Roller-Compacted Concrete Density: Principles and Practices

Introduction

One of the most common measurements used for quality control of earthfill placement is compacted density. The use of density testing for the control of fill placement and as a key indicator that material placed will meet specified parameters has broad application and a history of more than 50 years.

A key to design and construction using RCC is the application of testing procedures for both laboratory and field density that is representative of in-place conditions. Several test methods developed over the last 20 years are described in this publication. Also included is information on soil mechanics and concrete methodology aspects of RCC as well as a discussion on various standard compaction methods.

Soil Mechanics

Basic Properties. In soil mechanics practice, the density of a soil is defined as the weight per unit volume. The typical composition of a soil, subdivided into the three basic soil phases—solid, liquid (water), and gas (air)—is shown in Figure 1. Various relationships and engineering properties are derived from these soil phases, for example, density, unit weight, porosity, degree of saturation, specific gravity, and water content. Soil density is dependent on the relative volume of solid particles and void spaces. The relative amount of void volume in a soil mass can be expressed in terms of void ratio, or porosity: where the void ratio is defined as the ratio of the volume of the voids (air and water) to the volume of the solids in the soil mass, and porosity is defined as ratio of the volume of voids to the total volume of the soil mass. Basic engineering properties in soil mechanics are commonly defined as follows:

- V = total volume of soil mass
- V_s = volume of solid particles
- V_v = volume of void spaces (includes water and air voids)
- V_a = volume of air voids
- V_w = volume of water voids
- W = total wet weight of soil mass
- W_s = dry weight of solids
- W_w = weight of water in soil mass
- e = void ratio
- n = porosity, in percent
- A = percent air voids
- γ = wet density (total unit weight of soil mass)
- γ_d = dry unit weight or density
- γ_w = unit weight of water
- w = water or moisture content, in percent
- S = degree of saturation
- G_a = apparent specific gravity
- G_{ssd} = saturated surface dry specific gravity

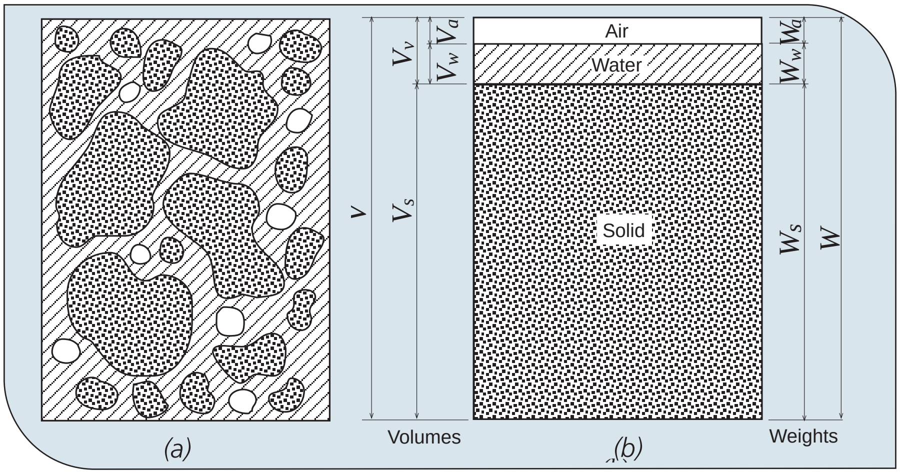

**Figure 1. Relationship among soil phases:
a) Visualization of a soil mass
b) Elements separated into phases of the soil mass.[1]**

The definitions of the basic properties are expressed by the following formulas.

Total volume:
$V = V_s + V_v$
Volume of voids:
$V_v = V_a + V_w$
Void ratio:
$e = V_v / V_s$
Porosity:
$n = V_v / V \times 100$
Percent air voids:
$A = V_a / V \times 100$
Degree of saturation:
$S = V_w / V_v$
Total water content (oven dry):
$w = W_w / W_s$
Density (total or wet):
$\gamma = W / V$
Density (dry):
$\gamma_d = W_s / V = \gamma / (1+W)$
Specific gravity (apparent):
$G_a = W_d / W_w$

Figure 1 graphically shows the parameters that are used in the various equations.

Soil Compaction Tests for Determining Maximum Density/Optimum Water Content

There are two commonly used soil compaction tests for monitoring and controlling fill placement material. They are the standard Proctor test (ASTM D 698) and the modified Proctor test (ASTM D 1557). Both tests determine an optimum moisture content that results in the maximum dry density unique to each material and the particular compaction method. The two test methods differ in the amount of energy used in compacting the test specimens.

Experience has shown that the modified Proctor test is more suitable to roller-compacted concrete, due to the coarse nature of RCC and the ability to achieve high compactive effort in the field through the use of large steel-drum vibratory compactors typically used on RCC projects. Both the standard and modified Proctor tests were developed for soils. The modified Proctor compaction test uses 56,000 ft-lb_f/ft^3 (2,700 kN-m/m^3) versus 12,300 ft-lb_f/ft^3 (600 kN-m/m^3) for the standard Proctor test. An important basis for the Proctor compaction test, as stated in the test standards, is that the standards only apply to soil containing less than 30 % retained on the 3/4 inch sieve. Because of the coarse nature of RCC mixtures, the Proctor compaction test procedures do not have direct applicability. Therefore, testing has been performed to explore the effects that the maximum size of aggregate, fines content, and cement and pozzolan contents could have on the compaction test. Tests by Casias et al.,[3] Arnold et al.,[4] Wong et al.,[5] and Reeves and Yates,[6] have investigated various aspects of the compaction tests on RCC.

The modified Proctor test has several different performance methods. The current version (reapproved in 1998) includes Procedures A, B, and C (earlier versions included a Procedure D that has since been discontinued, but is still referred to in some specifications). The method to be applied generally depends on the maximum particle size of the soil sample and the quantity of fine gravel and material larger than 3/4 inch. In most cases Procedure C with a 6-inch diameter mold, compared to 4-inch diameter molds for Procedures A and B, is used for RCC. The larger aggregates in RCC dictate the use of a larger mold to minimize the confining effect. The modified Proctor test consists of preparing a material at a moisture content and then compacting a sample using a specified energy in a container of known volume. The compaction process expels air from the soil mass by rearranging the particles to a denser configuration. The test continues with the compaction of the same material at different moisture contents and then plotting the results of dry density versus moisture content. The result is a curve showing a distinct maximum dry density and optimum water content, as seen in Figure 2.

Experience with compaction control for earthfill placement has shown that a material can be compacted to a high percentage (usually 95 %–98 %) of the maximum dry density with commonly available compaction equipment. Some variability inherently occurs in the soil properties (e.g., changes in gradation or proportions of soil fractions, the specific gravity and/or absorption), and the changes in soil properties may result in a different compaction curve. Consequently, a benefit of the modified Proctor compaction control process is that the compaction curve automatically changes when soil properties change naturally.

With compaction testing equipment, such as the nuclear density gauge to measure in-place density, compaction in the field can be compared to the maximum density that can be achieved using the modified Proctor test. Comparing the in-place density in the field with the maximum density achieved by the modified Proctor test provides compaction control as a specified percent compaction and has been used for field quality control for many RCC construction projects. However, as indicated in the following paragraph, placement of RCC at optimum moisture content (ASTM D1557) has resulted in a higher void content than is readily achieved for well consolidated RCC in the field. It should also be noted that fill control using the modified Proctor compaction test typically involves fill placement and compaction on loose lift thickness of 8 inches to 10 inches, in comparison with loose lift thickness up to 15 inches that are common to RCC dam placements. As a result RCC is usually placed at a water content above optimum moisture content (ASTM D1557), which provides more workability and transfer of energy for compaction to the lower portion of the lift.

There are some other relevant aspects of the modified Proctor compaction test that are noteworthy; namely the concept of a zero-air-voids curve and the wet density of a material. Theoretically, the dry density of the material will parallel the zero-air-voids curve (as shown in Figure 2) that is unique for each material based on the apparent specific gravity of the material. As a porous material, soil has an "apparent" specific gravity, which is defined as the ratio of the dry weight of a unit volume of soil (volume of solids plus volume of voids) to the unit weight of water. The apparent specific gravity (G_a) is defined in ASTM C 127 as the ratio of the weight in air of a unit volume of the impermeable portion of the aggregate to the weight in air of an equal volume of water. The zero-air-voids line is different from the air content as determined in concrete practice. This difference is obvious when the wet density of the material from a modified

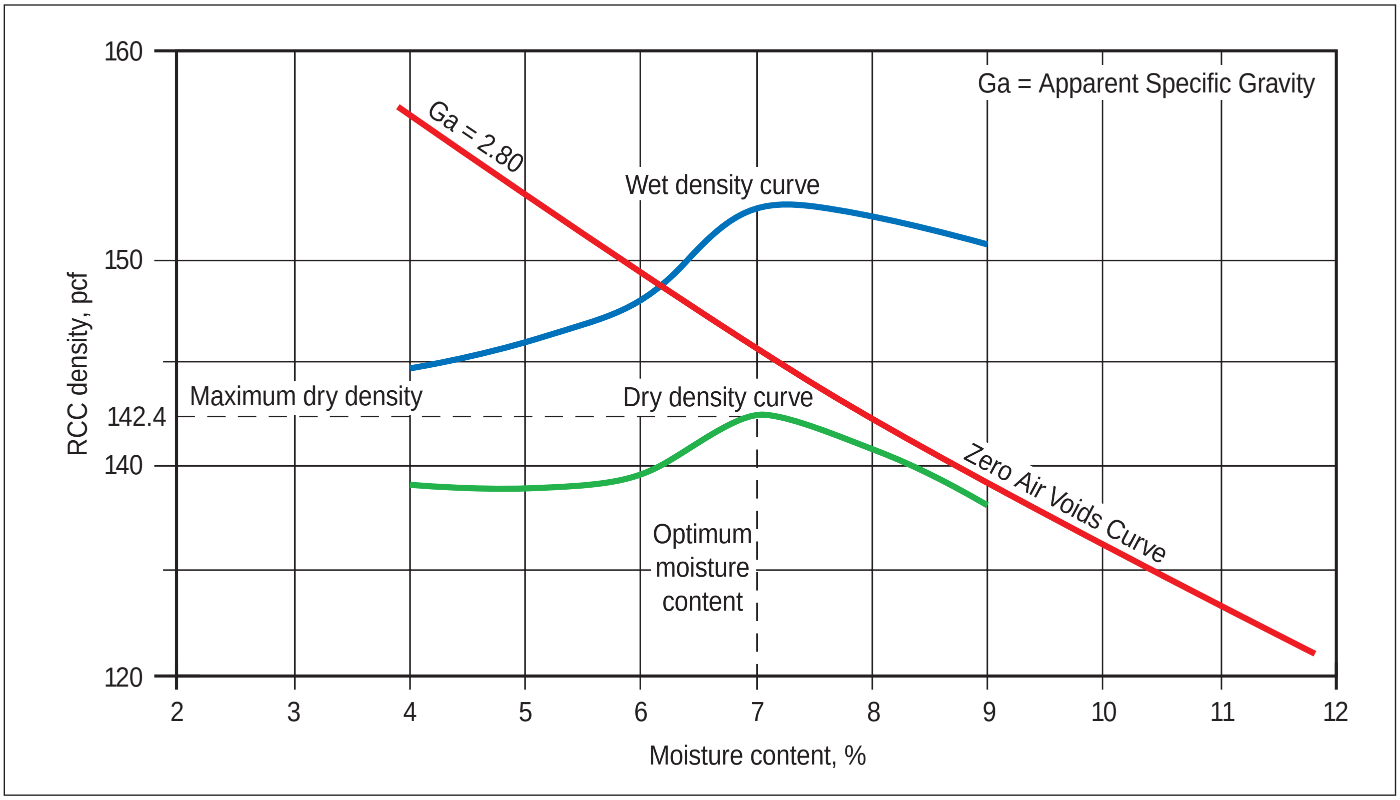

Figure 2. Compaction curve of an RCC mixture (ASTM D 1557).

Proctor compaction test is plotted with the zero-air-voids line (see Figure 2). In most material, the maximum wet density usually reaches a peak density at a higher water content than the maximum dry density. This is due to the fact that with increasing water content, the voids in the soil mass continue to be filled with water until the soil mass becomes too soft to sustain the compaction equipment. At higher water contents, the soil mass contains more voids (air and water), is less dense, and has increased plasticity (softness). Hence the wet density curve begins to fall off. This can be complicated by the absorption (both the percent of absorption and the absorption rate) of the soil.

In order to demonstrate the properties described above, an example problem will be used. With the definitions described above, the basic engineering properties of a soil (including an RCC mixture) can be calculated using soil mechanics. Example 1 below calculates various engineering properties, given the apparent specific gravity of the material and the results from a modified Proctor test on an RCC mixture. General material properties of the soil aggregate used in the test are summarized in Table 1.

Example 1: Assume one cubic foot (ft^3) of RCC has a maximum wet density of 152.40 pounds per ft^3 (pcf) and an apparent specific gravity (G_a) of 2.8. Using Figure 2, and an optimum moisture content of 7.0 %, a cement content of 412 pounds per cubic yard (pcy), and no pozzolan, the various engineering properties can be calculated as follows:

Determine dry density.

$$\gamma_d = \gamma / (1+w) = 152.40/(1+0.070) = 142.43 \text{ pcf}$$

Determine volume of constituents as shown in Figure 3:

$$W_w = 152.40 \text{ lb} - 142.43 \text{ lb} = 9.97 \text{ lb}$$

$$V_w = \frac{9.97 \text{ lb}}{62.4 \text{ pcf}} = 0.1598 \text{ ft}^3$$

$$W_c \text{ (cement)} = \frac{412 \text{ lb}}{27 \text{ ft}^3} = 15.26 \text{ lb}$$

$$V_c = \frac{15.26 \text{ lb}}{3.15 \times 62.4 \text{ pcf}} = 0.0776 \text{ ft}^3$$

V_s (soil) = Volume of the solids less the volume of cement

$$W_d \text{ (soil)} = 142.43 \text{ lb} - 15.26 \text{ lb} = 127.17 \text{ lb}$$

$$V_s = \frac{127.17 \text{ lb}}{2.8 \times 62.4 \text{ pcf}} = 0.7279 \text{ ft}^3$$

$$V_a = 1\ ft^3 - 0.7279 - 0.1598 - 0.0776$$
$$= 0.0347\ ft^3$$

Determine porosity:

$$n = V_v / V \times 100$$
$$= [(0.0347 + 0.1598)/1.0] \times 100 = 19.45\ \%$$

Determine void ratio:

$$e = V_v / V_s = V_a + V_w / V_s + V_c$$
$$= (0.0347 + 0.1598)/(0.7279 + 0.0776) = 0.24$$

Calculated Air Content

$$A = V_a / V \times 100 = 0.0347\ ft^3 / 1.0\ ft^3 \times 100$$
$$= 3.47\ \%$$

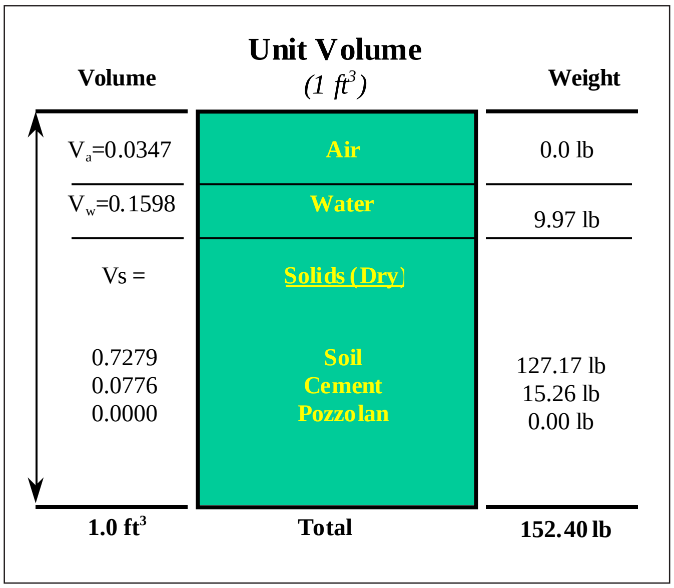

Figure 3. Constituent weight and volume distribution of RCC mixture based on soil mechanics definitions.[2]

There are important differences between soil mechanics properties and the properties used in concrete practice. For example, there are several different ways to calculate the specific gravity. The specific gravity of the solid particles of the soil, not including the void spaces, is called the "true or absolute" specific gravity, which usually ranges between 2.6 to 2.7 for most soil. This is different from the apparent specific gravity (dry weight) used in soil mechanics for compaction as described above, and the saturated surface dry specific gravity used in concrete mixture proportioning. Some of the resulting differences in properties are demonstrated in the next section.

Concrete Methodology

Proportioning RCC by Volumetric Method. Concrete proportioning can be performed by both weight and volumetric methods. Volumetric proportioning is performed using the specific gravity of each ingredient

Table 1 – Material Properties for Example Problem

Property	Coarse Aggregate (> No. 4)	Fine Aggregate (< No. 4)	Weighted Properties
Specific Gravity (Apparent)	2.69	2.95	2.80
Specific Gravity (Saturated Surface Dry)	2.63	2.85	2.72
Absorption	1.50 %	1.95 %	1.69 %
Aggregate Proportion	57 %	43 %	100 %
Property	**Cement**	**Water**	
Specific Gravity	3.15	1.0	

to calculate the absolute volume that will be occupied in a unit volume of concrete. The volumetric method is the more accurate method of proportioning and is used for illustration purposes in this publication.

The absolute volume used in concrete mixture proportioning is based on the saturated surface dry specific gravity. The specific gravity, saturated surface dry (G_{ssd}), is the ratio of the weight in air of a unit volume of aggregate, including the weight of water in the voids, compared to the weight in air of an equal volume of water. The volume (yield) of freshly mixed concrete is the sum of the absolute volumes of the cementitous material (cement, pozzolan), aggregates, water (exclusive of that absorbed in the aggregate), admixtures, and air. The absolute volumes of the constituents (based on the volumetric method of mix proportioning) are calculated using the material weight and specific gravity as shown below:

Absolute volume:

$$= \frac{\text{Weight of material}}{\text{Specific gravity of material} \times \text{Unit weight of water}}$$

The specific gravity or relative density of the aggregate used in mix proportioning design can be based on either saturated surface dry (SSD) or oven dry materials. For the following example the G_{ssd}, and a mixture with the same total unit weight as *Example 1*, is used.

Example 2: A no-slump concrete mix consists of 3,491.70 pcy of aggregate (saturated surface dry) with 57 % coarse aggregate, 412 pcy of cement, and a water to cement ratio of 0.5124 (note for purposes of the example problem that the water cement ratio used herein was carried to more significant digits than is typical in concrete practice). The same material used in *Example 1* will be used in *Example 2.* The mixture proportions including unit weights, absolute volumes, and air content are calculated on the next page.

Calculate unit weights for each of the constituents for a one yd^3 batch:

Coarse Aggregate(SSD) $= (3{,}491.70\ lb \times 57\ \%)$
$= 1{,}990.27\ lb$

Fine Aggregate(SSD) $= 3{,}491.70\ lb - 1{,}990.27\ lb$
$= 1{,}501.43\ lb$

Cement $= 412\ lb$

Water $= 412\ lb \times 0.5124 = 211.10\ lb$

The absolute volumes of the mix constituents are then calculated by dividing the known weight of each constituent by the product of its specific gravity and the unit weight of water.

Water $= \dfrac{211.10\ lb}{1 \times 62.4\ pcf} = 3.38\ ft^3$

Cement $= \dfrac{412}{3.15 \times 62.4\ pcf} = 2.10\ ft^3$

Coarse Aggregate $= \dfrac{1{,}990.27\ lb}{2.63 \times 62.4\ pcf} = 12.13\ ft^3$

Fine Aggregate $= \dfrac{1{,}501.43\ lb}{2.85 \times 62.4\ pcf} = 8.44\ ft^3$

Total volume of known constituents

$$= 3.38\ ft^3 + 2.10\ ft^3 + 12.13\ ft^3 + 8.44\ ft^3 = 26.05\ ft^3$$

Calculate air content

$$= 27.00\ ft^3 - 26.05\ ft^3 = 0.95\ ft^3$$
$$= 0.95\ ft^3 / 27.00\ ft^3 = 3.52\ \%$$

Next is to compare the different engineering properties used for concrete mixture proportions with the properties defined in soil mechanics. Figure 4 shows a side-by-side comparison of the calculations. The mix proportions are converted from 1 yd^3 to 1 ft^3 below, for comparison with the soil mechanics computations.

	Volume	
Constituent	**yd^3**	**ft^3**
Water	3.38	0.1252
Cement	2.10	0.0778
Coarse Aggregate (ssd)	12.13	0.4492
Fine Aggregate (ssd)	8.44	0.3126
Air	0.95	0.0352
Check Sum	**27.00**	**1.0000**

	Weight (lb)	
Constituent	**yd^3**	**ft^3**
Water (Free water above ssd)	211.10	7.82
Cement	412.00	15.26
Coarse Aggregate (ssd)	1,990.27	73.71
Fine Aggregate (ssd)	1,501.43	55.61
Air	0.0	0.0
Sum	**4,114.80**	**152.40**

The total water content (oven dry) and free water content (SSD) of the RCC mix can then be calculated, as shown on the next page.

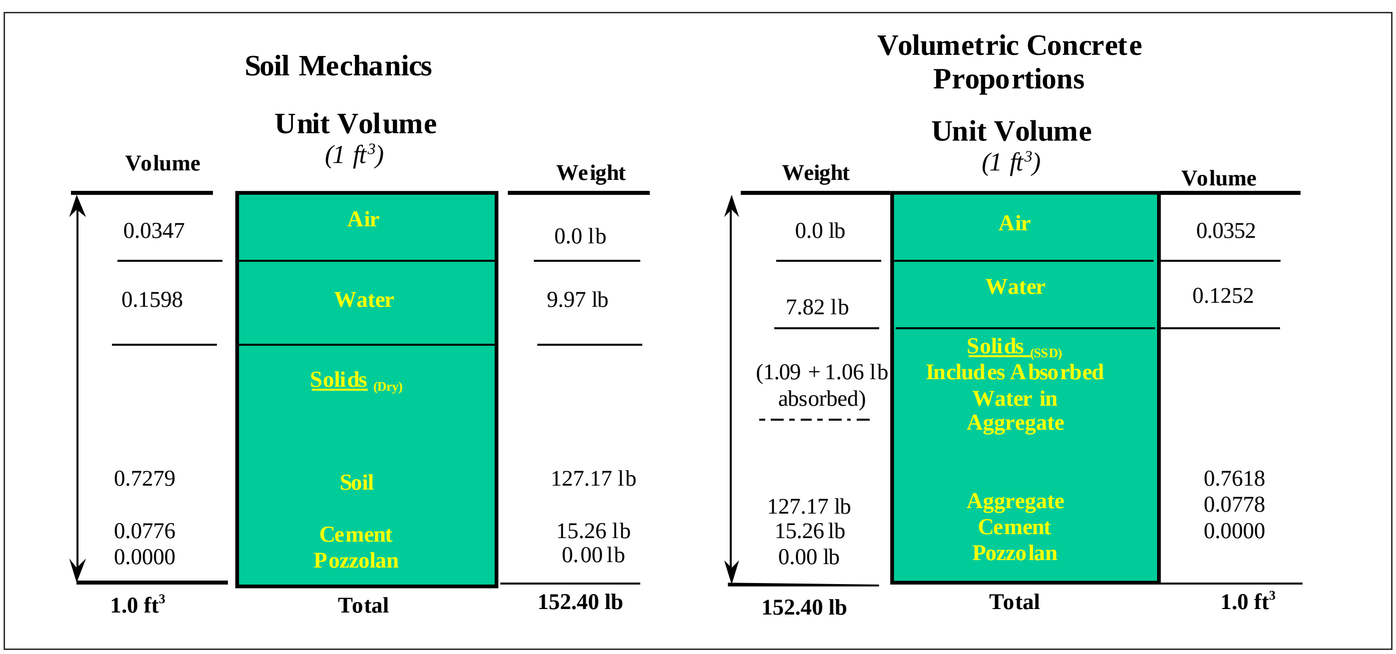

Figure 4. Comparison of constituent distribution based on soil mechanics definitions and concrete volumetric proportions.

Free water $= 7.82 \text{ lb}$

Absorbed water in coarse aggregate: $= 73.71 - \left[\dfrac{73.71}{(1+0.015)}\right] = 1.09 \text{ lb}$

Dry weight of coarse aggregate: $= 73.71 \text{ lb} - 1.09 \text{ lb} = 72.62 \text{ lb}$

Absorbed water in fine aggregate: $= 55.61 \text{ lb} - \left[\dfrac{55.61 \text{ lb}}{(1+0.0195)}\right] = 1.06 \text{ lb}$

Dry weight of fine aggregate: $= 55.61 \text{ lb} - 1.06 \text{ lb} = 54.55 \text{ lb}$

Dry weight of total aggregate: $= 72.62 \text{ lb} + 54.55 \text{ lb} = 127.17 \text{ lb}$

Total water content $= \dfrac{7.82+1.09+1.06}{127.17+15.26} = 7.00\ \%$

Free water content $= \dfrac{7.82}{127.17+15.26} = 5.5\ \%$

It is clear from the examples above that there are some variations in the calculated air content (3.47 % in soil mechanics versus 3.52% in concrete methodology) and water content (7.0 % oven dry water content following soil mechanics versus 5.5 % free water and 7.0% oven dry water content for concrete volumetric proportioning). The differences are primarily accounted for by the application of the definitions by the different practices (such as the specific gravity, water content, and water:cement ratio that is used for proportioning aggregate content, and proportioning aggregate as a percentage of saturated surface dry aggregate), and rounding of significant digits. The example problems demonstrate the importance of distinguishing between the terms used in soil mechanics and concrete practice (e.g. the total (oven dry) water content versus free water content), and in the communication of mix proportions in laboratory programs, design and specifications, mixing plants, and field testing. The properties for both methodologies should be determined and documented in the project record.

As mentioned earlier RCC placed at optimum moisture content (ASTM D 1557) contains a higher air content than is typically achieved in field placement and compaction.

Using the procedures shown in *Examples 1 and 2*, engineering properties at different water contents can be used to further evaluate RCC mixtures. Six different water contents were evaluated for the example material, corresponding to the six modified Proctor compactions test points as shown in Table 2. Evaluation of the engineering properties in Table 2, shows that the minimum void ratio occurs at the optimum moisture content. However, the air content of the mixture continues to decrease in the compaction test until a point approximately 1 % over optimum. Placement of RCC at optimum moisture content and maximum density would be expected to result in an air content of the compacted mix of about 3.5 %. In practice, most specifications accept a minimum compactive effort of 98 % of the maximum density resulting in a higher air content (5.5 %), for the material in that example. Lower entrapped air content provides more desirable hardened RCC properties. Also it is easier to compact slightly wetter mixtures. Therefore, for this example, selection of a mix at a water content that is 0.5 % to 1 % above optimum moisture content would provide the best opportunity for a workable, high density, low air content mixture. For actual application of RCC in a project, the mixture proportions shown above would be re-proportioned to a mix that would yield an air content of 2 % or lower (an example of re-proportioning is shown in Appendix A in the Design Manual for RCC Spillways and Overtopping Protection—PCA 2002).

The modified Proctor compaction test can be an efffective method of selecting a water content that is both workable in the field and suitable to meet the required RCC field properties Another benefit of the modified Proctor test for field control is that changes in basic material properties automatically change the compaction curve. Frequent measurement of the specific gravity, gradation and absorption during construction will also allow adjustments of the mix proportions to accommodate changes as they occur.

Cylinder Preparation

There are numerous methods for the preparation of cylinders at the laboratory stage that have been shown to be representative of actual field placement conditions. Cylinder preparation procedures that have been used include: a) 10-ton vibratory roller (cores), b) Hilti or Kango vibrating hammer, c) pneumatic tamper, d) Vebe table, e) internal vibrator, f) internal rodding, and g) Proctor test. The effectiveness of the different methods of cylinder preparation varies depending on the workability of the RCC mixture. The effectiveness of each method (represented as a percentage of the maximum achievable strength) over the approximate range of moisture content (in excess of the SSD aggregate condition) is shown in Figure 5.

The pros and cons of each of the cylinder preparation methods are summarized below:

- Certainly the use of a full-scale roller (i.e., 10-ton vibratory roller) would provide a close representation of actual field placement conditions. However this method would require large quantities of material, a large work area, and the use of equipment not readily available at testing laboratories, followed by coring after a time delay, to obtain samples for testing. Consequently this method is generally impractical except for large projects where test sections are often required.
- The Hilti/Kango hammer method can also be used for a moderate range of mixture workability. This method has the advantage of using equipment (see Figure 6) that is readily available, quite useable by laboratory personnel, and with amplitude and frequency very similar to normal field compaction

Table 2 – Summary of Engineering Properties at Modified Proctor Compaction Points

Property	Relative to Optimum Moisture	- 3 %	- 1 %	Optimum Moisture	+ 0.5 %	+ 1 %	+ 2 %
	Water Content	4 %	6 %	7.0 %	7.5 %	8 %	9 %
Soil Mechanics	Dry Density	139.13 pcf	139.53 pcf	142.43 pcf	141.12 pcf	139.72 pcf	138.17 pcf
	Porosity, n	21.4 %	21.2 %	19.5 %	20.3 %	21.1 %	21.9 %
	Void Ratio, e	0.2720	0.2684	0.2422	0.2539	0.2666	0.2810
	Wet Density	144.70 pcf	147.90 pcf	152.40 pcf	151.70 pcf	150.90 pcf	150.60 pcf
Concrete	Water Content (Free water)	93.62 pcy	169.12 pcy	211.10 pcy	228.21	244.89 pcy	279.54 pcy
	Water:Cement ratio[1]	0.2272	0.4107	0.5124	0.5539	0.5944	0.6785
	Entrapped air content	12.5%	7.75 %	3.52 %	3.14 %	2.01 %	3.29 %

Note: 1. Water to cement ratio is based on a cement content of 412 pcy.

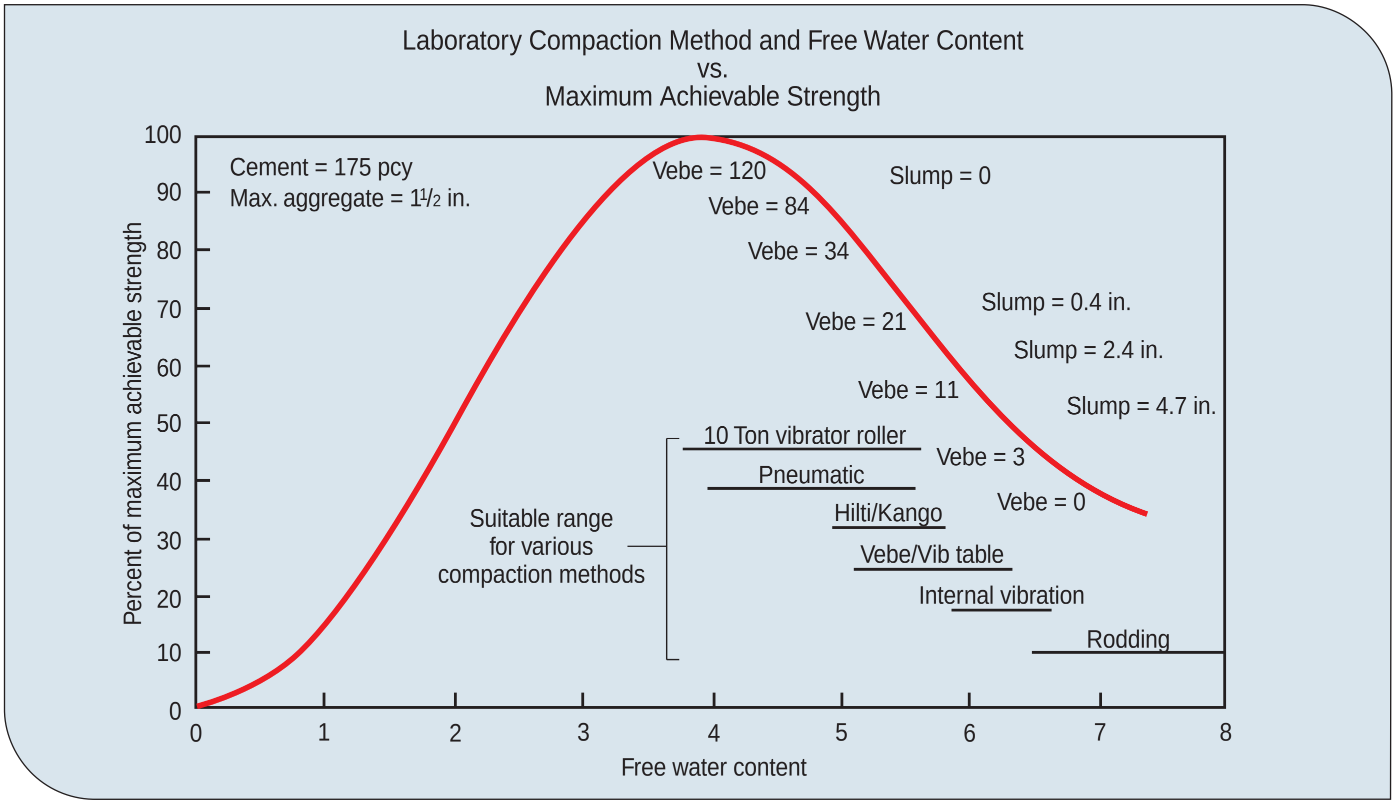

Figure 5. Cylinder preparation method versus relative workability range. (It must be noted that the curve above is based on conventional concrete definitions using the free water content, i.e. the moisture content not including water absorbed in the aggregate. The actual, oven dry, water content would be higher when the total water—absorbed plus free water—is included.) Ref 8.

equipment. A standard test procedure (ASTM C 1435) provides repeatable results; however, depending on the mix design, compacted densities may be less then that achieveable in the field. The method specifies placement of the material in three lifts, similar to the standard concrete test for rodding cylinders of slump concrete. However, RCC is a no-slump concrete with very low workability. As a result the number of lifts may need to be increased to four or five to provide a cylinder that would be expected to be similar to normal field compaction.

- The pneumatic tamper (see Figure 7) can be used for a moderate range of mixture workability. It is readily available at construction sites, can be easily rented for laboratory use, and has been shown to provide RCC cylinder densities that are similar to actual field conditions. The pneumatic tamper requires equipment not commonly used by laboratory personnel, and the amplitude and frequency are significantly different than with normal field compaction equipment. Also there are no ASTM standard test procedures available.

Figure 6. Vibrating hammer used to prepare RCC cylinder (ASTM C 1435).

- Cylinders prepared with the Vebe table method (see Figure 8) have also been shown to be similar to normal field compaction for mixes with a Vebe time of 35 seconds or less. A standard test procedure (ASTM C 1176) provides repeatable results. Experience has shown that the Vebe method works for a narrower range of mix workability than the pneumatic tamper or Hilti/Kango methods.
- Internal vibrators/rodding are not used for the preparation of RCC cylinders. These two methods are primarily suitable for slump concrete, and external compaction equipment used for RCC cannot operate effectively or efficiently on slump concrete.
- The modified Proctor compaction test is also an effective cylinder preparation method that represents normal field compaction. A test procedure (ASTM D 1557) provides a repeatable standardized method. The modified Proctor test actually covers a wider range of mixture workability than is typically employed by any other method. However, application of the modified Proctor test in the field is not practical due to the amount of time and labor required to prepare the cylinders for testing. Any delay in casting the standard 6-inch diameter cylinders can allow the mixture workability and properties to change due to cement hydration and evaporation loss.

Compaction Standards

Wet density is the most widely used method of reporting RCC density and should be the primary control standard used in RCC construction. Dry density, used in standard geotechnical construction practice, may provide some useful reference information. However, in RCC practice, one typically tries to achieve the fewest practical air voids that will occur at a higher water content than the maximum dry density, which is the objective used in typical geotechnical engineering practice. The difference between concrete practice and geotechnical practice generally follows from the fact that as RCC hardens its in-place density is reflective of the wet density of the material, not the dry density that is generally 10 to 15 pounds per cubic foot lower than the wet density. In general the wet density will remain constant throughout the chemical reaction (curing) process. While RCC does behave as a soil or granular base type material when it is first placed, the "optimum" water content from the modified Proctor test is typically less than required for full compaction (consolidation) of the RCC. The result is placement to the maximum dry density at optimum water content will generally result in more entrapped air voids than conventional concrete.

There are several methods that have been successfully used as compaction standards for RCC compaction control. The primary methods are: 1) theoretical air-free density, 2) field/laboratory cylinder density, and 3) average maximum density. These methods can generally be described as follows:

Theoretical Air-Free Density (TAFD) Standard – This method consists of a theoretically calculated density of an RCC mix based on the mass properties (specific SSD gravity and absorption). One factor that causes variations in the calculated wet density of the RCC is the percent of air contained within a sample of RCC, which can be difficult to accurately measure under field conditions. The percent of air measured in thoroughly compacted RCC mixes has typically ranged between 0.5 % and 2 %. Use of a percentage of the theoretical air-free density as a compaction control density eliminates this variability. Therefore measurement of the air content in the field would be academic. When differences in the field measured density and the TAFD are noted, it is more often due to variations in the aggregate proportions, which can be readily monitored by gradation analysis, or aggregate properties, such as the specific gravity and/or absorption of the material that may change throughout construction. The required compaction standard by this method usually ranges from 96 % to 98 % of the TAFD, with no individual test below 95 % of the TAFD.

Ongoing aggregate testing and mixing plant production during construction can be readily performed to monitor for changes in the proportions and/or properties. If variations are noted, the TAFD can be adjusted accordingly. This process is similar to performing gradation tests and compaction curves for conventional earthfill projects.

Cylinder Density Standard – Compaction control using cylinders compacted in the field or laboratory is based on measuring the average wet unit weight of standard 6 x 12 inch cylinders constructed of the RCC mix. As discussed above, the cylinders can be fabricated by the vibrating hammer method (ASTM C 1435), Vebe method (ASTM C 1176), modified Proctor (ASTM D 1557), or the use of a pneumatic tamper (which does not have a standardized test method). Test cylinders prepared by these four methods have been found to closely approximate the in-place density of RCC compacted under field conditions. When the cylinder density closely approximates the in-place field density, the compressive strength of the RCC cylinder can accurately approximate the compressive strength of the in-place compacted RCC. A metal mold should

Figure 7. Preparation of RCC using a pneumatic tamper.

be used to provide confinement and maintain the required cylinder dimensions during compaction.

Figure 8. Preparation of RCC cylinder using the Vebe Table.

The required compaction standard by the cylinder density method is usually at least 98 % of the average control cylinder density, with no individual test below 96 % of the average control cylinder density. Since entrapped air content is included in the results of all these methods, the density values will be less than the TAFD, by definition.

The vibrating hammer, Vebe, and modified Proctor test methods benefit from the existence of established standards that can be used in the laboratory during the design phase as well as for field control during construction. These test methods are repeatable and easy to perform. In the case of the vibrating hammer and Vebe test, the methods have similar compaction properties (frequency and amplitude of compaction) as field compactors typically used for construction. The pneumatic tamper, while showing good correlation with field compaction, has a significantly different amplitude and frequency of compaction (which varies widely based on the reaction force provided by the operator) compared to typical compaction equipment, and does not have a standardized test method.

Average Maximum Density (AMD) – The AMD test method involves the preparation in the field of a test section whereby the RCC is compacted with different compactors and various numbers of passes by the equipment, and the average maximum density achieved (as measured by the nuclear density gauge) is used as a control standard. The maximum density used for compaction control from a test strip is also sometimes referred to as the "optimum compaction density value" (although this term can be confused with the optimum moisture content and maximum density derived from the modified Proctor compaction test.) There are also several variations in terminology such as the maximum achievable density that are essentially developed in a similar manner. Based on the results of the field test section, the required placement density is specified as a percentage of the AMD. The standard for this method is similar to the development of a method specification for the control of rockfill placement.

During development of a method specification for fill placement, a full range of density, moisture, gradation, and void content analyses (either measured or compared with the theoretical air-free density) would also be expected to be performed. Therefore, more testing than the measurement of the in-situ density in the test fill is necessary to ensure that the AMD is representative of the required design conditions and not the result of the maximum density that can be achieved with an inappropriate compactor and/or a RCC mix that is too dry or too wet. The required compaction standard by this method is usually the average density no less than 98 % of the AMD determined in the test strip, with no individual test below 96 %.

The use of the AMD method should be combined with the measurement of the TAFD, void content, uniformity of the RCC density by depth, and engineering properties that may vary during construction (e.g., gradation, specific gravity, and absorption) that would require another test strip to establish a new AMD.

The end results of each method are actually quite similar. Using data from two actual constructed projects, the TAFD and cylinder densities can be summarized and compared to the compaction standard methods described above. Table 3 shows the TAFD, cylinder densities, and field densities for two projects.

Table 3 – Example Data for Compaction Standards

Density Method	Project A	Project B
Theoretical Air-Free Density (TAFD)	166.5 pcf	152.4 pcf
Cylinder Density	162.7 pcf	149.2 pcf
Field Density (average of tests during construction)	162.8 pcf	146.9 pcf

Using the data in Table 3, a comparison can be made of the compaction standard with conditions achieved in field. Typically, specifications using the TAFD as the compaction standard will require that field compaction achieve a minimum of 96 % of the TAFD. Using the example projects shown in Table 3, the field compaction standard density requirement for the two projects would be 159.8 pcf and 146.3 pcf as shown in Table 4, below.

Table 4 – Theoretical Air-Free Density Compaction Standard

Compaction Standard	Project A	Project B
Required Field Compaction Standard – 96 % TAFD	159.8 pcf	146.3 pcf

The actual field densities achieved during construction would meet the 96 % TAFD compaction standard.

Typically, specifications using the cylinder density as the compaction standard will require that field compaction achieve a minimum of 98 % of the average cylinder density. Using the example projects shown in Table 3, the field compaction standard density requirement for the two projects would be 159.4 pcf and 146.2 pcf as shown in Table 5, below.

Table 5 – Cylinder Density Compaction Standard

Compaction Standard	Project A	Project B
Required Field Compaction Standard – 98 % of Cylinder Density	159.4 pcf	146.2 pcf

Therefore, a similar objective is met using either of these compaction standards, and both methods have applicability of use in the laboratory and field. The field density tests for both example projects show that RCC can be compacted to an acceptable compaction standard.

Use of a test strip in the field as the compaction standard is much more subjective than the other methods described herein. For example, if the compactor used in a test strip is too light, the dynamic properties (frequency and/or amplitude) are not suitable for the RCC mix being used, or the mix is too dry or too wet, an AMD can still be developed. However, the result may be that the RCC placed may have a high enough void content that the strength, permeability, and/or durability could fall below the design objective or laboratory tests used for design. Therefore extra care and experience are needed when using the AMD method to establish a compaction standard. In all cases, knowing the air content of an RCC mixture (using the concrete practice definition) is critical to understanding the density of the in-place material, and it is important to use the extensive history of concrete strength, permeability, and durability when assessing the in-situ conditions of RCC.

Summary

Historically, different methods have been successfully used to establish a density standard for RCC placement during construction. Under project specific circumstances, some methods to control compaction and establish a maximum or target density may be more applicable than others. The most important objective in establishing a compaction standard for construction of RCC is to select a method that simulates the field conditions under which the RCC is being compacted and has a basis of repeatability and uniform application (of benefit to a contractor). The compaction method and method of arriving at the field target density should always be clearly described in construction documents.

Materials properties and mixture proportions should be clearly and completely defined. A complete listing of all of the properties (soil mechanics and concrete methodology) will greatly enhance communication and data interpretation and reduce the potential for misinterpretation of or confusion about the properties specified.

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Note: This document is written in English units. To convert to metric units use the conversion table presented below:

To Convert	Into	Multiply By
Inch (in.)	Millimeter (mm)	25.4
Foot (ft)	Meter (m)	0.3048
Square foot (ft^2)	Square meter (m^2)	.0929
Square yard (yd^2)	Square meter (m^2)	0.8361
Cubic foot (ft^3)	Cubic meter (m^3)	0.02832
Cubic yard (yd^3)	Cubic meter (m^3)	0.7646
Pound (lb)	Kilogram (kg)	0.4536
Pound per square inch (psi)	Kilopascal (kPa)	6.8948
Pound per cubic foot (pcf)	Kilogram per cubic meter (kg/m^3)	16.0185
Pound per cubic yard (pcy)	Kilogram per cubic meter (kg/m^3)	0.5933

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