Compaction of Forest Roads in Northwestern Oregon – Room for Improvement

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ABSTRACT

Monitoring the construction and as-built conditions of a low volume aggregate surfaced forest road in Northwest Oregon coupled with detailed laboratory testing of the subgrade soils allowed an analysis of the potential benefits of improved structural road design and construction control. Specifically, subgrade compaction was found to be far below desirable levels that would achieve greater subgrade strength, and based on a common design equation, allow for the use of significantly less aggregate. It is inferred that a combination of inadequate compaction energy and failure to account for the detrimental influence of high field moisture content resulted in poor subgrade densities. This case study showed that a 34 percent saving in aggregate cost may be possible.

Keywords: *roads, road structural design, aggregate surfacing, road construction*

Introduction

Forest roads are a significant component of the total operating cost of industrial forestry. A recent study in Chile showed that road construction can consume 14 percent of the operations budget (Epstein et al. 1999). The cost of the forest road system has become the focus of more concern in recent years as road standards have evolved and the cost of meeting environmental expectations has increased. At the same time, world competition in wood fiber markets has left forestland owners with the need to reduce all of their operating costs. Meeting project constraints while optimizing project objectives is the definition of engineering; thus, careful development of the design and control during construction will ensure that roads will be built to meet the overall objectives of the transportation system in the most efficient manner.

The research results presented in this research note provide graphic evidence of the potential cost savings from improved engineering and construction control of the structural section of a forest road. This work serves as a reminder of well established engineering principles that have been largely ignored in the forest industry due to an understanding of benefit-cost ratios that predates the current economic and environmental climate. Currently, the common approach for designing the structural section of roads used by the forest industry in Oregon is to specify the aggregate volume to be used on a per station basis from personal experience with little to no specific geotechnical information and no differentiation for local variation in subgrade strength along the road. Typical aggregate volumes are in the range of 37.5 to 52.5 m^3 loose measure in the truck per 30-m station (50 to 70 yd^3 per 100 ft station). Subgrade widths are typically 4.5 to 5 m, controlled to the nearest 0.3 m which means that the surfacing thickness ranges from ~25 to ~39 cm (~10 to ~15 in.) in a loose condition.

Proper control of compaction – the establishment of a design standard and construction control to meet that standard – will ensure that the subgrade strength will reach its potential and will allow for a surface design that will result in a lower cost road or a road that will better meet the required environmental performance. The primary environmental concern is sediment production which is understood to be directly associated with surfacing failure, all other things being held equal. An important and often ignored aspect of aggregate surface design is that compaction and, therefore, performance of aggregate surfacing is limited by the stiffness of the subgrade, hence a lack of subgrade compaction will limit the effective use of the structural potential of the aggregate surfacing.

This research note will compare the dry unit weight of the subgrade obtained from current construction practices for a forest access road in Northwest Oregon with the optimal compaction obtained from laboratory analysis. A brief discussion of the potential economic gain will be made by demonstrating how improved subgrade strength can reduce the amount of aggregate required for the surface layer.

Methods

A study site was located in the Clatsop State Forest in Northwest Oregon (**Fig. 1**). Approximately 1800 m of new single lane forest access road was built for a timber sale planned by the Oregon Department of Forestry. Natural Resources Conservation Services (NRCS) soil maps indicated that the soil along the road route is a Rinearson silt loam which, depending on depth of sample, is classified as a silt or clay of low plasticity. The Rinearson series consists of deep, well-drained soils that formed in colluvium weathered from siltstone (NRCS 1988). The road lo-

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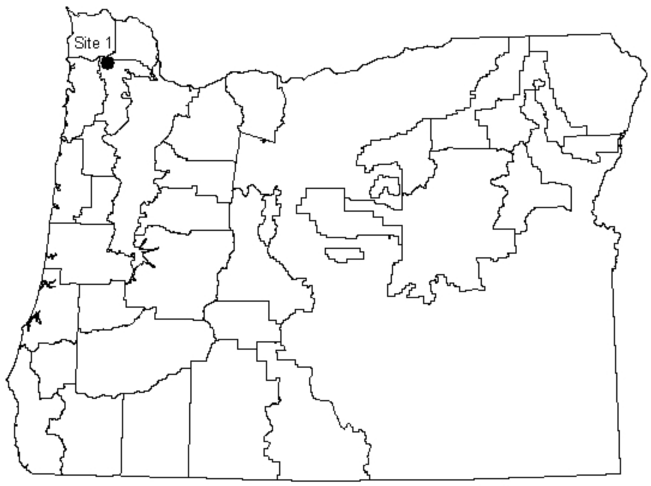

Figure 1. ~ *Map of Oregon counties with study site location marked.*

cation ranged from ridge-top through mid-slope to valley bottom at a stream crossing. Hillslopes ranged from level to 60 percent.

The subgrade was constructed using an excavator and dozer and compacted with a vibratory roller in July, 2004. Subgrade compaction was done with approximately two passes of a CAT model CS 573D vibratory roller. The subgrade surface was watered during compaction, but no moisture content (MC) control was employed. In other words, neither the project owner nor the road construction contractor had compaction test results available; they did not make *in-situ* MC measurements, did not measure the MC that resulted from adding water, and did not monitor the compaction achieved. Aggregate was spread while being dumped from highway-legal dump trucks and graded to produce the desired thickness and surface shape with a grader. Aggregate compaction was also done with the vibratory compactor, CAT model CS 573D, with regular watering of the surface by a water truck. The roller made approximately two passes on each wheel path during aggregate compaction. The aggregate surfacing layer was approximately 23 cm thick. Road construction was completed in August, 2004.

For sampling, the road was divided into eighteen, 100-m sections over the length of the road. Sampling and testing was done only as a part of this research and was independent of the road design and road construction processes. In that sense, the test results are an unbiased measure of the results of normal forest road construction practices in the area. Samples of approximately 40 kg each of the road subgrade soils were collected in July of 2004 for field and laboratory testing prior to final shaping and compaction of the subgrade. A sample of subgrade material was collected at a randomly selected location from each 100-m section of road, from the top 0.3 m of the subgrade (a sample from section 13 could not be obtained due to equipment activity at the time of sampling). Collecting the subgrade material directly from the road prism and not from the fill or cut bank eliminated any variability that may have existed in the soils surrounding the road.

Sand cone density tests of the subgrade following compaction and just prior to placement of the aggregate surfacing were done at the location of the subgrade sample sites. Five sample locations could not be reached because of equipment activities. Unified soil classification (**Table 1**) was performed on each subgrade sample (ASTM 2006, D4318; ASTM D422; and ASTM D2487). Strength potential of the subgrade was determined by a 15-point California bearing ratio (CBR) series (ASTM D1883) that included 80 percent of standard energy compaction (480 kN-m/m^3, ASTM D698), an intermediate energy compaction (≈1200 kN-m/m^3), and modified energy compaction (2700 kN-m/m^3, ASTM D1557). One advantage of the 15-point test is that it produces the CBR for a range in compaction MC and density combinations which can then be used in many aggregate thickness design equations. In all cases, soaked CBR with a surcharge equivalent to 0.3 m of aggregate surfacing was determined. Compaction MCs ranged from 26 to 46 percent to ensure that the optimal MC was bracketed.

Results

The soils on this road were classified primarily as a fine, silty sand, with SM being the dominant soil type defined by Unified Soil Classification System (USCS) (**Table 1**). The results from the CBR tests at the maximum dry unit weight for 80 percent of the standard compaction energy level (ASTM D698; AASHTO 2001, AASHTO T-99) showed that CBR ranged from 3 to 15. At the maximum dry unit weight for the intermediate-level compaction, specified in ASTM D1883 (AASHTO T-193), the CBR varied from 16 to 40. At the maximum dry unit weight for the modified compaction level (ASTM 1557, AASHTO T-180), the CBR ranged from 19 to 53. Statistical and graphical analysis showed that the optimum MC and maximum dry unit weight are the significant variables in predicting CBR. These independent variables, however, have non-normally distributed means and non-constant residuals which could not be corrected through transformation. Hence a simple linear regression model for CBR could not be constructed.

Using maximum dry unit weight for 80 percent of the standard compaction energy (ASTM D698) as a level that can be achieved through proper compaction control, a comparison was made between the field dry unit weight and the potential dry unit weight of the subgrade soils along the road alignment (**Fig. 2**). Based on the ASTM recommended interpolation (ASTM D1883), the maximum dry unit weight for the standard compaction test (ASTM D698) would be about 2.5 percent greater than the values obtained for the 80 percent energy level for the soils in this study. The more common standard compaction test in a 10.16 cm diameter mold rather than the 15.24 cm diameter CBR mold will typically produce a higher maximum dry unit weight at a lower MC (ASTM D1883).

The field dry unit weights ranged from 7.1 to 12.3 kN/m^3 (45 to 78 lb/ft^3). The comparison between the maximum dry unit weight obtained for 80 percent of standard compaction energy,

Table 1. ~ *Soil classification and representative laboratory CBR data of subgrade materials along the test road.*

Sample[a,b]	Road section	USCS	Percent fines	Liquid limit	Plasticity index	CBR at maximum density of compaction level indicated		
						Std[c]	Int[c]	Mod[c]
TM 1	0 – 100 m	SW-SM	6.6	36.7	1.5	4	21	47
TM 2	100 – 200 m	SC	12.6	33.1	12.2	3	26	20
TM 3	200 – 300 m	SW-SM	7.9	34.8	2.8	5	29	35
TM 4	300 – 400 m	SW-SC	10.8	32.2	7.7	3	16	44
TM 5	400 – 500 m	SW-SC	10.3	40.4	12.1	9	22	19
TM 6	500 – 600 m	SM	14.0	41.9	4.8	7	20	42
TM 7	600 – 700 m	SM	18.6	32.6	6.8	4	18	42
TM 8	700 – 800 m	SM	22.4	39.9	1.4	3	25	38
TM 9	800 – 900 m	SM	26.3	35.5	1.2	14	23	30
TM 10	900 – 1000 m	SM	12.9	36.6	7.0	8	25	29
TM 11	1000 – 1100 m	SM	15.7	35.0	1.5	11	21	34
TM 12	1100 – 1200 m	SM	16.4	37.1	2.3	15	24	51
TM 14	1300 – 1400 m	SC	19.1	34.4	8.5	11	25	43
TM 15	1400 – 1500 m	SM	15.8	38.2	1.2	12	20	41
TM 16	1500 – 1600 m	SW-SM	9.8	37.8	1.6	10	27	35
TM 17	1600 – 1700 m	GW-GM	10.6	42.8	1.0	3	40	47
TM 18	1700 – 1800 m	SM	18.4	27.5	2.1	10	23	53

[a] Sample taken from a randomly selected location within the road section indicated.
[b] A sample from TM 13 could not be obtained due to equipment activity at the time of sampling.
[c] Compaction levels from ASTM D1883, 10 blows, 25 blows, and 56 blows per soil layer respectively.

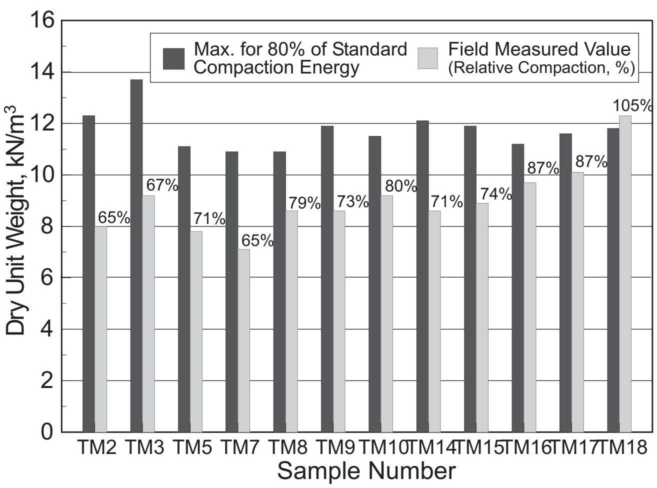

Figure 2. ~ *A comparison between the maximum dry unit weight for 80% of the standard compaction energy and field dry unit weight of subgrade materials along the test road (field measured dry unit weight bars are labeled with relative compaction values for completeness).*

and the actual dry unit weight, shows that this achievable level was not met in 11 of the 12 field samples. Further, as indicated by the relative compaction values, only one of 12 field samples was compacted to the common compaction specification of 95 percent relative compaction, albeit that the relative compaction values presented here are related to 80 percent of standard compaction energy rather than the standard compaction energy. One explanation for this low compaction level was the field MC at the time of compaction. Field MC at the time of road construction ranged from 28.7 to 54.7 percent (**Fig. 3**). Seven of the 12 field samples had a MC greater than the optimal MC for 80 percent of the standard compaction energy (**Fig. 3**). Generally speaking, it is not practical to obtain compacted dry unit weights that result in saturation levels greater than about 90 percent for a soil. These seven of 12 field samples were too wet for the maximum dry unit weight for 80 percent of the standard compaction energy to be obtained. The schematic relationship between field MC, saturation, dry unit weight, and standard compaction test results is illustrated in **Figure 4**.

The samples that were at or dry of the optimum near the beginning of the road generally faired worse in terms of relative compaction (**Figs. 3 and 4**) than the samples that were wet of optimum. Relative compaction values for samples TM2, TM5, and TM7 ranged from 65 to 67 percent. It should have been possible to compact the areas of the road subgrade represented by these samples to at or near the maximum dry unit weight according to the standard compaction test (ASTM D698). Given the low relative compaction achieved, it is reasonable to infer that the compactive effort provided by two passes of the CAT model CS 573D vibratory roller was not adequate to obtain the potential compaction, which demonstrates that control of compaction energy consistent with achieving compaction levels near the standard compaction test maximum was not employed.

Discussion

It is apparent that many forest road managers believe that they are able to save money by building forest roads without the expense of a geotechnical analysis that would be used to de-

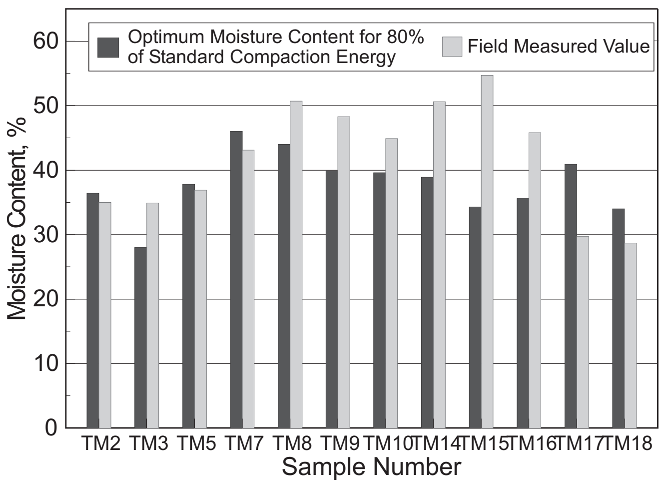

Figure 3. ~ *Comparison between optimum moisture content for 80% of standard compaction energy and field moisture content at time of construction.*

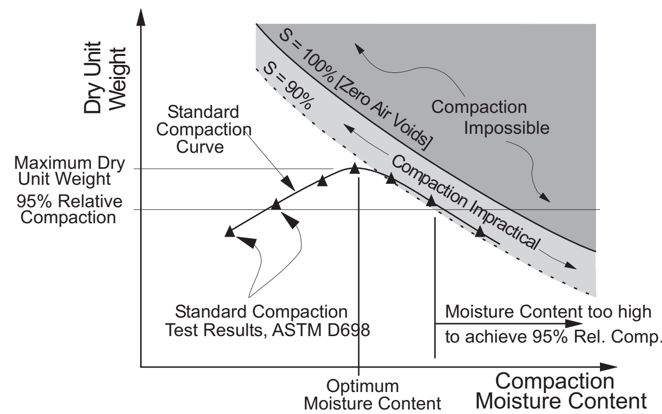

Figure 4. ~ *Schematic relationship between field MC, saturation, dry unit weight, and standard compaction test results.*

velop compaction standards and to control density and MC during road construction. We believe that the case illustrated above, which suggests that potential road subgrade strength is not being utilized is quite typical. To illustrate the potential improvement that can be realized through compaction, an aggregate surfacing design equation that includes the benefit of subgrade strength will be used. The 1978 Army Corps of Engineer's design equation, modified for standard log truck wheel loads and tire pressures, attempts to predict the surface rut that will form following a specified number of wheel loads (Bolander et al. 1996).

$$RD_{cm} = 20.76 \times \frac{R^{0.2478}}{[\log(t_{cm}) - 0.405]^{2.002} \times C_1^{0.9335} \times C_2^{0.2848}}$$

where:

RD = rut depth (cm)

R = number of loaded highway legal (356 kN) log trucks

t = aggregate thickness (cm)

C_1 = CBR of the aggregate (top) layer

C_2 = CBR of subgrade layer

Using a 5 cm maximum rut depth and constant traffic levels, the Equation can be used to demonstrate the potential savings in aggregate surfacing from an improved subgrade that can be obtained through compaction to laboratory determined levels. **Table 2** was developed to illustrate the potential savings for a road similar to the road in this case study.

The average relative compaction along the case study road was 76 percent. The lowest relative compaction value for an individual CBR sample from the laboratory testing was 83 percent. The lowest relative compaction values for laboratory CBR samples ranged from 83 to 90 percent. The CBR values for these samples ranged from 0.4 to 2.8. Using these values as a guide, we selected a CBR value of 2 for the as-built field condition on the case study road. This allows for some improvement over the initial as-built condition with traffic loadings before wet season hauling for which the soaked CBR can be expected to apply.

Table 2. ~ *Comparison of the as-built versus opportunity conditions based on the model.*

	As-built condition	Improved condition as a result of compaction
Subgrade CBR	2	7
Aggregate surface layer CBR	20	20
Equivalent number of loaded log trucks	2,000	2,000
Required aggregate layer thickness (cm)	38 (15 in.)	25 (10 in.)
Cost of compaction (per 30 m)	0	$25
Cost of aggregate at the pit (per 30 m)	$431	$278
Aggregate hauling cost (per 30 m)	$261	$152
Total costs (per 30 m)	$692	$454

For the improved condition that can result from better field compaction, we selected the average of the CBR's at the maximum dry unit weight for the 80 percent of standard compaction energy from the CBR tests (**Table 1**) as a reasonably obtainable value. Achieving this value (CBR = 7) corresponds to a relative compaction of 100 percent for 80 percent of the standard compaction energy. This compaction level will be less than 100 percent relative compaction for the standard compaction energy using the 10.16 cm diameter mold, which is achievable, and is a reasonable specification if the benefit is justified by the cost. The comparative analysis presented in **Table 2** suggests this to be the case.

A CBR of 20 was selected for the aggregate surfacing in both cases presented in **Table 2**. For similar compaction procedures, it is expected that the aggregate layer CBR will be slightly higher for the improved subgrade because the stiffer subgrade will result in higher aggregate design, but to be conservative, we have ignored this additional benefit in the analysis. The equivalent number of loaded log trucks corresponds to "highway legal" log trucks carrying approximately 30 m^3 of wood (4.5 Mbf).

Aggregate costs from the range described by Sessions et al. (2006) for the area were used in the analysis ($8.21 per m^3 [$7 per yd^3] crushing and pit cost; a 6.4-km [4 mile] haul to the site with a cost of $0.77 per m^3 -km [$0.70 per yd^3 mile]). The Oregon Department of Forestry (ODF) estimates compaction costs at $8.31 per 30 m (station) (Doyal 2007). It is reasonable that proper compaction and control will require more passes of the roller than current ODF estimates. We used a conservative estimate of three times the ODF cost for a $25 per 30-m station. The analysis results suggest a 34 percent, or $238 per 30-m station, savings in aggregate cost. Some of this gross saving will be spent on setting and controlling the compaction standard.

Conclusion

This conservative example shows some real potential savings from designing and controlling the subgrade compaction using relatively high prices for compaction and relatively low prices for aggregate. Some places in the Oregon Coast Range where aggregate is scarce can have aggregate costs at the pit (crushing included) approaching $20.00 per m^3 , or about two and a half times the cost we have assumed in this analysis. In these areas, the financial gains from improved design and construction should be even higher. Although the relationship between structural road design and construction control and cost is well known in the civil engineering world, it has been lost in much of the forest engineering world. We hope that this research note will encourage forest engineers to consider engineered and controlled subgrade compaction as a method for reducing transportation costs.

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