Research Article
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Aggregate Performance on Forest Roads in the Pacific Northwest

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Abstract

Eleven aggregate quarries from the Pacific Northwest, USA were sampled to measure the variability in rock properties. Additionally, road managers were asked to classify the aggregate source as good or marginal for forest roads with year-round timber hauling as the primary use. Seven of the eleven quarries were classified as good. A series of materials property tests were performed on the aggregate sampled from each quarry. The test included gradation, LA Abrasion, Micro-Deval, and sand equivalency tests. Three replicates were performed for the LA Abrasion, Micro-Deval, and sand equivalency tests. The results show that only two of the seven rated as good samples met the thresholds established from the literature review. None of the marginally rated aggregates met the thresholds for the material property tests. The results show that the road managers expectation of rock quality is inconsistent when compared with the results from tests. It suggests that in order to understand aggregate performance better, testing before placement is a necessity.

Keywords: Aquatic and terrestrial ecosystems, Forestry activities, Watershed management, Wood production

1. Introduction

As in the Pacific Northwest, USA, much of the forest roads are paved using an open-sealed aggregate material to allow for year-round use. The aggregate layer allows greater traction during hauling, especially during the wet season that can last most of the year. Additionally, the rock surface distributes the load from heavy vehicles to reduce the stress on the subgrades; thus, they can reduce the likelihood of potholes or ruts forming from subgrade failures. The cost can be high for the rock surfacing with aggregate cost up to $64,000 per kilometer (Sessions et al., 2006). To conserve this valuable resource, many are recycling rock from temporary roads. Others use only locally available rock without crushing to reduce this cost without any understanding of its material properties such as rock's resistance to mechanical breakdown from traffic or weathering. There is little formal knowledge to predict the aggregate's mechanical and environmental performance.

Forest roads can pose significant impacts on the environment (Boston, 2016), and much of this impact is on water quality from surface-generated sediments (Luce and Black, 1990; Toman and Skaugset, 2011). There are a variety of regulations at both state and federal levels of government to limit the pollution from forest sources (Boston, 2012). One element of the Clean Water Act, 33 U.S.C. §1251(a), is a requirement that water quality standards be assigned to all waters of the United States, 33 U.S.C. §1313(a). These describe the beneficial uses of water and place limits on the various amounts of pollutants allowed in a stream segment. Sediment is one of the most common pollutants that is to be controlled using total maximum daily loads, (TMDLs), which limit activities in the watershed.

Currently, many salmon runs are listed as threatened under the endangered species act (ESA), 16 U.S. C. §§1531-1544. Sediment transported from forest roads to streams and rivers are generally fine-grained materials, less than 2 mm in diameter (Cederholm et al., 1981). Fine sediment is the most detrimental to the survival of salmonid eggs as this limits the flow of oxygenated water around the eggs; thus, harming their breeding habitat. Under Federal regulations, the impairment of habitat can be ruled as an illegal taking as it impairs breeding habitat.

Additionally, many state regulations govern road practices, and the need is growing. These regulations involve the use of best management practices such as hydrologically disconnecting roads from a stream or

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constructing a road to minimize the generation of sediment. Regulation of water quality is likely to increase as clean water becomes one of the dominant resources produced from the forest; better practices are continually demanded from our forest roads.

Foltz et al. (2003) conducted a study to investigate the sediment production of various aggregates. They collected 18 aggregate samples, of which eleven were classified as good quality by the forest road managers that nominated them, and the remainder were classified as marginal quality. The standard performance tests they used to meet this objective are the following: sand equivalent (ASSHTO 176), durability (AASHTO T210), sodium sulfate (AASHTO T104), Oregon air degradation (Oregon Department of Transportation Laboratory Manual, and dimethyl sulfoxide (DMSO) test (FHWA A Method AG9, Region 10, Standard Method Test for Accelerated Weathering of Aggregate by Use of Dimethyl Sulfoxide). Their results showed high variability among quarries and poor predictive results from the quality estimated by the nominee of the quarry compared to the results from the materials tests (Foltz et al., 2003).

Toman and Skaugset (2011) showed that surface runoff does not originate from the subgrade but rather from the surface aggregates. They suggest that road managers who want to minimize the production of sediment from forest roads should be concerned with the quality of unbound aggregate pavement. Kemp et al. (2016) tested two qualities of aggregate under hauling conditions in Oregon, USA. They found that heavy truck traffic was the leading cause of sediment generation in an open-graded aggregate. The poorly-graded aggregate showed a greater tendency to break when exposed to truck traffic resulting in more fracturing and abrasion wear during hauling.

There is a need to understand better the environmental performance of aggregates used in forest roads and develop the tools that can categorize them as good or marginal before deployment in the field. Improved environmental performance is possible where rock selection is a deliberate design choice. For example, high-quality aggregate, one that resists mechanical and chemical weather, used on hydrologically connected streams, may lower pollution, where a ridge top road that is disconnected from the streams may allow the use of lower quality rock. There are multiple methods to predict rock performance; however, most timber companies rely on local knowledge of their road managers and do not conduct formal material testing. Thus, they rely on past performance to predict the future. There is an opportunity for errors in this method as rock quality from quarries may vary from good to bad depending on the spatial location in the rock. Thus, results from the road manager's expert view can be compared with several material property tests to describe if there might be a benefit from testing aggregate before use.

This study serves two purposes. One is to describe the variability of aggregate sources from quarries in the Pacific Northwest, and second is to compare the results from these material property tests and road manager's expert opinion on the quality of the rock. It will use four standard materials tests (i.e. gradation, LA Abrasion, Micro-Deval, and sand equivalency) to determine the rock quality.

2. Material and Methods

2.1. Study Area

The aggregate was collected from 11 sites in western Oregon and Washington (Figure 1, Table 1,). These represent the preferred geologic material, a mafic rock, used in the region for aggregate surfacing. The material was collected from piles from each quarry utilizing the procedure described by McNally (2002).

2.2. Material Tests

The four tests performed were Gradation tests (ASTM C136-06), Los Angles Abrasion test (ASTM C535 and ASTM C131), the Micro-Deval tests (ASTM D6928), and sand equivalency tests (ASTM D2419). These tests were selected as they represent both the mechanical and weathering performance of the rock and the byproducts generated from wear, sand or clay, to determine the potential environmental impact.

Paige-Green (1999) described the importance of particle size distribution in the effectiveness of compaction of the material by facilitating the interlocking of aggregate particles. Too few fines will result in the rock shifting in the road and increasing the wear. Large oversized stones can harm the performance of the road and screening was recommend for removing this material. Various parameters have been developed to interpret the gradation curves in terms of a single value. Among these is the grading coefficient (*GC*) (Paige-Green, 1999):

$$GC = (\%\ passing\ 26.5\ mm - \%\ passing\ 2.0\ mm) \times \%\ passing\ 4.7\ 5mm \times 100 \quad (1)$$

This measure has been used to predict the performance of gravel wearing course materials and was shown to correlate best with the performance of low volume roads. The optimum range for the grading coefficient is between 16 and 34 (Paige-Green, 1999).

Aggregate durability is a measure of resistance to fracturing or wearing through abrasion. Many tests have been developed to measure this property. Two methods are used in this study: Los Angeles Abrasion test and the Micro-Deval. The LA Abrasion has been a traditional test of aggregate durability method since it was developed in Los Angeles in the 1920s (Weyers et al., 2005).

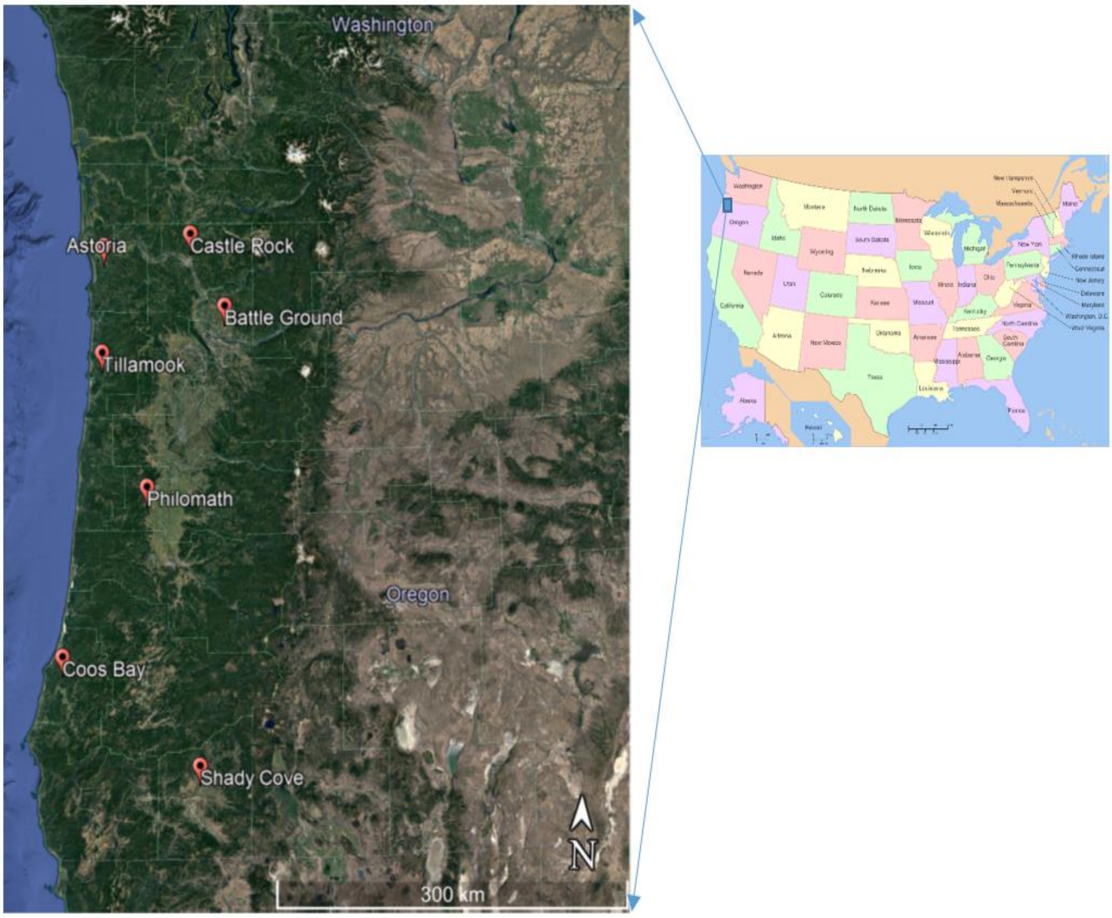

Figure 1. Study Area

Table 1. Sources, Mineralogy and Managers estimation of quality from 11 sources in western Oregon and Washington

Sample No.	City, State	Parent Material	Manager's Estimation of Quality
1	Philomath, OR	Gabbro	Good
2	Shady Cove, OR	Basalt	Good
3	Shady Cove, OR	Gabbro	Good
4	Tillamook, OR	Gabbro	Marginal
5	Tillamook, OR	Gabbro	Good
6	Astoria, OR	Gabbro	Marginal
7	Astoria, OR	Gabbro	Good
8	Coos Bay, OR	Gabbro	Good
9	Battleground, WA	Gabbro	Marginal
10	Battleground, WA	Gabbro	Good
11	Castle Rock, WA	Basalt	Marginal

According to a survey conducted by Prowell 2004 (as cited by Weyers et al., 2005), 96% of the agencies within the 48 states still use the LA Abrasion test to analysis aggregate durability. Despite its long history and continual use, some concerns regarding the results from this test have been well documented with its inability to distinguish among the quality aggregates (Senior and Rogers 1991). The threshold for good aggregate, by LA Abrasion, is one that produces less than 40% fines (Cuelho et al., 2007).

Another abrasion test is the Micro-Deval test that was developed in France during the 1960's and has become a standard test method used by the Ontario Ministry of Transportation as well as various departments of transportation (DOT) agencies within the United States (Seniors and Rogers, 1991). It is a wet abrasion test that is used to determine the potential for an aggregate to degrade during handling. The test was developed to include the effects of moisture on abrasion resistance, a property that cannot be determined by using the LA Abrasion test. Additionally, the test uses smaller charges and a smaller drum that limits the acceleration of the charges during the trial that reduces the impact loading on the material being tested (Weyers et al., 2005). One study had recommended that the Micro-Deval test should replace the LA Abrasion test due to its ability to reflect field conditions better and predict field performance (Senior and Rogers, 1991).

Cuelho et al. (2007) have established a standard of 18% fines produced Micro-Deval state as an indicator of good aggregate.

The sand equivalency test is a chemical weathering test that measures the byproducts from weathering sand particles into clay particles. This test determines the relative proportion of detrimental clay particles contained as compared to sand. Material with a high clay content can cause the aggregate to reduce water quality as the clay is much more transportable in the water than the larger sand particles. Also, the high clay composition in the aggregate matrix can produce large amounts of dust that can increase driving hazards and air pollution (Sanders et al., 1993). Aggregate producing greater than 35% content of sand is considered a high-quality aggregate (Foltz et al., 2003).

All tests except the gradation test had three replicates performed from each sample. All tests followed the ASTM guidelines and readers are encouraged to review those procedures. Road managers were interviewed and classified the rock as either good or marginal for aggregate for forest roads where the primary activity is timber hauling.

3. Results and Discussion

The results from the two abrasion and sand equivalency tests show minimal standard deviations between the three trials from each quarry sampled. They range from less than 1 to 3%. Thus, the tests show a high degree of consistency among their values with small variation. The range in values from the tests among the different quarries is high. The range in tests is at least double the minimum amount with the LA Abrasion between 12 and 27%, Micro-Deval between 7% and 38%.The results from the gradation test show that four of the 11 samples achieved the criteria for the gradation coefficient value recommended by Green-Page (1999) between 16 and 34 (Table 2) for wearing-coarse aggregates. Of the four samples exceeding the criteria, three were rated as good by the road managers. In the Oregon forest products industry, there are limited controls on aggregate crushing; thus, the range of values amongst the grading coefficient could be improved with additional controls during crushing. All of the samples met the threshold for the LA Abrasion test, with less than 40% material loss (Table 3).

Table 2. Ranked summary in order of decreasing grading coefficient values

Sample Number	Manager's estimation of Quality	Maximum Particle Size (mm)	Uniformity Coefficient	Grading Coefficient
10	Good	31.5	30.36	31
8	Good	37.5	19.11	25
1	Good	37.5	19.11	21
4	Marginal	63	40	17
7	Good	63	58.46	15
6	Marginal	63	27.85	**13**
5	Good	63	14.4	**13**
9	Marginal	63	42.5	**12**
3	Good	63	13.12	**9**
11	Marginal	100	15.55	**6**
2	Good	63	4.58	**6**

*Those denoted in bold fail to meet the desired values

Table 3. Ranked summary in order of decreasing fines produced from the LA Abrasion tests with their standard deviations

Sample Number	Manager's estimation of Quality	Average Loss	Standard Deviation
9	Marginal	12.60%	0.71%
7	Good	13.20%	0.21%
1	Good	15.00%	1.41%
10	Good	16.80%	0.51%
6	Marginal	19.40%	1.08%
8	Good	20.80%	0.82%
2	Good	21.10%	0.52%
3	Good	22.80%	0.22%
5	Good	23.00%	1.78%
11	Marginal	23.40%	2.38%
4	Marginal	27.40%	1.88%

The range in data is large from 12 to 27% fines produced from the various samples. However, Micro-Deval is a much more discriminating test with only six of 11 samples exceeding the criteria of less than 18% material loss produced from the test (Table 4).

Five of the six samples exceeding the threshold were rated as good by the road managers while two of samples evaluated as good produced considerable amount of fines than the test with the worst more than twice the threshold value.

The sand equivalency test had six of the 11 samples exceeding the 35% sand component value recommended as a threshold by Foltz et al. (2003). Five of the six of the aggregate samples exceeding the limit were rated as good by their road managers (Table 5). One was very close, with only 1% more clay than the criteria.

Combining the results from the three tests, excluding the LA Abrasion tests, shows that only two of the samples rated as good, by the road managers, met the threshold for the three tests, samples two and 10 (Table 6). None of the marginally rated samples were able to reach the desirable thresholds for the three tests.

Table 4. Ranked summary in order of decreasing fines produced from the Micro-Deval tests with their standard deviations

Sample Number	Rank	Manager's estimation of Quality	Average Loss	Standard Deviation
2	1	Good	6.90%	0.24%
7	2	Good	7.10%	0.38%
9	3	Marginal	11.80%	0.28%
10	4	Good	12.00%	0.62%
3	5	Good	13.80%	0.69%
8	6	Good	18.00%	0.72%
6	7	Marginal	**20.10%**	0.76%
1	8	Good	**21.50%**	1.23%
4	9	Marginal	**24.10%**	0.80%
5	10	Good	**35.90%**	2.78%
11	11	Marginal	**38.50%**	1.21%

Table 5. Ranked summary in order of decreasing sands produced from the sand equivalency test with their standard deviations

Sample Number	Rank	Manager's estimation of Quality	Average	Standard Deviation
7	1	Good	54%	0.58
4	2	Marginal	53%	3.61
10	3	Good	47%	3.00
2	4	Good	43%	1.15
8	5	Good	41%	2.31
5	6	Good	37%	0.58
3	7	Good	**34%**	1.53
9	8	Marginal	**34%**	3.61
1	9	Good	**28%**	1.73
11	10	Marginal	**26%**	1.53
6	11	Marginal	**25%**	0.58

*Bold values indicate those not meeting the standard

Table 6. Summary of the results for the 11 aggregate samples

Sample Number	Manager's estimation of Quality	Gradation	Mico-Deval	Sand Equivalency	Overall
1	Good	no	no	no	no
2	Good	**yes**	**yes**	**yes**	**yes**
3	Good	no	**yes**	no	no
4	Marginal	no	no	**yes**	no
5	Good	no	no	**yes**	no
6	Marginal	no	**yes**	no	no
7	Good	**yes**	no	**yes**	no
8	Good	no	**yes**	**yes**	no
9	Marginal	**yes**	**yes**	no	no
10	Good	**yes**	**yes**	**yes**	**yes**
11	Marginal	**yes**	no	no	no

4. Conclusion

The high variability in the results from the different quarries shows the need for testing of quarries as they do vary significantly throughout the region. There is no real pattern among the tests; high abrasion values may have high clay content as in sample seven revealing there is no single test of those performed that can describe the result. Thus, a suite of tests appears to be necessary to capture the properties of the rock.

Like the results from Foltz et al. (2003), of the road manager's good aggregate selection, only two of seven meet the thresholds for the three tests. If we assume that sample eight could meet the gradation requirement when subject to better crushing control, then at best three of the seven aggregates meet the thresholds described for good aggregate quality. None of the aggregates evaluated by the road managers as marginal met the three thresholds. Only one quarry, sample nine, met two of the three thresholds as a marginal quality aggregate.

Rock properties vary significantly among quarries, and future studies will need to consider a range of rock sources using a suite of tests that can estimate the mechanical and chemical breakdown and the potential compaction of the aggregate. Only two of the 11 samples met the threshold levels for good aggregate, which support the results from Foltz et al. (2003). By conducting these types of tests, there may be an opportunity to improve aggregate performance where it is needed most, creating a better understanding of the aggregate properties before it is placed in the roadbed.

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