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INCREASED SINGLE-LIFT THICKNESS FOR UNBOUND AGGREGATE BASE COURSES

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16. Abstract: A study was conducted to evaluate the feasibility of compacting unbound aggregate base courses in thicker lifts than currently permitted by state departments of transportation (DOTs). At present, the majority of states allow a maximum lift thickness of 8 inches or less. This project constructed and tested full-scale test sections using a variety of material types. Two test pads were constructed in an aggregate quarry in Texas utilizing crushed limestone. Three crushed granite test sections were built as part of a road widening project in Georgia, and two test pads were constructed of uncrushed and partially crushed gravel with loess fines at a gravel production facility near Memphis, Tennessee. Single-lift thicknesses varied from 6 inches to 21 inches. Moisture contents and densities were evaluated using the Nuclear Density Gauge (NDG). Nondestructive seismic testing, using the Spectral-Analysis-of-Surface-Waves (SASW) technique, was used to evaluate stiffness profiles within the compacted lifts. Cyclic plate load tests were accomplished by means of the Rolling Dynamic Deflectometer (RDD), modified for this static application. Results showed that compaction targets could be attained for lifts up to 21 inches thick. Density and stiffness results for 13-inch thick lifts in the Georgia tests were equal to, or better than, the results for the base placed in two lifts, a 7-inch lift followed by a 6-inch lift.

Higher moisture contents during compaction yielded lower shear wave velocity and Young's modulus values. Seismic results show that the upper 3 inches of the final test pads had lower stiffness values, presumably from lower effective stresses near the surface and possibly from some disturbance caused by the compaction equipment. This zone of lower stiffness and slightly less compaction is less evident in the density measurements.

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DISCLAIMER

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INTRODUCTION

State departments of transportation (DOT's) have used aggregate base courses for many years as an integral structural component of pavements. Specifications prescribe requirements for placement and compaction of aggregate bases in addition to quality requirements for the aggregates. Typically, specifications also limit the lift thickness of unbound aggregate bases. While advances have been made with regard to the capabilities of compaction equipment, lift thickness limits have generally remained unchanged, and this has raised the question of whether these specifications are too restrictive. To address this question, the International Center for Aggregate Research (ICAR) has conducted a study to investigate the results of compacting unbound aggregate base courses in lifts with thicknesses greater than those presently allowed by state DOT's.

BACKGROUND

A survey of all state departments of transportation was conducted concerning their requirements for placing and compacting unbound aggregate base courses. Analysis of the 36 responses showed that 12 states allow a maximum lift thickness of 6 inches or less, one state allows 7-inch lifts, and 16 states allow 8-inch lifts. Three states allow thicker lifts (Washington-9 inches, North Carolina-10 inches, Maine-12 inches). The other four respondents either do not use unbound aggregate bases or do not specify lift thicknesses. Recent evidence from two studies (Brignoli, 1996 and Wells, 1996) has shown that maximum lift thicknesses of 8 inches and less are too restrictive, and an excellent constructed product can be obtained with increased single-lift thicknesses; in particular, thicknesses from 10 to 16 inches have been successfully placed. Furthermore, it is believed that allowing the compaction of thicker lifts could result in considerable savings in time and money on future projects.

Based on this information, a research project (No. ICAR – 501) was undertaken to evaluate the feasibility of compacting unbound aggregate base courses in thicker lifts than currently permitted by the state DOT's. This project consisted of constructing and testing full-scale test sections of unbound graded aggregate base courses (Bueno et al., 1998). Two test pads were constructed in an aggregate quarry in Texas, three test sections were constructed as part of a road-widening project in Georgia, and two test pads were constructed at a gravel production site near Memphis, Tennessee. Moisture contents and densities of the graded aggregate base courses were evaluated using the conventional Nuclear Density Gage (NDG). In addition, nondestructive seismic testing by the Spectral-Analysis-of-Surface-Waves (SASW) method was employed to evaluate the stiffness of the compacted lifts. The nonintrusive nature of SASW testing makes it well suited for such an application. To obtain a more complete characterization of the compacted thick lifts, the relationship between the seismically determined stiffness of one of the Texas test pads and the displacements induced in the material under working load stresses was also investigated. Cyclic plate load tests with a variety of load magnitudes were applied by means of the Rolling Dynamic Deflectometer (RDD), modified for this static application. The RDD is a vibroseis truck which applies continuous rolling dynamic loads to a pavement while deflections are measured by rolling sensors. The load magnitude and frequency of loading can be varied through wide ranges.

TYPES OF MATERIALS TESTED

The Georgia test was part of a study conducted by the Georgia DOT, Georgia Crushed Stone Association, C.W. Matthews Construction Co., Vulcan Materials, and ICAR. The project, located on Georgia Highway 92 in Cherokee County, placed 13-inch single lifts of dense-graded crushed granite on two different sections. For one section, the material was soaked using a water truck and mixed with a motor grader. The material for the other section was delivered to the site at the desired moisture content and compacted without additional water. For comparison, a target strip was constructed with two lifts, a 7-inch layer followed by a 6-inch layer.

Capitol Aggregates, Ltd. donated dense-graded crushed limestone and a work site at their quarry near Georgetown, Texas. Ingersoll-Rand vibratory sheepsfoot and vibratory smooth drum rollers were provided by ROMCO Equipment Company of Austin, Texas, and Anderson Machinery Company of Austin provided Hypac compactors (vibratory sheepsfoot and vibratory smooth drum). Lifts of 12 and 21 inches were constructed, and the effects of moisture were evaluated.

The Memphis Stone and Gravel Company provided the test site, equipment, and material for the tests near Memphis, Tennessee. The Nuclear Density Gauge was provided by Troxler, Inc. Gap-graded uncrushed and partially crushed gravels with loess fines were placed in 12 and 14.5-inch lifts.

SPECTRAL-ANALYSIS-OF-SURFACE-WAVES (SASW) TESTING

Seismic testing was performed using the Spectral-Analysis-of-Surface-Waves (SASW) technique. This seismic technique is well suited for evaluating stiffness profiles of road bases because the test is both nondestructive and nonintrusive. The nondestructive nature of the test arises from the fact that all measurements are performed at small strains (strains less than 0.001%). As a result, the stiffness evaluations represent moduli values which are independent of strain level at these small strains. The test consists of measuring the propagation velocity of surface waves of the Rayleigh type, generating an experimental dispersion curve (wave velocity versus frequency) with this information, and evaluating a shear wave velocity profile (hence a shear modulus profile) by matching a theoretical dispersion curve with the experimental (field) curve (Nazarian et al., 1987, Rix and Stokoe, 1990). Surface wave energy is excited by vertical hammer impacts, and vertical surface motions are measured at various distances from the source. Fourier transforms are performed on the recorded time records of the two vertical receivers from which the phase difference relationship between receivers is evaluated using the cross power spectrum. This testing procedure is repeated for several receiver spacings. (Typically, receiver spacings ranging from 6 inches to 4 feet were used in testing the base courses.) The resulting phase spectra are used to construct a dispersion curve, a plot of phase velocity versus wavelength. An iterative inversion process is then performed to match the field dispersion curve with a theoretical dispersion curve (Stokoe et al., 1994). The final product is a shear wave velocity profile for the pavement layer from which a shear modulus or Young's modulus profile can be readily calculated using the following relationships:

$$G_{max} = (\gamma/g)V_s^2$$

$$E_{max} = 2(1 + \upsilon)G_{max}$$

Where γ equals the total unit weight of the base material, g equals the acceleration of gravity, and υ equals Poisson's ratio which had an assumed value of 0.25 in this study.

The SASW test provides several advantages over conventional quality control testing, such as density tests. One advantage is that the SASW test performs a direct measurement of the shear stiffness of the base course which can be directly used in the design of pavements. Another advantage is that SASW testing is nonintrusive so that no instrumentation needs to be placed within the base layer. Finally, during compaction on the base, the SASW test method enables one to monitor changes in the subgrade as well as within the entire depth of the graded aggregate base. It is because of these advantages that SASW testing was selected for use in this research effort.

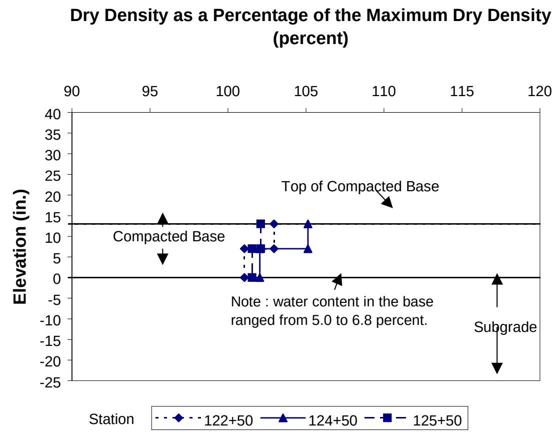
SUMMARY OF FINDINGS

Several observations can be made based on the in-situ density, water content, shear wave velocity, and plate load test results obtained at the three test sites. Stiffness and density results for the Georgia and Texas test sites are detailed in Reference (3). Reference (7) describes the load testing results from the Texas site. And Reference (8) contains the test results for the gravels in Memphis, Tennessee.

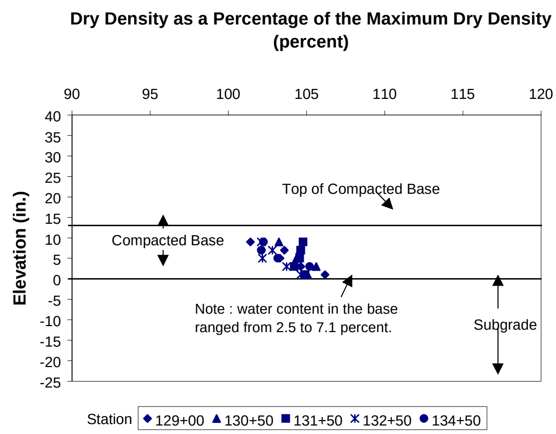
1. NDG results show that density requirements can be met with thick lifts for all four types of materials utilized in these tests. Figure 1 illustrates the density levels achieved in the crushed granite during the Georgia test series. It reveals that average densities for the sections with 13-inch single lifts (test sections 1 and 2) were slightly greater than those for the target strip, which was placed in one 6-inch and one 7-inch lift. Table 1 shows compaction data for one Test Pad in Texas in which the upper 12 inches of a 21-inch lift of crushed limestone was measured. Table 2 illustrates the gravel density data for a 12-inch lift at the Memphis site. The Nuclear Density Gauge (NDG) was equipped with a 12-inch probe, so moisture and density data were not obtained below 12 inches into the lift. However, seismic velocity and stiffness measurements revealed full-depth compaction. Similar results were obtained for the partially crushed material. The data confirms that density figures in excess of 100% of maximum, as determined by AASHTO T-180, can be achieved in the field.

2. Seismic data for all the tests reflect the effectiveness of the compaction effort throughout the full depths of the lifts by the high values attained for the wave velocities. The data also show

a. Dry Density Profile of the Target Strip (Two Lifts of 7 inches and 6 inches, respectively)



b. Dry Density Profile of Test Section 1 (One 13-in. Lift with Water added on site)



c. Dry Density Profile For Test Section 2 (One 13-in. Lift Delivered at the Proper Moisture Content)

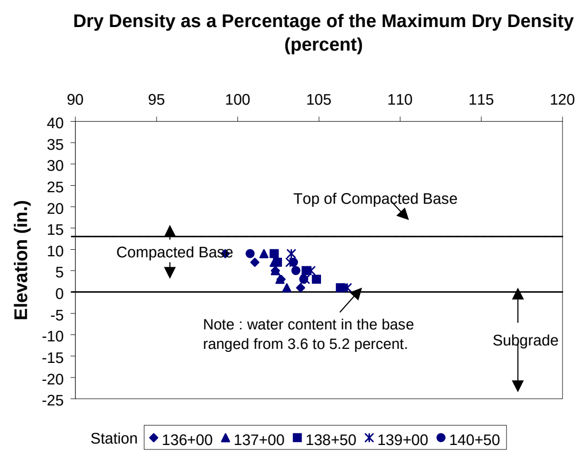


Figure 1 Dry Density Profiles for the Georgia Test Pads

DEPTH BELOW SURFACE OF COMPACTED LAYER	% COMPACTION (% AASHTO T-180 MAXIMUM DRY DENSITY)
2 inches	92.9 %
4 inches	95.0 %
6 inches	96.9 %
8 inches	98.2 %
10 inches	99.1 %
12 inches	100.8 %

Table 1. Percent Compaction for Crushed Limestone—Maximum Dry Density=141 pounds per cubic foot—NDG Data (Texas Site)

DEPTH BELOW SURFACE OF COMPACTED LAYER	% COMPACTION (% AASHTO T-180 MAXIMUM DRY DENSITY)
2 inches	103.0 %
4 inches	103.6 %
6 inches	102.0 %
8 inches	102.1 %
10 inches	100.7 %
12 inches	99.5 %

Table 2. Percent Compaction for Uncrushed Gravel—Maximum Dry Density=133 pounds per cubic foot—NDG Data (Memphis Site)

that the upper 3 inches or more of the compacted bases have lower wave velocity and stiffness values presumably from lower effective stresses near the surface and possibly from some disturbance caused by the compaction equipment. This trend was less evident in the compaction records, although near-surface density values were less than those obtained below this zone. Figure 2 shows this trend for one of the crushed limestone sections in Texas, and Figure 3 shows the same trend for a granite section in Georgia.

3. For the vibratory rollers used in this study, the vibratory smooth drum and the vibratory sheepsfoot rollers provided similar results and both provided adequate compaction.

4. Significantly, the research also showed that the SASW-measured layer stiffness, when evaluated in terms of Young's modulus, E, varied through a wide range of values. More importantly, these values of E were not well correlated with percent compaction. For example, crushed granite compacted to 105% of maximum dry density was significantly less stiff than crushed limestone compacted to 98-100% of maximum dry density (approximately 35 ksi vs. 65 ksi). This observation is partially explained by the effects of moisture. Small variations in moisture (2.2%) resulted in large variations in stiffness, with negligible variations in density. Figure 4 compares stiffness profiles for the Georgia granite and Texas limestone. Although not shown in the figure, the gravel results from Memphis revealed an almost constant value of E of approximately 70 ksi.

5. Moisture content impacts the ability to achieve the required level of compaction, as well as the stiffness of the compacted layer. In one test series at the Texas site, moisture contents in excess of optimum resulted in low compacted densities. A similar result occurred at the Memphis site, requiring the material to be scarified and mixed by a motor grader until sufficient drying was obtained. More significant was the deleterious effect of increased moisture on the stiffness of the base course. This condition is illustrated in Figure 5, which compares stiffness values for the Georgia test pads. Test Section 2 in Georgia, which had better moisture control (material delivered to the site at the desired moisture content) had the highest stiffness. Comparison of the records from Test Section 1 and the Target Strip, both of which had moisture added by the water truck at the site, show that Test Section 1, which was slightly denser, was less stiff. This difference is believed to be due to the higher moisture content of Test Section 1.

   Moisture effects are highlighted in Figure 6, which shows the large increase in shear wave velocity (and hence, stiffness) of the crushed limestone in Texas as it dried from a moisture content of 6.61% to 4.45%. Since lower stiffness values are indicative of larger pavement deflections under traffic loads, this data illustrates the importance of protecting an unbound granular layer from seasonal increases in moisture content.

6. SASW testing offers some advantages or additional benefits relative to NDG testing: 1) it is nonintrusive, 2) any layer thickness can be evaluated, 3) soft layers within the base or

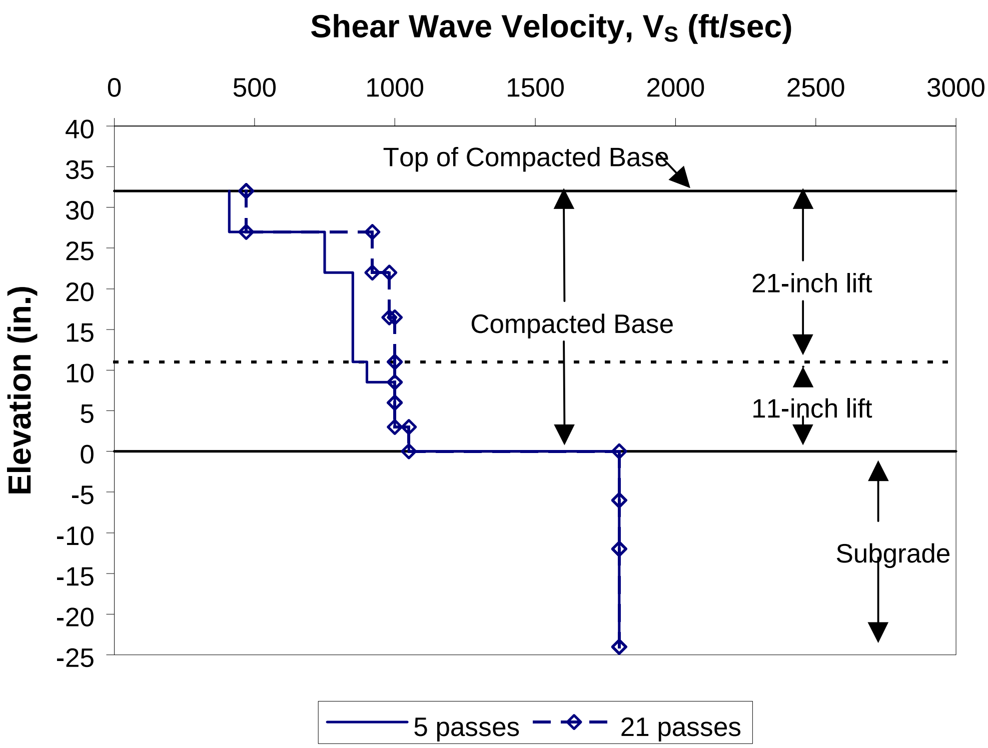
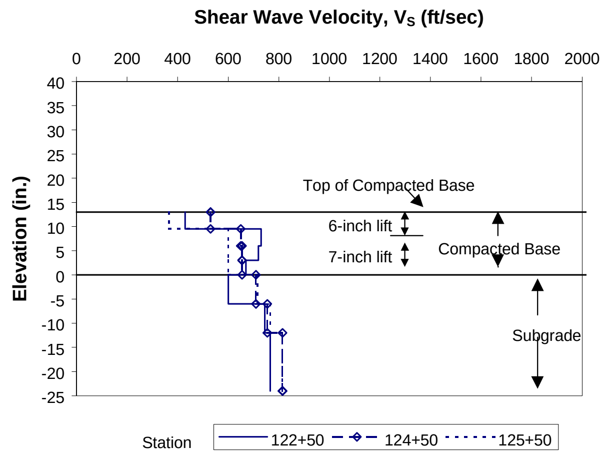
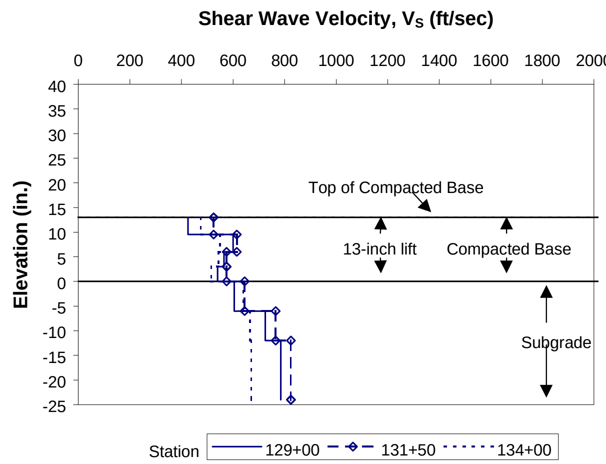


Figure 2. Shear Wave Velocity Profile Showing Increased Velocities Below Near-Surface Zone of Low Confinement and Possible Disturbance - Test Pad in Texas

a. Target Strip after the Base was Compacted



b. Shear Wave Velocity Profile Evaluated at Test Section 1 after the Base was Compacted



c. Shear Wave Velocity Profile of Test Section 2

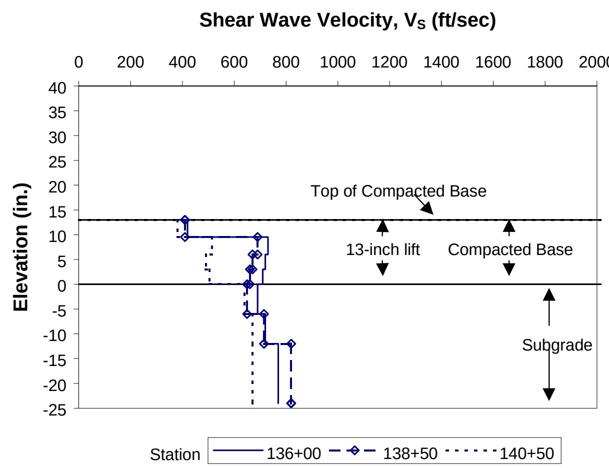


Figure 3. Shear Wave Velocity Profiles Showing Increased Velocities Below Near-Surface Zone of Low Confinement and Possible Disturbance – Georgia Test Sections

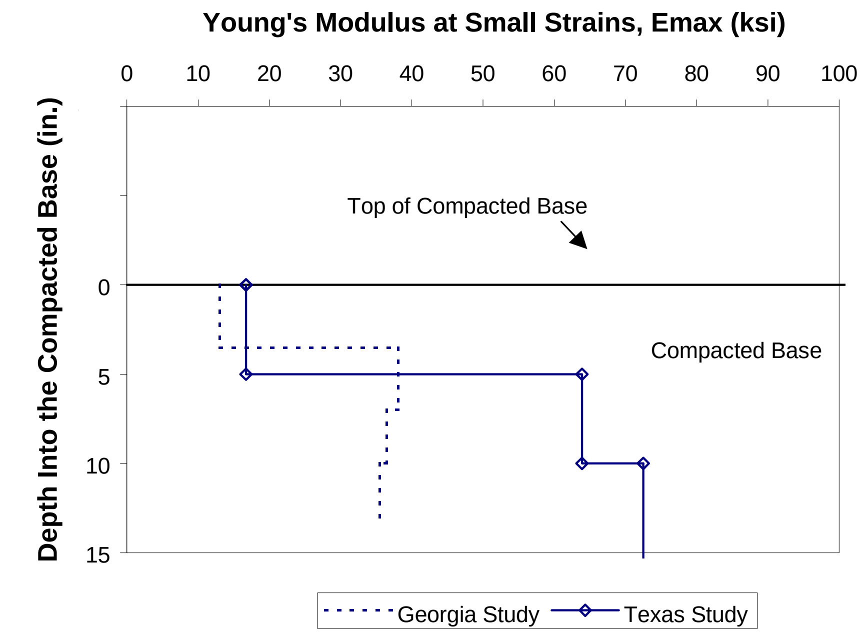


Figure 4. Typical Young's Modulus Profiles from the Georgia and Texas Studies

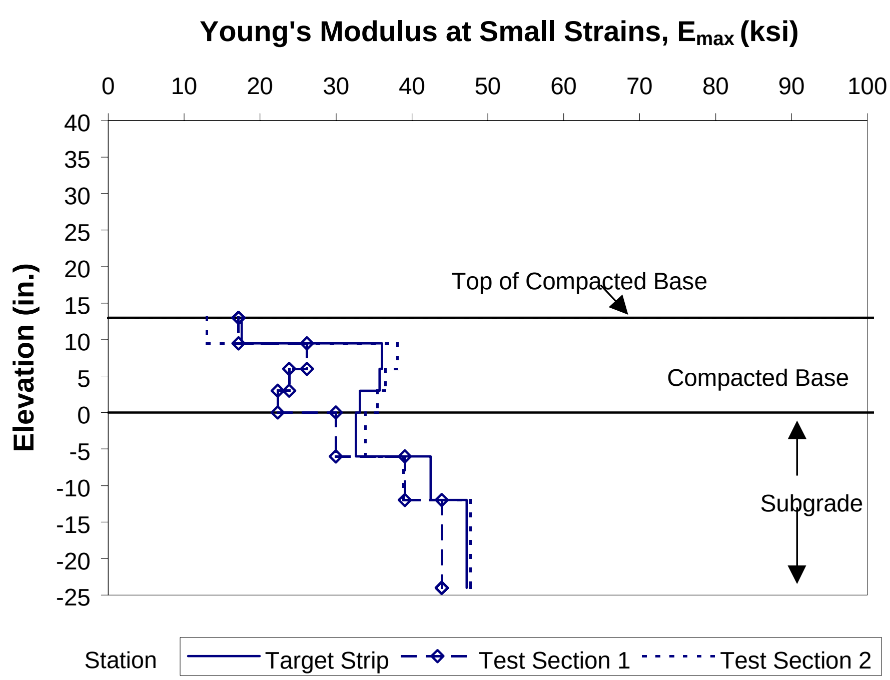


Figure 5. Comparison of Young's Modulus Profiles for the Crushed Granite Pads

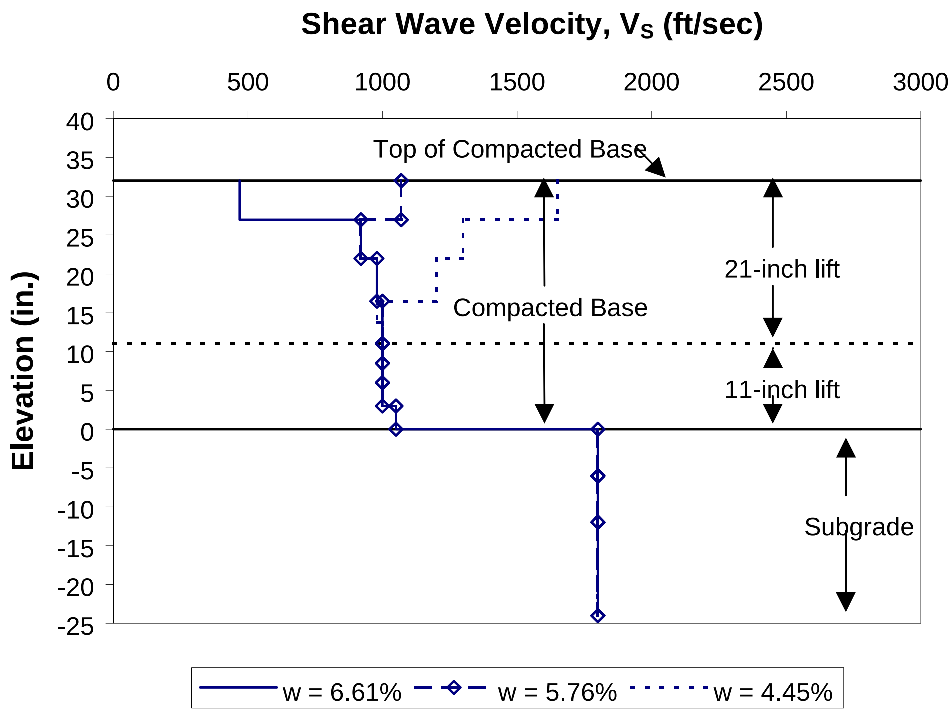


Figure 6. Shear Wave Velocity Profiles at Various Moisture Contents—Crushed Limestone

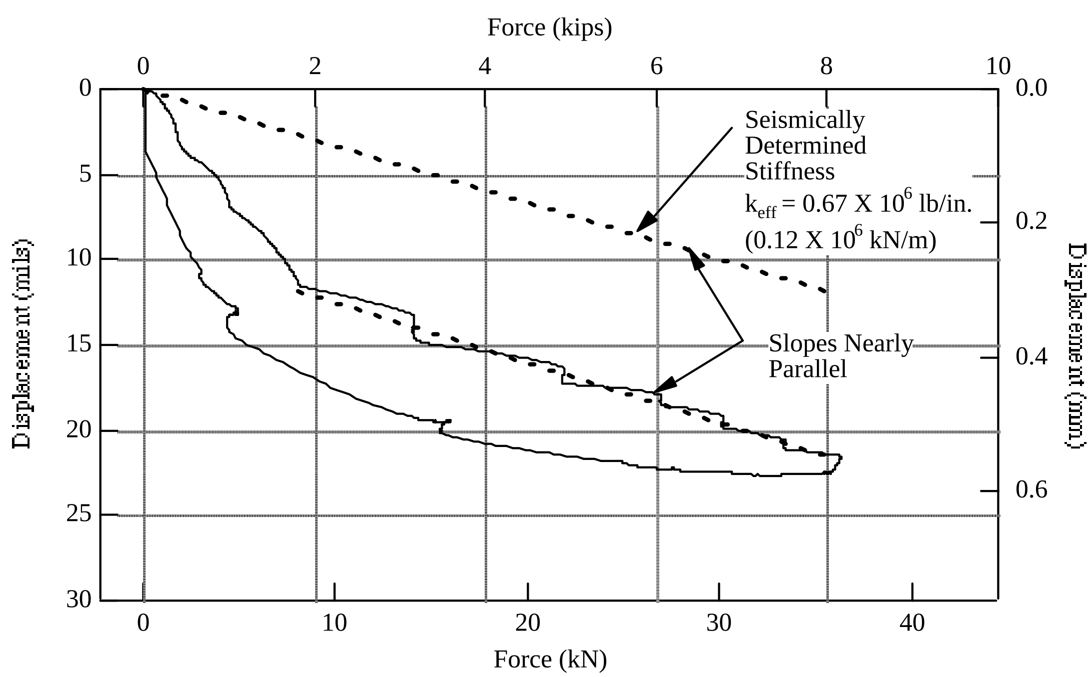


Figure 7. Comparison of Seismically Determined Stiffness with Plate-Load Stiffness for Large-Amplitude Cyclic Loading

subgrade may be detected after construction, and 4) the stiffness is a direct measure of how the pavement system will deflect under traffic loads. For these reasons, density tests and SASW tests complement each other and can be used together to gain a comprehensive assessment of the quality of the final compacted base or subbase.

The relationship between small strain seismic stiffness measurements and those obtained in the working load range typical of pavements was investigated by plate load tests. Surface displacements resulting from applied states of stress similar to those existing in flexible pavement base courses corresponded to strain amplitudes in the aggregate layer that fall in the nearly linear to mildly non-linear range of stiffness. To account for the larger strain effects on in-situ stiffness, a reduction factor of 5% to 20% is proposed for application of the seismically determined modulus values to resilient moduli values and in pavement design.

The presence of the softer near surface zone as detected in the SASW results is also shown in the plate load records. Figure 7 compares seismically measured stiffness with that determined from the plate load data. At larger strains, after the near-surface zone compresses, the stiffness under working loads becomes equal to that obtained under small-strain conditions.

DEVELOPMENT OF SPECIFICATION RECOMMENDATIONS FOR PLACING THICKER LIFT BASE COURSES

In addition to the survey responses referred to earlier, the following information was also received:

- Most states require a minimum compaction of 95-100% of the maximum dry density determined by AASHTO T-180 (or a similar state specification).
- Several states base minimum compaction on AASHTO T-99 (95-100%).
- Several states require mixing of aggregate and water by means of a pugmill or rotary type mixer.
- Most states allow roadway mixing by motor grader.
- Several states require placement of the aggregate with a spreader box.
- Most states leave equipment selection and number of passes to the contractor's discretion, provided compaction requirements are met.

The intent of the specifications provisions cited is to insure that aggregate bases are placed at proper moisture content, proper gradation, and with adequate compaction throughout. For example, plant mixing provides moisture control and avoids particle segregation which can result from excessive manipulation by the blade of a motor grader. Similarly, the use of mechanical spreaders, such as spreader boxes, minimizes segregation and facilitates grade control with minimal blading. Consideration of the factors affecting the resilient and shear behavior of unbound aggregates leads to the formulation of specification recommendations which will enhance the performance of thicker single lifts.

Factors Affecting Performance of Unbound Aggregate Pavement Layers

In flexible pavement structures, the role of the unbound aggregate base and subbase courses is to reduce the magnitude of stress and strain on the subgrade by distributing the wheel loads over a wide area. Furthermore, these layers affect the magnitude of the tensile strains in the asphalt layers, and thus, exert influence on fatigue of the surface layer (14) (16) (17). The aggregate layers' resilient properties, resilient modulus and Poisson's ratio, appear to have significant effect on fatigue in the asphalt, with the modulus being the more significant. Permanent deformations, or rutting, are major indicators of pavement performance and are impacted by shear strength and stiffness of the granular layers (12) (13) (17).

Similarly, strength and stiffness parameters of unbound granular subbases affect the performance of rigid pavements as measured by pumping and loss of support. Permeability of these layers becomes of more importance in this context.

In general, fatigue and rutting are major modes of failure in flexible pavements, and resilient behavior and shear strength of the aggregate layers play significant roles in the mechanisms of these distresses.

Several studies have identified the factors affecting the resilient response of unbound granular materials (9) (10) (14) (16). The factors exerting the greatest influence are level of compaction, moisture content, and state of stress. The resilient modulus increases as the percent compaction (representing in situ density) increases and as the bulk stress (sum of the principal stresses) increases. For well-compacted bases, the resilient modulus decreases as the moisture content increases. This response was shown in the field testing conducted during this study as well as in previous laboratory testing. Of all the factors, state of stress exerts the most control (14) (16). In comparison, the effects of compaction level are significantly less important (14) once a reasonable density level has been attained.

Other factors are less influential. Particle size distribution becomes significant in certain situations. The resilient modulus is reduced for very high percent fines in dense graded bases. In conjunction with high plasticity fines and high moisture contents, the effects of excess fines are exacerbated. Aggregate type is of minor consequence in determining resilient behavior. Crushed and uncrushed materials with similar gradations exhibit similar stiffnesses (14).

Shear strength of aggregate layers may exert a more significant influence on flexible pavement performance because of its influence on permanent deformations (11) (12) (17). Allen (14) showed that accumulated plastic deformations decreased with increased density. Thompson and Smith (11) linked poor granular base performance to excess fines and moisture contents in excess of optimum. They also linked increased permanent strain to larger principal stress ratios and to lower shear strength.

In summary, specifications for aggregate bases should provide for control of the following parameters to enhance fatigue and rutting performance of flexible pavements:

- Level of compaction--affects strength and stiffness

- Gradation--control excess fines, minimize segregation

- Moisture content--place near optimum, to enhance resilient modulus and resist rutting; if excessive amounts of water are added during compaction, significant modulus reduction occurs with potential deleterious performance

Key Specification Items

The following provisions should be included in specifications for thicker lift bases:

- Mixing method for aggregate and water--control moisture content and avoid segregation.

- Spreading aggregate and water mixture--control grade and avoid segregation.

- Lift thickness--obtain full depth compaction (field tests have demonstrated success with single-lift thicknesses greater than 13 inches) (15) (18) (3). Based on stiffness, lifts as thick as 21 inches were successfully compacted. NDG probes for measurements deeper than 12 inches were not available.

- Compaction equipment--Previous field tests (15) (18) (3) have shown typical vibratory equipment applying dynamic loads of 45000 to 55000 pounds is capable of compacting single lifts in excess of 13 inches thick.

- Minimum density requirements--important for shear strength and stiffness.

- Sampling and testing for density control--testing equipment and frequency.

- Optional use of test sections to demonstrate achieving minimum density.

Recommended Specification

On the basis of the results of the DOT survey, laboratory data and successful field tests, the following sections are proposed for inclusion in aggregate base course specifications.

Description. The contents of this section pertain to mixing, transporting, placement, and compaction of an aggregate base course on a prepared subgrade or subbase.

Materials. Gradation, particle size, angularity, and plasticity standards are addressed elsewhere in the typical specification.

Equipment. Mixing shall be accomplished by stationary plant such as a pugmill or by road mixing using a pugmill or rotary mixer. Mechanical spreaders will be utilized to avoid segregation and to achieve grade control. Suitable vibratory compaction equipment will be employed. Adequate compaction results for single lift thicknesses greater than 13 inches have been achieved with vibratory compactors applying 45000 pounds dynamic force. Stiffness measurements for 21-inch lift show that acceptable compaction was attained throughout the layer.

Mixing and Transporting. The aggregates and water shall be plant mixed (stationary or roadway) to the range of optimum moisture plus 1% or minus 2 % and transported to the job site so as to avoid segregation and loss of moisture.

Subgrade Preparation. The upper 6 inches of the subgrade shall be compacted to at least 98% of AASHTO T-99 maximum dry density.

Spreading. The material shall be placed at the specified moisture content to the required thickness and cross section by an approved mechanical spreader. If the compacted thickness of the base course exceeds 13 inches, the base shall be constructed in two or more layers with minimum thickness of 4 inches and maximum thickness of 13 inches. At the engineer's discretion, the contractor may choose to construct a 500 foot long test section to demonstrate achieving adequate compaction without particle degradation for lift thicknesses in excess of 13 inches. The engineer may allow thicker lifts on the basis of the test section results.

Should the mechanical spreader fail to shape the material properly, a motor grader may be applied as necessary. Similarly, a water truck may be applied to replace lost moisture. Care must be taken not to add excessive water. The material should be scarified and blade mixed by motor grader if moisture is added. All areas of segregated coarse or fine material shall be removed and replaced with well-graded material.

Compaction. Immediately following spreading and shaping the aggregate, the compaction effort will begin and will continue without interruption until the desired level of density is achieved. In the event inclement weather forces the compaction effort to terminate prior to completion, the material will be scarified, brought to proper moisture content, and the layer will be reshaped prior to resuming the compaction operation. Recommended minimum density requirements are as specified by the agency, but should be at least 95% of AASHTO T-180 maximum density for roadways carrying high volumes of truck traffic.

Sampling and Testing. Existing agency standards for frequency and spacing of elevation and density checks should be utilized.

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