Case Study: Evaluating Road Performance and Sediment Generation during Simulated Wet Weather Hauling

Erica Kemp, Ben Leshchinsky*, Kevin Boston
Oregon State University, College of Forestry
Department of Forest Engineering, Resources and Management, Corvallis, OR 97330, USA

Abstract

Aggregate roads are the primary means of access to managed forestlands in western Oregon, but may facilitate sediment transport during rainfall, especially with traffic from heavy trucks. This transported sediment, typically in the means of suspended sediment or turbid effluent, may have detrimental effects on aquatic ecosystems, especially when roads are in proximity to creeks, streams and rivers. However, due to past construction practices and difficult terrain, many existing roads are stream-adjacent, and may require retrofitting to address potential delivery of fine sediment from its surface during rainfall. To evaluate a potential treatment to this problem, a heavily-instrumented field test was performed on a reconstructed aggregate forest road in Western Oregon which sought to test the potential of geosynthetic materials to sequester road sediment and improve road performance during wet-weather hauling. A sand filter berm wrapped with a non-woven geotextile provided 70% and more reduction in turbidity when tested under idealized laboratory conditions. Additionally, a geogrid reinforcement placed on the native road subgrade material prior to placing the aggregate layer reduced subgrade pressures experienced during loading, improving mechanical performance. When applied to well-graded aggregate, the geogrid reinforcement reduced rutting, a potential channel for flow of turbid runoff. When applied to a poorly-graded aggregate the geogrid reinforcement reduced relative breakage. Aggregate degradation and road performance may be improved with use of the geogrid reinforcement and road sediment may be effectively sequestered with use of a geotextile-wrapped filter sand berm when applied correctly. Targeted applications of these approaches are recommended where desired levels of road performance and water quality improvement may justify the additional labor and materials required. However, more replicates and larger scale application may address some levels of variability that are difficult to address under the constraints of an intensive field test.

Keywords: Forest roads, Geosynthetics, Wet Weather Hauling, Oregon

1. Introduction

Aggregate roads are the infrastructure of choice for access into managed forested lands in western Oregon. Their ability to withstand repeated heavy traffic presents an economical means to maintain access to remote locations. Despite their practical utility, forest roads are a potential source of ecological disturbance. Over time, road systems generate sediment which can collect in runoff and deposit in nearby aquatic ecosystems; thus, they may be subject to increased regulatory scrutiny (Boston, 2012). For small order streams, this amounts to a substantial increase in the turbidity and Suspended Solids Concentration (SSC) of the stream—conditions that degrade sensitive habitats such as spawning grounds for threatened salmonid species (Lane and Sheridan, 2002; Madej, 2004). In the Pacific Northwest region of the United States, land managers must weigh the deleterious effects of sediment transport with the practical benefit of aggregate forest roads as a means of accessing and working in forested landscapes.

1.1. Forest Roads and Sediment Generation

The timber industry has long been under scrutiny for unfavorable environmental impacts. The construction of aggregate roads for timber harvest produces sediment loads orders of magnitude larger than logging itself (Megahan and Kidd, 1972). Most investigations found that the construction and presence of aggregate roads is a principal source of fine sediments (Megahan and Kidd, 1972; Johnson and Beschta, 1980; Reid and Dunne, 1984; Lane and Sheridan, 2002), but results conflict when identifying key drivers of sediment production which obfuscates predictions of sediment loads in streams (Luce and Black, 1999; Lane and Sheridan, 2002; Toman and Skaugset, 2011).

*Corresponding author: Tel: +1 541737-8873 E-mail: ben.leshchinsky@oregonstate.edu
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In the forests of the Pacific Northwest, sediment produced from anthropogenic activities often originates in logging roads or in disturbed terrain (Megahan and Kidd, 1972; Beschta, 1978; Reid and Dunne, 1984). In roaded areas, this includes disturbed soils, excavation sites, road cut and fill slopes, and the roads themselves (Bilby et al., 1989; Lane and Sheridan, 2002). In a controlled analysis of aggregate performance, it was found that particle size distribution, specifically percent by mass passing a 0.6-mm sieve (ASTM No. 30), was a strong indicator of sediment delivery from an aggregate road under wet weather log truck hauling conditions (Foltz and Truebe, 2003). They also found that a 12% fines content by mass to be ideal, above which excess sediment quickly exits the road prism, and below which, larger void sizes may be responsible for increased runoff capacity. This finding was confirmed in a similar investigation by Toman and Skaugset (2011) which found 14% to be an ideal fines concentration.

1.2. Hydrologic Relationships

Proportional to rainfall, runoff also corresponds to sediment yield (Foltz and Truebe 2003, Miller 2014) (Foltz and Truebe, 2003; Miller, 2014). Foltz and Truebe (2003) demonstrated that the amount of sedimentation from aggregate was directly proportional to the volume of runoff exiting a test track under simulated rainfall conditions. Other known indicators of sediment yield including truck hauling, road material composition, and ditch hydrology had less influence on sediment yield (Miller, 2014). This finding encourages further research under controlled rainfall conditions in order to observe the anthropogenic influences of sedimentation in aggregate roads.

1.3. Aggregate Strength and Material Properties

Lekarp et al. (2000) found that stress magnitude and direction, number of loading cycles, degree of saturation, load history, compaction, gradation size and distribution, and aggregate material were all parameters that influence the complex response to strain in unbound aggregates. Aggregate strength improves resistance to degradation in addition to other performance considerations. Leshchinsky and Ling (2013a, 2013b) found that on a study of railroad ballast, aggregate strength was tied to performance and longevity, as well as its ability to distribute loading to supporting subgrade materials. The same principles apply to aggregate roads, where the occurrence of rutting from repeated traffic can be minimized by the use of stronger aggregates to minimize subgrade stresses (Toman and Skaugset, 2011).

1.4. Influence of Truck Traffic

Truck traffic is a known mechanism of aggregate degradation. The rate of degradation is linked to number and magnitude of loading cycles (Lekarp et al., 2000; Sheridan et al., 2006). Foltz and Truebe (2003) also found relationships between rutting, runoff volume, and sediment production. Among different rock types, steady simulated rainfall, and repeated loading, an increase in sediment production was observed with both the presence and length of rutting (Foltz and Truebe, 2003). Although the investigation inspected test tracks which experienced only 200 truck passes, Foltz and Truebe (2003) were able to determine that the combined influence of truck traffic and aggregate quality created a statistically significant difference in sediment production. Reaching similar conclusions, Toman and Skaugset (2011) noted that among their three test sites, all using different aggregates, the roads that exhibited rutting were larger producers of sediment in runoff.

1.5. Use of Geosynthetics

Subgrades in the forest industry do not typically adhere to the specifications use for heavy civil projects. That is, controlled compaction is often not performed and the result is often low density and subsequently low strength (Boston et al., 2008). Thus, geosynthetics offer an opportunity to improve these weak subgrades that can contribute to rut formation that can contribute to increased sediment production. Giroud and Han (2004) quantified road rutting and its subsequent reduction with geogrid reinforcement within an aggregate road, linking heavy truck traffic, number of loads, and subgrade bearing capacity to road rutting. They illustrated how the use of geogrid reinforcement reduces the required thickness of a base course material given maximum rutting depth criteria (Giroud and Han, 2004).

Leshchinsky and Ling (2013b) found a positive correlation between increased confinement and improved aggregate strength and performance. Confinement with the use of geocells immobilized aggregate from deformation under loading, and prevented abrasion and fracture when confined (Leshchinsky and Ling, 2013b). Geogrids function using a similar mechanism, preventing movement and enabling confinement through granular interlock when aggregate grains are adequately sized and angular.

Geotextiles have long been used as a means of filtration (Wu et al., 2006). Non-woven geotextiles, often known as “filter fabrics” provide marginal tensile strength in comparison to geogrids or geocells, but allow water to permeate the fabric while retaining grains of a specified size (Wu et al., 2006). These membranes are chosen for filtration applications based on mean opening size - a property that can be connected to problematic sediment concentrations. While there are no solutions to entirely prevent sediment generation in an in-use, unpaved forest road, geosynthetic filtration presents itself as a means to sequester the sediment and prevent it from leaving the road network.

1.6. Field Testing

Past investigations revealed that use of high-quality aggregate, minimal truck traffic, and infrequent rainfall are all factors that reduce sediment transport from forest roads. Forest roads are often built with locally-sourced aggregate—for economic reasons—of poor quality and the roads are built only where required thus high traffic volumes are common (Foltz and Truebe, 2003). Solutions to mitigate sediment transport in forest roads must account for low-quality aggregate sources, high traffic volumes, and hydrologic site characteristics.

One approach to addressing the sediment generation from aggregate surfacing is to retain the sediment within the road prism. This research investigated the mechanisms of sediment generation within the surface aggregate of an unpaved road and the use of geosynthetic materials to sequester sediment from the system. Geosynthetic materials were tested for efficacy in improving road performance (reducing sediment generation) and filtering road runoff (sediment sequestration). The intended outcome of this study is to quantify the relationship between truck traffic and sediment production, and the benefit of each treatment type for sediment sequestration and road performance. Furthermore, this study seeks to evaluate runoff dependence on subsurface flow and sediment generation as a function of cyclic loading from truck traffic. Finally, geogrid reinforcement was tested at the aggregate-subgrade interface in two of the road segments to evaluate the improvement in mechanical performance of the aggregate surfacing.

To observe sediment contributions of different aggregates under wet weather hauling, prototype potential means of sequestering sediment and evaluate road and aggregate mechanical performance during traffic loading, a test track was designed and constructed to collect road runoff and examine aggregate degradation of four different test sections under controlled, simulated, wet-weather loading conditions. Each section was confined and segregated from the subgrade in order to isolate and study the sediment produced from the road surface aggregate. Rainfall was simulated over the road surface using a sprinkler system with a fixed intensity to eliminate runoff contamination from the hillslope. Testing took place over a dry, two-day period from June 30 to July 1, 2014 to represent intensive hauling under simulated rainfall. The limited scope of the field experiment is intended to serve as a means of prototyping possible sediment control techniques and evaluating hydrological and mechanical performance of forest roads under adverse conditions. More expansive field testing series would better inform a greater range of site conditions and longer term performance, but experimental constraints, particularly focused on intensive instrumentation, limited the scope of this study.

2. Materials and Methods

2.1. Site Description and Construction

The aggregate road test track was constructed on an existing road in Oregon, USA. The site is located in the eastern foothills of the central Oregon Coast Range in a mixed stand of predominantly Douglas fir (*Pseudotsuga menziesii*) and Grand fir (*Abies grandis*). The selected test track was a 36.6 meter section of road with a 4% grade. Each of the four test sections within the track was 3.6 meters in width by 6.1 meters in length with a continuous ditch on the inboard side of the road. The existing roadway was excavated to a depth of approximately 30 cm to expose native subgrade material. The subgrade was then graded at approximately 3-4% in-slope. Clegg impact values (CIV) were taken to measure in-situ subgrade harness (Clegg, 1980) and a vane shear was used to determine undrained shear strength of the subgrade. The Clegg Impact values were converted to California Bearing Ratio using the locally derived equation produced by Pattison et al. (2010) for these soils. Soil core samples were also collected to calculate subgrade water content prior to testing. Subgrade properties are summarized in Table 1.

Table 1. Summary of Clegg impact values, Computed CBR, undrained shear strength, and water content of road subgrade material at testing site

Property	Site Minimum	Site Maximum	Site Average
Clegg impact value	4.1	9.0	6.3
Computed CBR	4.4	12.0	7.7
Undrained shear strength (kPa)	135	260	189
Water content	0.25	0.42	0.34

Four pressure cells (Tokyo Sokki Kenkyujo KDE-500) were inset within the exposed subgrade underneath the centerline of the inside wheel track. Data from pressure cells were collected at a frequency of 50 Hz using two Campbell Scientific CR31000 Data Loggers. Prior to backfill with aggregate surfacing, a layer of biaxial geogrid (Alliance Geo BX2020) was placed beneath the two test sections as part of the geosynthetic application section (Figure 1). On top of the bare subgrade or the geogrid (depending on section), runoff collection flumes were installed in the center of each test section. The flumes were constructed from flexible Ethylene Propylene Diene Monomer (EPDM) liners at 2.5 mm of thickness, and bolted to flexible PVC water bars to maintain vertical side-walls. The excess EPDM liner material was maintained about 8 cm above the surface on both walls to prevent any leaching of turbid effluent from neighboring flumes.

Figure 1. Test track construction: geogrid placement over subgrade (left); buried runoff collection flumes in roadway (right)

The road was backfilled 8-10 cm with new aggregate material. The upper two test sections received well-graded basaltic aggregate (GW, C_u=6.65, C_c=2.97, 2% fines) and the lower two sections contained poorly graded micaceous schist aggregate (GP, C_u=2.51, C_c=0.92, 4.5% fines).

Over the first layer of aggregate, 10 cm diameter woven high density polyethylene (HDPE) bags filled with aggregate representative of a given section (approximately 1.2 meters long) were placed perpendicular to the road and in line with the pressure cells on the inside wheel track. This served as a means of retrieving representative samples of road material during fixed testing intervals. An additional 10 cm of aggregate was placed over the three aggregate separation bags (removed at different points during testing) until approximately 40 cm of aggregate had been placed on the road. Following backfill, a mechanical vibratory wheel roller compacted the aggregate on the final layer providing a total compacted surface of approximately 30 cm. A final road configuration is provided in Figure 2. The aggregate separation bags may impart some confinement on the testing, but separation was prioritized to avoid contamination from soft subgrade materials and adequate retention of all grain sizes during exhumation throughout testing.

2.2. Test Sections

Due to budgetary constraints, the experiment tested only included two sections for two different varieties of aggregate for a total of four test sections. The treatment included a filtration berms constructed of filter sand (Cu=3.44, Cc=0.86, D10=0.3 mm, SP) wrapped in a non-woven geotextile (Alliance #100 Filtration Geotextile) on the inside margin of the road and two reference sections for each aggregate variety (GW, GP), also reinforced with a geogrid reinforcement (Figure 3). These test sections are referred to as “WGG” and “PGG” for well-graded gravel/geosynthetic and poorly-graded gravel/geosynthetic, respectively. The reference sections for each aggregate type are referred to as WGC and PGC for well-graded and poorly graded aggregate surfacing, respectively.

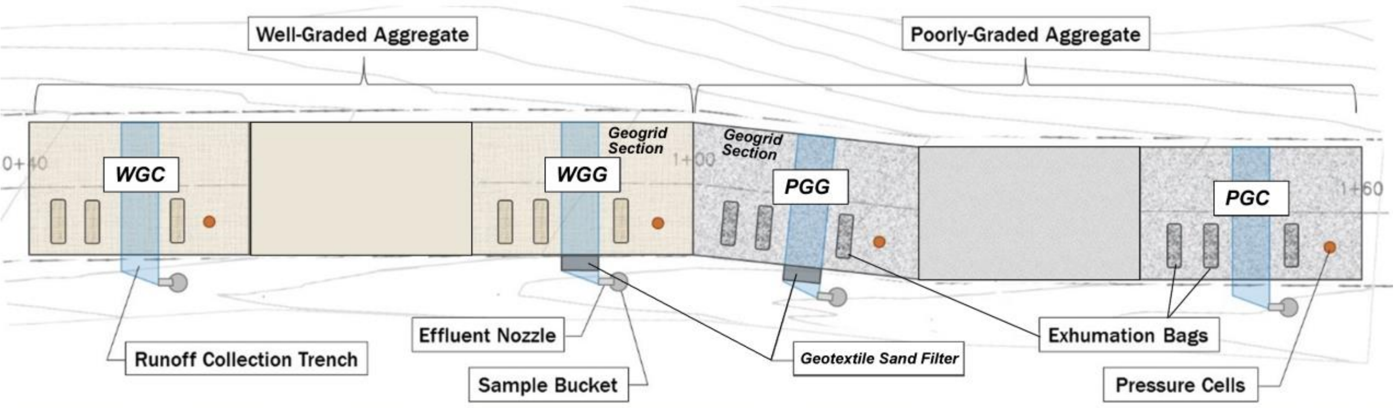

Figure 2. Dunn Forest test track configuration: road slopes downward at 4% grade from left to right

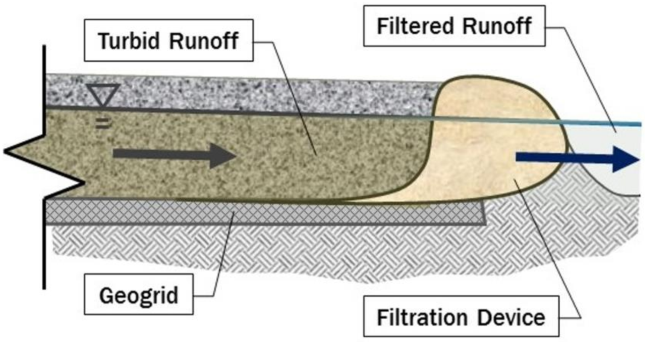

Figure 3. Cross-section of geosynthetic sections (includes filtration sand berm and geogrid underlay)

2.3. Hydrologic Sampling

A series of Rainbird 3500 Series Rotor sprinkler heads spaced evenly ran along the outer edge of the road to simulate rainfall. A water truck and pump supplied pressure to deliver an average precipitation rate of 15 mm per hour, representative of a semi-annual storm event in the central Oregon Coast Range (Goard 2003). Wedge rain gauges placed in the center of the road during testing measured rainfall intensity and coverage during the first 300 truck passes. Runoff from the rainfall was collected in the inboard ditch and later analyzed for turbidity and SSC.

Turbidity data were recorded from the road sections using the EPDM flumes to channel runoff towards the road ditch (Figure 1). The 1.5 meter by 3.7 meter runoff collection flumes within each test section provided a control volume from which to take runoff measurements and compare sediment volumes. The impermeable channel liner segregated the surface aggregate from the subgrade material such that all runoff from the road was funneled to a sampling bucket in the ditch. ISCO pump samplers took 500 mL runoff samples at approximate intervals of 25 truck passes. The sampling buckets were emptied every 25-50 truck passes to prevent enrichment from settling solid materials. Sampling took place over 600 truck passes. When truck traffic concluded, simulated rainfall continued for another 40 minutes in which time, the runoff was sampled every ten minutes. The last four samples were intended to provide information on how quickly the road flushed excess sediment out of the surface aggregate.

Gaps in the time series data indicate a sample omission. Reasons for omitting a sample include not enough water in the ditch (no sample), insufficient sample size, or a sampling error (human error).

2.4. Truck Traffic

Truck traffic was simulated with two fully loaded, 3-axle dump trucks, one steering and a set of tandem dual axles which had a vehicle weight of 21,300 kg, and ach rear axle load of 7,700 kg. Their approximate speed was 16 km/hr. One truck pass was defined as all three axles of the truck passing over the road in one direction. Two trucks were used to expedite load testing. Prior to burial within the road prism, three HDPE aggregate separation bags were filled with either well-graded or poorly-graded aggregate and placed in each section. Gradation of these materials was performed using standard ASTM screen sizes were used which included 50.00, 37.50, 25.00, 12.50, 9.50, and 6.30 mm. Upon exhumation from the road surface, the HDPE aggregate bags were emptied into buckets and air dried for several weeks. Once dry, the aggregate samples were re-screened to determine change in gradation by mass which served as a metric for determining rate of aggregate degradation.

Aggregate separation bags were removed with a jack hammer and pick axe. During removal, some of the aggregate bags were torn either from abrasion in the road prism or during the removal process and small amounts of material were lost or added to the sample. Due to the change in sample mass the percent passing by weight was calculated as a more accurate representation of the change in gradation as a function of truck traffic. This assumes that the sample mass lost or gained during the removal process was representative of the sample gradation.

In addition to the screen sieving for large diameter gradation, material that passed 6.3 mm was also wet-sieved using ASTM sieves numbers 4, 10, 40, 100, and 200 in order to determine the fines (material passing the no. 200 sieve) present in each aggregate sample. After mechanical agitation of the sieves, the sieve stack was placed under running water to wash away fines. The mass of the fine material was calculated as the difference between the total mass passing the 6.3 mm screen and the total mass of grain sizes retained above the no. 200 sieve. Because wet-sieving is a destructive process, only post-test gradation curves include particle sizes less than 6.3 mm.

2.5. Aggregate Performance

A continuous time series of subgrade pressure data was collected for each test section and can be compared to series of gradation analyses, as well as sediment concentration in runoff. The pressure data, collected at 50 data points per second (50 Hz), provided a means of quantifying applied stresses within the aggregate surfacing after repetitive loading, informing mechanical performance of the road and attrition of aggregate particles. In addition to subgrade pressure as a metric for aggregate performance, rutting measurements were also taken at 50, 100, 200, and 300 total truck passes as well as measurements of lateral spreading of the wheel tracks of the road.

3. Results

3.1. Turbidity

Turbidity was measured using a Hach 2100P turbidimeter. Each sample was agitated to suspend solids then 15 mL of the sample was poured into a sample vial and placed in the turbidimeter. The turbidimeter was only capable of reading samples up to 1000 NTUs, samples in excess of this threshold were diluted. Each dilution consisted of 5 mL of turbid water, to 10 mL of DI water; a 1:3 dilution ratio. This method of dilution continued until the turbidimeter provided a reading. The total turbidity for each sample was then calculated using the following formula:

$$Sample\ NTU = \frac{Measured\ NTU}{(1/3)^{Number\ of\ Dilutions}} \quad (1)$$

Turbidity from all road sections ranged from 954 to 306,000 nephelometric turbidity units (NTU). The WGG section produced the lowest minimum turbidity measured at 954 NTU. In contrast, PGG section produced the greatest maximum turbidity measured at 306,000 NTU. The well-graded aggregate sans treatment produced greater minimum and maximum turbidity values than the poorly-graded aggregate sans treatment.

Turbidity is grouped by aggregate variety in the time series shown in Figure 4a. The time series displays strong periodicity every 100 truck passes, corresponding to the time when truck traffic was stopped to take rutting measurements. Within each period, turbidity typically increases with the number of truck passes and then swiftly decreases when traffic ceases. During the last 300 truck passes, the PGG treatment section did not produce any measureable runoff, likely due to a puncture in the subsurface flume – not apparent to from the surface.

When comparing reference treatment sections, the well-graded aggregate generally produced less turbid effluent than the poorly-graded aggregate. The data did not show an apparent sediment sequestration benefit of the filter berm as originally hypothesized, likely due to gaps created from extreme lateral displacements due to rutting. Specifically, aggregate spreading dislodged filter berms from their original position and road runoff was observed flowing under the filter treatment systems along the impermeable channel liner of the runoff collection flume. However, this necessitated subsequent laboratory testing to observe filtration benefits under controlled conditions to evaluate potential performance under appropriate installation conditions.

3.2. Suspended Solids

Suspended solids attained from each sample taken from the sampling bucket and calculated via a simplified evaporation method. Wet samples were poured into metal tins of known mass and placed in an oven at 105º C for 24 hours. Mass of solids was calculated by taking the difference between dry pan weight and dry pan weight with sample. Once mass was determined, SSC were calculated using a procedure outlined by the USDA Redwood Science Laboratory. This method assumed the density of water to be 1 g/mL and the density of solids to be 2.65 g/mL (USDA, 2006). The total sample volume is then used to calculate SSC:

$$SSC\left(\frac{g}{L}\right) = \frac{weight\ of\ suspended\ solids\ (g)}{sample\ volume\ (L)} \quad (2)$$

SSC among all road section samples ranged from 0.605 to 259 g/L. The PGC section had the lowest minimum SSC measurements at 0.605 g/L. The WGC section had the highest maximum SSC value at 259 g/L. The full time series of SSC data is shown in Figure 4b where SSC is grouped by aggregate variety.

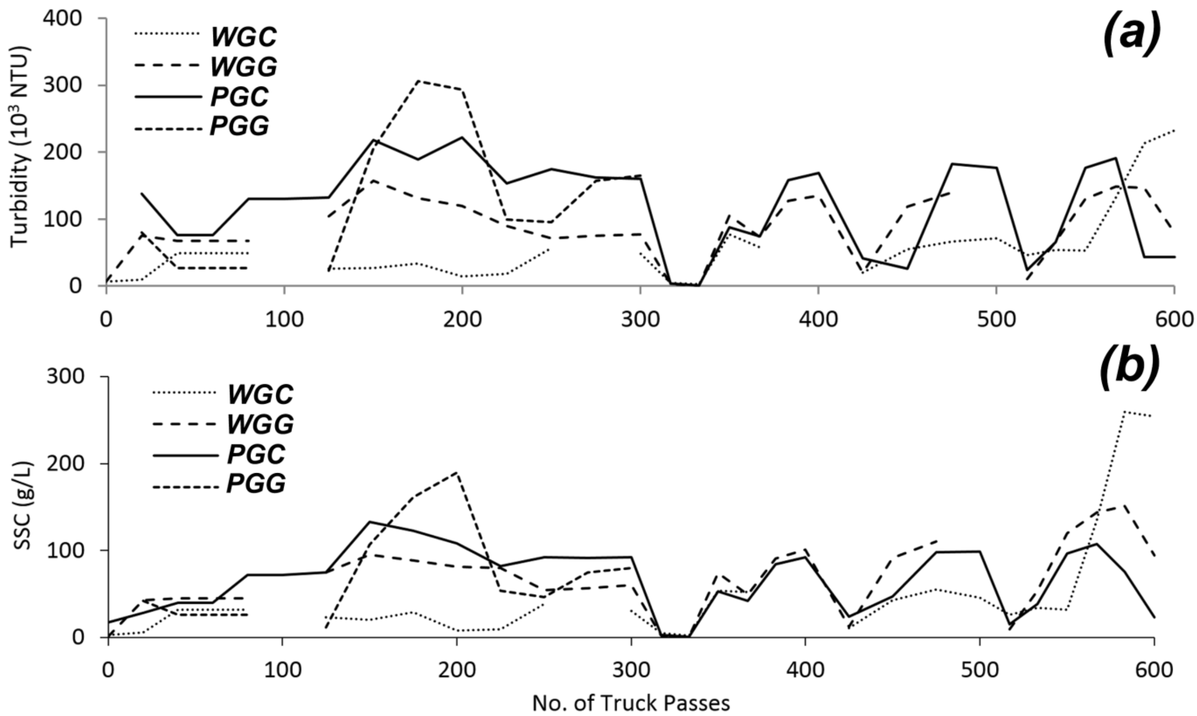

Figure 4. Measured turbidity and SSC in road runoff as a function of loading (truck passes)

Consistent with the turbidity data, the SSC time series displays periodicity for every 100 truck passes. Similar to turbidity, there are also gaps in the SSC time series data as the same samples were used to test both turbidity and SSC.

3.3. Rainfall

Periodicity seen in the turbidity and SSC time series data shows a flushing effect from the simulated rainfall after traffic ceased. All test sections show rapid reductions in turbidity and SSC during the flushing period. The constant rainfall rate indicates an immediate reduction in sediment availability upon termination of truck traffic which occurred every 100 passes. Reduced sediment in the runoff could be caused by a sediment deficit in the road prism, or may alternatively be caused by the loss of agitation from truck traffic which may aid in sediment transportation. The turbidity and SSC data do not provide information on which mechanism is at play but they do indicate that truck traffic is a dominant factor in sediment transport when controlling for rainfall rate.

3.4. Filtration

The geotextile filter berms were expected to reduce effluent turbidity when compared to the reference section of the same aggregate variety. However, spreading failure enabled periodicity due to onset and termination of truck traffic to be the dominating trend. It should be noted, however, that the PGG treatment section experienced road failure such that road runoff during the last 300 truck passes was reduced to one measurable sample. This reduced the turbidity and SSC test sample size for this section by more than 50% prompting further testing of the geotextile and sand filter system in a lab. This highlights that future design should account for potential spreading failure and sufficient clearance from the edge of the road to a given filtration berm.

Further laboratory testing under idealized conditions were performed using the Stayton filter sand and non-woven geotextile determined the sediment removal benefits of the geotextile wrap-faced berm treatment under idealized conditions. A 22 cm tall sand column placed in a 103 cm2 cylindrical permeameter measured the filtration benefits provided by the filter sand and non-woven geotextile. To determine the potential filtration benefits provided by the filter sand and geotextile, the same configuration (sand sandwiched between layers of non-woven geotextile) was applied under 30 cm of head, but turbid water was added to the sand column and effluent samples were measured for turbidity. Two of these trials included a flushing period after sediment loading to record the recovery time of the effluent to pre-event levels. Effluent samples were taken at decreasing frequency during both loading (turbid influent) and flushing (clean influent) phases of each test, to capture the expected decay behavior of turbidity (Sheridan et al., 2006). The filter sand acting alone produced a minimum turbidity reduction of 67%. When coupled with the geotextile used in the construction berm the minimum turbidity reduction increased to 74%. These data are derived from four different trials (Table 2).

Table 2. Summary of laboratory permeameter filtration tests

Filtration Treatment	Filter Sand Only		Filter Sand and Geotextile	
Influent Treatment	2% SSC	1% Fines	2% SSC	1% Fines
Influent Turbidity (NTU)	6,600	5,800	6,600	5,800
Maximum Turbidity (NTU)	2,200	1,500	1,200	1,500
Minimum Turbidity Reduction	67%	75%	82%	74%
Time to Peak Concentration (min)	8	5	5	10

Turbidity levels chosen for permeameter testing represent those found in road ditch runoff during sub-annual storms in the Oregon Coast Range (Miller, 2014). The first two trials performed used an influent material of 2% SSC by mass using solids recovered from the road ditch samples (Figure 5). After 12 minutes of sediment loading, the 2% SSC influent had clogged the permeameter nozzle and prevented flow through the filter sand column for trials with and without the geotextile. To avoid blockage of the permeameter nozzle, the third and fourth trials used an influent material of 1% fines by mass (particles passing no. 200 ASTM sieve) in the influent. The fine particles did not clog the permeameter tubes allowing both a 20 minute sediment loading phase, and a 20 minute sediment flushing phase to take place (Figure 5), chosen to be similar to the loading phase in the field trials.

All tests showed peak concentrations of effluent being achieved prior to any system flushing that occurred. For all trials, this took no more than 10 minutes to achieve. During the 2% SSC trials, time to peak concentration using the geotextile occurred three minutes before that of the trial using filter sand only; however, the peak concentration of the geotextile-treated effluent was nearly half that of the filter sand-only effluent (Figure 5a). The 1% SSC fines trials shows a five minute reduction in time to peak concentration with use of the geotextile filter but no significant difference in maximum turbidity. In the flushing stage of the 1% SSC fines trials, both treatments returned to within 50 NTU of initial turbidity values after 20 minutes of clean water influent (Figure 5b).

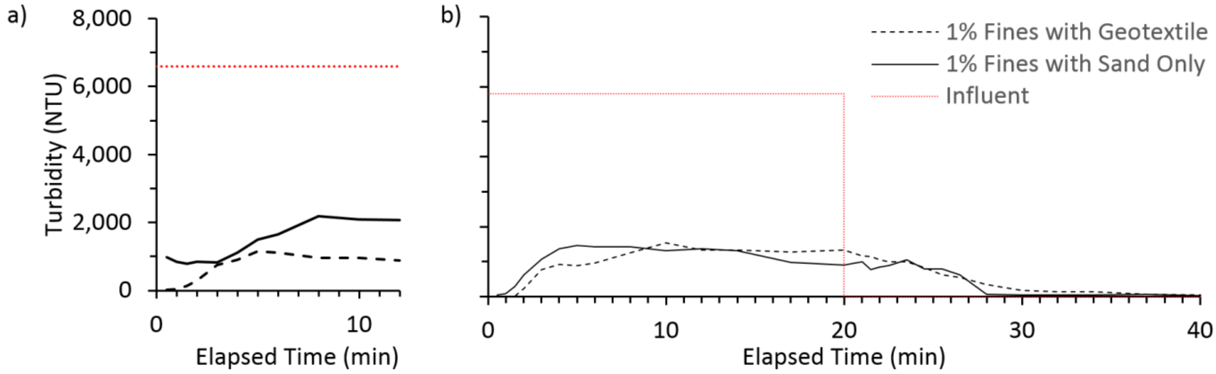

Figure 5. Permeameter trial time series using a) 2% SSC by mass influent and b) 1% Fines by mass influent. The dotted vertical line in plot 'b' separates the loading phase (turbid influent) from the flushing phase (clean influent)

3.5. Aggregate Degradation

Both the well-graded and poorly-graded aggregate varieties displayed quantifiable signs of degradation under traffic loading, producing fine materials from the breakdown of larger grain sizes. Figure 6 shows an increase in fine materials produced as a function of truck traffic. For the average gradation of the poorly-graded aggregate, the rate of change in fine particles increases as a function of truck traffic. Grain size distributions shown in Figure 6 are the results of the averages of the reference sections and the distributions of the reinforced sections from the aggregate samples tested after 100 (batch 1), 300 (batch 2), and 600 (batch 3) truck passes due to variability.

Measurement of particle breakage using techniques from Hardin (1985) provides a means of comparing the quantity of degradation both between aggregate varieties and among sample batches (number of truck passes), evaluated by Equation 3 which represents the "potential for breakage of a particle of a given size, *D*," down to the threshold minimum diameter, D_{min} (Hardin, 1985). To calculate the total breakage potential of an aggregate sample, the breakage potential of a given particle size, b_p, must be integrated over a differential of percent passing (Equation 4).

$$b_p = log_{10}\left[\frac{D}{D_{min}}\right] \tag{3}$$

$$B_p = \int_0^1 b_p df \tag{4}$$

The relative breakage, B_r, of an aggregate sample is defined as the ratio between total breakage and breakage potential, B_t, (Equation 5). Total breakage is the difference in breakage potential prior to, b_{po}, and after, b_{pl}, loading (Equation 6) (Hardin, 1985).

$$B_t = \int_0^1 (b_{po} - b_{pl}) df \tag{5}$$

$$B_r = \frac{B_t}{B_p} \tag{6}$$

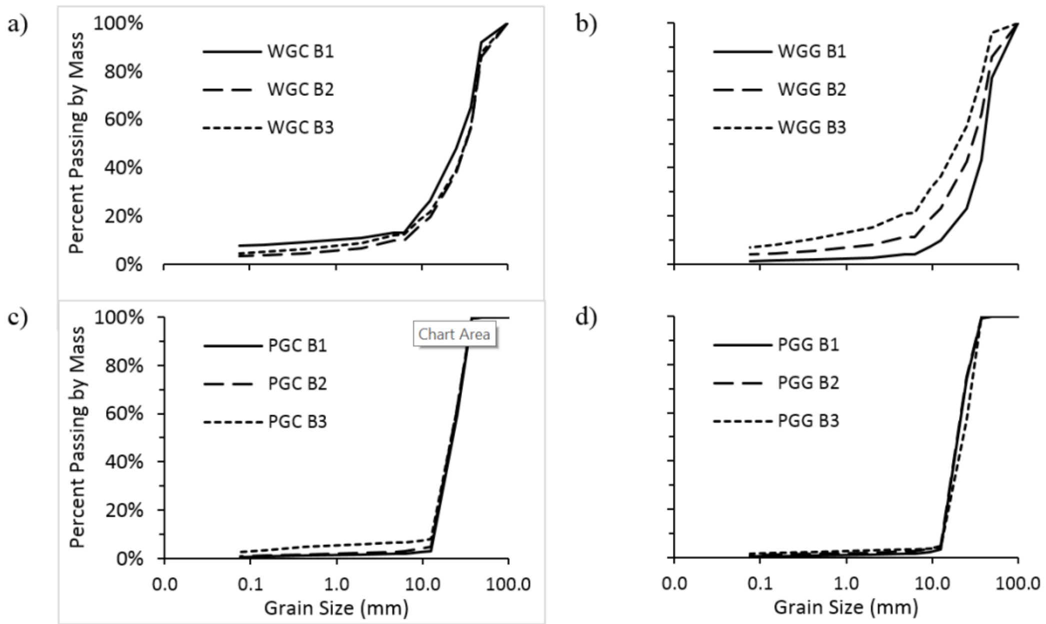

Figure 6. Particle size distribution by mass after 100 (B1), 300 (B2), and 600 (B3) total truck passes grouped by a) well-graded unreinforced aggregate, b) well-graded geogrid-reinforced aggregate, c) poorly-graded unreinforced aggregate, and d) poorly-graded geogrid-reinforced aggregate

The poorly-graded aggregate shows stronger breakage trends with truck traffic and with road treatment (Table 3). All poorly-graded test sections experienced increased relative breakage as a result of increased truck traffic. Among batches of poorly-graded aggregate, the geotextile/geogrid treatment section had the lowest relative breakage. These trends were not as clear in the well-graded aggregate sections, but higher breakage was noted for the last 300 passes.

Table 3. Hardin relative breakage values for each aggregate separation bag

Treatment	Batch 1	Batch 2	Batch 3
WGC	0.021	0.030	0.071
WGG	0.038	0.031	0.083
Averages	0.030	0.030	0.077
PGC	0.024	0.037	0.065
PGG	0.017	0.029	0.035
Averages	0.021	0.033	0.050

Pressure cells in the subgrade-aggregate interface provided quantifiable evaluation of stress transmitted through the surface aggregate during testing. Stress at the surface of the subgrade increased in each test section throughout experiment. The WGC section exhibited the highest subgrade stresses and the PGC section exhibited the lowest level of subgrade stress. During field testing, the WGC section experienced the greatest lateral spreading, indicative of higher stress concentrations encountered at the subgrade. The reduced aggregate thickness is attributed to the large subgrade stresses recorded (Figure 7). Maximum pressures demonstrated in Figure 7 are representative of maximums attained every 10 cycles of loading to reduce artificially low pressure readings due to trucks not passing directly over the pressure cell.

Trends in Figure 7 show that both geogrid sections provided a reduction in subgrade stress for the respective aggregate variety. Furthermore, the well-graded aggregate was more effective at distributing loads than the poorly-graded aggregate, even with geogrid reinforcement, during the first 300 truck passes as shown by lower subgrade pressure. During the last 300 passes, lateral spreading of the WGC section began to reduce aggregate thickness. The time series shows a marked increase in subgrade pressure for the WGC section during the last 300 truck passes.

3.6. Rutting

Rutting is failure mechanism that often occurs when there is a combination of deflection in the aggregate and subgrade layers (Dawson, 1997). Each test section presented wheel rutting and subsequent lateral spreading of the road surface. Ponding of water was present in deep ruts, but no overland flow was observed. After 300 truck passes, lateral spreading on the inboard side of the road, particularly in the WGC section, prevented further rutting measurements to be taken from the inboard wheel well. During the final 300 truck passes, rutting transitioned into a lateral spreading failure, making measurement difficult. Rutting geometry is shown in Figure 8 where the rutting depths for the reference treatment sections are averaged in order to compare rutting trends with and without the geogrid reinforcement. During the first 300 truck passes, rutting increased with the number of truck passes. The well-graded sections experienced the greatest rutting at 130 mm of depth and the poorly-graded section experienced the least amount of rutting at 51 mm after 300 total truck passes. During the last 300 truck passes, all wheel tracks exhibited substantial lateral spreading. The uppermost inboard wheel track of section WGC spread laterally into the inboard ditch, preventing consistent measurement of field test's rutting.

Figure 7. Maximum subgrade pressure per truck pass (0 to 600 truck passes) for given test sections

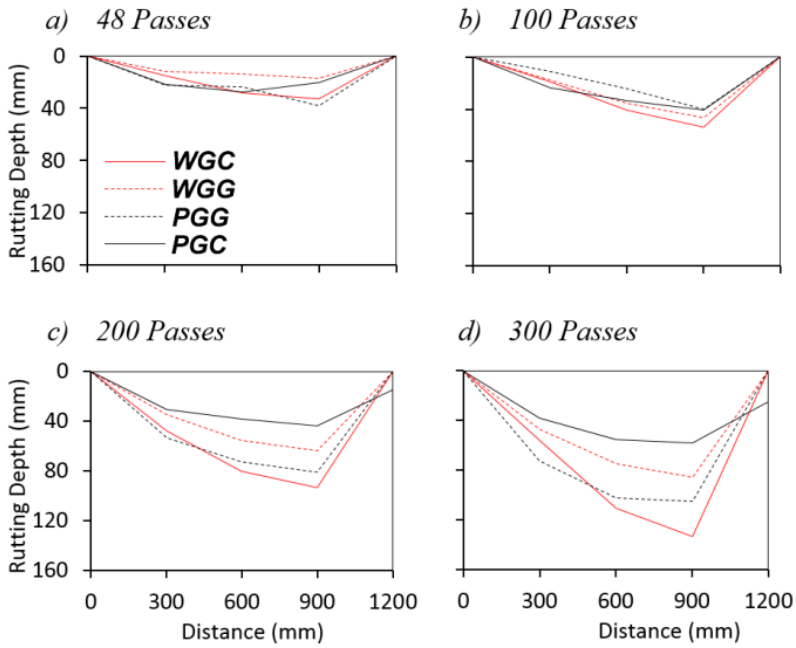

Figure 8. Measured rutting from 48 to 300 truck passes for well graded aggregate without reinforcement (WGC) well-graded aggregate with geogrid reinforcement (WGG), poorly-graded aggregate without reinforcement (PGC), and poorly-graded aggregate with geogrid reinforcement (PGG)

4. Discussion

4.1. Sediment Generation

Fine sediment material was produced as a function of truck traffic. Vehicular loading caused aggregate particles in both the well-graded and poorly-graded aggregates to break down into smaller particle sizes. Figure 6 shows an increase in fine materials present in both aggregate varieties. Also apparent is the increased rate of change of particle sizes smaller than 10 mm in the poorly-graded aggregate samples. When comparing relative breakage within batches and among aggregate varieties, the poorly-graded geogrid section consistently had lower relative breakage than the poorly-graded control section throughout the duration of testing. This trend was not apparent for well-graded aggregate, however increased truck traffic (600 passes) produced the highest relative breakage in all treatment sections. This is due to more loading cycles and associated breakage of asperities in the aggregate.

The geogrid reinforcement improved the load distribution over the native subgrade material. Subgrade pressure data indicates the geogrid reinforcement provided a benefit in load distribution, however rutting measurements show increased rutting in the PGG section. The geogrid reinforcement benefited the well-graded aggregate, while it enabled greater rutting depths in the poorly-graded aggregate, likely due to lateral spread and competent subgrade surfacing and poor interlock of the uniform aggregate particles. Softer subgrades and reduced road insloping would likely inhibit lateral spread and demonstrate improved aggregate performance with geogrid reinforcement.

4.2. Sediment Delivery

Sediment delivery for each road segment can be quantified by integrating the SSC data over time. SSC data, which was collected in mg/L can be integrated over time to determine the total mass of sediment escaping the runoff collection flumes in each road segment (Table 4). This was done by converting units of truck passes into units of liters from known traffic duration, rainfall rate, and volume of runoff collection flumes. The known quantities of solid mass escaping each road section was then compared to the known mass of available moveable material (defined in this study as material passing a 6.30 mm sieve) present in each runoff collection flume. Results in Figure 9 show that the percent of available material lost in the poorly-graded aggregate sections is roughly one order of magnitude larger than the percent of available material lost in the well-graded aggregate sections. While the well-graded aggregate lost less available material, there were no trends between the sections that may indicate a benefit of either the geotextile or geogrid treatments. In contrast, the poorly-graded aggregate retained more available material in the geosynthetic section.

Table 4. Cumulative mass of SSC in effluent escaping each road segment after 100, 300, and 600 total truck passes. All values shown are in mg

Passes	WGC	WGG	PGG	PGC
100	512,549	727,012	454,275	833,167
300	2,888,965	3,301,831	3,476,684	4,079,855
600	7,630,994	7,031,671	N/A	7,273,660

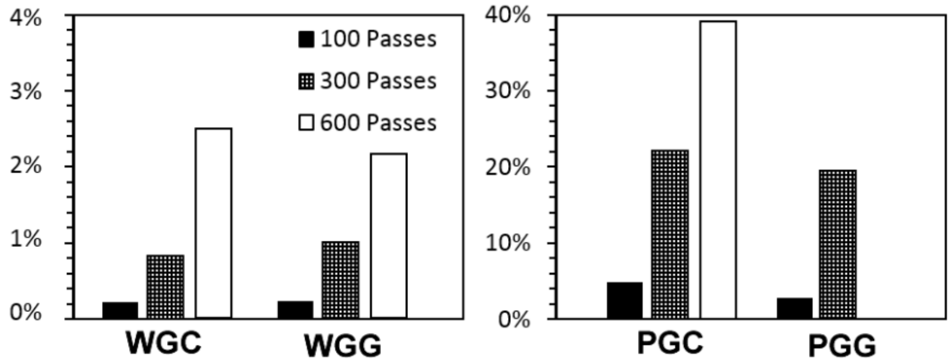

Figure 9. Percent of available material lost in each test section after 100, 300, and 600 total truck passes (No data available for PGG section at 600 truck passes)

A possible explanation of the discrepancy in the amount of available material lost among aggregate varieties may lie within the optimum fines (defined in this context as moveable material passing a 6.30 mm sieve) content of the aggregate. The well-graded aggregate bags average 8.1% fines content while the poorly-graded aggregate bags average only 0.5% fines content. One possible theory to explain the difference is that the larger void space in the poorly-graded aggregate lacks the fine materials needed to dissipate the energy of the runoff passing throughout the material. When aggregate breaks down, the voids are filled in, lengthening the path water must flow to escape the road by routing the water around a greater and greater number of particles. This reduces the water velocity leaving the road and reduces the carrying capacity of the runoff. This trend is expected to continue until optimal fines content is achieved (Foltz and Truebe, 2003).

4.3 Sediment Sequestration

The laboratory test results of the geotextile fabric and filter sand revealed that both the use of filter sand and nonwoven geotextile provided a substantial reduction in the turbidity of the effluent under idealized conditions (Figure 5). The first effluent sample in each test records the base level turbidity of water leaving the sand column. Although there is variability in the base level turbidity of each test, when allowed 20 minutes to flush the system, turbidity levels returned to near or below their base levels. The laboratory filtration tests were designed to simulate the immediate spike in turbidity caused by truck hauling on a wet aggregate surface. The 20-minute recovery time recorded in Trials 3 and 4 show how the filter sand not only reduces the turbidity of the effluent, but also returns the system to base-levels well within the 20-minute flushing period. In addition to the rapid flushing period seen in the laboratory, flushing was seen in field testing corresponding to the periodicity of the truck traffic cycles. As shown by Bilby et al. (1989), truck traffic is the predominant driver of sediment generation in an unpaved road while rainfall is the predominant driver of sediment transport. Sediment levels in ditch runoff at the initiation of truck traffic were substantially less than the sediment that exited the road during repeated truck passes. When truck traffic ceased, the flushing effect of the rainfall on the road lowered turbidity and sediment levels to near-initial conditions as shown in Figure 5 and as seen in the laboratory analysis of the filter berm.

Evaluation of the commercial viability of the geosynthetic treatment depends on the cost, ease of construction, and sediment sequestration benefit. Due to the labor required to construct a filter sand berm, this treatment is not feasible for long segments of forest roads. However, road segments that have been identified as major sediment sources or are at high risk of delivering sediment to streams would benefit from the sediment sequestration benefits of the sand berm. The reduction in peak turbidity and extended time to peak concentration of the geotextile and filter-sand combination make this prototype particularly viable for near-stream applications. Targeted application of this construction technique could provide a much needed reduction in effluent turbidity of forest roads, especially in light of trends towards stricter water quality standards for discharge into natural water bodies.

5. Conclusions

The use of geotextile fabric, in combination with a filter sand berm and geogrid-reinforced subgrade increased sediment sequestration under idealized conditions and may promise potential improvements if installed correctly in field operations. Follow up laboratory tests of idealized conditions showed an average reduction in effluent turbidity of 78 % when the filter sand was wrapped in non-woven geotextile. Flushing times under these conditions were shown to be less than 20 minutes. These results are expected to be consistent with in-field applications when use of channel liner (used only for experiment to isolate aggregate) is not present.

Both turbidity and SSC revealed periodicity and flushing patterns corresponding to the initiation and termination of truck traffic every 100 passes. Flushing was also seen in the permeameter filtration tests. This verifies established understanding that truck traffic is a driver of sediment generation (Bilby et al. 1989, Sullivan and Duncan 1989, Lekarp et al. 2000, Sheridan et al. 2000). Minimal time to concentration of sediment transport off the road during a rainfall event mirrors the quick recovery rate of road effluent during non-traffic flushing of the roadway.

Geogrid reinforcement reduced the load distribution for both well-graded and poorly-graded aggregate varieties. Rutting depths were reduced for well-graded aggregate when reinforced with geogrid but rutting depths were not reduced for poorly-graded aggregate using the geogrid. This indicates that low interlock between aggregate particles of the poorly-graded aggregate may be responsible for reducing load distribution capabilities.

Degradation of aggregate particles as a result of truck traffic began to fill voids in poorly-graded aggregate with a range of particle sizes. Degradation of well-graded aggregate produced mostly fine particles as a result of the limited void space available. These trends are consistent with the hypothesis that the roadway is moving towards an ideal fines percentage which maximizes road bearing strength and minimizes runoff energy (Foltz and Truebe, 2003; Toman and Skaugset, 2011).

The application of geosynthetic materials in this study on an aggregate forest road provide both sediment sequestration (under idealized conditions) and improved aggregate performance. Geotextile applications to filter runoff are moderately labor intensive and slow the speed of construction while geogrid placement is simple and less likely to slow the pace of road construction. It is practical to use a geotextile filtration system on segments of road that are prone to high sediment delivery given the sequestration benefits discovered in this study. Given the water quality benefits and reduced road maintenance, the geosynthetic treatments deserve both further investigation into use on a larger scale and are appropriate for small scale field applications.

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