FABRIC UTILIZATION IN TRANSPORTATION SUPPORT SYSTEMS

(LOW DEFORMATION CRITERIA)

Metz Reference Room
civil engineering department
E106 C. E. building
university of illinois
urbana, illinois 61801

M. R. Thompson
L. Raad

A report of the investigation of
the behavior of soil-fabric-aggregate systems

conducted by
DEPARTMENT OF CIVIL ENGINEERING
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EXECUTIVE SUMMARY

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by

M. R. Thompson, - L. Raad
Department of Civil Engineering
University of Illinois
at Urbana-Champaign
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The feasibility of using fabrics in the construction and/or rehabilitation of conventional transportation support systems such as secondary roads, track beds, etc., was considered. "Separation" and "structural improvement" concepts were analyzed.

Relevant current technical literature was reviewed and summarized. Several theoretical behavior models (ILLI-PAVE, LSTRN3, BISAR, and a simplified confinement model) were utilized in the structural analyses of soil-fabric-aggregate (SFA) systems.

Many beneficial effects can be achieved through the "separation" fabric function. Basically subgrade intrusion is prevented and the adverse effects of increased fines content on pertinent engineering properties (shear strength, resilient modulus, permanent deformation, moisture sensitivity, permeability, frost-action behavior, ballast pumping) of the aggregate layer are therefore not experienced. In addition, aggregate quantity and/or layer thickness are not decreased since the fabric prevents aggregate/subgrade intermixing.

Structural improvement effects, as evidenced by ILLI-PAVE calculated vertical stress distributions and vertical deflections in a conventional SFA system, are not achieved, thus confirming previous experimental data. However, BISAR structural analyses of a typical SFA system indicated the
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INTRODUCTION

Laboratory studies and field performance data have shown that soil-fabric-aggregate (SFA) systems are effective for "soft soil" (large rut-depth development) applications. Equivalent performance (SFA - conventional aggregate layer construction) can be achieved with a reduced aggregate thickness if a fabric is installed at the soil-aggregate interface.

The success of SFA systems for soft soil applications has led to the development of increasing interest in the potential of fabric utilization in conventional transporation support systems (railroads, highway pavements, airfield pavements). The major difference between conventional transporation support and SFA systems constructed over soft soils is the magnitude of tolerable levels of rut development and surface deflection. Permissible levels of rutting and resilient deflection for conventional transportation support systems are on the order of 1.5 inches and 0.500 inches, respectively. Rut depths on the order of 3 to 5 inches and resilient deflections in excess of 1 inch are commonly incurred in SFA systems on soft soils.

The primary purpose of this investigation was to determine the feasibility of using fabrics in the construction and/or rehabilitation of conventional transportation support systems such as primary and secondary roads and trackbeds.

FABRIC FUNCTIONS

The major fabric functions in transportation support systems are "separation" and "structural improvement."
Separation effects are well documented. In many cases the aggregate savings resulting from the prevention of aggregate-subgrade intermixing offset the fabric cost. U.S. Forest Service experience (1, 2) with minimum thickness granular flexible pavements and heavy logging type traffic indicates that the aggregate-subgrade intermixing may result in 4-8 inches of base contamination with subgrade fines.

The influence of fabric on the structural behavior and performance of "low deformation" (SFA) systems is not well established. Potential mechanisms of improvement are tensile reinforcement and improvement of the "slippage" conditions at the aggregate-soil interface.

FABRIC SEPARATION EFFECTS

Separation (prevention of soil and aggregate intermixing) has many beneficial effects. Increased fines content in the aggregate layer generally detrimentally influences important engineering properties of the aggregate.

Figure 1 demonstrates the various physical states of aggregate systems. Ballast gradations generally have "no fines" (3). Subballast gradations are "well graded" and have increased fines content. Typical ballast and subballast gradations are shown in Tables 1, 2, 3 and 4. "Dense graded" aggregate base and subbase materials for highway and airfield pavement construction generally are well graded and may contain significant quantities of fines as shown in Table 4. The properties and behavior of aggregate systems are significantly influenced by the amount of fines. With the accumulation of increased fines in an aggregate material, the behavior and performance of the aggregate layer may be significantly modified. The desirability of minimizing fines accumulation is apparent.
SHEAR STRENGTH

The shear strength of open graded aggregate systems containing no fines is developed through frictional resistance among the particles and aggregate interlock effects. The material does not possess cohesion and thus, as indicated in Figure 2, stability is controlled by the degree of confinement (4). As the fines content increases, cohesion may develop; and when the fines content becomes excessive (coarse aggregates are physically separated), the shear strength is decreased. Note in Figure 3 that shear strength initially increases with higher fines content, then decreases as fines content is further increased (4).

Huang et al. (5) studied the influence of geometric properties (shape, angularity, surface texture) on the shear strength of graded aggregates. The study showed that with increased fines content shear strength was reduced and the effects of geometric properties of the coarse aggregate fraction were less significant because the fines "separated" the coarse aggregate particles.

If the accumulated fines are plastic, the plasticity index of the fines in the aggregate system will be increased. Figure 4 demonstrates the adverse effect of PI increase on the shear strength of a well graded crushed stone aggregate (maximum size of 1.5 inches) (4).

RESILIENT MODULUS

The effect of the amount and plasticity of fines on the resilient behavior of aggregates has been researched by Hicks and Monismith (6) and by Barksdale (7). It should be noted that in any study of the effects on elastic behavior of fines, the degree of saturation of the material should be considered simultaneously because, for example, the strength of air dry clay samples is often extremely high.
Hicks and Monismith (6) observed increases in the resilient modulus of granular materials as the fines content decreased and as the degree of saturation decreased. Barksdale (7) tested blends of soil-aggregate in triaxial apparatus and concluded that the resilient modulus decreased as the percent fines and the degree of saturation increased.

Typical plots of resilient modulus versus repeated stress for fine-grained soils are shown in Figure 5, and a similar plot for ballast is shown in Figure 6. It is reasonable to assume that the resilient response of the "soil-aggregate mixture" will decrease if the granular material is permitted to mix with the fine-grained subgrade soil. Figure 7 illustrates the effects of "cleaning" on the resilient behavior of a ballast material.

PLASTIC DEFORMATION

Kalcheff (8) considered the effects of quantity and type of fines on the repeated load plastic strain behavior of aggregates. He concluded that the plastic strain increases as the amount of fines increases and that higher plastic strain occurs if the fines are plastic than non-plastic. Typical results are shown in Figure 8.

Barksdale (7) on the basis of triaxial testing concluded that "rutting" in aggregate base courses increases as the percentage of fines and the plasticity of the fines increase.

Both the Kalcheff (8) and Barksdale (7) studies show that resistance to plastic strain accumulation decreases as the degree of saturation increases. An increase in amount of fines increases the tendency for degree of saturation to be higher and results in decreased resistance to plastic strain accumulation.
Repeated triaxial loading studies of the permanent deformation behavior of "dirty" and "cleaned" ballast obtained from a track structure demonstrated (see Figure 9) the detrimental effects of increased fines.

**MOISTURE SENSITIVITY**

Moisture sensitivity (change in strength and stiffness properties effected by a moisture change) is increased if excess plastic fines accumulate in the aggregate. Granular materials with limited amounts of low plasticity fines (as shown in Figure 1) are fairly "insensitive" to moisture content changes. If the granular material contains excess plastic fines (as shown in Figure 1), the moisture sensitivity of the material is greatly increased.

**PERMEABILITY**

Figures 10 and 11 show the general range of coefficients of permeability for several different material gradations (9, 10). The permeability of an open graded aggregate is quite high. The presence of a limited quantity of fines drastically reduces the permeability. Well graded aggregate systems with fines are nearly impervious. If "free drainage" is an important function of the aggregate layer, fines content increases must be minimized if adequate levels of permeability are to be maintained.

**FROST ACTION**

For a material to be susceptible to frost action damage, three conditions must be present: frost susceptible soils, freezing temperatures, and a source of moisture. Typical aggregate layer applications in transportation support systems frequently meet the freezing temperature and moisture availability criteria. Thus, the criteria for identifying frost susceptible soils are of great significance.
The Corps of Engineers (11) considers any soil containing 3 percent or more material finer than 0.02 mm to be potentially frost susceptible. However, some allowances are made for gradation. For example, Corps criteria (11) indicate that uniform sandy soils can contain as much as 10 percent finer than 0.02 mm without being frost susceptible.

The rate of frost heave in soils cannot be linked directly to grain size. Although the height that moisture rises due to capillary action is inversely related to the grain size, the rate at which the water rises is directly related to the size of the soil pores and hence to the grain size. Therefore there exists an "optimum" condition for water to migrate to the ice lens area before it is frozen. Silt size materials generally provide that optimum condition. Figure 12 shows the heave rate of various categories of soils and also the percentages of each finer than 0.02 mm.

BALLAST PUMPING

Ballast pumping in track support systems may occur if excess fines accumulate in the ballast, the moisture content is excessive, and heavy repeated loading is experienced. Although pumping mechanisms are not well established, if ballast fines accumulation is prevented (either from subgrade intrusion, surface contamination or infiltration, or ballast degradation), pumping can be alleviated or prevented.

A recent report (13) on the FAST program (through 150-MGT of Traffic) indicated "extensive migration of subgrade fines into the ballast." It is important to note that the FAST subgrade is a nonplastic sand classified as SP in the United System. The 6-inch subballast at FAST is a local sandy-gravel material. Although sandy subgrades are not normally considered to be susceptible to "intermixing" and/or "intrusion," apparently the extensive and
heavy FAST loading was sufficient to "trigger" considerable intermixing and/or intrusion of the ballast, subballast, and subgrade.

The beneficial effects of fabric separation in preventing subgrade intrusion and/or ballast/subgrade intermixing are apparent.

SUMMARY

Many engineering properties of granular materials are adversely affected by an increase in fines content. Shear strength, permeability, resilient moduli, plastic deformation response, frost action potential, and ballast pumping properties are generally detrimentally influenced if fines contents accumulate in excess of those in the granular material originally placed.

It is apparent that the positive aggregate-soil separation that can be obtained with Mirafi fabric should have a significant beneficial effect on conventional transportation support system behavior and performance.

It is important to note that positive aggregate-soil separation can be affected by a fabric regardless (within limits) of the deformation (high or low) experienced by the fabric.

STRUCTURAL IMPROVEMENT EFFECTS

BEHAVIOR ANALYSIS

Fabrics are quite thin and exhibit resistance to applied tensile forces but little resistance to compressive forces. To simulate this structural behavior, the fabric should be treated as an element that can carry tension but no compression.
Fabric stiffness is defined as the force required to produce a unit displacement. If the given fabric is replaced by a transformed section of the same stiffness, the modulus of the transformed section is given by:

\[ E_E = \frac{E_F T_F}{T_E} \]

where \( E_F, T_F \) = modulus and thickness of original fabric

\( E_E, T_E \) = modulus and thickness of the transformed section

\( E_S \) = subgrade modulus

The transformed section concept was used to demonstrate how the responses of a soil-fabric system is affected if the original fabric is replaced by an "equivalent" transformed section. An elastic based finite element computer model, LSTRN 3, (14) incorporating "truss type elements" (elements can carry tension but not compression) was utilized. The responses summarized in Figure 13, which are expressed in terms of lateral strains \( (\varepsilon_t, \varepsilon_{t0}) \) in the fabric, vertical subgrade stresses \( (\sigma_V, \sigma_{V0}) \) and strains \( (\varepsilon_V, \varepsilon_{V0}) \), and surface deflections \( (\Delta, \Delta_0) \), are not affected if the transformed section has a thickness not exceeding 12 times the thickness of the original fabric.

\( \varepsilon_t, \sigma_V, \varepsilon_V, \) and \( \Delta \) are "transformed section" responses and \( \varepsilon_{t0}, \sigma_{V0}, \varepsilon_{V0}, \) and \( \Delta_0 \) are responses for the original section.

The transformed section concept was used in available nonlinear finite element (ILLI-PAVE) and linear elastic (BISAR) programs to analyze SFA systems.

RESILIENT BEHAVIOR CONSIDERATIONS

The potential effect of a fabric layer on a SFA system was considered by using ILLI-PAVE (a stress dependent finite element model developed at the
University of Illinois). A typical low traffic volume road section (8 inches of crushed stone) and a very soft subgrade were assumed. The very soft subgrade condition accents any beneficial effects of the fabric (increased fabric tensile forces are developed at high deflections). ILLI-PAVE assumes "full friction" (no slip) at all material interfaces. MIRAFI 500X properties (modulus = 30 lbs/%, Poisson's ratio = 0.2) were used. Subgrade and granular resilient properties are shown in Figure 14. Subgrade shear strength (cohesion) was 3 psi. A $\phi$ angle of 40° was assumed for the granular material. Pavement loading was a 9K wheel load and 80-psi tire pressure.

Figures 15, 16, and 17 show pertinent structural responses for the sections with and without fabric. Note:

1) There is no fabric effect on vertical stress distribution.
2) There is no fabric effect on the deflection pattern.
3) There is no fabric effect on the failure zones.

Previous experimental studies (15, 16, 17) and data from this study have demonstrated that the "resilient" behavior of SFA systems is not significantly influenced by the presence of a fabric. The ILLI-PAVE data confirm that finding. It is important to note that the surface deflection of the pavement was only 0.070 inch. Such a small deflection is not sufficient to "mobilize" the fabric "tensile reinforcement" effect. However, most transportation support systems will not display large resilient deformations except in special cases such as "spring thaw" or other situations where the subgrade is weakened.

SLIPPAGE CONSIDERATIONS

The BISAR elastic layered program can accommodate "slippage" between layers. The 8-inch crushed stone-fabric section was analyzed for "no
slippage" and "complete slippage." Comparative deflection data for the two conditions are shown in Figure 18.

Slippage at the interface between the granular base and subgrade increases the resilient deformations of the pavement which would hasten its rate of deterioration. Use of fabric at the interface should reduce the slippage effect and therefore improve performance. Reduction of resilient deflections is most pronounced in the subgrade and could be as much as 30%.

Barenberg's "shear layer" theory (18) also indicates an improvement in "load carrying capability" if aggregate-soil interface shear strength is increased. Field studies (19, 20, 21, 22) of granular layer behavior in pavements and railroads have also demonstrated the tremendous impact of "interface" conditions on granular layer performance (primarily rutting and shoving).

It is apparent that the improved interface condition afforded by the fabric layer will contribute to improved performance of SFA systems.

INCREASED CONFINEMENT CONSIDERATIONS

As the SFA system deforms, increased lateral confining pressures develop due to the horizontal component of the normal stresses at the fabric-subgrade interface. If the fabric-subgrade interface is "level," no horizontal component of the normal stress is mobilized.

Assume that the aggregate layer is incompressible and the deformed shape of the fabric is approximated by a circular arc as shown in Figure 19. Ignore the confining effect of shear stresses and tensile stresses in the fabric (they act in opposite directions). It thus can be demonstrated that:

\[ \Delta \sigma / \sigma = \frac{P_0(r)}{K_s K_0 h (h + r)} (1 + \alpha) \]
where

\[ \alpha = \frac{\Delta_p}{\Delta_r} \]

\( P_o \) = applied surface pressure

\( r \) = radius of loaded area

\( K_s \) = modulus of subgrade reaction

\( k_o \) = coefficient of earth pressure at rest

\( h \) = thickness of granular layer

\( \frac{\Delta \sigma}{\sigma} \) = increase in confinement at interface due to deformation of fabric, expressed in terms of original confinement \( (\sigma) \) before fabric deforms

\( \Delta_p \) = permanent deformation

\( \Delta_r \) = resilient deformation

**Example**

For \( K_s = 50 \text{ psi/in.} \) \( P_o = 80 \text{ psi} \)

\( h = 6 \text{ in.} \) \( k_o = 0.5 \)

\( r = 6 \text{ in.} \)

\[ \frac{\Delta \sigma}{\sigma} = 0.27 (1 + \alpha) \]

For \( K_s = 150 \text{ psi/in.} \)

\[ \frac{\Delta \sigma}{\sigma} = 0.09 (1 + \alpha) \]
\( \Delta \sigma / \sigma \) relations for \( K_s = 50 \) psi/in. and 150 psi/in. and varying \( \alpha \) values are shown in Figure 20. Note that \( \Delta \sigma / \sigma \) improvements on the order of 80% are realized for soft subgrade conditions and \( \alpha \) values (\( \Delta p / \Delta r \)) of approximately 2. It is apparent that the increased confinement effects are accentuated for the soft subgrade condition.

Small increases in confining pressure significantly improve the shear strength, stiffness, and permanent deformation behavior of granular materials. The improved characteristics of the granular material should contribute to better SFA system performance.

PERFORMANCE CONSIDERATIONS

Fabric separation effects contribute to improved performance by preventing aggregate-soil intermixing. Significant engineering properties of the aggregate and aggregate layer thickness are thus maintained throughout the service life of the transportation support system.

Although the resilient deflection of a transportation support system may not be decreased by introduction of fabric at the interface between the granular layer and subgrade, performance is significantly improved (16, 17). Figures 21 and 22 demonstrate that even though granular materials and fine-grained soils may be accumulating significant permanent deformation, resilient behavior does not markedly change. Thus, even though rutting is developing rapidly, the resilient (recoverable) surface deflection does not correspondingly increase.

The "confinement" analysis indicates that increased granular layer confinement can be developed in the SFA system. Even though the increased confinement is small, the increase does contribute to the development of
improved shear strength and stiffness of the granular material. Aggregate-soil interface conditions are also improved by the fabric and should contribute to the achievement of improved performance.

If substantial permanent deformation develops in the SFA system, tensile reinforcement similar to that developed in soft soil systems are mobilized and would therefore prevent SFA system failure.

Field performance data for low deformation SFA systems are limited. A recent WES (Waterways Experiment Station) study (23) indicated that a low deformation SFA system (6 inches crushed stone, T-16 membrane, CBR = 3 subgrade) provided the equivalent performance (based on a 3-inch rut depth criteria) of approximately 14.5 inches of crushed stone. Earlier WES studies for "soft soil" conditions indicated the improved performance of SFA systems with high modulus fabric (24).

GENERAL CONCEPTS--FABRIC UTILIZATION IN TRANSPORTATION SUPPORT SYSTEMS

SFA BEHAVIOR MECHANISMS

Fabric separation and structural improvement functions are both important in transportation support system applications.

The separation function is effective throughout the service life of the installation. Adequate separation maintains desirable engineering properties and thickness of the aggregate layer.

To mobilize the fabric structural improvement function, significant rutting is required to develop fabric tensile reinforcement effects. During most of the year, subgrade support is adequate and little structural improvement is achieved. In seasonal periods of high water tables, frost action, and cyclic freeze-thaw, subgrade support may be greatly reduced as illustrated in
Figure 23. "Thawed" CBR values may drop to <1 (25), and $E_R$ values are decreased as shown in Figure 24 (27). Permanent deformations also accumulate more rapidly after freeze-thaw action or at higher water contents as shown in Figures 25 and 26.

During the "weak" subgrade support period the SFA system will experience "rutting." With the development of significant rutting, the SFA system should "stabilize." High modulus fabric is desirable for stabilizing the SFA system without experiencing extremely large permanent deformations (ruts). The presence of fabric enables the SFA system to stabilize without loss of aggregate due to "aggregate-subgrade" intermixing.

If the fabric does not "creep," the SFA system should be "stable" for subsequent weak subgrade support conditions (following spring, etc.). If the fabric creeps following the period of weak subgrade support, some additional rutting may develop during subsequent weak periods before the SFA system again stabilizes.

**STAGE CONSTRUCTION**

The behavior and performance described in the preceding section indicate the validity of a "stage construction" concept for SFA systems. The concept can be used for low traffic volume roads and track systems. The SFA system for low traffic volume roads is not immediately surfaced.

Following the first period of weak subgrade support and after rut development has stabilized, the SFA system surface is graded (with or without the addition of aggregate) and smoothness is restored. The SFA system is then "surfaced" (probably with a surface treatment). If necessary, the SFA system could be initially surfaced and then resurfaced following the period of rut depth development.
A similar approach is possible for track system applications. Following initial permanent deformation development in the ballast-subgrade system, the track could be resurfaced thus restoring a desirable level of track geometry. Subsequent development of permanent deformation would be minimized because of the structural improvement affected by the fabric.

The staged construction procedure permits the utilization of the full potential of the fabric (separation and structural improvement). It is important to note that to maximize structural improvement effects it is necessary to develop significant permanent deformation in the fabric.

If the fabric was stretched during installation to produce tension in the fabric prior to the placement of the aggregate layers, then released following aggregate placement, the "fabric prestress" would contribute to structural improvement effects without the development of significant permanent deformation in the system. Prestressing concepts are currently being evaluated.

THICKNESS DESIGN CONSIDERATIONS

The current technology for designing unsurfaced transportation support systems (low traffic volume roads, track systems) is not refined. In fact, "experience based and rule of thumb" procedures are generally used. Such systems are normally maintained periodically to provide the required degree of surface smoothness.

Since it is not possible to precisely determine aggregate thickness requirements for unsurfaced transportation support systems, it is not feasible (based on current technology and data) to establish a "thickness reduction factor" for the SFA system. However, as indicated earlier in this report, for equivalent aggregate layer thickness, the SFA system should provide improved performance.
SUMMARY

The combined effects of "separation" and "structural improvement" should in many cases justify the use of fabric in some transportation support systems. Major applications are probably in "unsurfaced" or "surface treatment" type SFA installations (low traffic volume roads, railroads, etc.).

FABRIC REQUIREMENTS

The fabric must initially possess and satisfactorily retain throughout the service life of the installation those essential properties required for the fabric to fulfill its functions. Separation and structural improvement functions are important in transportation support system applications.

Separation can be achieved only if the fabric remains intact, retains its engineering properties, and does not puncture excessively. Thus, resistance to environmental factors (temperature, moisture, pH, etc.) and high abrasion and puncture resistance are absolutely essential.

If structural improvement effects are mobilized, a high modulus fabric is desirable. This is particularly important in transportation support system applications since the tolerable "rut depths" are less than those associated with "soft soil" applications. Fabric repeated load and creep behaviors are also important properties related to the depth of rut development and the ability of the fabric to retain those forces developed during the rut development process.
SUMMARY

The feasibility of using fabrics in the construction and/or rehabilitation of conventional transportation support systems was considered. Separation and structural improvement concepts were analyzed.

Many beneficial effects can be achieved through the separation fabric function. Basically subgrade intrusion is prevented and the adverse effects of increased fines content on pertinent engineering properties of the aggregate layer are therefore not experienced. In addition, aggregate quantity and/or layer thickness are not decreased since the fabric prevents aggregate/subgrade intermixing.

Structural improvement effects, as evidenced by ILLI-PAVE calculated vertical stress distributions and vertical deflections in a conventional SFA system, are not achieved, thus confirming previous experimental data. BISAR structural analyses of a typical SFA system indicated the beneficial effects of "no slippage" conditions at the aggregate-subgrade interface (it is postulated that fabric will decrease "slippage" at the interface).

A simplified "Confinement Model" indicated that if significant permanent deformation is developed in an SFA system, a substantial percentage increase in confinement can be developed. This effect is most pronounced for "soft" subgrade conditions.

Several references are cited demonstrating that SFA systems should exhibit better performance than an equal aggregate layer thickness without fabric. Of particular importance to SFA system performance is the "stabilizing" effect (additional permanent deformation does not accumulate with further loading) that can be mobilized during periods of reduced subgrade support.
Fabric to be utilized in conventional transportation support systems should have a high resistance to degradation in various environments (temperature, moisture, pH, etc.). Abrasion and puncture resistance are absolutely essential. A high modulus fabric with good resistance to fatigue and creep are desirable.

There are many situations where fabric can be beneficially utilized in transportation support system construction and/or rehabilitation. The most promising applications are unsurfaced aggregate layers (low traffic volume roads, track systems). It was postulated in this report that a stage construction procedure (surface treatment of an aggregate road following the initial period of "reduced subgrade support") would be feasible for low traffic volume roads. The stage construction concept also can be applied to track system problems.
REFERENCES


REFERENCES (Continued)


<table>
<thead>
<tr>
<th>Size No.</th>
<th>Nominal Size Square Opening (in.)</th>
<th>Amounts Finer Than Each Sieve (Square Opening)</th>
<th>Percent by Weight</th>
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<td></td>
<td>3 in.</td>
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<td>1 - 3/8</td>
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(1 in. = 2.54 cm)
Table 2. AREA Gradations for Gravel Ballast

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<tr>
<th>Size No.</th>
<th>Percent Crushed Particles</th>
<th>1-1/2 in.</th>
<th>1 in.</th>
<th>1/2 in.</th>
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<th>No. 8</th>
<th>No. 16</th>
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(1 in. = 2.54 cm)

Table 3. AREA Specifications for Pit-Run Gravel Ballast

<table>
<thead>
<tr>
<th>Sieve Size (Square Openings)</th>
<th>Amounts Finer Than Each Sieve Percent by Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Grade A</td>
</tr>
<tr>
<td>2 1/2 in. (6.35 cm)</td>
<td>97-100</td>
</tr>
<tr>
<td>No. 4</td>
<td>20-55</td>
</tr>
<tr>
<td>No. 200</td>
<td>0-2</td>
</tr>
</tbody>
</table>
Table 4. ASTM D1241 Specifications (Subballast-Base-Subbase)

<table>
<thead>
<tr>
<th>Sieve Size (Square Openings)</th>
<th>Weight Percent Passing Square Mesh Sieves</th>
<th></th>
<th></th>
<th>Type I</th>
<th></th>
<th></th>
<th>Type II</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gradation A</td>
<td>Gradation B</td>
<td>Gradation C</td>
<td>Gradation D</td>
<td>Gradation E</td>
<td>Gradation F</td>
<td>Gradation E</td>
<td>Gradation F</td>
<td></td>
</tr>
<tr>
<td>2 in. (50 mm)</td>
<td>100</td>
<td>100</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 in. (25.0 mm)</td>
<td>...</td>
<td>75 to 95</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3/8 in. (9.5 mm)</td>
<td>30 to 65</td>
<td>40 to 75</td>
<td>50 to 85</td>
<td>60 to 100</td>
<td>...</td>
<td>...</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 4 (4.75 mm)</td>
<td>25 to 55</td>
<td>30 to 60</td>
<td>35 to 65</td>
<td>50 to 85</td>
<td>55 to 100</td>
<td>70 to 100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 10 (2.00 mm)</td>
<td>15 to 40</td>
<td>20 to 45</td>
<td>25 to 50</td>
<td>40 to 70</td>
<td>40 to 100</td>
<td>55 to 100</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 40 (425 µm)</td>
<td>8 to 20</td>
<td>15 to 30</td>
<td>15 to 30</td>
<td>25 to 45</td>
<td>20 to 50</td>
<td>30 to 70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No. 200 (75 µm)</td>
<td>2 to 8</td>
<td>5 to 15</td>
<td>5 to 15</td>
<td>8 to 15</td>
<td>6 to 15</td>
<td>8 to 15</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Specifications are ASTM D1241.
Figure 1. Physical States of Aggregate Systems (Ref. 3).
Figure 2. Effect of Lateral Confinement on the Shear Strength of Crushed Stone with Varying Maximum Size ($n = 1/2$), (Ref. 4).

Figure 3. Effect of Fines (-#200) on the Shear Strength of a Crushed Limestone (max. size = 3/4 inch), (Ref. 4).
Figure 4. Effect of PI (Plasticity Index) on the Shear Strength of a Crushed Limestone (max. size = 1-1/2 inches, n = 1/3), (Ref. 4).
Figure 5. Resilient Response Data for Stiff, Average (Medium), and Soft Subgrade Soils.
Figure 6. Resilient Modulus - $\theta$ Relation for No. 4 Crushed Stone Ballast.
Gradation Data

<table>
<thead>
<tr>
<th>Sieve</th>
<th>Dirty</th>
<th>Cleaned</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 1/2&quot;</td>
<td>90.0</td>
<td>82.2</td>
</tr>
<tr>
<td>1&quot;</td>
<td>60.6</td>
<td>29.8</td>
</tr>
<tr>
<td>3/4&quot;</td>
<td>43.9</td>
<td>—</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>29.1</td>
<td>—</td>
</tr>
<tr>
<td>#4</td>
<td>15.9</td>
<td>—</td>
</tr>
</tbody>
</table>

\[
E_R = 3550 \cdot \theta^{0.71}
\]

\[
E_R = 4032 \cdot \theta^{0.64}
\]

Figure 7. Influence of Cleaning on the Resilient Modulus (\(E_R\)) of Ballast.
Figure 8. Effect of Quantity of Fines on the Plastic Strain Behavior of Two Dense-Graded Crushed Stones (Ref. 8).
Figure 9. Effect of Cleaning on the Permanent Deformation Behavior of Ballast.

*Note: Gradation Data Shown in Figure 7.
Figure 10. Typical Gradation - Permeability Relations (Ref. 9).

Figure 11. Estimating Coefficient of Permeability of Narrow Size-Ranged Aggregates with No Fines (Ref. 10).

Note: This chart applies only to aggregates having narrow ranges in particle sizes - D85 < 40, 15 and no fines.
Figure 12. Effect of Gradation on Heave Rate (Corps of Engineers, Standard Laboratory Test) (Ref. 12).
Figure 13. Transformed Section Responses.
Figure 14. Resilient Properties of Subgrade and Granular Materials.
Figure 15. Fabric Effect on Vertical Stress Distribution (ILLI-PAVE Model).
Figure 16. Fabric Effect on Vertical Deflections (ILLI-PAVE Model).
Tire Pressure = 80 psi

Figure 17. Fabric Effect on Failure Zones (ILLI-PAVE MODEL).
Figure 18. Effect of "Slippage" on Vertical Deformations (BISAR Model).
\[ \Delta_T = \text{Total Deformation} = \Delta_p + \Delta_r \]
\[ \Delta_p = \text{Permanent Deformation} \]
\[ \Delta_r = \text{Resilient Deformation} \]

Figure 19. Increased Confinement Effect Model.
Figure 20. Increase in Confinement for SFA Systems.
Fig. 21. Deformations of Crushed Stone under Repeated Loads (1 psi = 6.9 kN/m$^2$; 1 lb/cu ft = 16.0 kg/m$^3$).
Fig. 22. Deformations of Muscatine (B) and Fayette (C) under Repeated Loads.
Figure 23. Seasonal Changes in Bearing Capacity (Ref. 26).
Figure 24. Influence of Cyclic Freeze-Thaw on the Resilient Behavior of a Fine-Grained Soil [AASHTO A-7-6(27)] (Ref. 27).
Figure 25. Effect of Stress Level ($\sigma$) and Cyclic Freeze-Thaw (F-T) on Permanent Strain Response of Drummer B [AASHTO A-7-6-(28)] Compacted to 95% AASHTO T-99 Density at a Water Content of Optimum +4 Percent (Ref. 27).
Figure 26. Influence of Moisture Content on the Permanent Strain Response of a Loess-Derived Soil. [AASHTO A-7-6 (23)].