Automated Facility for Measurement of Pavement Sample Reflectance Characteristics

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Design methods for roadway lighting based on the concept of luminance require information on the light-reflecting properties of pavement surfaces. To evaluate and classify typical pavement materials used in North America, an automated test facility was designed and built at the University of Toronto for the Ontario Ministry of Transportation and Communications. The reliability of the measurements has been assessed in terms of equipment stability and the measuring procedure followed. Results indicated that the measuring accuracy was not limited by the equipment but by the measurement procedure. An estimate of system accuracy based on the limited number of samples measured to date is included. Measurements of the variation of pavement characteristics with variation of angle of observation showed that the direction of traffic need not be identified with accuracy greater than ±5°. Measurements were also made on the effect of the sample size on the characteristics. Results indicated that, for samples with a particle size of about 3 mm, two 15-cm-diameter samples that yield four sets of data would provide reliable values for the relevant characteristics. A measuring program to assess a larger number of samples and a variety of surface textures is in progress.

Roadway lighting design methods of past decades were based on illuminance (i.e., incident light), and simple manual calculations were possible by using precalculated utilization curves issued for each luminaire.

Design methods based on the concept of luminance (1) (i.e., reflected light) are more closely related to the night driving task than illuminance but were not generally used because of the complexity of the calculations. The development of the electronic computer has removed this obstacle, and luminance methods are now being incorporated in design procedures. This new approach, however, requires the evaluation and classification of pavement surfaces with respect to their light-reflecting properties (2).

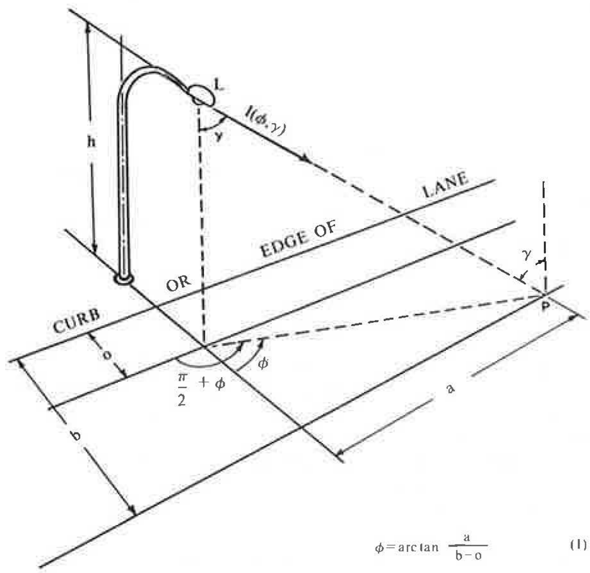
An automated apparatus for the measurement of the reflection properties of highway pavement samples has been developed at the University of Toronto for the Ontario Ministry of Transportation and Communications (3). The measurements are made in accordance with the recommendations of the International Commission on Illumination (CIE) (4). A pilot sequence of measurements on approximately 30 samples was carried out to determine both the equipment accuracy and the scattering of the measured data for different specimens of the same pavement.

LUMINANCE CONCEPT IN COMPUTER METHODS OF ROADWAY LIGHTING DESIGN

The point-by-point calculation of illuminance at a grid point P (E_p) is shown in Figure 1. Luminance is calculated from the corresponding illuminance value for the same grid point (P), but only that portion of the light that is reflected toward the driver's eyes is considered. As shown in Figure 2, the illuminance contribution (E_p) from each luminaire is multiplied by a coefficient q, which depends on the light-reflecting properties of the pavement surface. For each driver position, or each lane, the calculated luminance arrays are different (unlike illuminance arrays, which remain the same).

The luminance coefficient (q) is defined as the ratio between the luminance at point P and the horizontal illuminance at the same point (E_p). It is a function of four angles: α, β, γ, and δ, as shown in Figure 2. Thus,

Figure 1. Illuminance parameters.

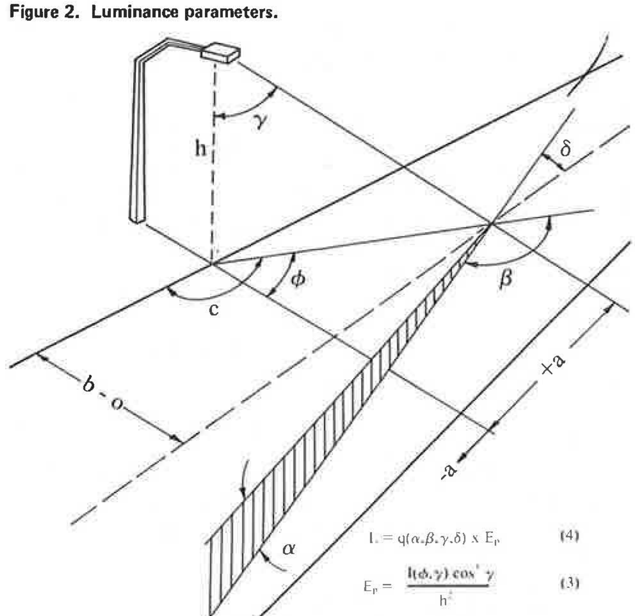


$$\phi = \arctan \frac{a}{b-o} \quad (1)$$

$$\gamma = \arctan \frac{\sqrt{a^2+(b-o)^2}}{h} \quad (2)$$

$$E_p = \frac{I(\phi,\gamma)\cos^3\gamma}{h^2} \quad (3)$$

Figure 2. Luminance parameters.



$$L = q(\alpha,\beta,\gamma,\delta) \times E_p \quad (4)$$

$$E_p = \frac{I(\phi,\gamma)\cos^3\gamma}{h^2} \quad (3)$$

Where: q = luminance coefficient
α = observation angle from horizontal
β = angle between planes of observation and light incidence
γ = light incident angle from vertical
δ = angle between plane of observation and road axis
φ and C as indicated

$$L = q(\alpha, \beta, \gamma, \delta) \times E_p \quad (1)$$

where q is the luminance coefficient [$(cd/m^2)/lx$], being a function of the angles α, β, γ, and δ for each particular pavement surface, and E_p is illuminance. In the metric system, the luminance coefficient [expressed as $(cd/m^2)/lx$], has a maximum value for perfect white diffuser of $q_{max} = 1/\pi = 0.318$.

At each grid point P, values of luminance must be calculated for each luminaire and then added together. The luminance created by one luminaire at a given point (subscript i) according to Equation 1 is as follows:

$$L = q(\alpha_i, \beta_i, \gamma_i, \delta_i)\, E_p\, (\phi_i, \gamma_i) \quad (2)$$

This is in accordance with Figure 2.

Adding the values for n luminaires, substituting for E_p, neglecting the influence of δ, and setting $\alpha = 1°$, the following equation for luminance is obtained:

$$L = \sum_{i=1}^{n} q(\beta_i, \gamma_i) \left\{[I(\phi_i, \gamma_i) \cos^3\gamma_i]/h^2\right\} \quad (3)$$

In conjunction with the work that went into the CIE recommendations, standard reflectance tables have been established in the form of reduced coefficients: $r = q \cos^3\gamma$ for $\alpha = 1°$. This combination of $\cos^3\gamma$ and q simplifies the reflectance measurements. Also, the combination $r = q \times \cos^3\gamma$ leads to tabulated values of r, which decrease with an increase in γ or $\tan\gamma$, whereas the pure reflectance function (q) alone increases tremendously for β being equal to or close to zero (5).

The number (n) of luminaires to be taken into account should include a longitudinal distance of 12 x h or more beyond the point P. Additional luminaires beyond this range contribute insignificantly. By substituting $r = q \times \cos^3\gamma$, Equation 3 can be rewritten as follows:

$$L = \sum_{i=1}^{n} \left\{[I(\phi_i, \gamma_i) r(\beta_i \tan\gamma_i)]/h^2\right\} \quad (4)$$

CLASSIFICATION OF ROAD SURFACES

The results of measurements from a sample pertaining to a particular road surface are tabulated in terms of $\tan\gamma$ and β and can be used as a design input after storage in a computer memory array. Figure 3 represents a typical array for a dark asphalt pavement surface. CIE-sponsored research in Europe has addressed the question of classifying such measurements into a manageable number of specularity classes. Usually there are four classes for dry pavements, although some suggestions go as far as eight in this category. More recently, there has been work done on four additional classes pertaining to wet pavement surfaces (6,7).

The most commonly known dry classes are designated RI, RII, RIII, and RIV, and an alternative system is known as N1, N2, N3, and N4--all proposed for European-type pavements (4,8). In the United States and Canada, the same or similar classes may apply, which will be subject to some research investigations. The example in Figure 3 is for RIII.

Classification of measured road surfaces is carried out by using certain parameters, which are Q0 (or q_0), S1, and S2, where Q0 or q_0 equals an average luminance coefficient over a defined roadway ground area or space angle; S1 = r(0,2)/r(0,0) (i.e., β = 0, $\tan\gamma$ = 2; and β = 0, $\tan\gamma$ = 0); and S2 = Q0/r(0,0).

The value Q0 can be understood as a parameter correlated to the average luminance of the pavement surface. The values S1 and, especially, S2 are parameters that indicate the degree of specularity.

It is stipulated that surfaces with identical parameters are equivalent, with very little differ-

Figure 3. Standard reflection table R-III.

tan γ \ β°	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294	294
0.25	326	326	321	321	317	312	308	308	303	298	294	280	271	262	258	253	249	244	240	240
0.5	344	344	339	339	326	317	308	298	289	276	262	236	217	204	199	199	199	199	194	194
0.75	357	353	353	339	321	303	285	267	244	222	204	176	158	149	149	149	145	136	136	140
1	362	362	352	326	276	243	226	204	181	158	140	118	104	100	100	100	100	100	100	100
1.25	357	357	348	298	244	208	176	154	136	118	104	83	73	70	71	74	77	77	77	78
1.5	353	348	326	267	217	176	145	117	100	86	78	72	60	57	58	60	60	60	61	62
1.75	339	335	303	231	172	127	104•	89	79	70	62	51	45	44	45	46	45	45	46	47
2	326	321	280	190	136	100	82	71	62	54	48	39	34	34	34	35	36	36	37	38
2.5	289	280	222	127	86	65	54	44	38	34	25	23	22	23	24	24	24	24	24	25
3	253	235	163	85	53	38	31	25	23	20	18	15	15	14	15	15	16	16	17	17
3.5	217	194	122	60	35	25	22	19	16	15	13	9.9	9.0	9.0	9.9	11	11	12	12	13
4	190	163	90	43	26	20	16	14	12	9.9	9.0	7.4	7.0	7.1	7.5	8.3	8.7	9.0	9.0	9.9
4.5	163	136	73	31	20	15	12	9.9	9.0	8.3	7.7	5.4	4.8	4.9	5.4	6.1	7.0	7.7	8.3	8.5
5	145	109	60	24	16	12	9.0	8.2	7.7	6.8	6.1	4.3	3.2	3.3	3.7	4.3	5.2	6.5	6.9	7.1
5.5	127	94	47	18	14	9.9	7.7	6.9	6.1	6.7										
6	113	77	36	15	11	9.0	8.0	6.5	6.1											
6.5	104	68	30	11	8.3	6.4	5.1	4.3												
7	95	60	24	8.5	6.5	5.2	4.3	3.4												
7.5	87	53	21	7.1	5.3	4.4	3.6													
8	83	47	17	6.1	4.4	3.6	3.1													
8.5	78	42	15	5.2	3.7	3.1	2.6													
9	73	38	12	4.3	3.2	2.4														
9.5	69	34	9.9	3.8	3.5	2.2														
10	65	32	9.0	3.3	2.4	2.0														
10.5	62	29	8.0	3.0	2.1	1.9														
11	59	26	7.1	2.6	1.9	1.8														
11.5	56	24	6.3	2.4	1.8															
12	53	22	5.6	2.1	1.8															

Values tabulated with Q_0 = 0.07

S1 = 1.11, S2 = 2.38

Note: Table of reflectance data: $q \cos^3\gamma \times 10^4$

Figure 4. System block diagram.

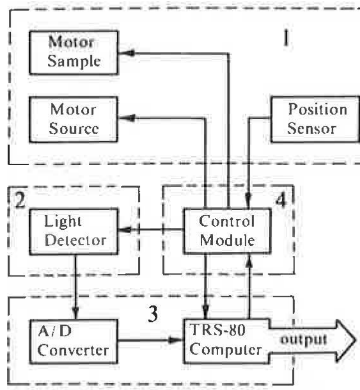
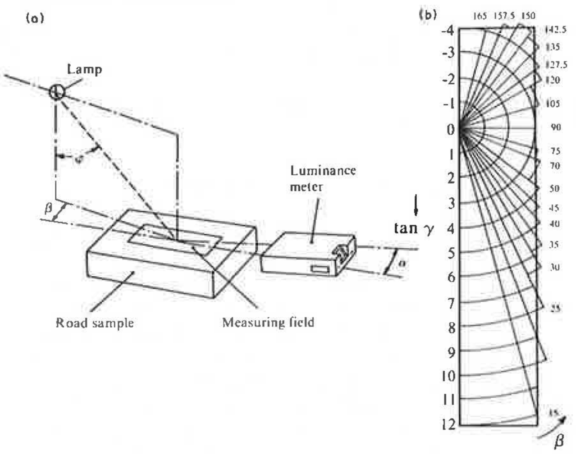


Figure 5. (a) Coordinates of lamp sample luminance meter system and (b) range of angles β and γ.



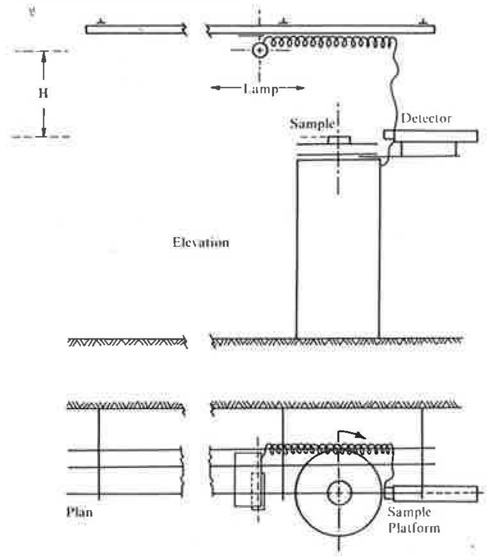
ences in the remaining r values, as measured and tabulated in the format of Figure 3.

DESCRIPTION OF APPARATUS

The Ontario road reflectance matrix photometer is an instrument designed to measure r-values as a function of β and tanγ. The apparatus consists of four major subsystems, as shown in Figure 4 and described below:

1. A mechanical system with photoelectric sensors that position the light source and the sample in accordance with the specified range of parameters β and γ as defined in Figure 5, thereby maintaining a constant height of the source.
2. An optical detection system that is rigidly attached to the sample and maintains the constant viewing angle α [see Figure 6 (note that scale is approximately 1:20)]. The core of this system is a 5x0.15-cm sector of a spherical lens of 35-cm focal length with a 1x0.5-mm iris located in the focal plane and an RCA 6217 photomultiplier tube, the cathode of which is located in the proximity of the focal plane. The dimensions of the lens sector define a field of view of approximately 5x8 cm while the focal plane iris defines the acceptance angle of 5' in the vertical and 10' in the horizontal planes.
3. An integrated data-acquisition and dedicated microcomputer system that stores the elements of the measured r-matrix, applies appropriate weighting factors, numerically integrates them, and evaluates the parameters S1, S2, and Q0. The output is in the form of a printout of the r-matrix with the associated values of the three derived parameters. If desired, there is a provision for storing the output on an audio tape. This feature is about to be augmented by providing the option for storing the output on a magnetic disc.
4. A control module that uses the primary inputs from the photoelectric sensors of the mechanical subsystem and, in conjunction with the microcomputer, governs the operation of the other subsystems.

Figure 6. Apparatus layout.



The module operates in an open-loop mode. Experience has shown that the intrinsic stability of the system is of the order of 1 percent in a controlled environment (temperature and humidity). The introduction of a closed-loop control system with continuous calibration monitoring is currently under consideration.

APPARATUS PERFORMANCE

The major performance parameters of the system are described in this section. The light source employed is a 400-W quartz halogen lamp moving on horizontal rails 60 cm above the sample level. The range of lamp movement is from directly above the sample to approximately 7 m away. With the integration time of about 15 ms, the signal-to-noise ratio provided by the detector employed (RCA 6217 photomultiplier) was about 10 dB for the weakest signal observed.

The choice of size of the field of view was dictated by the requirement that the equipment be designed to operate on circular samples of about 15 cm in diameter. The relative sizes of the field of view and the sample allow one to obtain two independent sets of measurements from one sample.

Experience has shown that the measurement cycle for one sample (two viewing fields), which includes mounting and alignment time, is about 1 h.

ASSESSMENT OF MEASUREMENT RELIABILITY

The reliability of measurements by the apparatus is affected by two phenomena:

1. Equipment stability and
2. Measurement procedure, such as mounting and alignment of the sample.

Table 1. Standard deviation of displaced measuring field characteristics.

Sample	Q0/$\bar{Q}$0 Left	Right	Δ (%)	S1/$\bar{S}$1 Left	Right	Δ (%)	S2/$\bar{S}$2 Left	Right	Δ (%)
EB 2-1	1.03	0.97	4.3	1.04	0.95	6.4	1.00	1.00	0
EB 6-1	1.01	0.99	1.4	0.95	1.06	7.8	0.98	1.02	2.8
EB 6-2	1.05	0.94	7.8	1.02	0.97	3.5	1.07	0.92	10.5

Table 2. Standard deviations of relative values of displaced measuring field characteristics evaluated for varying number of samples.

No. of Samples	Δ(Q0/$\bar{Q}$0) (%)	Δ(S1/$\bar{S}$1) (%)	Δ(S2/$\bar{S}$2) (%)
3	4	4.7	4.9
2 (EB2-1, EB6-1)	2.6	5.8	1.6
2 (EB6-1, EB6-2)	4.6	4.9	6.3
2 (EB2-1, EB6-2)	5.1	4.1	6.1

Equipment stability was tested by performing repeated measurements on a pavement sample in situ in the apparatus. The standard deviations for the characteristics Q0, S1, and S2 based on four measurements were as follows: Q0 = 0.7 percent, S1 = 2.2 percent, and S2 = 0.9 percent.

The repeatability of measurements on a sample being removed and remounted was checked on 13 samples. The standard deviations of relative variations of the three characteristics were as follows: Q0 = 2.7 percent, S1 = 5.9 percent, and S2 = 4.0 percent.

Comparison of the two sets of standard deviations indicates that the measurement accuracy is not limited by the equipment but by the measurement procedure.

Assuming that the values given above are good approximations of their limits for a large number of measurements, the results obtained can be interpreted by stating that the ranges of relative deviations from the means that occur with 95 percent probability are limited by the following values: 5.5 percent for Q0, 12 percent for S1, and 8 percent for S2.

It was then deemed desirable to test the sensitivity of the measured data with respect to the variation of the direction of observation or, from the operational point of view, the accuracy with which the traffic direction has to be specified. To this end, measurements were performed on samples in the normal traffic direction (0°) and rotated ±5° from this nominal position. The average values of the standard deviations for the three directions of observation were as follows: Q0 = 3.5 percent, S1 = 5.3 percent, and S2 = 3.5 percent.

The standard deviations for the S1 and S2 values for the misorientated observation directions, although close, are somewhat smaller than the corresponding set of values for the repeatability measurements. This may be due to the fact that 13 samples were measured in the repeatability measurements and 25 in the misorientation measurements. These results indicate that the traffic direction need not be specified with an accuracy greater than ±5°.

The next feature of the measurement process to be considered was the effect of the size of the viewing field on the results obtained. Measurements were made of two adjacent measuring fields on three of the samples investigated. Tables 1 and 2 list the relative value of the characteristics Q0/$\bar{Q}$0, S1/$\bar{S}$1, and S2/$\bar{S}$2 for each sample. Also included in the tables are the standard deviations of the relative values evaluated for all six measurements of the three samples and for three groups of four measurements on three different pairs of samples. The standard deviations range from 1.6 to 6.3 percent.

The particle size in the surfaces measured was of the order of 3 mm, and from the above data it is estimated that measurements performed on two 15-cm-diameter samples that yield four sets of data would provide reliable values for both the parameters (Q0, S1, and S2) and the elements of the r-matrix. The accuracy of these measurements would be consistent with the accuracy of the equipment and the measuring procedure.

No results are available currently for surfaces with a larger particle size. It is expected that either a larger field of view may be required or a larger number of samples would be necessary to obtain reliable data. The latter option would be preferable due to the convenience of obtaining and handling smaller-sized samples.

PILOT MEASUREMENTS FOR ONTARIO PAVEMENTS

The Lindsay, Ontario, test sections (9) were chosen to carry out pilot measurements on pavements of known composition. About 20 samples were measured from various sections, and each sample was measured at least three times in slightly changed angular position (+5°, 0°, and -5°). Comparing the results with the Erbay Atlas data in Figures 7a and b, it was found that, in terms of specularity (S1), the surfaces range from S1 = 0.49 to S1 = 1.45 (i.e., from below the standard surface RII to above RIII). The most specular surfaces contain at least 60 percent limestone coarse aggregates, and the least specular surfaces contain more than 70 percent igneous rocks. In the latter, the igneous stone projections feel gritty; in the former, the limestone projections feel smooth and polished. The surfaces were exposed to moderate traffic from summer 1978 to fall 1980.

The test sections had been skid tested by the old, nonstandard skid trailer in summer 1980. In Figure 8, the skid numbers (SNs) from these tests are plotted versus the specularity parameter (S1).

There is a weak negative correlation (-0.64) between the SN taken at 80 km/h and the parameter S1. Stronger correlations may be expected between low-speed or "zero-speed" SNs and S1. In any case, it is certain that the degree of specularity of pavement surfaces is related to the degree of smoothness or polish of coarse aggregates.

CONCLUSIONS

The Ontario road reflectance matrix photometer, as designed and tested to date, has provided measurement results that are well within the accuracy of existing design methods. The instrument provides reliable, rapid, and automatic measurements of pavement samples as small as 15 cm in diameter. Although the viewing angle (α) is fixed at 1° in the present apparatus, modifications are in progress to vary the range of α.

The availability of this test facility with its rapid measuring time and small sample size should assist highway agencies in the acquisition of relevant data for modern highway lighting design by the luminance method.

Figure 7. Plot of log S1 versus log S2.

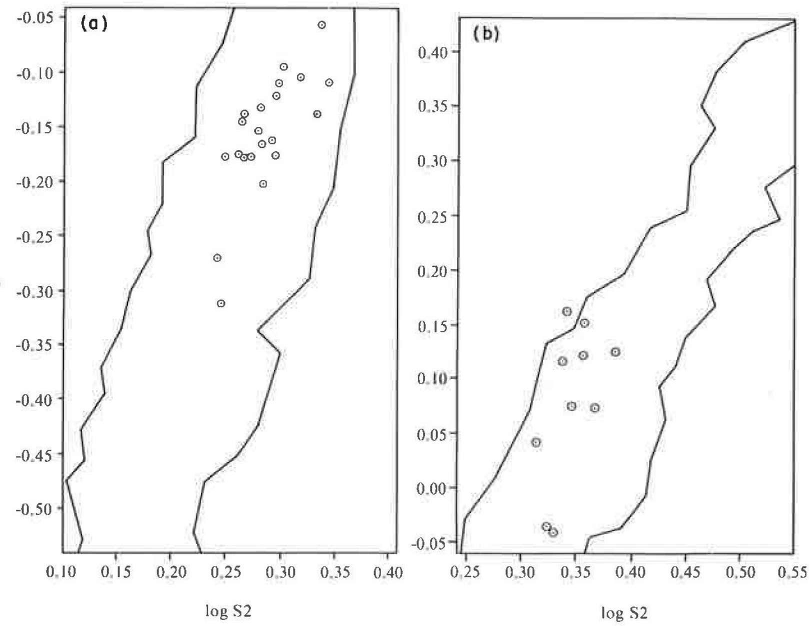
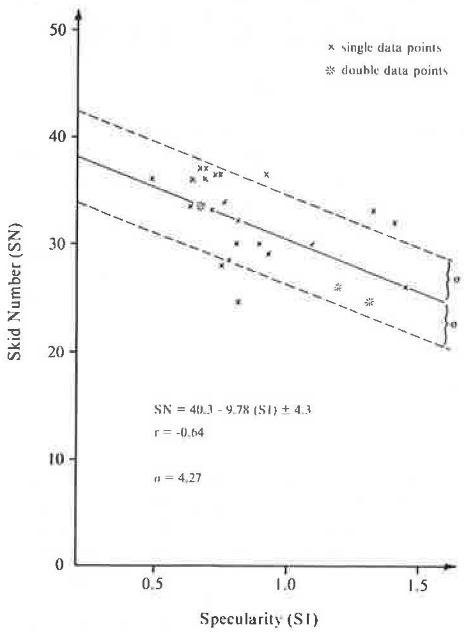


Figure 8. Plot of SN versus specularity.



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