To perform well, concrete structures must be built on firm soil. Soil consists of solids and voids that are filled with either air or water. It is the voids that compress when a soil is loaded, and the fewer the voids, the less chance there is that excessive settlement or sliding failures will occur. Proper compaction improves a loose soil by forcing out air and reducing the volume of voids; this strengthens the soil and minimizes potential settlement, rutting, sliding or other problems. Poor compaction or no compaction may cause a concrete foundation, floor slab or pavement to fail. The failure may take place immediately or it may occur weeks, months, or even years after construction (Figure 1).

Compaction is achieved by applying a pressure on the surface or by vibrating the soil mass. Different compaction methods are needed for different types of soils and the amount of compaction required for different soils must be established using standard testing procedures.

Measuring compaction

To find out how well a soil has been compacted we must measure the dry unit weight or dry density in pounds per cubic foot. Dry density is a measure of the weight of solid material present in a cubic foot of soil. The higher the dry density, the stronger and less compressible the soil will be. One method for determining dry density involves digging a hole in the compacted soil, finding the volume of the hole and determining the dry weight of the soil removed. The volume of the hole equals the sum of the volumes of soil solids, water and air and the dry weight of the soil equals the weight of soil solids. Dry weight of the soil, divided by the volume of the hole is dry density.

American Society for Testing and Materials (ASTM) standards describe several methods for measuring the dry density of an in-place soil. In the rubber balloon method (ASTM D 2167), water is used to find the volume of the hole and in the sand-cone method (ASTM D 1556) sand is used to find the volume. There is also a method for determining the in-place density of soils by nuclear methods (ASTM D 2922).

The rubber balloon method requires a level test location. A hole is dug, and all of the soil dug from the hole is carefully collected in a sealable plastic bag. The volume of the hole is measured, using a calibrated rubber device filled with water (Figure 2). The contents of the plastic bag are taken to a laboratory where they are weighed, oven-dried and reweighed. By dividing these wet and dry weights by the volume of the hole as measured with the rubber balloon, the wet and dry densities
In the sand-cone method, a hole is also dug and the removed soil is sealed in a plastic bag. Dry sand that has a carefully measured unit weight is allowed to run into the hole from a preweighed bottle. After the exact amount that fills the hole has run out, the bottle is returned to the laboratory for reweighing the remaining sand. The difference in weight is the amount of sand required to fill the hole. The volume of the hole is calculated by dividing the weight sand used to fill it by the unit weight of the sand. The rest of the method is the same as that for the rubber balloon method.

The rubber balloon method tends to be faster, but where there are sharp, angular particles in the soil, the method is of little use, since the balloons are often punctured and must be replaced and the water in the system recharged.

How much compaction is needed?

For the results of a field density test to have meaning, a reference point is needed. There are two tests that provide a reference point for granular soils. One (ASTM D 4524) determines the minimum index density of a cohesionless (granular) soil and the other (ASTM D 4253) determines the maximum index density of the soil. These are laboratory tests that determine how loose or how dense a given granular soil can be made in the laboratory. These become the reference points. Field densities can then be specified to fall within a desired range somewhere between the two reference points.

To determine how much compaction is required for cohesive soils, results of laboratory compaction tests are needed. Because the compacted density of clays and other cohesive soils is very sensitive to the water content at which they are compacted, these soils must have just the right amount of moisture to compact well. This moisture content is called the optimum moisture content. Optimum moisture content varies with the type of soil and the compactive effort used.

Moisture-density relationships

Laboratory compaction methods are used to determine the relationship between the moisture content and density of soils. A man named Proctor developed the methods as an aid in determining the amount of compaction that a contractor could reasonably expect to achieve in the field. In the standard Proctor test (ASTM D 698), samples of the soil are mixed at several different water contents in the laboratory, allowed to stand for at least 16 hours, and then compacted using a standardized procedure. After the wet weight is obtained, the soil is dried and the dry weight determined. For different

Figure 2. A rubber balloon device can be used to measure the volume of soil removed from a compacted fill. Dry density of the soil is then calculated by dividing the dry weight of the soil by the volume.

Figure 3. A typical five-point Proctor density curve for a clayey silt. The zero air voids line at the right represents the maximum density that could be achieved if the soil was completely saturated. If any field density test data falls above or to the right of a correctly calculated zero air voids line the data are suspect and should be rechecked.
moisture contents, the dry density is calculated and a graphical plot of dry density versus moisture content is made (Figure 3). The highest dry density on the graph is called the maximum Proctor dry density and the moisture content corresponding to the peak of the curve is called the optimum moisture content.

Different curves will be obtained for different soils, but in general, the more plastic the clay, the lower will be the maximum dry density and the higher the optimum moisture content. Two layers of soil in a borrow pit, one sandier than the other, will have different Proctor maximum dry densities and different optimum moisture contents.

Many years after the Proctor test had been put into use, a modified version of the test was developed to correlate better with compactive efforts comparable to those obtained with heavy rollers under favorable working conditions. In the modified Proctor test a heavier compaction hammer is dropped from a greater height. The number of blows per layer remains the same as for the standard test but more layers are used. The test results are similar except that the density is about 5 pounds per cubic foot greater and the optimum moisture content is 2 or 3 percent less than that obtained using the standard Proctor test (Figure 4).

If field tests on compacted cohesive soil indicate that field compaction procedures are providing densities of about 95 percent of the maximum density according to the standard Proctor method, or about 90 percent of the maximum density according to the modified Proctor method, compaction is relatively good. Obtaining 100 percent of even the standard Proctor maximum density may be practically impossible for some cohesive soils. The density that is required depends upon the loads that will be placed on the fill.

Figure 4. Maximum dry density is higher and the optimum moisture content is lower when the modified Proctor method instead of the standard Proctor method is used to compact a soil.

Figure 5. Surface tension in the water pulls moist sand or soil particles together and may make the soil more difficult to compact.

Figure 6. Vibration compacts loose granular soils. The compacted soil is stronger and less likely to settle in
Compacting clean granular materials

Clean granular materials (sands and gravels) are free-draining so that water can enter or leave the voids with relative ease. If voids in the sand are completely filled with water or are completely dry there are no forces holding the sand particles together. Vibration causes the particles to bounce around and roll or slide into a dense configuration. However, if the voids are only partially filled with water, surface tension in the water pulls the particles together as shown in Figure 5. When this happens, sand particles don’t move as freely and much more compactive effort is needed to reduce the void content. Figure 6a shows a loose structure, Figure 6b shows how vibration allows densification, and Figure 6c shows the resultant dense configuration.

Dumping sand or gravel from the bed of a truck or from a scraper places the granular material in a relatively loose condition, particularly if the sand contains only a small amount of surface moisture. This loose-dumped material must be compacted if it is to have adequate strength and not settle excessively under load. Left uncompacted, it is especially likely to settle if it gets wetter after a structure is built on it.

Smooth-wheeled or grid-wheeled vibratory rollers are specially designed to consolidate granular soils to a high density, compacting very efficiently to shallow depths. There are also excellent flat plate vibrators, with a gasoline engine mounted to a unit that causes a flat skid plate to vibrate. These will do an excellent job on sands and small gravels, compacting to a depth or lift thickness of about 6 inches.

One of the more successful methods for compacting a deep natural sand deposit is to drive piles into the sand, perhaps using a vibratory hammer, and then to pull them out again. An air or steam hammer also develops sufficient vibration to be quite effective, at least for a short distance around the pile. You can tell that it is effective because a cone-shaped depression forms at the ground surface in the sand around the pile for a distance equal to about 3 pile diameters. When 1-foot-diameter piles are driven, they must be spaced about 3 to 5 feet apart to be effective.

Another very effective device for compacting clean, free-draining sands and gravels is a patented vibrating probe. It resembles a standard internal concrete vibrator but is much larger and more powerful. The probe provides large capacity water jets which act downward and sideways, flooding the soil and breaking the surface tension. This allows the sand particles more freedom to settle into a compact configuration as the granular particles are vibrated.

Compacting clay soils with a sheepfoot roller

Sheepfoot rollers are commonly used to compact clays. The original sheepfoot compaction was just what the name implied. Ancients had found that paths used by sheep on clay soils were very firm, having been well compacted by the feet of the sheep. Today’s sheepfoot roller is a large drum that can be filled with water to make it heavier. Attached to the drum are a number of tapered feet with square cross section. Experience has shown that high plasticity, tough clays compact best under small feet, but silty cohesive soils require the use of large feet. The roller may be pulled by a dozer or a farm tractor or it may be self-propelled. Examples of self-propelled types are the two-wheeled tandem and three-wheeled sheepfoot rollers.

Clays don’t drain freely; it takes time and continuous effort to change their moisture content. Getting the right moisture content for compaction is accomplished either at the borrow pit or at the fill site. Water may be added to the soil to increase the moisture content or the soil may be aerated with a disc harrow to dry it. Neither of these procedures is simple or inexpensive. After the correct moisture content has been obtained compaction with a sheepfoot roller becomes the simple act of forcing out the air voids.

The first compacted layer is the most important one. Compaction can’t be accomplished on top of a spongy layer of soil. There must be a base to compact against. Therefore it’s necessary to strip down to sound material before beginning to compact a fill.

Prior to compacting a large area fill, the soil is brought to the site by hauling equipment and spread in about 8- to 10-inch lifts so that the finished compacted layer will be 6 inches thick. Clay cannot be properly compacted into lifts thicker than 6 inches. As previously mentioned, the clay should be brought to approximately optimum

Figure 7. During the first pass of a sheepfoot roller the feet punch full depth into the soil (upper drawing). With subsequent passes, compaction strengthens the soil and the feet don’t penetrate as deeply (lower drawing). When the roller walks out of the fill, adequate compaction is indicated.
moisture content before rolling. Tolerances on moisture content are usually given in contract specifications.

The sheepsfoot roller has a kneading action. During the first pass of the roller across the soil, the feet generally punch full depth into the loose material. As further passes of the roller work the soil and knead out the air voids, the soil becomes stronger so that the feet do not penetrate the soil to a great depth, and the roller is said to be walking out of the fill. Figure 7 illustrates this. Usually the specification will require that the fill be placed at a moisture content within about 2 or 3 percent of the optimum moisture content as determined by the Proctor density test, and compacted to a percentage (usually 90 or 95 percent) of the Proctor maximum dry density.

Tests confirm field observations

Being within specifications for density is not good enough unless the moisture content is also at the correct level. Soils having the same density but differing in moisture content will also have differing strength, compressibility and permeability characteristics. They will also have different tendencies to swell or shrink with changes in water content. It has been found that staying near the optimum moisture content minimizes these problems.

Moisture tests are relatively inexpensive to perform. If a fill is known to have the correct moisture content from several tests, if each layer of the fill has received uniform compactive effort, and if a few in-place density tests indicate that the specified density has been achieved, then it may be inferred that the untested areas of the fill also meet compaction specifications. To make such a decision requires continuous inspection of fill placement and observation of all spreading and compacting procedures by an experienced technologist.

Tests for both in-place density and moisture content will be done on the soil in the field. Moisture content and density tests require overnight drying of the soil, but waiting for the results would delay the contractor unnecessarily. After developing some experience on a project, the inspector may use a simple field test to determine whether the soil is at its optimum moisture content. A small sample of the soil is formed and squeezed by both hands, and then broken apart between two fingers and the thumb. If the ball breaks cleanly without crumbling it is an indication of near-optimum moisture content. If the contractor has the right water content in the soil and properly uses his compaction equipment, there is reasonably good assurance that compaction specifications will be met. Density tests simply confirm the inspector's observations.

If a cohesive soil is being compacted with a sheepsfoot roller weighing 4000 pounds per foot of drum length, with tamping feet at least 8 inches in length and a cross section of about 7 to 10 square inches (all of this appears in many specifications for this type of roller), and a reasonable number of passes are made to achieve compaction, proper compaction should be achieved if the soil is near the optimum moisture content. The U.S. Bureau of Reclamation suggests 12 passes of a fully ballasted roller to achieve 95 percent of the standard Proctor density. As few as 6 passes may do for some soils, but more are likely to be needed.

Other methods for compacting clays

Rubber-tired rollers are generally not as effective in clays as are sheepsfoot rollers. The practice of trying to compact with hauling equipment, by using rubber-tired large scraper pans to compact the fill while at the same time hauling additional soil to the site just does not accomplish proper compaction. Compaction occurs only under the wide tires which have low ground pressure for mobility, and then only for about 6 inches of depth. One pass of a scraper wheel is much less effective than a pass with a sheepsfoot roller. To achieve what 6 passes of the sheepsfoot roller will accomplish requires at least 12 properly routed passes of large loaded scrapers. It is virtually impossible to control individual operators so that they will follow the wheel paths of the previous machines or correctly distribute the compaction effort.

Timely inspection is needed

When a fill is totally in place and compacted, it is generally too late to determine whether or not the fill has been placed correctly according to the specifications. In natural ground, we can drill holes and perform tests to determine the adequacy of the ground both at the boring location and between the borings. Assumptions of conditions to be found between borings in natural ground are made on the basis of understanding the natural geologic processes of soil deposits and weathering. In earth fills, however, no such assumptions can be made. If assurances are required that a fill was placed according to the specifications, inspection during fill placement is necessary to confirm:

1. the condition of the ground surface before the fill was placed
2. the quality and loose lift thickness of the fill materials
3. the correct compaction procedure
4. the behavior of the compaction equipment as it progresses over the fill surface

Visual inspection helps in detecting problems that may occur during fill compaction operations. If the fill pumps or heaves at a particular location, the fill material is probably too wet at this location. If dust is flying at another location, the fill is probably too dry. These areas should be suspected of having low density fill, and density tests should be made in these locations. Remember—tests confirm the results of visual observations. If a fill tester is called upon only to make tests, without the benefit of inspection of placement and compaction, then he can only attest to the quality of the test result and not to the quality of the fill.
Compacting soils in small areas and against concrete walls and foundations

Flat plate vibrators and vibratory rollers come in many sizes and the smaller ones are well adapted for vibrating granular materials in close quarters or near concrete walls. A rammer-type machine that delivers rapid-impact blows is also useful for compacting granular soils in narrow trenches. The granular soil must be confined; otherwise the rammer will push it to the sides rather than compact it.

Compacting small areas of cohesive soil presents a very difficult problem. Rammers and rammer plate compactors can be used to force the air out of clays but it is most important to have the moisture content as close to optimum as possible. Water must be very well mixed into the soil being compacted and the soil itself must be well broken so that clumps are small. Lift thickness should always be less than the 6-inch compacted thickness of sheepsfoot roller lifts. Vibratory padfoot rollers with drums as little as 24 inches wide have also been used for compacting cohesive soils in trenches and other areas with restricted access. Again, moisture content of the soil must be maintained at or near optimum.

With several passes, heavy rubber-tired rollers can achieve compaction against concrete walls and against pipe, but caution must be exercised so that the compaction will not cause lateral loads high enough to endanger the concrete structure.

Extensive working of thin lifts may be needed to meet specification density requirements for cohesive soils in hard-to-reach areas. It may be more practical and economical to avoid problems in hand compacting these soils by backfilling with clean granular material and compacting using vibration as previously discussed.