Polishing of Aggregates and Wet-Weather Accident Rates for Flexible Pavements

PODURU M. GANDHI, BENJAMIN COLUCCI, AND SRINIVAS P. GANDHI

A high wet-weather accident rate on highways is a general indication of the low skid-resistance of the pavement surface. The polishing of aggregates under the vehicle tires decreases the microtexture, which is an important component of the skid resistance of the pavement. The rate of polishing depends on the mineralogical characteristics and the texture of the aggregates. A detailed laboratory study was conducted on different aggregate sources in Puerto Rico and their polishing characteristics by means of a British polishing wheel. It was found that carbonate rocks polish more than gravels and noncarbonate rocks. In a follow-up study, field data were collected on accident rates, pavement surface friction, and macrotexture of in-service flexible pavements. Samples also were collected from selected pavements to determine polish resistance and carbonate content of the recovered aggregates. Statistical analyses indicated that the relationship between the wet/dry accident ratio and pavement surface friction was statistically significant. Carbonate content of the aggregate showed better correlation with pavement surface friction than polished stone values, although both had significant influence. On the basis of the results, recommendations were made with respect to specifications of aggregates to ensure adequate skid resistance.

The high rate of accidents on highways in the United States and Puerto Rico is of concern to the driving public as well as to highway engineers. The costs of accidents run into billions of dollars in addition to loss of life. The Highway Safety Act passed by the United States Congress in 1966 requires that every state have a program of highway design, construction, and maintenance to increase highway safety (*1*). Although accidents result from many causes that involve vehicle, driver, pavement, and their interaction, the highway engineer is responsible for building as much safety as possible into the pavement. A significant portion of the total number of accidents is caused by the skidding of vehicles on wet pavement surfaces.

The research reported here is related to the improvement of skid resistance of pavements through the use of polish-resistant aggregates. It was conducted in two phases (Figure 1). In the first phase, aggregate samples were collected from a number of quarries in Puerto Rico, and their polishing characteristics and other properties were evaluated (*2*). In the second phase, information was collected on accident experience on highways, pavement surface friction, and macrotexture, as well as properties of aggregates, such as polish resistance and acid solubility (*3*). On the basis of the study, recommendations were made regarding specifications for aggregates used in asphalt pavements to ensure adequate skid resistance.

University of Puerto Rico, Mayagüez Campus, Mayagüez, Puerto Rico.

REVIEW OF PHASE 1 RESEARCH

Research during the first phase consisted of an island-wide inventory of aggregate sources and laboratory evaluations of physical and mineralogical characteristics of aggregates. The details are described in the following sections.

Aggregate Inventory

A field sampling team of two technicians and a geologist from the Puerto Rico Highway Authority was organized. The geologist visited most of the quarries and selected representative samples of rocks from which the aggregates are processed. In addition, the team collected about 50 lb of ¾- to ¼-in. representative aggregate samples from the stockpiles of the quarries. A total of 55 samples was collected from various parts of the island. These samples represent the active quarries and gravel extraction sites on the island that supply materials for road and bridge construction.

Laboratory Evaluations

The laboratory tests on each aggregate sample included specific gravity and absorption (ASTM C127), Los Angeles abrasion test (ASTM C131), acid insoluble residue (ASTM D3042), and polish value (ASTM D3319 and ASTM E303). The polish test was conducted in two parts. Initially, the stone samples were subjected to accelerated polishing by means of the British wheel. The state of polish reached by each sample was then evaluated by measuring the surface friction with the British Portable Tester. The result was expressed as polished-stone value (PSV) instead of polish value (PV), as specified in the ASTM procedure, because the auxiliary scale was used to correct for the smaller rubber slider. The auxiliary scale represents the actual friction value, and PSV refers to the readings from this scale.

Geological Evaluations

The following information was obtained for each rock sample:

- Macroscopic description (color, texture, hardness, and rough visual identification of the rock);
- Microscopic description (petrographic analysis of thin sections);
- Mineral composition (relative amounts of different minerals observed); and
- Rock name (identification of rock).

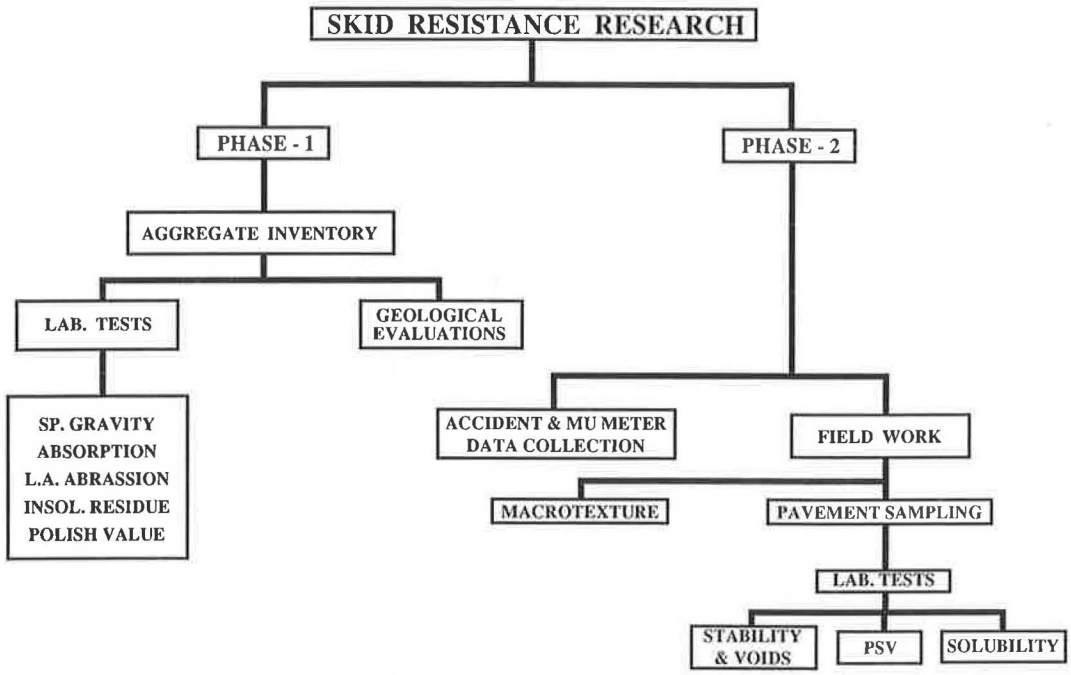

FIGURE 1 Flow chart of research activities.

Detailed tables of this information are available elsewhere (*2*). Aggregates in this study fall into two general categories: igneous and sedimentary. The igneous rocks, including those in gravels of alluvial deposits, consisted of volcanic breccia (mostly andesitic), andesite, volcanic sandstone, volcanic silt stone, granodiorite, granophyre, and diorite. The sedimentary rocks were mostly limestone except for one sample each of calcareous mudstone, conglomeratic mudstone, and mudstone.

River gravels were generally heterogeneous, with several types of rock in each sample. It was not possible to make thin sections of all rock types in the gravel samples. Even in the samples that were analyzed, only two or three thin sections of the most abundant rock types present in the sample were made.

PSVs

The PSVs in the 55 aggregate samples tested ranged from 39 to 59. The aggregates were classified into the following three groups: (*a*) carbonate rocks (22 samples), (*b*) noncarbonate rocks (13 samples), and (*c*) river gravels (20 samples). The term "gravel" is mainly a particle-size classification that may have different types of rocks and minerals. In this study, all gravels were from river beds and contained only noncarbonate rocks. The distribution of PSVs for each group is shown in Figure 2. Noncarbonate rocks and gravels as a group had higher mean PSVs than did carbonate rocks. Statistical analyses showed that there are significant differences in PSVs between these three groups of aggregates. The mean PSVs of noncarbonate rocks and gravels were found to be significantly higher than those of carbonate rocks, but the differences between noncarbonate rocks and gravels were not significant.

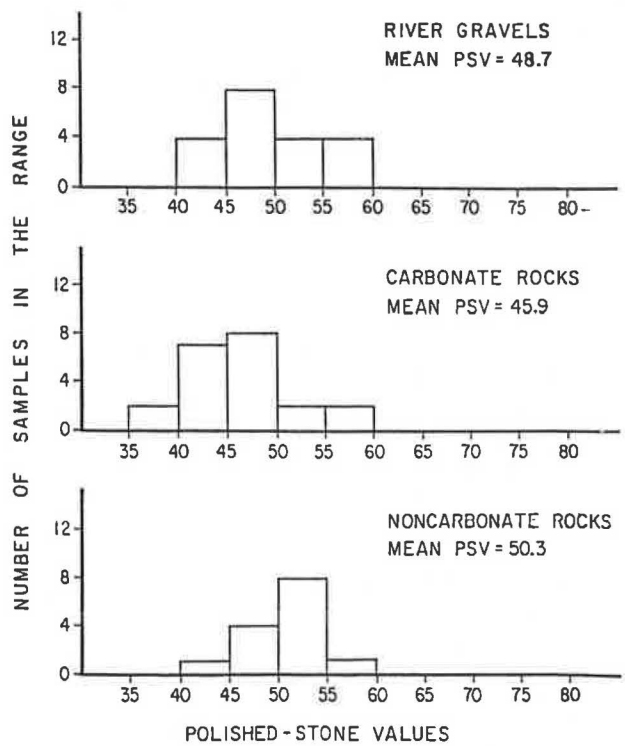

FIGURE 2 Distribution of PSVs in the three groups of aggregates.

Effect of Blending on PSVs

Tests also were conducted to study the effect of blending of aggregates with different polish characteristics. Five blends were tested. For each blend, two aggregate samples with high and low polish values were selected from nearby locations.

Specimens for the polish test were prepared by arranging the particles of the two aggregates alternately, using approximately 50 percent of each. The data obtained from these specimens are presented in Table 1. In general, it can be seen that the PV of the blend is much higher than the value of the softer component. Statistical analysis showed that this improvement is significant at a confidence level of 1 percent. This indicates the possibility of the use of some of the softer rocks in combination with others, instead of outright rejection of them. However, these findings are preliminary, and performance of these blends must be verified by experimental test sections.

Effect of Mineral Composition on PSVs

Results of this study showed that polishing of aggregates does not depend entirely on mineral composition but that other factors, such as texture of the rock (grain size, shape, and grain-to-grain relationship), degree of alteration, cementation, nature of cementitious material, nature of impurities present, porosity, and the like, can have considerable influence on polishing.

The following general observations can be made on the basis of mineralogical analysis:

- Among noncarbonate rocks, breccias, consisting of angular, coarse, usually heterogeneous rock and mineral fragments, showed high polish resistance with PSVs of 50 or higher. Andesites had PSVs close to 50. Serpentine showed a low PSV of 41, which was expected because it is a soft mineral.
- Several crushed river gravels had PSVs of 50 or higher, which can be attributed mainly to their heterogenous character and the rough surface texture of the crushed particles. However, some crushed gravels that had smooth textured particles or soft minerals had PSVs much lower than 50.
- Hard mineral particles embedded in a softer matrix can produce high polish resistance. As the matrix wears out, the relatively hard particles projecting up from the surface give high frictional resistance.
- Most of the carbonate rocks in this study were pure limestones. However, a wide variation exists in the nature of polishing of these aggregates. Dense limestones showed low PSVs, whereas porous limestones generally showed higher values. The porosity imparts a rough texture to the rock as it wears out.

On the basis of this research, the Puerto Rico Highway Authority specified a minimum PSV of 48 for aggregates used in surface courses of asphalt pavements. However, it was found later that it was difficult to get aggregates with a PSV of 48 or higher in some parts of the island. The Highway Authority became interested in determining whether the history of accidents on highways in Puerto Rico justifies this value. This led to the second phase of the research, which involved collection of accident data and pavement friction data on in-service pavements.

PHASE 2 RESEARCH

The principal objective of the second phase of research was to determine the relationship between the accident rate on

TABLE 1 POLISH DATA FOR UNBLENDED AND BLENDED SAMPLES

Sample No.	Classification	Location	PSV
12	Mudstone	Hormigueros	59
14	Limestone	Cabo Rojo	39
12-14	Blended		56
5	Andesitic Breccia	Bayamón	54
8	Limestone	Dorado	44
5-8	Blended		54
19	Gravel	Ponce	52
54	Limestone	Ponce	42
19-54	Blended		46
28	Breccia	Carolina	56
29	Gravel	Carolina	42
28-29	Blended		52
38	Gravel	Arecibo-Utuado	53
39	Limestone	Arecibo-Lares	41
38-39	Blended		52

wet pavements and pavement friction and to recommend aggregate specifications to control skidding on flexible pavements. The research tasks included collection of accident and pavement friction data, macrotexture determination, and laboratory tests on aggregates recovered from samples of in-service pavements.

Accident Data Collection

The Traffic Safety Commission furnished data on accidents that occurred in 1986. The analysis was limited to pavement sections in rural areas. The specific fields of information that were analyzed included location, date, type and severity of accident, alignment, pavement condition, and type of traffic control. The dBase III Plus computer program was used for the sorting and preliminary analysis of the accident data. Reports were generated by pavement condition (wet or dry) and for pavements without other defects in order to determine pavement segments most likely to be associated with true skidding problems.

Pavement Friction Data

Pavement friction data were obtained from the Public Works Department. The department uses a mu-meter for the evaluation of pavement friction. The test is conducted over a wetted pavement surface at a constant speed of 40 mph. The current testing procedure provides a continuous graphical record of the friction coefficient along the length of the test section and prints an average value for the section, which is referred to as the mu (μ) value. Figure 3 shows the mu-meter in operation at one of the pavement test sites. The mu-meter data were one-time only readings for each lane of the section that were taken during 1987 and 1988. Some older data consisted of multiple readings for each lane. Recent data consisted of graphical output for each lane. From these data, a computerized mu-meter data base was developed using dBase III Plus. The accident and mu-meter data bases were merged for conducting the statistical analyses.

Field Data Collection

A total of 20 pavement sections was selected for the field work. The data included general information about the site, geometric characteristics, surface macrotexture, level of polishing of the surface aggregates, pavement overall condition, and information relevant to other features, such as number of entrances, fixed-object location, and skid marks in the vicinity of the site. The field work was concentrated on the measurements of the surface macrotexture and the cutting and removal of representative pavement samples. The macrotexture of the pavement sections was measured using the sand patch method (ASTM E 965-83). The sand patch test was performed on four locations along the wheelpath, and the average texture depth was determined. For getting enough material for subsequent laboratory tests a 2- × 2-ft pavement slab was cut from the wheelpath of each section (Figure 4).

Laboratory Test on Field Samples

The laboratory procedures performed on the pavement samples are described below.

British Pendulum Number of Slabs (BPN)

The British Pendulum was used to determine the average friction value of the 2- × 2-ft flexible-pavement slabs. This gave another measure of pavement friction in addition to the measurements from the mu-meter. BPN readings correspond to the wheelpath, whereas in the mu-meter test, both wheels cannot be kept simultaneously on the wheelpath. Also, it was not determined whether the operators of the mu-meter were keeping even one wheel on the wheelpath during the test run. A wooden base was prepared and filled with sand to serve as a foundation to the 2- × 2-ft pavement sample for BPN determination (Figure 5). The testing procedure consisted of taking readings at four positions with five repetitions at each position. The average BPN values for the 20 test sections are presented in Table 2 along with other data. The average BPN values ranged from 39 to 63 with a standard deviation of 5.5. Two-thirds of the test sections were in the range of 50 to 60.

FIGURE 3 Mu-meter in operation.

FIGURE 4 Typical pavement sample.

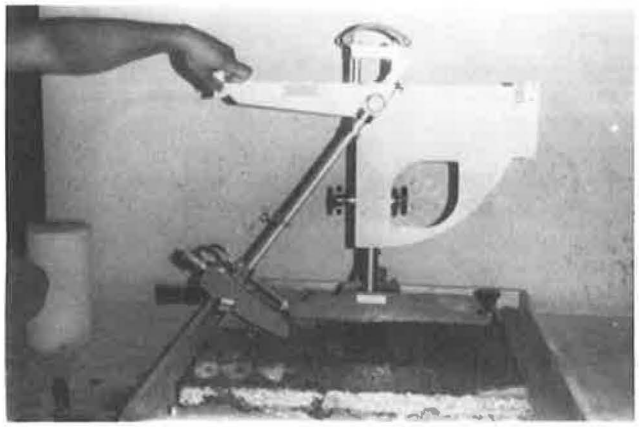

FIGURE 5 Testing pavement slab using British Portable Pendulum.

Mix Characterization Tests

Four cores (4 in. in diameter) were drilled from each of the 20 asphalt concrete blocks. The asphalt surface layer was separated from the cores and subjected to several characterization tests, such as Marshall stability, flow, voids, asphalt content, and aggregate gradation. The proportion of filler (passing the No. 200 sieve) and coarse fraction (retained on the No. 16 sieve) was determined from a gradation analysis.

PSV Determination

Coarse aggregate used in the mixes was recovered by extraction, and 4 test specimens (briquets) were prepared using the aggregate fraction passing the ⅜ in. sieve and retained on the No. 4 sieve. The aggregate particles were placed in the molds, and an epoxy resin was used for bonding the particles. Typical specimens are shown in Figure 6. The PSV was determined using the procedures explained earlier. The equipment used for polishing the specimens is shown in Figure 7, and the British Pendulum Tester used to determine the PSV is shown in Figure 8. The average PSV for the 20 pavement sections shown in Table 2 ranged from 40 to 55 with a standard deviation of 3.77. It may be noted that 75 percent of the test sections had a PSV of less than 48, which is the minimum value specified by the Puerto Rico Highway Authority for surface course mixes.

Acid Insoluble Residue Test

The acid insoluble residue test was performed on the recovered aggregate in accordance with ASTM D 3042-86, except that a 250 g sample was used instead of 500 g. Table 2 presents the percent of material soluble in hydrochloric acid for the 20 pavement test sections. The solubility ranged from 1.7 to 95.8 percent. In most samples, the insoluble material (residue) was river gravel, which was probably blended with the carbonate aggregates. Thus the amount of residue does not actually represent the residue within the carbonate aggregates. For this reason, instead of reporting the insoluble residue as the test requires, solubility of the aggregate in the acid, which indicates the percentage of carbonate rock in the sample, was calculated and reported as such.

TABLE 2 MU-METER AND LABORATORY DATA FOR PAVEMENT SECTIONS

Sec.	Average Mu	BPN	PSV	TD (in.)	Sol. (%)
01	26	53	41	0.02	95.8
02	44	53	48	0.02	13.8
03	46	62	49	0.03	24.4
04	20	53	42	0.02	83.2
05	25	53	47	0.01	37.1
06	20	39	43	0.02	75.0
07	54	63	55	0.03	1.7
08	28	57	45	0.01	61.7
09	30	56	45	0.02	76.7
10	40	53	44	0.02	30.1
11	50	60	49	0.06	13.9
12	42	56	52	0.02	1.9
13	53	55	45	0.01	1.9
14	38	54	40	0.01	16.1
15	49	49	45	0.04	11.4
16	33	61	53	0.05	5.1
17	46	55	46	0.02	5.3
18	44	53	46	0.02	4.6
19	44	58	44	0.03	1.7
20	46	45	46	0.01	3.1

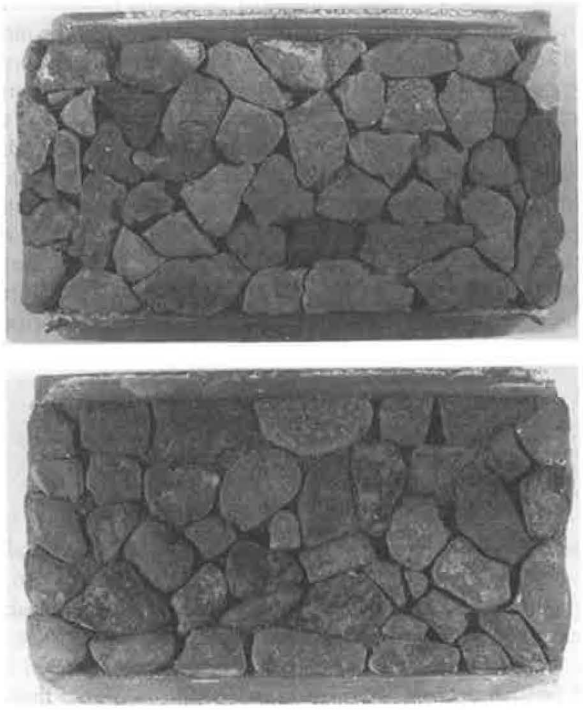

FIGURE 6 Typical specimens for polish test.

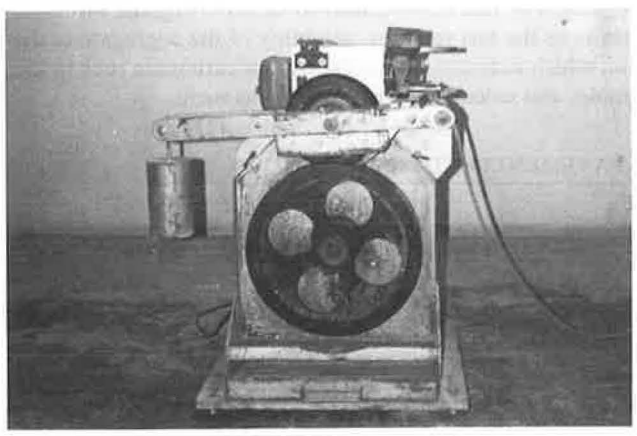

FIGURE 7 British accelerated polishing machine.

FIGURE 8 PSV determination using the British pendulum.

Statistical Analysis of Accident and Mu-Meter Data

Regression analysis were made to relate the wet-pavement accident rate, wet/dry (W/D), and wet/total (W/T) accident ratios to pavement surface friction values. The matching of accident and mu-meter data produced a set of 44 observations for these analyses. The independent variables considered were μ avg and μ min. The μ avg corresponded to the average μ value for all the lanes, and μ min is the lowest μ value among the lanes. Logarithmic transformations were also made on the independent variables μ avg and μ min. Furthermore, because the wet/dry accident ratio showed better response as a dependent variable, it was decided to pursue the statistical analysis with the wet/dry accident ratio as the dependent or response variable. As models having μ min as a variable were generally better than μ avg, only models with μ min are reported below; μ min is referred to as μ hereafter. For each regression model, correlation coefficients (r) and p-values are shown in parentheses. The p-value represents the observed level of significance. If it is equal to or less than 0.01, the contribution by the variable to the model is considered highly significant.

By using μ or its transformations as the independent variable, the following models were obtained:

$$W/D = 1.0230 - 0.016\,\mu$$
$$(r = 0.504,\ p = 0.0006) \quad (1)$$

$$W/D = 2.559 - 1.366 \text{ Log } (\mu)$$
$$(r = 0.530,\ p = 0.003) \quad (2)$$

$$\text{Log } (1 + W/D) = 0.80 - 0.431 \text{ Log } (\mu)$$
$$(r = 0.585,\ p = 0.008) \quad (3)$$

The correlation coefficients were low because several other factors, which are difficult to quantify, affect accidents. However, the low p-values indicate that pavement surface friction has a significant influence. Several researchers (*4–6*) had reported considerable scatter in the data while relating accident rates to pavement surface friction.

Statistical Analysis of Laboratory Data

Accident Ratio Correlations

An attempt was made to statistically correlate the data obtained from the laboratory tests, such as BPN, PSV, and the acid solubility (Sol) to wet/dry (W/D) accident ratios. The resulting models are described below:

$$W/D = 0.192 + 0.006 \text{ Sol}$$
$$(r = 0.57,\ p = 0.011) \quad (4)$$

$$W/D = 2.128 - 0.038 \text{ PSV}$$
$$(r = 0.418,\ p = 0.075) \quad (5)$$

$$W/D = 0.499 - 5.54\ \text{TD}$$
$$(r = 0.228, p = 0.35) \quad (6)$$

$$W/D = 0.913 - 0.01\ \text{BPN}$$
$$(r = 0.163, p = 0.51) \quad (7)$$

The relationship between the wet/dry accident ratio and solubility was more significant compared with PSV. It was surprising that BPN correlated so poorly with the W/D ratio. It was expected that BPN values may be more representative of the wheelpaths than mu values because both mu-meter wheels cannot be placed on the wheelpaths.

Correlation of Mu Values to Pavement Characteristics

Regression models relating pavement surface friction to various characteristics such as BPN, texture depth (TD), and aggregate characteristics such as PSV and solubility were tried. Solubility gave the best correlation, as shown by the following models:

$$\mu = 47.034 - 0.288\ \text{Sol}$$
$$(r = 0.836, p = 0.0001) \quad (8)$$

$$\mu = -23.0 + 1.325\ \text{PSV}$$
$$(r = 0.472, p = 0.041) \quad (9)$$

Multiple regression models including TD in addition to PSV and solubility did not significantly improve the predictive significance of the models in this study. However, it can be seen from Tables 2 and 3 that the pavement surface friction values are generally greater than 40 if the texture depth is equal to or greater than 0.03 in.

Discussion of Data Analyses

The relationship between wet/dry accident ratios and mu values was found to be statistically significant, although correlation coefficients were not very high. This is because several other variables related to driver, vehicle, and weather conditions not included in the models may also have considerable influence. Also, accident data and mu-meter data may not be highly reliable because the data were obtained from existing records and the authors had no control on the data collection.

The analyses also showed that the carbonate content of aggregates as measured by acid solubility has a significant inverse or negative relationship to pavement surface friction. The models having solubility term generally gave higher correlation coefficients. Although the correlation coefficients for models incorporating PSV were not high, the models were statistically significant.

The determination of PSV is more complicated and time-consuming, and equipment problems cause even more delays. Hence it may be better to place more emphasis on the solubility test instead of the polish test and require polish tests only for such major highways as expressways.

An examination of Figure 9 relating mu values to solubility indicates that mu values are low (less than 40) when solubility is higher than about 25 percent. This suggests that for primary highways a limit of 25 percent of carbonate rock in the mix is a reasonable value to specify.

From Figure 10, it also can be seen that for a pavement surface to have a mu value of 40, which is generally specified, the aggregate PSV should be around 48; the Puerto Rico Highway Authority currently specifies this value. However, it must be pointed out that the correlation between value and PSV is not high in this study. Nevertheless, it can be inferred that the currently specified PSV of 48 is reasonable, especially for such high-speed facilities as expressways and for high-risk locations on major highways. However, a range of PSV in the specification is needed because of the scarcity of high PSV aggregates in some regions.

From the average values summarized in Table 3 it can be seen that the wet-pavement accident experience is almost three times higher for pavements that have aggregates with PSVs of less than 45. However, there is little difference between the accident ratios of pavements with PSVs of 45 to 47 and those with 48 or higher. This suggests that for most highways the PSV specification for aggregates can be reduced to 45 from the current 48. For expressways and high-risk areas it would be desirable to keep a minimum PSV of 48.

TABLE 3 RELATIONSHIP OF PSV TO ACCIDENT RATIOS, SOLUBILITY, AND MU VALUES

PSV Range	No. of Pavement Sections	Average Values for the Sections		
		W/D	Sol.(%)	μ
< 40	0	-	-	-
40-44	6	0.75	50	31
45-47	8	0.24	25	40
48 or higher	6	0.23	10	45

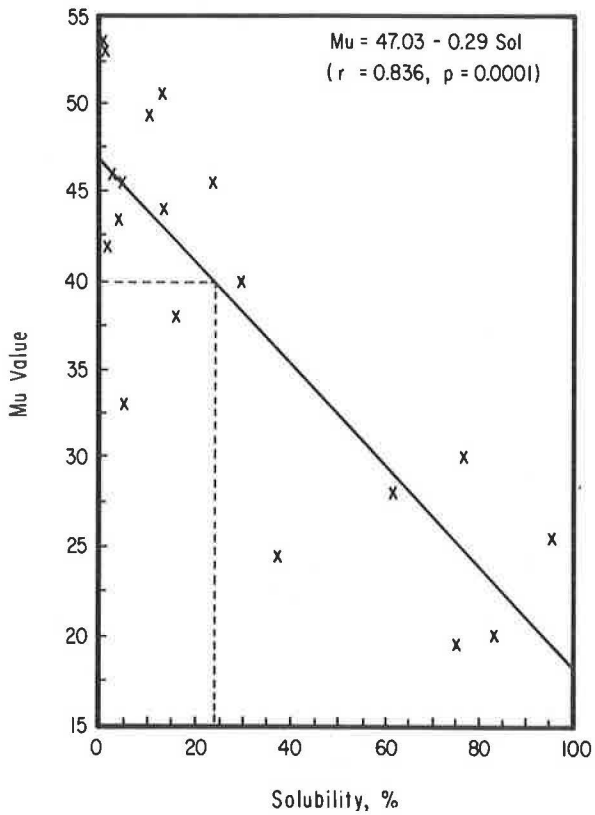

FIGURE 9 Relationship of mu to acid solubility.

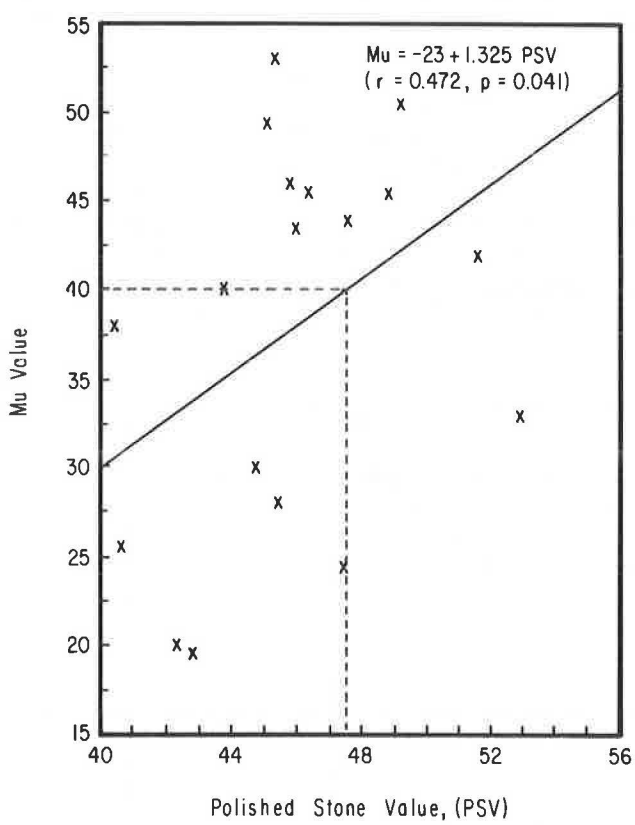

FIGURE 10 Relationship of mu to PSV.

It can be also seen from Tables 2 and 3 that aggregates that have acid solubility of 10 percent or less ensure higher pavement friction. However, reasonable pavement surface friction (mu value of 40) can be obtained if acid solubility does not exceed a value of 25. Values of acid solubility or carbonate content of aggregate that do not exceed 10 or 25 percent, depending on the highway, may be specified as alternatives to the polish value specification or in combination with it at the discretion of the highway authority.

These research findings are in accordance with the practices in the United States and several European countries. British specifications, for example, require the PSV of aggregates to be 40 to 75, depending on traffic and risk conditions, and a minimum texture depth of 0.04 in. (*7*). French specifications require a PSV of 45 or higher to classify an aggregate as good and a texture depth of 0.03 in. or higher for moderate- to high-speed facilities (*7*). Pennsylvania gives an excellent rating to gravels with less than 10 percent carbonate particles and a high rating to gravels having 10 to 25 percent carbonate particles (*8*). New York requires that limestones contain 20 percent chert particles or 10 percent sand-sized insoluble residue (*9*). AASHTO guidelines (*10*) recommend the use of either the Acid Insoluble or Polish test for evaluating aggregates and also the consideration of field experience. Thus, a requirement of a minimum PSV from 45 to 48 and maximum carbonate content of aggregate from 10 to 25 percent will be in accordance with the accepted national and international practice.

CONCLUSIONS

1. The relationship between the wet-pavement accident experience on highways (wet/dry ratio) in Puerto Rico and pavement friction (mu values) was found to be statistically significant, although the correlation coefficients were not high.
2. Among the aggregate properties that affect friction, PSVs and acid solubility (carbonate content) were statistically significant. However, the carbonate content gave a better correlation than PSV.
3. When texture depth was included as an additional variable in the models with either solubility or PSV, the correlation coefficients increased slightly. The pavement surface friction values were generally higher than 40 when the texture depths were equal to or greater than 0.03 in.

RECOMMENDATIONS

On the basis of this study, the following recommendations are made for conditions in Puerto Rico:

1. PSV may be required only for major highways (expressways and primary highways). A minimum value of 48 may be specified for expressways and high-risk areas of primary highways. The value may be reduced to 45 for low-risk areas.
2. Carbonate content of aggregates also may be included in the specifications to ensure adequate skid resistance. A maximum value of 10 percent for expressways and high-risk areas and 25 percent for primary highways is recommended. The polish-value specification may be replaced with a limit

on carbonates for secondary highways because the polish test is more time consuming and difficult to perform.

3. Because the macrotexture also influences the pavement surface friction, it is preferable that such high-speed facilities as expressways have a texture depth not less than 0.03 in. This may be used as a general guideline (and not a requirement) for mix designs and construction practices.

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