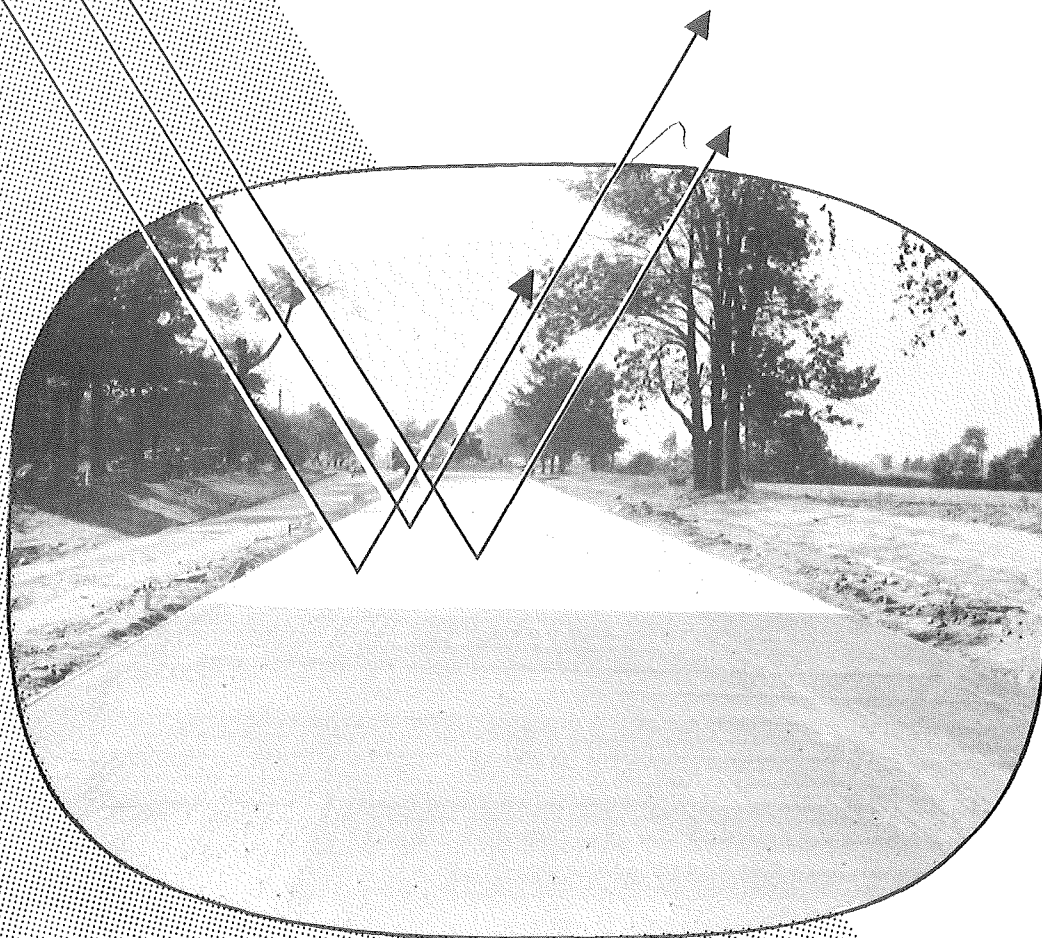


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REFLECTANCE TESTS for CONCRETE CURING MATERIALS



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REFLECTANCE TESTS FOR CONCRETE CURING MATERIALS

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A paper to be presented at the Annual Meeting
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REFLECTANCE TESTS FOR CONCRETE CURING MATERIALS

SYNOPSIS

Stress control through the regulation of early temperature changes in concrete is an important function of the curing operation. Since the primary purpose of using white curing materials is to reduce heat pickup from solar radiation, the measurement of reflectance is of considerable significance in procuring such materials. Because existing preference is divided between the luminous reflectance method of ASTM E 97 and the infrared reflectance method of Federal Specification TT-P-141b, this study was undertaken to provide a sound basis for evaluation of these two methods and development of reflectance tests in general.

Three factors enter into the development of a significant and practical reflectance test for concrete curing materials: 1) spectral distribution of solar radiation received at the earth's surface; 2) suitability of various photometers for measurement of reflectance in the most significant spectral range; and 3) spectral characteristic of the curing materials. An analysis of these three factors indicates that measurements in the visible range are as significant as those in the infrared and that ASTM Method E 97 for routine testing and Methods D 307 and D 791 for reference are the best that can be found at present using commercial photometric equipment currently available at a reasonable cost.

This is an advance copy of a paper to be presented at the Sixty-First Annual Meeting of the American Society for Testing Materials (1916 Race St., Philadelphia 2, Pa.) to be held in Boston, Mass., June 22-27. This advance copy is primarily to stimulate discussion. Discussion is invited and may be transmitted to the Executive Secretary. The paper is subject to modification and is not to be published as a whole or in part pending its release by the Society through the Executive Secretary.

REFLECTANCE TESTS FOR CONCRETE CURING MATERIALS

It has long been recognized that stress control through the regulation of early temperature changes in concrete is an important function of the curing operation. Since the principal purpose of using white materials of either the sheet or membrane-forming type is to reduce both the rate and amplitude of temperature change due to absorption of solar radiation, the specification and measurement of reflectance are of considerable significance in procuring such materials.

Probably the method most commonly used in the past for measuring reflectance of white curing materials is ASTM E 97, Standard Method of Test for 45-deg, 0-deg Directional Reflectance of Opaque Specimens by Filter Photometry. There seems to be a rather prevalent belief, however, that a reflectance test for curing materials should measure infrared rather than luminous reflectance and it has been proposed that the infrared method be incorporated in ASTM specifications for white curing paper. Thus there is a need for clarification of the principles involved and their application to reflectance specifications and tests for curing materials.

The purpose of this paper, therefore, is twofold: first to discuss some of the more important facts and principles which should govern the development of reflectance tests for curing materials; and second, to apply these facts and principles to the design of the best test possible within the limitations of currently available instruments and spectral characteristics of the materials themselves. In carrying out this purpose the discussion which follows is divided among four major topics: 1) fundamental concepts and data; 2) reflectometric methods and instruments; 3) spectral characteristics of curing materials; and 4) recommended test.

Fundamental Concepts and Data

Throughout the following discussion, the first and most important basic fact to remember is that, in general, all radiation is converted to

heat when absorbed by a body on which it falls. Exceptions to this rule, such as fluorescence and the production of photochemical and photoelectric effects need not be considered here. It follows, therefore, that equal amounts of radiant energy, in whatever portions of the spectrum they may occur, produce equal quantities of heat when totally absorbed. Choosing an interval of the spectrum, then, in which to make reflectance tests for curing materials depends largely on the spectral distribution of solar radiation reaching the earth's surface (insolation). Furthermore, the particular wavelength band selected should include as great a portion of the total insolation as possible. This being the case, it will be profitable to examine the composition of solar radiation rather closely. Since a knowledge of reflectometric terms is also necessary for an understanding of the significance of the measurements to be made, this aspect of the subject will also be presented briefly.

Solar Radiation

Solar radiation at normal incidence on the earth varies widely because of variations in the sun itself, variations in the distance from sun to earth, differences in atmospheric scattering, and differences in atmospheric absorption. As a convenient reference for comparison with irradiation at the earth's surface, the spectral distribution of solar energy outside the atmosphere plotted from data by Moon (1) is shown in Fig. 1. This curve corresponds closely to that of a blackbody radiator at 6000 K at wavelengths beyond about 1.25μ , but is depressed at the shorter wavelengths due to selective absorption in the sun itself.

Next, let us see what happens to this radiation by the time it reaches the earth's surface. Direct radiation from the sun is scattered by molecular nitrogen, oxygen, water vapor and other gases, and by dust. The degree of scattering is a function of wavelength and increases exponentially as the ultraviolet end of the spectrum is approached. This phenomenon gives rise to the characteristic blue color of the sky on a clear day. Absorption by the atmosphere modifies the amount and spectral distribution of solar radiation still further. Ozone absorbs selectively in the ultraviolet, and water vapor and carbon dioxide absorb heavily in the infrared. The net result of atmospheric effects is shown in the third curve of Fig. 1, which gives the spectral irradiance for air mass 2, that is, for a path through the atmosphere twice its length at normal incidence.

Additional data from Moon (1) are given in Table 1, wherein are listed results for five values of air mass, thus making possible the calculation of irradiation at any hour of the day except near sunrise or sunset. He suggests that the curve for air mass 2 be used whenever a single,

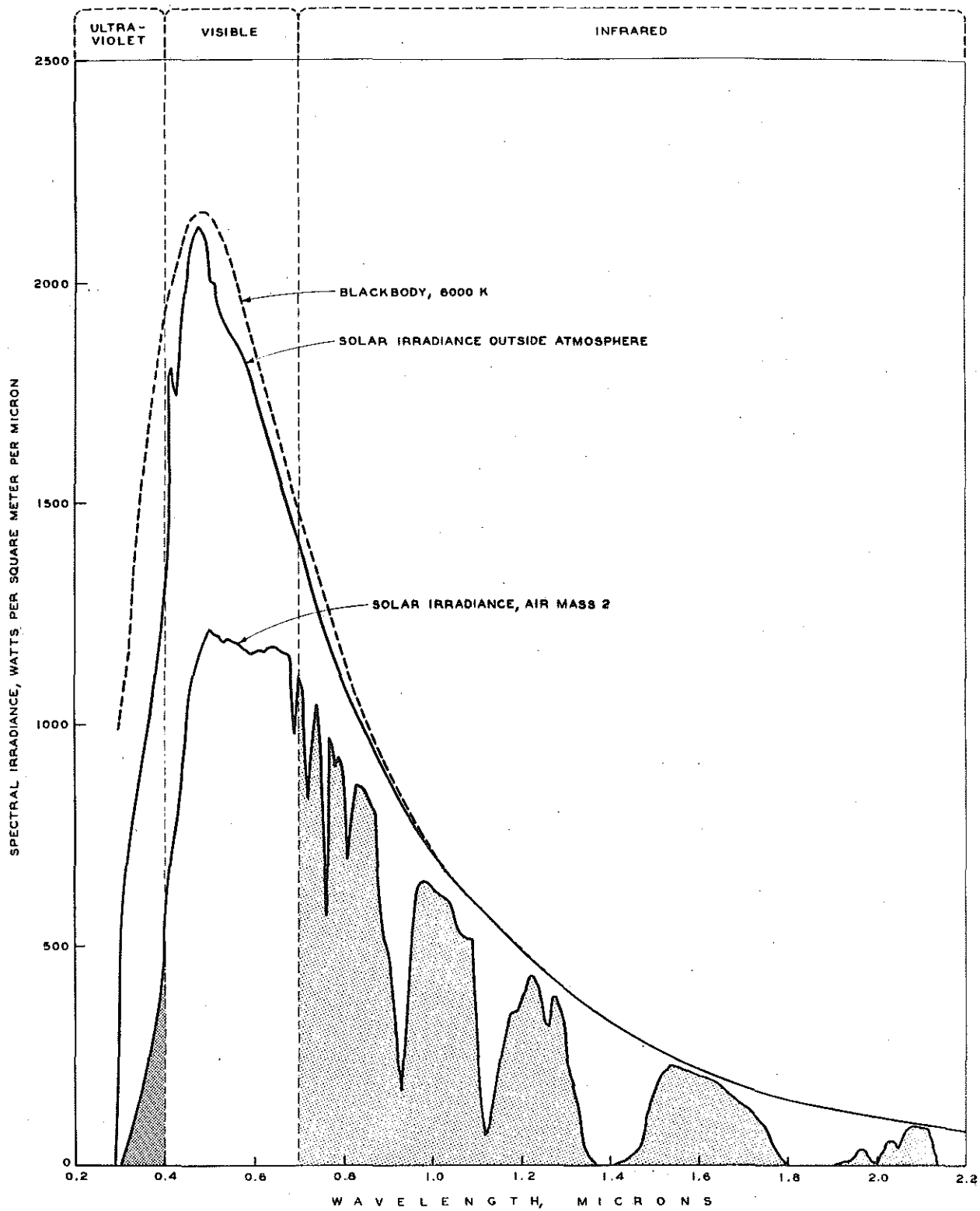


Figure 1. Spectral Distribution of Radiant Energy from the Sun and a Blackbody Radiator at 6000 K

standard solar-radiation curve is needed in engineering calculations for places near sea level. Values for air mass 2 are sufficiently representative for the present purpose and will be assumed in all subsequent discussion unless otherwise noted.

As may be seen from the curves of Fig. 1, and data of Table 1, almost 100 per cent of the sun's energy falls within the wavelength range of 0.3 to 2.2 μ . Of this range, the interval of approximately 0.3 to 0.4 μ constitutes the ultraviolet portion, 0.4 to 0.7 μ the visible, and 0.7 to 2.2 μ the infrared. The entire range of wavelengths beyond 2.2 μ contributes less than 2 per cent to the total insolation. However, the energy level is much higher in the visible portion of the spectrum and falls off quite rapidly with increasing wavelength in the infrared. There is also considerable absorption by the atmosphere in the infrared region so that the total energy, exclusive of the ultraviolet, is made up of almost equal portions of visible and infrared radiation. The amount of energy in the ultraviolet band is relatively small, only 4 per cent of the total, and is of little significance in the present instance.

Reflectometric Terms and Definitions

It is well known that illuminated objects do not appear equally bright from all directions and certain conditions and terms must be defined in order to understand the significance of reflectance measurements. Three quantities are of primary importance, namely, reflectance, specular reflectance and directional reflectance.

Reflectance is defined as the ratio of the total radiant energy reflected from an object to the total radiant energy incident on it, and will vary with the angular distribution of the incident energy (2, 3). Since no object can reflect more energy than falls on it, the value of reflectance cannot exceed unity.

Specular reflectance is the ratio of reflected to incident energy in the direction of mirror reflection only. Its value will depend on the angle of incidence and, again, cannot exceed unity. Gloss and sheen are examples of the manifestation of luminous specular reflectance, being defined by particular angles of illuminating and viewing.

Directional reflectance is the ratio of the radiance that the surface has under any specified irradiating and receiving conditions to the radiance that a perfectly diffusing, perfectly reflecting surface would have under the same conditions. Because directional reflectance is a ratio of the reflectance of two surfaces under any specified set of conditions, its value may be either greater or less than unity. The primary

Table I (a)

CALCULATED SOLAR IRRADIATION AT SEA LEVEL

Microns	Energy, watts per square meter					
	m = 0	1	2	3	4	5
0.29-0.40	94.6	40.1	19.8	10.0	5.4	2.7
0.40-0.70	540.0	419.7	327.8	258.6	205.8	163.7
0.70-1.1	365.4	309.2	267.5	233.4	205.1	181.5
1.1-1.5	162.5	95.3	70.4	57.0	48.1	40.7
1.5-1.9	72.8	50.8	45.1	41.0	38.0	35.2
1.9-infinity	86.8	12.8	9.2	7.5	6.5	5.8
Total	1322.1	927.9	739.8	607.5	508.9	429.6

(a) Taken from "Proposed Standard Solar-Radiation Curves for Engineering Use," P. Moon, Journal of the Franklin Institute, Vol. 230, p. 583 (July - Dec., 1940).

standard of reflection is freshly prepared magnesium oxide (MgO) which has a (total) luminous reflectance of more than 0.97 and a luminous directional reflectance of 1.00. Its total reflectance falls off somewhat in the infrared, reaching a value of 0.94 at 2.2 μ . Directional reflectance depends on the spectral and angular distribution of the incident energy and the direction of reception. The angles generally specified for irradiation and reception are 45 deg and 0 deg to the normal respectively.

The terms defined above are general for radiation of all wavelengths. When the incident energy is light, these terms are preceded by the word luminous. Other terms in general use with their definitions may be found in ASTM Method D 307 (4) which should be consulted. In this connection it is important to distinguish the difference in meaning of the two terms reflectance and reflectivity. The former refers to a property of an object or specimen, such as a coating-on-ground, where the indicated reflectance, total or directional, may be influenced by the reflectance of the substrate as well as that of the coating. On the other hand, reflectivity characterizes a material rather than a specimen and is determined at such a thickness of the material that any increase in thickness will not change the measured value.

In ASTM Method D 307 the symbol R_s designates luminous directional reflectivity. Total reflectance is usually designated by R and directional reflectance by R with subscripts indicating the angles of irradiation and reception respectively. For example, $R_{45,0}$ designates the directional reflectance of a specimen when irradiated at 45 deg and observed at 0 deg to the normal, and $R_{5,D}$ when irradiated at 5 deg and viewed diffusely. By the Helmholtz reciprocal relation (2) it can be shown that these conditions of irradiation and observation can be interchanged without affecting the results, that is, $R_{45,0} = R_{0,45}$. Importance of specifying geometrical conditions becomes evident when it is known that the radiance of surfaces is usually a maximum in the group of directions near specular reflection and that this maximum becomes more pronounced as the angle of incidence increases (3).

Reflectometric Methods and Instruments

With the foregoing very brief and much-abridged review of pertinent fundamentals let us now consider reflectometric methods and see how some of the more commonly available instruments fit into a significant reflectance test for curing materials. The two methods most widely used employ spectrophotometers and filter photometers respectively for making reflectance measurements. The former are capable of considerably

higher precision than the latter and are usually used in referee tests. On the other hand, filter photometers provide means for making simple, rapid measurements, accurate enough for many purposes and at a reasonable cost.

In this section only five commercial instruments will be discussed in relation to the present problem. Those wishing to become acquainted with other instruments developed for this purpose should consult especially references 2, 5 and 6. The five instruments selected are all of the photoelectric type and will serve to illustrate the principles of application involved.

Spectrophotometry and Spectrophotometers

Spectrophotometry consists in determining the ratio of two radiant energies, from sample and standard respectively, at successive wavelengths over the spectral range desired. By plotting this ratio (reflection factor) against wavelength, a complete spectrophotometric curve can be obtained, and the area under this curve represents the reflectance of the sample relative to the standard.

Since this procedure yields a ratio of two reflectances at each increment of wavelength, the resulting value of reflectance for the sample is independent of the spectral distribution of the incident energy and the spectral response of the photocell. Hence it is equivalent to the result which would be obtained with a source having an equal energy spectrum, that is, one emitting the same amount of energy at all wavelengths and a photocell having equal response at all wavelengths in the given range. The essential requirements are that the source have a continuous spectrum and the photocell a measurable response throughout the specified range.

If it is desired to know the reflectance of a sample when irradiated by a source with known spectral energy distribution, the reflection factor at each increment of wavelength is multiplied by the relative energy of the source at that wavelength and the area under the resulting curve again integrated. This area must then be divided by the area under the curve obtained when the standard is similarly irradiated. Thus, reflectance measurements made by use of an incandescent lamp can be readily converted to reflectance values for irradiation by any other source whose spectral characteristics are known, for instance, average daylight (ICI illuminant C) or any of the three sources whose energy distributions are given in Fig. 1.

Finally, in photometric problems involving appearance, the relative response of the observer's eye to visible radiation must be taken into account. The eye does not respond equally to equal amounts of radiation at all wavelengths. It is much more sensitive to radiation in the yellow-green region of the spectrum than in the blue or red and cannot perceive ultraviolet or infrared radiation at all. The relative brightness of equal amounts of energy is shown in the curve of Fig. 2 which is called the luminosity function and defines the response of the standard ICI observer (7). To evaluate the brightness of a sample illuminated by a given source and viewed by the standard observer, the product of reflection factor of the sample and relative energy of the source at each increment of wavelength must now be multiplied by the relative brightness at that wavelength and the area under the resulting curve integrated as before. Luminous reflectance of the sample is then expressed as a ratio of the value so obtained to that obtained for MgO when similarly illuminated and viewed. The calculation of luminous directional reflectance may be expressed as follows:

$$R_{45,0} = \frac{\sum_{\lambda} R_{\lambda} E_{\lambda} \bar{y}_{\lambda} \Delta\lambda}{\sum_{\lambda} E_{\lambda} \bar{y}_{\lambda} \Delta\lambda} \quad (1)$$

where

- $R_{45,0}$ = luminous directional reflectance,
- R_{λ} = spectral directional reflectance (reflection factor),
- E_{λ} = spectral irradiance (relative energy of source),
- \bar{y}_{λ} = spectral luminosity (relative brightness), and
- $\Delta\lambda$ = wavelength increment at which measurements are made.

Tables of values for E_{λ} (H_{λ} in ASTM D 307) for the ICI standard illuminants, A, B and C, and for \bar{y}_{λ} may be found in the literature (4, 7).

In general, spectrophotometers contain a lamp and a mechanical-optical system such that the radiant flux from the source is dispersed into its spectral components, which are then isolated successively in narrow bands to irradiate sample and standard. Reflected radiation is received by a photocell which measures the intensities of the reflected beams from the two surfaces. In the recording type of instrument sample and standard are illuminated alternately in rapid succession and a continuous curve of comparative reflectance is drawn. In the manual type,

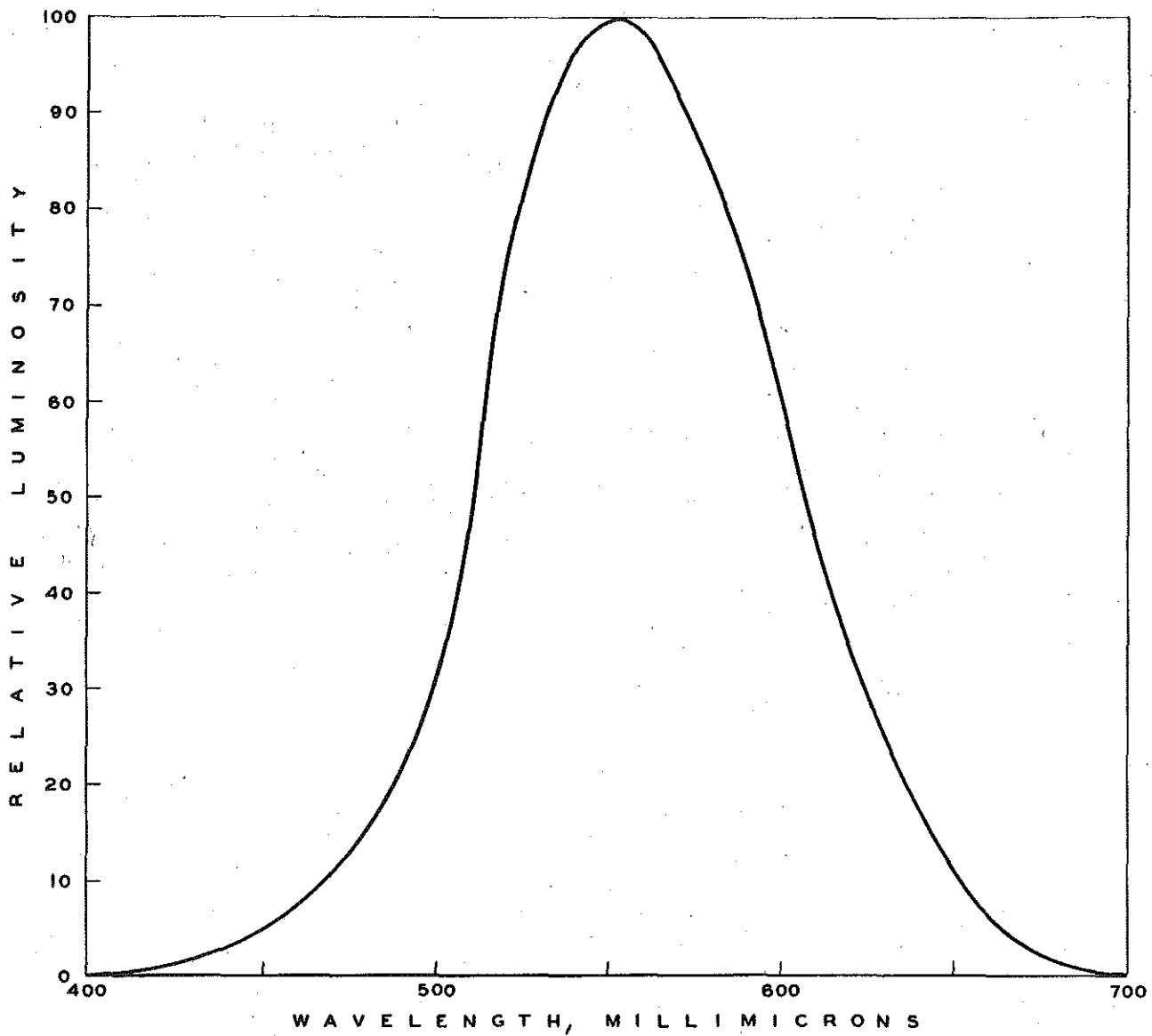


Figure 2. Luminosity Function

sample and standard are alternately placed in the beam and the reflectance ratio is recorded for each increment of wavelength. Wavelength settings are also made manually. Examples of both types are described by Gibson (2).

The two recording spectrophotometers considered here are the latest model of the Hardy, or General Electric, and the new Beckman DK-2R. Both employ integrating spheres for collecting the flux reflected from sample and standard, and the specular component can be either excluded from or included in the measurement. Illumination is at 6 deg in the GE instrument and 5 deg in the Beckman with diffuse reception in both. When the specular component is included they give values of total reflectance, $R_{6, D}$ and $R_{5, D}$ respectively, but in any case cannot be used to measure luminous directional reflectance, $R_{45, 0}$. An important distinction is the difference in range of the two instruments. As usually supplied the GE covers an interval of about 0.38 to 0.80 μ while the Beckman has a range of 0.38 to 2.50 μ . The wide range of the latter makes it especially useful in the study of infrared reflectance.

The spectrophotometer used in the Michigan State Highway Department Research Laboratory is a Beckman DU with reflectance attachment and is of the nonrecording type. With a tungsten lamp it has a range of about 0.38 to 1.2 μ . This instrument does not have an integrating sphere, the sample being illuminated perpendicularly and the reflected radiation collected at 45 deg by an ellipsoidal mirror ring which focuses it on the receiver. Thus the specular component is excluded from the measurement. There is a spread of about 20 deg about the axis of the reflected beam (35 to 55 deg) but the conditions closely approximate those recommended by the International Committee on Illumination for determining directional reflectance, $R_{45, 0}$.

Filter Photometry and Photometers

As we have just seen, the measurement of reflectance by spectrophotometric methods involves determining reflectance ratios at successive wavelengths in a given spectral range. With nonrecording instruments the determinations are made at such wavelength intervals that the spectrophotometric curve so obtained would not be changed significantly by taking further readings. Readings at 10- μ intervals are usually adequate.

For some purposes, readings taken at several spectral regions of relatively narrow width may be sufficient. In abridged spectrophotometry these regions are isolated by suitable optical filters selected for the particular application in mind.

While abridged spectrophotometry may have a limited application to reflectance measurements for curing materials, we are chiefly concerned here with filter photometry of another kind which is used in tristimulus colorimetry. In the latter method, three separate filters - amber, green and blue - of relatively wide spectral range are so selected that, in combination with a particular source and photocell, the tristimulus values defining the color of the sample under ICI standard conditions of illuminating and viewing may be directly determined (8). Without going into the subject of colorimetry, it is important to note that use of the green tristimulus filter in conjunction with a corresponding source and photocell may be made to yield a single value which is very nearly proportional to luminous reflectance. By comparison with a suitable standard, the reflectance of the sample relative to that of MgO is easily found.

Probably the best known photoelectric reflectometers of the tristimulus type are the Hunter and the Photovolt. Both of these instruments are constructed so that the conditions of illuminating and viewing conform to ICI recommendations for determining directional reflectance, $R_{45,0}$. In the Hunter instrument, illumination is at 45 deg and viewing at 0 deg. In the Photovolt these conditions are reversed but equivalent. With the green tristimulus filter both instruments give values of luminous directional reflectance relative to MgO from single readings on sample and standard respectively. The specular component of reflected flux is excluded from measurements of $R_{45,0}$ in both instruments.

For the measurement of infrared reflectance, both instruments are designed to filter out visible radiation from the incident beam and to give reflectance values comparable to those obtained by the photographic method specified in Method 624.1 of Federal Specification TT-P-141b. In this method reflectance is defined in terms of the effect of the reflected energy on infrared-sensitive film when the specimen is irradiated by infrared energy from a 200-w tungsten lamp. It is pertinent to note that the response of the specified film does not extend beyond approximately 0.9μ in the infrared.

Spectral Characteristics of Curing Materials

The third main factor entering into the design of a reflectance test for curing materials is the spectral characteristics of the materials themselves. To determine these characteristics, four types of material were selected for reflectance tests, namely, white curing paper, buff curing paper, white polyethylene sheets and white membrane curing compounds. All materials met applicable ASTM requirements in other respects.

Reflectance Tests

Samples of these materials were tested in four different ways: 1) 0-deg, 45-deg luminous directional reflectance by the Photovolt Reflectometer; 2) 0-deg, 45-deg luminous directional reflectance by the Beckman DU Spectrophotometer; 3) infrared reflectance by the Hunter and Photovolt Reflectometers; and 4) 0-deg, 45-deg directional reflectance by the Beckman DU over the wavelength range 0.31 to 1.20 μ weighted by the spectral distribution of solar energy but not by the luminosity function. To reduce variables to a minimum for the purpose of comparing test methods, the polyethylene and membrane compounds were tested for reflectivity rather than reflectance by using multiple thicknesses or coats.

Methods 1 and 2 cover the visible portion of the spectrum only and give values of reflectance which represent the appearance of the material when viewed by the standard ICI observer in average daylight (Illuminant C). About 45 per cent of the total solar energy is included in this wavelength interval.

Method 3 includes in the measurement a wavelength range of about 0.7 to 0.9 μ , which contributes approximately 23 per cent of the total insolation. Two reflectometers were used in this method, the Hunter for the papers, and the Photovolt for the polyethylenes and membrane compounds. This was necessary because of the lack of a complete set of secondary standards for either. Results from the two instruments checked to within 0.5 per cent in luminous directional reflectance determined on the same samples.

In Method 4, the range of measurement includes more than 85 per cent of the total insolation. While this method does not include the specular component of reflected energy in the measurement, it unquestionably gives the most significant results of any of the four methods and was used as a standard for evaluation of the others.

Results and Discussion

Data obtained from the four procedures applied to the four types of curing material are given in Table II and some illustrative spectrophotometric curves in Fig. 3. The curves in particular reveal some pertinent features of the different types of material.

First, the white papers are somewhat selective, with spectral reflectance reaching a broad maximum at around 0.7 to 0.8 μ , and declining very gradually or holding almost constant thereafter in the infrared.

Table II

REFLECTANCE OF CURING MATERIALS

	Sample No.	Reflectance, per cent			
		Method No. 1 ^(a)	Method No. 2 ^(b)	Method No. 3 ^(c)	Method No. 4 ^(d)
White Paper	1	57	58	64	60
	2	47	47	60	51
	3	49	50	56	51
	4	47	48	49	50
	5	42	42	45	43
	6	45	48	48	48
	7	54	55	62	57
	8	47	49	49	48
	9	44	47	45	46
Buff Paper	10	32	32	44	38
	11	33	32	51	43
White Polyethylene	12	94	93	92	89
	13	92	92	91	89
	14 ^(e)	77	76	79	73
White Membrane Compound	15	54	58	58	51
	16	80	82	84	76
	17	85	87	90	83
	18	76	77	84	74
	19	81	82	86	78
	20	81	83	85	78
	21	85	86	86	81
	22	84	86	86	80

(a) ASTM E 97-55, Photovolt Reflectometer, NBS standard plaque 50Q reference

(b) ASTM D 307-44, Beckman DU, MgO reference

(c) TT-P-141b, Method 624.1. Hunter Multipurpose Reflectometer used for white and buff papers, Photovolt Reflectometer for white polyethylenes and membrane curing compounds.

(d) Modified ASTM D 307-44, Beckman DU, MgO reference, ordinates weighted by Moon's data for solar radiation in the range 0.3 to 1.2 u.

(e) Curing paper faced on one side with white polyethylene

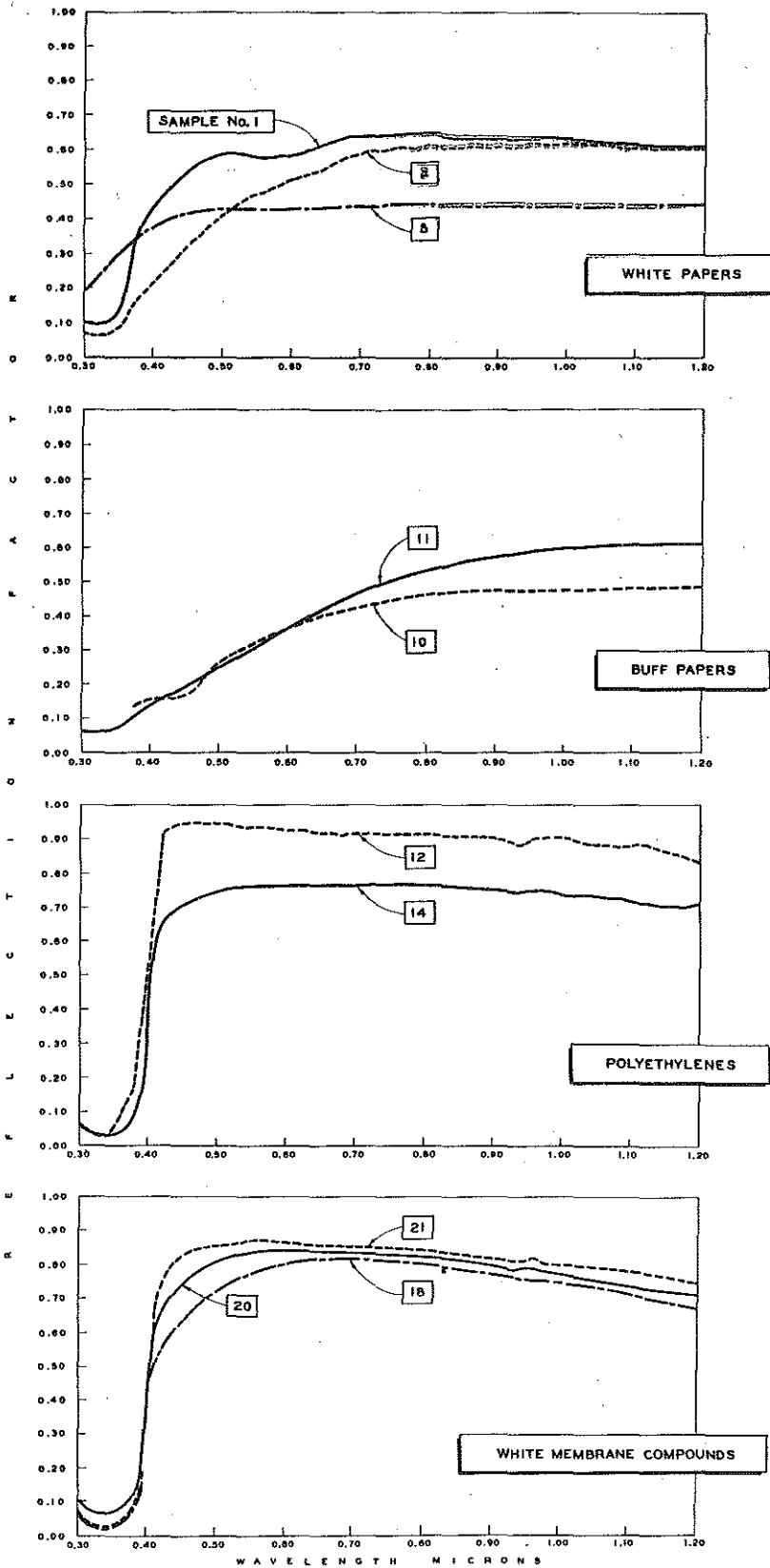


Figure 3. Spectral Reflectance of Curing Materials

Sample No. 2 is a 2-yr-old paper of the same make as Sample No. 1 and the depression of the curve in the visible region indicates the effect of age and possible bleeding of the bituminous layer through the surface. The three curves shown represent extremes in characteristics of the nine samples of white paper tested, the others being intermediate in both spectral selectivity and directional reflectance. All of the curing papers were highly diffusing, having 60-deg gloss values of only 4 to 6 units, measured with a Photovolt Model 610 Reflectometer and Carrara glass standard having a gloss of 96 units.

Second, spectrophotometric curves for both samples of buff paper show progressively decreasing reflectance from the red to the violet end of the visible spectrum. This comparatively low reflectance in the blue region gives rise to the characteristic brownish color of the kraft paper. Sample No. 11 is of special interest. Spectral reflectance of this sample continues to rise, although at a diminishing rate, past the visible region and out to a wavelength of about 1.1μ in the infrared before levelling off. This property enables it to equal the least reflective "white" paper in reflectance determined in accordance with Method 4 (Table II).

Third, the two polyethylene films, Samples 12 and 13, exhibited nearly identical characteristics, the spectral reflectivity rising almost vertically at 0.4μ to a well defined maximum at about 0.45μ and then diminishing gradually with increasing wavelength through the visible and into the infrared regions. The curve for Sample No. 14, curing paper faced with white polyethylene, shows the effect of film translucence on reflectance and spectral selectivity. A similar effect is produced by placing a white polyethylene sheet on a black background. All three samples exhibit appreciable specular reflection with 60-deg gloss values in the range of 35 to 50 units.

Finally, the spectrophotometric curves for white membranes are similar to those for the white polyethylenes in the given wavelength interval except for a falling off of spectral reflectance at the blue end of the visible region. Sample No. 18 had a distinct yellowish cast, with Samples 20 and 21 showing progressive increase in whiteness. All but two of the samples produced relatively "flat" finishes with 60-deg gloss values of less than 20 units. The two exceptions, Nos. 18 and 19, gave gloss values of 86 and 40 units respectively, which suggests the possible desirability of limiting the gloss of membrane compounds used for highway construction in order to prevent objectionable glare on newly opened pavements.

Recommended Test

As a final step in selecting a suitable reflectance test for curing materials, let us turn again to the data in Table II. Since existing preference is divided between the luminous reflectance method of ASTM E 97 and the infrared reflectance method of Federal Specification TT-P-141b, the primary comparisons will be of Methods 1 and 3 respectively with Method 4. Data for Method 2 are included in the table only to indicate the degree of correlation that can ordinarily be expected between results from a spectrophotometer and filter photometer in a single test. As a matter of interest, spectrophotometric curves obtained by Method 2 (ASTM D307) gave nearly the same results for R_{45,0} whether or not the ordinates were weighted by the luminosity function in the computations.

Reflectance values listed in Table II indicate that there is little to choose between Methods 1 and 3 for measurements on white papers. Both gave reasonably close approximations to the more representative results obtained by Method 4, although the values from Method 1 were somewhat more consistent. Moreover, because the curing papers are highly diffusing, values for directional reflectance can be assumed to give a reliable indication of total reflectance.

For buff papers neither Method 1 nor 3 gave satisfactory results, the indicated value being too low in the former case and too high in the latter. These results can be deduced from the spectrophotometric curves of Fig. 3; the low reflectance in the visible region overinfluences the values obtained by Method 1 and is not taken into account at all by Method 3.

For the white polyethylenes, both methods gave slightly higher values than Method 4. Method 3 appears to have a little advantage for the plain white polyethylene and Method 1 for the polyethylene-faced paper. These conclusions could also be drawn from the spectrophotometric data given in Fig. 3.

While both methods produced reflectivity values for white membranes which were somewhat high, the results obtained by Method 1 were consistently and appreciably nearer those obtained by the reference method and can be considered a satisfactory approximation. The spectrophotometric curves again provide the explanation; Method 1 takes into account the moderate falling off of spectral reflectivity in the blue region, while Method 3 does not.

Summing up, these tests indicate that ASTM Method E 97 is at least equal to Method 624.1 of Federal Specification TT-P-141b in significance and somewhat superior in consistency of results. In general, the former method yielded better reflection values for all of the white materials except the plain white polyethylene sheets. It should be emphasized, however, that both methods are empirical and depend for their validity on restriction to tests of relatively nonselective materials. We have already seen that neither method can be applied to the regular kraft papers or, by analogy, to other materials exhibiting highly selective spectral reflection.

On the basis of this study, then, it is concluded that ASTM Method E 97 for routine testing and Methods D 307 and D 791 for reference are the best that can be found at present using commercial photometric equipment currently available at a reasonable cost.

Postscript

It will be evident from the previous discussion that the only true indication of the ability of a given material to reflect solar energy would be furnished by an integrated measurement throughout all three regions of the solar spectrum, ultraviolet, visible and infrared. In such a measurement, total spectral reflection should be weighted by the energy distribution of solar radiation, but not by the luminosity function. Measurements of this kind can be made with sufficient accuracy by the use of the recording spectrophotometers described earlier. In most laboratories, however, the results would not justify the time and expense involved.

As a possible alternative it might be feasible to construct a reflectometer, or modify an existing one, so that an approximation of the true value of total reflectance could be obtained in a single reading. Following the design principles of the Hunter instrument (8), the source-filter-photocell conditions for such a measurement are that

$$E_s = E_I T s K \quad (2)$$

at all wavelengths in the solar spectrum. In this equation E_s is the solar energy distribution, E_I the energy distribution of the source in the instrument, T the transmission of the filter, s the relative response of the receiver and K a constant. By using a thermopile as the receiver, s can be made equal to 1, and the problem reduces to one of finding a source-

filter combination which will duplicate the energy distribution of solar radiation. No attempt has been made to find or make such a source-filter combination, and it is not known whether or not it is possible to do so.

Acknowledgment

The study reported here was originally undertaken in connection with an assignment from C. E. Proudley, Chairman of Subcommittee III-g of ASTM Committee C-9 to Task Group VI of which W. W. McLaughlin, Testing and Research Engineer, was chairman. This assignment was to develop a recommended reflectance specification and method of test for white curing papers to include in ASTM Specification C 171 for curing paper. The work was performed under the general supervision of E. A. Finney, Director of the Research Laboratory.

Finally, it is a pleasure to acknowledge the painstaking work of O. W. Tompkins and R. D. Cook of the Spectroscopy and Photometry Section of the Research Laboratory who performed the necessary photometric tests and computations.

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