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on

MEASUREMENT OF THE COLOR OF DENTAL SILICATE CEMENTS

by

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MEASUREMENT OF THE COLOR OF DENTAL SILICATE CEMENTS

Abstract

A method for measuring the tristimulus color values of dental silicate cements in water was devised. The method based on the use of a series of porcelain standards for instrument calibration gives reproducible results with different types of colorimeters. Color evaluation by this method is consistent with evaluation by eye in most cases, but some inconsistencies requiring further study were observed.

1. INTRODUCTION

Silicate cement is the most extensively used filling material for anterior teeth. The selection of the color of this material is an important consideration in producing an esthetically acceptable reproduction of the natural tooth. Because of the need for knowing the color of dental silicates, it was decided to develop a method for scientifically measuring and specifying the colors of these materials. The method selected for the measurement and specification of the color of a silicate cement should (1) show the true color relation between the colors of the various silicates, (2) give reproducible values on the same and different instruments, (3) provide for measurement of the color of the silicate in water since dental silicates deter-

iorate when not in an aqueous solution, and (4) permit measurement of a large number of specimens in a reasonable length of time. Although no method has been standardized for scientific specification and measurement of the colors of dental materials, there are several instruments available for measuring color and there are a number of color coordinate systems by which color may be specified.

The color of an object is dependent on three things (1) the light source illuminating the object, (2) the modification of the light on reflection from the object, and (3) the reaction of the eye to the reflected light.

1.1 Standard Observer and Coordinate System

According to generally accepted theories of color vision there are assumed to be three different color receptive elements in the normal eye. One element gives the highest response when stimulated by light in the blue portion of the spectrum, one when stimulated by green light and one when stimulated by red light. All three of the elements, however, respond to some extent to light over a large portion of the visible spectrum (approximately 400 to 700 mμ).

In color measuring devices the response of the eye to light of different wavelengths can be taken into account by means of the CIE (International Commission on Illumination) standard observer curves [1] Figure 1. These curves show the relative amounts of

three primary colors required to match the color of the spectrum at any wavelength. Since no combinations of any three actual lights can be made to match all spectrum colors the primaries, Y, X and Z, on which the curves are based are unreal or imaginary. Also the primaries were chosen so that all luminosity is represented by the green primary Y while the red (X) and blue (Z) primaries represent hue only. For a more complete discussion of the basis for the CIE curves and their significance the reader is referred to standard publications on color and colorimetry [1, 2, 3].

To obtain the tristimulus values Y, X and Z for a specimen the intensity of the reflected light relative to that reflected by a perfect diffuser at each point in the visible spectrum is multiplied by factors proportional to the heights of the $\bar{y}$, $\bar{x}$ and $\bar{z}$ curves at that wave length, and all of the values for each of the three curves are summed. Practically, this can be done by measuring the reflectance of a specimen by means of a spectrophotometer at small intervals of wave length, for example every 10 mμ, and multiplying these values by factors listed for $\bar{y}$, $\bar{x}$ and $\bar{z}$ at each interval. A more rapid determination of Y, X and Z can be made by means of a colorimeter which has source-filter-photocell combinations with spectral sensitivity curves similar to the $\bar{y}$, $\bar{x}$ and $\bar{z}$ curves so that the instrument gives values directly in terms of Y, X and Z.

Colors can also be designated in other coordinates based upon the tristimulus values. Chromaticity coordinates are calculated from the following equations:

$$y = \frac{Y}{Y + X + Z}$$

$$x = \frac{X}{Y + X + Z}$$

The two chromaticity coordinates x and y and the luminosity value Y then completely specify the color.

Some colorimeters measure colors in terms of Rd, a and b where Rd represents luminous reflectance, a represents redness when plus and greeness when minus, and b represents yellowness when plus and blueness when minus. Rd, a and b are related to the tristimulus values by the following equations:

$$Rd = 100Y$$

$$a = 175(0.51 \frac{21 + 20Y}{1 + 20Y})(1.02X - Y)$$

$$b = 70(0.51 \frac{21 + 20Y}{1 + 20Y})(Y - 0.847Z)$$

Color difference in terms of the National Bureau of Standards unit of color difference which is often used to indicate change in color or difference between a specimen and a standard can be calculated from Rd, a and b by means of the following equations:

$$\Delta E = \sqrt{\overline{\Delta L^2} + \overline{\Delta a^2} + \overline{\Delta b^2}}$$

where

$$L = 10\sqrt{Rd}$$

Some colorimeters give results in terms of primaries of R, G and B, where:

$$Y = G$$

$$X = 0.783R + 0.167B$$

$$Z = 1.18B$$

1.2 Reflection of Light

Light is usually reflected from a material both diffusely and specularly. The color of a sample as a function of reflectance is primarily dependent on the diffuse reflectance, while the gloss is primarily due to the specularly reflected light. The specularly reflected light is that which is reflected at an angle equal to that of the incident light.

Diffuse reflectance from a sample is the result of scattering of the incident light by the particles in the matrix composing the surface of the sample. A sample which is a perfect diffuser reflects light according to Lambert's cosine law $I = I_o \text{ Cos } \theta$ where

I = intensity of the diffusely reflected light at any angle between 0° and ± 90°.

I_o = intensity of the diffusely reflected light normal to the surface or at 0°.

An example of a nearly perfect diffuser is a scraped surface of plaster of paris [4]. It is seen from Lambert's law that the intensity of the light from a perfect diffuse sample is spherically distributed with the surface of the sphere tangent to the sample. However, most materials are not perfect diffusers and even though the color of a sample results primarily from the diffuse reflectance it is difficult to differentiate the reflected flux into diffuse and specular components particularly in the case of semiglossy and glossy samples [4]. As a sample becomes a less perfect diffuser, its reflected intensity becomes more elipsoidally rather than spherically distributed [1, 3, 5].

The geometry of the instruments for measuring color usually is one of two types (1) angle incidence - normal viewing or (2) angle incidence - diffuse viewing. In angle incidence - normal viewing geometry a pencil of light from the source is incident on the sample at some angle and the pencil leaving perpendicular from the sample is viewed either by a light-integrating sphere having filtered photocells or is viewed by a filter photocell combination directly. The instrument geometry recommended by the CIE is 45° illumination and normal viewing [6]. In angle incidence - diffuse viewing geometry a pencil of light from the source is incident on the sample and all the pencils of light reflected from the sample are collected except

for the specular component. The diffuse light in the solid angle of 180° is usually collected by means of a light integrating sphere having filtered photocells on it.

The eye usually observes at some angle to the surface of the sample which is diffusely illuminated from all directions (over a wide angle of 180°). This means that the geometry of angle incidence - diffuse viewing is similar to the way the eye observes a surface of a sample by virtue of the Helmholtz reciprocal relation [7] or the principle of reversibility of light path. In accordance with this principle it can be concluded that the eye determines color as a function of the volume of reflected flux from an incident pencil of light.

An instrument with the geometry of angle incidence - normal viewing observes the reflected flux at an angle from the surface of the sample, therefore it measures essentially the length of a reflected flux vector from a point on the surface of the sample to the outer surface of the reflected flux ellipsoid in the case of an imperfect diffuser. The reflected flux vector length is dependent on the shape of the ellipsoid, therefore two imperfect diffusers with equal volume "ellipsoids" which have different shapes would appear identical in color to the eye but different in color to an instrument with geometry of angle incidence - normal viewing. No data on the magnitude of this difference for commercial instruments are available.

Two perfect diffusers having spherical reflected flux distribution appearing the same color to the eye, would appear the same color to the instrument since the shapes of the reflected flux distribution would be the same. The shape of the reflected flux distribution from a surface which is an imperfect diffuser is dependent on the nature of the particles in the matrix making up the surface of the specimen. Therefore, two materials which have different particles in the matrix at the surfaces might give different shape reflected flux distributions even though their flux distributions were of the same volume and thus might appear different to an instrument although they appeared identical to the eye. In selecting an instrument for measuring color of dental materials, it appears that, from an instrument geometry point of view, the geometry of angle incident-diffuse viewing should be considered since it is similar to the eye and overcomes the problem of shape of reflected flux distribution since it measures the volume.

As mentioned previously, a dental silicate cement specimen should be measured in water, since it will deteriorate out of an aqueous media. This means that the instrument must have a holder to contain the specimen in water. The holder normally has a glass window through which the specimen is illuminated and observed. The diffusely reflected light leaving the specimen surface in water must cross a water-glass and glass-air boundary before reaching the light integrating sphere or photo-

cell of the measuring instrument. It is seen from Snell's law of refraction of light that the light diffusely reflected from the specimen surface in water at an angle greater than approximately 48° to the normal to the surface of the specimen is totally reflected at the glass-air boundary; therefore, an instrument having angle-incidence-diffuse viewing suffers from distorted color measurement as a result of this critical angle effect, since it measures all the light diffusely reflected between -90° and + 90°. The light reflected beyond 48° is either lost or again reflected from the surface of the specimen as a secondary reflection which causes distortion in the color measurement. An instrument having the geometry of angle incidence - normal viewing is not affected by this critical angle effect provided the angle is less than 48°. A second effect due to the boundaries is specular or Fresnel reflectance of the diffusely reflected light from the sample at the water-glass and glass-air boundaries. The amount of Fresnel reflectance at the boundary depends on the incidence angle of the diffuse light approaching the boundary. This reflectance results in loss or distortion of primary diffusely reflected light by absorption or by re-reflection by the surface of the specimen. The Fresnel reflectance effect is noted to be less in the case of angle incidence - normal viewing geometry than in normal incidence-diffuse viewing because in the first case Fresnel

reflectance results at only one angle, 0°, where it is slight, while in the second case it results at all angles between -90° and +90° increasing as the angle varies from 0°. The instrument geometry of angle-incidence-normal viewing appears superior in overcoming these two effects where boundaries are introduced. However, these effects may be overcome practically by selecting a standard which is stable out of water and has nearly the same type of surface matrix as the silicate cement specimen. Therefore, the standard and specimen will have similar reflected flux distributions. The standard should be placed under the same conditions (in the same position) behind the boundaries as the silicate specimen, when standardizing the measuring instrument. If the standard has the same shape reflected flux distribution and is in the same position as the specimen the losses due to the critical angle effect and Fresnel reflectance are proportional therefore minimizing the error in color measurement of the specimen in reference to the standard.

Since cement specimens are usually small and somewhat translucent the instrument's illuminating light spot at the surface of the specimen should be small, a millimeter or less. The translucent nature of dental materials necessitates a small illuminating spot at the surface compared with field of view of the surface of the specimen since otherwise some of the diffusely reflected light will be lost beyond the aperature of the field of view.

1.3 Color Measuring Instruments

There are a number of instruments of various types available for measuring color, although none of these combine all of the characteristics that would be ideal in measuring the colors of silicate cements and other dental materials. The preferred instrument would be one which (1) has a small illuminating spot at the surface of the specimen, (2) is rapid, (3) measures the volume of reflected light flux distribution (similar to the eye) rather than a reflected flux vector of the volume, (4) measures color in the fundamental color units (since measurements are to be used for specification purposes), (5) is reasonable in cost, and (6) minimizes the critical angle and Fresnel reflectance errors when the incident and reflected light must pass through a water-glass and a glass-air boundary.

The spectrophotometer is a fundamental instrument in the determination of color since it measures the color of secondary standards against a primary standard MgO. However, the spectrophotometer is not a rapid instrument for determining color since a number of spectral reflectance values must be obtained to compute the color. Also, the computation takes considerable time. In response to the need for a more rapid and inexpensive instrument for measuring color, the colorimeters have been developed. The colorimeter measures the color of a specimen compared to a standard of known color. A colorimeter is rapid, requiring

only one determination for each of the three tristimulus values since it has filters which nearly match the CIE tristimulus curves $\bar{y}$, $\bar{x}$, $\bar{z}$ over its photocells thereby giving the color coordinates directly, provided it is calibrated against standards of known color values. A colorimeter which has a small illuminating spot and which gives readings in tristimulus values Y, X and Z appears to be the closest commercial approach to the preferred instrument.

2. APPARATUS AND MATERIALS

2.1 Colorimeter

The colorimeter used was a Gardner-Hunter Color exposure head [7] in combination with either a modified Gardner automatic color difference measurement unit or with a measurement unit built for this investigation consisting of a tristimulus current balance [9], and a Rubicon galvanometer as the null indicator. The exposure head having geometry of 45° incidence - normal viewing consists mainly of (1) a tungsten source, (2) a field-of-view aperature (specimen aperature), (3) a light integrating sphere, (4) three filter photo-cell combinations whose spectral sensitivities are nearly proportional to the CIE tristimulus $\bar{y}$, $\bar{x}$, and $\bar{z}$ functions, and (5) a comparison photo cell under the tungsten source; this cell acts as a constant voltage in the current balance circuit.

A glass specimen holder cell was used so that the silicate cement specimens could be immersed in water during all measurements. This cell was 40 mm in diameter and 22 mm high. The cell was painted black with the exception of an area 18 mm in diameter in the center of the 2 mm thick boro-silicate optical glass bottom. A black aluminum ring lying on the bottom of the cell served to center the specimens. The cell was positioned on the exposure head by means of a cover plate with a recess to center the cell over a 12.7 mm aperature.

Voltage at the input of the light source was controlled by means of a Sorensen 500 voltage regulator.

2.2 Color Standards

The standards against which all silicate specimens were compared were made of porcelain similar to that used in artificial teeth. This material was selected because of its stability in both air and water and its simularity in color and translucency to silicate cements. Porcelain disks 4 mm thick by 22 mm in diameter were made to order for use as standards in this investigation by the Dentists' Supply Company of New York. A series of six disks covering roughly the range of natural tooth shades of silicate cements was used. The calibration of these standards in terms of tristimulus values is discussed under 3. PROCEDURE.

2.3 Materials Investigated

The brands of silicate cement used in this study are listed in Table 1. In most cases all of the natural tooth shades of

each brand were used. With few exceptions measurements were not made on blending shades. The cements were mixed at testing consistency as defined in American Dental Association Specification No. 9 for Dental Silicate Cement. Specimens were disks 3.3 mm thick and 20 mm in diameter formed by placing the cement in a ring mold between glass plates [10]. Specimens were allowed to set in the mold (ring and glass plates) for one hour in an atmosphere of 100% relative humidity of 37°C. Specimens were then removed from the mold and were thereafter kept in distilled water at 37°C except when placed on the colorimeter for measurement.

3. PROCEDURE

3.1 Calibration of Standards

The procedure for both calibration of standards and for measurement of specimens consisted of using a set of standards to obtain an accurate but temporary linearity or calibration curve for the colorimeter and then determining values for secondary standards or for specimens on the basis of this curve. The "primary" standards used for calibration of the porcelain standards were National Bureau of Standards 45° - 0° directional reflectance standards, set A. These "primary" standards are 4 inch square porcelain on metal plaques. They are a series of greys with tristimulus values from approximately 5 to 60.

Before any measurements were made the instrument was adjusted to provide a specific area of illumination at the specimen aperature. A white piece of paper was placed on the top surface of

the aperature and the light spot was adjusted until it was an elipse with a major diameter of 9.5 ± 0.5 mm and a minor diameter of 6.2 ± 0.2 mm. The standard 35A of the reflectance standards of set A was placed over the aperature and the color difference meter was allowed to warm up for three hours.

A linearity (calibration) curve for the color difference meter was determined in the following manner. First, one of the "primary" standards of set A was placed on the surface of the aperature and care was taken to center the standard used. Then, the color difference meter was adjusted to read or "was standardized" on the tristimulus values Y, X, and Z of the standard selected. Next, each of the other standards of set A was centered on the aperature and Y, X, and Z values were measured for each. The "standardization" of the instrument was checked after measurement on each standard.

The linearity curve was obtained by plotting the difference between the true value and the measured value versus the measured value of the standards of set A. Where the true value is the value assigned the standard and the measured value is the value as measured by the color difference meter. (In the case of the standard used for "standardization" of the color difference meter the difference between the true and measured is zero since the meter was made to read the true value). A curve was plotted for each of the three values Y, X, and Z.

To determine values for the porcelain disk standards the color difference meter was "standardized" on the same standard of set A which had been used for the "standardization" of the meter in the linearity measurements. Next, one of the six porcelain disk or dental standards was centered over the aperature and a light trap was placed over it; then the Y, X, and Z values were measured. The "standardization" of the color difference meter was checked and the next of the six dental standards was measured. The remainder of the six dental standards were measured in this manner. The measured values on each of the dental standards were corrected to the true values by means of the linearity curves.

3.2 Measurement of Tristimulus Values of Specimens

Measurement of the colors of silicate cement specimens was done by essentially the same procedure as was used for calibration of the porcelain disk standards, with the exception that specimens were measured in water rather than in air.

The glass specimen cell or holder was placed over the aperature. A piece of white paper was placed flat on the inside surface of the specimen-holder window and the light spot was again adjusted until it was an elipse with a major diameter of 9.5 ± 0.5 mm and a minor diameter of 6.2 ± 0.2 mm centered in the aperature. The paper was removed and a porcelain disk dental

standard was placed in the holder and covered with water. The specimen holder was covered with a light trap consisting of a box with a flat black inside surface. The instrument was then allowed to warm up for three hours.

After the warm-up period, dental standard 34 was placed in the holder and the instrument was "standardized on" or adjusted to read the tristimulus values for this standard. Next the tristimulus values for each of the other standards, 27, 27-D, 30-R, 30 and 36 were measured. "Standardization" of the instrument on standard 34 was checked after measurement of each specimen. The light trap was over the specimen holder during all "standardization" and measurements. From the data obtained a linearity curve of difference between the true value and measured value versus the measured value was plotted. A set of linearity curves for Y, X and Z was obtained once each day. Typical curves are shown in Figure 2.

To obtain tristimulus values for silicate specimens, the instrument was again "standardized" on standard 34, a silicate specimen was then placed in the holder and the tristimulus values for the specimen were measured. "Standardization" on 34 was checked after measurement of a specimen to assure that no instrument drift had occurred. The measured values for specimens were corrected by means of the lineary curves obtained on the same day.

4. RESULTS AND DISCUSSION

4.1 Standards

The tristimulus values assigned to the porcelain disk standards and used in all measurements of the color of silicate cement specimens are shown in Table 2. These values are the averages of four determinations made independently by two different operators and on two different exposure heads. Also shown are the maximum ranges of the four determinations in each case. It will be noted that for over one-half of the values the maximum range is 0.002 or less.

It should be noted that while the values assigned to the standards are reproducible when the procedure by which they were obtained is repeated, they should not be considered to be true or absolute values. It is known that the assigned values depend to some extent upon the size of the light spot and aperature used in illuminating them during calibration although no thorough investigation has yet been made of the magnitude of this effect. The effect of light spot and aperature size is thought to be due to the difference between the characteristics of the "primary" reflectance standards and the dental standards. The reflectance standards being made of a thin porcelain coating on a metal backing are opaque, while the dental standards are somewhat translucent. Thus some of the light incident on them may be scattered beyond the aperature and lost.

A more nearly absolute determination of tristimulus values for the dental standards could probably be made by using a spectrophotometer with MgO as a primary standard. Also use of a small area of illumination in comparison to the total observed area of the dental standards would tend to eliminate the effect of scattering beyond the aperature.

4.2 Tristimulus Values for Silicate Cements

4.2.1 Variation of Tristimulus Values With Age of Specimen

Initally the color aging characteristic of dental silicates were studied. It was noted that all the tristimulus color values of the various dental silicates investigated decreased rapidly at first, but began to slow down after the first week or two. The largest change occurred in tristimulus value Y. Typical curves of variation in Y with age are shown in Figure 3. The cements of four manufacturers practically stopped decreasing in tristimulus values by three weeks, however, those of three other manufacturers continued to decrease after three weeks. The rate of decrease of tristimulus values at three weeks compared to the rate of decrease at one day is noted to be small in the case of silicates of all manufacturers investigated; therefore, the three-week tristimulus values of the various dental silicates were selected as a measure of the color.

4.2.2 Distribution of Tristimulus Values for Cements of Different Shades

The tristimulus values for all of the shades of cement measured are plotted in Figures 4 and 5. (Average values for all shades are tabulated in an appendix to this report.) These plots show the colors of the cement at three weeks for all brands except DeTrey. Most of the values shown for this cement are for 2-year-old specimens prepared for an earlier study [10].* In some instances scheduling difficulties prevented measurements of specimens at 21 days. In such cases the values shown were obtained by interpolation between measurements made before and after 21 days. In almost all cases the values shown are averages of three specimens. In Figure 4 values for Y are plotted against X. As can be seen almost all of the values fall on a straight line which deviates only slightly from the Y = X line.

In Figure 5 values of Y are plotted against Z. In this plot the cements do not fall on a single straight line but are in a group roughly paralleling the Y = Z line.

An indication of the variation of different specimens is given in Table 3 and Figure 6. In Table 3 the average range of the three specimens of each shade of each brand of cement is shown.

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* Comparison of 3-week and 2-year specimens of five shades of this cement indicated that the average variation in tristimulus values over this period was 0.009.

Figure 6 shows average and individual values for eight shades of cement.

4.2.3 Variation of Measurements Made in Different Laboratories

To obtain information on the variation in values which would be found between different laboratories using different types of colorimeters, arrangements were made with the research staffs of the L. D. Caulk Company and the S. S. White Dental Manufacturing Company to have measurements made in their laboratories for comparison with those made at the National Bureau of Standards. Specimens of eight shades of dental silicates which had aged long enough so that they were color stable, were measured in each laboratory. The eight shades were chosen from the cements of two manufacturers. Three specimens of each shade were measured. Two of the colorimeters used were Gardner Color Difference Meters one of which (L. D. Caulk) measured color in the coordinates of Rd, a and b, and the other (NBS) which measured color in tristimulus coordinates Y, X and Z. The third instrument (S. S. White) was a differential colorimeter (Colormaster) which measured color in the primary tristimulus coordinates R, G and B. All three instruments had geometries of 45° illumination and 0° viewing. All the measurements on the eight shades were transferred to tristimulus coordinates. Differences between laboratores are shown in Figure 7. The maximum range between the average tristimulus values for any

shade as measured by three different laboratories was found to be 0.015 while the minimum range was found to be 0.001. From these results shown in Figure 7, it is concluded that the method of measurement gives reproducible measurements of color between different instruments and operators.

4.2.4 Comparison of Tristimulus Values With Visual Color Interpretations

Since as shown in Figure 4, Y and X are approximately equal for the cement specimens, the line $Y = Z$ in Figure 5 is also approximately the line for $Y = X = Z$ for these specimens. Thus specimens which fall on this line would be expected to be grey with the dark shades at low values of Y and Z and the light shades at the high values. Specimens which fall above and to the left of the $Y = Z$ line ($Z < Y = X$) would tend to be yellow while those which fall below and to the right of the line ($Z > Y = X$) would tend to be slightly blue. Visual examination of the cement specimens confirms that this type of color distribution does occur for most of the materials. However, in a number of instances specimens which have similar tristimulus values appear markedly different to the eye. The reasons for these differences have not yet been determined but there are several factors which warrent investigation. One is the effect of variations in flux distribution of the light reflected by the specimen as discussed in the INTRODUCTION. A second factor

which may be involved is the problem of metameric differences or differences in the spectral distribution of the reflected light which cause specimens to appear similar under some light sources and different under other sources. Other factors such as the opacity of the specimens may be involved.

5. SUMMARY

A method of measurement of tristimulus color values of silicate cements has been developed. By means of this method, which involves the use of a series of porcelain standards, reproducible results can be obtained when measurements are made in different laboratories using different types of colorimeters. In general, the colors as measured by this method are consistent with the evaluation of colors by the eye, but some inconsistencies which require further investigation have been observed.

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Table I

MATERIALS INVESTIGATED

Brand	Manufacturer
Ames Plastic Porcelain	The W. V-B Ames, Co.
Astralit	Premier Dental Products. Co.
Baker Plastic Porcelain	Baker and Co., Inc.
DeTrey's Synthetic Porcelain	The L. D. Caulk Co.
Durodent Enamel	Oskar Schaefer
Smith's Certified Enamel Improved	Lee Smith Co.
S. S. White Filling Porcelain Improved	The S. S. White Dental Mfg. Co.
S. S. White New Filling Porcelain	The S. S. White Dental Mfg. Co.

Table 2

TRISTIMULUS COLOR VALUES OBTAINED
for
TWO SETS OF DENTAL STANDARDS

Standard	Set 1					
	Y	R_Y	X	R_X	Z	R_Z
27-1	0.562	0.004	0.544	0.003	0.601	0.001
27-D-1	.510	.001	.493	.002	.473	.003
30-1	.202	.001	.208	.003	.123	.002
30-R-1	.138	.001	.142	.001	.076	.003
36-1	.464	.001	.453	.003	.358	.001
34-1	.345	.002	.344	.003	.242	.002
	Set 2					
27-2	0.562	0.005	0.544	0.004	0.609	0.002
27-D-2	.510	.001	.493	.003	.472	.005
30-2	.206	.001	.212	.004	.127	.002
30-R-2	.138	.002	.142	.003	.076	.002
36-2	.462	.003	.451	.004	.354	.003
34-2	.345	.002	.344	.003	.243	.002

These values were obtained using an aperature of 12.7 mm (1/2 in.) diameter with an eliptical light spot having a major diameter of 9.5 ± 0.5 mm and a minor diameter of 6.2 ± 0.2 mm.

R_Y, R_X and R_Z indicate the maximum range of the four values averaged to obtain Y, X and Z.

Table 3

AVERAGE RANGE OF 3 VALUES FOR Y, X AND Z OF EACH SHADE

	R_Y	R_X	R_Z
S. S. White	0.010	0.010	0.008
S. S. White New	.011	.010	.010
DeTrey	.009	.009	.009
Durodent	.010	.009	.008
Baker	.013	.012	.009
Ames	.015	.014	.013
Smith	.008	.008	.010
Astralit	.006	.007	.008

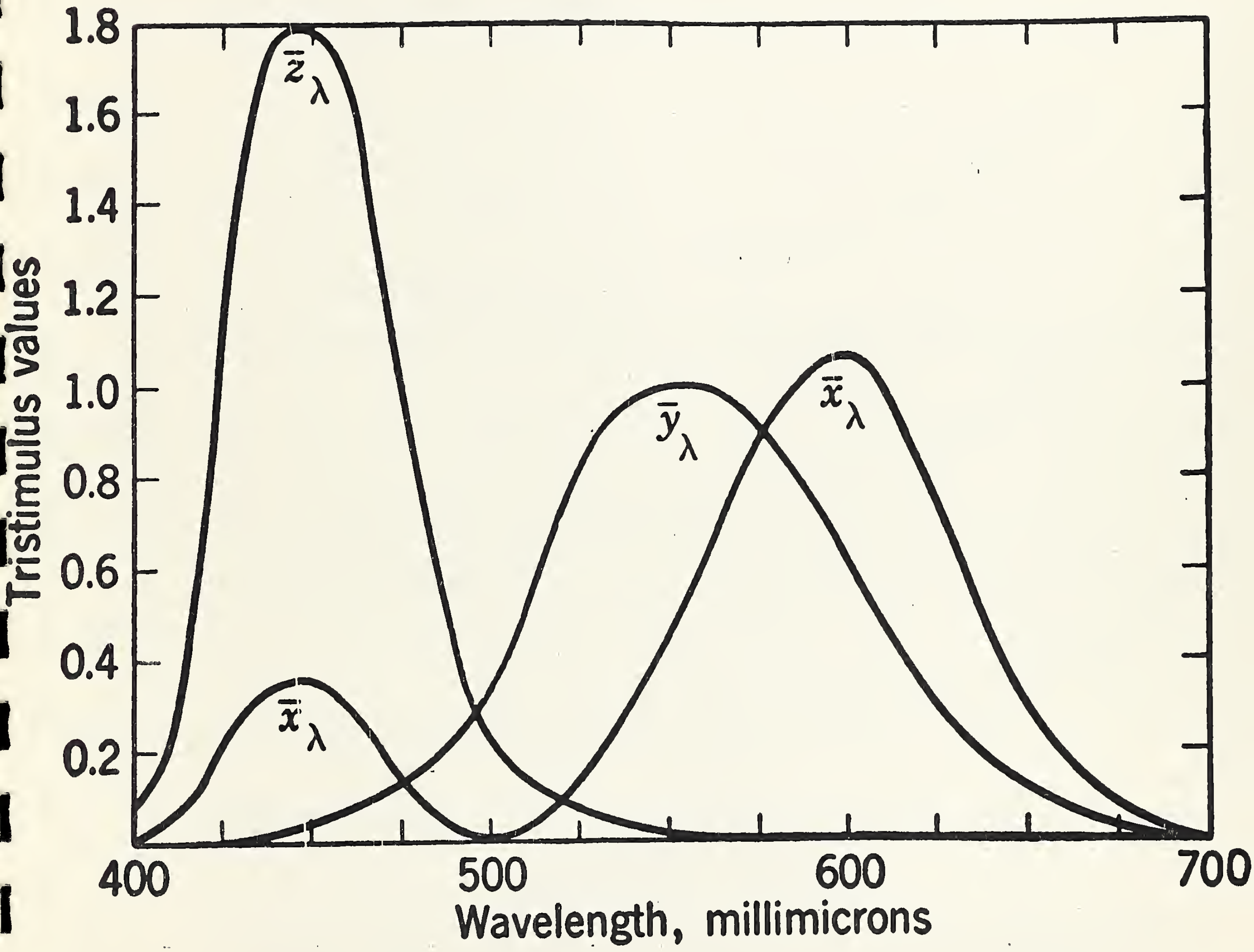

Figure 1. Tristimulus values of spectrum stimuli of unit irradiance according to the standard observer and coordinate system recommended by the International Commission on Illumination (the CIE system). By reading the three ordinates at any wave length the amounts of the three primaries required in an additive combination to color match the spectrum at that wave length may be found.

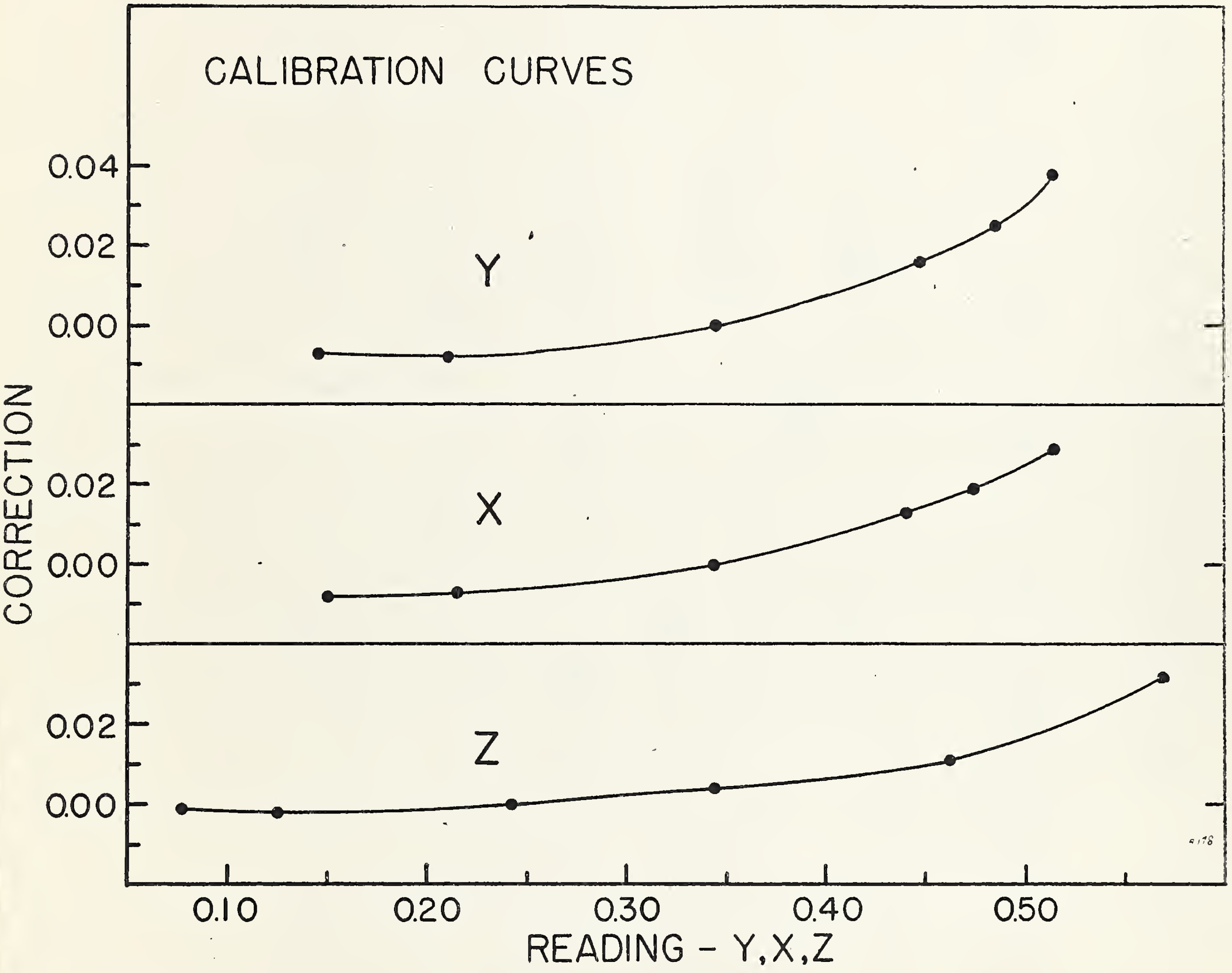

Figure 2. Typical linearity or calibration curves for the colorimeter used for determining tristimulus values of silicate cements. The curves show the correction which must be added to the readings of the colorimeter to obtain tristimulus values for specimens based on the values assigned to the standards.

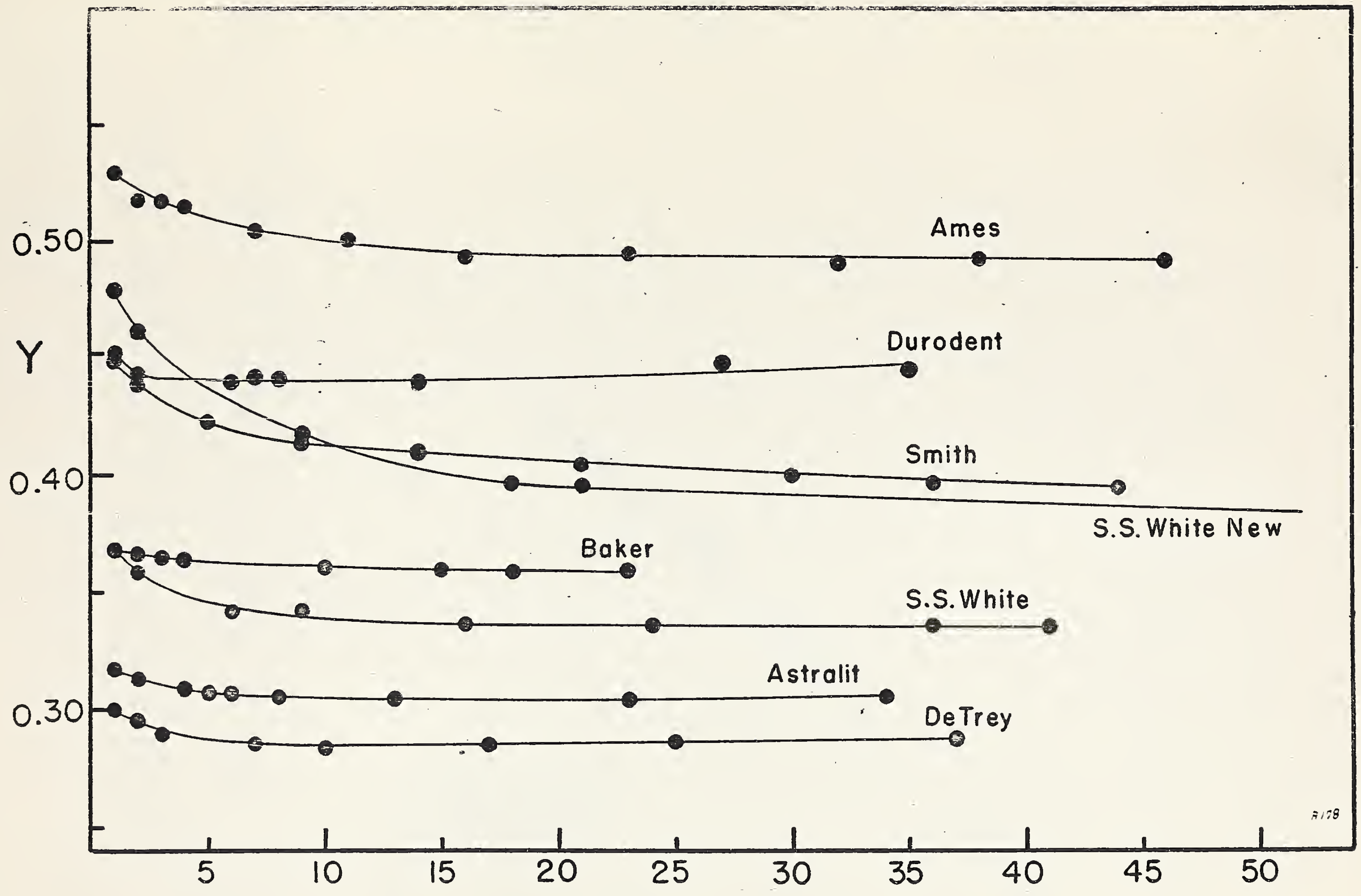

Figure 3. Effect of age of specimen on tristimulus value Y of silicate cements. The curves shown are for one shade of each brand. In general, changes of Y for all shades of the same brand were similar.

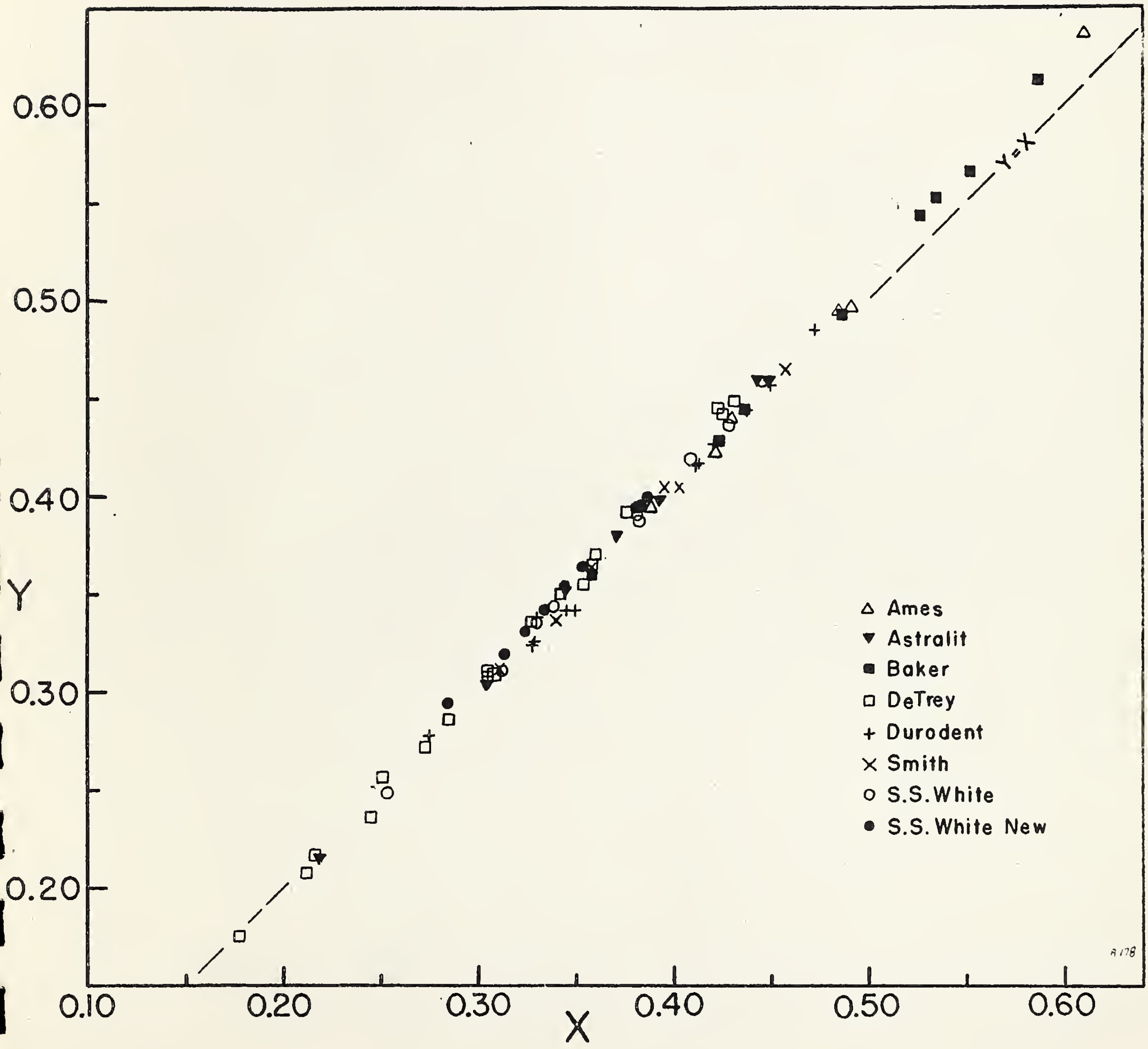

Figure 4. Tristimulus values Y and X for silicate cements

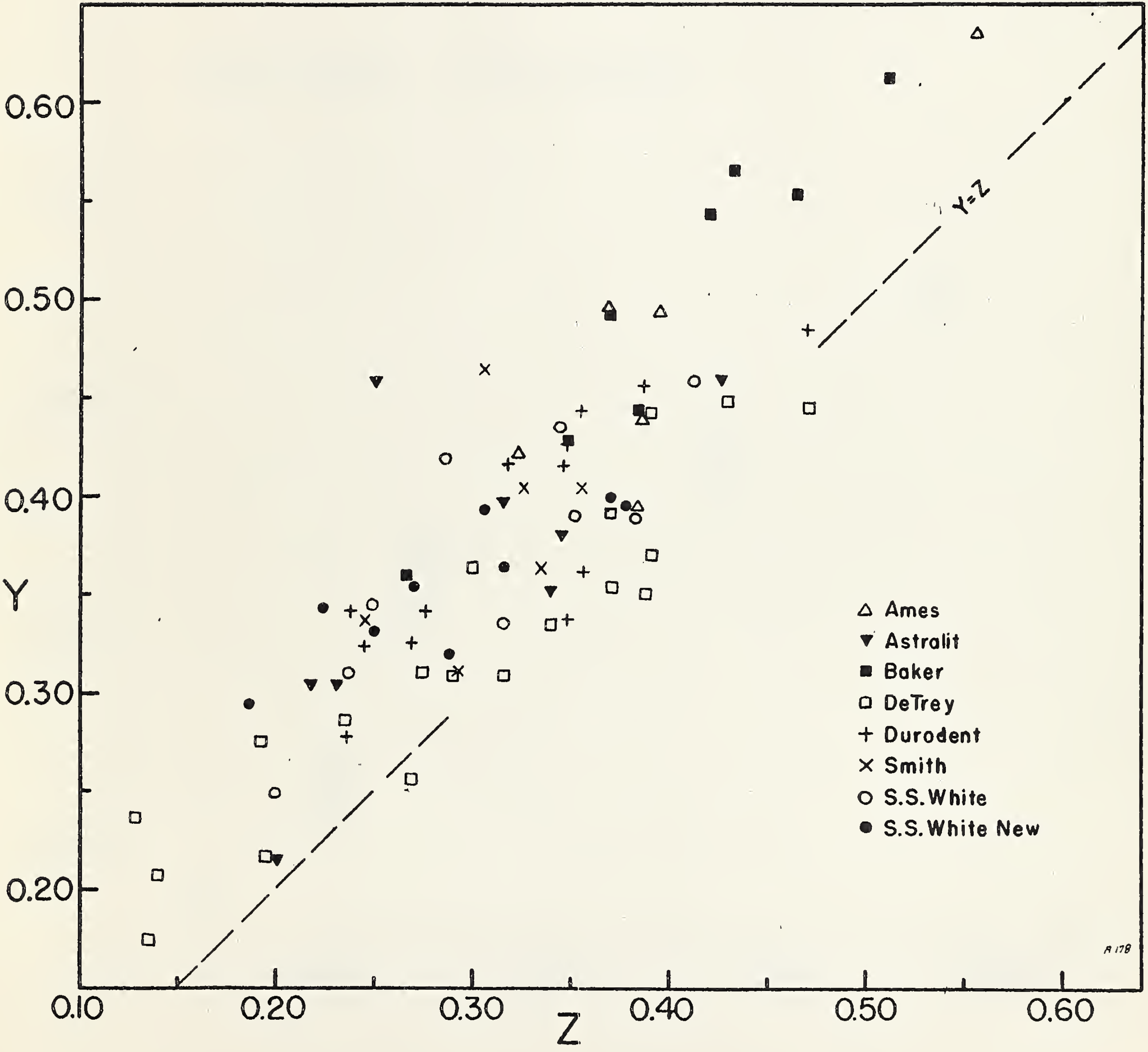

Figure 5. Tristimulus values Y and Z for silicate cements.

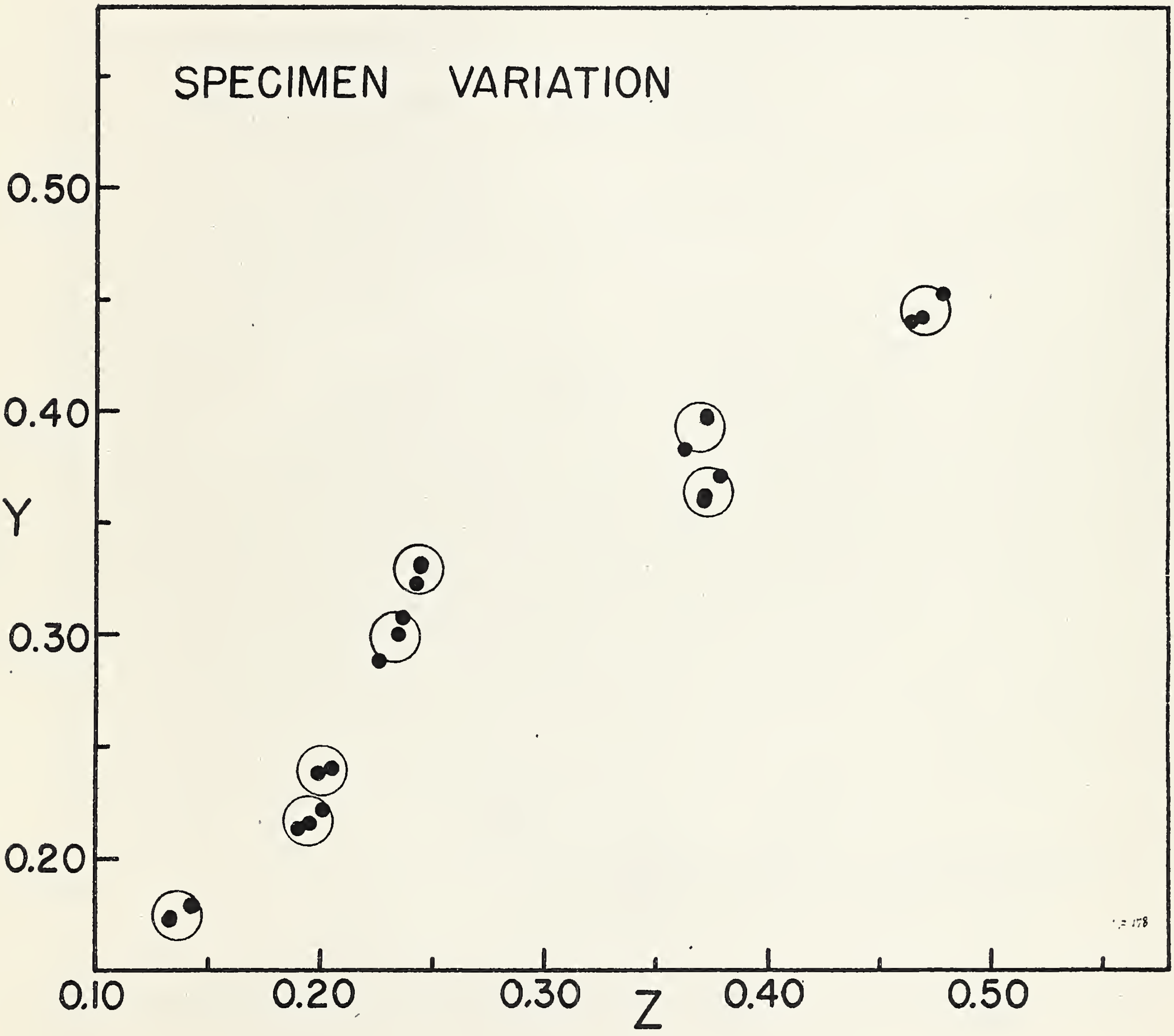

Figure 6. Typical variation tristimulus values Y and Z of three "duplicate" specimens of silicate cement. The large open circles are centered on the average value for each group of three "duplicate" specimens.

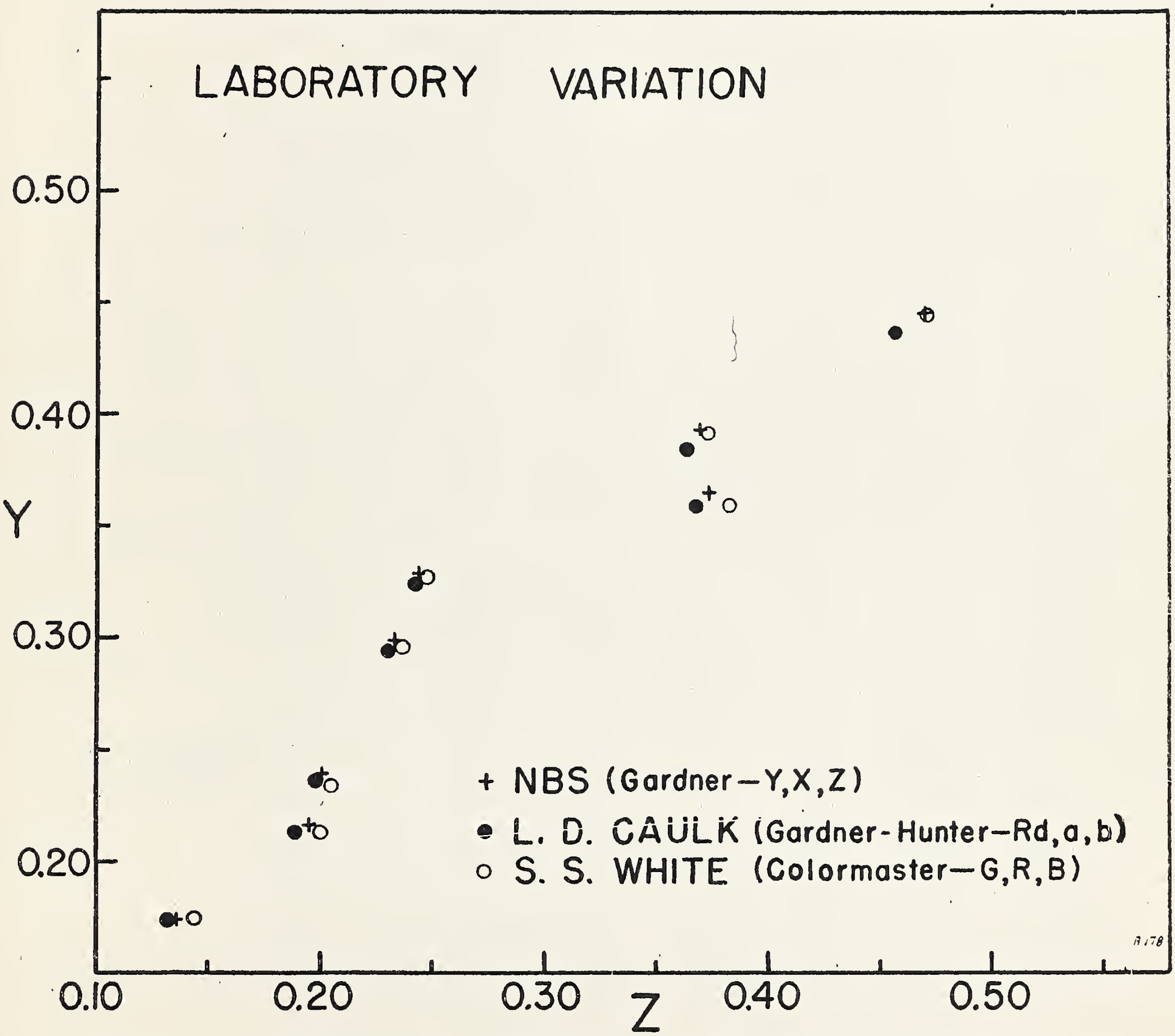

Figure 7. Variation of average values for Y and Z obtained in three laboratories for eight groups of three "duplicate" specimens. (Variation of individual specimens of each group as measured at NBS is shown in Figure 6.)

TRISTIMULUS COLOR VALUES FOR SILICATE CEMENTS AT THREE WEEKS

Brand	Shade	Tristimulus Values					
		Y		X		Z	
		Avg.	Range of 3	Avg.	Range of 3	Avg.	Range of 3
AMES	1	0.637	0.043	0.610	0.036	0.556	0.030
	2	.495	.002	.485	.002	.395	.004
	3	.497	.012	.491	.013	.369	.010
	4	.440	.025	.430	.023	.396	.023
	5	.423	.004	.422	.005	.323	.008
	7	.395	.002	.389	.003	.384	.005
ASTRALIT	20	.381	.017	.371	.019	.345	.019
	21	.398	.003	.393	.004	.306	.005
	22	.305	.000	.304	.001	.218	.001
	23	.305	.008	.300	.008	.231	.011
	24	.352	.002	.345	.003	.340	.006
	25	.460	.006	.443	.007	.426	.010
	26	.216	.003	.218	.004	.201	.002
	28	.459	.008	.449	.008	.251	.007

Appendix (Cont'd)

		Avg.	Range of 3	Avg.	Range of 3	Avg.	Range of 3
BAKER	5	0.360	0.002	0.358	0.002	0.266	0.000
	2	.544	.009	.526	.007	.420	.003
	3	.567	.010	.552	.013	.433	.008
	4	.429	.008	.424	.008	.329	.009
	1	.613	.048	.586	.041	.511	.023
	6	.493	.006	.486	.005	.370	.008
	7	.553	.016	.532	.018	.565	.018
	8	.445	.004	.437	.004	.384	.003
DeTREY	20*	.393	.015	.377	.016	.370	.010
	21*	.365	.021	.358	.021	.300	.021
	22	.272	.004	.273	.005	.192	.003
	23	.287	.003	.285	.003	.235	.000
	24	.310	.005	.309	.003	.316	.003
	25*	.371	.007	.361	.006	.391	.008
	30*	.175	.006	.177	.005	.136	.009
	31*	.208	.007	.212	.007	.140	.009
	32	.237	.000	.245	.000	.129	.002
	34*	.311	.009	.305	.009	.275	.007
	35*	.443	.013	.425	.009	.390	.009
	36*	.449	.004	.431	.003	.430	.006

* Specimens approximately two years old.

		Avg.	Range of 3	Avg.	Range of 3	Avg.	Range of 3
DeTREY (Cont'd)	40*	0.351	0.024	0.343	0.025	0.388	0.019
	41*	.445	.012	.423	.016	.471	.014
	42*	.354	.011	.345	.011	.371	.014
	43*	.336	.009	.328	.008	.340	.011
	44	.309	.001	.305	.001	.290	.003
	45*	.257	.006	.251	.010	.269	.009
	46*	.217	.008	.217	.007	.195	.011
DURODENT	3	.485	.013	.473	.008	.470	.004
	15	.342	.005	.345	.007	.276	.006
	20	.457	.006	.450	.005	.387	.006
	21	.444	.008	.438	.008	.355	.006
	22	.326	.005	.329	.005	.269	.007
	23	.278	.008	.275	.007	.236	.011
	24	.362	.010	.358	.010	.357	.012
	25	.338	.008	.330	.008	.348	.011
	NH65	.416	.021	.412	.024	.346	.017
	NH66	.427	.020	.421	.018	.348	.013
	NH67	.417	.008	.413	.006	.318	.004
	NH69	.324	.004	.328	.004	.245	.003
	NH87	.342	.009	.350	.009	.238	.005

* Specimens approximately two years old.

Appendix (Cont'd)

		Avg.	Range of 3	Avg.	Range of 3	Avg.	Range of 3
LEE SMITH	20	0.405	0.010	0.396	0.009	0.356	0.012
	21	.405	.002	.403	.004	.326	.000
	22	.465	.005	.458	.004	.306	.004
	23	.337	.001	.340	.002	.245	.002
	24	.364	.002	.358	.002	.335	.007
	25	.312	.031	.311	.028	.292	.033
S.S.WHITE	20	.459	.012	.446	.012	.412	.000
	21	.436	.013	.429	.015	.344	.005
	22	.419	.008	.409	.004	.286	.015
	23	.389	.018	.382	.018	.383	.020
	24	.336	.003	.330	.005	.316	.006
	25	.390	.003	.382	.004	.352	.002
	26	.311	.019	.312	.016	.237	.011
	27	.249	.004	.253	.006	.203	.009
	E	.345	.009	.339	.008	.249	.002

Appendix (Cont'd)

		Avg.	Range of 3	Avg.	Range of 3	Avg.	Range of 3
	1	0.396	0.005	0.383	0.007	0.378	0.009
	2	.400	.017	.387	.017	.370	.020
	3	.365	.006	.354	.005	.316	.004
	4	.320	.004	.313	.004	.288	.008
S.S.WHITE NEW	5	.394	.016	.381	.016	.306	.009
	6	.355	.008	.344	.008	.270	.009
	7	.332	.021	.324	.022	.250	.021
	9	.343	.009	.334	.009	.224	.004
	10	.295	.013	.285	.002	.186	.004

U.S. DEPARTMENT OF COMMERCE
Frederick H. Mueller, Secretary
NATIONAL BUREAU OF STANDARDS
A. V. Astin, *Director*

THE NATIONAL BUREAU OF STANDARDS

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Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

Chemistry. Organic Coatings. Surface Chemistry. Organic Chemistry. Analytical Chemistry. Inorganic Chemistry. Electrodeposition. Molecular Structure and Properties of Gases. Physical Chemistry. Thermochemistry. Spectrochemistry. Pure Substances.

Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

Building Technology. Structural Engineering. Fire Protection. Air Conditioning, Heating, and Refrigeration. Floor, Roof, and Wall Coverings. Codes and Safety Standards. Heat Transfer.

Applied Mathematics. Numerical Analysis. Computation. Statistical Engineering. Mathematical Physics.

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Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

NBS