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ABSTRACT

Extreme heat is a critical challenge that negatively impacts human health, energy use, air quality, social equity, and economic prosperity. In a world that continues to grow hotter by the year, cities in particular are suffering from an increase in heat waves and heat-related deaths. Buildings can play an integral role in urban heat island (UHI) mitigation through the use of solar-reflective "cool" surface materials. While cool roofs are one commonly used solution, research has demonstrated that cool exterior walls are also effective at mitigating UHIs and reducing cooling loads. As rising temperatures drive the need for more heat-resilient buildings, building energy codes, standards, and voluntary programs are adopting cool exterior wall provisions. ASTM Standard Test Method C1549 is the primary standard used to measure the solar reflectance (SR) of building materials, but this standard does not contain details for accurately measuring vertical surfaces. Currently, the CRRC-2 Wall Product Rating Program Manual, a proprietary document developed and maintained by the Cool Roof Rating Council (CRRC) for its Wall Product Rating Program, is the only document that contains scientifically backed instructions for measuring the SR of vertical surfaces using ASTM C1549. Since codes and standards developers prefer to reference non-proprietary documents, such as ASTM and ANSI standards, some codes and standards direct users to test

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methods that do not account for the nuances of vertical surfaces. This paper summarizes the heat-mitigation impacts of cool exterior walls and describes the development and technical foundation of the testing requirements found in the CRRC-2 Wall Product Rating Program Manual. It also discusses opportunities to incorporate procedures for measuring vertical surfaces into ASTM C1549 and other areas for improvement around the adoption of cool exterior walls.

Keywords

Urban heat, solar reflectance, albedo, reflectometer, product rating, cool walls, ASTM C1549

Introduction

Cool roofs have been used for decades across the United States to reduce energy use and mitigate the urban heat island (UHI) effect. As the Earth continues to become hotter—with June 2024 marking the 13th month in a row of record-breaking global surface temperatures according to the National Oceanic and Atmospheric Administration[1]—embracing additional built environment strategies for combating extreme heat is imperative. Cool exterior walls are a scientifically backed mechanism for improving resilience to extreme heat that has been adopted into building energy codes, model standards, and voluntary programs, including but not limited to the Honolulu Building Energy Code, 2024 International Energy Conservation Code (IECC), ASHRAE Standard 90.1-2022, and LEED v4.1.[2]

In January 2022, the Cool Roof Rating Council (CRRC) launched an independent, third-party product rating program for the key radiative properties of exterior wall products: solar reflectance (SR) and thermal emittance (TE)) . The program is modeled after the longstanding CRRC Roof Product Rating Program and is operated in accordance with a set of strict technical requirements and procedures documented in the CRRC-2 Wall Rating Program Manual (CRRC-

2), a proprietary manual developed and maintained by the CRRC. As the world's only database of radiative property data for exterior wall products, the CRRC Rated Wall Products Directory is a key resource for identifying products that comply with various policies and programs. However, most current codes and standards directly reference test methods that do not contain procedures for accurately measuring the SR of vertical surfaces, and some reference incorrect metrics altogether.

Here, we present a summary of the activities that were completed to develop and validate the exterior wall testing requirements found in CRRC-2 and discuss opportunities to improve adoption of cool exterior walls in codes, standards, and programs by revising ASTM C1549-16(2022), *Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer*[3] to be applicable for vertical surfaces; removing Solar Reflectance Index (SRI), an inapplicable metric for exterior walls, from codes, standards, and programs; establishing a voluntary consensus standard for measuring SR with a directional-hemispherical portable reflectometer; and increasing references to the CRRC Rated Wall Products Directory in policies and programs with existing cool exterior wall provisions.

Literature Review

Solar-reflective or "cool" exterior walls that are white, light in color, or formulated with special pigments that reflect near-infrared (NIR) radiation can be as effective at reducing building solar heat gain, lowering wall surface temperature and indoor air temperature, and decreasing air conditioning (AC) use as cool roofs.

With respect to energy use, Rosado and Levinson[4] assert that cool exterior walls produce annual heating, ventilation and air conditioning (HVAC) energy savings for buildings across the southern half of the United States (U.S. Climate Zones 1 through 4) and in all 16 of California's climate zones. Further, an Oak Ridge National Laboratory study on the energy savings potential of cool exterior walls that modeled a single-story, ranch-style house in Phoenix, Arizona and Jacksonville, Florida estimated annual cooling energy savings ranging between 4 and 13 percent.[5] With increasing summer temperatures and the strain of electrical demand on the power grid in those two locations, the combination of cool roofs and walls, or at the very least, the use of cool exterior wall materials alone, can help residents reduce the need to use AC during warmer weather.

Though roofs are typically exposed to more sunlight than walls, the comparable savings from cool exterior walls result from walls having less insulation than roofs, with about half the amount of resistance to heat flow achieved by a roof. Further, cool exterior walls influence the HVAC energy use of every floor of a multi-story building, whereas cool roofs mainly affect the HVAC energy use of only the top floor.[4]

With respect to UHI, Zhang et al.[6] demonstrated that cool exterior walls are a viable mechanism for UHI mitigation and that the ability of cool exterior walls to mitigate the UHI effect is comparable to cool roofs. For example, their research found that cool exterior walls in Los Angeles, California, yield about 86 percent of the daily average air cooling achieved with cool roofs in the month of July.[6] The researchers used the Weather Research and Forecasting model to simulate the effects of cool exterior walls and cool roofs on the near-ground outdoor air temperature (2 m above ground level) in the Los Angeles Basin. For equal increases in SR, cool exterior walls were nearly as effective as cool roofs, despite the fact that walls receive less daily solar irradiation than roofs. The two key drivers are (a) there is about 50 percent more net wall area (walls minus windows) than roof area in Los Angeles, and (b) walls are closer to the near-ground outdoor air than the roofs (the average wall height is half the average roof height).[6]

Though the impacts of cool exterior walls are comparable to those produced by cool roofs, there are important differences in the way sunlight interacts with vertical surfaces compared to low-sloped and steep roofs. First, since solar spectral irradiance (incident solar power per unit area per unit wavelength) depends on surface orientation, the spectral power distribution of sunlight striking a wall differs from that on a roof.[7,8,9,10] This must be considered when measuring the radiative properties of exterior wall materials in a laboratory setting. Second, several of the environmental factors that affect the temperature of a surface in the sun, including downwelling and upwelling solar irradiance (incident solar power per unit area), downwelling and upwelling thermal infrared irradiance (incident radiant power per unit area in the 4 - 80 µm thermal infrared spectrum), and convective heat transfer coefficient, differ between roofs and walls. Therefore, radiative metrics such as SRI that assume environmental conditions typical for a roof may require redefinition to apply to a wall.[11]

Materials and Methods

ASTM C1549 is the most common standard used to measure the SR of building materials among accredited independent testing laboratories in the United States. This test method and its industry-vetted variants for variegated surfaces and tile and wood materials are the only SR test methods that are used by all six laboratories that perform testing for the CRRC Roof Product Rating Program and the three laboratories that perform testing for the CRRC Wall Product Rating Program.[12] However, this standard does not contain details for measuring the SR of vertical surfaces in a way that accurately characterizes the solar irradiance they receive. Currently, CRRC-2 is the only document that contains scientifically backed instructions for measuring the SR of vertical surfaces using ASTM C1549.

ASTM C1549 DESCRIPTION AND LIMITATIONS

ASTM C1549 describes how to determine the SR of an object's surface when measured in a laboratory or on-site in the field.[3] The ASTM C1549 test method can be used to determine both the initial (i.e., unweathered) surface SR of flat opaque surfaces and the changes in their surface SR over time due to soiling and weathering.

In ASTM C1549, SR measurements of materials at least 2.5 cm in diameter with either specular (mirrorlike) and diffuse (matte) reflectances are taken with a calibrated portable reflectometer. A baffled tungsten halogen lamp illuminates the test specimen with highly diffuse light. Four filtered photodetectors at the end of a tube angled 20° away from the specimen's surface normal collect reflected light in spectra peaking at 380 nm, 500 nm, 650 nm, and 1220 nm.[3, 8]

In this test method, the air mass, or the "path length of solar radiation through the earth's atmosphere to the site of interest," that is to be associated with the measurements can be changed by specifying how the instrument weights the outputs of its four detectors.[9] According to the test method, users may select air mass 0, 1, 1.5, or 2, with air mass 1 being the "path of normal solar radiation at the earth's equator" and air mass 2 being two times said path length.[8] Absent from the list of air mass options mentioned in the standard is air mass 1.5 GV (air-mass 1.5 for a sun-facing, 90° [vertical] tilted surface), which is the appropriate air mass for measuring the SR of vertical surfaces, as described later in this paper.[8] The standard also does not describe other outputs available from the current version of the instrument (6), such as air mass 1 global horizontal (AM1GH) SR.[13, 7, 8]

ASTM C1549 states that exterior wall materials fall under its scope, noting under the standard's Significance and Use that "[t]he temperatures of opaque surfaces exposed to solar radiation are generally higher than the adjacent air temperatures. In the case of roofs or walls enclosing conditioned spaces, increased inward heat flows result"[8] from absorbed solar radiation. In the Procedure of the standard, users are instructed to "position the measurement head manually against a surface such as a roof or wall."[8] However, the absence of procedures for using the appropriate air mass setting for vertical surfaces in ASTM C1549 creates potential challenges for demonstrating compliance with cool exterior wall policies in codes, programs, and standards.

As a point of comparison, other SR test methods include procedures for measuring vertical surfaces. For example, another test method approved by the CRRC to measure the SR of roofing and exterior wall materials is the *Standard Test Method for Determining the Directional Hemispherical Solar Reflectance of Materials Using a Directional-Hemispherical Portable Reflectometer* (410-Solar Test Method). The test method describes a technique used for determining the directional-hemispherical SR of materials in a laboratory or on-site in the field using a portable solar reflectometer, and includes a solar irradiance option of "G197GT90," which provides the SR at air mass 1.5 for a sun-facing, 90° (vertical) tilted surface.[14] Though the 410-Solar test method is published as Appendix 3 of CRRC-2, the test method is non-proprietary and can be used outside of the CRRC-2 Wall Product Rating Program.

CRRC-2 DEVELOPMENT AND TESTING REQUIREMENTS

CRRC-2[14] was first published in September 2021 in preparation for the launch of the CRRC Wall Product Rating Program in January 2022. CRRC-2 contains the radiative property testing and weathering requirements and program procedures for the CRRC Wall Product Rating Program. It is a proprietary document developed and maintained by the CRRC. As of September 2024, CRRC-2 is the only available technical document containing credible, comprehensive procedures for testing the initial and aged radiative properties of exterior wall materials, though the CRRC is in the process of revising its American National Standard, ANSI/CRRC S100, *Standard Test Methods for Determining Radiative Properties of Materials*,[15] to incorporate the technical testing and weathering requirements currently found in CRRC-2 into the standard. The next version of the standard is expected to be published in 2025.

The CRRC-2 was developed by the CRRC Wall Rating Program Steering Committee (Steering Committee) and CRRC Wall Rating Program Committee (Wall Committee) between 2019 and 2022, and the first edition was approved by the CRRC Board of Directors (CRRC Board) in September 2021. The CRRC Board periodically updates CRRC-2 at the recommendation of the Wall Committee. When CRRC staff become aware of potential improvements that can be made to CRRC-2, the Wall Committee reviews, deliberates, and votes on the potential changes. Changes that pass the Wall Committee vote are then presented to the CRRC Board for approval. This process to update CRRC-2 when needed ensures that the document contains the most technically accurate testing and weathering methods and procedures available and supports the credibility of the CRRC Wall Product Rating Program.

The Steering Committee was an official committee of the CRRC that operated from July 2019 to September 2020 and reported to the CRRC Board. It was responsible for contributing to the design of a rating program for exterior wall products, including testing and exposure protocols; developing a financial model for the program; providing regular updates to the CRRC Board; and developing a program plan document for CRRC Board approval. As of its dissolution in September 2020, the Steering Committee had 30 members representing manufacturers and trade associations in the architectural coating, metal, film, and vinyl and polymeric siding industries; suppliers to these industries; state and local governments; a building enclosure consultant; a non-governmental organization; and a national laboratory.

The CRRC Wall Rating Program Committee (Wall Committee) was formed in December

2020 following the CRRC Board's approval of the Steering Committee's program proposal and subsequent dissolution of the Steering Committee. This is a permanent committee of the CRRC that reports to the CRRC Board and is responsible for evaluating technical issues, such as test methods, standard practices, and weathering protocols for the CRRC Wall Product Rating Program, as well as developing program procedures and requirements; providing guidance on program marketing activities; and collaborating with other CRRC committees in the dissemination of educational information about cool surfaces.[16] The Wall Committee's makeup is similar to that of the Steering Committee, and the Wall Committee strives for balanced representation from exterior wall product industries and non-industry general interest stakeholders (e.g., laboratories and governments).[16, 17]

The CRRC-2 was based on the CRRC-1 Roof Product Rating Program Manual (CRRC-1),[18] which contains the participation requirements for the CRRC Roof Product Rating Program and was first published in 2002. However, CRRC-2 contains important technical differences that were developed by the Steering Committee (2019-2020) and the Wall Committee (2021-Present) to ensure its accuracy for vertical surfaces. These key wall-specific requirements include the air mass setting used for measuring SR; tilt for natural exposure of specimens; Color Family Program requirements; architectural coating substrate requirements; the absence of an SRI metric for exterior wall products; and the absence of a laboratory soiling and weathering procedure for exterior wall radiative properties.

Solar Reflectance Air Mass Setting

Early in the development of CRRC-2, the Steering Committee determined that the SR at air-mass 1.5 global vertical of a sun-facing vertical (90°) tilted surface (AM1.5GV) should be measured for exterior wall materials, as opposed to SR at air mass 1.5 or 1.5E, which are used for roofing materials.[15] This decision was based on work completed by Levinson et al.[19] to determine metrics and methods to assess cool exterior wall performance, which found that AM1.5GV is the appropriate air mass at which to measure the SR of vertical exterior wall surfaces. While no single solar irradiance spectrum can match that incident on every orientation of wall at every latitude and at every hour of year, selecting the AM1.5GV SR spectrum supports accurate estimation of the wall's SR rise (the extent to which using a cool surface material boosts the wall's SR) and its daily solar heat gain (daily solar irradiation absorbed by the wall).[19] For example, the NIR fraction of the AM1.5GV solar irradiance (53.3%) aligns better with the peak global irradiance on a sun-facing wall (54.7% NIR) on a clear day than does the air mass 1.5 global horizontal (AM1.5GH) clear-sky solar irradiance (49.1% NIR).[19, 7] The AM1.5GV solar spectral irradiance is derived and tabulated as "Global 90°" in ASTM G197-14(2021), *Standard Table for Reference Solar Spectral Distributions: Direct and Diffuse on 20° Tilted and Vertical Surfaces*.[9]

To obtain the AM1.5GV SR of a surface using a Devices & Services Solar Spectrum Reflectometer (SSR) in accordance with ASTM C1549, a custom part is required. The Devices & Services GV-9 EPROM is compatible with Version 6 of the SSR and provides custom irradiance selections including AM1.5GV (selection "1.590" on the device). Each of the laboratories that performs testing for the CRRC Wall Product Rating Program[20] has a Version 6 SSR equipped with a GV-9 EPROM. In addition to ASTM C1549 with output 1.590, the following test methods can be used to obtain SR at AM1.5GV in accordance with CRRC-2: (a) ASTM E903-20, *Standard Test Method for Solar Absorptance, Reflectance, and Transmittance of Materials Using Integrating Spheres*,[10] employing the AM1.5GV solar spectral irradiance to compute a weighted average of solar spectral reflectance; (b) *Standard Test Method for Determining the Directional Hemispherical Solar Reflectance of Materials Using a Directional-Hemispherical Portable*

Reflectometer (410-Solar Test Method) with output "G197GT90;" and (c) CRRC-1 Test Method #1, a variant of ASTM C1549, with output "1.590."[14] ASTM E903 is not used by any laboratories that perform testing for CRRC product ratings.

Natural Exposure Tilt

The natural aging requirements in CRRC-2 were developed by the Wall Committee in early 2021, after initial investigation by the Steering Committee and its Rating/Technical Working Group (Working Group). The Working Group found that a three-year natural weathering requirement was necessary to align CRRC-2 with CRRC-1; provide end-users with an indication of longer-term product performance; and potentially inform the development of a laboratory aging protocol. The Wall Committee determined that products shall be exposed at a 90° south-facing tilt for a period of three years in three climate zones: hot/humid, cold/temperate, and hot/dry, as defined by their annual heating degree-days (HDD), cooling degree-days (CDD), and average yearly relative humidity. Since wall specimens are vertically adhered to the exposure rack, the specimens must be staggered on offset racks to prevent cross-contamination (i.e., dripping).[14] These requirements differ slightly from CRRC-1, which also requires three years of natural exposure in the same climate zones, but requires specimens to be mounted at 5°S for low-slope roofing or 45°S for steep-slope roofing and does not require the use of offset racks.

The three-year weathering requirement for exterior wall products is supported by research performed by Chen et al., which found that, after three years of natural exposure at three sites across the U.S. (New River, AZ, Miami, FL, and Medina, OH), most materials exhibit little change in SR. The average albedo loss after three years across all three sites was 0.02 (0.01 in AZ, 0.02 in FL, and 0.02 in OH).[21]

Color Family Program Requirements

As described in CRRC-1, color family ratings may be obtained for coil-coated metal roofing products only. Products that use the same binder/resin technology and fall within a set color range may be tested and rated as a group, meaning that only one product (the representative element) must undergo three years of natural exposure and aged testing, while the remaining products in the group (additional elements) only need to undergo initial testing (testing of brand new specimens). After completing initial testing, all color family elements receive assigned SR and TE values that are pre-determined by the CRRC for the given color family group, as long as the tested values meet or exceed the assigned values. After the representative element completes aged testing, the aged SR and TE values or the initial assigned values, whichever are lower, are reported as the aged values for all elements in the color family group.[18]

By contrast, CRRC-2 contains provisions for both coil-coated metal products and architectural coatings to obtain color family ratings. The color family protocol for architectural coatings was developed by the Steering Committee based on research performed by the CRRC and Dunn-Edwards Paints. The CRRC tested the SR of 45 colors drawn down over Leneta Opacity Charts and Dunn-Edwards performed data analysis to correlate the SR values with Light Reflectance Values (LRV) and pigment information. The analysis found that, in general, for colors that do not contain carbon black, the following is true: lowest LRV + most colorant = lowest SR. The addition of carbon black can cause a drastic decrease in SR.[22] Based on the study, the Steering Committee developed typical LRV and required CIELAB color space ranges for nine (9) color family groups for architectural coating products.[14]

For coil-coated metal, there are 17 color family groups, which are defined using the same Hunter L,a,b ranges that are used in CRRC-1. However, for both architectural coatings and coil coated metal, there are no assigned radiative property values defined in the CRRC-2. Instead, the tested initial values for all color family elements are reported. When the representative element for a given color family group completes aged testing, the tested aged radiative properties of the representative element are reported for all products within the color family. The Steering Committee determined that tested values should be used instead of assigned values because different pigment technologies can have a significant impact on the SR of a given color, and removing assigned values provides more flexibility in grouping colors to avoid assigning relatively low values to products with a much higher measured SR.[22] For both architectural coatings and coil-coated metal, the representative element for a given color family group must have the lowest SR of the group (lowest TE in the event of a tie and lowest L value in the event that both SR and TE are tied).[14]

Architectural Coating Substrates

One of the primary focuses of the Steering Committee was to develop parameters for architectural coating substrates that would accurately reflect coating performance in the field and be durable for natural exposure and shipping between laboratories and test farms, while also being commercially available. Beginning in early 2020, CRRC staff and members of the Working Group evaluated the effects of substrate characteristics including color, texture and the presence or absence of primer on coating SR to identify a suitable standard substrate.

To determine the effects of substrate color on coating SR, the Working Group worked with an architectural coatings manufacturer to obtain and compare SR data for products applied over white and black substrates. The manufacturer measured the SR of six different architectural coating products, each applied to the black and white portions of Leneta 2C Opacity Charts at estimated dry film thicknesses (DFTs) of 3 mils (1 mil = 0.001 in = 25.4 µm; 3 mil = 76.2 µm) and 6 mils (152 µm). On average, the measured SR of each coating on the white substrate was

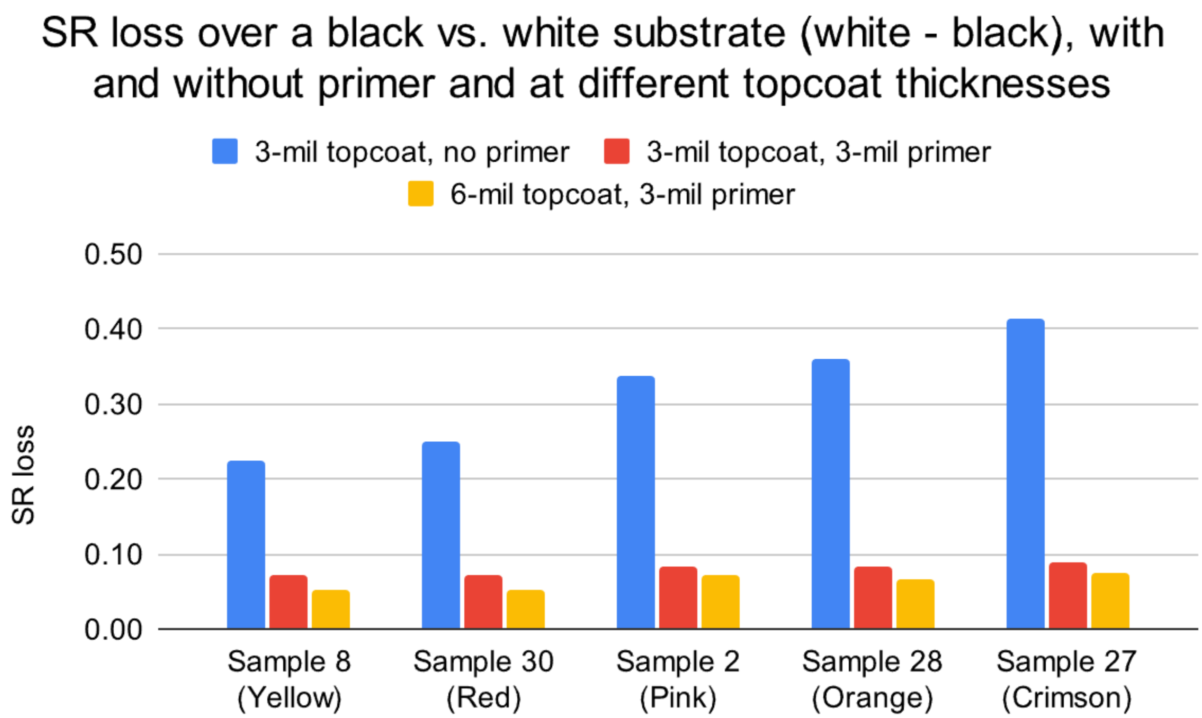
0.08 higher than the same coating on the black substrate when applied at a DFT of 3 mils. The architectural coatings that were applied at a DFT of 6 mil experienced a less pronounced difference between the white and black substrates (average 0.03).[23] Another manufacturer provided supporting information regarding the performance of a cool pigment technology over white vs. black substrates. In these examples, the SR values of dark blue, dark brown, and black pigments were 0.14, 0.06, and 0.10 higher over white substrates than black substrates, respectively.[24] Based on this information, the Working Group determined that black (i.e., low SR) substrates should be used to return the most conservative SR values for architectural coatings.

To understand the impacts of primer on topcoat SR, the Working Group went on to evaluate the differences in SR of architectural coating colors with and without primer over Leneta Opacity Charts. Testing was completed on five colors by the CRRC and nine colors by an independent testing laboratory. The five colors tested by the CRRC were selected based on the existing data for 45 different colors from the study that was performed in the development of the color family program for architectural coatings. The colors that demonstrated the greatest difference in SR when applied over the black vs. white portion of the Leneta Charts in the color family study were selected for this experiment.[22]

For each of the five colors, three specimens were prepared: one with no primer and a 3-mil topcoat; one with a 3-mil primer and a 3-mil topcoat; and one with a 3-mil primer and a 6-mil topcoat. The use of primer significantly decreased the loss of SR when the coating was applied over the black substrate compared to the white substrate (see Figure 1).

FIGURE 1. Bar chart showing SR loss of five coating colors applied to a black substrate compared to a white substrate (SR over white substrate minus SR over black substrate) using a three-mil topcoat with no primer; a 3-mil topcoat with a 3-mil primer; and a 6-mil topcoat

with a 3-mil primer. The use of primer reduces SR loss when comparing SR over a black versus white substrate; and increasing the thickness of the topcoat when a primer is used has a minimal effect on reducing the SR loss.

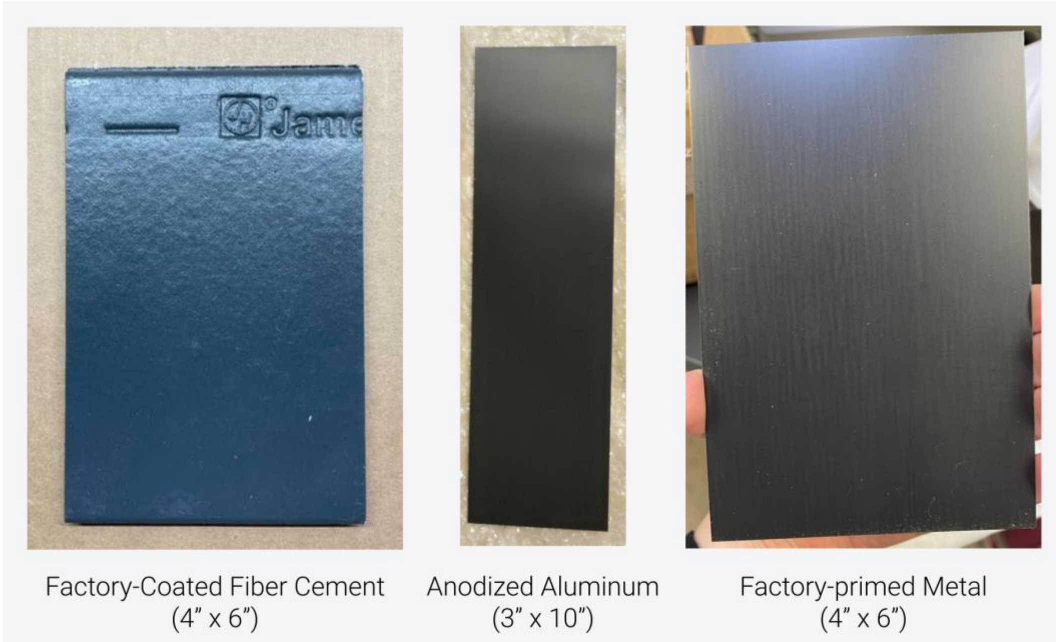


The independent laboratory testing of nine additional colors compared the SR of each color applied at 3 mil over no primer and applied over 3 mil of primer on black and white substrates. The results of this testing were consistent with the CRRC's findings and confirmed that the effect of substrate color decreases when the coating is applied over a white primer, though the magnitude of the difference depends on the specific color and pigment. The study also found that the effect of the substrate color diminished as the number of topcoats increased.[22] Based on these findings, the Working Group determined that specimens tested for Wall Product Ratings should be prepared using the primer thickness (if applicable) and topcoat thickness that are consistent with their product specifications. The study findings further confirmed that the use of a dark substrate color will provide conservative SR values without over-penalizing program participants.[22]

Related to texture, the Working Group evaluated the effects of substrate texture on coating SR in three different scenarios. First, an architectural coatings manufacturer tested the same topcoat applied over smooth and textured primers. The study found very little difference in topcoat SR due to the primer roughness or smoothness. Another architectural coating manufacturer measured three different shades of gray coating, each prepared over four different textured substrates ranging from smooth to heavy texture. The study found that, for the lightest shade, the difference in average SR between the heavy and smooth texture (smooth - heavy) was 0.07. For medium gray, it was 0.05, and for dark gray, it was 0.02. Finally, the CRRC performed testing of two colors of acrylic-based finishes and two colors of cement-based stucco finishes over various textures of stucco substrates. For the acrylic coatings, the difference in average SR between the finest and coarsest (finest - coarsest) substrates was 0.05 for white, and 0.02 for gray. For the yellow cement-based coating, the difference between the finest and coarsest texture (finest - coarsest) was 0.10, and for gray cement-based the difference between the finest and coarsest texture was 0.03.[25] The researchers concluded that the SR of architectural coatings decreases as substrate texture increases, and lighter colors see larger differences in SR due to texture. They further concluded that a smooth white substrate may overstate performance, while a textured black substrate may understate performance.[26] Based on these findings, the Steering Committee determined that requiring a substrate that is both textured and low SR is not necessary for accurate measurement of coating SR.

Based on the work performed by the Working Group in 2020 and subsequent evaluation by the Steering Committee, the CRRC Board approved including a requirement in CRRC-2 that architectural coating substrates must have an SR less than 0.20. At the time of its initial publication in 2021, the allowable substrates were limited to metal panels with SR less than 0.20 for products that must undergo three years of natural exposure (most products) and black Leneta Charts for products that do not undergo natural exposure (Color Family Additional Elements). In 2023, the Board revised CRRC-2 at the Wall Committee's recommendation to allow the use of non-metal panels for products that undergo natural exposure so long as they meet the SR requirement and are able to withstand exposure to the elements for the specified period. Individual manufacturers may choose the exact material, size, chemistry, and supplier of architectural coating substrates as long as they meet the requirements of CRRC-2.[14] Manufacturers are responsible for verifying coating adhesion to the selected substrate, and substrate SR must be reported along with the coating radiative properties. The CRRC provides a list of example substrates that can meet the program requirements, which include anodized aluminum panels; factory-coated fiber cement panels in dark (low SR) colors, factory-primed metal panels in dark colors, and metal panels coated with liquid-applied dark primer (Fig. 2).

FIGURE 2. Photographs of architectural coating substrate materials, including black factory-coated fiber cement siding, a black anodized aluminum panel, and a metal panel coated with a factory-applied black primer.



Solar Reflectance Index

Another important difference between CRRC-2 and CRRC-1 is the absence in the former of a reference to ASTM E1980, *Standard Practice for Calculating Solar Reflectance Index of Horizontal and Low-Sloped Opaque Surfaces* and accompanying requirements for calculating the SRI of exterior wall materials in CRRC-2. SRI is a calculated value that uses the measured SR and TE, along with other assumptions, to estimate the relative temperature of a surface when compared to the temperatures of black and white surfaces.[27] The SRI metric is commonly used for roofing products and is often specified in policies and programs that promote the use of cool roofs, in addition to measured SR and TE.

As its name suggests, ASTM E1980 is applicable for horizontal and low-sloped surfaces, and the calculations in the standard take into account multiple variables including solar absorptance (1 - SR), solar flux, thermal emissivity, steady-state surface temperature, sky temperature, convective coefficient, and air temperature.[27] The Wall Committee identified several additional assumptions that would need to be included to develop an SRI calculation that would be suitable for vertical walls, such as whether or not the wall is sun-facing; wall orientation (north, south, east, or west); whether there are nearby buildings, since walls are more likely than roofs to be shaded by same-height neighboring buildings; and the SR and temperature of the surrounding ground.[28] The Wall Committee's decision not to include the calculation of SRI for exterior wall products is further supported by Levinson et al., who stated that SRI is meant for a well-insulated horizontal surface and should not be used for walls.[29]

Despite the inapplicability of SRI for exterior wall products, some policies and programs that promote the use of cool exterior walls use this metric instead of measured SR and TE. For instance, California's Green Building Standards Code (Title 24, Part 11), commonly known as CALGreen, contains a voluntary requirement that can be adopted by local jurisdictions for the installation of cool exterior walls. The code calls for a minimum aged SRI of 25.[30] Codes and standards developers have been working to address misuse of SRI for exterior wall products. For example, ASHRAE Standard 90.1 includes prescriptive requirements for exterior wall SR in Climate Zone 0 and offers a compliance credit for installing cool exterior walls in any climate zone.[31] Earlier versions of the standard used SRI as the metric, but the 2022 version, which was published in January 2023, was revised to replace SRI with the equivalent SR and TE values.[31] Relatedly, the 2024 version of the International Green Construction Code (IgCC) includes requirements for above-grade walls that align with the provisions in ASHRAE 90.1-2022, replacing the previous version of IgCC which used SRI as a metric.[32] The CRRC has submitted several inquiries and public comments to decision makers for other codes, programs, and standards that reference SRI for exterior walls encouraging them to instead use the appropriate SR and TE metrics.

Laboratory Soiling and Weathering

A final notable difference between CRRC-2 and CRRC-1 is the absence in the former of a laboratory soiling and weathering procedure for exterior wall products. In CRRC-1, such a procedure is offered to provide interim aged values for products that are currently undergoing natural exposure. Radiative property values obtained in accordance with this procedure may be used for compliance with some cool roof code requirements, most notably in the 2022 California Building Energy Efficiency Standards (Title 24, Part 6).[33] The laboratory soiling and weathering procedures in CRRC-1 reference ASTM D7897-18(2023), *Standard Practice for Laboratory Soiling and Weathering of Roofing Materials to Simulate Effects of Natural Exposure on Solar Reflectance and Thermal Emittance.*[34] As noted in the title, this standard contains procedures that were developed specifically for roofing products and would not be accurate for vertical surfaces without modification. For example, the quantity and pattern of soiling matter applied to the specimens must be adjusted to accurately simulate soiling of a vertical surface, as would intensity of exposure to ultraviolet light. A considerable dataset from specimens naturally weathered and soiled at 90°S will be required before these adjustments can be made.

ROUND ROBIN VALIDATION OF CRRC-2 REQUIREMENTS

As described in the previous section, the testing and weathering protocols in CRRC-2 were developed by subject matter experts based on extensive technical evaluation. After CRRC-2 was published in September 2021, the CRRC validated the testing requirements by conducting a round robin study. The objective of the study was to verify that results obtained in accordance with CRRC-2 requirements are consistent when testing is performed by multiple laboratories using their own testing equipment. The round robin was also an opportunity to verify that the tests were conducted correctly, including proper calibration and operation of equipment. The study included six new exterior wall product samples—three architectural coating products and three factory-coated metal products—that each contained three individual test specimens. Since the objective of the study was to verify consistent test results, the round robin only included new product samples. The specimens were circulated to seven different laboratories that had been trained by the CRRC on CRRC-2 requirements. Five of the participants were accredited independent testing laboratories, which tested all six samples, and two of the participants were manufacturer testing laboratories, which tested the product type that they manufacture and are equipped to test (one architectural coating laboratory and one factory-coated metal laboratory), resulting in a total of six laboratories testing each sample.

Each of the participating laboratories performed SR, TE, and colorimetry testing on the specimens. The laboratories that tested the architectural coating specimens also performed thickness testing. Round-robin testing was completed by all participants between January 2022 and July 2022. After testing was completed, the CRRC analyzed the results and presented the findings to the Wall Committee in August 2022. An eighth laboratory performed testing on the round-robin specimens in July 2023 as part of its training to become an approved laboratory to perform testing for the CRRC Wall Product Rating Program. The results from this laboratory were not included in the analysis reported to the Wall Committee in August 2022 and presented here, but they were consistent with the seven original study participants. The study findings are detailed in the Results and Discussion section of this paper.

Results and Discussion

RESULTS OF ROUND ROBIN STUDY

Here we present the results of the round robin study for SR and TE, the properties that are published on the CRRC Rated Wall Products Directory. The colorimetry and thickness results are not included in this paper, as these properties do not directly relate to our thesis, but the results of this testing supported CRRC-2 procedures and, in the case of thickness testing, identified areas for improvement that have since been addressed in CRRC-2.

Sample Set

The following samples were tested as part of this study, with the same physical samples sent from one laboratory to the next (Table 1 and Fig. 3).

TABLE 1. List of sample number, material, color, number of specimens, and specimen size for each of the six samples tested in the round robin study.

Sample Number	Material	Color	Number of Specimens	Specimen Size
1	Factory-coated metal	White	3	10 cm by 15 cm (4" by 6")
2		Tan	3	
3		Brown	3	
4	Architectural coating applied to anodized aluminum substrate	White	3	8 cm by 25 cm (3” by 10”)
5		Gray	3	
6		Black	3	

FIGURE 3. Photographs of the samples tested for the round-robin study, including (a) samples 1-3 (factory-coated metal) and (b) samples 4-6 (architectural coating).

Fig. 3a(a)

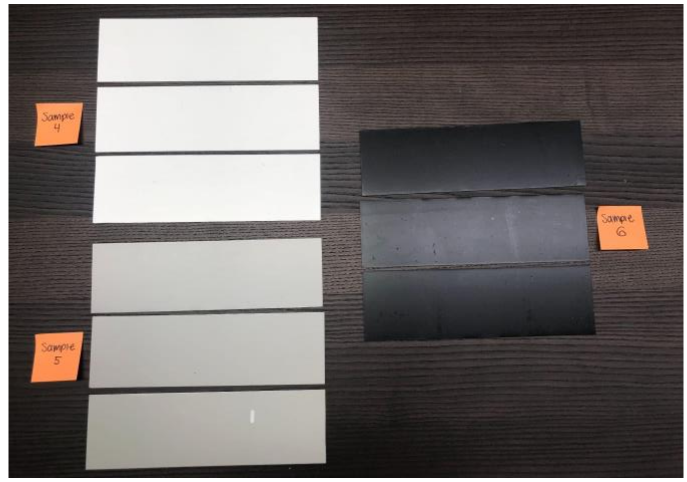


Fig. 3b(b)

Solar Reflectance Testing

Each laboratory measured the SR of each sample in accordance with Section 3.3 of CRRC-2, which contains the SR testing requirements for exterior wall products. Six laboratories used the Devices & Services Solar Spectrum Reflectometer (SSR) v6 with GV-9 EPROM following ASTM C1549 using global SR at air-mass 1.5 for a sun-facing vertical surface (specified as output 1.590 on the SSR). One laboratory used the Surface Optics Corporation 410-Solar Reflectometer following the 410-Solar Test Method using global SR at air-mass 1.5 for a sun-facing vertical surface (specified as output G197GT90 on the 410-Solar). This laboratory only performed measurements on Samples 4-6 (architectural coatings).

The results of SR testing are displayed in Figure 4. When comparing SR values, the CRRC considers a difference of greater than 0.05 to be significant. The results from each laboratory for samples 1, 2, 3, 5, and 6 were consistent with each other and none of the reported measurements approached a significant difference from average (Fig. 5). For sample 4, five of the laboratories reported consistent results, while one laboratory (Lab D) reported a result that was slightly higher than average, though still less than 0.05 from average. The CRRC investigated this datapoint. The higher result was obtained by the laboratory that used the 410-Solar Reflectometer instead of the SSR. This specimen also experienced some soiling and scuffing over the course of the study (Fig. 6) and, with the exception of Lab D and Lab F, the reported results trended downward over time. This also caused Sample 4's SR standard deviation to be much higher than the rest of the samples (Fig. 9). Due to the presence of scuffing and soiling on the specimens, the CRRC determined that variation in where the measurement head was placed on the specimens likely contributed to the unusual datapoint. The fact that a different type of instrument was used may also have contributed, though the results reported by Lab D for Samples 5 and 6 were consistent with the other laboratories' results.

FIGURE 4: Bar chart showing the measured SR reported by each participating laboratory for each sample.

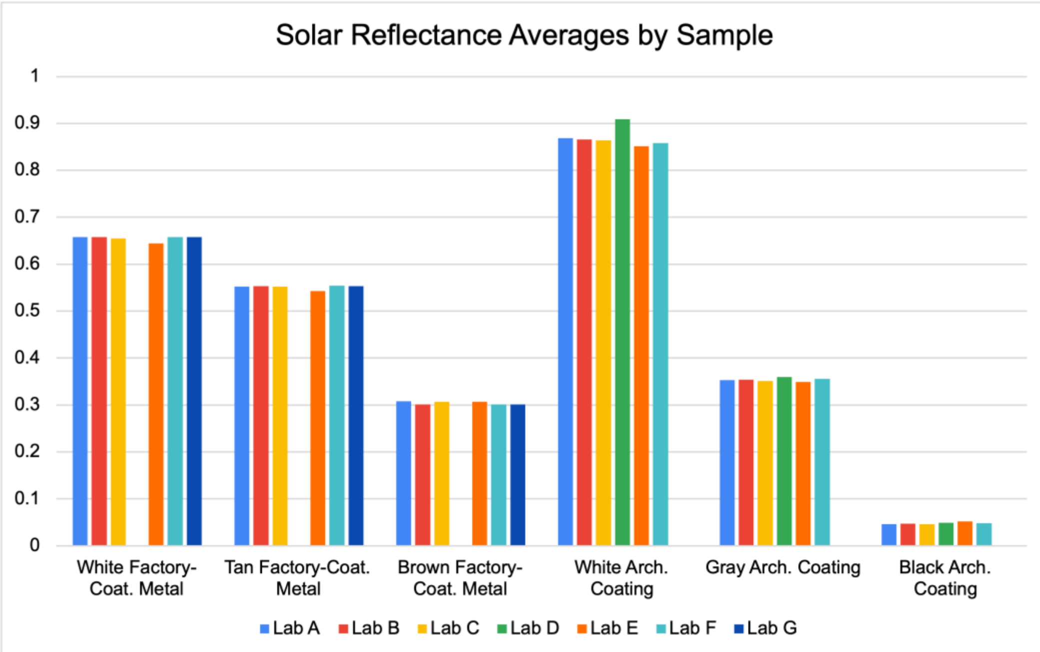


Figure 5. Bar chart showing the difference from average (measured value - overall average) of each laboratory's measured SR value for each sample.

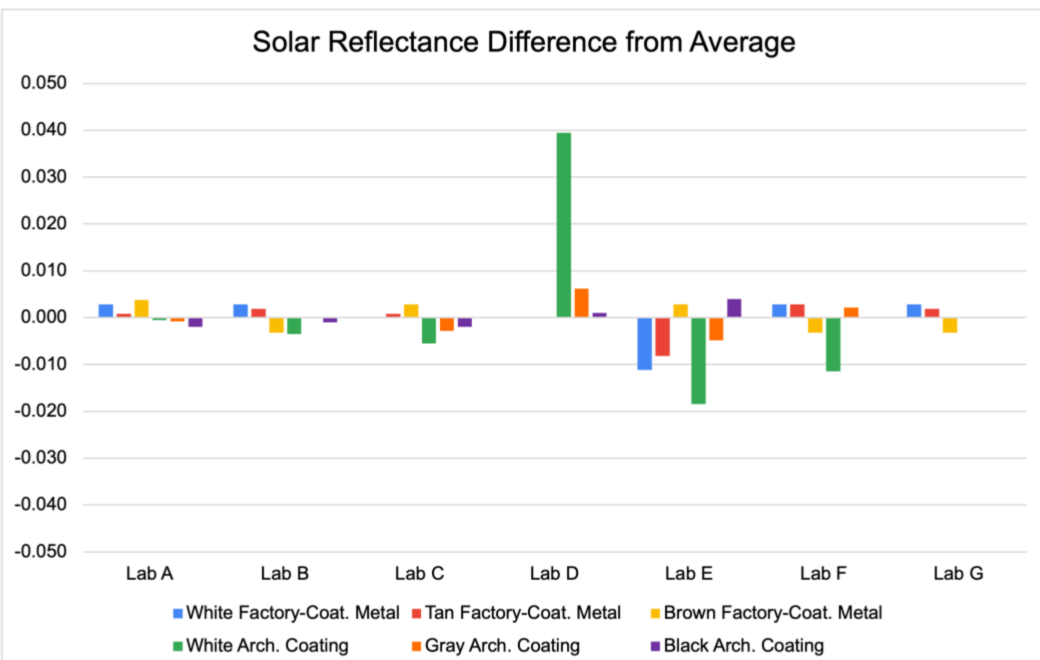
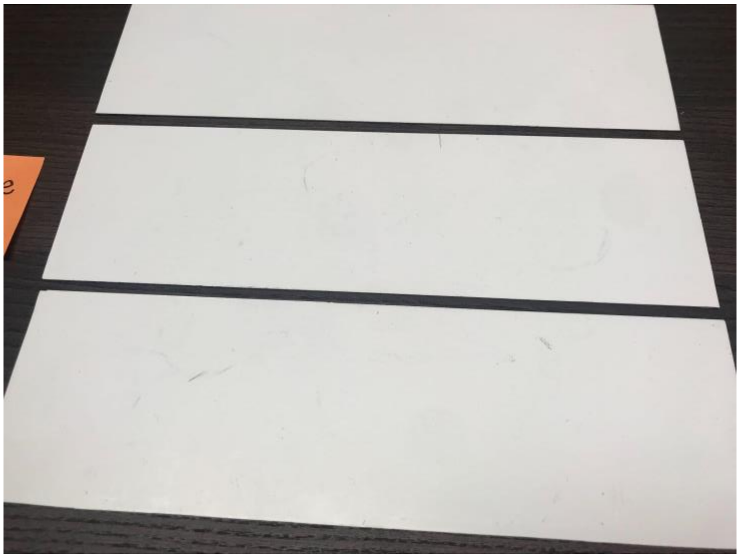


Figure 6. Photograph of three specimens that comprise sample 4 (white architectural coating), which show dark markings on the surfaces of the specimens.



Thermal Emittance Testing

Each laboratory measured the TE of each sample in accordance with ASTM C1371, *Standard Test Method for Determination of Emittance of Materials Near Room Temperature Using Portable Emissometers* (ASTM C1371), as permitted by Section 3.4 of CRRC-2 at the time the study began (January 2022). At the time, ASTM C1371 was an allowable TE test method for factory-coated metal and architectural coating products, along with an industry-vetted variant of ASTM C1371 known as the Slide Method and published in *Devices and Services Technical Note 11-2*.[35] When using the Slide Method, the instrument operator moves the emissometer head without lifting it from the specimen surface every 15 seconds in order to minimize infrared radiative heating of specimens with low thermal conductance. A special port adapter for the emissometer, the Devices & Services AE-ADP, is required for using this method. In June 2022, the CRRC revised CRRC-2 to require the Slide Method for testing the TE of architectural coating products due to the potential for some architectural coatings (e.g., those applied thickly) to have a thermal conductance less than 1,100 $W/m^2 \cdot K$. ASTM C1371 is only suitable for specimens with a thermal conductance greater than 1,100 W/m^2·K.[37] ASTM C1371 is still permitted for use when measuring the TE of factory-coated metal, which has very high thermal conductance.

The results of the round robin TE testing are displayed in Figure 7. When comparing TE values, the CRRC considers a difference of greater than 0.05 to be significant for materials with a TE less than or equal to 0.30 and a difference of greater than 0.10 to be significant for materials with a TE greater than 0.30. Despite the use of ASTM C1371 for all samples, the results from each laboratory for all samples were consistent with each other and none of the reported measurements approached a significant difference from average (Fig. 8).

FIGURE 7. Bar chart showing the measured TE reported by each participating laboratory for each sample.

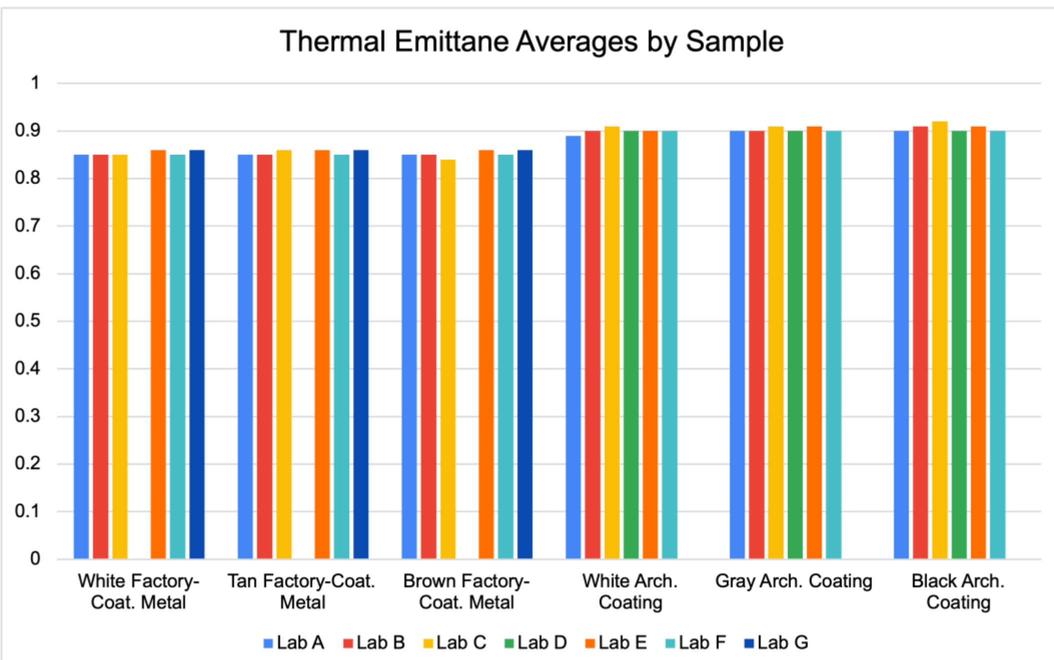


FIGURE 8. Bar chart showing the difference from average (measured value - overall average) of each laboratory's measured TE value for each sample.

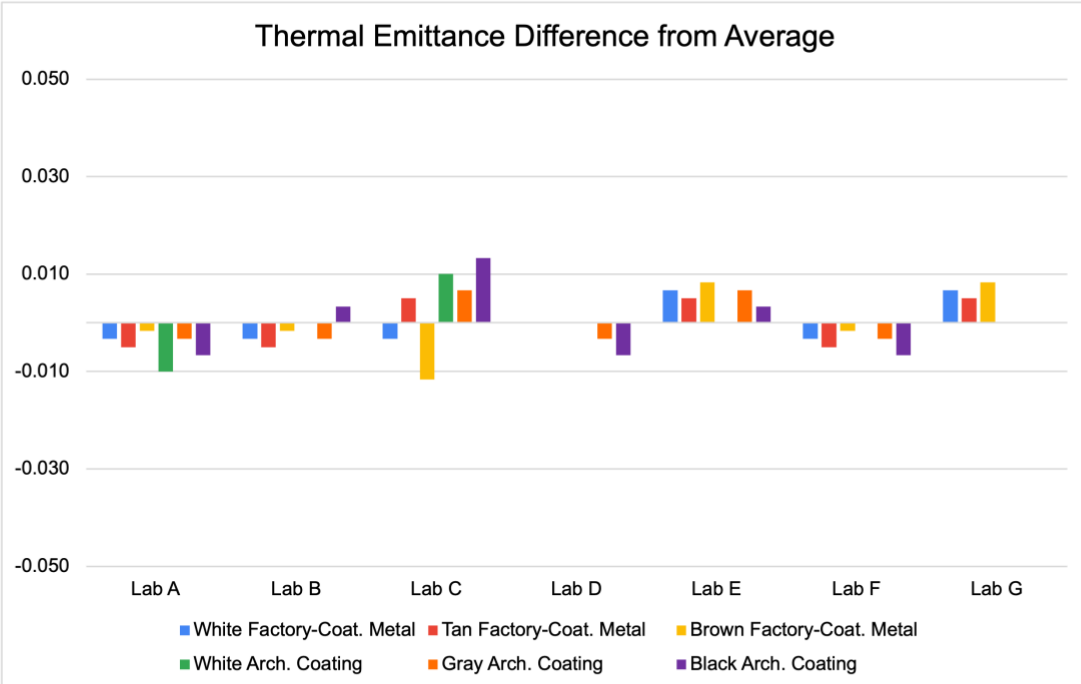
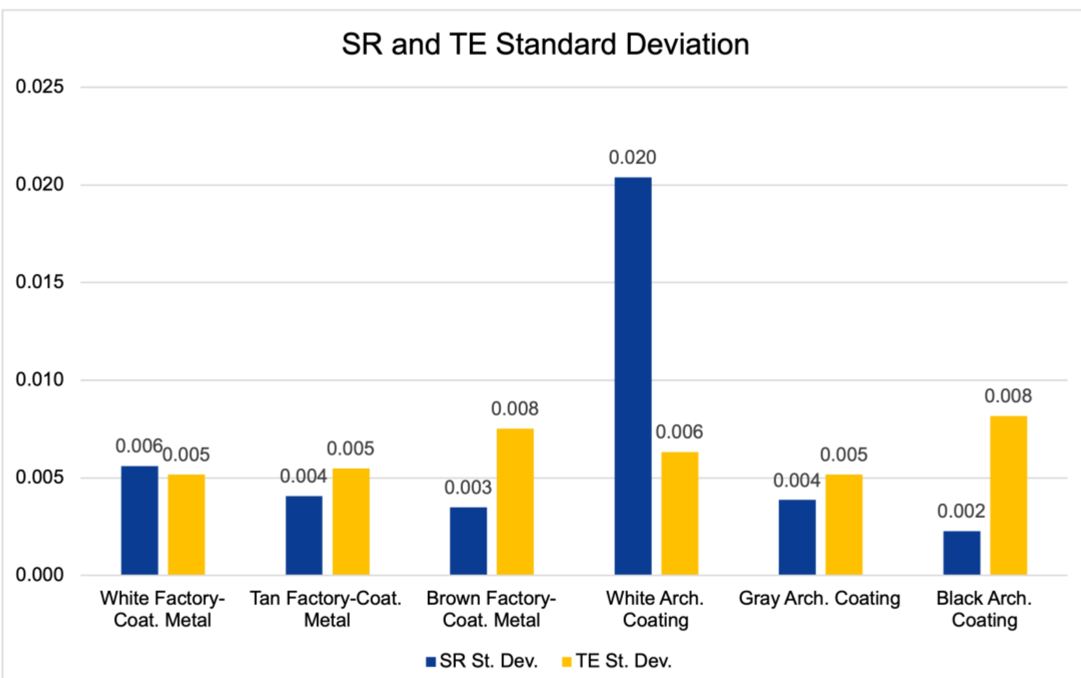


FIGURE 9. Standard deviation of reported SR and TE values for each sample.



DISCUSSION

The results of the 2022 round robin study indicate that SR and TE measurements taken in accordance with CRRC-2 are consistent when performed by multiple laboratories using their own equipment. The work of the CRRC Wall Committee and Steering Committee and the results of the round robin study described in this paper provide a strong technical foundation for the requirements and procedures found in CRRC-2 and position it as the preeminent technical guideline for evaluating the radiative properties of exterior wall materials. However, some codes, standards, and programs developers are hesitant to reference proprietary publications for compliance, preferring to reference non-proprietary standards such as ASTM Standards. This is why it is important for ASTM C1549 to include adequate provisions for measuring the SR of vertical surfaces.

Consider ASHRAE Standard 90.1-2022, *Energy Standard for Sites and Buildings Except Low-Rise Residential Buildings* (ASHRAE 90.1), which establishes minimum requirements for energy efficient building design and becomes mandatory upon adoption by state or local jurisdictions (amendments permitted). ASHRAE 90.1 contains provisions for the use of cool exterior walls and references ASTM C1549 to demonstrate compliance. It also specifies that output AM1.5GV must be used.[31] The LEED v4.1 Sustainable Sites pilot credit for *Heat Island Mitigation with Cool Walls* (SSpc154) contains similar language.[37] Expanding the procedures for measuring vertical surfaces in ASTM C1549 would remove the burden from standards developers to include such caveats. It would also prevent the inclusion of incomplete or incorrect compliance paths, which currently exist in some standards. For example, standard GS-11-2021, *Green Seal Standard for Paints Coatings, Stains, and Sealers* establishes requirements related to performance and environmental and health impacts of architectural coatings. GS-11-2021 specifies minimum SR and TE values for elastomeric wall coatings and references ASTM C1549 as one test method that may be used to verify compliance. However, the standard does not specify the use of the air mass 1.5 GV spectrum.[38]

A similar issue confronts the 410-Solar Test Method, which is currently published within CRRC-2. While some policies and programs, including ASHRAE 90.1, include the test method as an approved measurement option, others do not. The CRRC has actively supported the development of a new, or inclusion in an existing, standard test method for the 410-Solar Test Method. However, there are some outstanding barriers to this process which the developers of the test method should work to address.

An additional area for improvement around the adoption of cool exterior walls is the continued removal of SRI from codes, programs, and standards that promote the use of cool exterior walls and replacement with the more appropriate metrics SR and TE. While considerable improvements have been made in this area, this inappropriate metric is still used in some policies and programs and by some manufacturers offering solar-reflective exterior wall products.

Conclusion

Cool exterior walls are a demonstrated strategy for adapting to rising temperatures, improving building energy efficiency, and mitigating the urban heat island. This is reflected in the adoption of cool exterior walls in model building energy codes and standards and voluntary certification programs for green buildings and materials. From 2019 to 2021, subject matter experts in radiative properties and exterior wall materials completed technical studies and evaluation to develop CRRC-2, a comprehensive, proprietary document containing technical requirements for measuring the initial and aged SR and TE of exterior wall materials. In 2022, the CRRC validated these procedures through a round-robin study, which found close agreement among test results provided across seven laboratories for six different samples. The CRRC continues to maintain and periodically update CRRC-2 to ensure that the requirements remain current with advancements in the field of radiative property testing.

Despite its technical rigor, the proprietary nature of CRRC-2 creates challenges for some codes, standard, and program developers to reference it for compliance with policies that promote the use of cool exterior walls, with many preferring to reference non-proprietary standards like ASTM C1549, which does not contain a procedure specific to measuring the SR of vertical surfaces. Further, some policies incorrectly specify a minimum SRI value for exterior walls, which is an inapplicable metric for vertical surfaces. To ensure that the reported radiative properties of exterior wall materials that are used for compliance are accurate, we recommend the following:

- ASTM C1549, which purports to be applicable for vertical wall surfaces, should be updated to include procedures for obtaining a material's global SR at air-mass 1.5 for sun-facing, 90° (vertical) tilted surfaces
- 410-Solar Test Method should be revised to address the concerns of consensus-based standard developers and be adopted as a voluntary consensus standard
- Codes, programs, and standards that specify a minimum SRI for exterior wall materials should replace this with the equivalent minimum SR and TE values
- Codes, programs, and standards that promote the use of cool exterior walls should add references to the CRRC Rated Wall Products Directory to help users identify compliant products that have been tested in accordance with the most rigorous available procedures

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