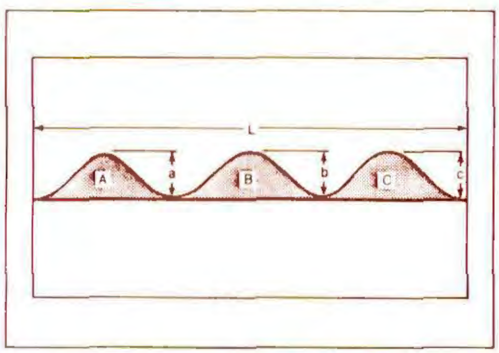
Report No. FHWA/RD-81/107

PB82-202565

AGGREGATE MICROTEXTURE: PROFILE MEASUREMENT AND RELATED FRICTIONAL LEVELS

October 1981

Final Report



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$$\text{Average shape factor} = \frac{\text{average height}}{\text{average width}} = \frac{\frac{a + b + c}{3}}{\frac{L}{3}}$$

U.S. Department of Transportation

Federal Highway Administration

Offices of Research & Development
Materials Division
Washington, D.C. 20590

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FOREWORD

This report presents the results of a study of aggregate surface microtexture (features less than 0.5mm in size) and its correlation with frictional forces measured on the aggregate.

The aggregate microtexture is characterized by three measurement parameters: asperity (peak) heights, asperity density (number of peaks per unit length of profile), and asperity shape factor (height to width ratio). The measurements were correlated with polish values determined with the British Pendulum Tester.

This report is being distributed to appropriate members of the FCP project team.

Charles F. Scheffey
Director, Office of Research

NOTICE

Technical Report Documentation Page

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15. Supplementary Notes

This staff study, done by the Paving and Structural Materials Group, (HRS-22), is a work unit of FCP Project 4G, "Substitute and Improved Materials to Effect Materials and Energy Conservation in Highways," managed by E. T. Harrigan.

16. Abstract Reduction of skidding accidents is an ongoing objective of the highway community. Since skid resistance depends, in part, on the frictional characteristics of the pavements surface, improvements in pavement friction are constantly sought. In order to have adequate wet-weather friction, a pavement must have surface relief or texture. This texture may be divided into two size ranges: macrotexture, those features over 0.5mm in size; and microtexture, those features less than 0.5mm in size.

In this study microtextural profiles were measured using an optical image analysis system. The profiles were characterized by three parameters: average asperity (peak) height, average asperity density (peaks per unit length of profile), average asperity shape factor (peak height to width ratio). These measurements were correlated with test results (polish values or PVs) using the British Pendulum Tester, which measures the friction of a pavement surface mainly due to microtexture. The resulting correlation coefficients indicate that the shape factor measurement correlates the best with the British Pendulum Tester. Optimal (highest corresponding PVs) asperity shape factor values appear to be in the range of 0.16 - 0.20. Aggregate types measured included both natural and synthetic material, as well as natural aggregate treated with an impregnant.

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INTRODUCTION

A decrease in the number of skidding accidents is a continuing goal of the highway engineer. Since skid resistance is influenced by pavement friction, among other factors, improvement in a pavement's initial frictional characteristics as well as better methods for maintenance of friction under traffic have constantly been sought. Past research has indicated that to have good skid resistance, any pavement, whether new or old, must possess a certain surface topography or texture. This texture may be divided into two-size ranges, each of which contributes to the overall pavement skid resistance. Macrotexture (those surface features greater than 0.5mm in height) provides a drainage system for water on the pavement surface, thereby preventing buildup of a layer of water under a vehicle's tires with resultant hydroplaning. In addition, the macrotexture provides the hysteresis component of the tire/pavement friction; that is, the resultant energy loss as the tire deforms around the pavement asperities. Microtexture (those surface features less than 0.5mm in height) is necessary to penetrate the film of water on a wet pavement so that intimate contact with the tire surface is made; this provides the adhesion component of the tire/pavement friction. The ultimate goal of surface texture research is to determine optimal levels of macrotexture and microtexture so that pavements can be designed with these optima in mind.

In order to determine optimal levels of pavement texture, measurement techniques are required to adequately characterize or quantify those textural components which contribute to pavement friction. Numerous procedures have been developed to measure surface macrotexture, either directly (surface tracers, profilometers, etc.) or indirectly (sand patch, grease test, outflow meter, etc.) and in a given application, these methods work quite well. However, microtexture is much more difficult to measure because of the size of the features involved. Contact profiling systems become less practical at the lower end of the scale simply because of the size limitations in styli and attendant hardware. The one measuring device which is in limited use is the British Pendulum Tester (see reference 1, ASTM E303, Standard Method for Measuring Surface Frictional Properties Using the British Pendulum Tester) which measures microtexture indirectly, by sliding friction. However, it cannot completely isolate the microtextural effects from the effects of other features of the surface with which the sliding pad comes in contact. It doesn't distinguish between characteristics of the microtexture; it only determines that some surfaces possess higher frictional levels than others. What is needed is a measurement (or series of measurements) which would characterize the microtexture of a surface so that those features which contribute to good frictional values can be identified and their optimal characteristics determined. This was the objective of the research reported here.

MEASUREMENT EQUIPMENT AND TECHNIQUES

Before measurement of microtexture could begin, equipment had to be obtained which was capable of measuring features in the size range required (possibly down to 10 m). Since no off-the-shelf instrument was available with the required capability, an image analysis system was constructed under contract for use in this study. The specifications for the equipment were written so that in addition to measuring texture profiles, it would also have the capacity to perform air void analyses on portland cement concrete samples. Also, since it is programmable, it can be made to perform other measurements as the need arises. Figure 1 is a photograph of the image gathering portion of the device. It consists of a binocular microscope mounted on a specially designed stage which is capable of programmed movement in both the "X" and "Y" directions in steps of 0.005in. (12.7 m) in order to scan a sample. Objectives of 2.5, 4, 10, and 20 power are available on the rotating nosepiece. The object to be viewed may be either examined directly through the microscope, or its image may be transmitted to the image scanner (TV camera) which then relays it to the main console shown in figure 2. The image is displayed on the screen for viewing by the operator and also is available for measurement using the processor controlled system. For a more detailed description of the system's hardware, see reference 2.

For texture measurement, profiles across a sample's surface are produced by the illumination technique. An opaque straight knife edge is included in the path of light within the illuminator. This knife edge keeps half the beam of light from impinging on the object being viewed and produces a sharp, straight line of demarcation between the illuminated and the dark halves of the field of view. Where this demarcation line intersects the sample surface, it takes on a shape reflective of a profile across the sample at that location. To translate this profile into a true vertical profile, a correction factor is applied (in the software) which varies according to the angle of the illumination from the horizontal.

The profile is transmitted to the display screen for measurement and analysis. The equipment differentiates between features based on their relative position on the gray scale. Therefore, in order to make the profile surface easy to detect, a high contrast was desired. To accomplish this, the sample's surface is coated with a thin layer of white paint to produce a white, evenly reflective surface. This makes the profile a particularly distinct line of contact between the bright illuminated area and the dark unlit portion of the sample. The threshold of detection (gray level) is then easily set so that all the features of the profile are accurately detected (see figure 3).

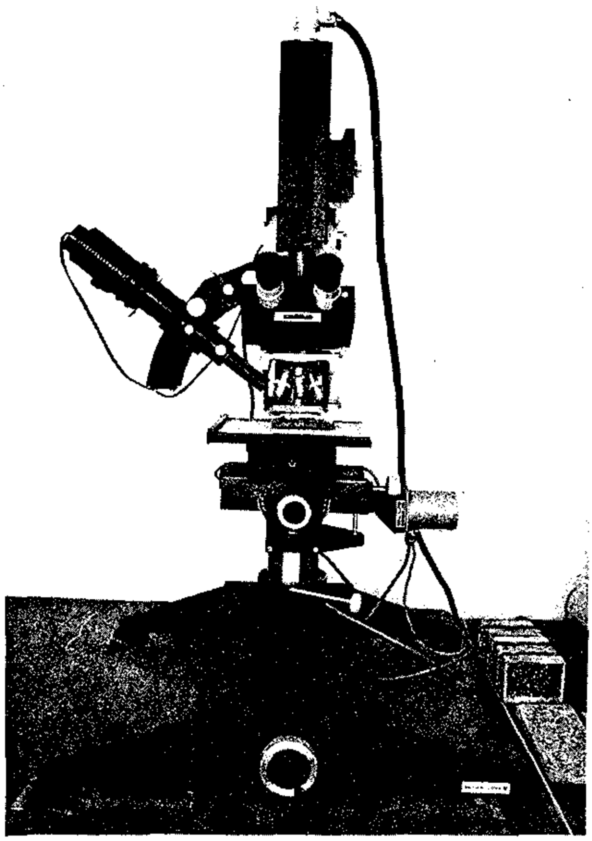


Figure 1. Image gathering portion of the microtexture measuring device.

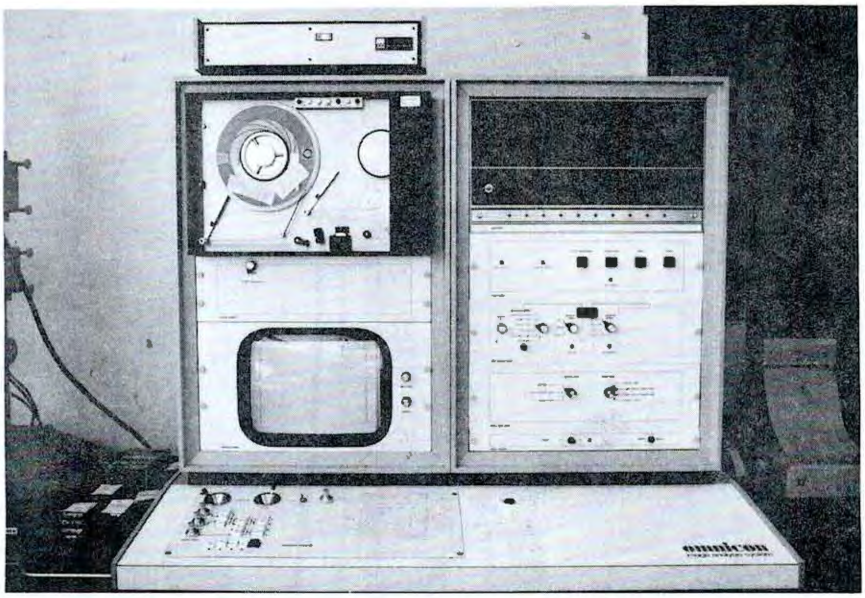


Figure 2. Main console (display and image analysis) portion of the microtexture measuring device.

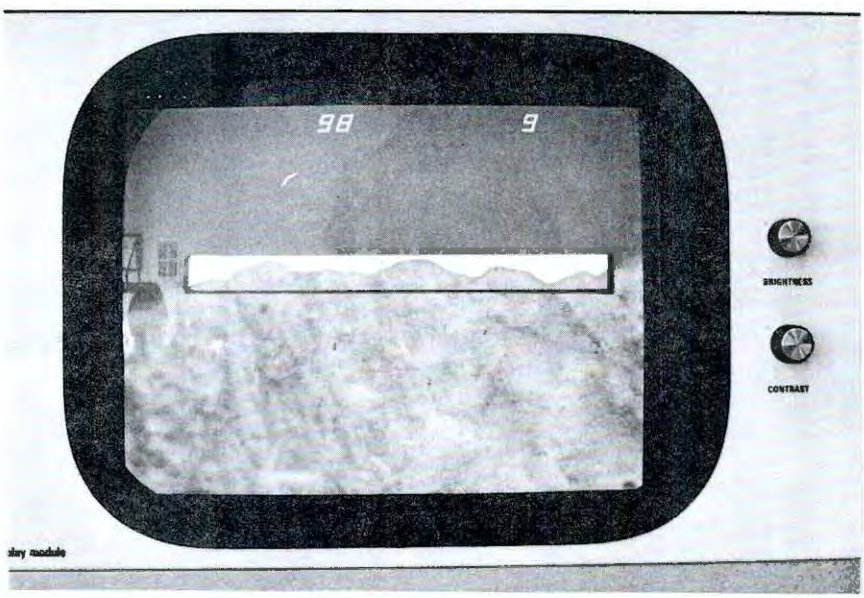


Figure 3. Typical aggregate profile (length is approximately 2mm).

Using software developed for the equipment, 2 direct and 1 derived parameters of the profile are obtained (see figure 4). The average asperity height is the average "Y" dimension of all the peaks (asperities) as measured from their tops to the bottom of the adjacent valley on the right and is expressed in micrometers. The average asperity density is computed by dividing the number of peaks in a profile by the profile length with units of peaks/micrometer. The derived parameter is a measure of the cross-sectional shape of the asperities, and is calculated by dividing the average height by the average width. This parameter is called the shape factor.

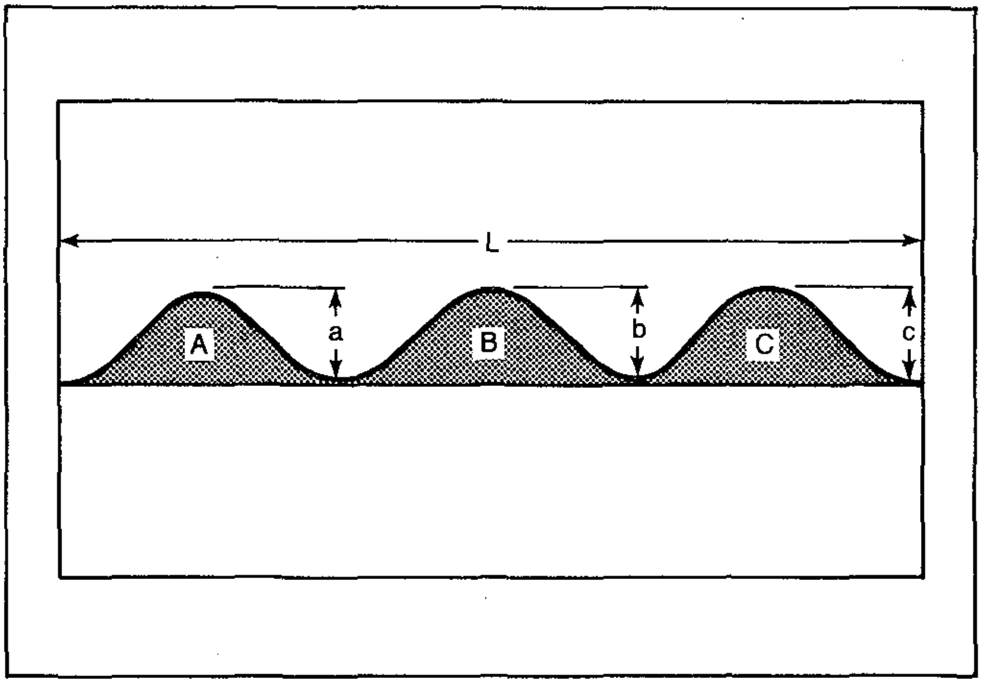
DATA COLLECTION

Sample Size Determination

The data collection dealt with measurement of profiles on specimens prepared for polish testing on the British Wheel (see figure 5). This sample type was chosen for measurement because it contains only coarse aggregate particles (see figure 6) and, therefore, the additional variables of binder and fine aggregate did not have to be considered. The first series of tests were run to determine the sample size (number of profiles) required to obtain representative, repeatable measurements on a specimen. Since the specimen is composed of a number of particles, the repeatability was tested for individual particles as well as the specimen as a whole. It was found after repeated measurements on Specimen 15A (a limestone) and 27B (an artificial aggregate) that 7 profiles per aggregate piece were sufficient to arrive at average asperity density, average asperity height and average asperity shape factor within ±4, 9, and 12 percent, respectively, of the estimated true sample mean values, as determined by measurements of 20 profiles on a single aggregate piece. Increasing the number of profiles per piece within a reasonable range did not produce sufficient improvement in accuracy to justify the additional work.

The determination of the minimum number of stones necessary for measurement on a given specimen in order to get averages representative of that specimen was more difficult. First, in many cases, even when dealing with crushed aggregate there can be substantial differences in surface texture among the pieces of aggregate making up a single specimen. This variation relates to the heterogeneity of the original rock material. To compensate for this variation, texturally distinct types of aggregate pieces were chosen for measurement in proportion to their percentage of occurrence in the entire British Wheel specimen.

Second, because of the cross section of the tire tread used on the British Polishing Wheel, those aggregate pieces near the centerline of a given specimen undergo more polishing action during a run than those aggregate pieces near the lateral edges. Therefore, to more accurately assess the effects of the British Wheel test on micro-texture, aggregate pieces selected for measurement were located in a strip along the central portion of the specimen.



$$\text{Average asperity density} = \frac{\text{count of peaks}}{\text{length of profile}} = \frac{3}{L}$$

$$\text{Average asperity height} = \frac{\sum \text{heights}}{\text{count}} = \frac{a + b + c}{3}$$

$$\text{Average shape factor} = \frac{\text{average height}}{\text{average width}} = \frac{\frac{a + b + c}{3}}{\frac{L}{3}}$$

Figure 4. Definitions of texture parameters as measured.

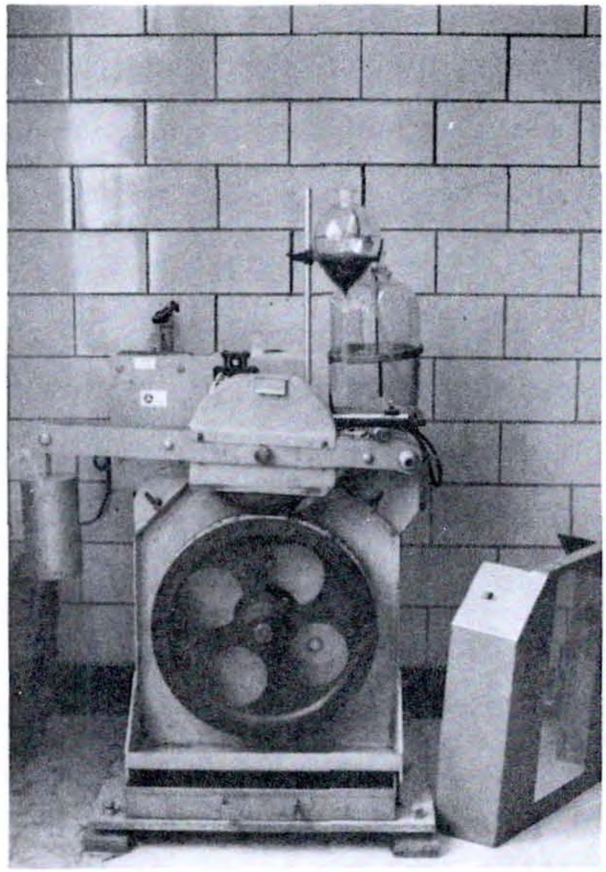


Figure 5. British polishing wheel apparatus.

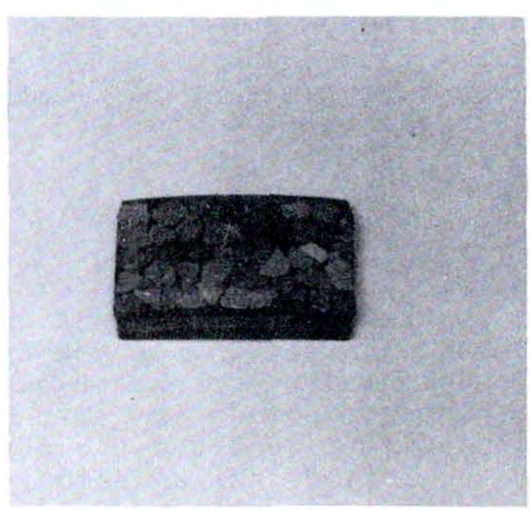


Figure 6. British wheel specimen.

A third factor in the selection of aggregate pieces for measurement within a specimen is their surface shape and orientation. Although the procedure for fabrication of the specimen stresses the orientation of individual aggregate pieces with more or less planar surfaces against the bottom of the mold (what will be the exposed surface of the specimen), some pieces may not have even a reasonably planar surface. Also, shifting during casting of the specimen may cause some aggregate pieces to be below the general level of the specimen surface or tilted from the general surface. These variations in the making of the specimen may result in certain aggregate pieces not being in full contact with the tire during the test. If these stones were chosen for measurement, they would indicate the aggregate has a lesser susceptibility for polishing than may actually be the case. Therefore, for this study, aggregate pieces with proper shape and positioning in the specimen were measured.

With these precautions in mind, trials were run to determine how many stones (using 7 profiles/stone) need to be measured in order to get an accurate representation of the whole specimen. It was determined that 5 stones were sufficient to determine the standard measurements within ±5 percent for the average height, ±5 percent for the average density, and ±5 percent for the average shape factor of the overall specimen mean values as estimated by repeated measurements of the 11 centerline stones on specimen number 27B.

Significance of Parameters Measured

1. Average Asperity Height

In order to maintain contact between the tire and the road during wet-weather driving, the microtexture must penetrate the thin-water film which is always present on the surface, even when sufficient macrotexture is present to prevent hydroplaning. Therefore, the microasperities must have an average height which is sufficient to penetrate the film but not so great as to create excessive tire wear (0.01-0.1mm according to reference 3).

2. Average Asperity Density

Another important factor in determining the skid resistance contribution of the microtexture is the spacing of the microasperities, that is, the number of peaks (asperities) per unit length or unit area of pavement surface. The density of the microasperities largely determines the adhesion component of skid resistance, which is the portion due to contact between the tire and the road surface. The larger the average asperity density, the more contact area present, and therefore the higher the adhesion.

3. Average Shape Factor

The average asperity shape factor is a computed parameter calculated by multiplying the average asperity height by the average asperity density. It increases with an increase in either of the other two parameters. Since average density is, for these measurements, very close to the inverse of average asperity width, the shape factor is a close approximation of average asperity height to average width ratio. Therefore, higher values are indicative of sharper asperities which would tend to adhere to the tire better than rounded ones.

Correlation with British Pendulum Tester Measurements

To test the ability of the measured microtextural parameters to predict associated frictional levels, they had to be correlated with a measurement thought to best isolate the frictional effects due solely to microtexture. The British Pendulum Tester (BPT) is the best available device for the correlation, particularly when dealing with British Wheel specimens. Any influence macrotexture may have on the BPT is nearly constant since the British Wheel specimens are composed of one size (1/2-3/8 in. [12.5-9.5mm]) of aggregate pieces which are fairly evenly spaced across the specimen. As a result, differences in polish values should be due mainly to differences in specimen microtexture. The BPT was used in accordance with ASTM E 303, Standard Method for Measuring Surface Frictional Properties Using the British Pendulum Tester (see reference 1).

Specimens examined included those from (1) polishing tests previously run at the Fairbank Highway Research Station; and (2) concurrent studies on improved aggregate materials conducted by Brookhaven National Laboratory (BNL) and the U.S. Bureau of Mines at Tuscaloosa (BMT). The aggregates polished in the FHWA Laboratory included a variety of natural and artificial aggregates from across the country. In the BNL work, improvement in the wear resistance of several types of natural aggregate was sought by means of impregnation with a variety of polymer materials. The BMT investigated the manufacture of aggregates by ceramically processing mainly low cost or no cost waste products. Table 1 in the appendix is a listing of all specimens examined and their compositions.

For each of the 3 profile measurements, correlations with polish values (PV's) obtained using the BPT were evaluated. Figures 7, 8, and 9 are plots of average asperity density versus PV, average asperity height versus PV, and average asperity shape factor versus PV. Linear single regression, linear multiple regression, and various exponential regression models were used to compare the data; however, the linear regression gave the best correlations and the results are shown on each figure. As can be seen, the shape factor produced the best correlation (.74) with PV for all available data.

In an attempt to obtain higher correlation coefficients, the shape factor data was grouped according to source and also whether taken before or after the polishing test had been run on the specimens.

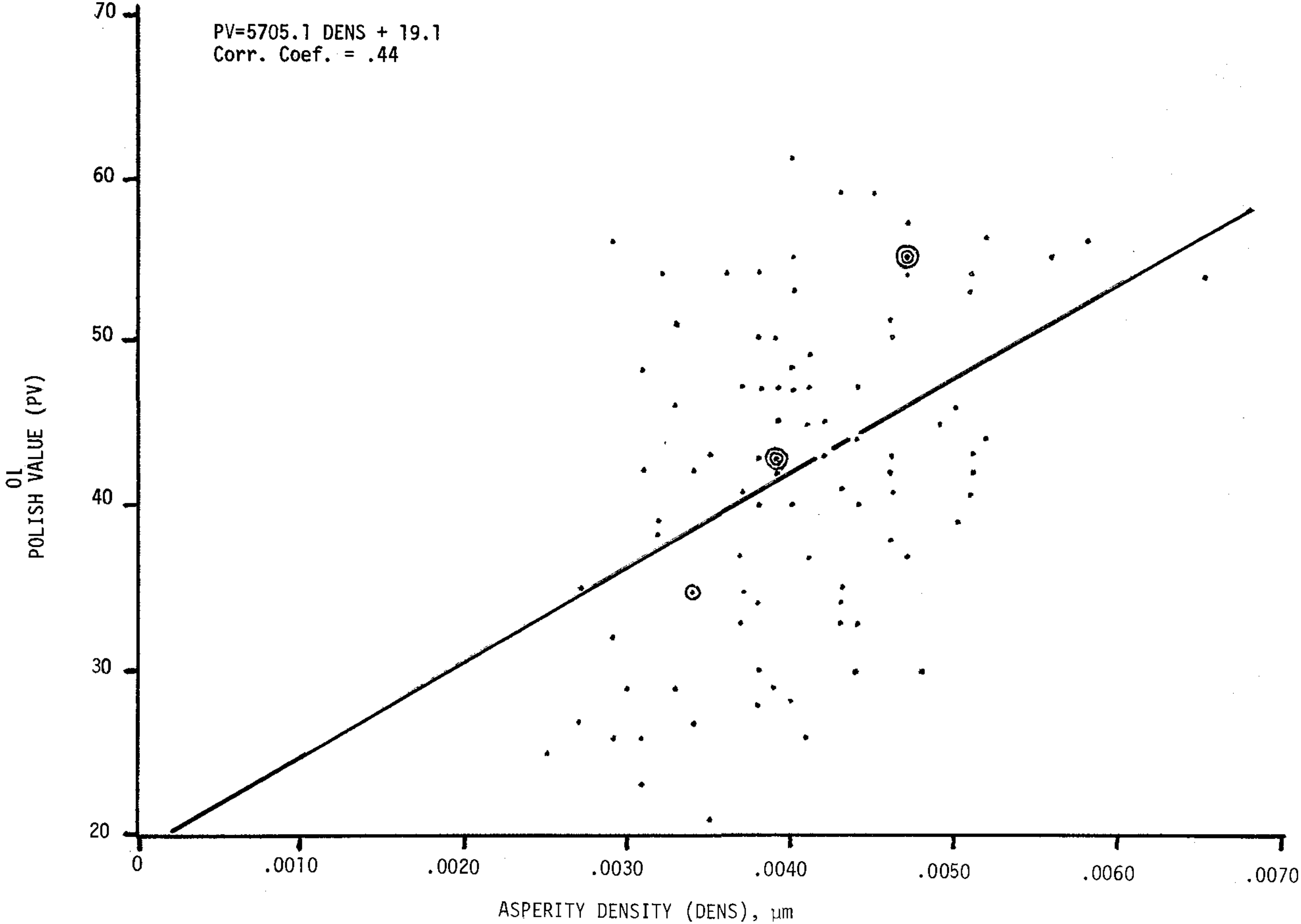


Figure 7. Polish Value Versus Average Asperity Density for All Specimens Examined

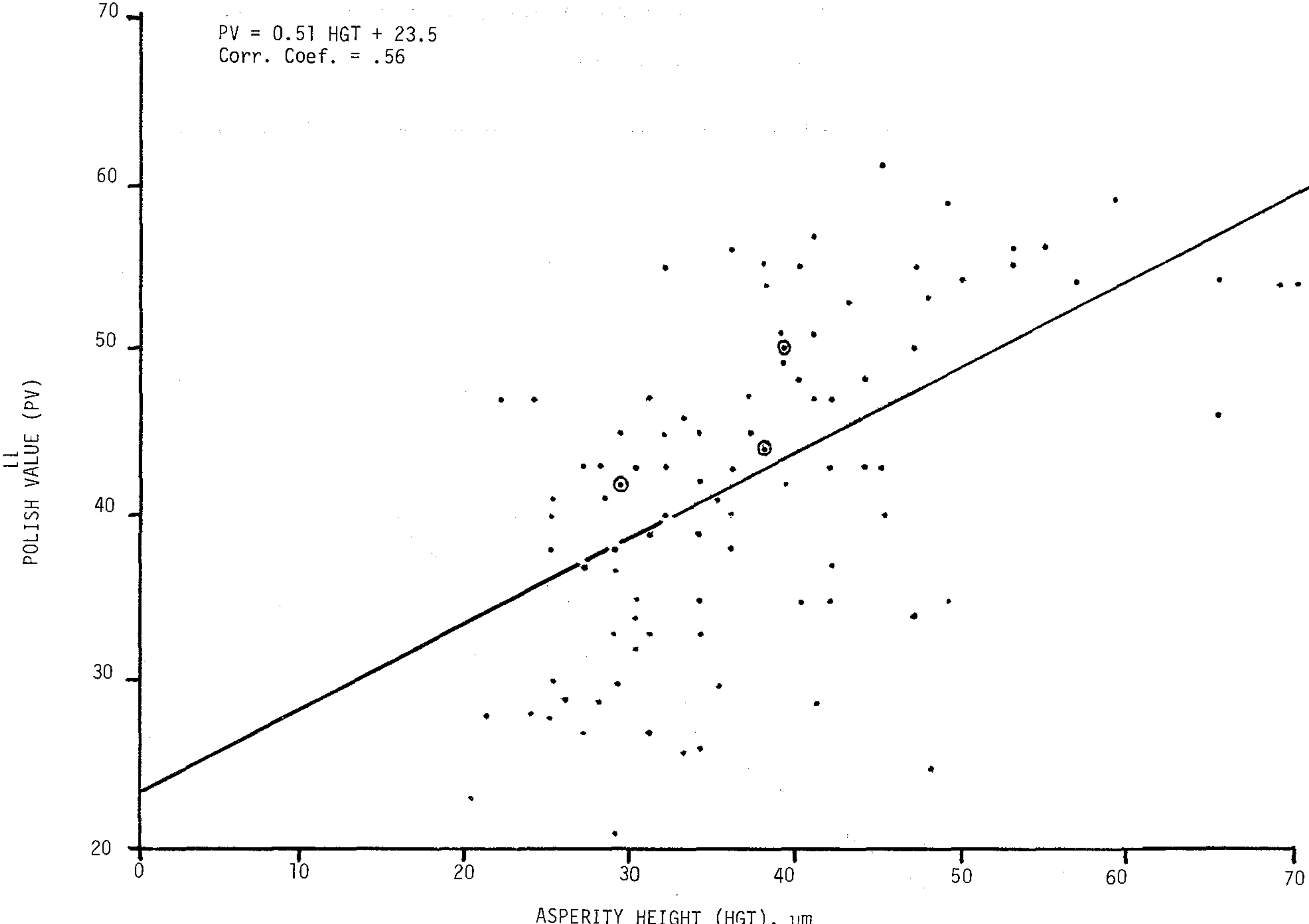


Figure 8. Polish Value Versus Average Asperity Height for All Specimens Examined

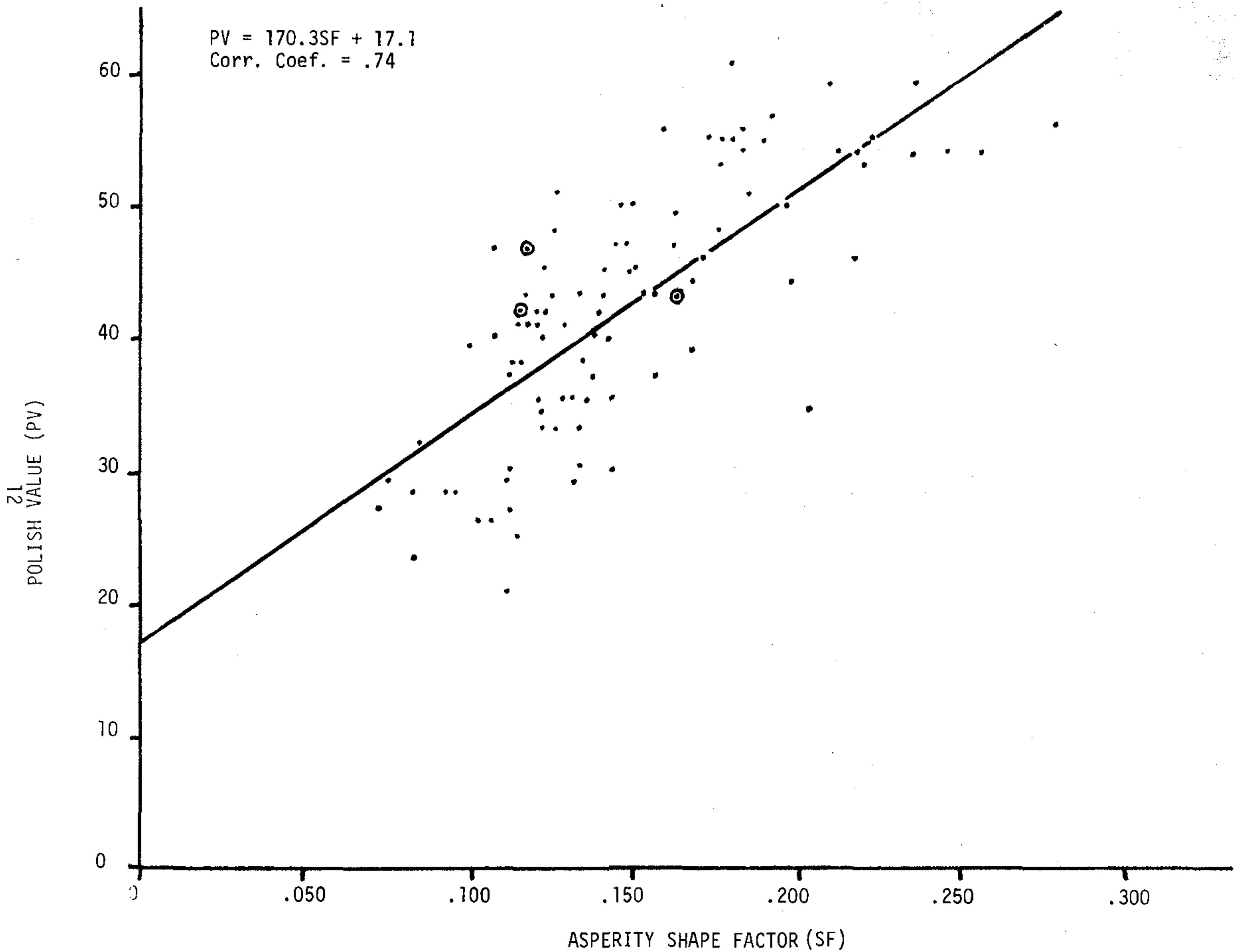


Figure 9. Polish Value Versus Average Asperity Shape Factor for All Specimens Examined

If the data is grouped according to sample source, the correlation coefficients are only approximately 0.60. This indicates that before and after polishing specimen data relate somewhat differently to PV, even when dealing with the same general types of material. For the BMT data (figure 10), many points were at or near the upper limits of PV encountered, for a range of shape factors (0.16 - 0.27). This seems to indicate that there is a value of shape factor for which maximum frictional levels (as indicated by PV) are obtained, and above which no additional frictional benefits are realized. This distribution of points would explain the low correlation coefficient obtained. These materials were all synthetic types and therefore have a rougher initial microtexture than that normally seen in natural aggregates. For comparison, BNL worked only with natural aggregates, and it can be seen in the graph (figure 11) that the shape factors obtained were not as high as some of those BMT dealt with. The plot for the BNL data has a more or less constant positive slope which doesn't flatten at the upper end like the BMT plot. The low value of the correlation coefficient in this case is simply due to the scatter of the points.

Next, the points were plotted according to whether the measurements were made before or after the polishing run. These two graphs are shown in figures 12 and 13. The correlation coefficients (0.72 and 0.73) for both of these plots were higher than those of figures 10 and 11. The higher correlation was predictable for the post-polishing plot since that portion of the BMT data (pre-polishing) in figure 10, for which PV does not show a good correlation with shape factors, is excluded. However, it is not as easy to explain why the pre-polishing data, which includes these points, had an equally good correlation. The shape of the best fit line is closer to the horizontal which means the BMT data has less of a disruptive influence on the overall plot; this may account for the reasonably good correlation coefficient.

For all data obtained (see figure 9), the final correlation coefficient between shape factor and polish value is 0.74. That this correlation coefficient is not higher may be due to several things. First, as noted above, there is some scatter in the data points due simply to limits of the repeatability of both the texture measurements and the BPT results.

Second, the BPT results may be influenced by other sample characteristics besides microtexture. As mentioned above, the British Wheel specimens are prepared to try and limit obvious variations in macrotexture; however, some variation in particle size and spacing may still occur.

Third, there were two basic types of surface profiles noted during the examination of these specimens. The most common type is that generally seen in natural aggregates in which a system of peaks or asperities consisting of mineral grains or crystals are exposed above the background matrix material (see figure 14). The second less common type is seen in some of the BMT artificial aggregates as well as some natural volcanic rocks and slags. In this case the

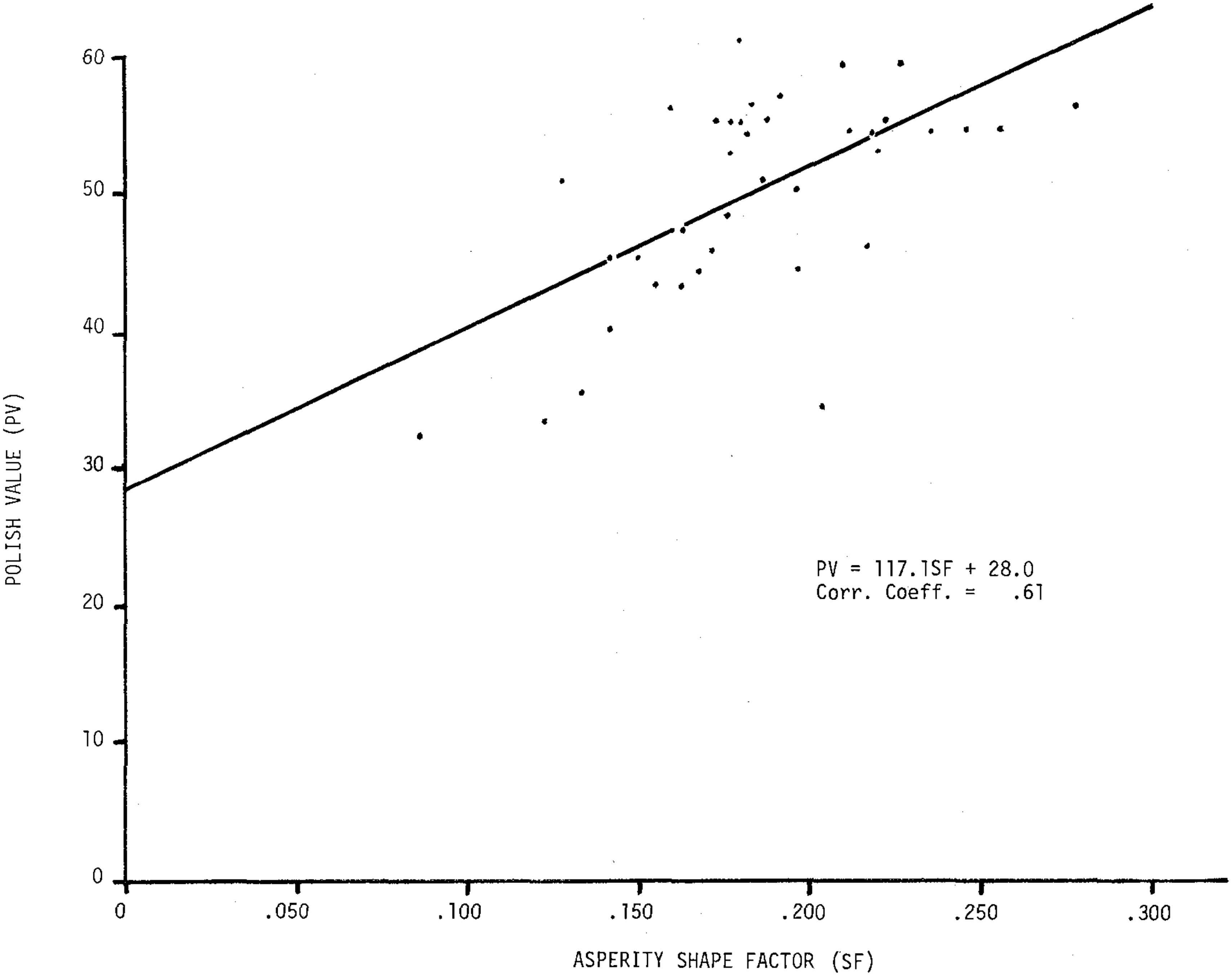


Figure 10. Polish Value Versus Average Asperity Shape Factor for the U.S. Bureau of Mines Specimens

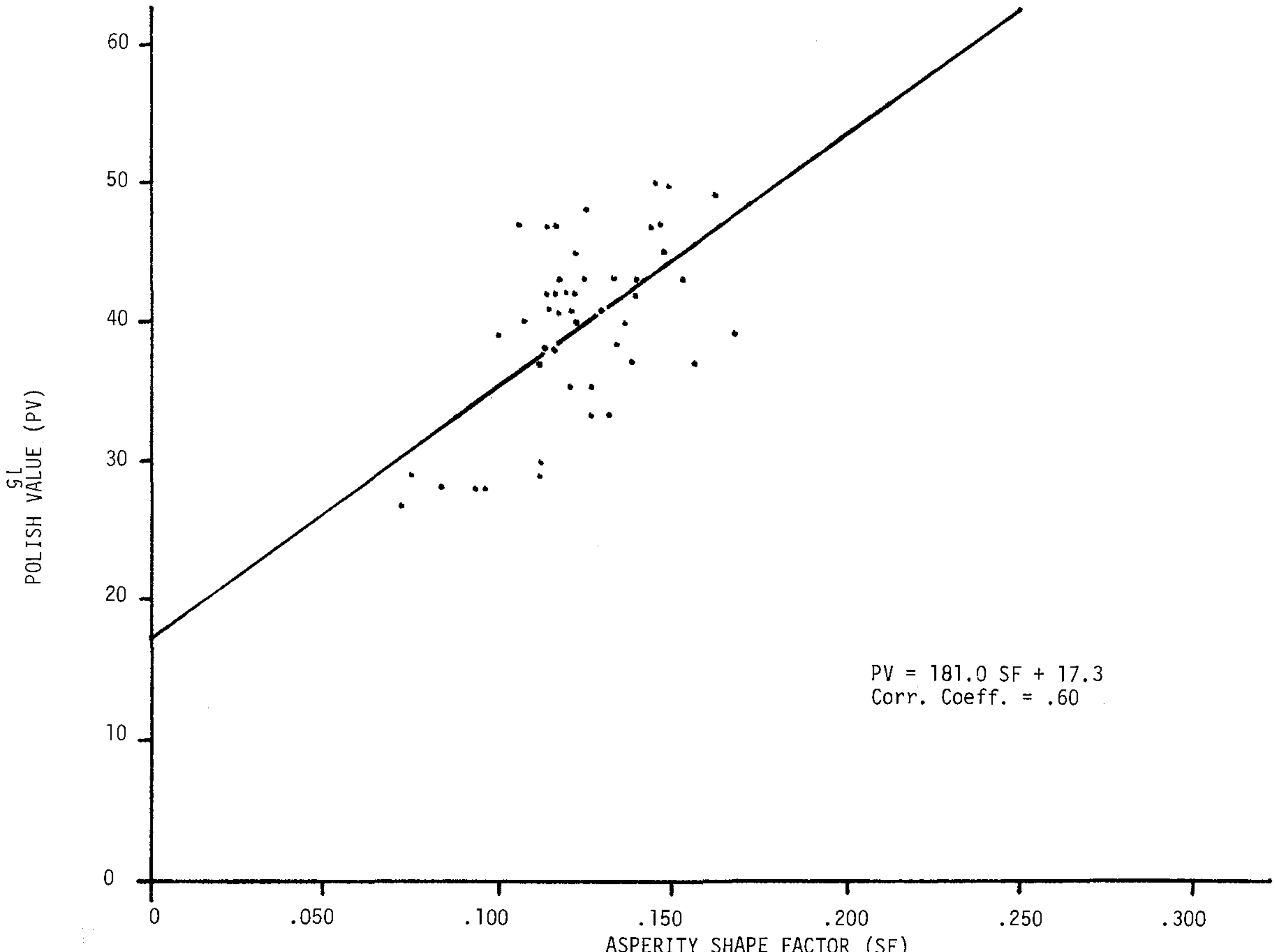


Figure 11. Polish Value Versus Average Asperity Shape Factor for the Brookhaven National Laboratory Specimens

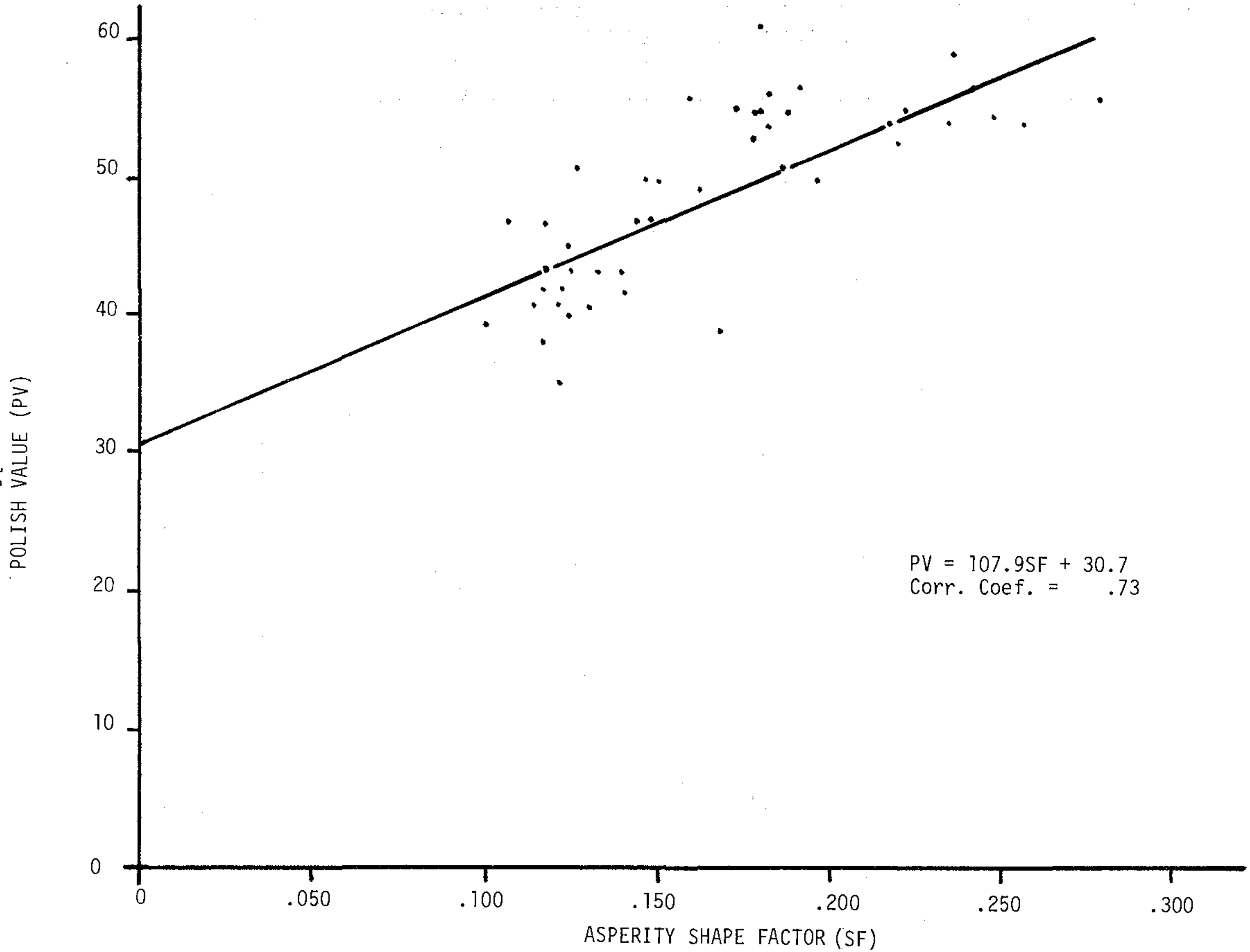


Figure 12. Polish Value Versus Average Asperity Shape Factor for All Specimens Examined Before Polishing

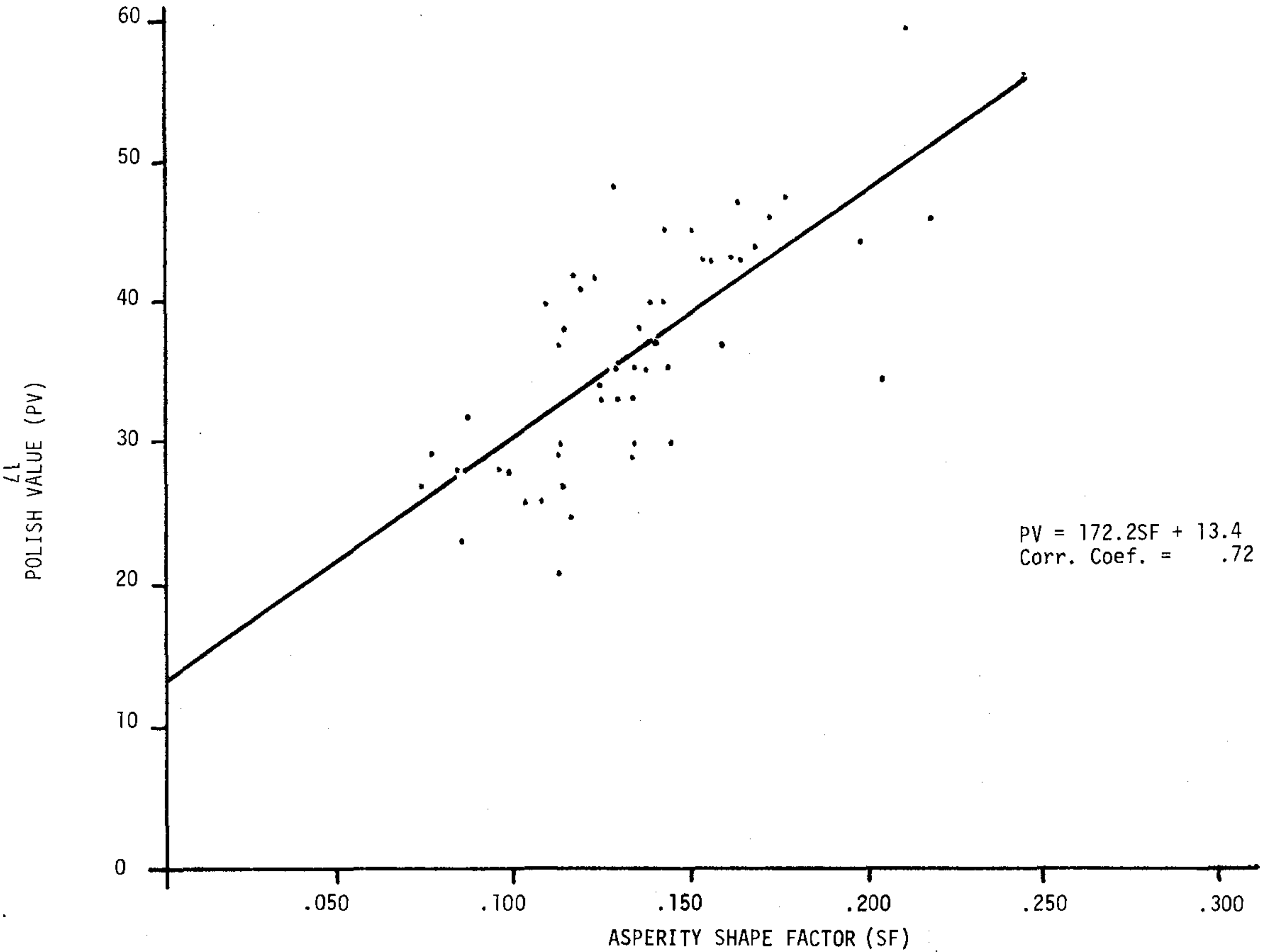


Figure 13. Polish Value Versus Average Asperity Shape Factor for All Specimens Examined After Polishing

texture is produced by a system of voids or vesicles extending below the general surface level of the aggregate (see figure 15). Either

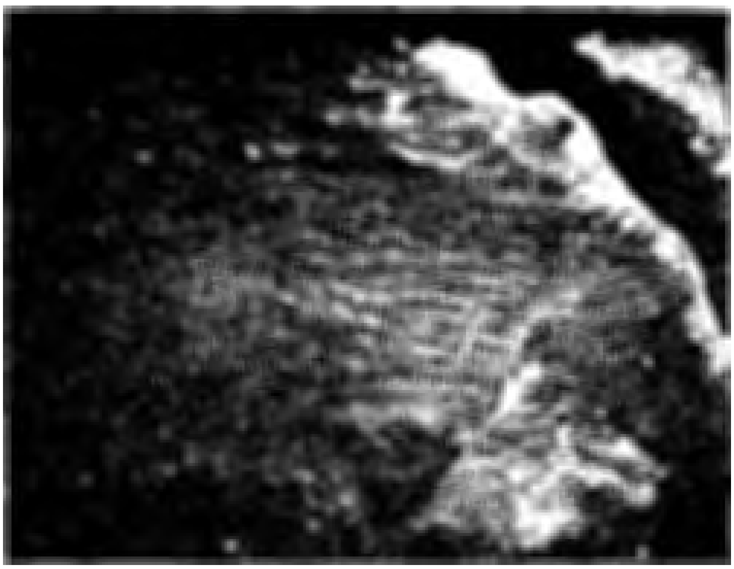


Figure 16. Rippled aggregate surface produced by the action of the British polishing wheel. (Magnification = 10X. Tire crossed the stone from right to left.)

The microtexture measurements were also evaluated to determine if they could predict the polish susceptibility (as measured by the BPT) of a given aggregate based only on the measurement of unpolished samples. To do this, shape factor measurements made on specimens before polishing were compared with PVs taken on the same specimens after being run on the polishing wheel. The results are shown in figure 17. While the plot shows a definite correlation (correlation coefficient of 0.63), it is not high enough to allow elimination of the laboratory polishing of the aggregate as part of the evaluation procedure. The correlation is relatively low because some of the crushed aggregate types showed good initial microtexture (i.e., high initial shape factors) because of their mineralogic and crystallographic composition, but did not retain the microtexture through the polishing run because of the lack of hardness of the minerals. The individual mineral grains/crystals are also tightly bonded together in these aggregates so the surface microtexture is not renewed by particle attrition during polishing. Based on this analysis, the polish susceptibility of an aggregate can not be reliably determined solely from the examination of the microtexture of a freshly fractured surface.

SUMMARY

Using automated optical measuring equipment, a series of British Polishing Wheel specimens were examined in an attempt to quantify the microtextural characteristics of an aggregate's surface which contribute to its frictional properties. Profile measurements were correlated with frictional results obtained on the samples using the British Pendulum Tester (BPT). The BPT measurements (polish values) are thought to best represent the microtextural frictional component of the coarse aggregate. Aggregate types examined included natural aggregates, ceramic aggregates produced by the U.S. Bureau of Mines, and impregnated natural aggregates made by Brookhaven National Laboratory. The best correlation with the polish values was obtained using the shape factor measurement, which is a ratio of the height to width of the asperities encountered in a profile. The shape factor versus PV plot indicated a possible optimal shape factor value in the 0.16 - 0.20 range.

Since the shape factor is a ratio of height to width, it is a unitless number and therefore does not help to define a possible optimal size for microtextural peaks. Attempted correlation between asperity height or width with PV shows no strong relationship, making selection of an optimal size difficult at this time.

CONCLUSIONS

As a result of this research, the following conclusions are reached:

1. Measurements on a microtextural scale (500 m) on profiles from British Wheel specimens do correlate with polish value results obtained with the British Pendulum Tester.

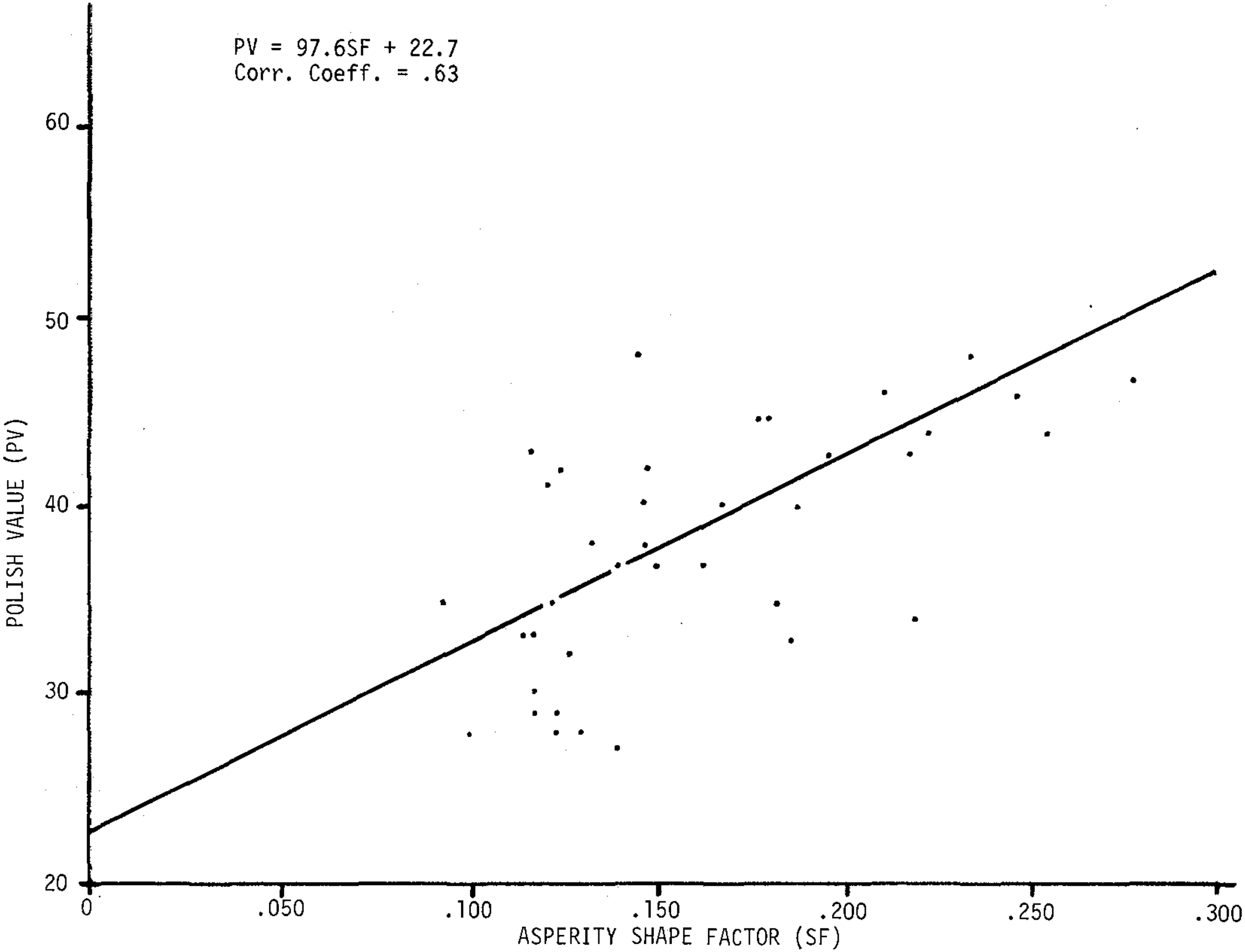


Figure 17 Polish Value Before Polishing Versus Average Asperity Shape Factor After Polishing

2. The best correlation with PV (0.74 using linear regression) was obtained for the shape factor measurement which is a ratio of the average height to average width of all asperities (peaks) encountered along a series of profiles constituting a sample.

3. The available data makes determination of an optimal asperity shape difficult, although height to width ratios in the 0.16 - 0.20 range appears to result in maximum PV's.

4. Based on the presently available data, designation of an optimal microtexture size range is not possible since PV's increase with asperity size over the entire range of data points.

FUTURE WORK

Because this research indicates a correlation between an aggregate's microtextural parameters, as measured, and its frictional properties, follow-up work is underway.

This additional work involves measuring microtextural parameters on actual pavement samples. These profile results will first be correlated with BPT measurements made on the same samples. Secondly, pavement samples will be obtained from roadways on which skid-resistant measurements had just been made using the procedures and equipment in ASTM E274, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-scale Tire (see reference 4). The microtextural measurements will then be combined with a measure of macrotexture (such as the sandpatch) for correlation with the skid trailer results. The analysis will help to define the ranges of microtexture which produce the best frictional results in the field.

LIST OF REFERENCES

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2. S. W. Forster, Automated Aggregate Microtexture Measurement: Description and Procedures, in Public Roads, Vol. 42, No. 3, December 1978, pp 99-104.

3. G. G. Balmer, Pavement Texture: Its Significance and Development, in Pavement Surface Properties, Evaluation, and Shoulders, Transportation Research Record 666, Transportation Research Board, Washington, D.C., 1978, pp-1-6.

4. ASTM E274, Standard Test Method for Skid Resistance of Paved Surfaces Using a Full-Scale Tire, in Annual Book of ASTM Standards, Part 15, American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania.

APPENDIX

TABLE 1

Test Aggregate Description

Sample No.	Source	Aggregate Type
2C	FHWA*	Crushed Diabase
3C	FHWA	Crushed Quartzite
4D	FHWA	Crushed Limestone
5D	FHWA	Crushed Serpentinite
6D	FHWA	Crushed Dunite
8D	FHWA	Crushed Marble
9A	FHWA	Crushed Limestone
10A	FHWA	Crushed Quartzite Gravel
13C	FHWA	Expanded Clay
15A	FHWA	Crushed Quartzitic Limestone
18C	FHWA	Crushed Granite
20A	FHWA	Quartzite Gravel
28D	FHWA	Crushed Granite
22A	BMT**	Tabular Al_2O_3 + Low PCE Clay
27B	BMT	SiC + Low PCE Clay
31B	BMT	Bubbled Al_2O_3 + Low PCE Clay
55B	BMT	SiC + Waste Glass
71B	BMT	Calcined Guyana Bauxite
76B	BMT	Sand + High PCE Clay
84A	BMT	Sintered Coal Refuse
108A	BMT	Refractory Clay + Waste Glass
114A	BMT	Sand + Waste Glass
122A	BMT	Expanded Slate

* Aggregate collected by Materials Division Office of Research, FHWA

** Aggregate made by the Bureau of Mines at Tuscaloosa, Alabama. (These materials were crushed after formation).

TABLE 1
(continued)

Sample No.	Source	Aggregate Type
83	BMT**	Coal Refuse
203	BMT	Aluminum Waste + Refractory Clay
274	BMT	Calcined Clay + Waste Glass
273	BMT	Periclase + Waste Glass
277	BMT	Calcined Clay + Copper Mine Tailings
289	BMT	Calcined Clay + Low PCE Clay
290B	BMT	Calcined Serpentine Waste
3201F	BNL***	Crushed Quartz Sandstone
3201SF	BNL	Crushed Quartz Sandstone Impregnated With Styrene Polymer
3201PF	BNL	Crushed Quartz Sandstone Impregnated With Phenol Formaldehyde
3603F	BNL	Crushed Limestone
3603MF	BNL	Crushed Limestone Impregnated With With Methyl Methacrylate Polymer
3606F	BNL	Crushed Friable Sandstone
3606MF	BNL	Crushed Friable Sandstone Impregnated With Methyl Methacrylate Polymer
3606PF	BNL	Crushed Friable Sandstone Impregnated With Phenol Formaldehyde
3607F	BNL	Crushed Quartzite
3607MF	BNL	Crushed Quartzite Impregnated With Methyl Methacrylate Polymer
9	BNL	Crushed Porous Limestone
9M	BNL	Crushed Porous Limestone Impregnated With Methyl Methacrylate Polymer
9S	BNL	Crushed Porous Limestone Impregnated With Styrene Polymer
23	BNL	Crushed Porous Dolomite
23M	BNL	Crushed Porous Dolomite Impregnated With Methyl Methacrylate Polymer
23S	BNL	Crushed Porous Dolomite Impregnated With Styrene Polymer

** Aggregate made by the Bureau of Mines at Tuscaloosa, Alabama.

*** Aggregate collected by Brookhaven National Laboratory.

TABLE 1

(continued)

Sample No.	Source	Aggregate Type
43	BNL***	Crushed Porous Sandstone
43M	BNL	Crushed Porous Sandstone Impregnated With Methyl Methacrylate Polymer
43S	BNL	Crushed Porous Sandstone Impregnated With Styrene Polymer
48	BNL	Crushed Porous Quartzite
48M	BNL	Crushed Porous Quartzite Impregnated With Methyl Methacrylate Polymer
48S	BNL	Crushed Porous Quartzite Impregnated With Styrene Polymer
20	BNL	Crushed Marble
GU	BNL	Calcined Guyana Bauxite
33	BNL	Crushed Granitic Gneiss

*** Aggregate collected by the Brookhaven National Laboratory.

TABLE 2

Measurement Results on Aggregate Before Polishing

Sample No.	PV	Average Asperity Density (peaks/μm)	Average Asperity Height (μm)	Average Shape Factor
22A	53	.0040	48	.178
27B	50	.0046	47	.196
31B	56	.0058	53	.279
55B	54	.0036	70	.212
71B	54	.0032	69	.183
76B	55	.0040	47	.174
84A	54	.0047	57	.235
108A	54	.0038	65	.219
114A	55	.0047	53	.222
122A(1)	59	.0045	59	.236
83	54	.0051	50	.256
122A(2)	54	.0065	38	.247
150	55	.0047	38	.179
159	56	.0029	55	.160
203	61	.0040	45	.180
262	55	.0056	32	.180
271	56	.0052	36	.184
273	57	.0047	41	.191
274	55	.0047	40	.189
277	53	.0051	43	.220
289	51	.0046	41	.186
290B	51	.0033	39	.128
3201F	43	.0042	28	.125
3201SF	42	.0039	29	.121
3201PF	39	.0050	34	.169
3603F	35	.0034	34	.121
3603MF	38	.0032	36	.117
3606F	47	.0044	24	.118
3606MF	47	.0041	22	.107

TABLE 2

(continued)

Sample No.	PV	Average Asperity Density (peaks/μm)	Average Asperity Height (μm)	Average Shape Factor
3606PF	43	.0046	27	.134
3607F	42	.0046	29	.140
3607MF	45	.0049	29	.149
9	50	.0039	39	.150
9M	41	.0037	35	.130
9S	45	.0039	32	.124
23	47	.0039	31	.118
23M	40	.0038	32	.123
23S	39	.0032	31	.100
43	41	.0046	25	.115
43M	41	.0043	28	.121
43S	42	.0034	34	.116
48	50	.0038	39	.147
48M	47	.0037	41	.149
48S	47	.0040	37	.145
20	43	.0039	36	.140
GU	49	.0041	39	.163
33	43	.0038	32	.119

TABLE 3

Measurement Results on Aggregate After Polishing

Sample No.	PV	Average Asperity Density (peaks/μm	Average Asperity Height (μm)	Average Shape Factor
2C	35	.0034	42	.137
3C	30	.0048	29	.144
4D	23	.0031	20	.083
5D	21	.0035	29	.111
6D	35	.0037	40	.143
8D	25	.0025	48	.115
9A	26	.0029	34	.103
10A	27	.0034	31	.113
13C	43	.0039	44	.163
15A	34	.0038	30	.122
18C	29	.0033	41	.132
20A	26	.0031	33	.107
28D	30	.0038	35	.134
22A	45	.0042	34	.142
27B	43	.0039	42	.163
31B	47	.0038	42	.163
55B	46	.0033	65	.217
71B	35	.0027	49	.133
84A	48	.0040	44	.177
108A	43	.0035	45	.156
114A	44	.0044	38	.169
122A(1)	59	.0043	49	.210
83	44	.0052	38	.197
122A(2)	46	.0050	33	.171
203	45	.0041	37	.150
274	40	.0040	36	.142
277	34	.0043	47	.203
289	33	.0037	34	.123
290B	32	.0029	30	.086
3201F	42	.0051	23	.116
3201SF	41	.0051	23	.119
3201PF	40	.0044	25	.109

TABLE 3

(continued)

Sample No.	PV	Average Asperity Density (peaks/μm)	Average Asperity Height (μm)	Average Shape Factor
3606F	43	.0051	30	.154
3606PF	38	.0045	25	.114
3607F	37	.0041	27	.111
3607MF	38	.0046	29	.135
9	37	.0047	29	.139
9M	28	.0040	24	.097
9S	29	.0030	26	.076
23	30	.0044	25	.112
23M	28	.0041	21	.084
23S	28	.0038	25	.095
43	33	.0044	29	.129
43M	35	.0043	30	.129
43S	33	.0043	31	.132
48	40	.0031	45	.138
48M	42	.0031	39	.122
48S	48	.0031	40	.127
20	27	.0027	27	.072
GU	37	.0037	42	.159
33	29	.0039	28	.111

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH AND DEVELOPMENT

The Offices of Research and Development (R&D) of the Federal Highway Administration (FHWA) are responsible for a broad program of staff and contract research and development and a Federal-aid program, conducted by or through the State highway transportation agencies, that includes the Highway Planning and Research (HP&R) program and the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board. The FCP is a carefully selected group of projects that uses research and development resources to obtain timely solutions to urgent national highway engineering problems.*

The diagonal double stripe on the cover of this report represents a highway and is color-coded to identify the FCP category that the report falls under. A red stripe is used for category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, green for categories 6 and 7, and an orange stripe identifies category 0.

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion, and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements that affect the quality of the human environment. The goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge and technology of materials properties, using available natural materials, improving structural foundation materials, recycling highway materials, converting industrial wastes into useful highway products, developing extender or substitute materials for those in short supply, and developing more rapid and reliable testing procedures. The goals are lower highway construction costs and extended maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highways at reasonable costs.

6. Improved Technology for Highway Construction

This category is concerned with the research, development, and implementation of highway construction technology to increase productivity, reduce energy consumption, conserve dwindling resources, and reduce costs while improving the quality and methods of construction.

7. Improved Technology for Highway Maintenance

This category addresses problems in preserving the Nation's highways and includes activities in physical maintenance, traffic services, management, and equipment. The goal is to maximize operational efficiency and safety to the traveling public while conserving resources.

0. Other New Studies

This category, not included in the seven-volume official statement of the FCP, is concerned with HP&R and NCHRP studies not specifically related to FCP projects. These studies involve R&D support of other FHWA program office research.

* The complete seven-volume official statement of the FCP is available from the National Technical Information Service, Springfield, Va. 22161. Single copies of the introductory volume are available without charge from Program Analysis (HRD-3), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.