an architectural fabric, is both a product and a material. A field-applied coating sold as liquid paint is a product, but not a material; the same coating applied to a substrate, such as a piece of wood, becomes a material.

c) Individual pieces of each material (10 cm by 10 cm) installed on exposure racks and retrieved quarterly for laboratory characterization are referred to as "specimens".

d) Each material is labeled "CWXX", where the prefix "CW" refers to the project name ("cool walls") and "XX" is a two-digit anonymous code (01 – 77).

e) We abbreviate the names of the six exposure locations with the following two-letter codes: BK = Berkeley, CA; LA = Los Angeles, CA; FR = Fresno, CA; AZ = New River, AZ (roughly 50 km north of Phoenix); FL = Miami, FL; OH = Medina, OH (roughly 40 km south of Cleveland).

Table 1. Summary of materials exposed in this study.

Product category	Substrate	Count	Colors [a]	Texture/surface finish[b]
Factory-applied coating	Metal	15	Black, dark brown, burgundy, tan, light gray, white	Smooth surface, textured surface
Field-applied coating	Metal	8	Dark green-gray, tan, peach, peach-orange	Flat finish
Field-applied coating	Concrete	5	White	Flat finish, satin finish, semi-gloss finish
Field-applied coating	Wood	24	Dark brown, dark blue-gray, dark purple-gray, peach, peach-orange, gray-green, tan, white	Flat finish, satin finish, semi-gloss finish
Field-applied coating	Fiber cement	11	Gray, tan, salmon pink, light green, white	Satin finish, flat finish
Architectural membrane	N/A	3	White	N/A
Vinyl siding	N/A	1	White	Wood grain texture
Composite metal cladding	N/A	6	Silver metallic, off-white, white	N/A
Retroreflective & reflective film	NA	4	White & metallic (pattern), mirror	N/A

[a] Color names subjectively chosen by the researchers.

[b] While most entries in this column represent manufacturer-reported properties, some were determined subjectively by LBNL research staff. A detailed breakdown can be found in Table 2.

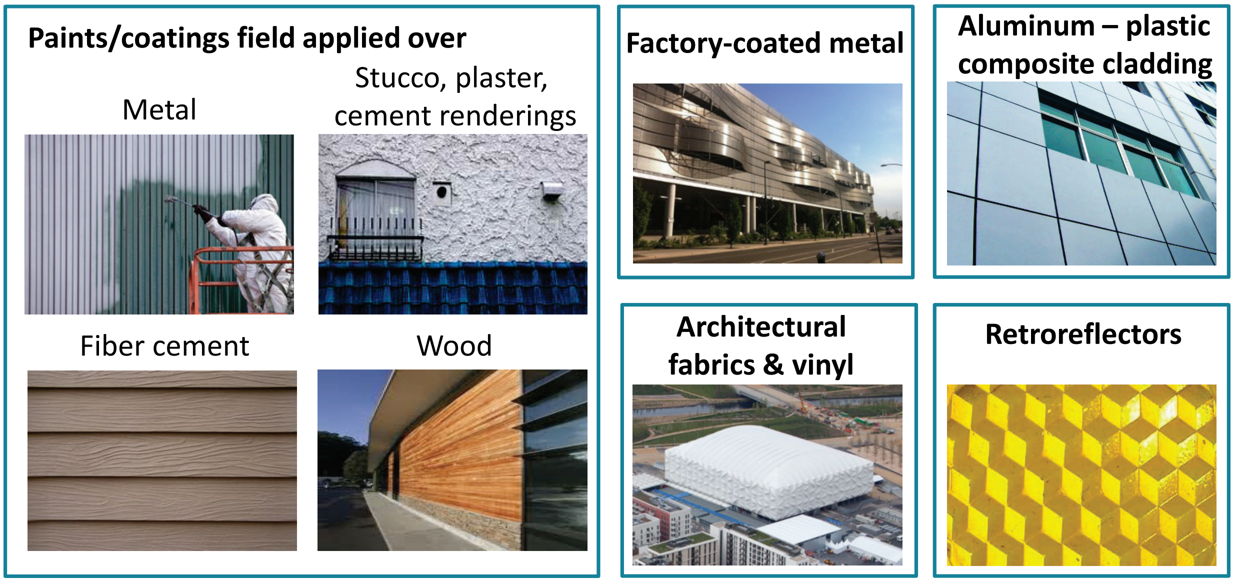


Figure 1. Examples of types of products exposed in this study.

Table 2. Description of materials used in natural exposure tests.

Code [a]	Color	Category	Description [b]	Substrate	Surface finish [c]	Commercial product (C) or experimental prototype (E)	Exposure: U.S., CA, or both
01	white	coating (factory)	fluoropolymer (PVDF) resin; smooth control for CW02	metal (aluminum)	N/A	C	CA
02	white	coating (factory)	fluoropolymer (PVDF) resin; surface texture	metal (aluminum)	N/A	C	CA
03	burgundy	coating (factory)	fluoropolymer (PVDF) resin	metal (aluminum)	N/A	C	CA
04	light gray	coating (factory)	fluoropolymer (PVDF) resin	metal (aluminum)	N/A	C	CA
05	black	coating (factory)	fluoropolymer (PVDF) resin	metal (aluminum)	N/A	C	CA
06	white	coating (factory)	fluoropolymer (PVDF) resin	metal (steel)	N/A	C	both
07	tan	coating (factory)	fluoropolymer (PVDF) resin	metal (steel)	N/A	C	both
08	dark brown	coating (factory)	fluoropolymer (PVDF) resin	metal (steel)	N/A	C	both
09	light gray	coating (factory)	fluoropolymer (PVDF) resin	metal (steel)	N/A	C	both
10	dark brown	coating (factory)	fluoropolymer (PVDF) resin	metal (steel)	N/A	C	CA
11	dark brown	coating (factory)	fluoropolymer (PVDF) resin	metal (steel)	N/A	C	CA
12	dark brown	coating (factory)	silicone-modified polyester (SMP) resin; smooth control for CW13	metal (steel)	N/A	C	CA

Code [a]	Color	Category	Description [b]	Substrate	Surface finish [c]	Commercial product (C) or experimental prototype (E)	Exposure: U.S., CA, or both
13	dark brown	coating (factory)	silicone-modified polyester (SMP) resin; surface texture	metal (steel)	N/A	C	CA
14	white	coating (factory)	polyester resin	metal (steel)	N/A	C	CA
15	white	coating (factory)	polyester resin	metal (aluminum)	N/A	C	CA
16	tan	coating (field)	non-photocatalytic control for CW17	metal (aluminum)	flat	E	CA
17	tan	coating (field)	photocatalytic	metal (aluminum)	flat	E	CA
18	dark green-gray	coating (field)	non-photocatalytic control for CW19	metal (aluminum)	flat	E	CA
19	dark green-gray	coating (field)	photocatalytic	metal (aluminum)	flat	E	CA
20	peach	coating (field)	non-photocatalytic control for CW21	metal (aluminum)	flat	E	CA
21	peach	coating (field)	photocatalytic	metal (aluminum)	flat	E	CA
22	peach-orange	coating (field)	non-photocatalytic control for CW23	metal (aluminum)	flat	E	CA
23	peach-orange	coating (field)	photocatalytic	metal (aluminum)	flat	E	CA
24	white	architectural membrane	PTFE-coated fiberglass; non-photocatalytic control for CW25/26	N/A	N/A	C	both
25	white	architectural membrane	PTFE-coated fiberglass; photocatalytic	N/A	N/A	C	both
26	white	architectural membrane	PTFE-coated fiberglass; photocatalytic	N/A	N/A	[to be disclosed]	both

Code [a]	Color	Category	Description [b]	Substrate	Surface finish [c]	Commercial product (C) or experimental prototype (E)	Exposure: U.S., CA, or both
27	white	vinyl siding	polyvinyl chloride (PVC); wood grain surface texture*	N/A	N/A	C	both
28	white	composite metal cladding	fluoropolymer (FEVE) resin	N/A	N/A	C	both
29	off-white	composite metal cladding	fluoropolymer (FEVE) resin	N/A	N/A	C	both
30	silver metallic	composite metal cladding	fluoropolymer (FEVE) resin; mica flakes	N/A	N/A	C	both
31	silver metallic	composite metal cladding	fluoropolymer (FEVE) resin; metallic flakes	N/A	N/A	C	both
32	white	coating (field)	[to be disclosed]; dirt-resistant	wood (pine; sealed)	satin*	E	both
33	white	coating (field)	[to be disclosed]; dirt-resistant	wood (pine; sealed)	flat*	E	both
34	white	coating (field)	[to be disclosed]; dirt-resistant	wood (pine; sealed)	satin*	E	both
35	white	coating (field)	[to be disclosed]; dirt-resistant	wood (pine; sealed)	flat*	E	both
36	white	coating (field)	[to be disclosed]; dirt-resistant	wood (pine; sealed)	flat*	E	both
37	white	coating (field)	[to be disclosed]; self-cleaning	concrete paver	satin*	E	both
38	white	coating (field)	[to be disclosed]; self-cleaning	concrete paver	satin*	E	both
39	white	coating (field)	[to be disclosed]; self-cleaning	concrete paver	flat*	E	both
40	white	coating (field)	[to be disclosed]; self-cleaning	concrete paver	semi-gloss*	E	both
41	white	coating (field)	[to be disclosed]; non self-cleaning control for CW37-40	concrete paver	satin*	[to be disclosed]	both
42	green	coating (field)	acrylic resin, water-based	wood (pine; sealed)	flat	C	both

Code [a]	Color	Category	Description [b]	Substrate	Surface finish [c]	Commercial product (C) or experimental prototype (E)	Exposure: U.S., CA, or both
43	peach-orange	coating (field)	acrylic resin, water-based	wood (pine; sealed)	flat	C	both
44	peach-orange	coating (field)	acrylic resin, water-based	wood (pine; sealed)	flat	C	both
45	dark brown	coating (field)	acrylic resin, water-based	wood (pine; sealed)	flat	C	both
46	dark brown	coating (field)	acrylic resin, water-based	wood (pine; sealed)	flat	C	both
47	white	coating (field)	acrylic resin; non-dirt-resistant control for CW48/49	wood (pine; sealed)	semi-gloss	C	both
48	white	coating (field)	acrylic resin; dirt pick-up resistance	wood (pine; sealed)	semi-gloss	C	both
49	white	coating (field)	acrylic resin; dirt pick-up resistance	wood (pine; sealed)	semi-gloss	E	both
50	dark blue-gray	coating (field)	acrylic resin; non-cool control for CW51	wood (pine; sealed)	semi-gloss	E	both
51	dark blue-gray	coating (field)	acrylic resin; spectrally-selective pigment	wood (pine; sealed)	semi-gloss	E	both
52	dark purple-gray	coating (field)	acrylic resin; non-cool control for CW53	wood (pine; sealed)	semi-gloss	E	both
53	dark purple-gray	coating (field)	acrylic resin; spectrally-selective pigment	wood (pine; sealed)	semi-gloss	E	both
54	white	coating (field)	fluoropolymer (PVDF) resin, water-based	fiber cement	satin	C	CA
55	white	coating (field)	fluoropolymer (PVDF) resin, water-based	fiber cement	satin	C	CA
56	light green	coating (field)	fluoropolymer (PVDF) resin, water-based	fiber cement	satin	C	both

Code [a]	Color	Category	Description [b]	Substrate	Surface finish [c]	Commercial product (C) or experimental prototype (E)	Exposure: U.S., CA, or both
57	salmon pink	coating (field)	fluoropolymer (PVDF) resin, water-based	fiber cement	satin	C	both
58	gray	coating (field)	fluoropolymer (PVDF) resin, water-based	fiber cement	satin	C	CA
59	tan	coating (field)	fluoropolymer (PVDF) resin, water-based	fiber cement	satin	C	both
60	white	coating (field)	acrylic resin, water-based; control for CW62	wood (pre-primed cedar)	flat	C	both
61	white	coating (field)	acrylic resin, water-based; control for CW63	fiber cement	flat	C	both
62	white	coating (field)	acrylic resin, water-based; improved dirt pick-up resistance	wood (pre-primed cedar)	flat	C	both
63	white	coating (field)	acrylic resin, water-based; improved dirt pick-up resistance	fiber cement	flat	C	both
64	tan	coating (field)	acrylic resin, water-based; control for CW66, 68	wood (pre-primed cedar)	flat	C	both
65	tan	coating (field)	acrylic resin, water-based; control for CW67, 69	fiber cement	flat	C	both
66	tan	coating (field)	styrene acrylic resin, water-based; spectrally-selective pigment	wood (pre-primed cedar)	flat	C	both
67	tan	coating (field)	styrene acrylic resin, water-based; spectrally-selective pigment	fiber cement	flat	C	both
68	tan	coating (field)	acrylic resin, water-based; spectrally-selective pigment; improved dirt pick-up resistance	wood (pre-primed cedar)	flat	C	both
69	tan	coating (field)	acrylic resin, water-based; spectrally-selective pigment; improved dirt pick-up resistance	fiber cement	flat	C	both
70	tan	coating (field)	acrylic resin, water-based; spectrally-selective pigment; dirt pick-up resistance	plywood (exterior-grade)	semi-gloss	C	U.S.

Code [a]	Color	Category	Description [b]	Substrate	Surface finish [c]	Commercial product (C) or experimental prototype (E)	Exposure: U.S., CA, or both
71	peach	coating (field)	acrylic resin, water-based; spectrally-selective pigment; dirt pick-up resistance	plywood (exterior-grade)	semi-gloss	C	U.S.
72	white & metallic (pattern)	plastic film	plastic film with UV-protective over-laminate; retroreflective	metal (steel)	N/A	C	U.S.
73	white & metallic (pattern)	plastic film	plastic film with UV-protective over-laminate; retroreflective	metal (steel)	N/A	C	U.S.
74	white & metallic (pattern)	plastic film	plastic film with UV-protective over-laminate; retroreflective	metal (steel)	N/A	C	U.S.
75	mirror	plastic film	plastic film with UV-protective over-laminate; reflective film	metal (steel)	N/A	C	U.S.
76	white	composite metal cladding	fluoropolymer (PVDF) resin	N/A	N/A	C	U.S.
77	silver metallic	composite metal cladding	fluoropolymer (PVDF) resin	N/A	N/A	C	U.S.

[a] For compactness, the prefix “CW” has been omitted from material labels in this column.

[b,c] Descriptions of texture or surface finishes that are followed by an asterisk (*) were determined subjectively by LBNL research staff. All other entries represent manufacturer-reported properties.

2.2 Selection and setup of exposure sites

2.2.1 Identification of sites

Three sites in California were selected to span different climates and major urban areas:

a) a building roof at the Lawrence Berkeley National Laboratory in Berkeley;

b) a parking lot at the University of Southern California, in downtown Los Angeles; and

c) a ground level concrete platform belonging to one of our industry partners in Fresno.

The Fresno site provided mostly exposure to air containing pollution associated with agricultural activity, typical of the Central Valley. The Los Angeles site was representative of pollution found in a large mega-city. The Berkeley site was cleaner, because the Laboratory is located on a hill overlooking the San Francisco Bay Area, far from highways and heavy traffic.

2.2.2 Exposure racks

Specimens were exposed vertically, facing westward. LBNL designed and built exposure racks at each of the three California exposure sites. Each rack was designed to hold a maximum of 280 specimens, arranged in 14 rows of 20 each. The rows were offset from each other to prevent contamination between vertically adjacent rows. To accommodate the complete set of specimens, three racks were required at each site, as shown in Figure 3.

As shown in Figure 2, the skeleton of each rack was assembled from hot-dip galvanized strut channels. Metal specimen holders, bent from galvanized sheet metal, formed the backbone of the 2.1 m (7')-long rows of specimens. The specimen holders were sized to accommodate both the specimens (of various thicknesses) and a 1.27 cm (0.5")-thick plywood strip (providing insulated backing for the specimens). A deeper discussion of the exposure rack design can be found in the Task 4.1 report: *Metrics and methods to assess cool wall performance.*

The final construction of the racks at each site differed in minor ways from the proposed design. At the Fresno site, the wooden sleepers at the base of the rack were foregone in favor of anchoring the rack frame directly to the concrete platform underneath. At the Berkeley site, special earthquake retrofitting attachments were required because the racks were close to a pedestrian path. At the Los Angeles site, it was determined that the racks were stable enough without wooden sleepers at the base.

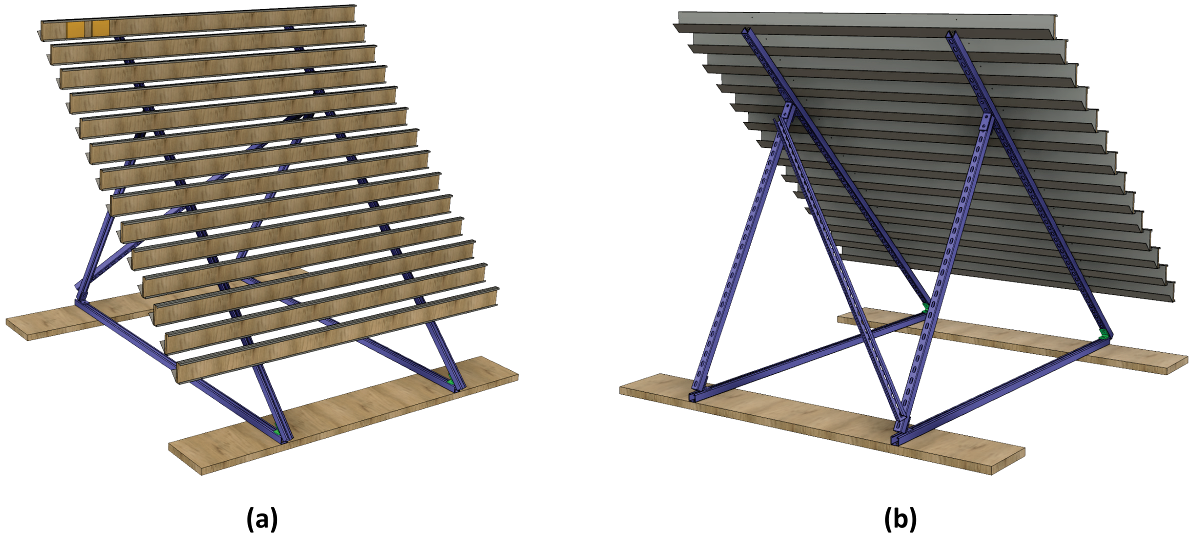
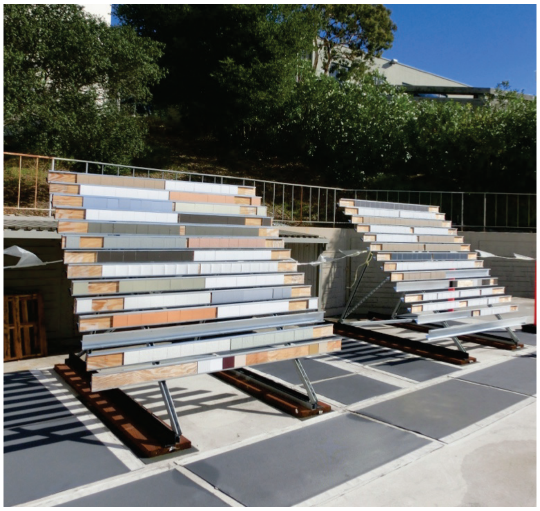


Figure 2. Front-angle (a) and back-angle (b) CAD drawing views of the exposure rack design.



(a)

(b)

(c)

Figure 3. Newly-installed and populated exposure racks at the three California exposure sites: (a) Berkeley; (b) Fresno; and (c) Los Angeles.

2.2.3. California exposure

All three California sites were built between March and April 2016, and materials CW01 to CW69 were installed immediately after their construction. Specimens have been retrieved quarterly, following the schedule presented in Table 3. Figure 4 describes how many samples per product category have been exposed in California.

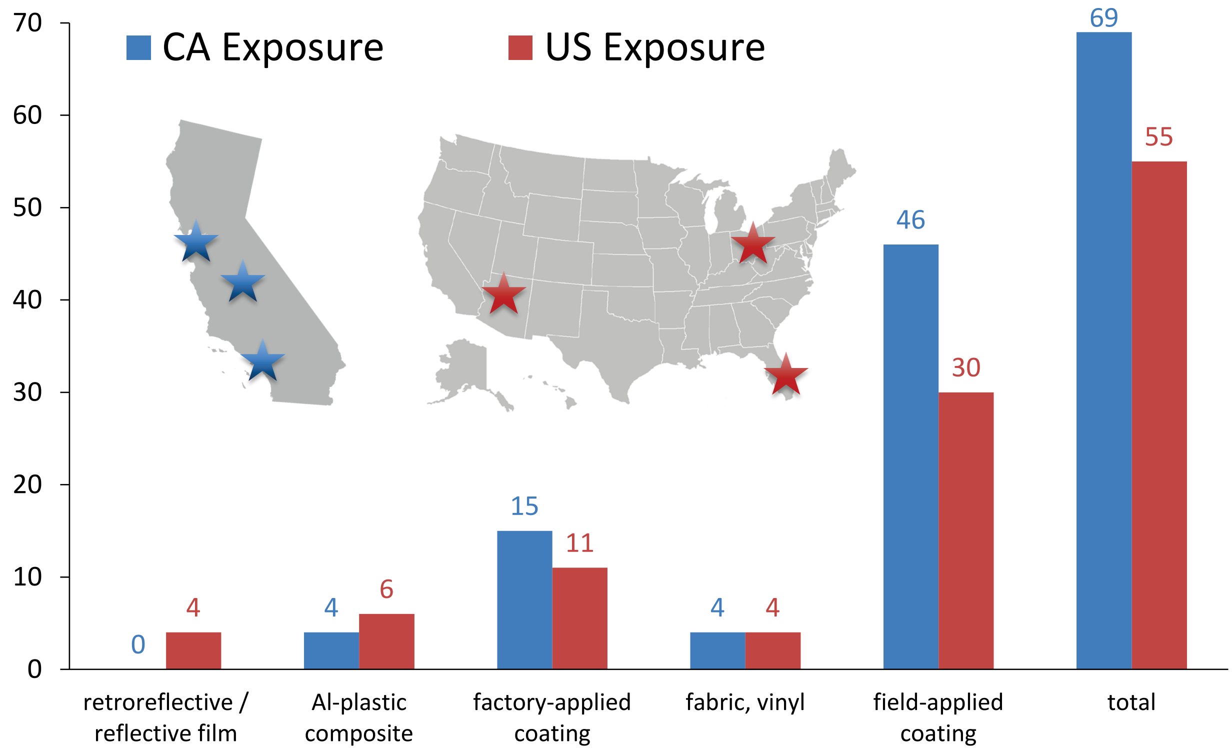


Figure 4. Location of the six exposure sites, and the number of materials per product type exposed at each site.

Table 3. Experimental schedule for California exposure.

Site	installed	3 mo	6 mo	9 mo	12 mo	15 mo	18 mo	21 mo	24 mo
BK	Mar 2016	Jul 2016	Oct 2016	Jan 2017	Apr 2017	Jul 2017	Oct 2017	Jan 2018	Apr 2018
LA	Apr 2016	Jul 2016	Oct 2016	Jan 2017	Apr 2017	Jul 2017	Oct 2017	Jan 2018	Apr 2018
FR	Mar 2016	Jun 2016	Oct 2016	Dec 2017	Apr 2017	Jul 2017	Oct 2017	Jan 2018	May 2018

2.2.4. National exposure

Once the California sites were operating, the team also secured permission from several manufacturers to expose materials at the three sites used by the Cool Roof Rating Council for roofing rating. These "U.S." exposure sites in New River, AZ; Miami, FL; and Medina, OH are operated by a commercial weathering firm that uses west-facing vertical racks such as those shown in Figure 5. In total, 55 materials from 10 partners are undergoing exposure in this campaign, 47 of which are also participating in the California campaign. The remaining 8 materials (CW70 – CW77) are exposed at U.S. national sites but not at any California sites. Exposure began in August 2016 and is scheduled to run for five years, with annual specimen retrievals occurring each summer following the schedule presented in Table 4. Figure 4 provides a count of how many materials per product category are represented in the national exposure campaign.

(a)

(b)

Figure 5. Racks used in the U.S. exposure campaign. Panel (a) shows the Medina, OH racks shortly after the specimens were installed. Panel (b) shows a close-up of the rack design.

Table 4. Experimental schedule for national exposure.

Site	installed	1 yr	2 yr[a]	3 yr[a]	4 yr[a]	5 yr[a]
AZ	Aug 2016	Aug 2017	Aug 2018	Aug 2019	Aug 2020	Aug 2021
FL	Aug 2016	Aug 2017	Aug 2018	Aug 2019	Aug 2020	Aug 2021
OH	Aug 2016	Aug 2017	Aug 2018	Aug 2019	Aug 2020	Aug 2021

[a] Pending at the time this report was prepared.

2.2.5. Rainfall at each site

Monthly rainfall data at each exposure site was obtained from nearby Global Historical Climatology Network (GHCN) weather stations. The data sets were downloaded from the National Oceanic and Atmospheric Administration Climate Data Online database (NOAA, 2018). The weather stations selected for each site were

a) US1CAAL0018, in Berkeley, 3.2 km southeast of the Berkeley exposure site;

b) USW00093134, on the University of Southern California (USC) campus, 1.4 km west of the Los Angeles exposure site;

c) USW00093193, at the Fresno Yosemite International Airport, 9.9 km north of the Fresno exposure site

d) US1AZMR0416, in Anthem, AZ, 3.1 km southeast of the Arizona exposure site;

e) USC00087020, in Miami, Florida, 2.5 km northeast of the Florida exposure site; and

f) US1OHMD0002, in Brunswick, OH, 16 km northeast of the Ohio exposure site.

2.3 Experimental procedures

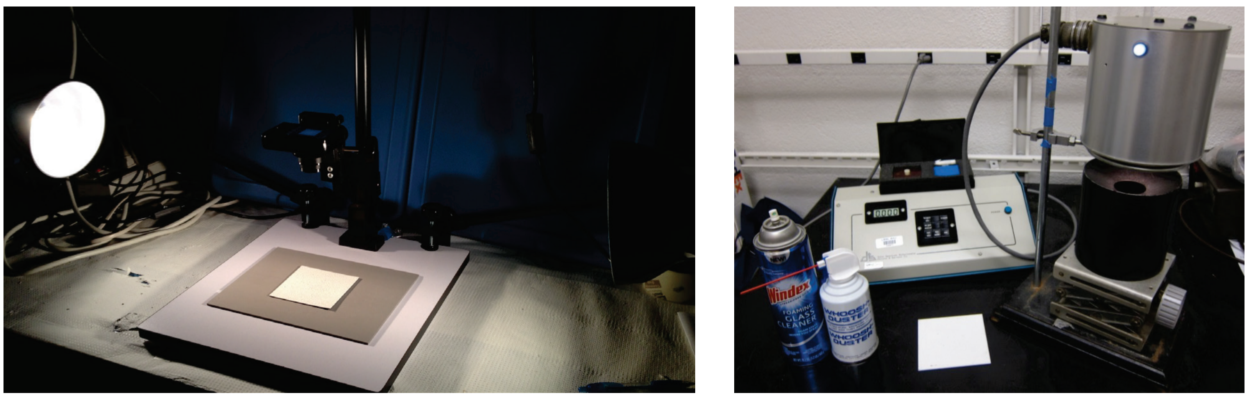
The general experimental procedures implemented to perform measurements in the laboratory have been described in the Task 4.1 Report *Metrics and methods to assess cool wall performance*. The key measurements are highlighted in this section.

2.3.1 Specimen retrieval, shipping and storage

Specimens exposed in California were retrieved quarterly and returned to LBNL for laboratory analysis. One specimen from the ten units exposed side-by-side for each product were retrieved from the racks, recorded, packed and shipped to LBNL. Individual glassine envelopes were used to protect each sample from contact with the others and with packing materials. The samples were stored inside the same envelopes prior and after laboratory measurements.

2.3.2 Solar reflectance and spectral measurements

Solar reflectance was measured on all specimens with a Devices & Services Solar Spectrum Reflectometer, version 6 (Figure 6). Solar spectral reflectance (250 to 2,500 nm) was recorded for a sub-set of samples using a Perkin Elmer Lambda 900 UV-vis-NIR spectrophotometer with 150 mm Labsphere integrating sphere. The solar reflectance results are presented using the air mass 1 global horizontal (AM1GH) solar spectrum (relevant for roofs). Future analyses will report the air mass 1.5 vertical (AM1.5GV) solar reflectance (relevant for walls).



(a) (b)

Figure 6. Photography setup (a) and solar reflectometer (b) used in this study.

2.3.3 Photography of specimens

Each specimen was photographed on a copy stand using a digital point-and-shoot camera with two lamps (of color temperature similar to sunlight) providing illumination. A gray card was placed in the specimen background to control white balance.

3 Results and discussion

3.1 Rainfall recorded at each site

Rainfall at the three California sites followed similar patterns (Figure 8). Across the state we observed a dry season from April/May to October, and a rainy season through the late fall, winter and beginning of the spring. Maximum precipitation at all three sites occurred in January 2017. Berkeley was the wettest of the three locations, having experienced the most cumulative rainfall to date. One significant difference in the rain patterns was that precipitation in LA was mostly taking place during the winter months (December through February), while the other two sites showed a broader distribution, with significant levels from October through April.

Rain patterns at the national exposure sites show larger differences, as shown in Figure 9. Total precipitation was very low in Arizona (5 - 10 cm/month in winter), highest in Florida (20 - 40 cm/month in summer) and intermediate in Ohio, with consistent levels across most of the year (5 - 15 cm/month).

3.2 Performance of wall products

In this section we describe wall product performance from the perspective of how well they retain their initial albedos as they undergo natural exposure. We refer to albedo changes in terms of “losses”, calculated by subtracting the final albedo from the initial albedo. A positive albedo loss indicates that specimen reflectance *decreased* with natural exposure; a negative albedo loss indicates the specimen reflectance *increased* with natural exposure.

The data currently presented in this report covers 24 months of exposure at the three California sites and up to 1 year of exposure at the three U.S. national sites. Overall, changes in albedo, whether losses or gains, were small and, in some cases, negligible (Figure 7). At the three California sites, 24-month albedo losses of all but two materials did not exceed 0.06. At the three U.S. national sites, 1-year albedo losses of all materials did not exceed 0.05. Compared with similar results from natural exposure of roofing materials, wall materials seem to fare much better. Changes in solar reflectance of roofing materials is more marked during the first year of exposure, and in many cases that initial drop is the dominant feature over the three years required for CRRC rating (Sleiman et al, 2011; Sleiman et al, 2014).

For the same reason, we observed to date relatively little effect of seasonality, which in the case of California could be attributed primarily to rainfall.

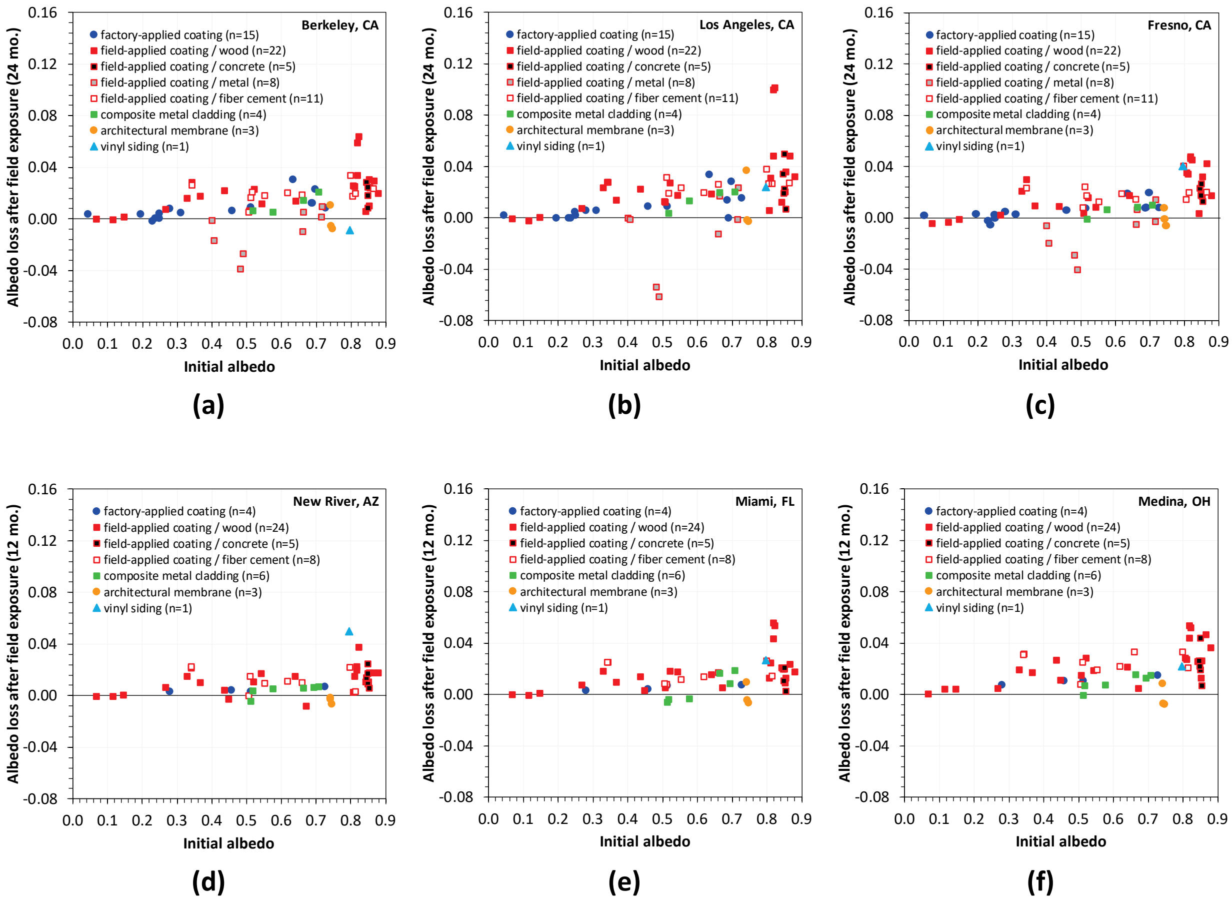


Figure 7. Summary of 24-month albedo losses of materials exposed at three California sites (panels a – c) and 12-month albedo losses of materials exposed at three U.S. national sites (panels d – f). Albedo losses observed thus far have been modest to negligible. Only three materials experienced albedo losses exceeding 0.05.

3.2.1 High performance wall products

The product categories showing highest performance were factory-applied coatings and composite metal claddings. Examples of the performance of these two categories of products are illustrated in Figure 10 for factory-applied coatings and in Figure 11 for composite metal claddings. In both cases, exposure in all six sites has not led to a significant change in solar reflectance over the course of the studied period.

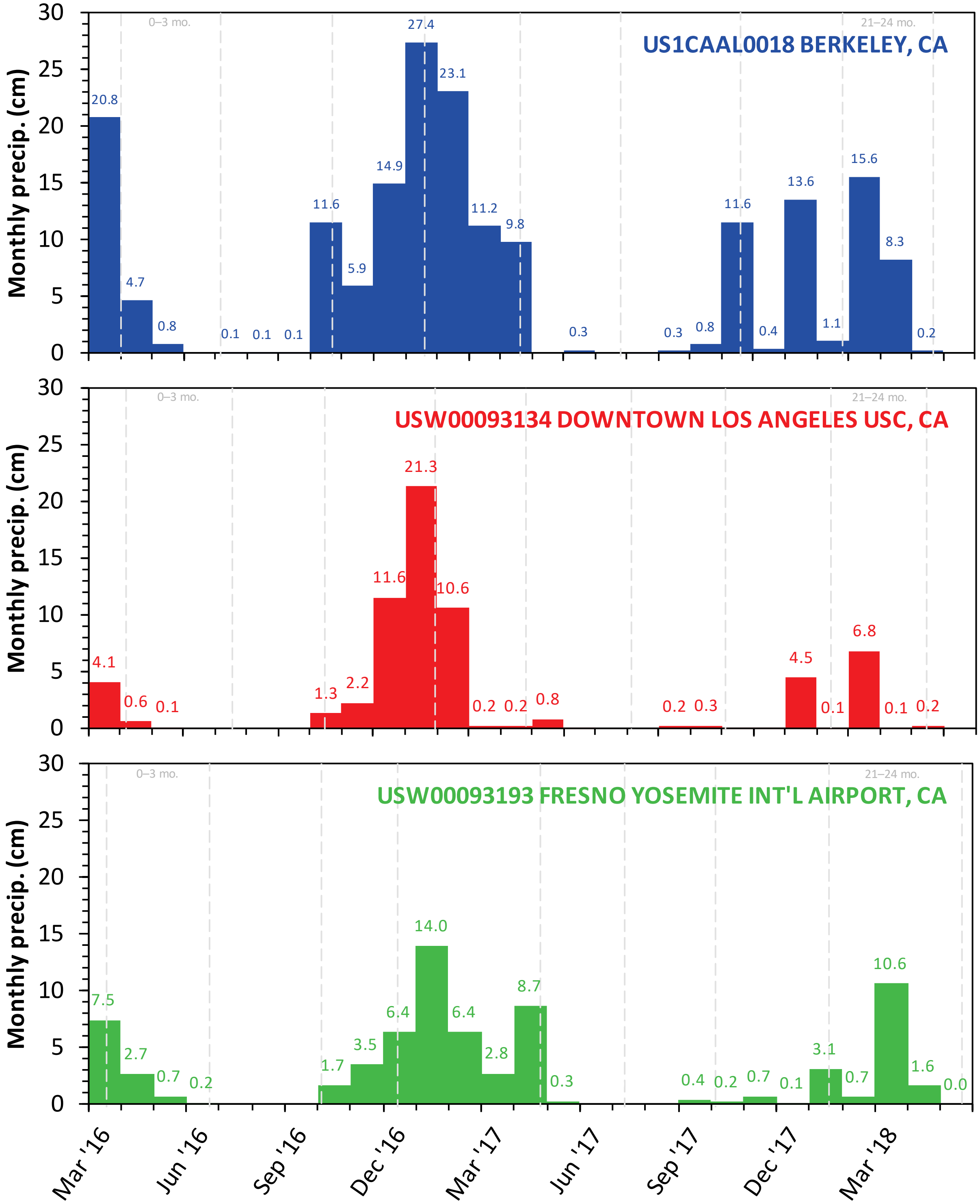


Figure 8. Rainfall patterns at the California exposure sites.

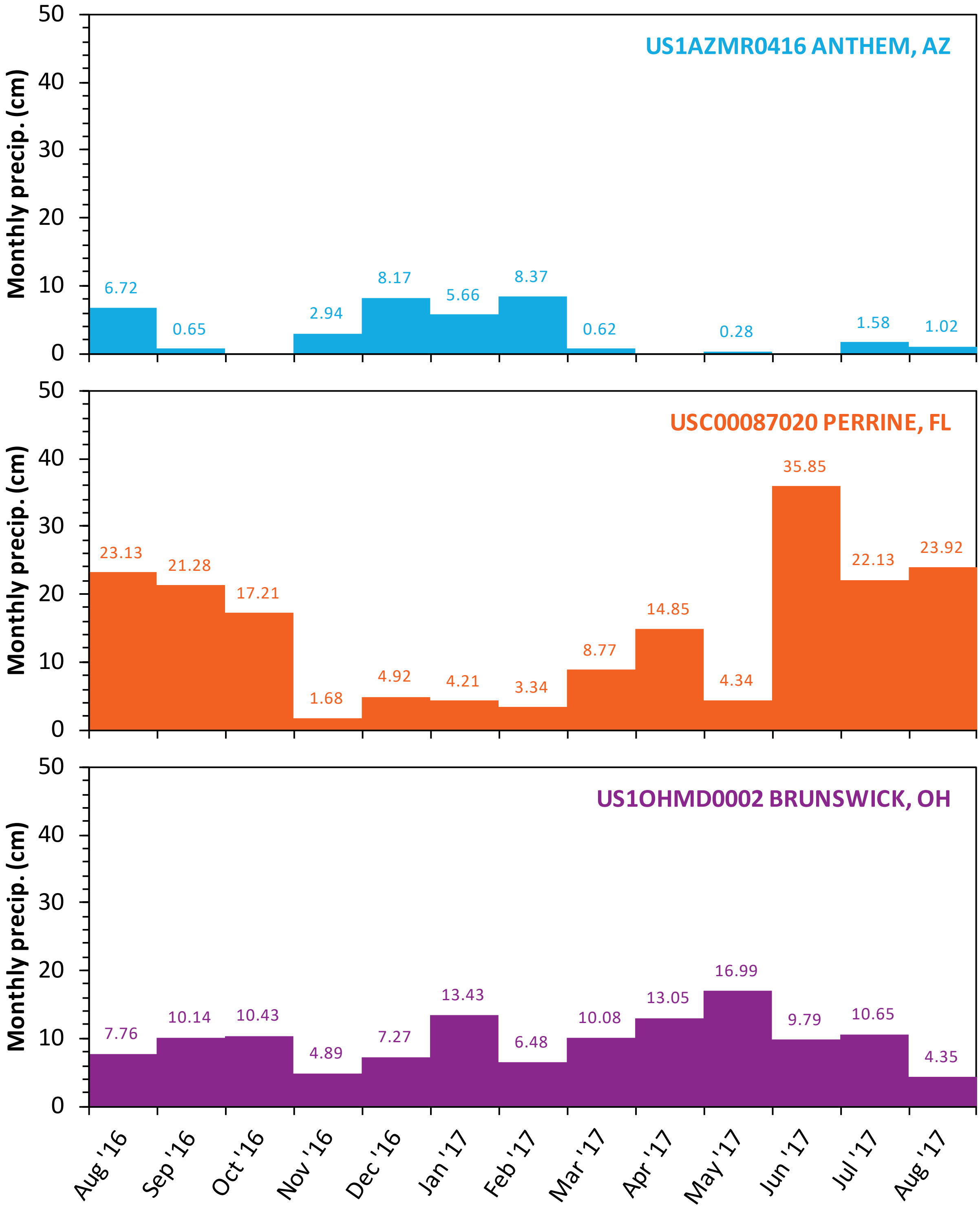


Figure 9. Rainfall patterns at the U.S. national exposure sites.

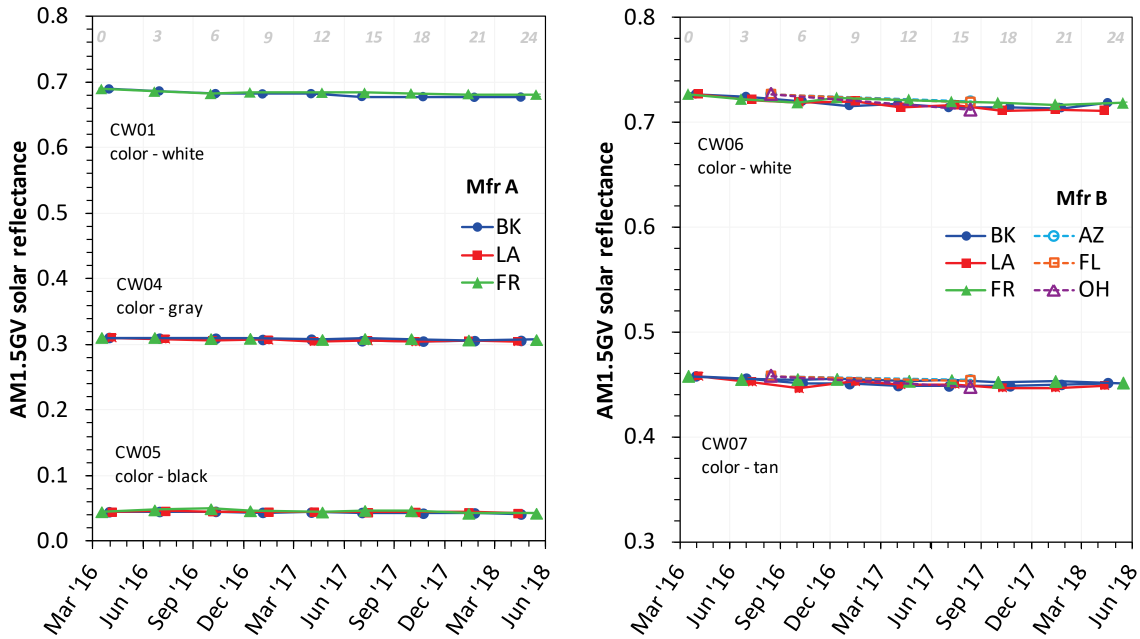


Figure 10. Solar reflectance of factory-applied products exposed in California and U.S. national sites.

Albedo losses for these products range from -0.01 to 0.03. Figure 12 shows that the largest changes are associated with initially high solar reflectances corresponding to white or light color materials, which are most affected by soiling. Negative values correspond to increases in albedo, often recorded in dark color materials as they are covered with soiling that is lighter in color. The results also suggest a site-related correlation, with Berkeley being the site in which changes are largest, and Florida, Arizona and Fresno those in which changes are of smaller magnitude.

Three different type of factory-applied coatings were tested, that included the following dirt-resistant constituents:

a) the thermoplastic polymer polyvinylidene fluoride (PVDF)

b) silicone-modified polyester

c) polyester

The first two types of products showed significantly good performance. Samples containing polyester showed the highest albedo losses, as shown in Figure 13.

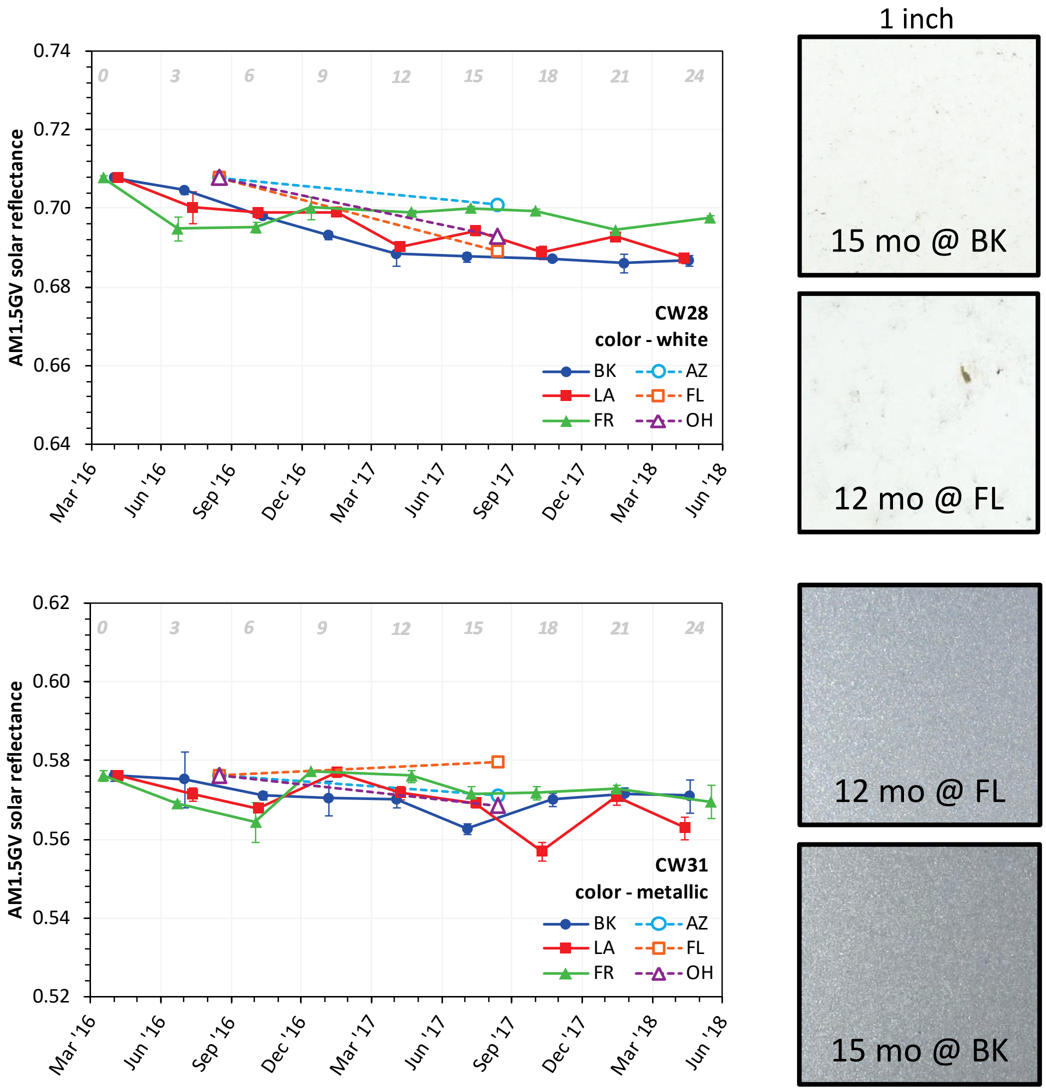


Figure 11. Solar reflectances of two different composite metal claddings exposed in California and U.S. sites.

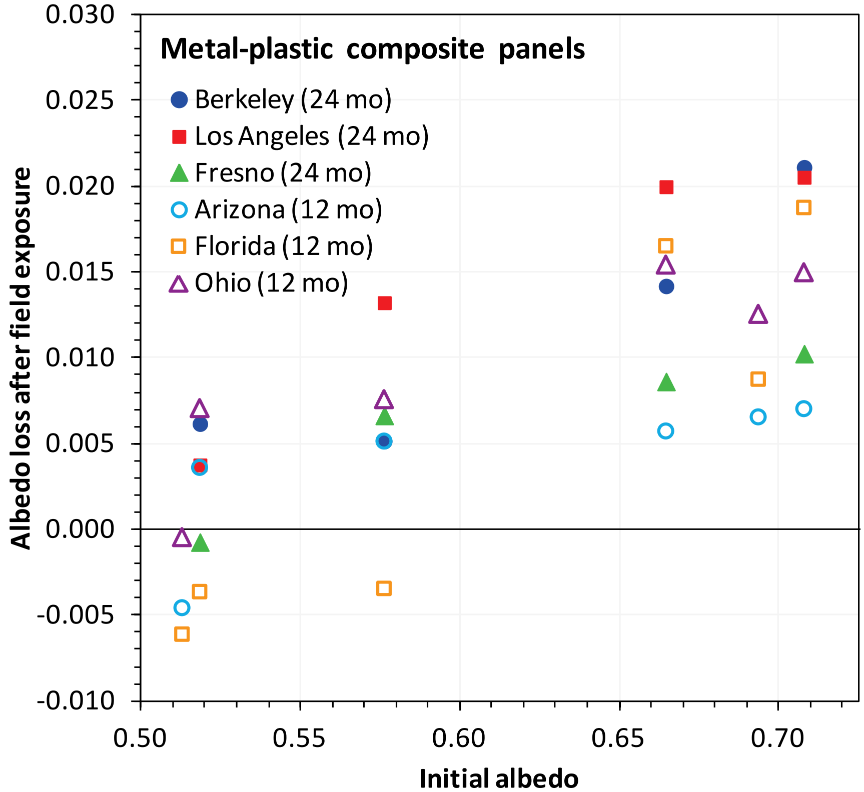
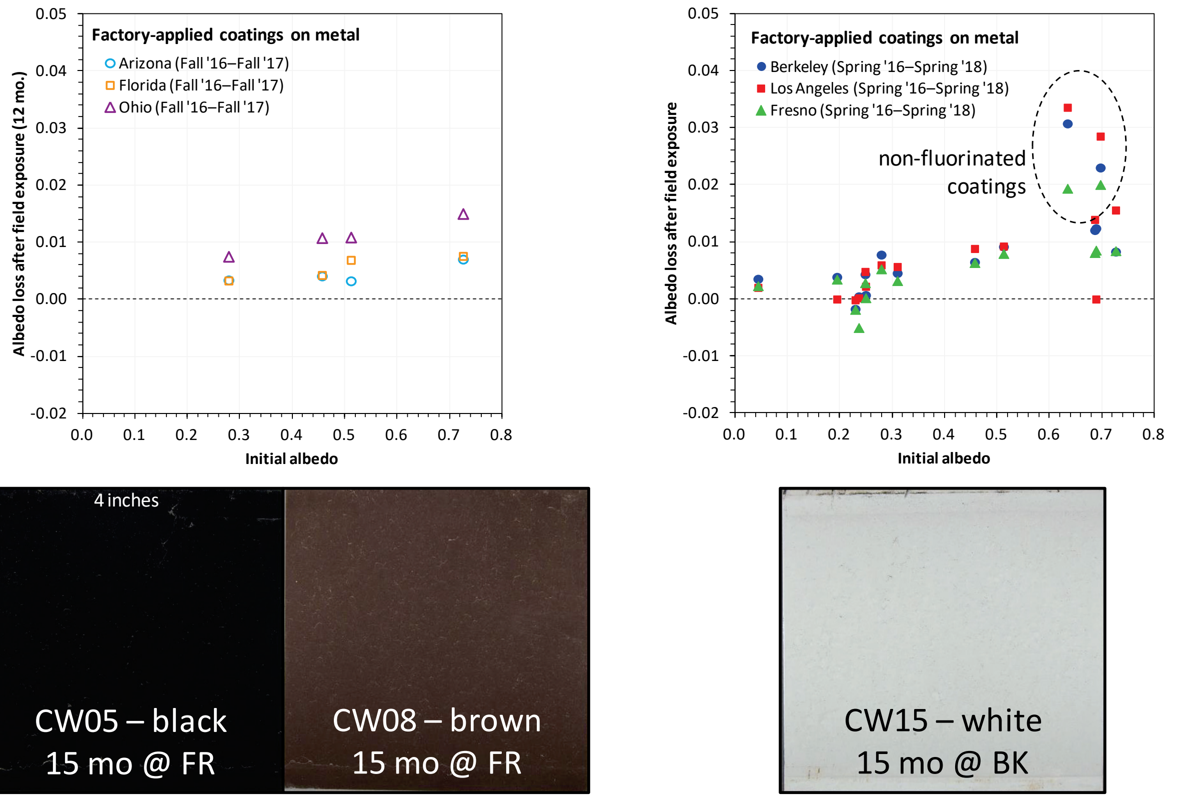


Figure 12. Changes in albedo of composite metal claddings after 24 months of exposure in California and 1 year of exposure at the U.S. national sites.



For these materials, albedo increases as materials are soiled

Soiling accumulated on CW15, a light-colored non-fluorinated coating

Figure 13. Changes in albedo of factory-applied coatings after 24 months of exposure in California and 1 year of exposure at the U.S. national sites.

3.2.1.1 Effect of surface texture

The effect of different surface textures was investigated using two different factory-applied coating products, for which we also received the equivalent smooth surface, used as control. In the first case (shown in Figure 14), the textured product had an initial albedo that was about 0.02 lower than the control sample. That gap between those two products was retained over the exposure period, in all three sites. However, a similar analysis carried out with the other textured (embossed) product and its corresponding smooth control sample did not show a significant difference between the two (Figure 15). Hence, no strong effect can be derived from these observations.

It should be noted that in Figure 15, the results for Los Angeles could not be recorded because specimens were exposed without removing their protective transparent plastic cover.

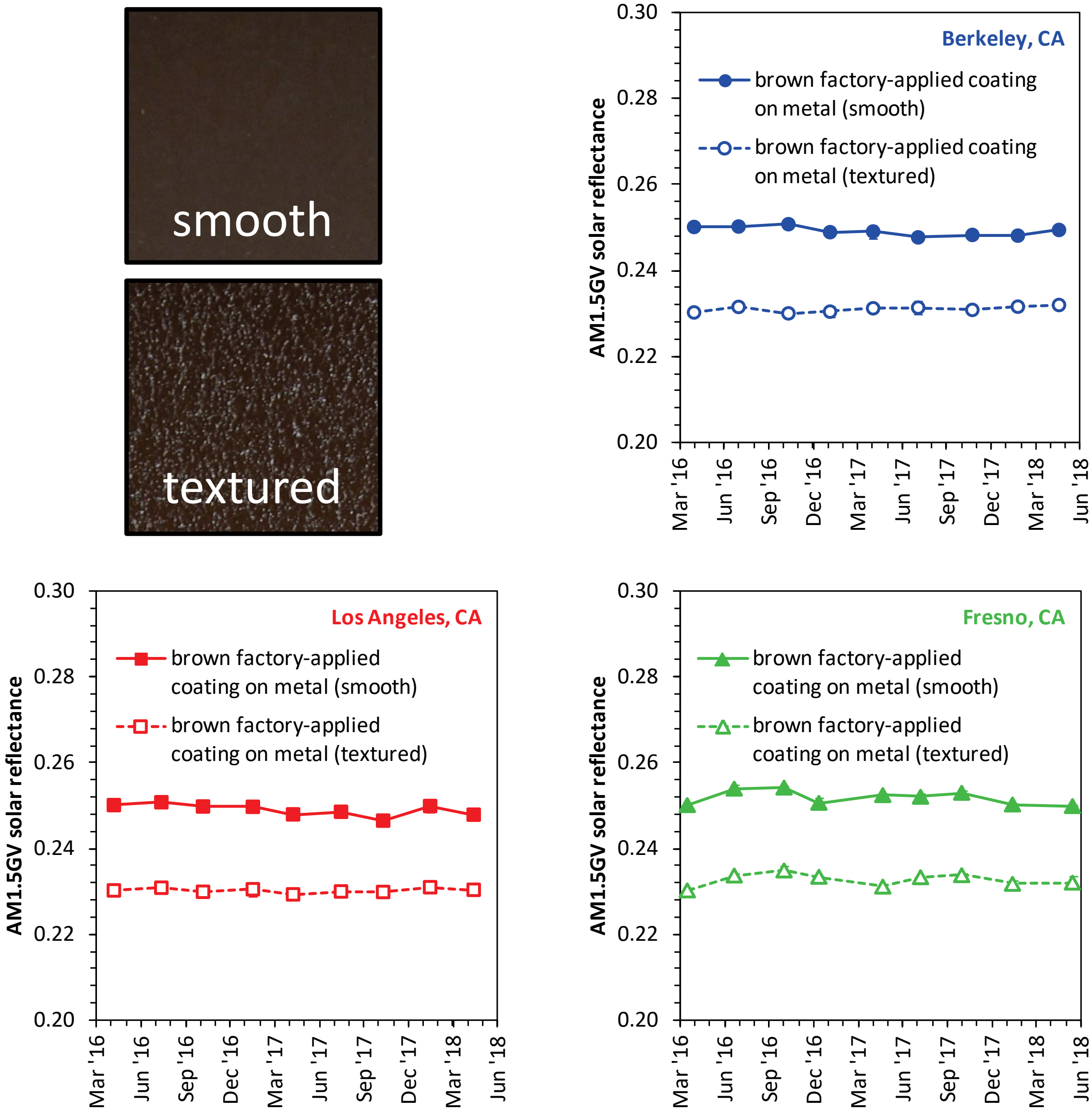


Figure 14. Comparison of solar reflectances measured for smooth and textured factory-applied coatings.

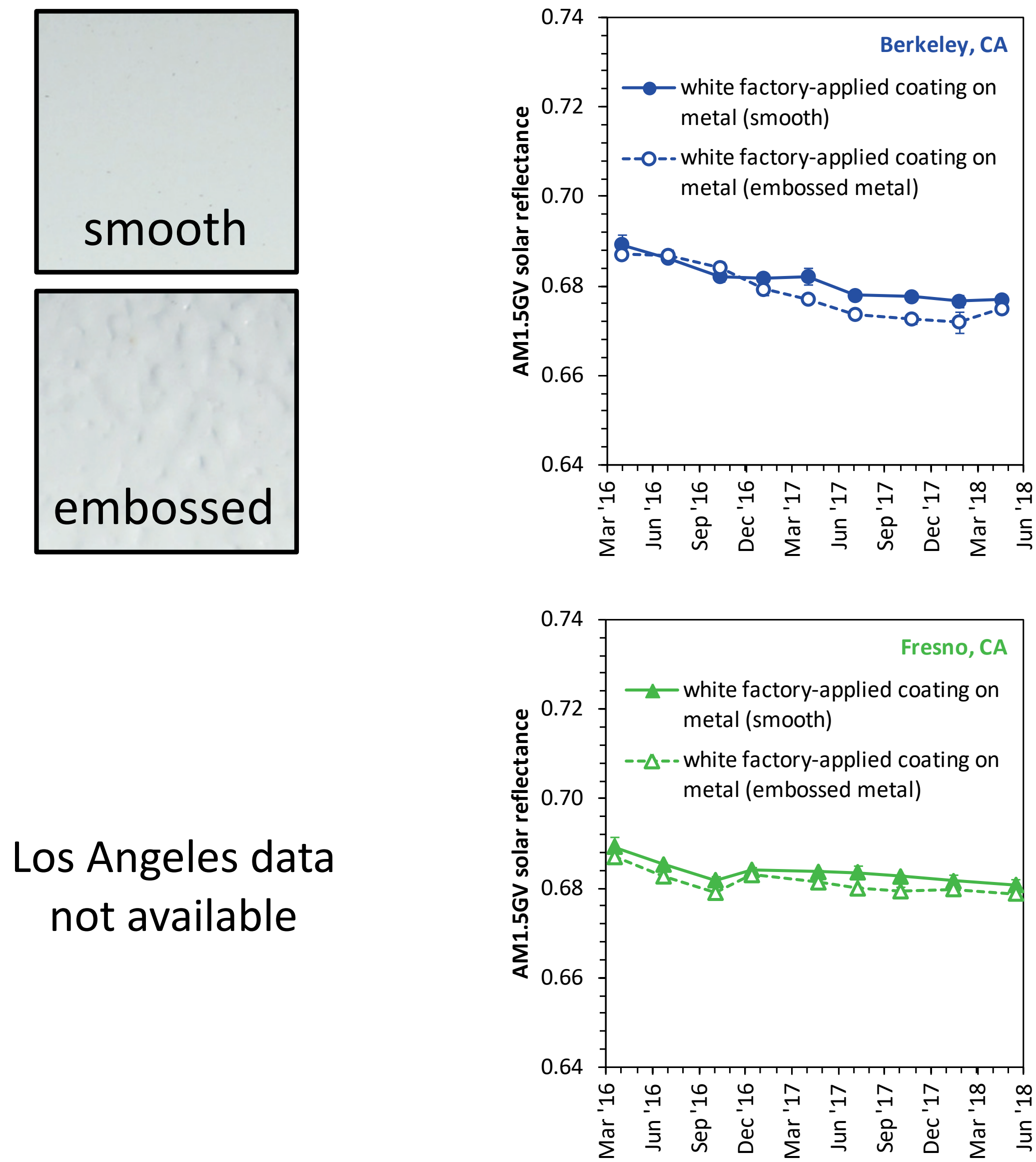


Figure 15. Comparison of solar reflectances measured for smooth and embossed factory-applied coatings.

3.2.2 Field-applied coatings

This category groups the majority of materials analyzed in this study. For that reason, the analysis was performed as a function of various other characteristics of the different products received from manufacturers.

3.2.2.1 Effect of different substrates

Field-applied coatings were evaluated on four different substrates: wood, concrete, metal, and fiber cement. Figure 16 presents the complete set of results for all products applied to all substrates, grouped by site of exposure (California and U.S. national). There is no difference in performance (with statistical significance) between paint coatings applied over wood and fiber-cement substrates. Those applied over wood substrates seem to have slightly higher solar reflectances, possibly due to higher surface smoothness and potentially also the fact that if the coatings are not thick enough to be fully opaque, the reflectance of the substrate can modestly affect the material's albedo. In the case of the materials with concrete substrates, all of the coating products were white, and differences among the five materials could be attributed to different formulations.

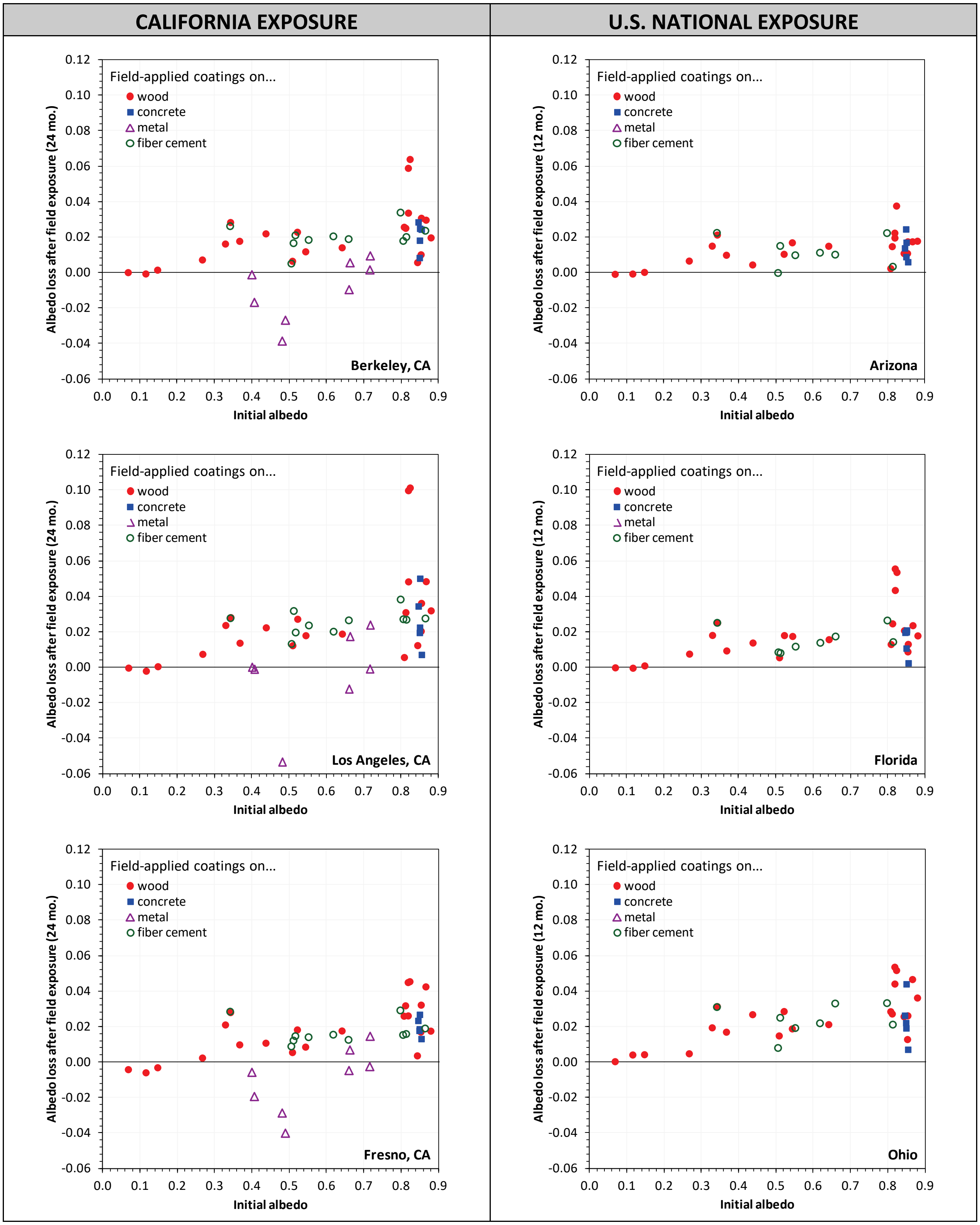


Figure 16. Changes in albedo of field-applied coatings exposed in California and U.S. national sites (all materials).

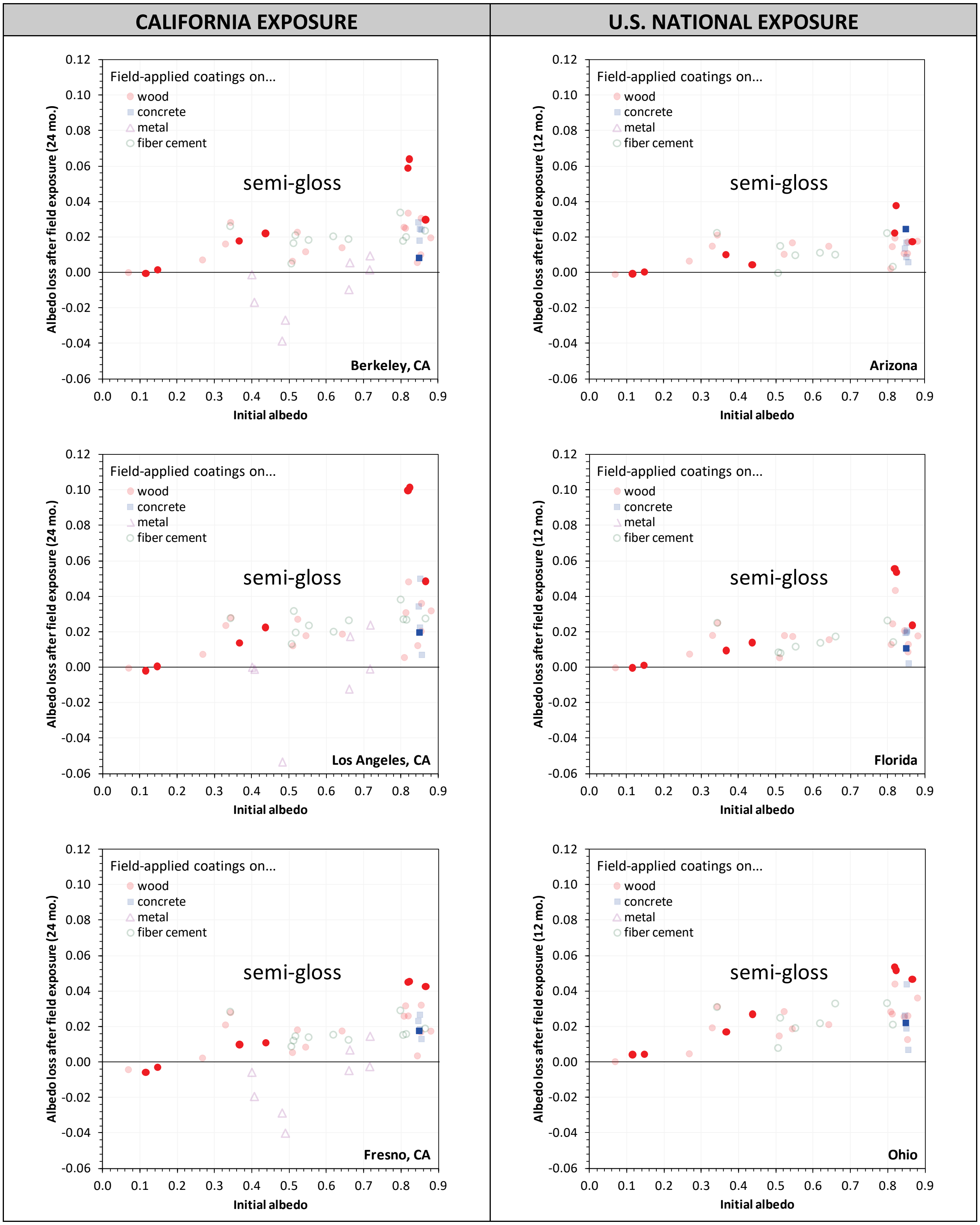


Figure 17. Changes in albedo of field-applied coatings exposed in California and U.S. national sites (semi-gloss finish).

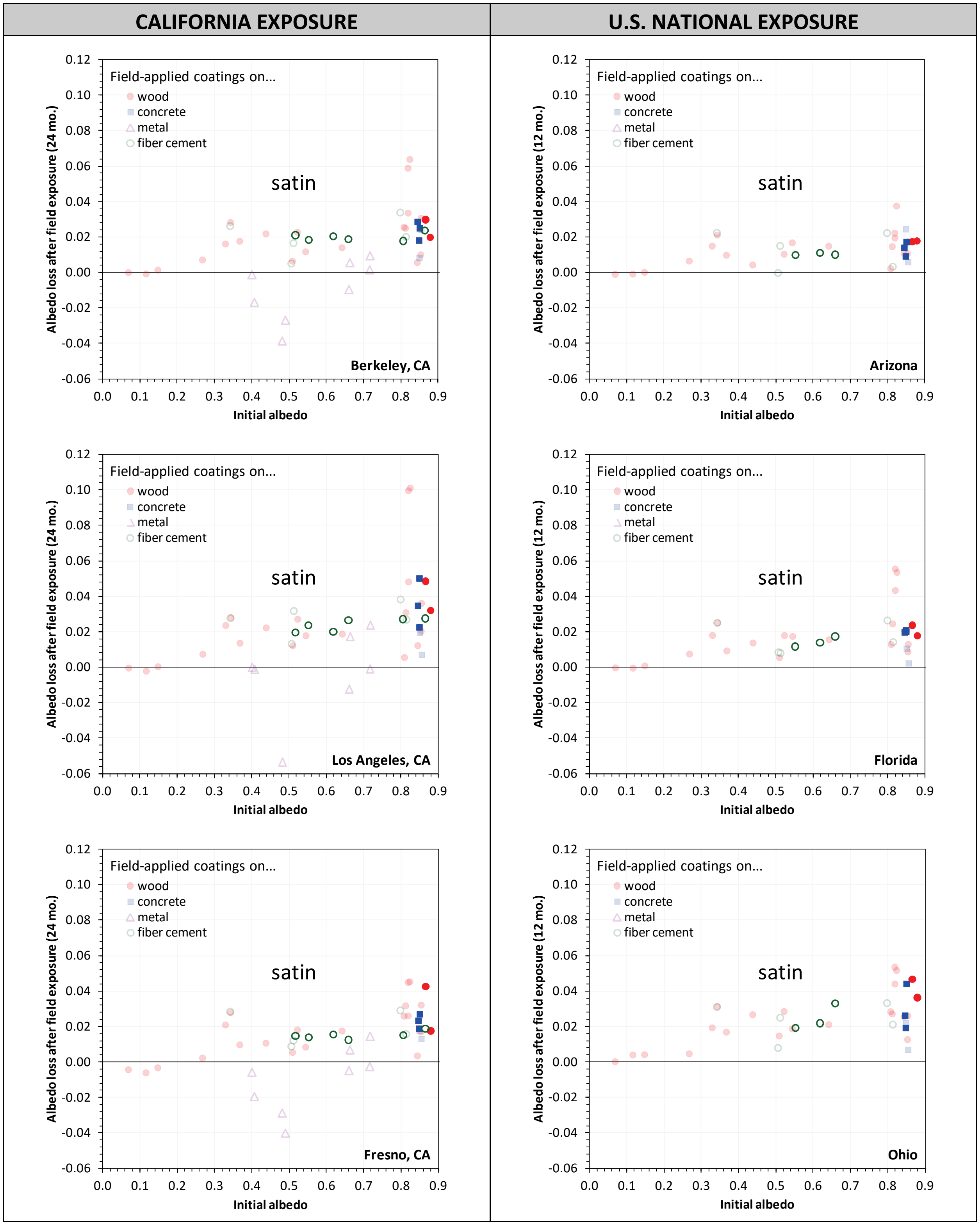


Figure 18. Changes in solar reflectance of field applied coatings exposed in California and U.S. national sites (satin finish).

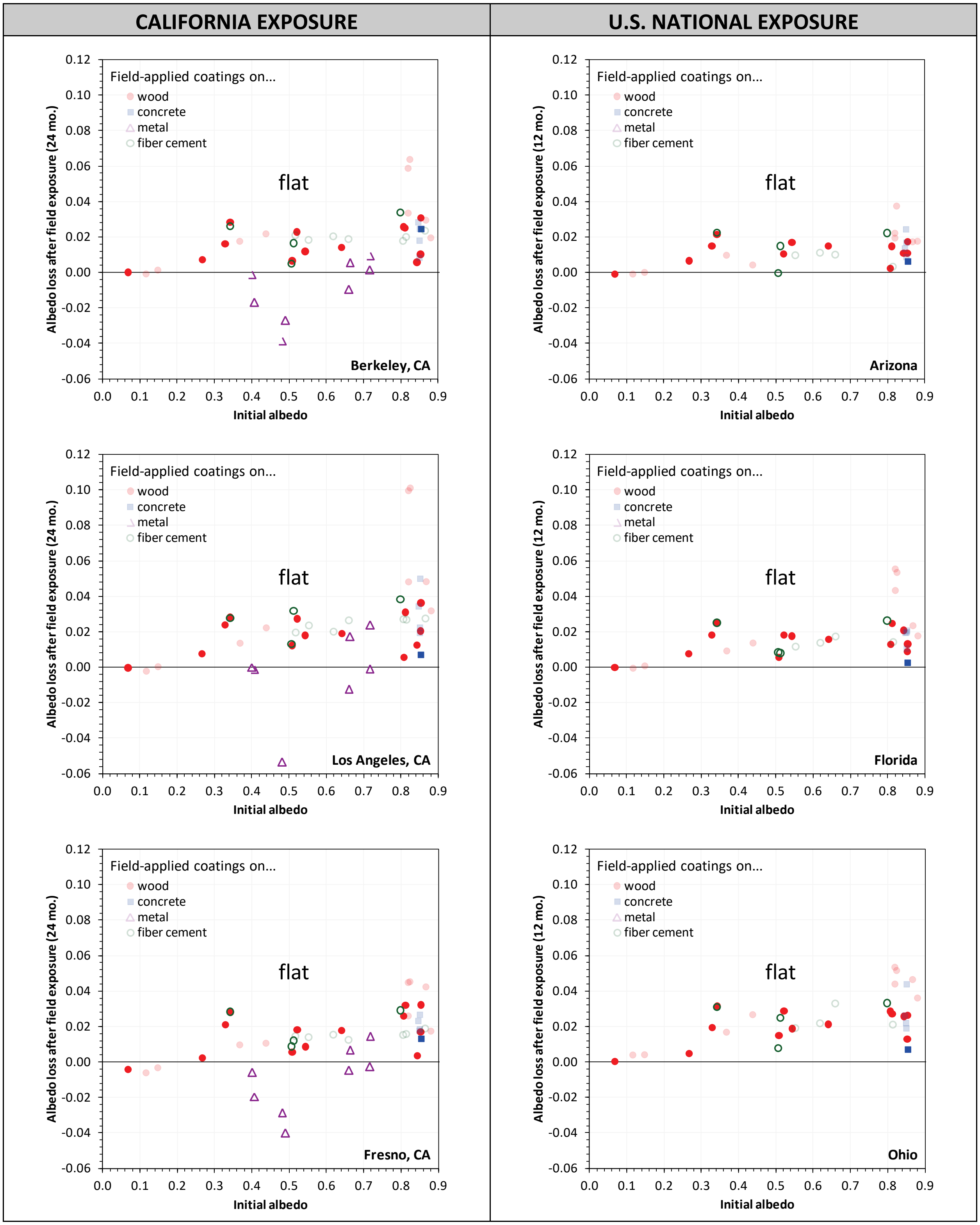


Figure 19. Changes in solar reflectance of field applied coatings exposed in California and U.S. national sites (flat finish).

3.2.2.2 Effect of surface finish

The sub-set of field-applied coating samples that corresponded to semi-gloss, satin and flat finishes, are presented in Figure 17, Figure 18 and Figure 19 respectively. Most materials fall in the latter category, and show a significant dispersion. However, for a given value of the initial albedo, the semi-gloss and satin samples tend to present a higher loss of performance than the corresponding flat material.

3.2.2.3 Effect of formulations containing cool pigments

Coloring coatings with spectrally-selective “cool color” pigments can boost albedo while providing a broad palette (Levinson et al., 2007). This enhanced performance is achieved by increasing reflectance in the near-infrared spectrum (700 – 2,500 nm), which accounts for about half of the total solar energy. Several manufacturers offer cool versions of their paint formulations and in this study we were able to compare cool paints with conventional versions of the same color used as their control samples. Figure 20, Figure 21 and Figure 22 illustrate this effect on three cool paints of different colors applied on wood. The increase in solar reflectance attributed to the use of spectrally-selective pigments over conventional pigments is in all cases between 0.2 and 0.3. Exposure at three different California sites did not significantly alter this effect.

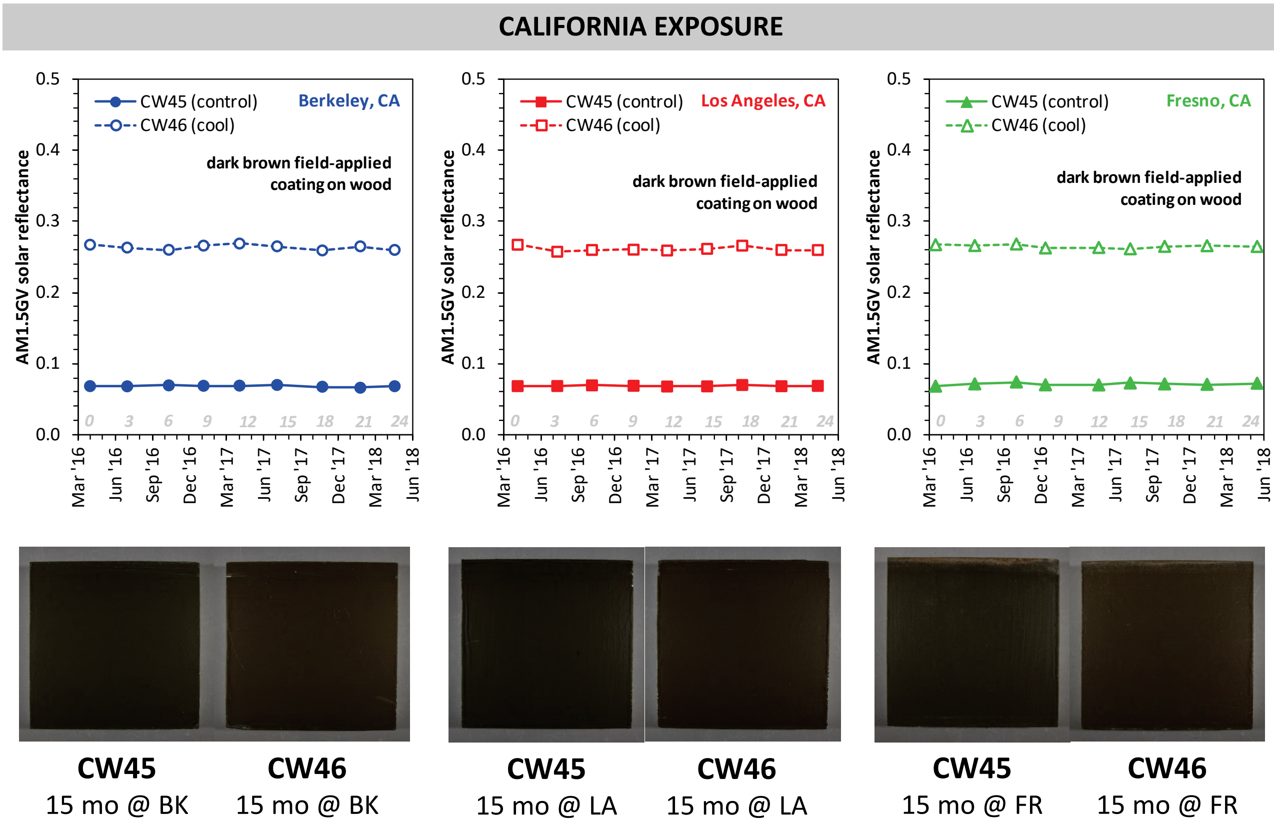


Figure 20. Solar reflectance of field applied coatings exposed in California (cool pigment vs. control).

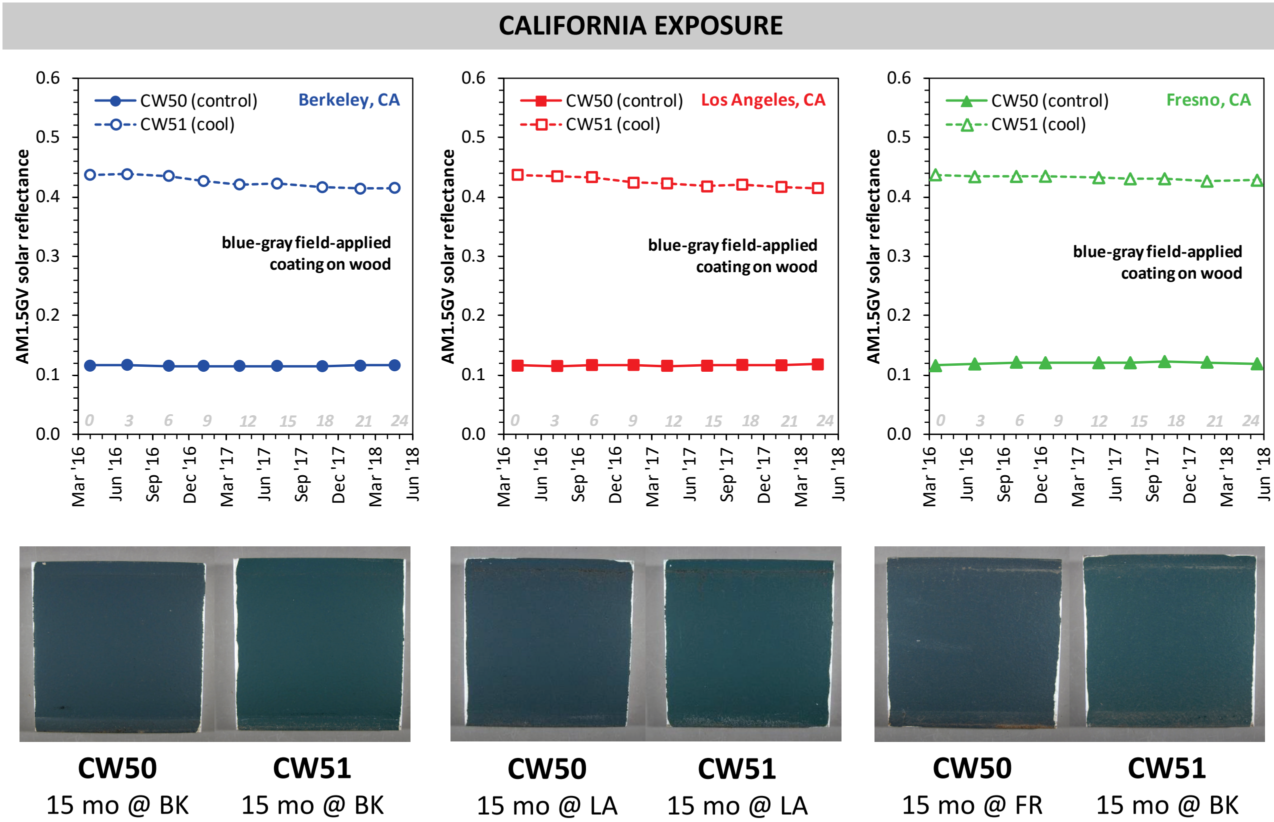


Figure 21. Solar reflectance of field applied coatings exposed in California (cool pigment vs. control).

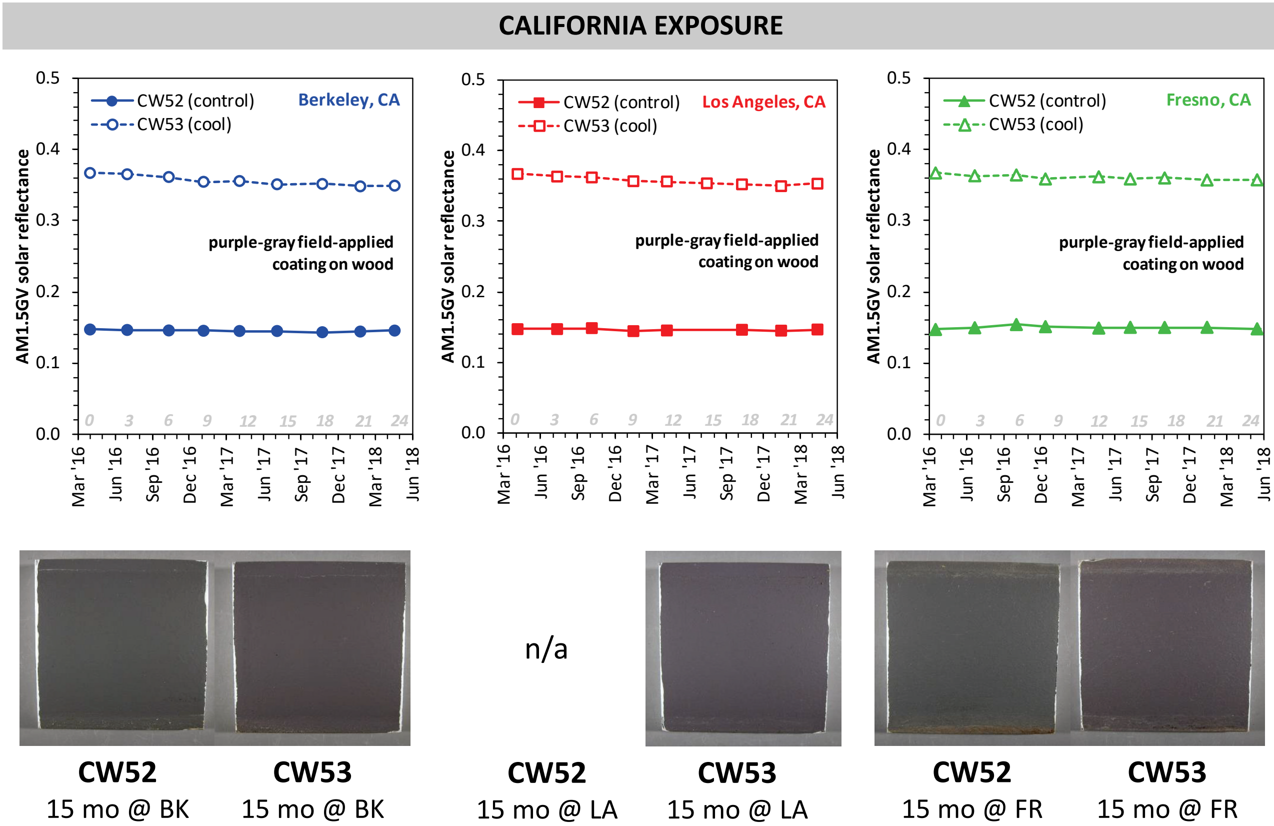


Figure 22. Solar reflectance of field applied coatings exposed in California (cool pigment vs. control).

3.2.2.4 Effect of dirt-resistant formulations

Some of the products evaluated in this study were paints formulated with dirt-resistance additives. Figure 23 illustrates the effect attributed to these additives on samples exposed in the three California sites. The control material consisted of a paint of the same general characteristics and color, but which did not have dirt-resistance additives. In all three sites, the initial solar reflectance was similar for the control and dirt-resistant samples, but a gap between them grew as a function of exposure time. This gap was less significant in Berkeley and Los Angeles than in Fresno, suggesting that the nature of soiling deposited on the surface plays an important role. Both dirt-resistant formulations seemed to perform very similarly in all three locations.

Figure 24 compares results from these same materials, corresponding to 24 months of exposure in California and 12 months in the U.S. national exposure locations. In most cases, the dirt-resistant formulation presented a smaller reduction in albedo than the controls. Photos of those same specimens are presented in Appendix 1.

Another pair of products—a white dirt-resistant paint formulation and a non-dirt-resistant paint formulation of similar type and color—were applied on two different substrates to compare the effect of the substrate on this property (Figure 25). On all three California sites, the dirt-resistant paint applied over fiber-cement substrates showed a modest improvement in performance with respect to the non-dirt-resistant paint. In this pair, the observed albedo loss in the non-dirt-resistant formulation was 0.01 – 0.02 greater than that for the dirt-resistant formulation. When the two products were applied on wood, the difference in albedo loss between them was marginal in Berkeley and Fresno (~0.001), but modest in Los Angeles (albedo loss in the non-dirt-resistant formulation was 0.025 greater than in the dirt-resistant formulation).

Figure 26 illustrates a third set of results, corresponding to a paint formulation combining cool pigments with dirt-resistance additives. Compared to a similar non-cool and non-dirt-resistant product, the spectrally-selective pigments in this formulation boost the initial albedo by roughly 0.15. We did not observe any significant performance improvements in this dirt-resistant and cool product over a similar product with cool pigments but no additional dirt-resistant additives.

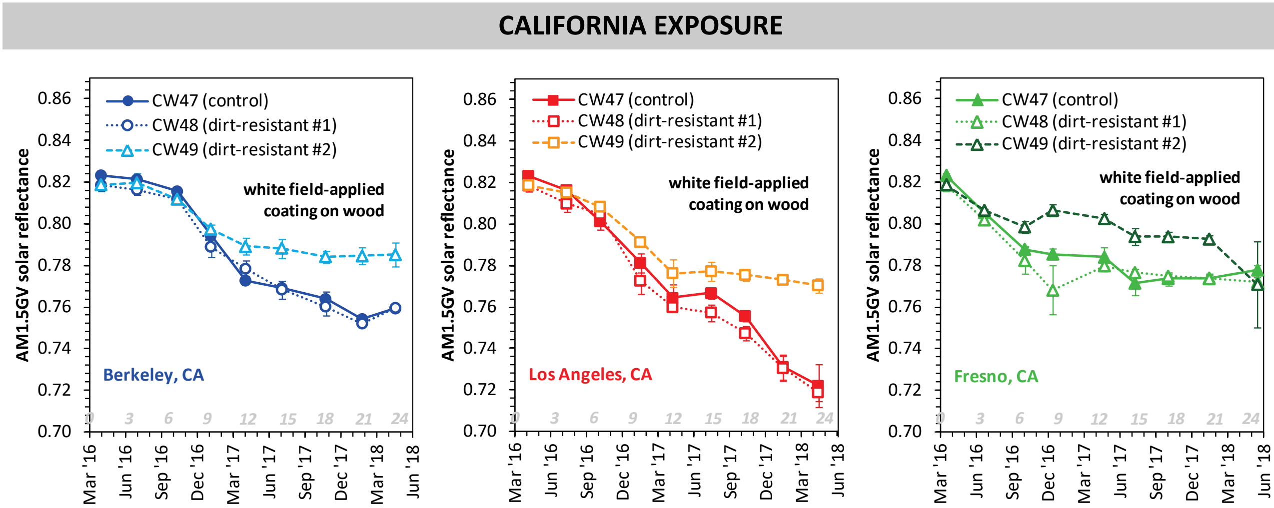


Figure 23. Solar reflectance of field applied coatings exposed in California (dirt-resistant vs. control).

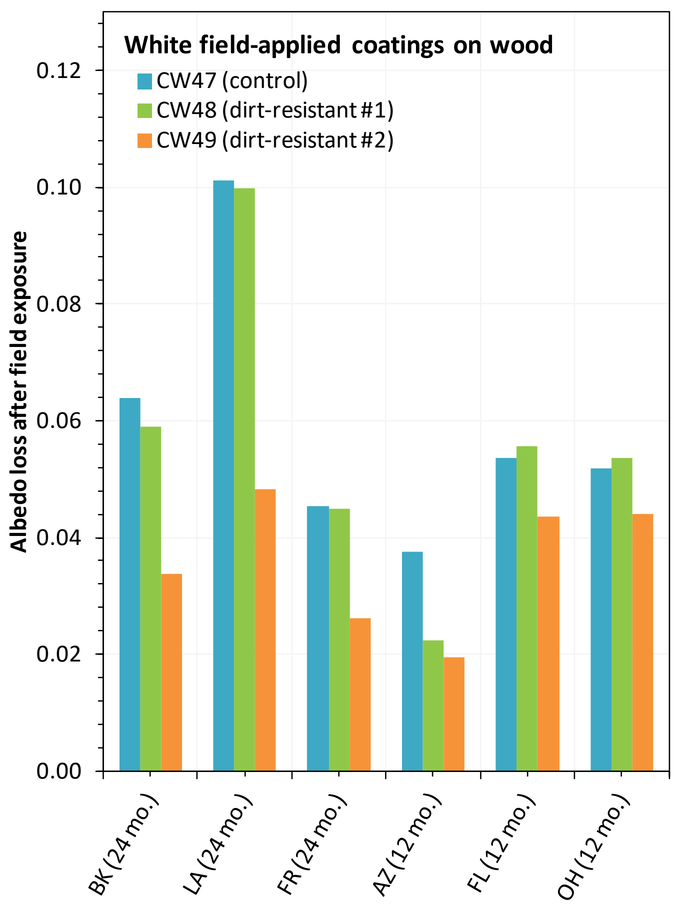


Figure 24. Change in solar reflectance of field applied coatings exposed in California and U.S. national sites (cool pigment vs. control).

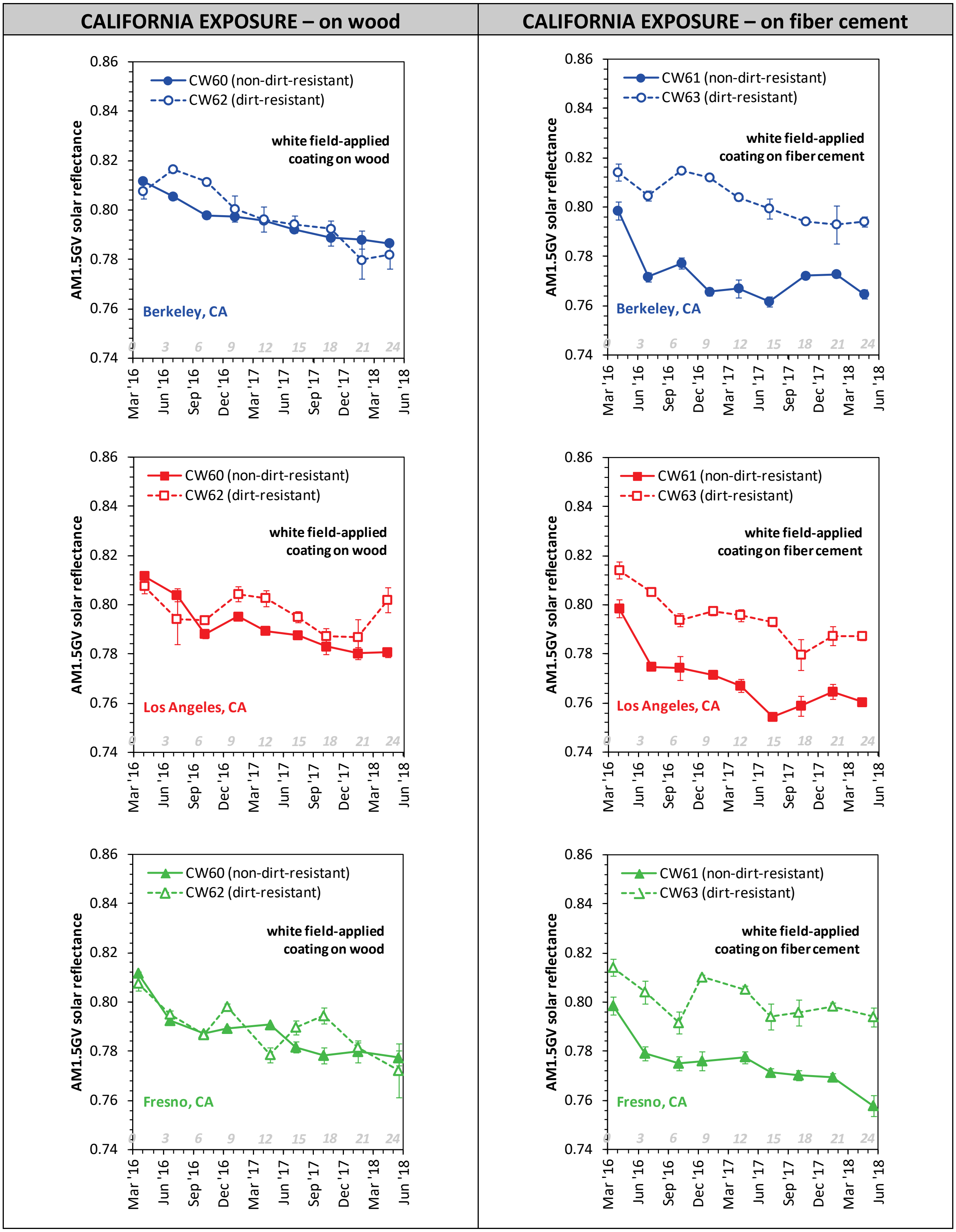


Figure 25. Solar reflectance of field applied coatings exposed in California on two different substrates (cool pigment vs. control).

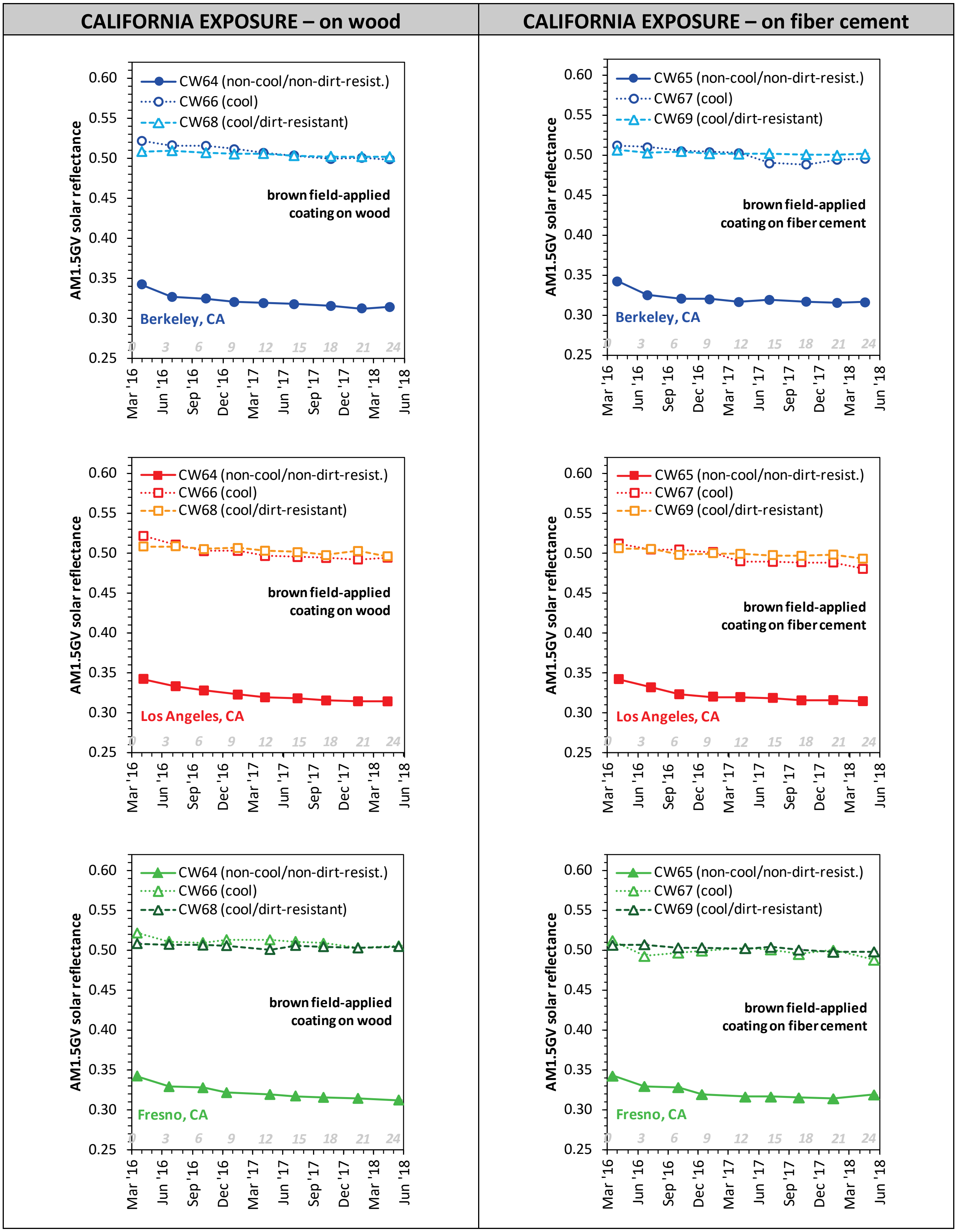


Figure 26. Solar reflectance of field applied coatings exposed in California (cool pigment + dirt-resistant vs. cool pigment vs. control).

3.2.3 Color changes due to product aging

In general, albedo loss is attributed to the presence of soiling agents such as dust deposition and microbial growth. However, in a few cases we observed a noticeable color change, which is likely the main reason for the albedo changes.

In Figure 27 and Figure 28, we illustrate the results obtained for vinyl siding specimens that were initially white, after exposure in the California and U.S. national sites. Many of the retrieved specimens had turned yellow, showing corresponding decreases in solar reflectance.

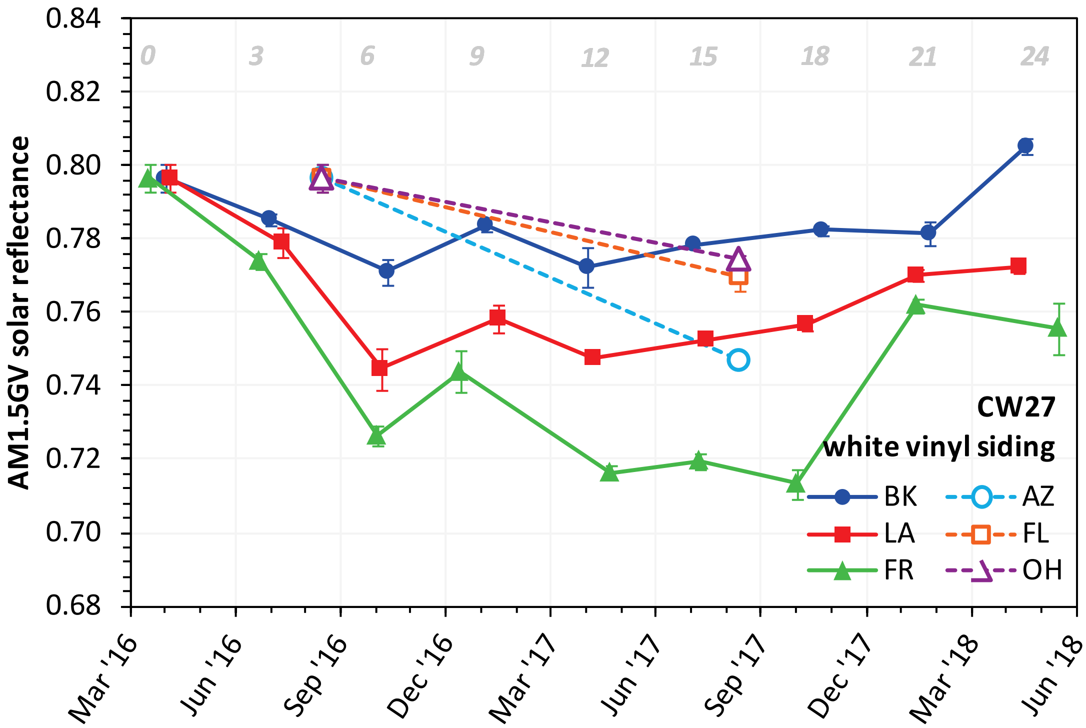


Figure 27. Solar reflectance of vinyl siding specimens exposed in California and U.S. national sites.

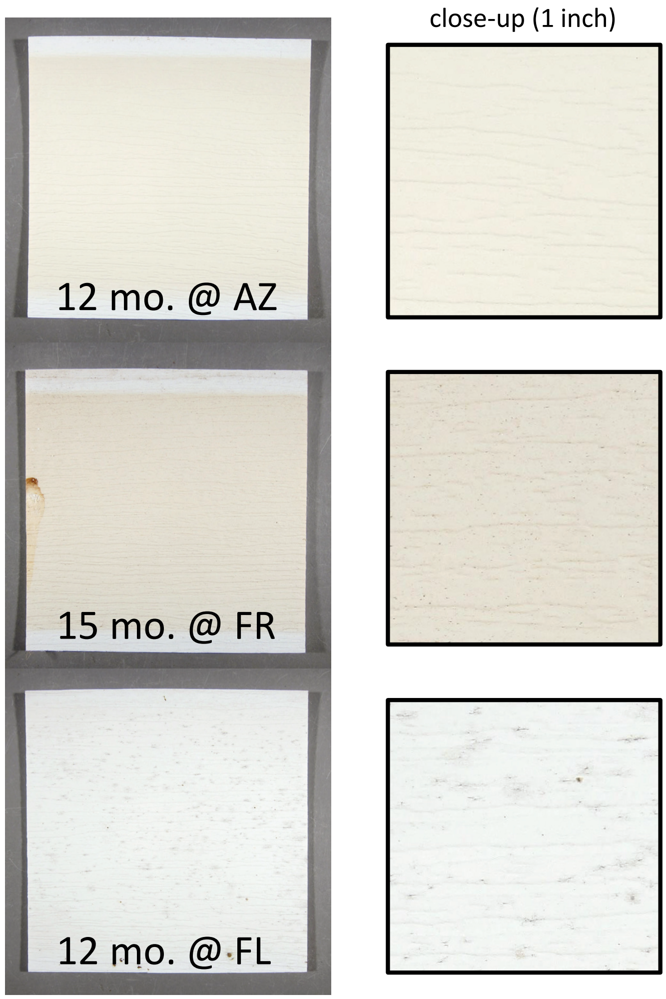


Figure 28. Images of vinyl siding specimens exposed in California sites after 12 months.

By contrast, a set of paint formulations that included photocatalytic self-cleaning pigments showed an increase in solar reflectance compared with the corresponding non-photocatalytic control, which could be attributed to the enhanced bleaching of the pigment due to the oxidative action of the photocatalyst (Figure 29).

On a similar set of products, including a photocatalytic formulation and a control, both samples showed bleaching upon exposure, with the largest effect being for the samples exposed in Los Angeles (Figure 30).

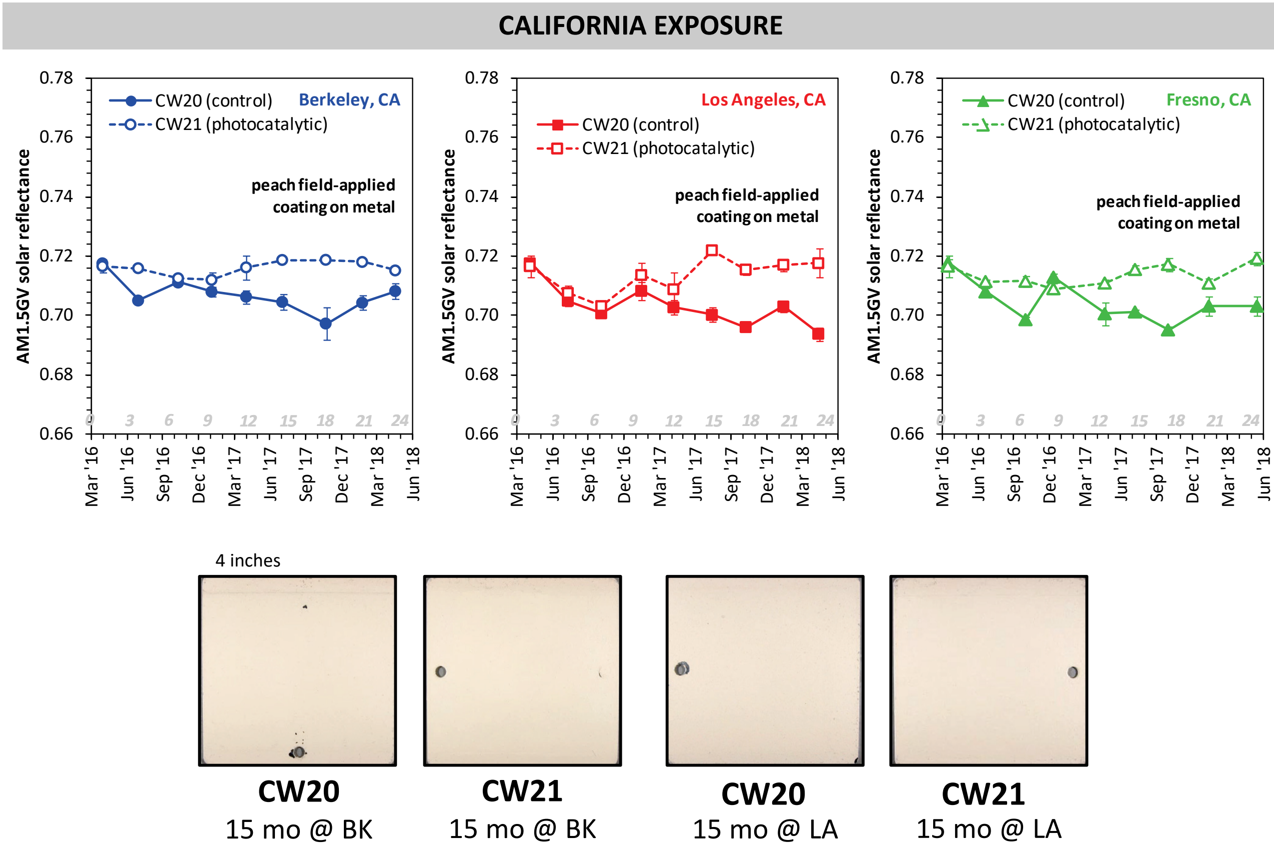


Figure 29. Solar reflectance of photocatalytic paint and their control, at the California exposure sites.

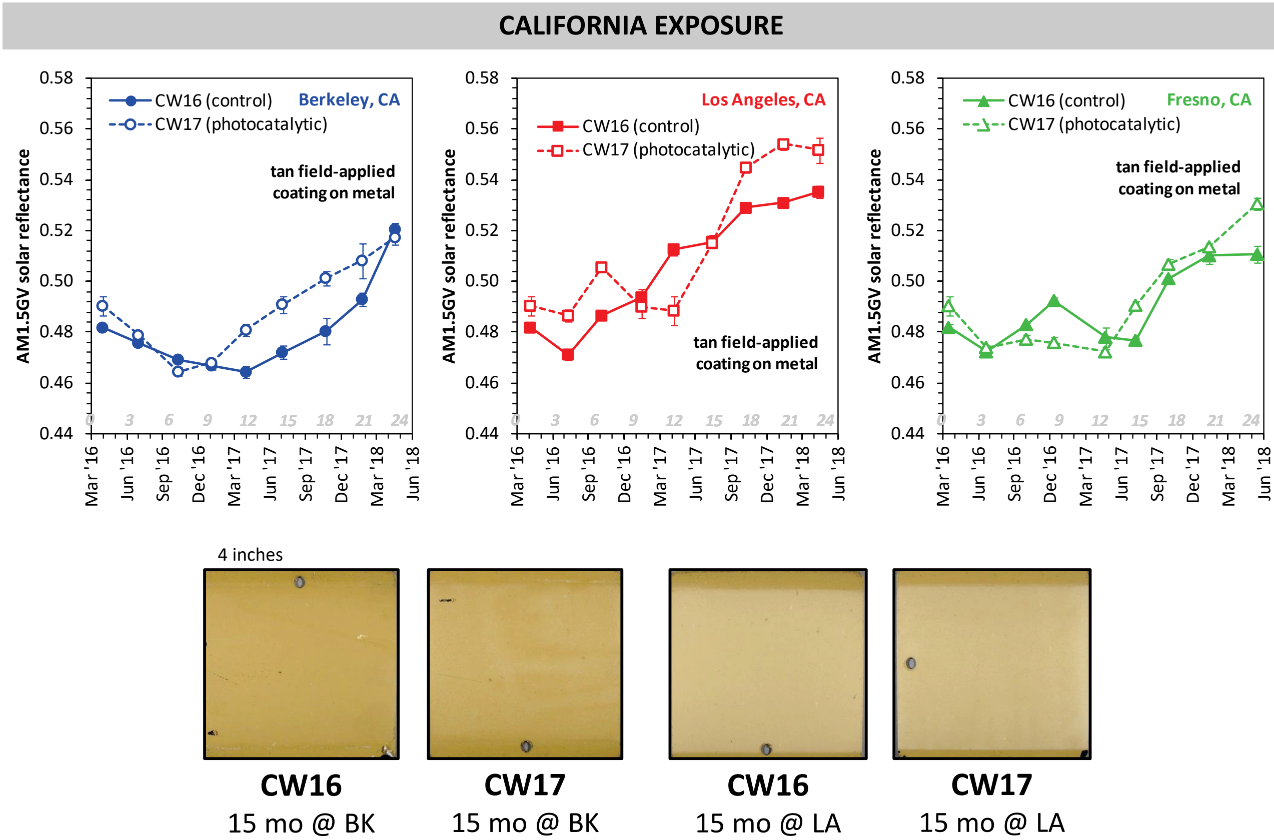


Figure 30. Solar reflectance of photocatalytic paint and their control, at the California exposure sites.

3.2.4 Self-cleaning products

Results shown in Figure 29 illustrate the effect of photoactive pigments on paint formulation. It was impossible to assess whether some of the changes in solar reflectance were due to the oxidation of soiling agents by the photocatalyst, or simply to the color change due to pigment bleaching. The results shown in Figure 30 suggest that other photocatalytic paint formulations did not have a major de-soiling effect.

Photocatalytic architectural fabrics were also investigated in detail. Those results are presented in the Task 4.3 report: *Evaluation of self-cleaning and de-polluting photocatalytic wall materials*.

4 Conclusions

Overall, the natural exposure of wall products over the course of 24 months at three California sites and 1 year at three U.S. national sites has shown modest to negligible changes in solar reflectance. Changes in albedo were caused by both soiling accumulation and color changes. We observed the highest albedo retention in factory-applied fluoropolymer coatings and varying levels of albedo retention in field-applied coatings and other products.

5 Future work

The results of this natural exposure study will be further systematized during the preparation of an archival journal article summarizing the key results. This information will also support efforts to propose implementation of cool walls rating systems.

National exposure is schedule to continue through 2021. We will coordinate with industrial partners to retrieve and measure those specimens in August of 2018, 2019, 2020, and 2021.

Acknowledgements

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