

Albedo as an engineering property of concrete pavements

Sushobhan Sen¹ and Jeffery Roesler², PhD, PE

Abstract

Albedo or solar reflectance is a thermal property of concrete pavements that is used in pavement design as well as life cycle assessment. In either application, it has a major impact on distress predictions and the urban heat island quantification, respectively. Hence, understanding the factors that affect the albedo of concrete pavement is important. The spectral reflectance of three types of concrete, one made of white cement and no supplementary materials, one with white cement and 15% fly ash, and one with gray cement and 15% fly ash, were determined using a spectrophotometer. Using the SMARTS 2.95 model, the solar spectrum adjusted for pavements in two locations, San Antonio (Texas) and Singapore, were determined at an altitude of 200 m and 3,000 m for representative days and hours in the year 2000. The albedo was determined as a solar spectrum-weighted average of the solar reflectance and compared to that determined with the current ASTM G173 standard. The most important variable affecting concrete albedo was found to be the mix design, followed by the time and geographical location of measurement. While the maximum error as compared to the current standard was small, the error with respect to the value used in practice was very large, indicating the need to measure albedo to avoid overly conservative albedo inputs into pavement design and LCA.

Introduction

Pavement design and assessment have evolved over time from engineering experience to empirical and now mechanistic-empirical methods. One of the most widely used methods is the statistical models in the AASHTO 1993 Pavement Design Guide (AASHTO 1993). Increasing axle loads of vehicles, emerging or recycled construction materials, lightweight aggregates, fiber reinforcement, etc., make it very difficult to use empirical pavement design methods with reasonable reliability. This led to the development of mechanistic-empirical methods, i.e., the Mechanistic-Empirical Pavement Design Guide (MEPDG) (NCHRP Project 1-37A 2004), now renamed AASHTO Pavement ME. While this should, in theory, be the preferred method of pavement design, NCHRP Synthesis 457 (Pierce and McGovern 2014) showed that as of 2014, only 13 state agencies in the US and Canada had adopted the MEPDG and fewer still used other ME design procedures, while 39 used the AASHTO 1993 Design Guide and some used other empirical methods, clearly indicating that a decade since the introduction of the MEPDG, it does not yet enjoy widespread use. A principal cause of this lack of implementation has been

¹ Student Member, Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N Matthews Ave., Urbana, IL - 61801 -2352, USA, Phone: +1-(502)-641-2388, E-mail: sen6@illinois.edu

² Vice-President, Professor, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, 205 N Matthews Ave., Urbana, IL - 61801 -2352, USA, Phone: +1- (217)-265-0218, E-mail: jroesler@illinois.edu

difficulty in obtaining data related to material properties and local calibration. Almost all the agencies that have adopted the MEPDG rely on the default values for most properties with many reporting that they are in the process of local calibration.

Concurrent to the adoption of ME design methods has been the focus on pavement sustainability through a Life Cycle Assessment (LCA) framework (Van Dam, et al. 2015, Santero, Masanet and Horvath 2011). The goal of pavement sustainability is to minimize the environmental impact of pavements, for which extensive collection of not just material properties but also energy used in the various processes, e.g., material extraction, transportation, construction, and use phase, has to be undertaken. Bueno, Vassallo & Cheung (2015) discussed several methods to assess pavement sustainability, with a common requirement among them being the availability of data regarding material properties and processes.

Taking the emerging trends of ME design and pavement LCA together, it is apparent that much more pavement input data needs to be collected, with a focus on the most important factors that affect both. One of these is the albedo or average solar reflectance of the surface of the pavement. In ME design, this is expressed as the surface shortwave absorptivity, which is simply one minus the albedo. Sensitivity analyses of the MEPDG (Schwartz, et al. 2011, Hall and Beam 2005) showed that the development of distresses in JPCP was extremely sensitive to the surface shortwave absorptivity, while LCA studies (Sen and Roesler 2016, Gui, et al. 2007) have shown that albedo plays a very significant role in creating a sharp difference between urban and adjacent rural areas, a phenomenon known as the Urban Heat Island (UHI) (Kleerekoper, van Esch and Salcedo 2012). High-albedo ‘cool pavements’ have been studied to mitigate UHI (Santamouris, Synnefa and Karlessi 2011), although some concerns have been raised over their effects on adjoining buildings and local climatic patterns (Yang, Wang and Kaloush 2015).

Despite its importance to ME design and LCA, albedo is not regularly measured by agencies or pavement engineers. The MEPDG recommends a default value of 0.85 for surface absorptivity (which corresponds to an albedo of 0.15) for concrete pavements, and this is what most agencies use. Albedo is not an intrinsic material property but an engineering property that is affected by multiple factors such as time (in terms of hour, month, age, etc.), mix design, cloud cover, etc. (Li, Harvey and Kendall 2013, Levinson, Akbari and Berdahl 2010a, Levinson and Akbari 2002). Because pavement distresses and UHI are sensitive to albedo, it is important to understand how some of these factors affect albedo. The objective of this study is to determine the effects of mix design, geographical location, and time on the concrete’s albedo. A new method that overcomes some of the shortcomings of the existing standard method outlined in ASTM E903 (2012) is also proposed.

Methodology

Test matrix. Albedo was previously defined as the average solar reflectance. Thus, it is the ratio of the amount of energy reflected by a surface to the amount incident at a given wavelength, averaged over the solar spectrum at the location of interest. The solar spectrum varies with time, geography, and other factors, while the reflectance depends on the material under observation. Hence, the three variables chosen to model a concrete pavement in the city for this study were geography, time, and concrete mix design.

Geography was further divided into two factors: latitude and elevation. The solar spectrum at any location depends on the length of the atmosphere that the incoming solar energy has to traverse, which is described by the atmospheric Air Mass (AM) of the location and can be calculated using Equation 1, where Z is the latitude, for most regions on the earth except near the poles. At the equator at sea level, the AM is 1 and increases with latitude. Moreover, elevation also affects the length traveled by solar energy, although this is not reflected in the AM.

$$AM = \frac{1}{\cos Z} \quad (1)$$

Two locations with varying latitudes were adopted for this study: Singapore (Latitude: 1.28°N, AM: 1.00) and San Antonio, Texas (Latitude: 29.42°, AM: 1.15). While the former is city-state very close to the equator, the latter is located in the mid-latitude region. Both are large cities with a dense urban road network. For each city, the albedo was evaluated at two hypothetical elevations: 200 and 3,000 m above mean sea level. This does not imply that such elevations are actually found in these cities, but is only to evaluate the effect of elevation, which could then be extended to cities that do have such elevations.

The variation of concrete's albedo with time was evaluated at two levels: over a year and over a day. For this analysis, the year 2000 was chosen and the fifteenth day of each month was assumed to represent the entire month. Albedo was mathematically evaluated for every hour between sunrise and sunset for the fifteenth day of each month. Thus, a total of 12 days over the year were considered, with the hours of sunshine varying with the month in question. Finally, three concrete mixture designs known to the authors were used to calculate albedo, as summarized in Table 1. These mixes vary in terms of the type of cement and supplementary cementitious materials. As shown in a previous study (Levinson and Akbari 2002), coarse aggregates do not have an impact on albedo except in the case of surface abrasion and therefore, mortar albedo is approximately equal to the albedo of concrete of the same mix.

Table 1. Mix Designs

Case	Mix Design Details	Reference
White	Concrete made of white cement (with a small percentage of titanium dioxide nanoparticles), sand and coarse aggregates	(Sen, Roesler and King 2016)
White + 15 FA	Mortar made of white cement (with a small percentage of titanium dioxide nanoparticles), sand, and 15% fly ash	(King 2015)
Gray + 15 FA	Mortar made of Type I (gray) cement, sand, and 15% fly ash	

Material Spectral Reflectance. As previously discussed, one of the two factors that goes into evaluating albedo is measuring the spectral reflectance of each of the concrete/mortar mixes. This can be done using a Cary 5000 UV-Vis-NIR spectrophotometer as described in ASTM E903. The instrument is capable of measuring spectral reflectance from 280 to 2,600 nm, which covers approximately 99% of the irradiance of the solar spectrum.

Solar Spectra. For each location and time in this study, the solar spectrum has to be calculated, which is the second factor that goes into the albedo calculation. ASTM E903 recommends using the AM 1.5G standard solar spectrum from ASTM G173 (2003). However, as discussed in (Levinson, Akbari and Berdahl 2010b), this spectrum is not representative for pavements, but actually represents the spectrum for tilted solar panels in open fields in the northern states of the contiguous US. Furthermore, it does not represent the solar spectrum at all times of the day. Fortunately, the spectrum is determined using the SMARTS (A Simple Model of the Atmospheric Radiative Transfer of Sunshine) Model version 2.95, which was developed and validated by Gueymard (1995, 2001). In this study, the same model was used, but its parameters were changed to match those for a pavement in the year 2000. These parameters are presented in Table 2 and compared to the values used in ASTM G173, with a detailed explanation of the most important ones in the last column. The model is run with these parameters for each hour of the analysis to determine the corresponding solar radiation incident on a pavement.

Table 2. Major Input Parameters for SMARTS v 2.95 Model

Card	Input		Comment
	ASTM G173	This study	
7	370	400	CO ₂ mixing volume ratio (ppm). The value of 370 ppm was an average based on the 1978 value, and is now 400 ppm (NOAA 2015)
8	S&F_RURAL	S&F_URBAN	Aerosol profile (Rural or Urban)
10	38	18	Far field spectral albedo (38 = light sandy soil, 18 = concrete slab). Takes into account multiple reflections
10b	1	0	Tilt calculation: 1 = yes (solar panels), 0 = no (pavements)
13	1	0	Circumsolar calculation mode (1 = yes, 0 = No): used only for solar concentrators
17	2	3	Solar geometry (2 = air mass, 3 = year, month, day, hour, latitude, longitude, and time zone)
17a	1.5	2000 Month 15 Hour Lat Long Time zone	Input based on card 17

The comparison shown in Table 2 makes clear how the SMARTS model can be modified to properly represent a pavement (horizontal surface) and to evaluate the solar spectrum accordingly. The other inputs parameters between this study and ASTM G173 were either the same or differed as a logical consequence of differences enunciated in Table 2, and are therefore

not shown. All the input parameters essentially model processes that change the solar spectrum as radiation passes through the atmosphere.

Albedo Calculation. Having determined the reflectance spectra $R_i(\lambda)$ of the i^{th} specimen using a spectrophotometer, where λ is the wavelength, and the solar spectrum $E_j(\lambda, t)$ at the j^{th} geographical location (combination of latitude and elevation) and time t , the albedo $\alpha_{ij}(t)$ was evaluated using Equation 2 (ASTM E903 2012), where the integration was performed from 280 nm to 2,600 nm.

$$\alpha_{ij}(t) = \frac{\int R_i(\lambda)E_j(\lambda, t)d\lambda}{\int E_j(\lambda, t)d\lambda} \quad (2)$$

As seen in Equation 2, $\alpha_{ij}(t)$ is a function of the three variables – geography, time, and mix design – whereas the default albedo in the MEPDG assumes a constant value of 0.15 for concrete across these variables. In addition to this, the albedo is also calculated based on the ASTM G173 (standard AM 1.5 G) spectrum and the maximum error between the two is evaluated for each case.

Results

Spectral Reflectance. For each of the three mix designs presented in Table 1, the spectral reflectance is reproduced in Figure 1. In the far infrared region beyond 2,000 nm, all three mixes have essentially the same spectrum, with some noise near 2,600 nm as the limit of the instrument is reached. For the most part however, the Gray + 15 FA mix had a significantly lower spectral reflectance across wavelengths than the White and White + 15 FA mixes, which were similar. In addition, Figure 1 also shows the AM 1.5G Standard Solar Spectrum as well as a sample spectrum obtained from the SMARTS model for a specific time in San Antonio as an illustration; these can be thought of as the relative weights of each value of spectral reflectance $R_i(\lambda)$ used for estimating albedo.

Albedo. Using the measured spectral reflectance and simulated solar spectra, the albedo for each case was calculated from Equation 2 and presented in **Error! Reference source not found.**(a), (b), and (c) for the samples White, White + 15 FA and Gray + 15 FA, respectively. Within each case in Figure 2, a column indicates a latitude (city) and a row indicates the elevation at which the solar spectrum was simulated using the model. Not all the hours for every month presented in Figure 2 had corresponding albedo data, as the time of sunrise and sunset varied by month. In addition, the albedo calculated using the solar spectrum from the ASTM G173 standard is also shown and labeled ‘Standard’.

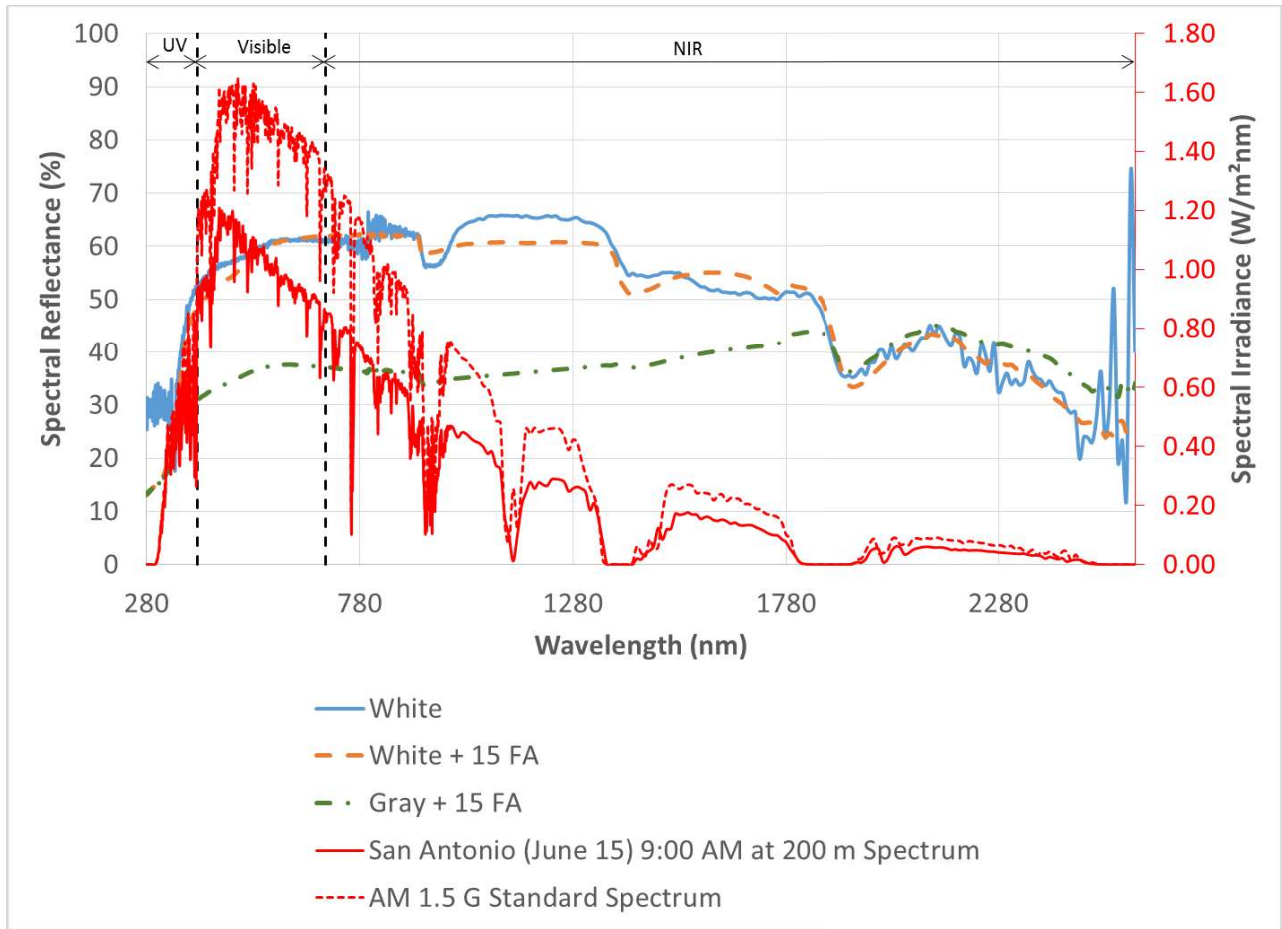


Figure 1. Spectral Reflectance of the Mixes shown with AM 1.5 G Standard Spectrum as well as a Sample Spectrums on the secondary axis. Ultraviolet (UV), Visible and Near Infrared (NIR) regions of the spectrum are also shown

Maximum Error. The maximum error between the albedo calculated using the standard AM 1.5 G spectrum (ASTM G173) and the albedo at any hour in the days considered in the year for a given geographical location, elevation, and material is calculated and presented for each case in Figure 2. Calculated albedo across days in a year and hours of sunshine in those days for the two geographical locations and elevations for the cases of (a) White (b) White + 15 FA (c) Gray + 15 FA. The legend shown above the figures is the same for all cases. ‘Standard’ refers to the albedo calculated using the AM 1.5 G spectrum from ASTM G173.

. Mathematically, this error ε is determined using Equation 3, where the index s represents the standard and the other symbols are the same as used in Equation 2.

$$\varepsilon(\%) = \left(\frac{\max_t (\alpha_s - \alpha_{ij}(t))}{\alpha_s} \right)_{ij} \times 100 \quad (3)$$

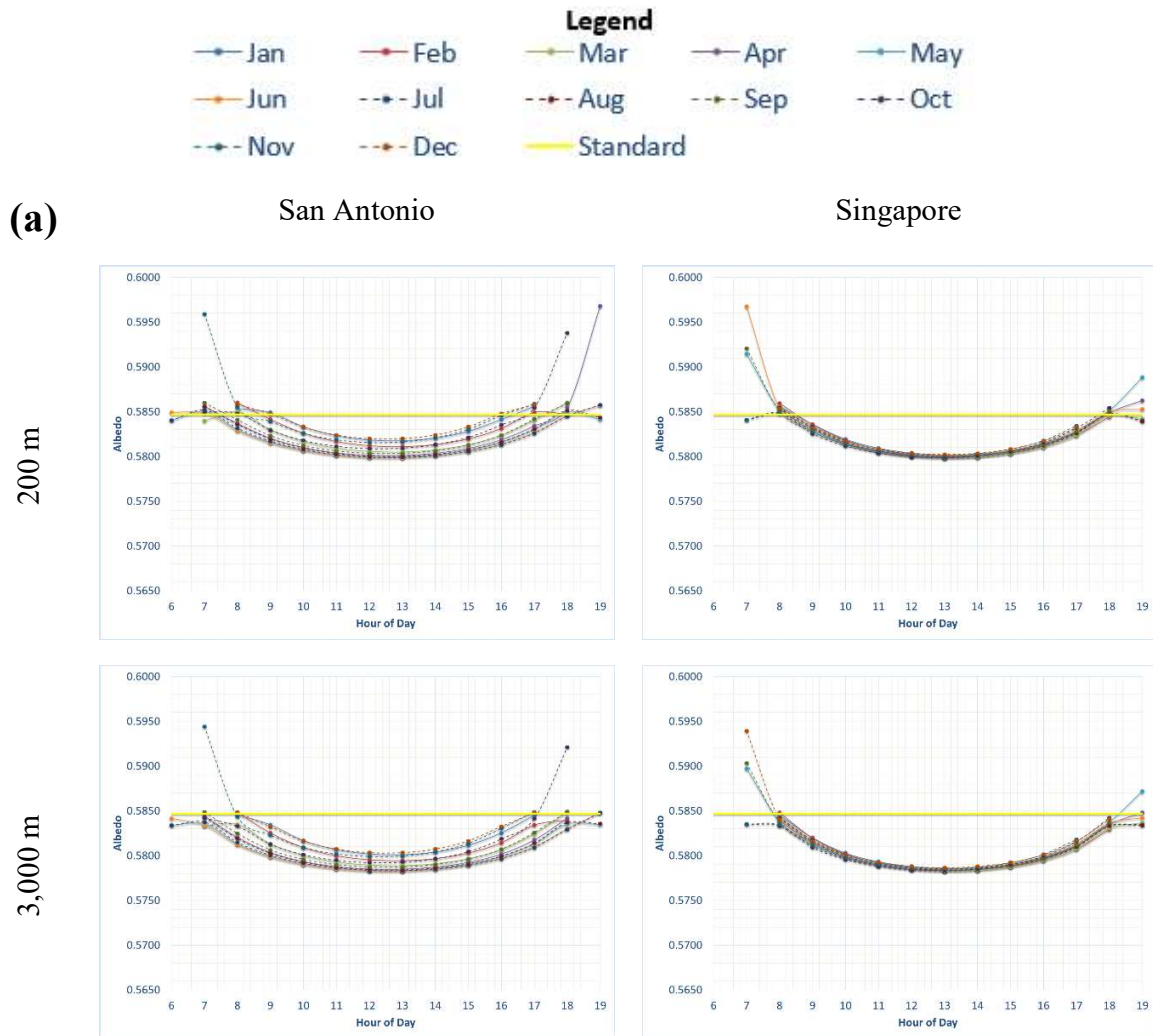
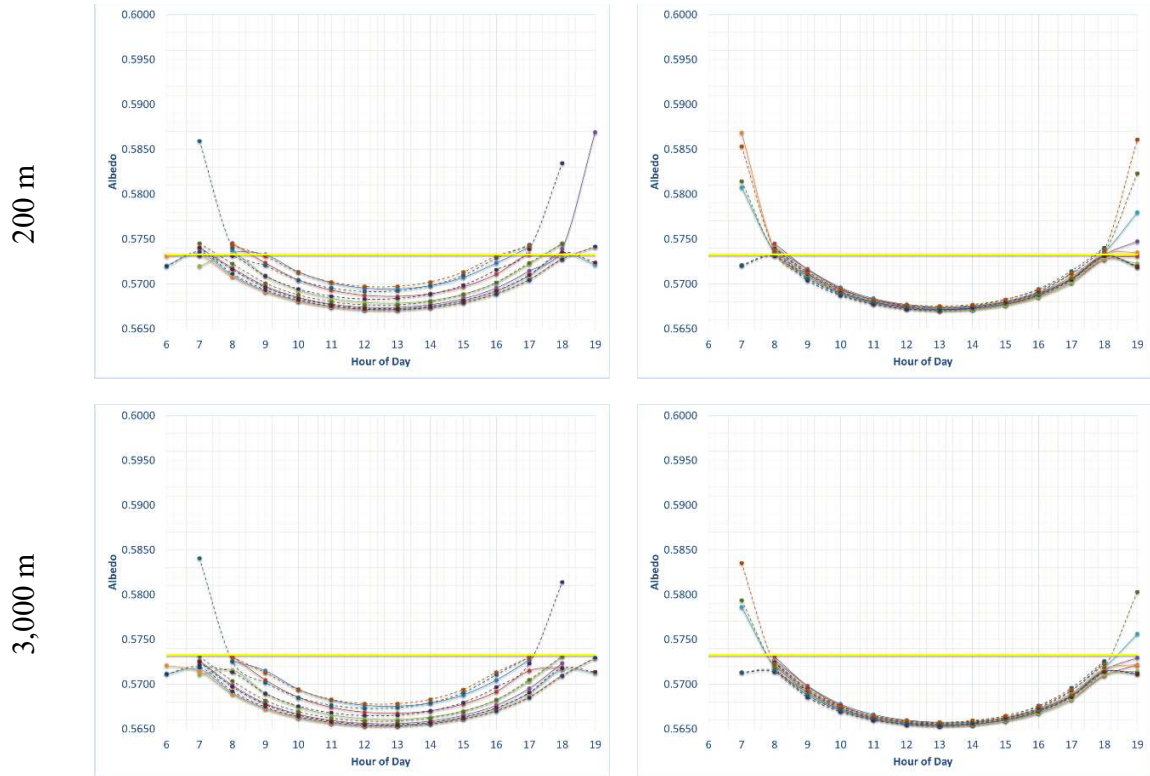


Figure 2. Calculated albedo across days in a year and hours of sunshine in those days for the two geographical locations and elevations for the cases of (a) White (b) White + 15 FA (c) Gray + 15 FA. The legend shown above the figures is the same for all cases. ‘Standard’ refers to the albedo calculated using the AM 1.5 G spectrum from ASTM G173.

(b)

San Antonio

Singapore



(c)

San Antonio

Singapore

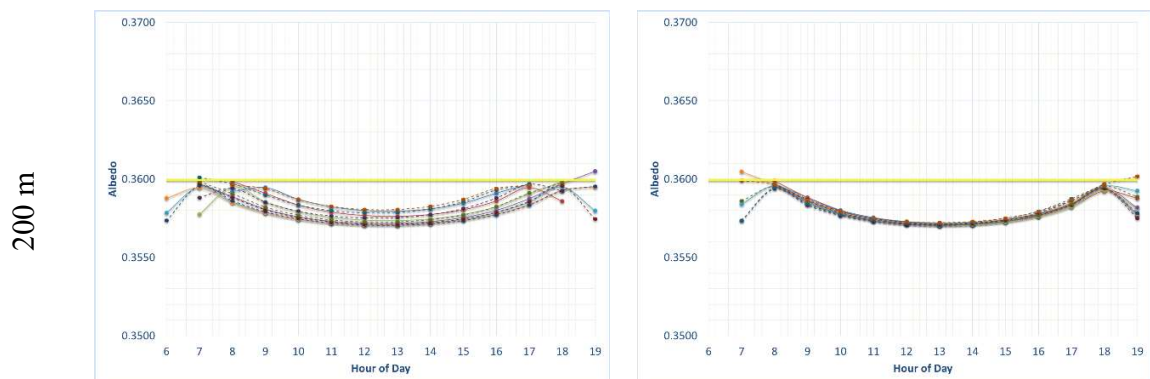


Figure 2 (contd.)

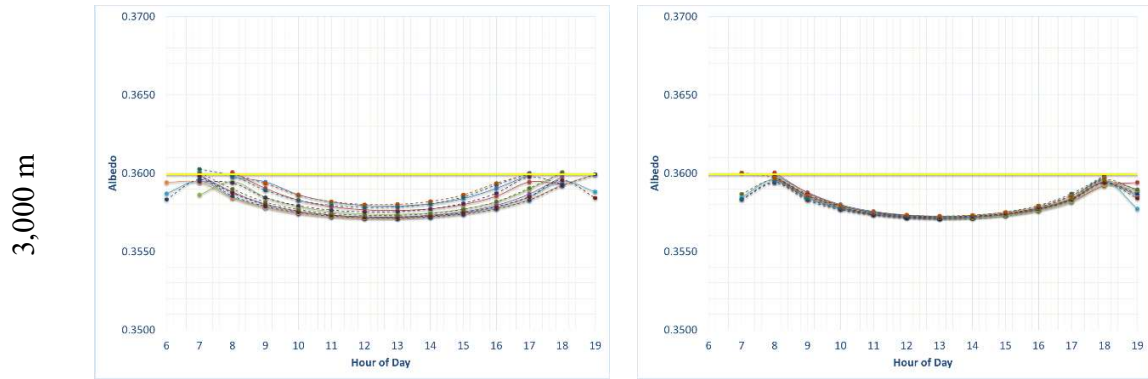


Figure 2 (contd.)

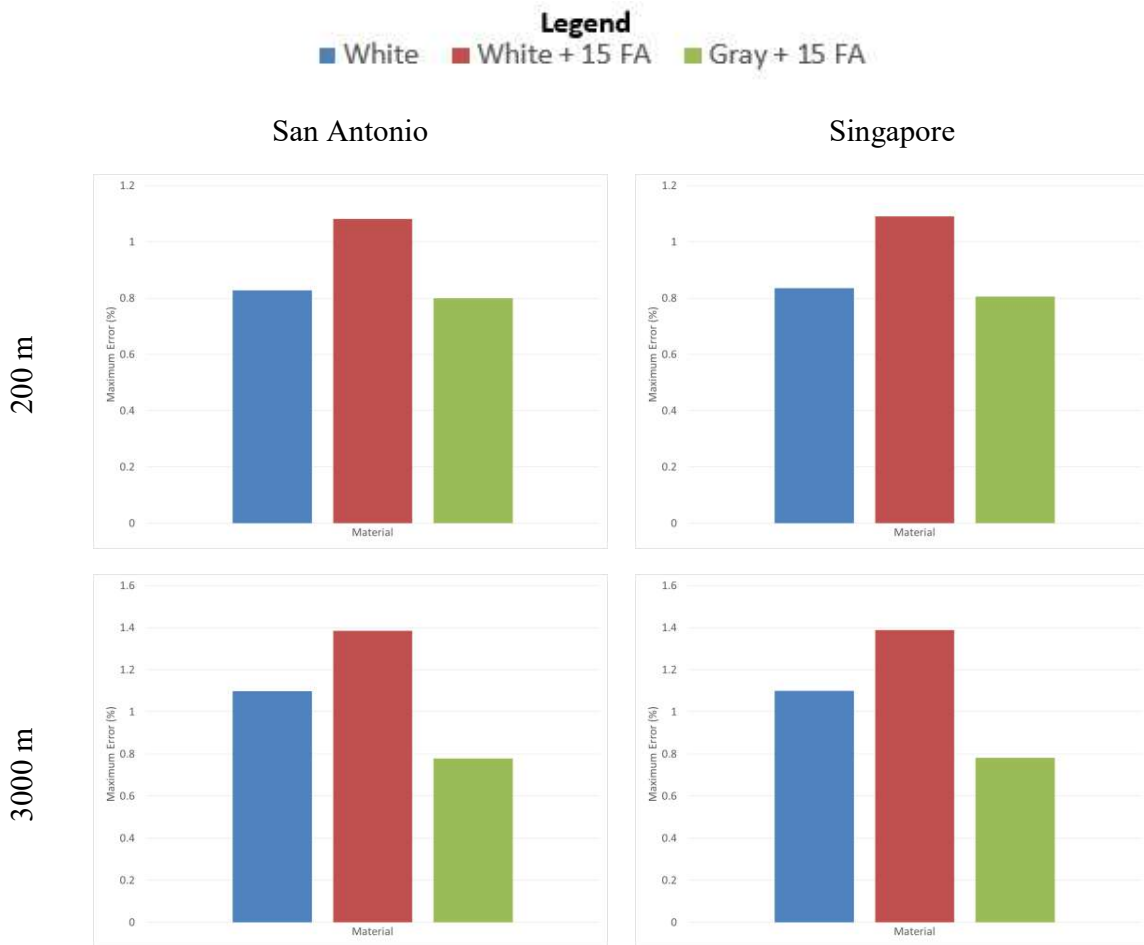


Figure 3. Maximum error (%) of new albedo relative to the albedo calculated from the ASTM G173 standard solar spectrum for each case.

Discussion

Variation of Albedo with Mix. The biggest variation of albedo was observed with changes in the constituent materials of the concrete or mortar, specifically the type of cement and addition of fly ash. As seen in Figure 2(a) and (b), the albedo of case White varies from 0.5800 to 0.5850, but the addition of 15% fly ash (case White + 15 FA) decreased the albedo to a range of 0.5650 to 0.5750, approximately 1 to 3%. However, when conventional gray cement is used in place of white cement with 15% fly ash, as in case Gray + 15 FA, the albedo range decreased to a range of 0.3550 to 0.3600 [Figure 2(c)], a decrease of about 40%. Moreover, all these ranges differed significantly from the MEPDG default value of 0.15, leading to a two- to four-fold error in albedo. As discussed in the introduction, pavement distresses and UHI impact are both very sensitive to albedo and therefore, such a large error can significantly impact the reliability and accuracy of the resulting pavement design and LCA.

Variation of Albedo with Time. For each case in Figure 2, the albedo decreases after sunrise, reaches a minimum and then increases again up to sunset. A previous field study (Li, Harvey and Kendall 2013) showed a similar pattern, with the albedo increasing dramatically a few minutes near the times of sunrise and sunset. Another discussion (Levinson, Akbari and Berdahl 2010a) explained that the reason for this is the low angle of the sun during dawn and dusk. By suitably modifying the SMARTS 2.92 model, this behavior could be theoretically replicated. Although the albedo variation is largest near dawn and dusk and does change throughout the year, the change is not large. As shown in Figure 3, the maximum error ranges from 0.8 to 1.5%. Thus, while time has an effect on albedo, it is small and can be considered negligible for engineering purposes.

Variation of Albedo with Geography. The geographic variable can be evaluated under the categories of latitude and elevation. Referring to all the three mixes in Figure 2, for a given mix and latitude, albedo does not change much with elevation, although the variation over time decreases very slightly, mainly during the middle of the day. Across latitudes, for a given mix and elevation, the way in which albedo varies within a day does not change much, but the way in which it varies over the year changes more substantially. The change in albedo with time of the year is much higher in San Antonio than in Singapore for both assumed elevations. This can be attributed to the fact that, at a location such as Singapore that is very close to the equator, the position of the sun in the sky does not change much over the year, whereas the position changes significantly at higher latitudes such as San Antonio. The position of the sun determines the length sunlight has to travel through the atmosphere and thus the incident solar spectrum. Therefore, as one goes farther away from the equator, it might be necessary to measure albedo more than once per year to account for this variation.

Other issues. The preceding analysis showed that among the three variables considered in this study – time, geography and mixture – the most significant variable was mixture constituents, followed by time, and finally geography. There are some factors that have not been taken into account, such as clouds, local atmospheric variations, local ratio of diffuse to specular incident solar radiation, etc. Three studies (Sen, Roesler and King 2016, Krimpali and Karamanis 2015, Akbari, Levinson and Stern 2008) have shown that the results of field methods for measuring albedo systemically differ from laboratory results using a spectrophotometer given the same mixture. While this study explained some of the differences on account of the spectrum from ASTM G173, this is only small and not enough to explain the differences between field and lab methods, which are typically 5 to 10%. While the SMARTS model can simulate the atmosphere

with good accuracy, it does not explain this error. A significant cause of the error could be interference from surrounding surfaces in the field method as well as material and atmospheric heterogeneity, which are not captured by the spectrophotometer method. For a heterogeneous material such a concrete being tested for albedo in an urban area, surrounded by buildings and roads that interfere in the measurement, together with possible high altitude clouds, a difference of 5-10% in albedo seems reasonable, although the relative impact of each is not yet known and left for a future study.

Conclusion

It is necessary to collect a large amount of input data when adopting mechanistic-empirical pavement design methods and conducting pavement LCA studies. Albedo is one such variable that can strongly impact concrete pavement design as well as the urban heat island in an LCA. Currently, the MEPDG recommends a default albedo value of 0.15 (corresponding to a surface shortwave absorptivity of 0.85) for all concrete pavements, which is used by almost all agencies. Those using empirical design procedures such as the AASHTO 1993 Pavement Design Guide do not even take albedo into account.

The impact of three factors – mix design, geography, and time – on albedo was determined by averaging spectral reflectance, obtained using a spectrophotometer, with local solar spectra, obtained by suitably modifying the SMARTS v 2.95 solar spectrum simulation model. Using this data, the diurnal and annual variations of albedo were calculated for each mix design for geographical locations, San Antonio and Singapore. The most important variable affecting albedo, among those considered, was found to be the concrete mix design itself, followed by time and finally geography, which had only a marginal impact. The most striking observation was that all the values of albedo calculated differed greatly from the MEPDG default value of 0.15, indicating that designs and LCAs that use this default value are likely too conservative. Thus, pavement engineers need to measure the albedo of both new and existing pavements in order to perform more accurate structural designs and LCA.

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