Available online at www.sciencedirect.com
ScienceDirect
Solar Energy 100 (2014) 159–171
SOLAR ENERGY
www.elsevier.com/locate/solener

Reflectometer measurement of roofing aggregate albedo

Ronnen Levinson [a,*], Sharon Chen [a], Paul Berdahl [a], Pablo Rosado [a], Louis A. Medina [b]

[a] Heat Island Group, Lawrence Berkeley National Laboratory, Berkeley, CA, USA
[b] A-1 Grit Company, Riverside, CA, USA

Received 1 July 2013; received in revised form 7 November 2013; accepted 9 November 2013
Available online 27 December 2013

Communicated by: Associate Editor Matheos Santamouris

Abstract

A solar reflectometer is commonly used to determine the albedo of roofing products. This study validates against pyranometer measurements of albedo three new methods for solar reflectometer measurement of the albedo of the irregular surface presented by a bed of roofing aggregate. Method A determines the albedo of an aggregate bed by averaging many reflectometer readings of a small sample of aggregate. Method B relates the albedo of the aggregate bed to reflectometer measurements of the albedo of an opaquely thick pile of finely crushed aggregate. Method C relates the albedo of the aggregate bed to reflectometer measurements of the albedo of a faux roofing shingle surfaced with finely crushed aggregate. When applied to the 17 specimens tested in this study, Method A worked well for all but the largest aggregates; Methods B and C worked well for all aggregates. The absolute mean error of each method was less than 0.01, and the RMS error of each method did not exceed 0.021.

As an ancillary note, we find that beds of mineral particles have albedos that decrease with increasing particle size, up to sizes at which the particles become opaque to sunlight.

Keywords: Albedo; Roofing aggregate; Solar reflectometer; Pyranometer

1. Introduction

Modern building energy efficiency standards prescribe or credit the use of solar-reflective "cool" roofs in warm climates to save energy (Akbari and Levinson, 2008). Decades of progress in cool roof science, technology and policy have been summarized in reviews of cool roof materials (Santamouris et al., 2011), energy savings (Akbari and Konopacki, 2005; Levinson et al., 2005), urban heat island mitigation (Santamouris, 2012; Navigant, 2009), global cooling (Akbari et al., 2012), standards (Akbari and Levinson, 2008), weathering (Berdahl et al., 2008), and albedo measurement (Levinson et al., 2010a,b; Akbari et al., 2008).

Roofing product albedo is often determined with a solar reflectometer. This laboratory instrument can measure the albedo of a flat surface following ASTM C1549-09 (Standard Test Method for Determination of Solar Reflectance Near Ambient Temperature Using a Portable Solar Reflectometer) (ASTM, 2009). However, if the surface is irregular, with a roughness scale comparable to the diameter of the reflectometer's sample port, displacement of the surface from the port can reduce sample illumination. This can lead the instrument to underestimate the albedo of the surface. For example, Moore (2008) found that displacing a diffuse white tile 7 mm from the 2.5 cm diameter port of a reflectometer reduced its measured albedo by 25% (to 0.63 from 0.85).

One popular roofing material is aggregate, or rock, applied to a roof to provide ballast, thermal mass, and protection from the sun. A layer of roofing aggregate (particle size about 1–4 cm) tends to form an irregular surface that

* Corresponding author.
E-mail address: RML27@cornell.edu (R. Levinson).

0038-092X/$ - see front matter © 2013 Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.solener.2013.11.006

can be displaced from a reflectometer port. Two prior studies in which a reflectometer was used to measure the albedo of aggregate either masked the port to make its opening smaller than the face of the rock (Levinson and Akbari, 2002), or finely crushed the rock to make its particle size much smaller than the diameter of the port (Marceau and VanGeem, 2007). In neither case was an attempt made to relate the measured albedo to that of a layer of the original aggregate. A review of published literature and a discussion with the manufacturer of a widely used solar reflectometer (Moore, 2013) have turned up no prior studies of the accuracy with which a reflectometer can be used to measure the albedo of a bed of roofing aggregate, or the albedo of a comparable surface.

As is well known, the reflectance of a rough surface is less than that of a smooth, flat surface of the same composition. The underlying reason is that a photon reflected by a smooth, flat surface will escape, whereas a photon reflected by a rough surface may return. Aida (1982) used a pyranometer to compare the albedo of an array of concrete cubes to that of a flat horizontal surface of the same composition. He found that the midday albedo of the flat surface was 0.43 in winter and 0.38 in summer, the difference being attributable to the higher solar altitude in summer. The midday albedo of the cube array was about 0.28, both summer and winter, exhibiting loss of albedo due to roughness. More recently, Fortuniak (2008) investigated analytically the reflectance of an urban canyon, assuming that the angular distribution of reflectance was perfectly diffuse (Lambertian). For a linear canyon of surface albedo 0.40, with height equal to width, albedo ranged from about 0.18 to 0.22, varying with solar altitude and azimuth. Here again, the surface roughness caused a substantial reduction in albedo.

Matthias et al. (2000) investigated how roughness affects the albedo of soil. They found that a smooth soil layer ("seedbed") had an albedo that increased slightly at low solar altitude. Averaging over sun angles, they found that increases in surface roughness always yielded lower albedos. For the most reflective soil studied, rough plowing reduced albedo to 0.21 (plowed) from 0.28 (smooth).

In the past, pyranometer measurements have been the only technique for determining the albedo of aggregate-covered surfaces. One pioneering study was that of Reagan and Acklam (1979), who used a silicon pyranometer to determine the solar reflectances of roofs with various types of aggregate. The use of a silicon detector does limit accuracy since it misses the roughly 25% of solar energy incident at wavelengths longer than 1.1 μm. Another concern is that the minerals used for aggregate have natural variations in composition. Thus, sample-specific measurements are required if confidence is needed in estimation of albedo.

Reagan and Acklam asserted that a rough estimate of solar albedo can be made by evaluating visual brightness. For many materials this is a reasonable procedure, although for spectrally selective materials large errors are possible. Despite the obstacles faced by Reagan and Acklam, their 70+ tabulated albedo values for various roofing types are in good general agreement—where comparison is possible—with more modern spectrometer-based measurements of non-aggregate roofing made by Parker et al. (2000) and by Berdahl and Bretz (1997).

Unlike overall measurements of aggregate albedo, spectral measurements of the reflectance of minerals are fairly plentiful (Touloukian and DeWitt, 1972; Clark et al., 2007). These measurements, taken together with an evaluation of visual brightness, offer a rough means for estimating the albedo of an aggregate-covered surface.

A solar reflectometer offers several potential advantages over a pyranometer for measurement of the albedo of a layer of roofing aggregate. First, the area of the sample tested in reflectometer method C1549—typically 25–1000 cm^2, depending on surface uniformity and the need for random sampling—can be several orders of magnitude smaller than the minimum 4 m diameter target required by pyranometer method ASTM E1918-06 (Standard Test Method for Measuring Solar Reflectance of Horizontal and Low-Sloped Surfaces in the Field) (ASTM, 2006). The large diameter is needed to properly fill the pyranometer's field of view. Second, a reflectometer provides its own light source, permitting use indoors or outdoors, without regard to solar position or sky condition. Third, this internal light source is regulated and consistent in spectrum and geometry, avoiding the variabilities in spectral power distribution and incidence angle associated with use of a natural light source (Levinson et al., 2010a,b).

This study explores whether it is possible to (A) accurately measure the albedo of an aggregate bed by averaging many solar reflectometer measurements; (B) relate the albedo of an aggregate bed to reflectometer measurements of the albedo of an opaquely thick pile of finely crushed aggregate; and/or (C) prepare a durable coupon of finely crushed aggregate bound to a substrate, whose albedo can be related to that of the aggregate bed. These reflectometer methods would serve generally as techniques for laboratory measurement of roofing aggregate albedo, and specifically to evaluate albedo within the context of a roofing product rating program (Appendix A). Such ratings are referenced in building energy standards, green building codes, and energy efficiency incentive programs used around the world.

2. Experiment

2.1. Terminology: bed, pile, faux shingle, and opacity

In this manuscript, an aggregate "bed" is a layer of aggregate applied at a rate (mass/area) consistent with typical roofing practices and large enough for E1918 measurement of albedo (at least 4 m in diameter, or 4 m on a side). A "pile" is a layer of rock in a shallow container, such as a petri dish or cardboard box. A granule is finely crushed rock, about 1 mm in diameter. A "faux shingle" is a monolayer of granules adhered to a metal substrate (Fig. 1).

"Opaque" means opaque to sunlight. A pile is considered opaquely thick when its albedo is independent of that