Forest Service
U.S. DEPARTMENT OF AGRICULTURE

National Technology & Development Program 2277–1804–NTDP 7700–Transportation Management October 2022

Guidelines for Road Surface-Course Aggregate

Cover photo—Rutting and potholing can occur when surface aggregate is of poor quality or gradation.

Guidelines for Road Surface-course Aggregate

Peter Bolander (retired)
Professional Engineer, Geotechnical Engineer, U.S. Department of Agriculture, Forest Service, Pacific Northwest Region

Vincent Barandino, Jr.
Civil Engineer, U.S. Department of Agriculture, Forest Service, National Technology and Development Program

Gordon Keller (retired)
Professional Engineer, Geotechnical Engineer, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region

U.S. Department of Agriculture, Forest Service

National Technology and Development Program

October 2022

Acknowledgments

Leslie J. Boak, deputy director of Engineering, U.S. Department of Agriculture, Forest Service, Pacific Southwest Region

John Fehr, director, U.S. Department of Agriculture, Forest Service, National Technology and Development Program (retired)

Justin Humble, transportation engineer, U.S. Department of Agriculture, Forest Service, Intermountain Region

Maureen Kestler, civil engineer, U.S. Department of Agriculture, Forest Service, National Technology and Development Program (retired)

Jim Kozik, roads operation and maintenance engineer, U.S. Department of Agriculture, Forest Service, Southern Region (retired)

Marie Messing, transportation engineer, U.S. Department of Agriculture, Forest Service, Alaska Region (retired)

Contents

Introduction

The U.S. Department of Agriculture, Forest Service uses the "Forest Service Supplemental Specifications (FSSS) to the Standard Specifications for Construction of Roads and Bridges on Federal Highway Projects (FP-14)" (table 1) for untreated aggregate courses on National Forest System roads. Ideally, a surface course is applied over a base-course aggregate. Because of the lack of an available commercial source for surface aggregate, the high cost to crush small quantities of surfacing material, or simply the lack of understanding about how to use surface aggregate on roadways, base-course aggregate specifications often are used instead of surface-course aggregate specifications.

Forest Service staff developed this document to provide guidance and to increase awareness of the benefits for low-volume road aggregate, such as the cost-effective selection and use of surface aggregate versus base-course aggregate specifications. This guide also provides an understanding of the function of surface aggregate when composed of hard, durable aggregate and a well-graded material with adequate fines (material passing the No. 200 sieve) and plasticity to help bind the aggregate-wearing surface together.

Table 1—Target value ranges for surface gradation in percent by mass passing the designated sieve, AASHTO T27 and T11 (FP-14 Forest Service Supplemental Specification, table 703-3). Values in parentheses are the allowable deviation (±) from the target values. If the target value for the No. 200 sieve is less than 12 percent, then the plasticity index should be between 2 and 9. If the target value is greater than 12 percent, then the plasticity index should be less than 2. – = no requirement

Sieve size	F	G	H	S	T	U
1½ inch	100	–	–	100	–	–
1 inch	97–100	100	–	72–92 (6)	100	–
¾ inch	76–89 (6)	97–100	97–100	–	–	100
½ inch	–	–	–	–	71–91 (6)	–
⅜ inch	56–68 (6)	70–80 (6)	80–92 (6)	51–71 (6)	–	71–90 (6)
No. 4	43–53 (7)	51–63 (7)	58–70 (7)	36–53 (7)	43–60 (7)	50–68 (7)
No. 8	–	–	–	26–40 (6)	30–46 (6)	34–51 (6)
No. 16	23–32 (6)	28–39 (6)	28–40 (6)	–	–	–
No. 40	15–23 (5)	19–27 (5)	16 – 26 (5)	14–25 (5)	16–28 (5)	19–30 (5)
No. 200	10.0–16.0 (4)	10.0–16.0 (4)	9.0–14.0 (4)	8.0–15.0 (4)	8.0–15.0 (4)	8.0–15.0 (4)

Poor Surface Aggregate Quality and Gradation

The use of material with poor surface aggregate quality and gradation will lead to several problems. Poorly selected surface aggregates for surfacing material can:

- Increase the amount of raveling
- Create washboarding (corrugating)
- Create potholing
- Create rutting
- Cause contamination from the subgrade or underlying material (pumping)
- Contribute to sediment runoff
- Contribute to surface deformation
- Contribute to aggregate loss

Any of these problems requires more frequent surface maintenance and surface rock replacement. Figures 1 through 6 show common problems associated with poor surface aggregate quality and gradation.

Figure 1—This road had rutting and pumping due to poor gradation. Surface aggregate is typically the most costly component of a gravel road. An aggregate with insufficient fine material will ravel. An aggregate with too much fine material will weaken the structural support, generate excessive sediment, and rut.

Figure 2—This road had rutting in the surface due to a lack of surface aggregate, excessive clay, poor compaction, and poor road surface drainage combined with weak subgrade soils.

Figure 3—Lack of road surface drainage in conjunction with a poor aggregate gradation can create potholes that can weaken the structural section of the road. Ensure that any ruts and potholes are reprocessed and compacted before placing any new aggregate.

Figure 4—Insufficient fine material in the surface aggregate will ravel and form windrows of material outside the wheel tracks—typically along the center and edge of the road—and will also lead to high aggregate loss.

Figure 5—Too much clay or the use of low-durability aggregate in the surface aggregate can lead to the retention of excessive moisture and can cause rutting, excessive runoff, surface deformation, and damage to the road, especially during thaw cycles and after rain events. Good roadway surface and subsurface drainage are the most cost-effective actions to take to maintain or improve the quality and strength of any soil or aggregate.

Figure 6—Too much clay within the surface aggregate can migrate to the surface of the aggregate, thereby increasing the amount of sediment runoff during rain events and the amount of dust during dry conditions.

Properties of Surface Aggregate

An ideal aggregate pavement structure has two layers: a surface course and an underlying base course. The surface course provides a durable, smooth-riding surface and user comfort, resists ravel, maintains strength and stability during the period of use, provides skid resistance, and sheds surface water.The base course distributes the wheel loads to minimize the deformations at the road surface (rutting). In other words, it keeps vehicles out of the mud.

Chemical and physical properties that influence surface aggregate performance are the particle size distribution, the amount and plasticity of fines, the particle shape, and the quality of the material. The preferred surface aggregate is compact, angular, durable, well-graded with some plasticity, and crowned to shed water.

The preferred base aggregate is compact, angular, durable, and open- to well-graded (free draining). Because the base aggregate is relatively free draining, capping with an impermeable surface layer will prevent the infiltration of water. Potential pumping and movement of the underlying material into the base aggregate should also be a consideration. The larger the maximum size, the greater the potential to help distribute wheel loads over a larger surface area on the subgrade, thereby reducing the stress and resulting strain on the subgrade.

A compacted surface prevents raveling and helps shed water off the surface to prevent potholing. Potholes are a common problem on gravel-surfaced roads. They typically develop at local soft spots or areas that hold/pond water. Traffic combined with water further weakens the material and displaces the weakened material from the top down. An adequate structural section with good surface drainage helps minimize the formation of potholes.

An angular aggregate interlocks and helps prevent raveling, provides stability, and helps distribute the wheel loads to the underlying subgrade. Typically, angularity in aggregate is accomplished by crushing and is measured in the fractured faces test requirement.

A well-graded surface aggregate has a higher density and lower permeability compared to base aggregate, which is commonly open-graded. Being well-graded, it resists raveling and washboarding because the particles interlock. An open-graded aggregate provides strength when confined, but when used as a surface course it is not confined, and it ravels easily and has lower strength and skid resistance. A surface course with too many fines will float the larger particles, tend to hold water, deform under traffic when wet, erode easily, and generate dust under traffic when dry.

Durability of the surface aggregate also is important. A low-durability material used for the surface course will degrade with traffic. It will degrade even faster when water is present. The degradation creates more fines in the surface, thereby creating problems described previously for a surface course with too many fines.

Benefits of Using Surface Aggregates

Because base aggregate has a relatively low percentage of fines (more open-graded) and no plasticity, it tends to ravel when it is used as a surfacing material. This raveled material is a waste of aggregate resources. Typically, the better the quality of the aggregate and the more well-graded aggregate it is, the smoother the road surface becomes. This results in the need for less road maintenance and less frequent surface aggregate replacement. Thus, one pays more initially for aggregate production or one pays later with additional maintenance costs to correct raveling, washboarding, potholing, and rutting (figures 7 and 8).

The use of high-quality, well-compacted roadway materials, such as those shown in figure 9, can produce a durable, longer lasting, structurally sound road with minimum maintenance costs. It also will reduce sedimentation and water quality degradation. Aggregate that is well graded and has plasticity compacts well. It develops a tightly bound surface that needs less maintenance, as shown in figures 9 and 10.

Figure 7—This road had corrugations (washboarding), which resulted from insufficient fines in the surface aggregate (as well as lightweight traffic and lack of timely maintenance). Corrugations and washboarding can be removed temporarily by grading. However, the real problem is an insufficient amount of fines and/or no plasticity.

Figure 8—The grader operator is sometimes blamed for gravel maintenance/rehabilitation problems when the actual problem is often material related.

Figure 9—The use of high-quality aggregate surfacing will resist erosion, make it reasonably firm, perform well, and stretch the life cycle before regraveling is needed. A well-maintained road, particularly with a dust palliative, reduces road user costs, prevents road damage, and minimizes sediment production.

Figure 10—These roads had well-compacted surfacing materials with an appropriate gradation of aggregates and a sufficient amount of fine material.

Cost Comparison for Surface Aggregate

The following is an example of the life-cycle costs for using a surface-course aggregate with a higher initial cost versus the cost of using a more readily available local aggregate that meets the base-course aggregate specifications for the surface course.

Assumptions

1. One mile of road with 12-foot-wide running surface, 3H to 1V aggregate edge slope, and 6-inch-thick layer.
2. Design period for the road is 15 years.
3. Cost to obtain and place good quality aggregate that meets surface-course aggregate quality and gradation requirements is $35 per cubic yard ($yd^3$).
4. Cost to obtain and place local aggregate that meets base-course aggregate quality and gradation requirements is $25 per yd^3.
5. Typical maintenance for surface-course aggregate is one blading per year, no dust abatement, and 4 inches of surface rock replacement needed at year 15. Blading cost is $1,000 per mile.
6. Typical maintenance for base-course aggregate when used as a surface aggregate is two bladings per year, no dust abatement, and 4 inches of surface rock replacement needed at year 7.5 and at year 15. Blading cost is $1,000 per mile.
7. Interest rate is 4 percent.

Initial Cost

To obtain and place good quality aggregate:

5,280 feet (ft) × ((12 ft + 15 ft) ÷ 2) × 0.5 ft × 1/27 × $35 per yd^3 = 1,320 yd^3 × $35 per yd^3 = $46,200

To obtain and place local aggregate:

5,280 ft × ((12 ft + 15 ft) ÷ 2) × 0.5 ft × 1/27 × $25 per yd^3 = 1,320 yd^3 × $25 per yd^3 = $33,000

Cost to Maintain

For good quality aggregate:

$1,000 per year and $30,800 for surface rock replacement at year 15.

For local aggregate used as a surface course:

$2,000 per year and $22,000 for surface rock replacement at year 7 and at year 15.

Net Present Worth

Net present worth is the initial cost plus the present worth of yearly blading plus the present worth of surface rock replacement.

For surface course:

= $46,200 + (11.118 × $1,000) + (0.5553 × $30,800) = $74,421

For local aggregate used as a surface course:

= $33,000 + (11.118 × $2,000) + (0.7599 × $22,000) + (0.5553 × $22,000) = $84,170

So, over the 15-year life of the road, the cost savings using a surface-course aggregate instead of a local base-course aggregate for the surface course would be $9,749 ($84,170 – $74,421) for this example.

Selecting Surface Aggregate

A fairly wide range of aggregate gradations may be used for aggregate surfacing. Before selecting the aggregate gradation for a road, consider the following questions:

- Who are the users, what types of vehicles will they be driving, and what is the intended comfort level?
- What aggregate materials are available, and what is the cost to obtain and place these materials?
- What grades are planned for the road?
- What is the expected season of use?
- What is the expected maintenance?
- What environmental considerations associated with the roadway must be addressed?

Once these questions are answered, the appropriate aggregate gradations can be established for the project (Bolander et al. 1996).

Commonly, the aggregate properties to choose for the surface aggregate are the maximum particle size, the amount and plasticity of the fine particles, the gradation of all the particles, the amount of fractured faces on the coarse particles, and the quality of the aggregate material. Many of these components go hand in hand, and of course, the long-term cost effectiveness of the available material is a primary factor as well.

The recommended aggregate properties shown below are based on the authors' experiences and information obtained from the various references cited in this report.

Maximum particle size (smoothness, strength, maintainability)—If the primary traffic is passenger car and/or recreational vehicle use, use a maximum size of ¾ to 1½ inch (19 to 38 millimeter [mm]). If the primary traffic is for high-clearance vehicle and/or commercial truck traffic, use a maximum size of 2 to 4 inches (50 to 100 mm). Larger maximum-size aggregate can result in a rougher ride, increased tire wear, and higher maintenance costs. Additionally, using larger aggregates makes it more difficult to maintain (blade) the surface of the road.

Amount and plasticity index of fine particles (raveling, strength, rutting, dust)—The amount of clay in the aggregate (approximated by the plasticity index [PI]) will vary depending on local climate and material used (Bloser et al. 2012). The "Selection Criteria of Plasticity Index for Surface Aggregate" section and table 2 describe selection criteria for the amount and PI of the fines for surface aggregate. Avoid using aggregate below or above the recommended PI ranges unless you are willing to accept substandard performance, as noted in the "Poor Surface Aggregate Quality and Gradation" section.

For example, in a wet environment, aggregate with a high percentage of fines may rut easily or create excessive runoff. In a dry environment, aggregate with a high percentage of fines, may ravel, washboard, or generate a fair amount of dust. The degree of performance also will depend on the other aggregate properties, the grade of the road, and the vehicles using the road.

Selection Criteria of Plasticity Index for Surface Aggregate

- Step 1: Determine the predominant moisture content of surface aggregate during use—either “dry” or “wet.”
- Step 2: Determine the percent of surface aggregate passing the No. 200 sieve—either less than 8, 8 to 12, 12 to 18, or greater than 18.
- Step 3: Determine the recommended PI for surface aggregate based on the predominant moisture content and percent passing the No. 200 sieve in table 2.

Gradation (strength, dust)—As noted above, surface aggregate performs best if it is well graded. Well-graded aggregate has an even distribution of coarse to fines, such that the coarse particles are in contact with each other and are not “floating” in a matrix of finer material that is used to fill the voids created by the coarse particles. A method known as the theoretical maximum density curve (National Stone, Sand and Gravel Association 2013), also known as the Talbot Equation, is frequently used as an aid in selecting a suitable gradation for pavement structures. Using this curve, you can obtain the precise gradation curve for the gradation that produces maximum density. It is recommended to ensure that the curve is drawn through the nominal maximum aggregate size (typically the size associated with 90 to 95 percent passing), not the 100 percent passing sieve. Also, you can ignore sieves smaller than the No. 16 if you follow the No. 200 and plasticity requirements noted previously. Following this gradation curve provides maximum density (figure 11) and provides strength while also providing low permeability.

Table 2—Recommended plasticity index (PI) for surface aggregate based on the predominant moisture content and percent passing the No. 200 sieve. NP = nonplastic

Percent passing No. 200 sieve	Recommended PI for dry surface aggregate	Recommended PI for wet surface aggregate
Less than 8	Do not use	Do not use
8 to 12	6 to 10	2 to 6
12 to 18	2 to 5	NP to 2
Greater than 18	NP	Do not use

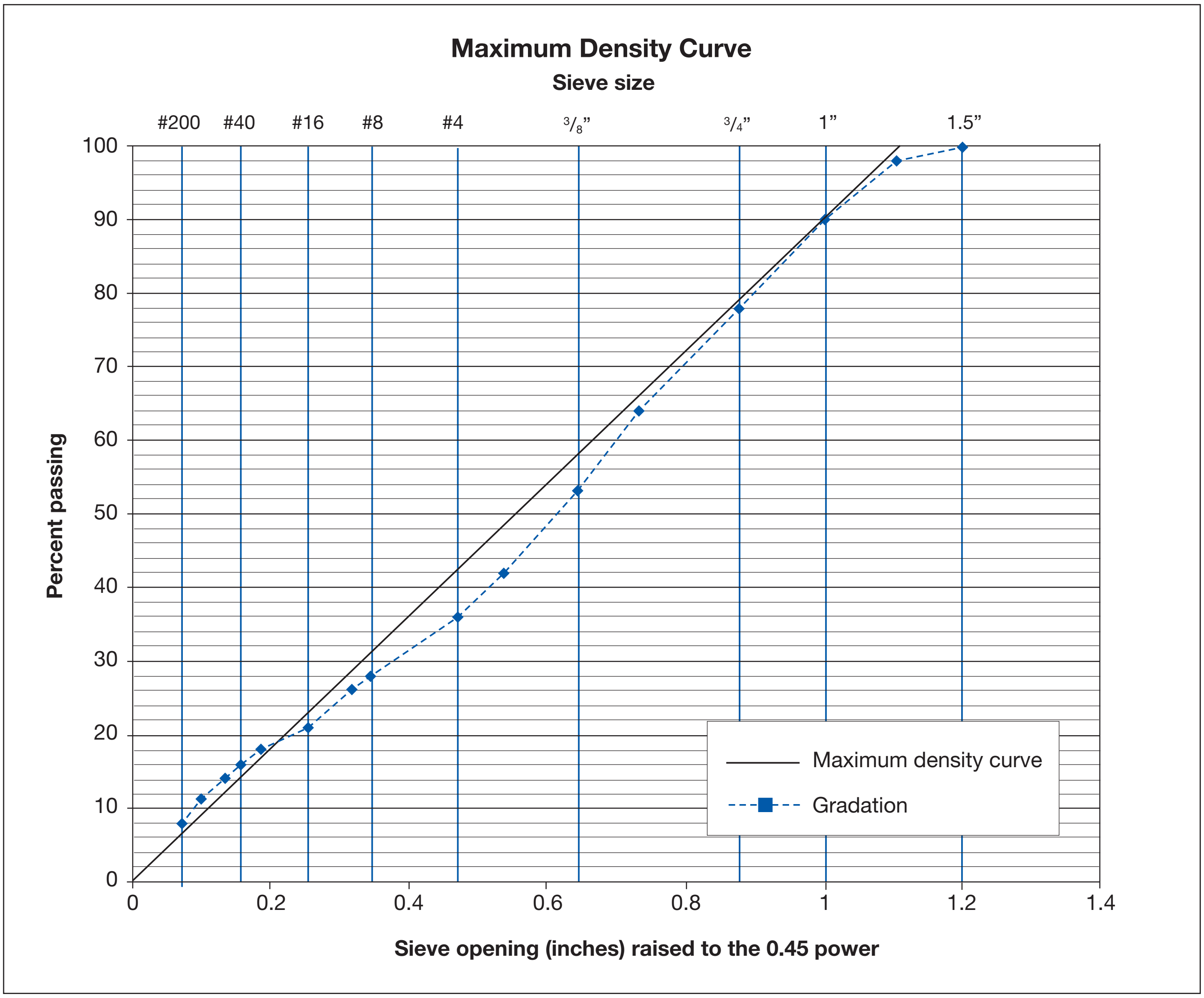
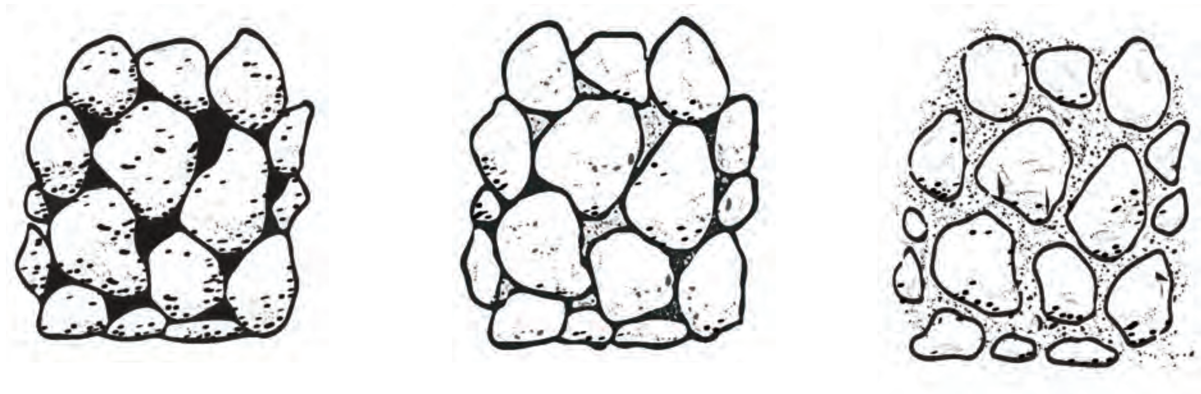


Figure 11—A maximum density curve.

To increase the resistance to raveling, the percentage of material retained on the No. 8 (2.36 mm) sieve should be between 20 and 60 percent. To optimize stability and reduce permeability, the fines-to-sand ratio should be between 0.20 and 0.60. A dense aggregate mix requires some fines, but fines of more than about 15 percent reduce the structural strength of the material. With material having more than about 25 percent fines, point-to-point contact of the rock particles is lost, and the fines begin to control the strength of the aggregate. Figure 12 shows the relationship between aggregate with no fines, with an ideal amount of fines, and with excessive fines. Each blend of materials has distinct physical characteristics. Too little or too many fines are undesirable for road aggregates, particularly on the road surface. Table 1 shows common gradations the Forest Service uses.



Aggregate with no fines (0 fines)	Aggregate with sufficient fines for maximum density (8 to 15 percent)	Aggregate with high amount of fines (greater than 25 percent)
Grain-to-grain contact	Grain-to-grain contact with increased resistance against deformation	Grain-to-grain contact destroyed, aggregate “floating” in soil
Variable density	Increased to maximum density	Decreased density
Pervious	Low permiability	Low permeability
Nonfrost susceptible	Frost susceptible	Frost susceptible
High stability if confined, low if unconfined	Relatively high stability in confined or unconfined conditions	Low stability and low strength
Not affected by adverse water conditions	Not greatly affected by adverse water conditions	Greatly affected by adverse weather conditions
Difficult to compact	Moderately difficult to compact	Not difficult to compact
Ravels easily	Good road performance	Dusts easily

Figure 12—Physical state of soil-aggregate mixtures. Note that soil passing the No. 200 sieve are fines. —Reprinted with permission of John Wiley and Sons, Inc. Adapted from Yoder and Witczak (1975), a Wiley-Interscience publication.

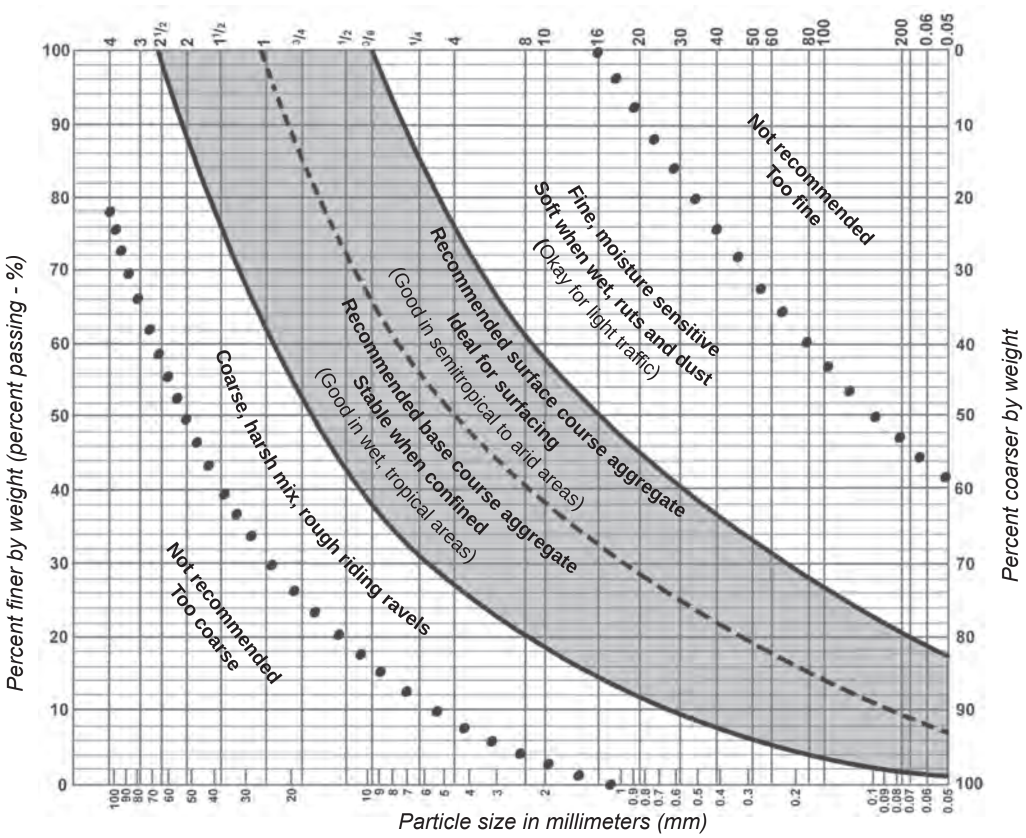
Figure 13 graphically presents the requirements of road aggregate plotted as a range of gradation curves. This curve was developed by plotting the range of a variety of existing aggregate specifications and by evaluating performance data from several crushing projects. Surface-course aggregate must be somewhat finer to retain moisture and minimize raveling as well as typically have some plasticity.

An aggregate too rich in fines loses its strength, is moisture sensitive, and produces dust. Thus, base-course aggregate and surface-course aggregate both have ideal gradation ranges. To have a well-graded aggregate, the desired gradation should be in the middle of the ranges shown and parallel to the curves.

Grain Size Distribution

(Gradation curve)

Sieve Analysis	
Size of openings in inches	Number of mesh—U.S. Standard



Cobble	Course	Fine	Coarse	Medium	Fine	Silt
	Gravel		Sand			

Note: Gradation ranges are approximate.

The best roadbed surfacing materials have some plasticity and are well graded. They have gradations parallel to the curves shown above, and are closest to the "ideal" dashed curve in the middle of the gradation ranges shown above.

Figure 13—Ideal grain size distributions for surface-course and base-course aggregate (Keller and Sherar 2003).

Fractured faces (stability)—To ensure a stable surface for road grades less than 8 percent, the amount of fractured faces on the coarse particles should be at least 75 percent. For road grades greater than 8 percent, the amount of fractured faces on the coarse particles should be 100 percent.

Particle quality (durability)—Table 3 shows durability requirements for the fine and coarse fraction of the aggregate material.

Although we try to use quality construction materials, at times marginal or poor-quality materials are available and are cost effective. Suitable unbound aggregate or pit-run materials may be used if they are well-fractured. Pit-run, grid roll, mobile rock crusher, or tractor-rolled aggregates are all ways to produce aggregate at a relatively low cost. However, the minimal processing usually results in a less than ideal gradation, depending on the characteristics of the original material used.

A well-fractured, dirty (high fines) rock source may make a good roadway surfacing material or aggregate to fill in soft spots, particularly for a low-use road. It is appropriate and cost-effective to use poor- or marginal-quality aggregate for low-volume roads (see table 4 for guidance). The tradeoff is usually reduced performance and increased maintenance costs. Thus, the savings in initial production of the aggregate must be weighed against poorer performance and increased operation and maintenance costs. The cost effectiveness of marginal material depends on the type and amount of road traffic driving over that material.

Table 3—Aggregate wear and durability (quality) requirements (Keller et al. 2011)

Test requirement	Base and subbase	Surfacing
Los Angeles abrasion, American Association of State Highway and Transportation Officials (AASHTO) T 96	40 percent maximum	40 percent maximum
Sodium sulfate soundness loss, AASHTO T 104	12 percent maximum	12 percent maximum
Durability index (coarse and fine), AASHTO T 210	35 minimum	35 minimum
Fractured faces, American Society for Testing and Materials (ASTM) D 5821	50 percent minimum	75 percent minimum
Liquid limit, AASHTO T 89	25 percent maximum	35 percent maximum
Plasticity index, AASHTO T 90	Nonplastic	2 to 9[1] < 2[2]

[1]If the percent passing the No. 200 (75 µm) sieve is less than 12 percent.

[2]If the percent passing the No. 200 (75 µm) sieve is greater than 12 percent.

Table 4—Typical design situations with helpful design hints. Adapted from "Earth and Aggregate Surface Design Guide For Low-Volume Roads" (Bolander et al. 1996)

Situation	Helpful hint
Wet weather commercial haul	Use the maximum economically feasible size aggregate (i.e., 3 inch or greater). Note: Larger rock gradations, if good quality and openly graded, may have a tendency to ravel and shove, especially on curves or steep grades. Large rock may also increases tire damage and wear.
Predominately low clearance	Use ¾- to 1-inch maximum size aggregate that meets the surfacing recreation traffic requirements.
Year round "wet area"	Design wet area as a separate design segment. Consider using 3-inch or greater maximum size aggregate or geotextiles that provide strength and separation.
Grades between 12 and 18 percent	Minimize sharp radius curves. For adverse grades with commercial haul, use grading F or G (see table 1). For favorable grades with commercial haul, use grading F or G and tighten gradation band. Use low tire pressures on commercial vehicles. Follow tips under the "Aggregate that ravels (no binder)" situation. Pave or stabilize surface. Consider consequences of black ice conditions on paved surfaces.
Grades greater than 18 percent	Most States require the use of an assist vehicle with commercial haul. To help gain traction: See "Grades between 12 and 18 percent" above. If there is dry weather with fine-grained subgrade, an earth surface should suffice.
Marginal aggregate that degrades	Use larger, maximum-size, open-graded aggregate, and adjust the gradation to account for the amount that the aggregate degrades (e.g., require less passing the No. 4 sieve). Stabilize by adding Portland cement. If the fine aggregate degrades more readily than the coarse aggregate, consider scalping before crushing. Use low tire pressures on commercial vehicles.
Aggregate that ravels (no binder)	To provide tighter control on the gradation requirements: Use grading F or G (see table 1) or narrow the allowable gradation band. Add natural fines (silt or clay), manufactured fines, or a clay additive. Stabilize by adding cement, flyash, lime, asphalt, dust abatement, or other product. Apply a bituminous surface treatment (BST).
Need for alternative specifications	Write aggregate specifications for the intended use considering economically available materials and local experience (i.e., replacing plasticity index requirements with a finer or denser gradation or incorporating blending, scalping, or washing).
Changes in subgrade strength	Adjust the aggregate thickness to correspond with changes in the subgrade along the road strength.

Situation	Helpful hint
Placing additional aggregate on an existing "dirty" surface	Blade-mix a thin lift of open-graded aggregate with the existing aggregate. The size and thickness of the aggregate is a function of the existing gradation and necessary structural requirements.
River-run gravel	These sources typically produce a loose surface. Options for mitigating include: Options listed in the "Aggregate that ravels (no binder)"situation. Use an impact crusher (tends to increase the number of fractured faces). Create a special project specification that increases the percent of fractured faces, similar to what State agencies require for hot mix asphalt.
Aggregate source with seams or pockets of low strength or quality fines	Scalp before crushing to remove low-quality material. Use a smaller maximum size gradation, which could increase the amount of manufactured fines.

Base-course aggregate often is used as road surfacing material because it is the only aggregate available. This is not ideal but realistic if only base-course aggregate is available commercially. Custom crushing to produce a surface-course aggregate can be very expensive, especially for a small quantity of material. Again, with use, the base-course aggregate ravels and requires relatively high maintenance when compared with a surface-course aggregate.

Related Studies, Experiments, Investigations, and Reviews

Several agencies have conducted studies on surface aggregate and base-course aggregate materials. However, there has been no testing done to compare the cost benefits of using surface aggregate versus base-course aggregate specifications for low-volume road surfacing materials. While a lot of research exists concerning aggregates for asphalt and concrete pavement mixes, research regarding the performance and cost-effectiveness of unbound aggregates for surfacing unpaved roads is minimal.

While attention is usually given to the hardness or quality of material used for unpaved road aggregates, the importance of selecting the proper size gradation for the aggregate is often overlooked. Researchers have performed several studies to compare the performance of "good quality" aggregates to "poor quality" aggregates. Virtually all these studies, however, focused on the quality of the parent material of the aggregate and the durability of the fine material (Bilby et al. 1989; Foltz and Truebe 1995, 2003).

Table 5 lists aggregate gradations throughout the United States that are designed specifically as a driving surface for unpaved roads. The limited number of aggregates and the wide range in gradations in table 5 indicate that more study and analysis is needed concerning surface-aggregate gradations for unpaved roads.

Table 5—Size gradations for “unbound surface aggregates” from around the United States. The first three gradations (shaded) are the ones used in this study (Bloser 2007). All values except plasticity index are total percent passing. AASHTO = American Association of State Highway and Transportation Officials. – = no requirement

Source	Sieve size 50 mm (2 inch)	Sieve size 38 mm (1.5 inch)	Sieve size 25 mm (1 inch)	Sieve size 19 mm (0.75 inch)	Sieve size 12 mm (0.5 inch)	Sieve size 9.5 mm (0.375 inch)	Sieve size 4.75 mm (No. 4)	Sieve size 2.36 mm (No. 8)	Sieve size 2.00 mm (No. 10)	Sieve size 1.18 mm (No. 16)	Sieve size 0.6 mm (No. 30)	Sieve size 0.42 mm (No. 40)	Sieve size 0.15 mm (No. 100)	Sieve size 0.075 mm (No. 200)	Plasticity index
Driving surface aggregate	–	100	–	65–95	–	–	30–65	–	–	15–30	–	–	–	10–15	–
PennDOT 2RC	100	–	–	–	–	–	15–60	–	–	–	–	–	0–30	–	–
PennDOT 2A	100	–	–	52–100	–	36–70	24–50	16–38	–	10–30	–	–	–	0–10	–
S. Dakota “gravel surfacing”[1]	–	–	–	100	–	–	50–78	37–67	–	–	–	13–35	–	4–15	4–12
“Gradation D”[2]	–	–	100	60–90	–	–	30–55	–	–	–	11–27	–	–	6–15	–
Surface-course aggregate[3]	–	–	100	–	–	66–100	50–76	40–60	–	32–50	25–40	22–37	–	8–18	2–10
“Gradation F”[4]	–	100	97–100	76–89	–	56–68	43–53	–	–	23–32	–	15–23		10.0–16.0	If No. 200 sieve <12%, PI is 2 - 9, if No. 200 sieve >12%, PI < 2

[1]Skorseth and Selim (2000)

[2]Foltz and Truebe (2003)

[3]Keller and Sherar (2003)

[4]U.S. Department of Agriculture, Forest Service (2022)

[5]U.S. Department of Transportation, Federal Highways Administration (2014)

[6]Ohio Department of Transportation (2005)

[7]Maine Department of Transportation (2018)

[8]Iowa Department of Transportation (2009)

Source	Sieve size 50 mm (2 inch)	Sieve size 38 mm (1.5 inch)	Sieve size 25 mm (1 inch)	Sieve size 19 mm (0.75 inch)	Sieve size 12 mm (0.5 inch)	Sieve size 9.5 mm (0.375 inch)	Sieve size 4.75 mm (No. 4)	Sieve size 2.36 mm (No. 8)	Sieve size 2.00 mm (No. 10)	Sieve size 1.18 mm (No. 16)	Sieve size 0.6 mm (No. 30)	Sieve size 0.42 mm (No. 40)	Sieve size 0.15 mm (No. 100)	Sieve size 0.075 mm (No. 200)	Plasticity index
"Gradation G"[4]	–	–	100	97–100	–	70–80	51–63	–	–	28–39	–	19–27	–	10.0–16.0	If No. 200 sieve <12%, PI is 2 - 9, if No. 200 sieve >12%, PI < 2
FHWA FP-14 surface course aggregate[5]	–	–	100	–	70–80	–	40–50	–	25–40	–	–	15–25	–	8–14	10 +/- 3
Ohio "411" spec[6]	–	100	75–100	60–100	–	35–75	30–60	–	–	–	7–30	–	–	3–15	< 6 on – No. 40
Maine surface aggregate[7]	95–100	–	–	–	30–65	–	–	–	–	–	–	–	–	7–12	–
AASHTO Class A and B[8]	–	–	100	95–100	70–90	–	30–55	15–40	–	–	–	–	–	6–16	4–9
AASHTO Class C[8]	–	–	–	100	–	–	50–80	25–60	–	–	–	–	–	–	4–9

[1]Skorseth and Selim (2000)

[2]Foltz and Truebe (2003)

[3]Keller and Sherar (2003)

[4]U.S. Department of Agriculture, Forest Service (2022)

[5]U.S. Department of Transportation, Federal Highways Administration (2014)

[6]Ohio Department of Transportation (2005)

[7]Maine Department of Transportation (2018)

[8]Iowa Department of Transportation (2009)

Pennsylvania's Dirt and Gravel Road Maintenance Program

Bloser (2007), of the Pennsylvania Dirt and Gravel Road Maintenance Program, conducted a study to better understand the wearing of coarse aggregates. The research also evaluated several of Pennsylvania's commonly used surface aggregates and placement methods to determine the most economic and environmentally sensitive strategies for surfacing unpaved roads.

The study also used cross-sectional profiles to quantify the degree of rutting in each of the aggregates to determine the bulk aggregate loss. The result of the test over the first winter showed severe rutting occurred on both aggregate placement methods (tailgate and paver) using PennDOT 2RC aggregates that contained clay fines.

Paver placement of road aggregates resulted in a more uniform and controllable aggregate thickness. The quality and thickness of tailgated aggregates was highly dependent on the skill and experience of the motorgrader or bulldozer operator who determined the final road shape. Throughout the 3-year study, researchers found that there was no significant difference in performance between aggregate sections placed with a paver when compared with the same aggregate placed by tailgating. The report states that "It is likely that any potential differences caused by the two placement methods may arise after this 3-year study has been completed. Longer term monitoring of the aggregate is suggested to determine if the extra cost of using a paver to place aggregate will result in long-term cost and maintenance reductions" (Bloser 2007). For more details on the study, see Bloser (2007).

Center for Dirt and Gravel Road Sediment Production Studies

The Center for Dirt and Gravel Road Studies at Penn State University conducted a test in the Allegheny National Forest to compare the sediment production on "as is" roads with pit-run material (phase 1) to roads with newly placed aggregate (phase 2). The purpose of the study was to quantify sediment generation rates from the oil drilling access roads and to determine differences in sediment production after placing new aggregate in the Allegheny National Forest. Runoff from unpaved roads is a large source of sediment pollution in the Allegheny National Forest.

See Bloser and Scheetz (2012) for more details about the study using a rainfall simulation device to measure sediment entering the streams.

Forest Engineering Research Institute of Canada (FERIC)

Légère and Mercier (2004), of Forest Engineering Research Institute of Canada (FERIC [now FP Innovations]), conducted a literature review of aggregate specifications designed for wearing-course applications (i.e., unsealed surfaces) and for base-course applications. Dawson (2004) contains the literature review. The review showed that few provincial agencies in eastern Canada provide specifications designed for unsealed surfaces (e.g., for wearing courses rather than for highway shoulders); most only provide specifications suitable for the base and subbase layers. Specifications for the latter two layers generally lack sufficient fines (materials that can pass through a No. 200 sieve), which are needed to provide good cohesion (binder) between particles if the aggregate is to be used as a wearing course. Because base layers must drain freely, their fines content is generally kept under 5 percent.

In the literature review of wearing-course specifications used around the world, Légère and Mercier (2004) found most specifications had similar criteria. The surfacing layer requires more fines, with a desired range of 8 to 15 percent (Tyrrell 2000) or 4 to 15 percent (Skorseth and Selim 2000). These fines must also contain plastic materials (clays) to improve their cohesion (Ferry 1986). Various authors have reported the recommended PI for these clays:

- AASHTO (2001) and Tyrrell (2000) report a PI between 4 and 9.
- Skorseth and Selim (2000) report a PI between 4 and 12.
- Giummarra (2009) reports a PI between 4 and 15.

Also, the liquid limit should not exceed 35 percent (AASHTO 2001, Tyrrell 2000).

Paige-Green (1999) suggests the following physical characteristics:

- A particle-size distribution that permits a good interlock between particles without excessive amounts of fine or coarse material.
- Appropriate cohesion to resist raveling.
- Adequate material strength to resist shear failures.
- Adequate aggregate hardness to retain the structural integrity of the compacted material.

Figure 14 compares a typical base-course specification (Ontario Ministry of Transportation 1993) with a typical wearing-course specification (Skorseth and Selim 2000). In this figure, the recommended range of compositions for wearing courses has higher overall proportions of fines, sands, and fine gravels than the corresponding range for base courses. Figure 14 also highlights various particle-size distributions that are prone to different surface-distress problems.

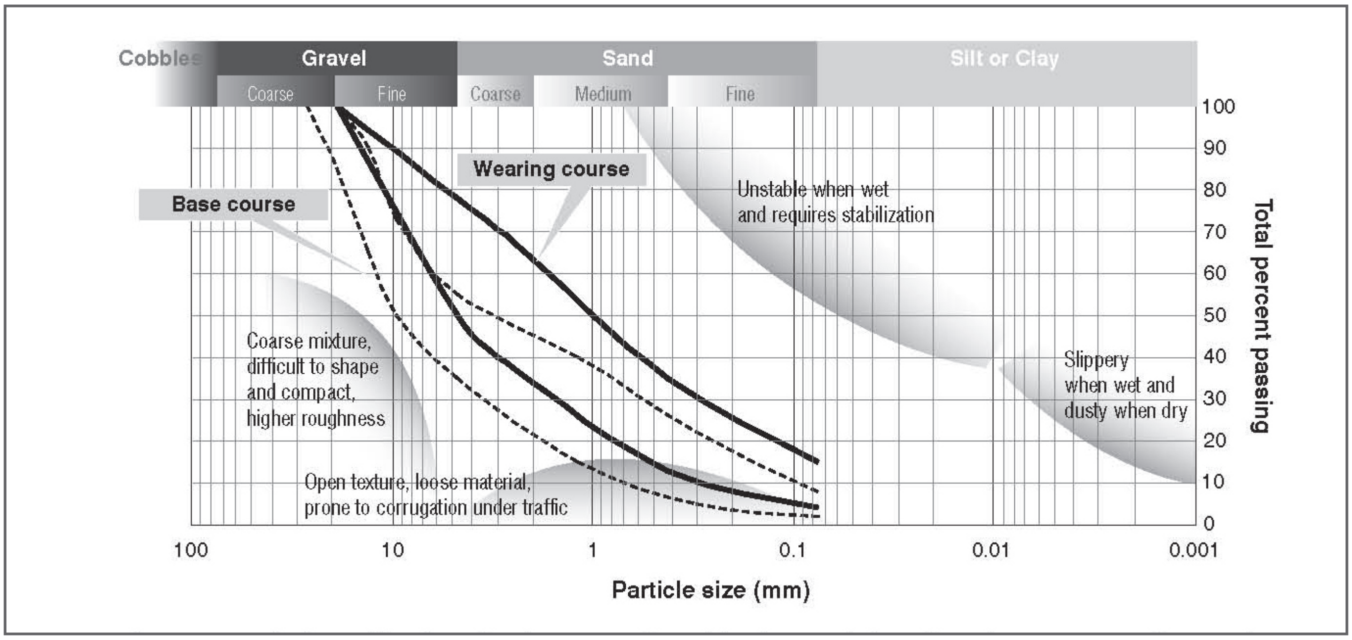


Figure 14—Typical specifications for the range of particle-size gradations for a base course and a wearing course and size distributions that typically pose surface-distress problems (Légère and Mercier 2003).

U.S. Army Corps of Engineers

The U.S. Army Corps of Engineers at the Vicksburg District conducted an investigation to improve the Engineers Mississippi Valley Division specifications for unbonded aggregate surface roads. They characterized various aggregate types in the laboratory and collected performance data under traffic. "Both natural and crushed sources of aggregate were included in this study. Trafficking and performance monitoring were accomplished under controlled test track conditions. A review of specifications used by other agencies was also conducted in order to take advantage of their knowledge" (Freeman et al. 2006).

The results of this investigation supported the ideas that a wide range of crushed materials is well suited for use in levee road maintenance situations (i.e., overlay of new aggregate) and that aggregate grading is critical when building a new levee road directly on top of fine-grained soil.

Freeman et al. (2006) also reported that "There was no indication in this study that the limestone had an advantage over sandstone and igneous aggregates, because of its ability for developing natural cementation between particles over time. The limestone test items did not form any hard crust surfaces and the dynamic cone penetrometer did not detect any increases in strength over time. The limestone, sandstone, and igneous aggregates were all equally capable of maintaining pavement cross-slope."

The U.S. Army Corps of Engineers publication by Freeman et al. (2006) provides results of the study, discusses material requirements for aggregate surfacing materials (unbound aggregate), and compares the specifications of several different agencies, including the Forest Service.

Summary

Several agencies have conducted studies about surface aggregate, but the overall results failed to quantify the cost benefit. However, some benefits of using surface aggregate for the driving surface seem clear. As discussed in the "Benefits of Using Surface Aggregates" section of this guide, using a dense, well-graded surface-course aggregate as a driving surface will lead to lower maintenance cost, longer lasting roads, and reduced sediment pollution. Therefore, long-term evaluation is needed to quantify the cost benefit of using surface aggregate versus base-course aggregate. In addition, most agencies agree that more research is needed to determine the optimum gradation for surface aggregates.

The three major factors that determine desirable surface aggregate characteristics are material quality, material gradation (size distribution), and shape of the larger material. Other factors, such as the amount and plasticity of the fines, moisture, compaction, depth, and placement method, also are important for good aggregate performance when placing surface aggregates on the road.

The authors' recommendation is to require surfacing aggregate where economically feasible to provide a serviceable, maintainable, and long-lasting road surface. Surfacing gradation and plasticity requirements should follow proven local experience, but if this experience is not available, we recommend following the surfacing gradation requirements for grading designations F or G from the FSSS shown in tables 1 and 5. Use the information found in the "Selecting Surface Aggregate" section to fine tune any of the surfacing aggregate requirements in table 5. Lastly, the authors strongly recommend documenting your successes and failures to improve your local experience and to avoid "reinventing the wheel" for future generations of road designers, users, and maintainers.

References

American Association of State Highway and Transportation Officials (AASHTO). 2001. Standard specification for materials for aggregate and soil-aggregate subbase, base, and surface courses. AASHTO M 147. Washington, DC: American Association of State Highway and Transportation Officials.

Bilby, R.E.; Sullivan, K.; Duncan, S.H. 1989. The generation and fate of road-surface sediment in forested watersheds in southwestern Washington. Forest Science. 35(2): 453–468.

Bloser, S.M. 2007. Comparative analysis of commonly used aggregate materials and placement methods for a surface wearing course on low-volume roads in Pennsylvania. University Park, PA: Pennsylvania State University, College of Engineering. 75 p. M.S. thesis.

Bloser, S.; Scheetz, B. 2012. Sediment production from unpaved oil well access roads in the Allegheny National Forest. University Park, PA: Pennsylvania State University, Center for Dirt and Gravel Road Studies. 62 p.

Bloser, S.; Creamer, D.; Napper, C.; Scheetz, B.; Ziegler, T. 2012. Environmentally sensitive maintenance practices for dirt and gravel roads. 1177–1802–SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 126 p.

Bolander, P.; Marocco, D.; Kennedy, R. 1996. Earth and aggregate surfacing design guide for low volume roads. EM–7170–16. Washington, DC: U.S. Department of Agriculture, Forest Service, Engineering. 302 p.

Dawson, A. 2004. Pavements unbound: proceedings of the 6th international symposium on pavements unbound (UNBAR 6), 6–8 July 2004, Nottingham, England. Boca Raton, FL: CRC Press. 378 p.

Ferry, A.G. 1986. Unsealed roads: a manual of repair and maintenance for pavements. R.R.U. Technical Recommendation TR-8. Wellington, New Zealand: Road Research Unit, National Roads Board.

Foltz, R.B.; Truebe, M.A. 1995. Effect of aggregate quality on sediment production from a forest road. In: Low-volume roads 6 proceedings. Washington, DC: Transportation Research Board.

Foltz, R.B.; Truebe, M. 2003. Locally available aggregate and sediment production. In: Low-volume roads 8 proceedings. Washington, DC: Transportation Research Board.

Freeman, R.; Goss, D.; McCaffrey, P.; Tom, J.; Poole, T.; Lee, L.; Taylor, P. 2006. Unbonded aggregate surface roads. ERDC/GSL TR-06-26. Vicksburg, MS: U.S. Army Corp of Engineers, Research and Development Center, Geotechnical and Structures Laboratory. 250 p.

Giummarra, G. 2009. Unsealed roads manual: guidelines to good practice, 2009 ed. Vermont South, Victoria, Australia: Australian Road Research Board (ARRB Group, Ltd.).

Iowa Department of Transportation. 2009. Aggregate gradation table. https://www.iowadot.gov/erl/archives/2009/april/GS/common/english_gradations.htm. (29 July 2022).

Keller, G.; Sherar, J. 2003. Low-volume roads engineering: best management practices field guide. Washington, DC: U.S. Department of Agriculture, Forest Service, Office of International Programs and U.S. Agency for International Development. 158 p.

Keller, G.; Wilson-Musser, S.; Bolander, P.; Barandino, V. 2011. Stabilization and rehabilitation measures for low-volume forest roads. 1177–1801–SDTDC. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center. 333 p.

Légère, G.; Mercier, S. 2004. Material and performance specifications for wearing-course aggregates used in forest roads. Pointe-Claire, QC, Canada: Forest Engineering Research Institute of Canada (FERIC). 8 p.

Maine Department of Transportation. 2018. Roadway gravel in Maine. Augusta, ME: Maine Department of Transportation, Community Services Division. 7 p. https://www.maine.gov/mdot/mlrc/docs/technical/180223MaintainingGravelRoadsSpecs.pdf. (29 July 2022).

National Stone, Sand and Gravel Association. 2013. Aggregates handbook, 2nd ed. Alexandria, VA: Sheridan Books, Inc.

Ohio Department of Transportation. 2005. 2005 construction and materials specifications, 700 aggregate. https://www.dot.state.oh.us/Divisions/ConstructionMgt/OnlineDocs/Specifications/2005CMS/700/703.htm#a_703_18__. (29 July 2022).

Ontario Ministry of Transportation. 1993. Material specification for aggregate—granular A. Ontario Provincial Standard Specification 1010. Toronto, Ontario, Canada: Ontario Ministry of Transportation. 4 p.

Paige-Green, P. 1999. Geological factors affecting performance of unsealed road materials. In: Seventh international conference on low-volume roads, Baton Rouge, Louisiana. Washington, DC: Transportation Research Board: 10–15.

Skorseth, K.; Selim, A. 2000. Gravel roads maintenance and design manual. Washington, DC: U.S. Department of Transportation, Federal Highway Administration and South Dakota Local Transportation Assistance Program (LTAP). (Reprint April 2005, LTAP-02-002). https://www.epa.gov/sites/default/files/2015-10/documents/2003_07_24_nps_gravelroads_gravelroads.pdf. (29 July 2022)

Tyrrell, R.W.W. 2000. Aggregates for forest roads. In: Dawson, A.R., ed. Proceedings of the 5th international symposium on unbound aggregates in road construction (UNBAR 5), Nottingham, United Kingdom. Rotterdam, Netherlands: A.A. Balkema: 335–341.

U.S. Department of Agriculture, Forest Service. 2022. Forest Service supplemental specifications (FSSS) to the standard specifications for construction of roads and bridges on Federal highway projects (FP-14). Washington, DC: U.S. Department of Agriculture, Forest Service.

U.S. Department of Transportation, Federal Highway Administration. 2014. Standard specifications for construction of roads and bridges on Federal highway projects (FP-14). Washington, DC: U.S. Department of Transportation, Federal Highway Administration. 746 p. https://highways.dot.gov/sites/fhwa.dot.gov/files/docs/federal-lands/specs/12851/fp14.pdf. (29 July 2022).

Yoder, E.; Witczak, M. 1975. Principles of pavement design, 2nd ed. New York, NY: John Wiley and Sons, Inc. 736 p.

About the Authors

Peter Bolander (retired) received a bachelor's degree in civil engineering from Michigan State University and a master's degree in soils and foundation engineering from Oregon State University. He began his career with the U.S. Department of Agriculture, Forest Service as a geotechnical engineer on the Willamette National Forest (NF). Bolander served as the assistant regional geotechnical engineer for the Pacific Northwest Regional Office between 1990 and 2000. In 2000, Bolander transferred to the subregional engineering organization based on the Willamette NF as the subregional geotechnical engineer, and he held this position until he retired in September 2016. Peter was a licensed civil engineer in the State of Oregon, a member of the American Society of Civil Engineers, and an affiliate member of the Association of Engineering Geologists.

Vincent L. Barandino, Jr. is a civil engineer at the U.S. Department of Agriculture, Forest Service, National Technology and Development Program, San Dimas, CA. He has a Bachelor of Science degree from University of the East in Manila in civil engineering and completed his Master's Certificate in Project Management at George Washington University. Barandino has 34 years of combined experience in the waterworks and sewerage system, manufacturing operation, and project management. He is certified Lean Six Sigma Black Belt.

Gordon R. Keller is a licensed civil and geotechnical engineer in California. He has a Bachelor of Science degree in civil engineering from University of California, Los Angeles and a Master of Science degree in geotechnical engineering from University of California, Berkeley. He has worked with the U.S. Department of Agriculture, Forest Service for over 40 years and is currently retired but continues working as a private engineering consultant and is involved in international roads training on rural road design and best management practices, storm damage repairs, and environmental impact mitigation.

About NTDP

The U.S. Department of Agriculture, Forest Service, National Technology and Development Program, provides Forest Service employees and partners with practical, science-based solutions to resource management challenges. We evaluate, design, and develop new technologies, products, and systems to solve problems and deliver solutions.

Library Card

Bolander, P.; Barandino Jr., V.; Keller, G. 2022. Guidelines for road surface-course aggregate. Tech. Rep. 2277–1804. San Dimas, CA: U.S. Department of Agriculture, Forest Service, National Technology and Development Program. 25 p.

U.S. Department of Agriculture, Forest Service, National Technology and Development Program staff developed this report to provide guidance and to increase awareness of the benefits—such as the cost-effective selection and use of surface aggregate versus base-course aggregate specifications—for low–volume road aggregate. This report also provides an understanding of the function of surface aggregate when composed of hard, durable aggregate and a well–graded material with adequate fines (material passing the No. 200 sieve) and plasticity to help bind the aggregate-wearing surface together.

Keywords: aggregate, base course, drainage design, low-volume roads, maintenance, road construction, surface course

Contact Information

Contact the National Technology and Development Program (NTDP) for additional technical information:

USDA Forest Service
National Technology and Development Program
Phone: 406–329–3978 or 909–599–1267
Email: wo_mtdc_pubs@usda.gov

Find electronic copies of NTDP documents on the internet at:

Search NTDP:
<https://www.fs.usda.gov/t-d/index.php>

Forest Service and Bureau of Land Management employees can search NTDP documents, CDs, DVDs, and videos on their internal computer networks at:

Search NTDP: <https://fsweb.wo.fs.fed.us/ntdp/>

Produced by
U.S. Department of Agriculture, Forest Service
National Technology and Development Program

2277–1804–NTDP