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Locally Available Aggregate and Sediment Production

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Selection of suitable locally available materials to build strong and durable roads with aggregate surfaces is desired to minimize road construction and maintenance costs and to minimize the detrimental effects of sedimentation. Eighteen aggregates were selected from local sources in Idaho, Oregon, South Dakota, and Washington State. Aggregate was placed in shallow metal frames and compacted to simulate a forest road. The levels of runoff and sediment from a high-intensity, long-duration simulated rainstorm were measured. The material tests selected for use in the study included ones that define the basic characteristics of the aggregate, along with a number of tests intended to predict susceptibility to erosion. Each of the tests was statistically evaluated to identify those that best predicted the perceived aggregate quality. The two best indicators of aggregate quality were the results of the sand equivalent test and the P20 portion of the Oregon air degradation test. The best indicator of either runoff or sediment production was the fraction passing the 0.6-mm sieve. Acceptable aggregates, both those of good quality and those of marginal quality, exhibited a 2-order-of-magnitude range in both runoff and sediment production.

The selection of locally available materials to build strong and durable surfaces has many potential advantages. The primary advantage is the lower cost, because hauling costs for imported materials are often the highest-cost component of the material. The trade-off in cost savings can be poor structural performance or high levels of sediment production. An awareness of the large variation in how much runoff and sediment may be produced from those locally available materials would be useful to road design specialists.

Local materials can be obtained from borrow pits, gravel bars, or hard rock sources. Some of these materials perform very well, whereas others break down under heavy traffic or during wet weather. Aggregate materials can be classified in a number of ways. One method of classification considers the intrinsic properties of the material. These properties relate to basic geologic origin, mineralogy, and other properties such as specific gravity and absorption.

A variety of aggregate tests has been developed by ASTM and AASHTO. Such tests and specifications are typically empirical in nature and focus on mechanical wear or chemical degradation because of the interaction with water. Some tests do not concentrate on a single property but are common engineering indexes that, in combination with local experience, can be used to judge the performance of an aggregate.

Road engineers commonly use aggregate quality to describe the suitability of an aggregate for use on forest roads. However, the authors know of no formalized procedure that can be used to rate the quality of an aggregate. Resistance to both mechanical breakdown from traffic and resistance to chemical breakdown from weathering are two factors often considered in this rating. Aggregate considered of good quality in one area may be considered of only marginal quality in another because of differences in climate and road use.

The Rocky Mountain Research Station and the Willamette National Forest conducted a 4-year study comparing the runoff and sediment production from two low-volume roads with aggregate surfaces (*1*). A section of road with marginal-quality aggregate produced 3.7 to 17.3 times as much sediment as a similar section with good-quality aggregate. One mechanism that caused the increase in sediment production from the marginal-quality aggregate was the increase in the flow path on the marginal-quality aggregate. After road maintenance, water flowed diagonally from the road crown to the road edge. With traffic, the cross slope was reduced, causing the flow to take a longer flow path. The marginal-quality aggregate had less resistance to cross-slope flattening and, therefore, longer flow paths and hence more sediment production. Another mechanism was the inability of the marginal-quality material to resist crushing or chemical degradation, which resulted in a constant replenishment of the fine material to be transported by the flowing water.

OBJECTIVES

A study was undertaken to investigate the sediment production of various aggregates. The objectives of this study were (*a*) to evaluate the ability of standard performance tests to predict the subjective rating of aggregate quality, (*b*) to evaluate the erodibility of a range of aggregate surfacing materials and relate it to standard performance tests, and (*c*) to provide a ranking of the erosive potential of the selected aggregates.

Methods

To meet these objectives, several aggregates from the Pacific Northwest were selected on the basis of their quality and geologic parent material. A suite of aggregate specification tests was performed to characterize each aggregate selected. The level of sediment production from a simulated rainstorm on a freshly constructed

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road section in a test track was measured. Traffic equivalent to 200 passes of a fully loaded logging truck was then applied, and the level of sediment production from a simulated rainstorm was again measured.

Selection of Aggregates

Forest Service personnel from the states of Montana, Idaho, Utah, South Dakota, Washington, and Oregon responsible for aggregate selection for forest roads were asked to nominate what they believed were both good- and marginal-quality aggregates. Determination of aggregate quality was left up to the Forest Service individual. Two further requirements were that the aggregate be widely used on roads in their forests and that the aggregate have a maximum size of 25 mm and be dense graded, that is, contain all material sizes from the maximum to the fines. The authors selected 18 aggregates. Eleven of them were classified as good quality by the individuals who nominated them, and the remainder were classified as marginal quality.

Performance Tests

Various tests exist to quantify the performance of aggregates when subjected to traffic and moisture. Performance is generally characterized by an amount of degradation and is reported as an index of how the material degrades.

The AASHTO T176 sand equivalent test (*2*) indicates the amount of fine dust or clay-size material. The AASHTO T210 durability test (*2*) is an index that indicates the resistance to the production of clay-size fines during exposure to water. AASHTO T104 sodium sulfate tests (*2*) measure the resistance to weathering action such as freeze–thaw and wet–dry cycles. The Oregon air degradation (*3*) tests are similar to the durability test, but with the addition of a jet of air. The dimethyl sulfoxide (DMSO) test (FHWA Method AG9, Region 10, Standard Method of Test for Accelerated Weathering of Aggregate by Use of Dimethyl Sulfoxide) is an accelerated weathering test that uses the chemical DMSO to measure an aggregate's resistance to the production of clay-size fines during periods of exposure to water longer than those used in the durability test.

For each performance test result, an analysis of variance (ANOVA) was used to determine if there was a difference between good- and marginal-quality aggregates. A test was deemed acceptable if it had a p-value of .05 or less.

These performance test results were also analyzed to determine the best single estimator of sediment production potential. Both an ANOVA and a correlation coefficient between the test and sediment production were used.

Aggregate Section Preparation

A test track was constructed by using steel frames 1.25 m wide, 4.83 m long, and 0.20 m deep to hold the aggregate during rainfall and traffic application. The bottoms of the steel frames consisted of 50-mm box members placed on 50-mm centers. Expanded metal with openings of 12 mm and a geotextile fabric (Phillips 6-WS) were placed on the tops of the box members. These allowed water to pass out the bottoms of the frames.

Aggregate was compacted in two lifts at optimum moisture content and 95% of maximum density (AASHTO T99). Each lift was compacted with a 130-kg vibrating roller.

Road Conditions Simulated

Three road conditions were simulated for each aggregate by varying the amount of traffic. These simulations varied the degree of rutting and effective cross-drain spacing.

One road condition simulation consisted of a short road section (~30 m) on a 6% grade without sufficient traffic to leave wheel ruts. Road sections that have been recently graded and that have not had sufficient traffic to produce wheel ruts would be similar to the short section.

The second road condition simulation also consisted of a short section (~30 m) on a 6% grade but had continuous wheel ruts. Low-volume roads that are not sufficiently maintained to keep wheel ruts from forming are represented by this section.

The final road condition simulation consisted of a long road section (~140 m) on a 6% grade with continuous wheel ruts. A road section with cross-drain spacing of about 140 m and with wheel ruts would be similar to this road section.

All sections were placed on a stand that held the frame at a 6% grade under a Purdue-type simulator. The ruts were oriented down slope. Runoff flowing in the ruts and overland flow from the nonrutted areas were combined at the bottom of the frame and flowed into a weir box with a 22.5-degree V notch at the outlet. The water depth above the weir box was measured with an ISCO 3230 flow meter. Sediment concentrations were determined by oven drying grab samples taken from the outlet of the frame collector.

Both short sections received a simulated rainstorm with an intensity of 50 mm/h for 30 min. The long section received the same simulated rainstorm, but with the addition of 28 L of flow per min to simulate the additional runoff from the longer road section.

Traffic Simulator

A traffic simulator consisting of the rear two axles of a standard tractor-trailer was constructed. The dual axles were loaded with cement blocks to a weight of 14,180 kg, approximately the same load as the rear axle of a fully loaded, highway-legal logging truck. The simulator was pulled at a speed of 0.3 km/h for a distance of 7.3 m with a hydraulics-powered winch. A treatment section containing aggregate was placed in the path of each set of dual tires, which allowed two aggregates to have traffic simultaneously.

Traffic Application

Each treatment section received the equivalent of 200 logging truck passes. A pass was defined as one unloaded logging truck plus one loaded logging truck. The 14,180-kg dual-axle load was converted to a single-axle equivalent by using the *Earth and Aggregate Surfacing Design Guide for Low Volume Roads* (*4*). The simulator required 600 passes to equal 200 passes of a logging truck. The traffic simulator reproduced near-static loads well. Dynamic loads were not well represented because the axles were not driven, which resulted in no wheel slip. Three cross sections located at one-quarter, one-half, and three-quarters of the length of each treatment section were taken before traffic and after the equivalent of 67, 133, and 200 round-trips.

Added Finer Fractions

Two of the aggregates were deficient in the fraction passing the 0.6-mm sieve. Another sample of one of them that did meet the grading D specification (finer than 25 mm and dense graded) was taken. For the other, sufficient material passing the 0.6-mm sieve was added until the grading D specification was obtained. The added material was from the same source as the original material. Both of these aggregates were completely retested.

Near-Saturated Traffic Conditions

Four of the aggregates came from the west side of the Cascades, where traffic often occurs on nearly saturated roads. To simulate these conditions a constant rainfall of 6 mm/h was applied during the traffic application, which kept the section in a near-saturated condition. The rainfall–traffic–rainfall sequence was repeated for these four aggregates.

RESULTS AND DISCUSSION OF RESULTS

The results of this study are divided into three parts. The first part reviews and discusses how well the suite of performance tests predicted the perceived aggregate quality. The second part focuses on the sediment production from each aggregate and what performance tests were best correlated to sediment production. Finally, the relative sediment production ranking is discussed.

Selected Aggregates

Table 1 describes the 18 aggregates selected for the study. There were nine basalts, three quartzites, two welded tuffs, two alluvials, and one each of glacial outwash and limestone. Basalt parent materials are a common aggregate source throughout the Pacific Northwest, so they dominated this study. All aggregates were crushed to meet local Forest Service specifications. None contained any added material.

The AHM aggregate (the definitions of the aggregate abbreviations are provided in Table 1) was a recycled alluvial material from the Willamette National Forest in Oregon. This material had been recovered from forest roads and stockpiled after being in place for at least 20 years. All other aggregates were collected from stockpiles near the source pit.

TABLE 1 Parent Material, Locations, and Sediment Production from Short, Rutted Section

Parent Material and Abbreviation	Source Name and Forest	Runoff Volume (L)	Sediment Production (g)
Limestone (LG)	Black Hills Black Hills, SD	1.0	0
Western Cascades basalt (BWG)	Springfield Quarry Willamette, OR	18.7	3.6
John Day basalt (BJG)	Highland Ochoco, OR	14.1	8.8
Columbia River basalt (BC3G)	Umatilla B Umatilla, WA	20.7	31.0
Welded tuff (WM)	Montane Wallowa-Whitman, OR	43.7	44.4
Columbia River basalt (BC1G)	Harvard Pit Clearwater, ID	5.5	46.7
Welded tuff (WG)	Fir Tree Ochoco, OR	4.0	91.9
Yachats basalt (BYM)	Saddle Mountain Siuslaw, OR	73.4	101.3
Columbia River basalt (BC2G)	Top of the World Clearwater, ID	21.7	131.9
Quartzite (Q2M)	Stage Nez Perce, ID	87.4	217.3
Western Cascades basalt (BCM)	Lowell Willamette, OR	64.2	325.1
Columbia River basalt (BCM)	Twin Ravens Nez Perce, ID	29.4	339.1
Alluvial High Cascades (AHM)	Recycled Surfacing Willamette, OR	86.2	548.7
Quartzite (QG)	Tyler Ridge Panhandle, ID	59.7	719.0
Glacial Outwash (GG)	Johnson Creek Panhandle, ID	86.4	740.1
Alluvial (AG)	Strawberry Pit Unita, UT	75.0	986.8
Quartzite (Q1M)	Forage Mountain Panhandle, ID	76.2	1020.6
John Day basalt (BJM)	Sherwood Saddle Ochoco, OR	111.2	1322.2

NOTE: Abbreviations were formed from the first letter of the parent material, sufficient additional letters to further uniquely describe the aggregate, and G for good quality or M for marginal quality.

Aggregate Gradations

The aggregate gradations and a grading D specification are shown in Table 2. Although the request was for aggregates that met the grading D specification, only 5 of the initial 18 aggregates, indicated by gray shading, actually achieved this (LGa is shaded in Table 2 but was not an initial aggregate). All of them except one were rated good quality. Additionally, for one other aggregate, rated good, sufficient material less than 0.6 mm was added so that it met the specifications. Twelve of the aggregates had out-of-specification values that were from the larger sizes (25 and 19 mm). There was a nearly even mix of good-quality versus marginal-quality aggregates (five good quality and seven marginal quality). Five aggregates had out-of-specification values that were from the smaller sizes (4.75, 0.6, and 0.075 mm). Among the aggregates in this group the good quality predominated (four good quality and one marginal quality). By requesting aggregates that met the grading D specification, gradation was intended to be eliminated as a variable in the study. As can be seen, the variations in gradation were greater than desired. The tests were performed on these as-received aggregates as well as those to which the finer fraction was added, as noted above, because of a desire to test the actual gradations being placed on forest roads.

The selection of an optimum gradation is a trade-off between various factors (primarily aggregate stability, permeability, and detrimental sedimentation). Generally, a dense-graded material with sufficient fines is desirable for a surfacing aggregate, because it produces a stable structure able to resist traffic forces when wet or dry. When an aggregate is of marginal quality it is sometimes desirable to specify a more open-graded aggregate, one that lacks sufficient sand and fines, because the aggregate will tend to break down and produce more of the finer fraction. A higher percentage of fines (8% to 15%) may be desirable in producing a stable structure when dry and sealing the aggregate from water infiltration when wet, but it can lead to undesirable erosion and sedimentation if excessive rutting is allowed, especially if the material is of marginal quality. Therefore, a designer generally sets the specification limits on gradation after considering road use and aggregate quality. The results of this study should begin to provide the designer with a tool to better assess the ramifications of these types of trade-offs.

Predictors of Aggregate Quality

Table 3 shows the results of an ANOVA between the aggregate performance tests and the aggregate qualities. The tests with the lowest *p*-values were the ones best able to match the perceived aggregate quality. The five best single indicators of perceived aggregate quality were the P20 portion of the Oregon air degradation test (*p*-value of .0004), the sand equivalent test (*p*-value of .0023), the durability of fines test (*p*-value of .007), the sodium sulfate fines test (*p*-value of .012), and the DMSO test (*p*-value of .015).

Oregon Air Degradation Test

The P20 portion of the Oregon air degradation test resulted in the most statistically significant difference between the average values for the good-quality and the marginal-quality aggregates (*p*-value of .0004). The average value of the P20 test for the good-quality aggregate was 8.5%, whereas it was 19.6% for the marginal-quality material. All aggregates had a test value generally well below the traditional standard of a maximum value of 35%. The test of the sediment height (H) resulted in a *p*-value of .0376, with an average value for good-quality material of 1.1 in. and an average value for marginal-quality material of 3.8 in. Three of the marginal-quality materials failed to pass the traditional requirement of less than a maximum of 3.5 in.

Sand Equivalent Test

The sand equivalent test was the second-best indicator of a difference between good or marginal quality, with a *p*-value of .0023.

TABLE 2 Size Gradations of the 20 Aggregates Sorted by Decreasing Mean Particle Size

	Size (mm)						
Parent Material	**50.8**	**25.4**	**19**	**4.75**	**0.6**	**0.075**	**Mean**
Grading D specification		100	90-60	55-30	27-11	15-6	-
WM	100	**79**	**66**	36	15	7.3	12.2
BCM	100	**83**	71	**33**	16	8.1	9.5
LG		100	93	**24**	**10**	6.8	9.3
BJG		100	98	**34**	**9**	**4**	6.9
BYM		**93**	80	40	19	10.7	6.9
LGa		100	95	41	14	9.8	6.8
Q1M		100	91	40	24	13.9	6.8
QG		100	96	39	18	11.4	6.2
WG		100	99	43	14	7	5.6
BWM		**96**	87	46	15	8.1	5.5
BWG			**100**	44	**11**	5.7	5.4
Q2M	**100**	**92**	83	48	20	9.2	5.2
BC3G		100	99	47	13	9.7	5.1
AG		100	92	49	30	12	5.0
BWGa		100	**99.7**	48	17	10.3	5.0
BJM		100	**99**	50	23	9.4	4.8
AHM		100	**99**	54	21	11	3.6
BC2G		**99.8**	96	60	21	9.7	3.3
GG		100	**99.7**	56	23	15	3.1
BC1G		**93**	77	**24**	**9**	6	1.8

NOTE: The data in the table body represent the percentage passing the indicated sieve size. Aggregates with shading met all the grading D specifications. Values in boldface did not meet the grading D specification.

TABLE 3 ANOVA of Difference Between Aggregate Quality and Aggregate Performance Tests

Test Value	Typical Specification	Averages of Good Aggregates	Average of Marginal Aggregates	p-value
Oregon Air – P20	35 max	8.5	19.6	0.0004
Sand Equivalent	35 min	36.7	22.8	0.002
Durability – Fine	35 min	60.1	38.3	0.007
Sodium Sulfate – Fine	12 max	1.6	9.3	0.012
DMSO	12 max	9.0	27.3	0.015
Sodium Sulfate – Coarse	12 max	1.7	6.5	0.017
Oregon Air – H	3.5 max	1.1	3.8	0.038

NOTE: Tests are listed in decreasing order of statistical significance.

The good-quality aggregates had an average sand equivalent test value of 36.7, whereas the marginal-quality aggregates had an average value of 22.8. Compared with the required traditional minimum value of 35, all of the known marginal aggregates failed to meet the specification, whereas only 3 of 10 good-quality materials failed. On the basis of experience in Region 6, the authors prefer this test to the Oregon air degradation P20 test because it is simpler and faster.

Durability of Fines Test

The durability of fines test resulted in the third most significant difference between the averages for good- and marginal-quality materials, with a *p*-value of .0072. In addition, five of the eight marginal-quality aggregates failed to meet the traditional standard of a minimum test result of 35. Only one of the good-quality aggregates failed and had a borderline test result of 34.

Sodium Sulfate Test

The results of the sodium sulfate test with both fine and coarse fractions exhibited statistically significant differences between good- and marginal-quality materials, with *p*-values of .012 and .017, respectively. All of the good-quality materials passed with values less than the traditionally allowed maximum of 12%. For the marginal-quality aggregates, three of the aggregate sources had test values for the fine fraction that were greater than 12%, and one aggregate source had a test value for the coarse fraction that exceeded the maximum value.

DMSO Test

The DMSO test, which was run on the material finer than 4.75 mm, had a *p*-value of .015, indicating that it was able to distinguish between the perceived aggregate qualities. Noteworthy was that the average for the marginal-quality material was 27.3%, which was well in excess of the maximum specification value of 12%. The average for the good-quality material was 9.0%.

All tests with highly significant *p*-values were performed with the finer portion of an aggregate, which indicated that the characteristics of the fine material in an aggregate had a greater impact than the characteristics of the coarser material on whether a material was perceived as being of good quality or marginal quality.

Runoff Volume

Table 1 shows that there was a wide range of runoff volumes among the 18 aggregates. The runoff volumes from the short, rutted section ranged over 2 orders of magnitude, with similar ranges for the short section and the long, rutted section.

Table 4 shows the average runoff volumes for the three road conditions grouped by aggregate quality. Comparison of the runoff volumes from the short section showed that there was a statistically significant difference between the two aggregate qualities (*p*-value of .047). The average runoff volume for the good-quality aggregate was 28.8 L, whereas that for the marginal-quality aggregate was 68.4 L. Knowing whether an aggregate was classified as being of good or marginal quality was sufficient to predict whether it had a high or a low runoff volume.

Neither rutted section showed a statistically significant difference between the mean runoff volumes for the two aggregate qualities (*p*-values of .22 and .23, respectively). In a rutted condition, simply knowing whether an aggregate was classified as being of good or marginal quality was not sufficient to determine whether it would have a high or a low runoff volume.

These three tests indicated that to achieve the reduced runoff volume from the use of good-quality aggregate, the road should be maintained free of wheel ruts. If this is not done, the runoff benefit of the good-quality aggregate will not be realized.

The best single predictor of runoff volume for both of the short sections was the fraction passing a 0.6-mm sieve, with *p*-values of .0004 and .0006, respectively, and correlation coefficients (r^2 values) of .73 and .72, respectively. For the long, rutted section the fraction passing a 2-mm sieve was the best single predictor of runoff volume.

TABLE 4 Average Runoff Volume and Sediment Production by Aggregate Quality for Each Road Condition

Road Condition	Runoff Volume (L)		p-value	Sediment Production (g)		p-value
	Marginal	Good		Marginal	Good	
Short	68.4	28.8	0.047	601.4	208.8	0.041
Short rutted	60.2	41.3	0.221	489.8	279.8	0.255
Long rutted	366.9	313.8	0.235	4095.5	3309.2	0.597

The fraction passing a 0.6-mm sieve was second, with only slightly lower *p*-values and correlation coefficients (*p*-value of .0013 and r^2 value of .68). A measure of the smaller-diameter fraction as the best predictor of infiltration was a logical result, because infiltration was controlled by the size of the pore space between the larger aggregates. Increasing fines filled the pore space and reduced the level of infiltration, resulting in increased runoff. Figure 1 shows the relationship between the runoff volume and the fraction passing a 0.6-mm sieve for the short, rutted section.

Sediment Production

Sediment production for each of the three road conditions grouped by aggregate quality is shown in Table 4. For each road condition, the marginal-quality aggregates produced more sediment. In the short section there was 2.9 times as much sediment from the marginal-quality aggregates as from the good-quality aggregates. ANOVA showed that there was a statistically significant difference (*p*-value of .041) between the average sediment production for marginal-quality aggregates and that for good-quality aggregates for the short road section. This indicated a statistically significant difference in sediment production between aggregate qualities for a short unrutted road section.

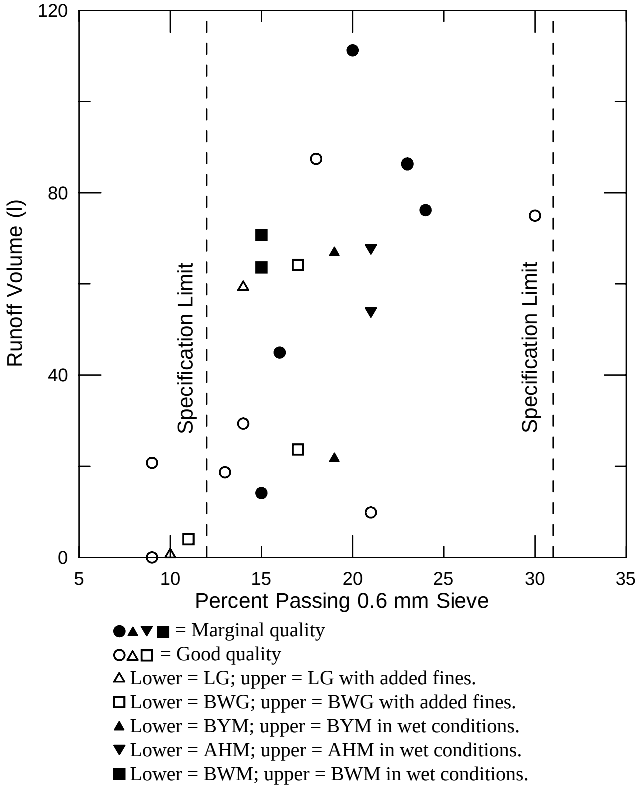


FIGURE 1 Relationship between runoff volume and fraction passing 0.6-mm sieve.

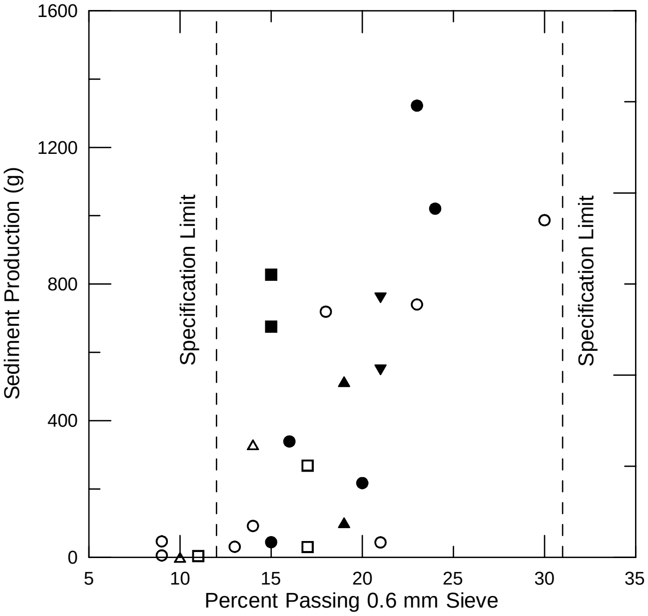
For the rutted conditions, the marginal-quality aggregates produced 1.2 to 1.8 times as much sediment as the good-quality aggregates. However, ANOVA indicated that there was no statistically significant difference in the average sediment production between marginal- and good-quality aggregates when the road section was in a rutted condition (*p*-values of .26 and .60, respectively).

These tests indicated that differences in aggregate quality became less apparent as the length or the degree of rutting increased. This suggests that to derive maximum benefit from the better-quality aggregate, deep ruts should not be allowed to remain in the road during heavy rainfall periods, and the road side slope or crown should be maintained.

The importance of testing aggregates under traffic conditions was highlighted by these results. Had the study been conducted without traffic, the conclusion would have been that aggregate quality alone results in a statistically significant difference in sediment production. In the presence of traffic; however, aggregate quality alone did not result in a significant difference in sediment production. Testing of sediment production potential from aggregates should include traffic.

The best predictor of sediment production from each of the three road sections was the fraction passing the 0.6-mm sieve, with *p*-values ranging from .0005 to .0001 and correlation coefficients ranging from .72 to .79. A measure of the smaller fractions as the best predictor of sediment production was again a logical result. Similar to the influence of fraction size on infiltration, this size range was the most susceptible to erosion by raindrop impact and concentrated flows. Figure 2 shows the relationship between sediment production and the fraction passing the 0.6-mm sieve for the short, rutted section.

It would appear that to minimize sediment production, the fraction passing the 0.6-mm sieve should be minimized. However, the overall aggregate gradations must be considered. The larger pore spaces of a dense-graded aggregate, one that contains material of all sizes from the maximum to the fines, will be occupied by sand and fines. This is a highly desirable condition because it provides for stability and waterproofing. Alternatively, an aggregate that is too open graded, one that lacks sufficient sand and fines to occupy the larger



●▲▼■ = Marginal quality
○△□ = Good quality
△ Lower = LG; upper = LG with added fines.
□ Lower = BWG; upper = BWG with added fines.
▲ Lower = BYM; upper = BYM in wet conditions.
▼ Lower = AHM; upper = AHM in wet conditions.
■ Lower = BWM; upper = BWM in wet conditions.

FIGURE 2 Relationship between sediment production and fraction passing 0.6-mm sieve for the short, rutted section.

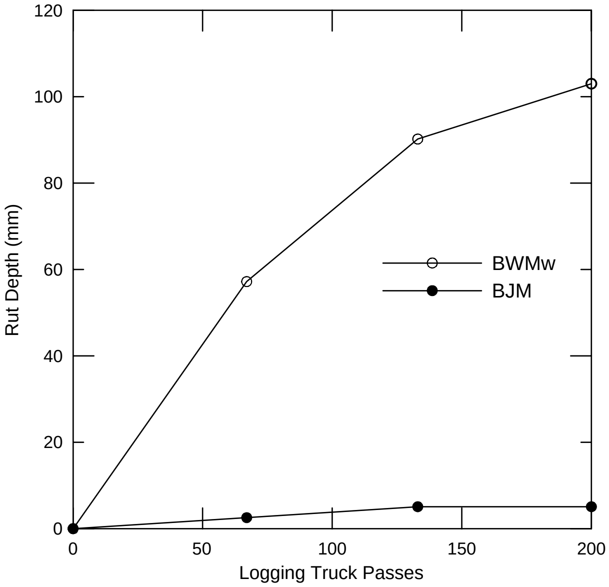


FIGURE 3 Rut depth development with traffic for the deepest and the shallowest rut.

pore spaces, will be unstable and will allow water to infiltrate and saturate the subgrade. If an aggregate is unstable, it can severely rut and allow subgrade pumping, which can greatly increase road sedimentation.

A conflicting relationship exists between gradation and sedimentation. Dense-graded materials will have more material passing the 0.6-mm sieve and will produce more sediment but remain stable to protect the subgrade. Gradations—and specifically, the fraction passing the 0.6-mm sieve—must be selected to satisfy the conflicting requirements of sediment production and aggregate performance under traffic.

Average Rut Depths

Figure 3 shows the development of the deepest rut (BWMw aggregate) and the shallowest rut (BJM aggregate). Rut depth was defined as the depth from the peak to the valley of the rut, and one pass was a loaded plus an unloaded logging truck. All other aggregates followed this general pattern and were contained within the envelope defined by these two aggregates. Because the width of the truck tires was 0.2 m, the frames were 6.25 times as wide as the truck tire, whereas the depth was equal only to the width of the truck tire. From a consideration of the vertical stress in the aggregate, the frame width was sufficient to represent a forest road. However, the frame depth equal to the tire width was not sufficiently deep to reproduce a pressure distribution similar to what would occur on an actual road. Additionally, it had a more rigid bottom, resulting in stresses in the aggregate that were higher than those that would be applied by a fully loaded logging truck to an actual road. Greater crushing of the aggregate near the bottom of the frame would be expected in the shallow frame that was used. Possible consequences would be greater depth of rutting and increased sediment production if those fines were able to move to the surface. Aggregates with lower crushing strengths would be affected more than those with higher crushing strengths.

The BWMw aggregate reached only 50% to 60% of its final rut depth after the passage of one-third of the traffic (Figure 3). This is probably because in this study the aggregate test frames were relatively small compared with those used in other studies (*4, 5*) and the aggregate was placed and compacted on a metal base. The aggregate was uniformly compacted to the desired density. In the other studies the placed materials consisted of both subgrade soils and aggregates and were generally of lower quality. It was probably not possible to get these materials compacted to as uniform a level, and therefore, a greater level of initial rutting was measured.

Figure 4 displays the final rut depth for each of the 18 original aggregates plus the 4 aggregates tested under wet conditions (aggregates with “w” appended to the name) and the 2 aggregates tested with added fines (aggregates with an “a” appended to the name). Note the difference of a factor of 20 between the shallowest and the deepest final rut depths. The four aggregates tested under wet conditions had deeper ruts under wet conditions than under the standard condition.

A stepwise linear regression (*p*-value of .0003) resulted in the identification of an increase in the rut depth when the water content of the aggregate increased and a decrease in the rut depth when the specific gravity of the aggregate particles increased. Increased water content reduces the strength of the aggregate and would be expected. The specific gravity of a material is generally related to the degree of weathering (the lower the specific gravity, the greater the degree of weathering). Geologically, weathering indicates the presence of secondary minerals (clay minerals) that cause a material to be less durable in the presence of water, which leads to increased rutting.

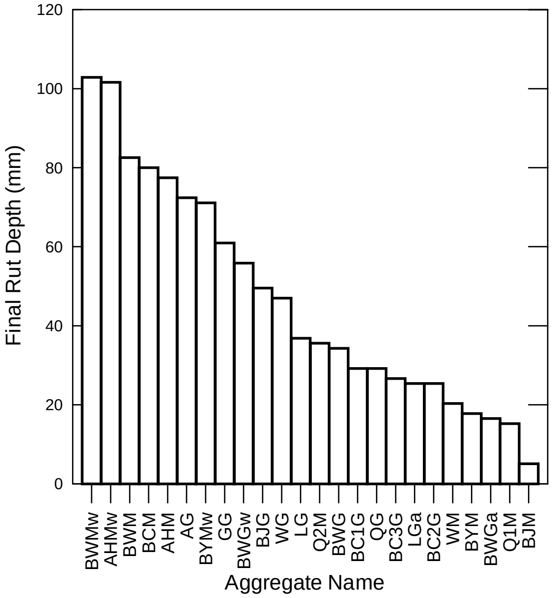


FIGURE 4 Final rut depths (peak to valley) after 200 logging truck passes.

Traffic Under Wet Conditions

Four of the aggregates (BYM, AHM, BWM, and BWG) with added fines were tested under a wetter precipitation regime, because these aggregates were used in forests with high levels of precipitation. Under the wetter precipitation regime, all three of the marginal aggregates had greater runoff and produced more sediment compared with those achieved under the base condition. The good aggregate (BWGa) produced less runoff and less sediment under the wetter precipitation regime than under the base condition.

Traffic under wet conditions can increase the degree of rutting. The increased moisture content can "soften" the fines (decrease the apparent cohesion of the fines), thus decreasing the shear strength of the aggregate. In other cases, when the aggregate durability is low, the aggregate may break down into a less stable gradation and be more susceptible to permanent deformation (or rutting).

Effects of Added Fines

The amount of runoff and the sediment yield increased after the fines content was increased. As shown in Figure 1 (for the LG aggregate, compare the filled triangles; for the BWG aggregate, compare the filled inverted triangles), these aggregates with increased fines had runoffs consistent with those for other aggregates with the same fraction of fines passing a 0.6-mm sieve. Similarly, Figure 2 indicates that the addition of fines to these aggregates resulted in levels of sediment production consistent with the amount of new fines added.

The addition of fine material passing a 0.6-mm sieve resulted in shallower ruts compared with the depths of the ruts achieved under the base condition (compare LG with LGa and BWG with BWGa in Figure 4). The reductions in rut depths were 31% and 52%, respectively. This was probably because the resultant gradation with the addition of material passing the 0.6-mm sieve provided a more dense-graded aggregate that would be more stable under traffic loading.

Relative Ranking of Aggregates

One of the objectives of the study was to provide a relative ranking of the different aggregates on the basis of the level of sediment production. Because there were three road sections, ranking could be done on any of the three. To determine if there was a statistical difference between the rankings, a Spearman's rank correlation was performed. A high level of correlation between ranks meant there was no statistical reason to prefer one ranking scheme over the alternative one.

The *p*-value for the correlation of the rankings between the short section and the short, rutted section was .0001. For the correlation of the rankings between the short section and the long, rutted section, the *p*-value was .0002. The pairing of short, rutted sections and long, rutted sections had a *p*-value of .0001. These values show that the relative rankings of the aggregates on the basis of the degree of sediment production were not statistically different, regardless of the ranking method. One can use any of the treatments and the relative ranking of the aggregates tested will not be statistically different. The authors interpret this to mean that one should expect that one aggregate will have a relative degree of sediment production comparable to that of another aggregate regardless of the road segment length or the degree of rutting.

CONCLUSIONS

Road designers using locally available materials should keep in mind several items from this study. For the suite of aggregates tested, the P20 portion of the Oregon air degradation test and the sand equivalent test were the best indicators of aggregate quality. Both tests had statistical significance corresponding to *p*-values of .002 or less. Based on experience, the authors prefer use of the sand equivalent test to classify an aggregate as being of marginal or good quality.

For the rutted condition treatments (both the short, rutted section and the long, rutted section), simply identifying an aggregate as being of good or marginal quality was not sufficient to determine whether it would have a high or a low runoff volume. Only for the short section treatment could the classification of good or marginal be used to predict whether the runoff would be high or low or whether the level of sediment production would be high or low. Relying on the classification of aggregates into good or marginal quality was not useful for determination of the sediment erosivity under rutted road conditions.

Runoff volume was directly proportional to the fraction passing the 0.6-mm sieve. Sediment production was also directly proportional to the fraction passing the 0.6-mm sieve. To minimize either runoff or sediment production, one should minimize the fraction passing the 0.6-mm sieve but not go below the minimum acceptable 12% for stability reasons.

A relative ranking of the aggregates was determined. The range of sediment production was 2 orders of magnitude.

Under the conditions used in the study, the range of rut depths was 5 to 103 mm, a factor of 20. Aggregate quality alone was not able to predict whether a final rut depth would be comparatively deep or shallow. The addition of material less than 0.6 mm to achieve the grading D specifications resulted in additional sediment production. This additional production was consistent with what would be expected from an aggregate with a similar fines content. A reduction in final rut depth was observed from the addition of fines.

The aggregates tested showed a wide range of rut depths, rainfall runoff volumes, and sediment production levels. To achieve the sediment reduction available from good-quality aggregate, ruts should not be allowed during heavy rainfall.

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