APPENDIX E
COMPACTION CHARACTERISTICS AND EQUIPMENT

When the Materials Division designs a pavement structure, there are a number of factors that influence it's outcome. Projected traffic counts, percentage of heavy trucks and design life are considered. Another aspect taken into consideration is the support the pavement will receive from it's foundation (the embankment and subgrade). VDOT uses the California Bearing Ratio Test (CBR) to determine the relative strength of a soil compared to a dense, well graded aggregate mixture. The CBR value of a given material is in fact a percentage of the strength of the reference material. For example, a material with a CBR Value of 2 is only 2% as strong as a dense graded aggregate. Another very important point to know about the CBR test is that it is run on material which has been compacted to within 97.5% of it's maximum dry density. The results of the CBR test is a primary factor used by the pavement designer to calculate the thickness of pavement required. Since the CBR is based on a highly compacted sample, the success of the design is greatly impacted by the amount of compaction achieved in the field. Compaction gives our embankment the strength required to support a load, and it prevents subsequent natural settlement of an embankment under its own weight. It is critical that the required density is achieved in our embankments and subgrades.

Once a soil or aggregate mixture has been placed in a layer on the embankment, the contractor can use various types of compaction equipment to densify the soil to the desired level of compaction. As stated earlier, soils are made up of many different types, shapes and sizes of particles. There are many types of compaction equipment available. Some work better on one soil type than others. In this section we will discuss commonly used equipment, and the soils for which they are appropriate.

There are many types and sizes of compaction equipment. The equipment ranges from large rollers such as pneumatic tired, vibratory, tamping foot etc. to small walk behind or hand held compactors. In any case, the equipment should be of the proper type and size to provide the compactive effort required for the material being placed. For example, a vibratory roller is well suited for a granular type material. Vibrations move the finer particles into void spaces. For cohesive soils, a tamping foot (sheepsfoot) roller is ideal. The tamping feet provide a kneading action which compacts the material.

The efficiency of compaction equipment often depends on such things as ballast, roller speed, vibration amplitude and frequency, etc. Checking the equipment should be part of the construction activities. The compaction equipment selected should be determined by the type of soils encountered.

Pneumatic-tired compactors achieve compaction by the interaction of (a) wheel load, (b) tire size, (c) tire ply, (d) inflation pressure, and (e) the kneading action of the rubber tires as they pass over the lift. Pneumatic-tired rollers should be ballasted to meet at least the minimum wheel load.

Vibratory drum compactors develop their compactive effort by load and vibrations. Five machine features must be known in order to rate vibratory rollers: (a) unsprung drum weight, (b) rated dynamic force, (c) frequency at which the rated dynamic force is developed, (d) amplitude of the drum vibration, and (e) drum width. The dynamic force is proportional to the square of the frequency. A reduction in the frequency will significantly reduce the compactive force.

Compaction of granular soils is mostly due to the dynamic force created by a rotating eccentric weight. Vibratory compactors dramatically lose their effectiveness when the vibration is shut off because the compaction is due solely to the weight of the machine.

When sheepsfoot rollers are used, the feet must penetrate into the loose lift. If they ride on top, the machine is too light and the ballast must be increased. With succeeding passes, the feet should "walk out" of the layer. The number of passes required for the feet to walk out of the layer will be used to control compaction of subsequent layers. If the feet do not walk out, the machine is too heavy and is shearing the soils, or the soil is too wet.

COMPACTION CHARACTERISTICS OF SOILS AND AGGREGATES

No one method of compaction is equally suitable for all types of soil. The following review of methods for compacting fills are divided into three groups: those suitable for cohesionless soils, those for sandy or silty soils with moderate cohesion, and those for clays. Many different compaction methods are used, each with its own benefits and limitations that must be understood to by employed effectively. Compaction problems are often the result of the use of improper compaction equipment or its improper application.

For greatest efficiency the applied compactive force must be high enough, and of sufficient duration, to rearrange the particles. However, this effort must not be so high as to cause shearing of the compacted mass. A cohesionless material's strength is affected by confinement. This is most easily accomplished by wide area of load application. In cohesive materials, the strength is affected by void ratio and moisture, and less dependent on confinement.

In cohesionless materials efficient compaction results are obtained with moderate force applied to a wide area while using vibration. In cohesive materials efficient compaction requires higher pressure for dry versus wet material, with a smaller loaded area preferable.

Along with the following discussion, Tables E.1 and E.2 provide basic guidance concerning various compaction methods, equipment, applicable materials and conditions.

COMPACTION OF COHESIONLESS MATERIALS

For granular materials such as sand and gravel, the best results are achieved by use of vibratory compaction equipment (vibratory rollers). Ideally, equipment should vibrate at a frequency close to the resonant frequency of the material. When this is conducted properly, void reduction can be 20 to 40 times greater than that produced by an equivalent static load. Rock fills can also be compacted effectively using vibratory equipment.

The maximum size of particles is controlled by the thickness of compacted layers. Two to four passes of vibratory rollers, moving at a speed up to 1.5 mph, are usually sufficient to achieve the desired level of compaction. Moisture control may not be necessary for granular materials due to their high permeability. Granular materials can also be compacted by use of pneumatic-tired rollers pulled by heavy track-mounted equipment. Vibrations induced by the tracked equipment work in conjunction with the static pneumatic tired rollers. Six to eight passes of such equipment are typically required to attain a satisfactory degree of compaction. Water may be added to the material to facilitate the compaction process by temporarily "lubricating" the granular material (i.e. temporarily reducing inter-particle friction).

In confined areas the use of small self-propelled, hand-operated vibratory compactors is often necessary. The weight of these compactors varies from several hundred to several thousand pounds. The vibrating force is delivered to the material with a flat plate or roller. Four to eight inch layers can be effectively compacted.

The use of static rollers to compact cohesionless granular materials is inefficient and generally ineffective. A high degree of saturation is necessary to achieve acceptable results.

COMPACTION OF SANDY OR SILTY MATERIALS WITH MODERATE COHESION

As cohesion (and plasticity) of a material increases, the compacting effect of vibrations decreases greatly. Even a slight bond between particles interferes with their tendancy to move into a more stable position. The lower permeability of these materials results in the development of excess pore water pressures. Use of vibratory equipment often results in shear failure of the material rather than densification. Compaction in layers by static rollers usually provides satisfactory results.

Two types of rollers are effective with materials of this type: pneumatic-tired (rubber –tired) rollers and sheepsfoot or padfoot rollers. Pneumatic-tired rollers are most effective for compacting slightly cohesive sandy materials, mixed-grained materials ranging from gravels to silts and clays, and non-plastic silty materials (clean silts). Sheepsfoot rollers are most effective for compaction of cohesive, plastic materials.

Pneumatic-tired rollers usually consist of a cart or bin loaded with ballast, supported on a single row of four or more wheels. Tires are inflated at pressures ranging from 50 to 125 psi. The wheels have independent suspensions so that the weight is transmitted roughly equal to all wheels, even over non-uniform ground surfaces. Embankment materials are compacted in lifts or layers of six to twelve inches (when loose), using high tire pressures, and heavy loads (30 to 50 tons). Four to eight passes generally achieve the required level of compaction.

The surface of sheepsfoot rollers are usually covered with slightly rounded pads or feet. The size, shape and arrangement of the pads can vary greatly, with a typical arrangement of approximately one pad for every 100 $in.^2$ of roller surface area. The feet extend distances typically in the range of four to eight inches from the drum, with surface areas ranging from approximately 5 to 14 $in.^2$ Depending on the size and arrangement of the feet, contact pressures typically vary from 300 to 600 psi. Material lifts are generally thin, not exceeding six inches when compacted.

Regardless of the type of compaction equipment and the degree of cohesion and plasticity, the efficiency and effectiveness of the compaction procedure depends largely on the moisture content of the material – especially for low to non-plastic uniform fine grained materials. If the moisture content during compaction is not almost exactly equal to the optimum moisture content (for the specific level of compactive effort), these materials cannot be compacted to a stable condition.

If an embankment is constructed using uniform material under carefully controlled conditions (layer thickness, type of compaction equipment, and number of passes kept constant), the effectiveness of compaction depends only on the moisture content of the material at the time of compaction. If all conditions remain the same except a lighter roller is used for compaction, the value of the maximum dry density is lower, and the optimum moisture content is higher. Similar changes in the moisture-density relation for a given material will occur with variations in layer or lift thickness, type and/or weight of compaction equipment, roller speed, and rate of energy application. Therefore, the values of maximum dry density and optimum moisture content for a given material, will be specific with a given compaction procedure.

The water content at which a material is compacted affects the resulting density, strength, stability, and permeability. An increase in initial water content from a value below optimum moisture, to a value above optimum moisture, generally accompanies a large decrease in the material's permeability. The decrease generally is larger with increasing clay content.

COMPACTION OF CLAY

If the natural water content (natural moisture content) of a clay is not near the optimum moisture content, it may be difficult to change the moisture, especially if the water content is too high. When clay is excavated, it is generally removed in solid blocks or chunks. An individual block of clay cannot be compacted by any of the conventional compaction procedures previously discussed. Neither vibration nor short duration pressures results in significant change in water content. Use of a sheepsfoot roller can be effective in reducing open spaces between clay chunks. Results are best if the moisture content is slightly greater than the plastic limit of the material.

If the moisture content is too high, the clay tends to stick to the roller, or the roller starts rutting or sinking into the surface. If the moisture content is considerably less than optimum, the chunks are too stiff and do not yield, with the spaces between clay blocks not effectively closed.

Table E.1 Compaction Equipment and Methods (Navdocks DM-7)

Equipment Type	Applicability	Requirement for Compaction of 95 to 100 Percent Standard Proctor Maximum Density			Possible Variations in Equipment
Sheepsfoot roller	For fine-grained soils or dirty coarse-grained soils with more than 20 percent passing the No. 200 sieve. Not suitable for clean coarse-grained soils. Particularly appropriate for compaction of impervious zone for earth dam or linings where bonding of lifts is important	6	4 to 6 passes for fine-grained soil; 6 to 8 passes for coarse-grained soil	soil type / Foot contact area in^2 / foot contact pressures, psi fine-grained soil Pl > 30: 5 to 12, 250 to 500 fine-grained soil Pl <30: 7 to 14, 200 to 400 coarse-grained soil: 10 to 14, 150 to 250 Efficient compaction of soils wet of optimum requires less contact pressures than the same soils at lower moisture contents	For earth dam, highway and airfield work, drum of 60-in dia., loaded to 1.5 to 3 tons per lineal foot of drum is generally utilized. For smaller projects 40-in dia. Drum, loaded to .75 to 1.75 tons per lineal foot of drum is used. Foot contact pressure should be regulated so as to avoid shearing the soil on the third or fourth pass.
Rubber tire rollers	For clean, coarse-grained soils with 4 to 8 percent passing the No. 200 sieve For fine-grained soils or well-graded, dirty coarse-grained soils with more than 8 percent passing the No. 200 sieve	10 6 to 8	3 to 5 coverages 4 to 6 coverages	Tire inflation pressures of 60 to 80 psi for clean granular material or base course and subgrade compaction. Wheel load 18 000 to 25 000 lb Tire inflation pressure in excess of 65 psi for fine-grained soils of high plasticity. For uniform clean sands or silty fine sands, use large size tires with pressures of 40 to 50 psi	Wide variety of rubber tire compaction equipment is available. For cohesive soils, light wheel loads, such as provided by wobble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased. For cohesionless soils, large-size tires are desirable to avoid shear and rutting.
Smooth wheel rollers	**Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures** May be used for fine-grained soils other than in earth dams. Not suitable for clean well-graded sands or silty uniform sands	8 to 12 6 to 8	4 coverages 6 coverages	Tandem type roller for base course or subgrade compaction, 10 to 15 ton weight, 300 to 500 lb per lineal inch of width of rear roller 3-Wheel roller for compaction of fine-grained soil; weights from 5 to 6 tons for materials of low plasticity to 10 tons for materials of high plasticity	3-Wheel rollers obtainable in wide range of sizes. 2-Wheel tandem rollers are available in the range of 1 to 20 ton weight. 3-Axle tandem rollers are generally used in the range of 10 to 20 ton weight. Very heavy rollers are used for proof rolling of subgrade or base course.

Table E.1 Compaction Equipment and Methods – continued (Navdocks DM-7)

Equipment Type	Applicability	Requirement for Compaction of 95 to 100 Percent Standard Proctor Maximum Density			Possible Variations in Equipment
		Compacted Lift Thickness, (inches)	Passes or Coverages	Dimensions and Weight of Equipment	
Vibrating baseplate compactors	For coarse-grained soils with less than about 12 percent passing No. 200 sieve. Best suited for materials with 4 to 8 percent passing No. 200 placed thoroughly wet	8 to 10	3 coverages	Single pads or plates should weigh no less than 200 lb. May be used in tandem where working space is available. For clean coarse-grained soil, vibration frequency should be no less than 1600 cycles per minute	Vibrating pads or plates are available, hand-propelled of self-propelled, single or in gangs, with width of coverage from 1 ½ to 15 ft. Various types of vibrating-drum equipment should be considered for compaction in large areas.
Crawler tractor	Best suited for coarse-grained soils with less than 4 to 8 percent passing No. 200 sieve, placed thoroughly wet	10 to 12	3 to 4 coverages	No smaller than D8 tractor with blade, 34 500 lb weight, for high compaction	Tractor weights up to 60 000 lb.
Power tamper or rammer	For difficult access, trench backfill. Suitable for all inorganic soils	4 to 6 in for silt or clay, 6 in for coarse-grained soils	2 coverages	30-lb minimum weight. Considerable range is tolerable, depending on materials and conditions	Weights up to 250 lb; for diameter 4 to 10 in

Table E.2 Compaction Equipment for Different Conditions			
Soil	**First choice**	**Second choice**	**Comment**
Rock fill	Vibratory	Pneumatic	--
Plastic soils, CH, MH	Sheepsfoot or padfoot	Pneumatic	Thin lifts usually needed
Low-plasticity soils, CL, ML	Sheepsfoot or padfoot	Pneumatic, vibratory	Moisture control often critical for silty soils
Plastic sands and gravels, GC, SC	Vibratory, pneumatic	Pad foot	--
Silty sands and gravels, SM, GM	Vibratory	Pneumatic, pad foot	Moisture control often critical
Clean sands, SW, SP	Vibratory	Impact, pneumatic	--
Clean gravels, GW, GP	Vibratory	Pneumatic, impact, grid	Grid useful for oversize particles