Roller-Compacted Concrete Quality Control Manual

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Concrete Thinking for a sustainable world
PCA Portland Cement Association

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1.0 SCOPE

Over the past decade, roller compacted concrete (RCC) has been successfully used on projects ranging in complexity from large dams to small building pads. Regardless of the project's size or importance, field quality control is necessary. RCC designs are based on a level of quality achieved during construction. The purpose of this manual is to provide a field quality control guide for RCC projects.

This document provides general guidelines for establishing a field quality control program for the production and placement of RCC. Using this guide, development of a project specific program should be established as part of final design, through coordination with the project owner and design engineer. The actual frequency and extent of inspection and testing should be determined according to the size of the project, the sensitivity of the design to variations in quality, and the quantity and rate of RCC production. This document includes the presentation and explanation of standard or developing quality control testing procedures for production and placement of RCC.

2.0 DEFINITIONS

There are different components to quality including quality of the data generated, quality of the test procedures and quality of the overall day-to-day operation. All projects should have a quality program consisting of quality assurance and quality control. Although these terms are often used interchangeably, there is a significant difference drawn between the two terms, and it is important to clarify the meaning of these terms in the context of this document. The distinction is as described below:

Quality Assurance (QA) can be defined as the process by which quality can be independently measured to demonstrate that quality is maintained. The result is documentation of the quality program.

Quality Control (QC) is defined as a series of operations or tests and observations, which are designed to ensure that the product is produced and placed within known limits of accuracy and precision. The results are test data and measurements that are compared to specific criteria.

Quality Control Program. A document, separate from the construction plans and specifications that details the activities, procedures and responsibilities for the specific project.

This document primarily describes Quality Control with some discussion of Quality Assurance.

3.0 RESPONSIBILITIES AND QUALIFICATIONS

It is of paramount importance that the roles and responsibilities for the individuals and organizations participating in the construction of an RCC project to be clearly established. The roles are often established by the Owner and Engineer and are detailed in the technical specifications and contract documents. However, it is recommended that the field quality control program for a RCC project include a specific description of the roles and responsibilities assigned to the individual(s). The following paragraphs provide a general guideline of the responsibilities for representatives of the Engineer, Owner and Contractor involved in the construction of an RCC project.

Engineer – The Engineer is usually responsible for quality assurance during construction, which may include field observation and testing, as well as preparing documentation and providing responses to project specific questions and concerns from the Owner and Contractor. The Engineer will typically monitor day-to-day RCC operations for adherence to the technical specifications. These usually include RCC batching, transportation, placement, surface preparation, compaction, curing/protection and strength testing. Specific operations performed by the Engineer could include in-place density testing, temperature monitoring, cylinder preparation, and compressive strength testing, among others. Quality Control testing can be included in the responsibilities of the Engineer.

Owner – The Owner is responsible to retain a qualified firm, with the appropriate staffing level, to perform the required quality control testing and inspection. This typically may be the Engineer (preferable) or a third party testing agency.

Contractor – The contractor is responsible for the quality of the construction. The contractor should have at a minimum, a RCC superintendent and foreman experienced in the construction of RCC projects to manage the construction personnel. Frequently, contract construction documents will require that the contractor and its superintendent have experience in RCC.

4.0 PRODUCTION AND MATERIAL QUALITY – TESTING METHODS, PROCEDURES, AND REPORTING

4.1 Roller Compacted Concrete Constituents

RCC is generally produced by mixing aggregate cement, pozzolan, and water. Occasionally, admixtures will be introduced into the RCC in order to modify a particular behavior. The following sections briefly describe each constituent and provide guidelines for inspection and testing of each. Details regarding test methods and testing frequency are presented on Table 4-1.

4.1.1 Aggregates

Generally, RCC contains coarse and fine aggregates similar to conventional concrete. However, a wider gradation bandwidth, than used for conventional concrete aggregate, is frequently specified. Acceptable aggregate gradations can be supplied from a single "all-in gradation" or from two or more stockpiles depending on the gradation specified, the uniformity of the raw material supplied, and the design requirements. An example of an all-in gradation would be a standard state Department of Transportation or a county roadbase specification. Independent of stockpiling, several important aspects of the aggregate must be considered as part of a field quality control program.

a. **Source** – The aggregate source should be inspected and tested for quality and consistency throughout the construction period. It is advisable to perform multiple tests to confirm consistency of the material gradation, and engineering properties such as absorption, specific gravity, plasticity index, durability, etc.

b. **Stockpiling** – Proper aggregate stockpiling procedures should be followed including: a) stockpile side slopes should be flatter than the angle of repose of the aggregate, b) building stockpiles in layers by placing adjacent piles no larger than a truck load and leveling a layer for placement of a succeeding layer (in no event should material be pushed over the edge of the stockpile; which will cause segregation of the aggregate), c) prevent overlap of different sizes between stockpiles, and d) provide a clean stockpile base and haul road to prevent contamination from the underlying material and from hauling unit travel. Separating the aggregate into multiple size fractions is also a good method to control segregation of the material.

On large volume RCC projects, the temperature of the aggregate stockpiles may also require monitoring for use in the planning and control of the RCC placement temperature. It is often advised to stockpile aggregate during colder weather in order to take advantage of cooling the aggregate, for use during warm construction seasons. ACI 304R (Guide for Measuring, Mixing, Transporting and Placing Concrete) provides a good reference for stockpiling procedures and controls.

c. **Gradation** – Due to the significant impact of gradation on the workability, mix proportions, and required compaction effort, it is recommended that gradation testing be performed at the source processing facility as well as at the project stockpile(s). Testing at the source can prevent delivery and hauling of material not meeting the project specifications. In addition, comparison of tests from the source and at the project can also provide information on potential aggregate breakdown from the handling, hauling and stockpiling activities.

During RCC production, the aggregate stockpiles should be tested at least once per shift and the results systematically compiled to evaluate consistency over time. The technical specifications will usually provide the frequency for gradation testing. The results can be presented in a graphical format in order to provide a visual representation of the results over time. In addition, a running average can be calculated and graphed to indicate overall trends in gradation over time. Sampling should be conducted at several different locations on the stockpile in accordance with ASTM D-75 procedures.

d. **Moisture Content** – The moisture content of the aggregate stockpiles can vary considerably depending on weather conditions during and subsequent to stockpiling, and throughout the day during RCC production. It is not uncommon for changes of aggregate moisture content as little as a few tenths of a percent, to affect the workability and compaction characteristics of the RCC. Uniform moisture content of the aggregate feed to the mixing plant can be largely controlled by careful selection of material from the stockpile.

Ideally, the aggregate should be tested for moisture content several times per shift at the start of production activities and following periods of rain, and taper off to once per shift later in production. The technical specifications will often provide method and frequency of testing. The results will be used to calibrate the mixing plant as well as to calculate the actual amount of water being introduced to the RCC.

e. **Mining** – Mining of the aggregate stockpiles during production is a vital but often overlooked part of quality control. One significant difference between conventional concrete and RCC is the lower amount of water that is added to the mix. Due to the fact that most of the water in RCC can originate from moisture in the aggregate stockpiles, small changes in the moisture content of the aggregate can affect the final product. With projects that have stringent temperature requirements, the mining location can have a significant affect on the RCC mix temperature as well.

Although mixing plants can accommodate gradual changes in the overall moisture content or temperature of the RCC when they are identified in testing or by inspection on the fill, sudden changes are difficult to anticipate and control. Therefore, it is important during production to supply aggregate with consistent moisture (and temperature when necessary) to the mixing plant. Each operator designated to mine the aggregate stockpiles should be informed as to importance of carefully mining a stockpile face to provide a uniform gradation and moisture content.

Table 4.1
SAMPLE QUALITY-CONTROL TESTS

Material Tested	Test Procedure	Test Standards[1]	Frequency[2]
Water	Quality	ASTM C94	Prior to construction or as required
Cement	Physical/Chemical Properties	ASTM C 150 or equivalent	Manufacturer's certification or prequalified
Pozzolan	Physical/Chemical Properties	ASTM C 618 or equivalent	Manufacturer's certification or prequalified
Admixtures	Chemical Properties	ASTM C 494 ASTM C 260	Manufacturer's certification
Aggregates	Quality	ASTM C33	At initial project start. 1/week to 1/month thereafter depending on history with source.
Aggregates	Specific Gravity – Absorption	ASTM C 127 ASTM C 128	1/week to 1/month per aggregate stockpile
Aggregates	Grading	ASTM C 117 ASTM C 136	1/shift or 1/day
Aggregates	Moisture Content	ASTM C 566 ASTM C 70	Before each shift/and as required
Aggregates	Flat/Long Particles	ASTM D	1/month or as required
Aggregates	Atterberg Limits	ASTM D 4318	1/week or 5,000 yd^3 (4,000 m^3)
RCC	Consistency and Density	ASTM C 1170	2/shift or as required
RCC	In-place Density	ASTM C 1040	1/hour or every 250 yd^3 (200 m^3)
RCC	Oven-dry Moisture	ASTM C 566	1/shift or every 500 yd^3 (400 m^3)
RCC	Mixture Proportions		Each batch ticket or each 10 minutes for continuous flow mixing plants
RCC	Mixture Proportions – RCC Mix Variability	ASTM C 172, C 1078, ASTM C	1/week or every 5,000 yd^3 (4,000 m^3)

		1079, with special requirements	
RCC	Temperature	ASTM C 1064	1/four hr or every 500 yd^3 (400 m^3)
RCC	Compressive Strength[3]	ASTM C 1176 or Vibrating Hammer	1/day or every 2,000 yd^3 (1600m^3)

[1] Other appropriate industry standards may be substituted.
[2] The frequency shown is an example typical of smaller projects and/or thorough agency testing. On projects with less stringent designs, and as a history of project specific results are developed, less frequent testing may be appropriate.

4.1.2 Cementitious Material

RCC can be produced with portland cement or a combination of cement and pozzolan. Although the percentage of cementitous material used in RCC is relatively low (generally ranging between 3 and 15 percent), it is often the constituent with the smallest allowable variance as defined in the technical specifications. Too little cement can lower the ultimate RCC strength and durability to unacceptable levels, whereas too much cement can cause additional heat generation and increase the potential for cracking in the final RCC product. RCC is used for mass concrete placements where heat generated is usually a design and performance concern.

Generally, cement and pozzolan are accepted based on the manufacturer's certification, although sampling and independent testing is sometimes performed. Type II cement is frequently specified. However, low heat cements such as Type IV, special Type II with the optional requirements and some Type V cements are often specified. Special low heat Type II cements are available in a few areas of the United States. Before specifying a low heat type cement, the Engineer must determine its availability in the project area. Certain special cements may not be available in some areas, and availability can vary with time. Type IV cements are not generally available. Blended cements are sometimes available such as Type IP. These cements have a predetermined percentage of a pozzolan blended in with the cement.

Confirmation of the cement and pozzolan properties versus the project requirements is an important, early QC function. Testing to confirm special requirements that can be specified, such as Type II cement with a maximum 7-day heat of hydration of 70 cal/gm (290kJ/gm) should be confirmed at the outset of the project. In addition, certificates for each delivery of cement or flyash should be required and reviewed by the QC Manager. General requirements and characteristics of cement can be found in ASTM C150. Silos and portable storage pigs should be organized and clearly marked to prevent deliveries being transferred to the improper storage unit and inadvertent use of pozzolan instead of cement.

4.1.3 Water

The water available for chemical hydration within RCC comes from two sources. A portion originates from water added by the mixing plant while the majority typically is contained as excess (free) water in the aggregate. The quality of the water is also important. Water quality is usually specified to meet the requirements of ASTM C-94. The Engineer should test the water source prior to construction and, if possible, use site specific water to conduct RCC mix designs. It is important to know the location of the construction water source and any limitations on its utilization early in the project.

4.1.4 Admixtures

Occasionally, admixtures will be used to influence the behavior of the wetter consistency RCC mixes, with the results providing varying degrees of success. Air entraining and water reducing admixtures have been effective in improving workability, reducing the water content and delaying the set time. Some success in obtaining air entrainment has been achieved in bench scale laboratory testing. Quality control of admixtures primarily focuses on confirming that the specified quantities and type of admixture are introduced into the mix. Measurement of air entrainment on field RCC mixes has not been consistently successful. Test procedures for determining the air content of compacted RCC have not been developed. ASTM C-231 (with some modifications) can be used for determining the air content of RCC mixes with a vebe time of about 45 seconds or lower. Damage to the "air pot", in particular the top edge that seats the pressurizing apparatus, can occur when compacting the RCC in the air pot. Modifications have been made by fabrication of a guide sleeve to protect the edge of the "air pot" during compaction of the RCC in multiple lifts. Standardizing lift placement procedures for the test have also not yet been developed.

4.2 Roller-Compacted Concrete

RCC can generally be described as a zero slump concrete that has many of the same characteristics and associated quality control measurements as conventional concrete. The following sections describe RCC and discuss the various methods typically employed to test the quality prior to placement. Additional procedures for monitoring RCC quality during and after placement are discussed in Section 5 of this document.

4.2.1 Testing

Testing should be initiated in the early stages of construction. Laboratory testing can be started as soon as material is produced, or a commercial source is identified for the project. It is especially important when design strengths at ages greater than 28 days are specified. Submittal of RCC materials is frequently required early in the construction schedule. There is a battery of tests that assess the quality of RCC as it is produced by the mixing plant. However, there is no single test or set of tests that can accommodate all RCC mix designs.

Due to generally rapid placement rates, and for large volume projects where around-the-clock production schedules are frequently required or utilized (20 to 24 hours per day), the following quality control tests must be performed, checked, reported, and evaluated in a timely fashion. Table 4.1 provides a reference for typical test type, reference standard, and common frequencies of testing. Typical staffing requirements for various size projects are listed in Table 4.2. A summary of the primary testing categories follows:

Table 4.2
TYPICAL TESTING PERSONNEL REQUIREMENTS

Testing	Small Project <10,000 cy	Medium Size Project 10,000 to 100,000 cy		Large Project > 100,000 cy
		Single shift	Double shift	
Personnel Required	1-2	2-3	4-5	3+/shift

a. **Sampling** – When testing RCC for specification compliance, it is important to properly sample the RCC in order to obtain a representative sample. There are two primary locations for sampling: 1) after mixing and prior to placement, usually from the conveyor belt (some plant setups have a tripping mechanism to divert material from the belt); and 2) from the RCC lift at the placement area. In either case, a sufficient size sample in accordance with ASTM D 75 should be obtained and then quartered to obtain the appropriate test sample size, ASTM C 702. It is important to recognize that material sampled from the lift placement area may have experienced some degree of segregation caused by the conveyance system or placing method. The QC inspector should be careful to evaluate if segregation is occurring in the construction process, and/or by the sampling method.

b. **Consistency-Modified Vebe Test** – The Vebe test provides a measure of the RCC mix consistency or workability for some RCC mix designs. The standard concrete Vebe test has been modified for RCC testing. The Vebe test result consists of the time (seconds) required for a ring of mortar to appear around the periphery of the surcharge plate (Figure 4.1). This generally corresponds to the time necessary to fully consolidate the RCC sample under a given surcharge load. This test is suitable for RCC mixes with a Vebe time of between 10 and 60 seconds. The general test procedure for RCC is provided in ASTM C 1170. The test can be used for general assessment of the RCC workability but is generally not suitable for control of the uniformity of the mix during production and placement. This test method is also not suitable for RCC mixes with a Vebe time in excess of 60 seconds.

Figure 4.1—*Vebe consistency test with a ring of mortar on the consolidated sample.*

c. **Modified Proctor Compaction Test** – The modified proctor compaction test (ASTM D1557) is a widely used test for compaction control of fill. The test establishes the relationship between the moisture content and dry density of a material for the specified compaction energy, and yields a maximum dry density at an optimum moisture content. For compaction control of earthfill, a moisture content range and a percent compaction of the maximum dry density is usually specified. Compaction equipment has been developed that can efficiently achieve greater than 95 percent of the maximum dry density in the fill, and the relationship between the "workability" (the ease with which the material can be compacted to the specified percent compaction), compaction equipment and number of passes, is understood by engineers and contractors.

The equipment and procedures for the modified proctor test requires some modifications for use with most RCC mixtures. In the modified proctor compaction test, the sample is compacted in a mold in five equal layers by 25 blows of a 10 pound hammer, falling 18 inches. The mold is 6 inches in diameter and the sample height is 4.584 inches. The test with RCC is usually modified by: 1) not using the replacement of the plus _ inch size fraction as specified by the standard, 2) wet screening the RCC mixture to remove material greater than 1.5 inches in diameter, and 3) placement in 3 layers with 42 blows per lift, instead of 5 layers with 25 blows per lift. It has also been found that, due to the relatively large gravel size fraction (usually greater than 60 percent), material breakdown can occur during compaction using the standard compactor face. Therefore, a modification in the test equipment to use a full face (5_") compaction plate has been used to limit material breakdown. RCC testing using the modified proctor compaction procedure has been reported by Reeves and Yates (1985) and Wong, Bischoff and Johnson (1988).

d. **Cylinder Preparation** – The primary objective of cylinder preparation is to duplicate the compaction effort and consequently the in-place density of RCC after compaction. Cylinder preparation methods have included: 1) Vebe method ASTM C1176, 2) vibrating hammer method ASTM C1435, 3) modified proctor method ASTM D1557 with some modifications, and 4) pneumatic tamper. A steel mold with plastic liner is typically used for preparing RCC cylinders. The steel mold has been constructed using 6-inch diameter steel pipe that is split on one side with one or two adjustable clamps to tighten the mold around a standard plastic concrete mold that is used as a liner. The steel mold is usually attached to a base plate either permanently or mechanically, and a collar is used for overfilling the cylinder for the top lift of RCC. The RCC cylinders are constructed in lifts (ranging from 3 to 5) depending on the consistency of the mix and tamping method used to prepare the cylinders.

The Vebe apparatus is used for cylinder preparation with wetter consistency mixes (generally 10 to 35 second Vebe times). The vibrating hammer (Figure 4.2) method can be used for a wide range of mix consistencies (generally from 10+ second Vebe times). Cylinders for drier consistency mixes (45+ second Vebe times) can be prepared using the vibrating hammer, pneumatic tamper (Figure 4.3) and modified proctor compaction apparatus. Discussions of the various methods of RCC cylinder preparation can be found in Arnold, Feldsher and Hansen (1992), and Wong, Bischoff and Johnson (1988).

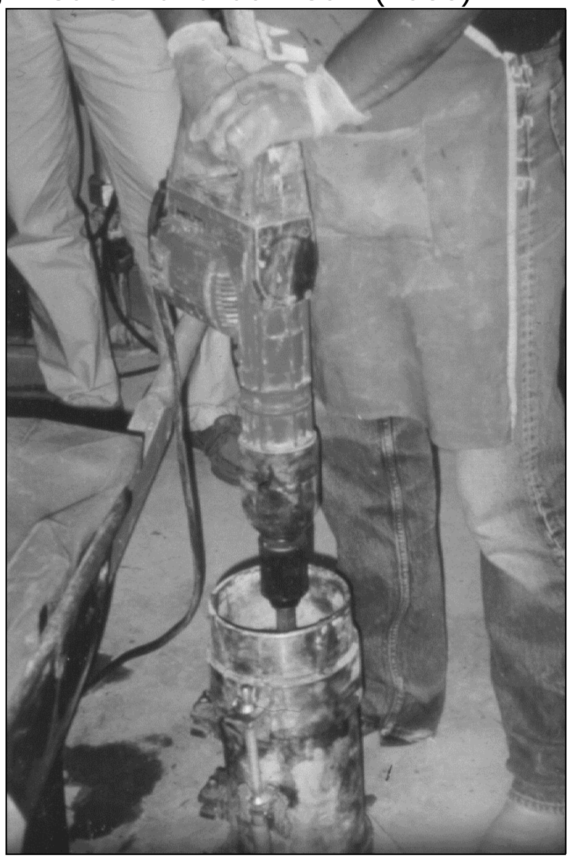

Figure 4.2*—Preparation of RCC cylinders with a vibrating hammer.*

Figure 4.2*—Preparation of RCC cylinders with a vibrating hammer*

The engineering properties of no-slump RCC are more variable than conventional concrete. Measurement of the wet density of RCC cylinders can be used to evaluate the uniformity of the cylinders that are prepared for testing. The wet density of each cylinder in the batch should be measured in accordance with ASTM C138. Variations in cylinder wet densities are normally within a range of 2± percent of the mean weight. Cylinders with a wet density that is more than 2 percent off of the mean should be discarded and replaced with a new cylinder.

e. **Moisture Content** – The moisture or water content of RCC provides: 1) valuable information required for calculating RCC mix proportions and the water/cement ratio, and 2) an indication of the uniformity and workability of the RCC. The water content can be calculated using drying tests (ASTM C 566, D 4643, and D 4959), nuclear density meter tests (ASTM D 3017), and chemical tests (ASTM C 1079). Due to the chemicals required and the need for a relatively clean laboratory environment, the chemical test is rarely used in the field.

Three drying methods (hot-plate, oven and microwave) are widely utilized on RCC projects. However, it should be noted that evaporation and chemical hydration of cement can affect the test accuracy because these affects are specifically a function of time, temperature, moisture content, mix proportions, and material properties. The results of hot-plate and oven-dry tests compare favorably to the theoretical water content with controlled sampling and testing, if the sample is covered immediately after sampling and tested within one hour after batching. Results from the microwave oven tests have not proven to be as reliable as either the hot-plate or the oven-dry tests. Because the water content of RCC will vary from that tested immediately after mixing to that tested after compaction, each test result should include date, time, and location.

The nuclear density meter is generally utilized to measure in-place density. It can also be used to estimate water content. The moisture content measured by the nuclear density meter can be affected by compaction, paste content in the zone of moisture testing, surface moisture changes due to evaporation or precipitation, and curing water. The single-probe nuclear density meter, which is the primary testing method used for RCC field testing, measures the water content only near the surface (the top 2± inches). The results are usually indicative of the water content of the mix, but may not provide an accurate measurement of the water content of the full lift thickness. The double-probe meter is capable of testing at user specified depths from 2 to 24 inches, but the equipment is not as widely available and can be more difficult to use.

f. **Cement Content** – RCC generally contains a relatively low percentage of cement. The most common tests consist of the chemical test ASTM C 114 (Chemical Analysis of Hydraulic Cement) and ASTM C 1078 (Method of Determining Cement Content of Freshly Mixed Concrete). These tests require specialized equipment, training and/or off site testing which have limited ability to obtain the real-time results. The heat of neutralization test (ASTM D5982, Method of Determining Cement Content of Fresh Soil-Cement) is likely the easiest test to perform in a field laboratory. This test involves preparing the RCC mix at different cement contents. The temperature rise of the mix is then measured after a chemical is added. A curve of cement content versus temperature rise is developed. Subsequent tests on the RCC mix as produced, can be used to estimate the cement content using the temperature rise due to the chemical reaction, and the calibration curve.

At a minimum, monitoring of the cement content should include: a) calibration of the cement added by batch, or by time interval for continuous flow mixing plants, and b) mass balance of cement usage on a daily basis. The method of plant calibration and monitoring of the mass balance will vary depending on the type of cement feeder involved. Weight based cement feeders are generally more reliable than a vane, belt or screw feeder. Calibration of a weight based feeder can be accomplished by directing cement into a box on a truck and measuring the actual weight of the material, box and truck. The actual weight and the plant recorded weight are then compared and adjustments are made to plant calibration factors. The process is repeated until the weights are within an acceptable, 1 percent or less, tolerance. The quantity that is measured in this method is typically small due to the difficulty of transporting from the plant in to a truck, concerns with waste of cement, and truck limitations. Weights reported by plants using vane, belt or screw feeders are based on the number of rotations of the vane, belt or screw to the calibration factor. With these types of devices, the vane or screw can continue to operate and report weights, even if no cement is flowing into the mixer. More care and inspection is needed to identify and avoid this potential problem.

To overcome calibration limitations using small quantities, an effective way to calibrate a plant using a larger volume of cement is to run 5 to 10 tons through the plant and pump the cement into an empty cement truck. This allows calibration using a larger volume and potential reuse of the product by transferring the cement back into the plant silo. This procedure has been used on several projects to calibrate the plant. If this procedure is to be used, it should be included in the project specifications.

In addition to an initial plant calibration, periodic checks are important throughout production. An effective method is to run a “dry silo test”. A dry silo test consists of starting with the silo essentially dry and then filling the silo from a cement truck with a certified weigh ticket. The plant would then be operated until the same “dry” silo level and the plant reported weight is compared to the truck weight. This method requires planning and coordination in advance by the contractor.

g. **Pozzolan Content** – There is no approved industry standard for determining the pozzolan content of the mix. Calibration of the plant, monitoring of the batch records, mass balance and silo tests should be used, as described above for cement content.

h. **Compressive Strength Testing** – As with conventional concrete, compressive strength testing has limited use as a real-time field quality control tool. In addition, many RCC project design strengths are associated with 90 day to 365 day tests, except for most spillway and overtopping protection projects which are tested at 28 days. RCC compressive strength tests results for 7 day and 28 day time intervals provide a data base to evaluate uniformity of the product with time, as well as the trend in strength results with time. Variations in the compressive strength data can indicate a change in the RCC mix that may require further investigation and adjustments. Compressive strength test results also serve to provide an early indication of the actual field RCC properties for comparison with specification requirements, laboratory mix designs and documentation of the product placed for comparison with design criteria. By the time reliable results indicating a low ultimate strength are available, the project may have progressed well beyond the questionable area. However, the collective test results from cylinder breaks are valuable for indicating the overall quality maintained during the project.

i. **Temperature** – Limits on RCC temperature are often provided in the technical specifications. Frequent checks of the RCC temperature should be conducted particularly in very hot or cold weather. The temperature readings are generally estimated by using hand held thermometers, or thermocouples installed in specified lifts, placed in the RCC. All thermometers should be calibrated on a routine basis throughout RCC production. Variations in RCC temperatures are to be expected throughout each shift. Temperature variations in RCC at placement will generally parallel the weather conditions.

Placement temperature requirements will be stated in the project specifications, if required. RCC temperature requirements are usually specified as a maximum acceptable temperature at placement, or as a degree-hour criteria that can be monitored using a conventional concrete thermometer, inserted into RCC at the placement area. Monitoring using the degree hour methodology usually involves monitoring of air temperature versus time, and a comparison of the time of exposure of a lift surface with the sum of the temperatures hourly over the time of exposure. Temperature measurements can be based on a standard thermometer or a mechanical clock thermometer with a strip chart, maintained near the RCC placement area. Based on the comparison, joint surface treatment is implemented as detailed in the project specifications. Example calculations of the degree hour procedure are presented in ACI 207.5R.

j. **Mixer Uniformity** – In order to evaluate the relative uniformity of RCC, the technical specifications will often require mixer uniformity or variability tests. These tests generally require large samples (> 400 lbs.) at 3 locations in a batch or at 3 time intervals from a continuous mixing plant. On some projects, the samples are collected at several times during a shift. As described above, mixer uniformity tests are labor and equipment intensive. Significant planning and an increase in testing personnel are required to complete the tests in the required timeframe.

Table 4.3
Uniformity Test Parameters

Test	Maximum Allowable Difference (See Note 1)	ASTM Standard
Water content of full mix (percent by weight)	15%	D 2216
Coarse aggregate (plus No. 4, percent by weight) of RCC mix	15%	C 94 (Annex)
Unit weight of air-free mortar (Ib/cy)	2%	C 94
Air content of full mix	100%	C 231
Wet unit weight (density) of full mix	2%	C 1170
Compressive strength at 7 days	25%	C 39
Vebe time	15%	C 1170

(1) Maximum Allowable Difference = (maximum value minus minimum value, divided by average of three tests).

k. **Gradations** – Gradations of the RCC after mixing are sometimes performed to evaluate the uniformity of mixing. ASTM C-94, Annex A1 is often specified for performing mixer uniformity testing. The standard mixer uniformity test is usually modified to accommodate the difference between conventional concrete and RCC. The primary differences are: a) RCC properties are more variable, b) the cement content is much lower, c) RCC is often mixed in a continuous mix plant in contrast to drum mixing a batch plant, and d) additional mixing and/or segregation of the mix can occur at the fill placement.

Gradation tests of the RCC mix usually focus on the percent of coarse and fine aggregate. Sampling for gradation tests at batch plants usually consist of 3 samples (1 each at the beginning, middle and end, one third of the batch). With continuous mixing plants, it is important that the sampling times for mixer uniformity tests are obtained at similar production rates and with aggregate from the same stockpile locations to minimize variations induced by outside influences. Sampling for gradation tests has also been specified to occur on the fill on some projects.

Because of the large sample volume required, and the necessity to wash the samples quickly due to the cement in the sample, the mixer uniformity test is a very labor-intensive test. Additional manpower and equipment is needed to accomplish the testing in the necessary timeframe.

4.2.2 Reporting Forms

Due to the potential variability in the properties of RCC and its' constituents, individual test results may not represent the overall quality of the material. Therefore, it is generally accepted that a trend (defined by a series of test results) is much more effective in identifying changes in material performance and establishing corrective measures. The result of any single quality control test should be weighed against previous results in order to evaluate the significance of the test result.

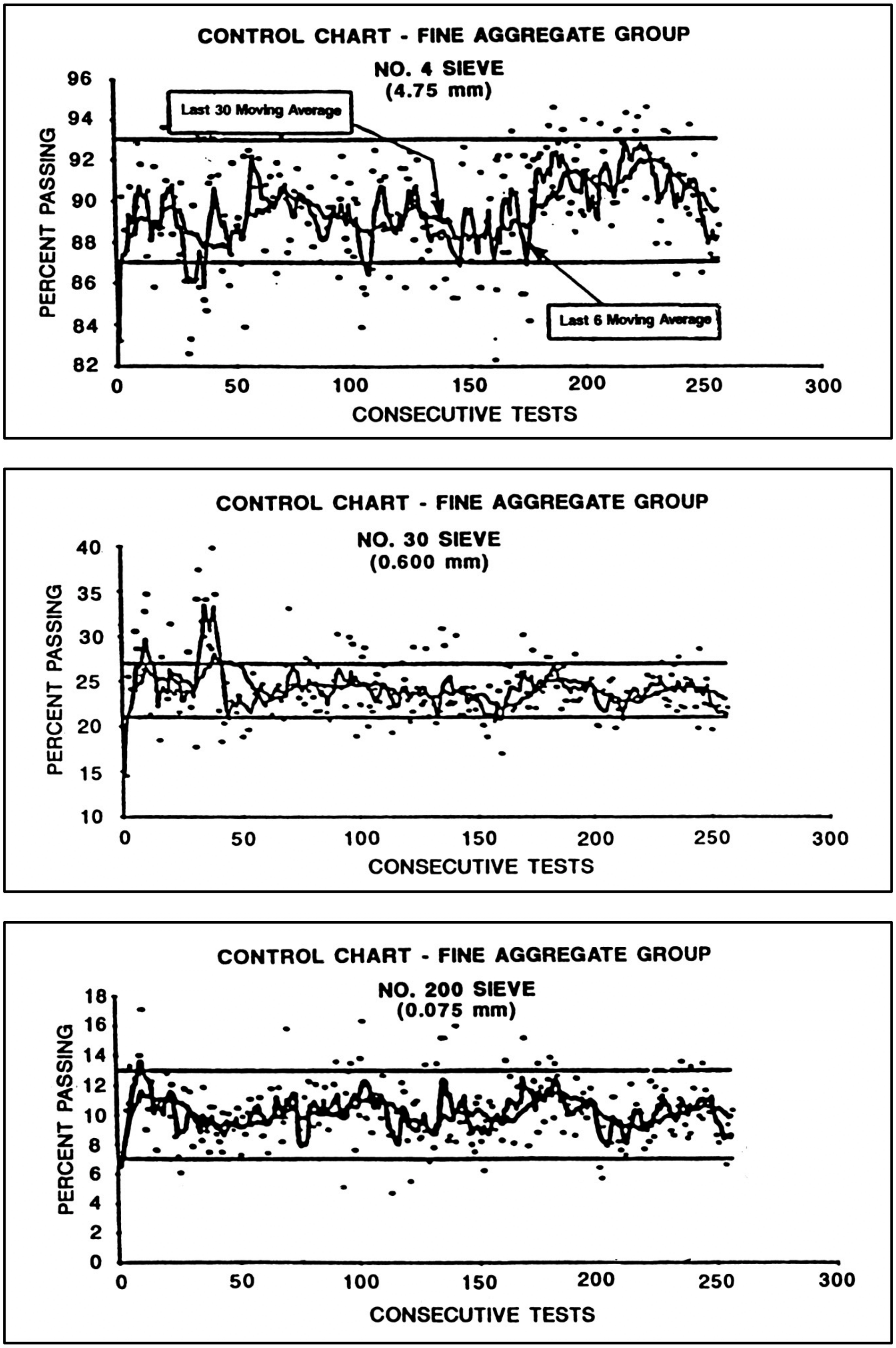

Figure 4.4*—Typical control charts for tracking fine aggregate grinding results by selected individual sieves.*

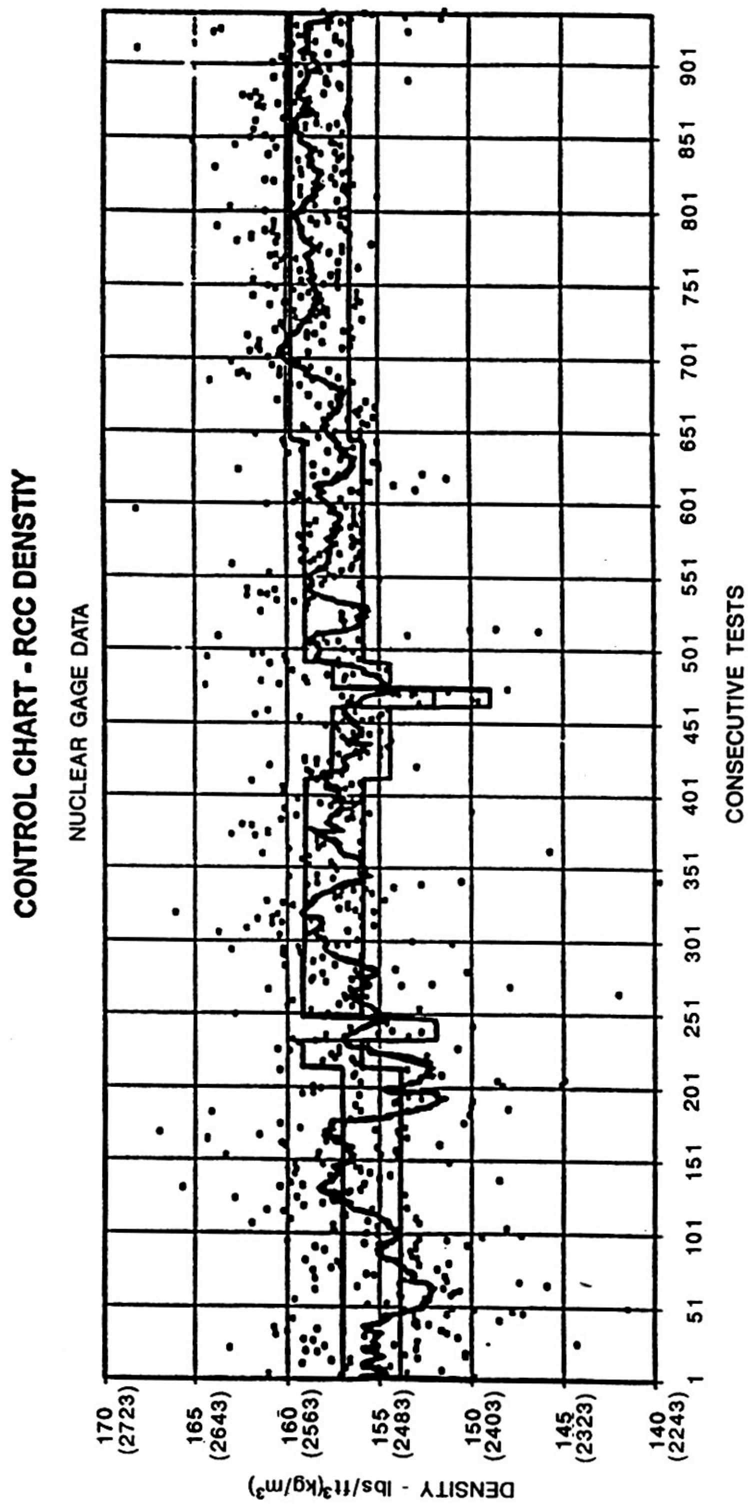

***Figure 4.5**—Typical control chart for consecutive wet density test results.*

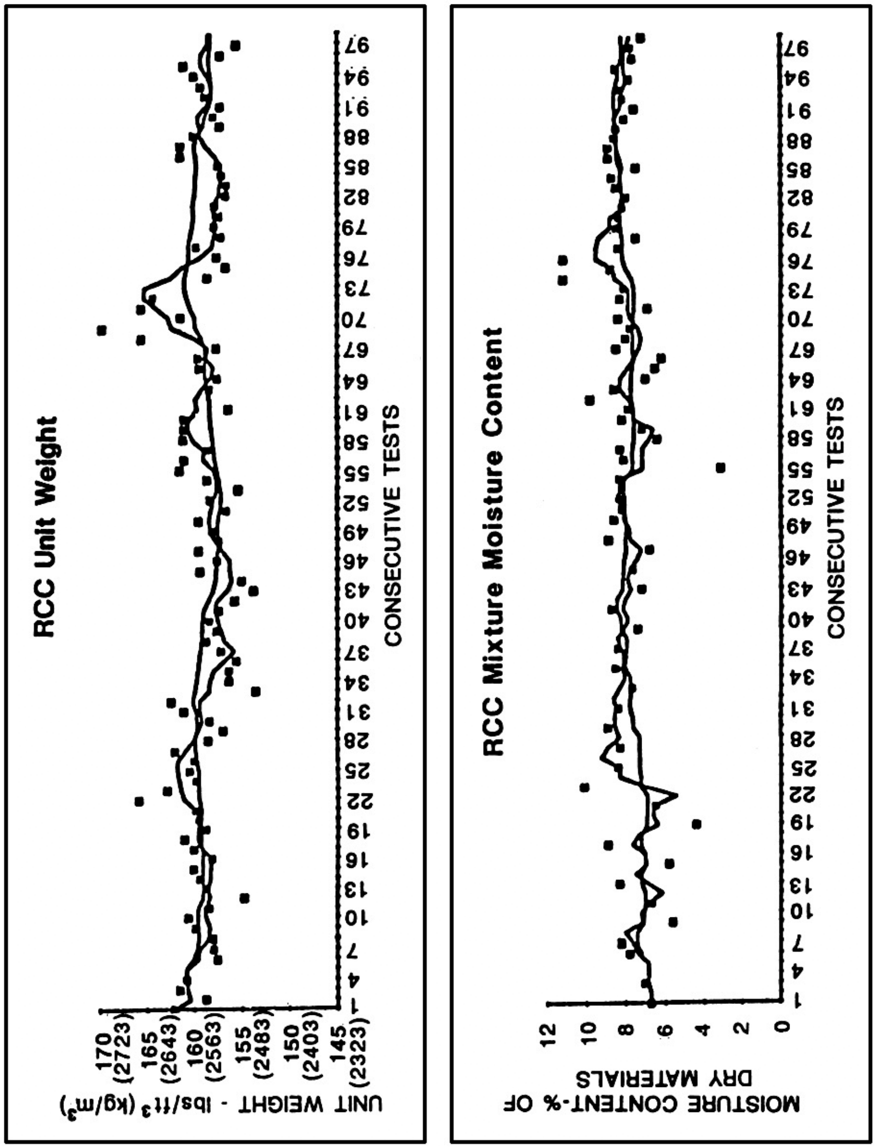

Figure 4.6*—Typical control charts for consecutive test of unit weight and moisture content.*

The most effective means of collecting, reducing and interpreting quality control test data is through the use of “control charts”. Tabulating, summarizing, and calculating data trends using personal computers is a relatively simple process. Control charts should be initiated at the test section construction and maintained throughout RCC placement. The most important data to monitor includes the mixture proportions (by batch or time interval), in-place density, moisture content, aggregate gradation, temperature, and compressive strength. Sample control charts for aggregate grading, wet density, unit weight, and moisture content are shown on Figures 4.4, 4.5, and 4.6.

4.3 RCC Test Section

The RCC test section is an important stage in an RCC project and it is vital for the ultimate success of a project for several reasons. First, it allows the contractor to demonstrate equipment and procedures to be used for mixing, handling, and placing RCC. Second, compaction procedures can be established that produce RCC densities that meet the project specifications. Third, the test section can serve as a training area for quality control and construction personnel. Fourth, the RCC design mix can be evaluated through workability, density and laboratory testing, thus allowing fine tuned adjustments in water content, cement content or the ratio of coarse and fine aggregate. Sometimes, several smaller test strips are constructed in advance of the test section to evaluate mix handling characteristics and compaction performance. It is preferred that the location of the test strips and test section be either in an area away from the structure or in a non-critical section of the work. The test section dimensions often depend on the size and complexity of the project. However, test sections are generally at least four vibratory roller widths wide, six or more vibratory roller lengths long, and at least 3 lifts high.

The RCC wet density for compaction control should be specified in the contract documents. Compaction control is usually specified by one of three methods: 1) a percent compaction of the theoretical air free density (TAFD), 2) a percent compaction of control cylinder density, or 3) a percent compaction of the density achieved in a test section (such as an “average maximum density value).

The use of a percent compaction of the theoretical air-free density or a percent compaction of control cylinder densities for compaction control has several advantages. Advantages include: a) the results are predictable and repeatable,

b) the percent compaction methodology is widely understood by engineers and contractors, c) the results will naturally vary with changes in material properties, and d) perhaps most importantly, these methods can be used in both laboratory and field programs, with the result that field test results can be correlated to laboratory test results.

Disadvantages of these methods will include: a) use of the TAFD is not related to the “compactibility” of a mix and in the case of a mix that is too wet or too dry, may not be readily achievable in the field; and b) mixes with too little paste may result in cylinders that have voids; however, the affects of such defects should be reflected in the laboratory test results. Overall, these disadvantages can be resolved in the laboratory design phase.

When the average maximum density value is specified for a project, the value is determined in the test section, or a test pad constructed immediately prior to the start of RCC placement. The value is typically determined by placing the specified mix on a firm foundation, and then compacting the RCC lift by a series of roller passes (usually 4, 6 and 8). A density test(s) is then obtained after each series of roller passes using a nuclear density gage. The roller passes and density tests are continued until no significant increase in wet density is measured. Several different rollers are frequently used in a trial section to identify what equipment will be suitable for the RCC mixture and placement conditions.

The average maximum density value procedure is a satisfactory method for RCC compaction control; however, there are several disadvantages and/or complications. These are: 1) this methodology cannot be used in the laboratory design phase, 2) this methodology is not widely understood by contractors and engineers, in contrast to a percent compaction of control cylinders procedure which is similar to the percent compaction of a standard density test approach, 3) there can be a large number of tests to be performed in the field when selecting a vibratory roller (i.e., two to three compactors are usually tried in a test section, and each compactor typically has two or more frequency settings and one to two amplitude settings), 4) using a field test placement for RCC compaction control could result in different wet density results than the basis for design yet meet specification requirements, which would ultimately lead to conflicts after a contract has been awarded, and 5) with some mixes (such as dry or harsh mixes) the average maximum density value from the test section could be significantly (>5 percent) lower than theoretical air free density. Consequently, the field properties may be inadequate for the design conditions. If the project design properties are based on a compacted RCC density of between 96 and 98 percent of the theoretical air free density. When determining average maximum density in a test section for a project, the density should also be compared with the theoretical air free density of the mixture.

In general, more consistent results can be obtained if both the laboratory design program and field control are based on compacted RCC control cylinders (either method ASTM C 1176 or C1435) representative properties can be obtained and this procedure assimilates standard widely understood fill control practices. The TAFD method would also be recommended over the average maximum density method.

4.4 RCC Mixing Plant

The two distinct methods of mixing RCC are batch-type and continuous-flow mixing plants. Batch type plants generally proportion the components by weighing the aggregates, cement and pozzolan, and volumetric measurement of mixing water. Continuous flow mixing plants use either volumetric measurement of each constituent or a combination of weight measurement and volumetric measurement. An essential element of quality control is the monitoring of batch weights or volumetric proportions during RCC production. However, perhaps the most important aspect of quality control for plant production is understanding the plant measuring and control system. The type of measurements and control system definitions are critical to accurate communication of mixture proportions and plant records between the plant operator and the QC staff.

4.4.1 General

Batch Plant – The aggregate is generally stored in bins above the batching hopper, and cement is fed into the hopper by means of an auger. A typical batch plant is shown in Figure 4.7. The specified amount of aggregate and cement are weighed for each batch. Water is added through spray bar(s) mounted above the mixer and the RCC constituents are then mixed for a specified time period (generally about one minute). Total batch size can range from 2 to 7 cubic yards depending on the capacity of the mixing chamber. Since RCC is dryer and “bulkier” than conventional concrete, batch plants usually cannot achieve thorough, uniform mixing using the full rated capacity of the drum or hopper. Most modern batch plants operate through computer controls.

The batch weights of constituents should regularly be reviewed for conformance of each batch with the specified proportions. Batch plant summary forms (Form 1a and 1b in Appendix A) can be used to evaluate individual batch data, or cumulative quantities for several batches. A summary of the RCC placed should also be maintained (at an appropriate frequency ranging from hourly to daily dependent on the project needs) and evaluated.

Continuous-Flow Plant – Continuous flow plants generally used for RCC consist of an aggregate feeder (one or two), a cement silo and feeder, a main feeder belt, a water supply system, a pugmill mixer, and a discharge belt. A typical pugmill mixing plant is shown in Figure 4.8. If a pozzolan is required, a separate silo can be placed adjacent to the plant and a feeder system connected to the pugmill. The aggregate is metered onto the main belt and conveyed to the pugmill where the water and cementitious material are added. Materials are added based on calculated feed rates in tons/hr. All of the constituents enter the pugmill at one end and are transported to the other end by a belt through the mixing chamber with spinning paddles. Total mix time generally ranges from about 10 to 30 seconds. Most continuous pugmills cannot adjust their mixing times.

Several methods of measuring the mixing time in pugmill mixers have been used with varying degrees of success. Typical methods have included: a) introducing a different colored aggregate during mixing, b) switching aggregate feed between two bins and then measuring the time for the change in aggregate to travel through the mixing chamber, c) introducing painted aggregate and d) introducing a marker to the beginning of the mixing chamber and measuring the travel time. If problems develop with the plant producing a constant uniform mix, a different plant may be required.

In contrast to weights for a specific batch in a batch plant, a continuous flow mix plant measures the flow rate at which each product is supplied to the pugmill. RCC mix records can be generated with some plants by computer reports at selected time intervals (typically selected in the range of 5 to 16 minutes) or by manually recording the reading at the selected time intervals if the plant is not computer controlled. Plant summary forms for a continuous flow mixing plant are shown on Figures 1c and 1d in Appendix A.

It should be anticipated that some volume of material (between 1 to 5 cubic yards or more) might need to be wasted during start-up with continuous flow plants. Many continuous flow mixing plants can be stopped “midstream” and restarted at the same proportions. By nature of the

Figure 4.*7—Batch-type concrete plant producing RCC.*

Figure 4.8*—Continuous-flow type plant producing RCC.*

continuous mixing process, the initial RCC produced after a prolonged shut-down generally may not conform to project requirements. Waste of material after a restart needs to be evaluated on a case-by-case basis and depends on the visual appearance, and/or testing, of the mix and the length of time that the plant is on hold in a midstream stop.

4.4.2 Operational Monitoring

During start-up operations, the mixing plant (batch or continuous) must be properly calibrated prior to producing RCC. Both plant types are relatively easy to calibrate and operate. Calibration of each constituent should occur at the minimum, average, and maximum production rates expected for the project. If the plant experiences a mechanical shutdown or there is an unexpected change in the properties of the RCC, re-calibration may be necessary.

Tolerances for the various constituents of the RCC mixture generally consist of the following:

Table 4.4
Tolerances for RCC Constituents

Constituent	Tolerance (%)
Cement	±2
Pozzolan	±2
All Aggregate	±3
Water	±3

This section provides several example calculations to demonstrate converting RCC mix proportions to weights that are used for typical RCC mixing plants. The RCC mix proportions that are used in the example are shown below. Conversion factors to metric units are included in Table 4.5 at the end of this section.

Given: <u>**RCC Mix Proportions**</u>

Cement	350 pounds per cubic yard (pcy) Type II
Specific Gravity	3.15
Free Water	280 pcy
Total Aggregate (SSD)	3402 pcy

Aggregate Proportion

	Coarse	Fine
Percent of Total Aggregate (SSD)	58.1%	41.9%
Specific Gravity (SSD)	2.7	2.7
Absorption	0.6%	2.9%
Field Moisture Content	1.6%	6.3%

**SSD = Saturated Surface Dry*

Example 1 – Batch Type Mixing Plants

When RCC is mixed in a batch-type plant, the materials are weighed for each batch before being transferred to the mixer. An example of determining the batch weights of aggregate, cement, and water for a 6 cubic yard batch follows:

Procedure:

1. Weight of Aggregate – Dry (pcy)
   Coarse Aggregate = [(3,402 x 0.581) ÷ 1.006] = 1,964.8 lbs
   Fine Aggregate = [(3,402 x 0.419) ÷ 1.029] = 1,385.2 lbs

2. Batch weights (6 cy) based on dry aggregates:
   Cement: = 6 x 350 = 2,100 lbs
   Coarse Aggregate = 6 x 1,964.8 = 11,788.8 lbs
   Fine Aggregate = 6 x 1,385.2 = 8,311.6 lbs
   Total Water (absorbed water plus free water):
   (11,788.8 x 0.006) + (8,311.6 x 0.029) + (280 x 6) = 1,991.8 lbs

3. Field moisture in aggregate per batch:
   (11,788.8 x 0.016) + (8,311.6 x 0.063) = 712.3 lbs

4. Batch weights corrected for field moisture in aggregate:
   Cement = 2,100 lbs
   Coarse Aggregate: (11,788.8 x 1.016) = 11,977.4 lbs

Fine Aggregate: (8,311.6 x 1.063) = 8,835.2 lbs
Add Water: (1,991.8 – 712.3) = 1,279.5 lbs
(170.8 gallons)

A continuous comparative record of the weight of the aggregate, cement (pozzolan if specified), and water added should be maintained and evaluated as part of the QC program. Sample forms for evaluating actual plant production are shown in Appendix A (Forms 1a and 1b).

Example 2 - Continuous-Flow Mixing Plants

When RCC is mixed in a continuous-flow type plant, mixture portions must be calculated on a percentage basis, and the quantity per unit time, for each constituent. The water required to bring the RCC mixture to design water content is based on the amount of aggregate, cement, and flyash coming into the mixing chamber per unit of time. The following example shows the calculations necessary to determine constituent proportions per unit time and the approximate amount of U.S. gallons required per minute for the design water content:

Procedure:

1. Convert mix design to dry weights:

Coarse Aggregate (SSD) = 3,402 x 0.581 = 1,976.6 lbs
Dry Weight = 1,976.6 ÷ 1.006 = 1,964.8 lbs
Absorbed Water = 1,976.6 - 1,964.8= 11.8 lbs

Fine Aggregate (SSD) = 3,402 x 0.419 = 1,425.4 lbs
Dry Weight = 1,425.4 ÷ 1.029 = 1,385.2 lbs
Absorbed Water = 1,425.4 - 1,385.2= 40.2 lbs

Total Weight of RCC Mix
= cement + free water + total aggregate (SSD)
= 350 + 280 + 3402 = 4032 lbs/c.y.

2. Convert mix design to proportions of each constituent as a percent:

Cement Content (by dry weight of aggregate)

$$= \frac{350}{1,964.8 + 1,385.2} = 10.45\%$$

Total Water Content (by dry weight of constituents)

$$= \frac{280 + 11.8 + 40.2}{350 + 1,964.8 + 1,385.2} = 9.0\%$$

Field Moisture Content of Combined Aggregate

$$= \frac{(1,964.8 \times 0.016) + (1,385.2 \times 0.063)}{1,964.8 + 1,385.2} = 3.5\%$$

Total Aggregate (dry weight) to the total mix weight

$$= \frac{1,964.8 + 1,385.2}{4,032} = 83.1\%$$

3. Calculate material flow rates and the Add Water Requirement:

Assumed production rate: 260 tons/hour (weight of total RCC mix).

a) Convert the weight of aggregate per hour entering the mixing chamber, to weight of dry aggregate per minute:

$$\frac{260 \text{ tons} \times 0.831 \times 2,000 \text{ lbs/ton}}{60 \text{ min.}} = 7,202 \text{ lbs/min}$$

b) Calculate total aggregate at field moisture entering the mixing chamber per minute:

7202 x 1.035 = 7454.1 lbs/min

c) Calculate weight of cement required per minute:

7202 x 0.1045 = 752.6 lbs/min

d) Calculate the combined weight of dry aggregate and cement per minute:

7202 + 752.6 = 7954.6 lbs/min

e) Calculate the gallons of water required per minute per 1% moisture:

$$\frac{0.01 \times 7{,}934.6}{8.33} = 9.5 \text{ gallons per minute (gpm)}$$

f) Calculate the approximate gallons of add water required per minute to bring the mixture to the design moisture (percentage of moisture required equals the design moisture content of the RCC mixture minus the field moisture content of the aggregate):

$$(9.0 - 3.5) \times 9.5 = 52.3 \text{ gpm}$$

As previously discussed, most mixing plant controls provide real-time information regarding constituent weights and RCC produced. This data must be routinely collected and reviewed for batch or for the design and time interval in order to monitor the production process. Example forms for evaluating actual plant production are shown in Appendix A (Forms 1c and 1d).

4.4.3 Plant Calibration

Before mixing and placing operations begin, it is necessary to measure the quantities of material supplied by the plant and to adjust metering devices so that the proper proportion of each material will be produced. Central mixing plants can be calibrated as described below.

Aggregate is usually calibrated first. This can easily be done by passing the aggregate through the plant and discharging it into a dump truck. Each aggregate bin is calibrated individually. For the first trial, the aggregate discharged in one minute is weighed to determine tons produced per hour. Aggregate is discharged for three minutes on the second trial and sometimes on a third trial for five minutes to determine the average tons per hour produced and the uniformity of flow. The second trial should produce three times the amount as the first and the third five times as much as the first.

The moisture content of the aggregate is then determined to find the dry weight of aggregate, which will be used to establish the required weight of cement.

The cement output is calibrated next. This is done with the plant running at the planned operating capacity or several rates bracketing the operating capacity.

The cement is diverted from the cement feeder into a container with capacity to hold the cement quantities obtained during the calibration and adjustment trials. Generally, periods of 15, 30, and sometimes 45 seconds are used for quantity measurements. The quantities delivered in these periods indicate the uniformity of cement flow. This calibration can also be done by diverting the cement into dump trucks or portable “cement pigs” and weighing them on truck scales.

Water quantity is the third item to be calibrated. This can be done theoretically by weighing the amount discharged for one minute, two minutes and 3 minutes, and comparing it with the meter on the mixer that measures gallons per minute.

To determine quantity of water needed for the mixture, the moisture content in the aggregate and the percent of moisture required must be known.

Example 3 – Add Water

Assume a production rate of 260 tons per hour of total RCC mix
Assume 10.45% cement by dry weight of aggregate
Total RCC mix weight: 4032 lbs/c.y.
Total Aggregate (Dry Weight) to total mix weight: 83.1%
Assume 9% total moisture content
Field moisture content of combined aggregate: 3.5%

<u>Procedure:</u>

Delivery rate of dry aggregate: 260/0.831 = 216.1 tons per hour
Water in Aggregate: 216.1 x 0.035 = 7.6 tons per hour
Dry Aggregate and cement: 216.1 x 1.1045 = 238.7 tons per hour
Total Water required: 238.7 x 0.09 = 21.5 tons per hour
Water to add: 21.5 - 7.6 = 13.9 tons per hour

$$\text{OR } \frac{13.9 \times 2{,}000}{8.33 \times 60} = 55 \text{ gallons per minut}$$

Calibration of plants with variable gate openings can be accomplished by determining the relationship between various feeder gate openings or revolutions per minute (depending on type of feeder) and amount of the constituent discharged. The relationship can then be plotted to find the gate opening or revolutions per minute (RPM) for the required amount of constituent.

A second method is to operate the plant with aggregate material feeding onto the main conveyor belt. The material on a selected length of conveyor belt is collected and its dry weight determined. The plant is then operated with only cement feeding onto the main conveyor belt. If a variable-speed screw or vane cement feeder is being used, several trials are made at different revolutions-per-minute (RPM) settings on the cement feeder. If a belt cement feeder is being used, trails are made at different cement feeder gate openings. The cement on the selected length of conveyor belt is collected and weighed for each trial run. A calibration graph can then be drawn by plotting the RPM setting or gate opening on the cement feeder on the horizontal scale and the computed percent of cement by dry weight aggregate of the vertical scale. Thus, for a constant supply of aggregate, the setting on the cement feeder for the required quantity of cement can be determined from the graph.

Example 4 – Cement Meter Setting

Determine cement meter setting.

Given: Specified cement content by weight of dry aggregate 6%
Moisture content of aggregate 5.5%

Procedure: Determine the weight of aggregate on the main conveyor belt at various feeder gate openings.

Gate Opening		Moist Soil Material on Belt	
in.	(mm)	lb on 5 ft	(kg on 1.5m)
8	(200)	225	(100.4)
7	(175)	191	(85.3)
6	(150)	156	(69.6)
5	(125)	121	(54.0)

Calculate the weight of dry aggregate by dividing the quantity of moist aggregate by the quantity 1 plus the moisture content expressed as a decimal.

$$\frac{\text{Moist aggregate}}{(1.0 + 0.055)}$$

Gate Opening		Dry Aggregate on Belt		Dry Aggregate Per Unit Length of Belt	
In.	(mm)	lb on 5 ft	(kg on 1.5 m)	lb/ft	(kg/m)
8	(200)	213	(95.2)	42.6	(63.5)
7	(175)	181	(80.8)	36.2	(53.9)
6	(150)	148	(66.0)	29.6	(44.0)
5	(125)	115	(51.2)	23.0	(34.1)

Determine weight of cement on main conveyor belt at various RPM settings of feeder:

	Cement on Belt		Cement Per Unit Length of Belt	
Rpm setting	lb on 10 ft	(kg on 3.0 m)	lb/ft	(kg/m)
14	28.7	(12.8)	2.87	(4.27)
12	25.5	(11.4)	2.55	(3.80)
10	22.2	(9.9)	2.22	(3.30)
8	19.0	(8.5)	1.90	(2.86)

For production, the main feeder belt is set at 8 in. (200m). Calculate the cement content by weight of dry soil material at 8 in. (200m) aggregate feeder belt setting for each cement feeder setting.

Example for RPM setting of 14.

$$\frac{2.87 \text{ lb cement}}{42.6 \text{ lb dry aggregate}} \times 100 = 6.7\% \text{ cement}$$

RPM Setting	Cement Content by Weight of Dry Aggregate , %
14	6.7
12	6.0
10	5.2
8	4.5

An RPM setting of 12 will supply the required cement content of 6% by weight of aggregate.

Example 5 – Gate Opening for Cement Feeder Setting

Find the production of the plant with the 8 in (200mm) feeder gate opening and 12 RPM cement feeder setting.

Given: Total length of main feeder belt 165.0 ft
Average time for one revolution of belt 26.7 seconds

Procedure: Calculate average belt speed:
165.0/26.7 = 618 ft/second (1.88 m/s)

Dry aggregate plus cement going through plant:

Aggregate:	42.6 lb x 6.18 ft/sec x 3600 sec ÷ 2000 lb =	474.0
Cement:	2.55 lb x 6.18 ft/sec x 3600 sec ÷ 2000 lb =	<u>28.4</u>
	502.4	
	455.8 t/h tons/hour	

5.0 CONSTRUCTION AND PLACEMENT QUALITY

5.1 Transport, Placement and Compaction

The quality of in-place RCC depends on many variables. Time may be one of the most important variables. Most technical specifications specify a maximum allowable time from the addition of water until the RCC is compacted in the lift. The allowable time will generally range between 30 and 60 minutes. The methods of transportation, placement and compaction are critical to meeting this time requirement. In some climates, or during overnight shifts, RCC can still be satisfactorily compacted up to about 90 minutes after initial mixing. Judgement is needed in deciding if RCC is still "alive" when the time after water is added, exceeds 30 minutes. In addition, testing of RCC cylinders at different time periods (i.e., compaction of RCC cylinders at 45, 60, 70, 80 and 90 minutes after spreading) can be used to evaluate the "compactability" and strength gain or loss of RCC with time. These tests are referred to as "time to compaction" tests. It should be noted that a significant number of test cylinders may need to be prepared to cover the wide range of temperature and conveyance conditions that can be experienced on a project. Also, changing the time limits for completing compaction after the contract has started, can also cause problems. Therefore, changes in time limits in the field must be carefully considered before implementing. In general, RCC should be compacted within no more than 90 minutes after water is initially added to the RCC mixture. Several forms that can be used to record and evaluate various facets of the RCC construction and testing are included in Appendix A.

5.1.1 Transport

The method of transporting RCC from the mixing plant to the placement site is highly dependent on allowable time to compaction (discussed above), total volume, site-specific physical constraints and available equipment. Important items that are considered in specifying or selecting a transportation system include distance from mixing plant to site, average temperature during the construction season, and required production rate to meet schedule. Several methods of transport include end-dump trucks, front-end loaders, and conveyor systems. Regardless of the method selected, it is important to consider the following: preventing systematic rutting of the lift surface by rubber tired equipment, degradation or mechanical breakdown of the RCC by track equipment, keeping the lift surface free from debris, preventing segregation, and providing access for all necessary equipment (truck, dozer, compactor). If trucks are used, bed covers should be available to protect the RCC during transport to protect against rain and sun. Requiring the use of bed covers should be based on haul distance and weather conditions. Conveyors should also be covered to protect against rain and sun.

5.1.2 Lift Placement

Once the RCC has been transported to the lift surface, it is generally spread with a dozer such as a Caterpillar Model D4H or a Komatsu Model D37P. Laborers with shovels are required in areas not accessible to a dozer. Most technical specifications will not allow tracked equipment on recently compacted RCC. Therefore, construction procedures must be implemented to protect the RCC surface from the dozer tracks. Treatment of an RCC surface damaged by dozer tracks depends on the age of the RCC. Recently compacted RCC may simply be recompacted if the specified time to compaction has not been exceeded; whereas treatment of older RCC may involve removal of loose material with brushes, compressed air and/or water.

The uncompacted lift thickness typically ranges from 8 to 14 inches. It is important to maintain a consistent lift thickness because the required density will likely not be achieved for lifts of variable thickness, and poor bonding between lifts (delamination) may occur for lifts too thin (less than 6 inches) or too thick (greater than about 14 inches). Manual measurement of the lift thickness can be performed to the proper grade with a stiff ruler or stake, or a level and rod. The most effective method of maintaining consistent lift thickness is the level laser. Laser attachments on a dozer provide the operator with a guide to provide a uniform surface at the proper lift thickness prior to compaction.

5.1.3 Compaction

a. **Equipment**: Many different types of compactors are capable of achieving the required in-place density typical for RCC. General requirements usually include a smooth-drum, vibratory roller (Figure 5.1), with a turning radius compatible with the project site requirements. Typical compactors include the Caterpillar 10 ton CS-563 single drum roller, the Ingersoll-Rand SD-100 single drum roller, and Dynapac CC42 dual drum roller. Although each of these compactors usually can achieve the required density, each compactor requires a unique combination of number of passes, vibration frequency and amplitude that should be developed during test section construction. For areas not accessible by one of these larger rollers, it is common to use jumping jacks (Figure 5.2), walk behind steel wheel vibratory rollers, such as the Ingersoll-Rand RX-75 and the Ingersoll-Rand BX-12, walk behind steel wheel rollers.

During compaction, the surface of the fresh RCC mixture may become dry, as evidenced by graying of the overall surface or whitening of the aggregate. This could be an indication of moisture being lost due to evaporation or the mix arriving on the fill too dry, and may indicate that the RCC has exceeded its time to compaction. If the RCC has not exceeded the design water:cement ratio, or the time to compaction, areas experiencing surface drying should be moistened with a light spray of water prior to compaction. If this situation occurs, changes to the mixing and placement program capable of alleviating the issue should be developed.

Figure 5.1*—RCC surface during compaction with a smooth-drum vibratory roller.*

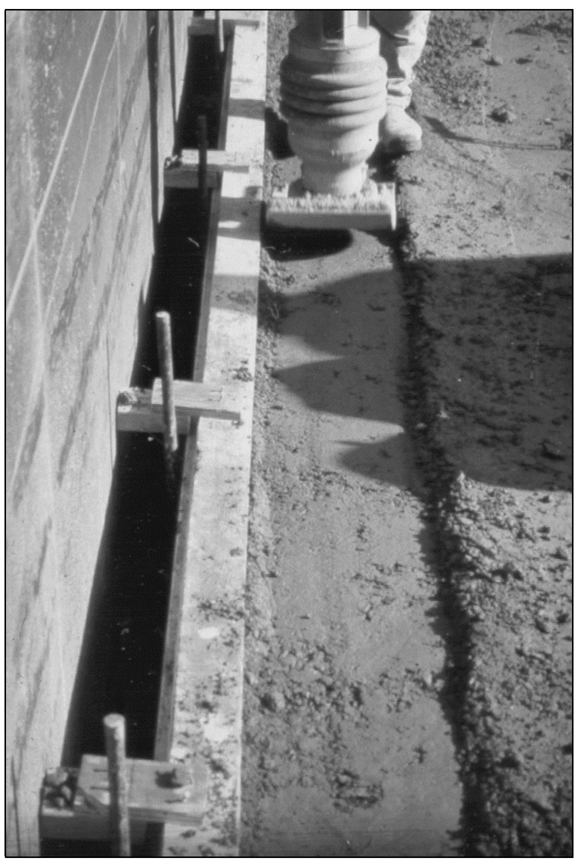

Figure 5.2*—RCC compaction in confined area using a "jumping jack" type compactor.*

b. **Testing**: In-place density testing is used as a method to measure the degree of compaction of the RCC. Generally, the technical specifications will provide the minimum acceptable density as a percent of the theoretical maximum wet density, control cylinder wet density, or a wet density to be determined in a test fill. It is also common for technical specifications to require a minimum density on a “running average” basis for a series of test results (usually 10 to 20) and an absolute minimum density for a single test. The running average basis is a practical method to identify deficiencies in the compaction process and enact corrective measures in a proactive fashion.

Density testing should be performed immediately after final rolling of each lift at several locations. Delays in testing allow chemical hydration to occur which in turn can effect the test results. Experience with conventional concrete has shown that a 5 percent reduction in density will significantly reduce the compressive strength of the material. Typically, an average of 98 or 99 percent compaction, relative to control cylinders (or a field test strip) with no individual test below 96 percent, is specified for field control.

The most reliable method of testing RCC density is through the use of a calibrated nuclear density meter. Sand cone and balloon density test methods are generally not suitable due to the difficulty and time required excavating the test hole. Two types of nuclear density meters are commercially available and acceptable for testing RCC. The single-probe and double-probe meters are illustrated in Figures 5.3 and 5.4, respectively. Because the RCC is placed in 12 inch lifts, the nuclear density meter must have a 12 inch probe. Nuclear density gages should be calibrated before their use in the field. Gage calibration will include: a) calibration of the gage each day, b) calibration of the gage to compacted RCC mixtures, and c) moisture calibration.

Each gage should be calibrated using the standard count block in accordance with the manufacturers recommendations. Calibration of the gage(s) to the RCC mixture and moisture content also needs to be performed. Gage calibration for wet density can be performed by construction of a RCC block constructed with a known volume and then weighed to obtain a wet density for correlation with the gage reading. The RCC block is typically 1 cubic yard in size which is needed to minimize the affects of sample size and boundary conditions on the results. A second calibration method consists of conducting one to three density tests in a compacted RCC lift (such as during a test fill) and then obtaining one to two cores in the area beneath the base plate of the gage, at each location. The measured wet density of the cores is then calibrated to the nuclear density gage reading. Both methods have been found to be suitable.

Both the single and double-probe meters have been used; however, each gage has some limitations due to their design and geometry. The single-probe meter can usually measure up to 12 inches in depth and records the average density of the lift from the bottom of the inserted probe to the top surface (base of the meter). However, the density measured by the meter is weighted to the top of the lift which is more easily compacted than the lower portion of the lift which can be more difficult to compact. Testing at multiple depths (such as 12-, 8- or 4-inch depths) can be performed to evaluate the effectiveness and thoroughness of compaction throughout the full depth of the lift. A

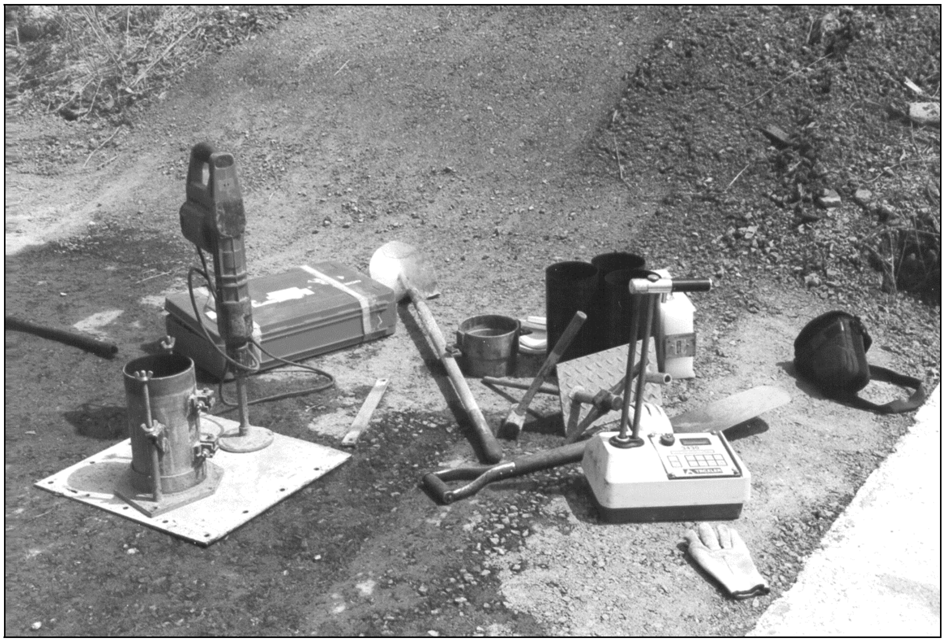

Figure 5.3*—Vibrating hammer for perparation of RCC cylinders, and single-probe nuclear density gauge.*

Figure 5.4*—Double-probe nuclear density gauge.*

higher wet density at a shallow depth (4 inches) than at full depth (12 inches) indicates that the compactive effort is not reaching full depth and additional compactive effort is needed. The inability to increase the density at depth could indicate that the roller is inadequate, is operating at the wrong frequency or amplitude, or too much time has elapsed to allow complete compaction, and/or the RCC mixture has insufficient paste or is too dry. Alternatively, a lower density at shallow depth than full depth can also be encountered. This can occur due to incomplete compaction or loosening of shallow RCC by the vibratory roller. Often, the density of shallow material can be improved by compacting without vibration for several passes.

The geometry related limitations of the single-probe meter can be offset with the double-probe meter. The density with the double probe meter is measured horizontally from the source probe to the detector probe at the same depth. Therefore, individual strata can be measured at different depths. The double-probe meter can measure up to 24 inches in depth. Though more desirable than the single-probe meter, the double-probe meter is more costly, heavier and more time consuming to use. In addition, significant problems occurs if the pilot holes for the two probes are not nearly parallel to each other and perpendicular to the surface of the RCC. Due to the granular nature of RCC, driving two parallel vertical holes and proper seating of the double probe meter is difficult.

Difficulty is usually encountered when preparing the probe holes for the nuclear density meter test due to the coarse aggregate in most RCC mixes. It is sometimes difficult to drive a straight hole for testing. This is a particular problem for testing with the double-probe meter. When using the double-probe meter, a composite test result should be calculated as the average of tests performed at the bottom, middle and top of the lift. Calibration of the moisture reading from the nuclear density gage is more difficult than calibration of wet density. This is due to both the method that the gage measures moisture (by measuring hydrogen ions), and that moisture content tests with field samples are primarily obtained by specified drying procedures, such as ASTM C566. Moisture content measurements by drying tests are likely affected by the chemical reaction of the cement with water during drying. Consequently, wet density is primarily used for field control of RCC placement, with moisture control by a combination of: a) nuclear density gage moisture readings correlated with a drying test (ASTM C566), and b) comparison with the water content and water:cement ratio based on the mixing plant records.

Correlation of drying tests with nuclear density meter tests should be performed for use by the field quality control personnel.

5.1.4 Moisture Control

With a little experience, the moisture content of an RCC mixture can be monitored by observation and feel. An RCC mix at or near optimum moisture content for compaction by the modified proctor density test (ASTM D1557) is just moist enough to dampen the hands when it is packed in a tight cast. Mixes above optimum will leave excess water on the hands whereas mixes below optimum will tend to crumble easily. If the mix is near optimum, it is possible to break the cast into two pieces with little or no crumbling. The hand-squeeze test is not a replacement for more traditional methods of measuring moisture content.

Changes in moisture content of the RCC mixture can also be noted qualitatively by observation of the roller during compaction. Most RCC mixes are proportioned to be over the optimum moisture content as determined by a modified proctor density test. Mixes at optimum moisture content (based on the modified proctor compaction test) to about 1 percent above optimum, will show little or no deflection after several passes of the roller. The RCC mixture under the load of a 10-ton vibratory roller at 1 percent or more above optimum moisture, should show some deflection (approximately 1 inch or more) under the roller after several passes of the roller. RCC mixtures proportioned at higher moisture contents will leave excess water on the hands using a hand squeeze test, and will deflect 1 to 2 inches under the load of a 10 ton vibratory roller.

If it is determined, by moisture content test result or experience, that the RCC mix is either too wet or too dry, small changes in the amount of water added by the mixing plant can be made to the RCC mix. The change in moisture content should be noticeable within minutes of modifying the add water amount. Communication between the placement area and the mixing plant (such as radios) should be maintained to accommodate timely changes in the water content of the RCC mix.

5.2 Surface Edge and Joint Preparation

5.2.1 Curing and Protecting

Quality control measures after placement should include periodic inspections of the lift surface to ensure that the RCC is being continuously cured and properly protected. During each shift (production or non-production), a record should be maintained documenting the extent of curing and any action that should be taken to correct the deficiencies.

If rain is imminent or starting, the uncompacted RCC surfaces should be immediately compacted. When necessary, the RCC can be protected from rain, dust or freezing temperatures by covering the lift surface with plastic or insulating mats. Observation of the protective measures should be performed several times during the day.

For multiple lift construction where bonding of one lift to another is necessary, curing compound must be avoided. If curing compounds are used after all the RCC is placed, it is normal to have to use twice the dosage rate as would be used on conventional concrete surface.

5.2.2 Lift Joint Treatment

RCC lift joints are similar to that of conventional concrete in that a joint is formed when a compacted lift is overlaid by a subsequent lift. The condition of the RCC lift below an advancing lift of fresh RCC is critical to forming a successful bond between the two lifts. The surface of the previous RCC must be prepared to accept the fresh RCC. Acceptable methods for preparing the lift surface depend upon whether the joint is considered a cold or fresh, whether the joint is transverse or longitudinal and to whether the design criteria requires bonding between the lifts. The following text discusses the difference between the joint types and treatment methodologies. Also, a lift summary form (such as Form 3 in Appendix A) can be used to record information for joint treatment, observations, and test results during fill placement.

Cold Joint

A lift joint is generally considered cold when it is unlikely that the previous RCC surface will bond with fresh RCC. The actual definition of a cold joint will vary from project to project and from Engineer to Engineer. The technical specifications should clearly define the criteria for determining whether a joint is cold or fresh. The two most widely used methodologies for defining a cold joint include the following: (1) A time limit between compaction of the underlying lift and placement of the overlying lift has been exceeded, or (2) an established degree-hour (ambient air temperature x hours between lift subsequent compaction and placement) limit has been exceeded. For example, for 12.5

hours at an average ambient air temperature of 69ºF, the degree-hour calculation (12.5 x 69) produces 862.5 degree-hours. The degree-hour method of control is described in ACI 207.5R, Roller Compacted Mass Concrete. The ambient air temperature should be measured in an area nearby the RCC placement area in similar conditions. It is preferable to use a standard weather monitoring shelter for the temperature measuring device.

Temperature variations occur throughout each shift during the day and night, and the development of a "true" cold joint is also variable depending on the particular season (i.e., winter, spring, summer). Once a joint has been defined as a cold joint, particular treatment methods are required to prepare the surface for the subsequent RCC lift. In order to create an acceptable bonding surface, these treatments generally require that the RCC aggregate be exposed without undercutting. Specific techniques for cleaning the lift surface and exposing the RCC aggregate can include high-pressure water and a combination of high pressure air with a small quantity of water as shown in Figure 5.5.

Figure 5.5*—RCC surface preparation using high-pressure air-water.*

Fresh Joint

Simply stated, a lift joint is considered fresh when the criteria for a cold joint have not been meet. Similar to a cold joint, the compacted lift surface must be prepared to accept the fresh RCC. The lift surface should be clean and moist as the fresh RCC is placed. Surface cleaning can be accomplished using high-pressure air or moderate-pressure air with some water. After cleaning a joint surface, it is important to keep equipment and traffic off of a lift. Even with the best efforts to clean a lift surface and minimize traffic, some "debris" will develop on the surface. It is recommended that the surface have a final cleaning of loose debris using moderate pressure air immediately prior to spreading of the RCC.

Transverse/Longitudinal Joint

The transverse and longitudinal joints (perpendicular and parallel to the longitudinal axis of the dam, respectively) occur at stoppages of work. The joints should be trimmed to form straight edges generally at a slope of 1 horizontal to 1 vertical. The technical specifications should define treatment for these joints. It is important that the RCC be trimmed back to fully compacted RCC and the exposed surface cleaned of loose material. The elevation and station of each joint should be recorded in the project records.

5.2.3 Bedding Mortar/Concrete

Bedding mortar/concrete (bedding) is typically specified for a portion of the lift, ranging from the perimeter of the lift surface to complete coverage of the lift surface. Bedding is also used on the contact between RCC and foundation. Bedding mortar is a combination of cement (and sometimes pozzolan), sand, water, and usually a set retarder, with a compressive strength greater than the RCC. The slump should range from 7-9 inches. Bedding mortar on the lift surface typically ranges from 3/8 inch to 1 inch thick. Bedding concrete has the same ingredients as bedding mortar but with coarse aggregate with a MSA of _ inch. Bedding concrete is typically used over irregular foundations, and is spread to a thickness ranging from _ to 1 inch. Bedding should be spread evenly over the RCC surface to the required thickness. Both hand and mechanical methods have been used to spread bedding, these ranging from shovels and asphalt rakes to utilizing a shotcrete pump on irregular rock surfaces. If the bedding is spread too thick, “pumping” of the overlying RCC can occur during compaction. Bedding is also utilized at the contact between the RCC and the rock foundation contact. Where the contact is steeper than about a 2:1 slope, bedding “concrete” will generally be easier to place and is typically an abutment placed about 2 to 4 inches thick. Use of a set retarder (with about 3 hours of set delay) is desirable for bedding mortar/concrete.

Bedding should not be allowed to dry out. If it does, the bedding should be removed, the lift surface cleaned and the bedding reapplied. An excellent way to prevent bedding from drying out is to place it in piles and then, spread it just before the RCC arrives at the placement site.

In some mixes, the bedding can segregate. When this occurs, the bedding will take on a sand-like appearance as it ages. If this condition occurs, the bedding should be removed, the lift surface cleaned, and the bedding reapplied. Segregation of the bedding can be reduced by the modification of the mix design. Possible modifications include the addition of flyash to the mix, the inclusion of admixtures into the mix and the reduction of water.

Testing for the bedding can include the following:

Slump (ASTM C143)
Time to initial set (ASTM C191)
Unconfined Compressive Strength (ASTM C39)
Aggregate Gradation (ASTM C136)
Air Entrainment (ASTM C 231)
Temperature (ASTM C 1064)

5.2.4 Contraction Joints

Contraction joints are often placed in RCC structures to control cracking caused by temperature changes. The joints are typically required in each lift of RCC and can be installed during the placement and compaction of the RCC lift, or shortly thereafter. If the joints are to be installed during RCC placement, metal plates wrapped in plastic are typically used to provide a surface to place the RCC against. Once the RCC has been placed around the metal plates, the plates are removed leaving the plastic behind, and the area compacted. If the joints are to be installed after placement and spreading, they must be completed prior to placing the subsequent lift. This would generally involve inserting galvanized steel plates with a vibratory pneumatic hammer. Adequate survey controls need to be in place so the joints line up over one another with each subsequent lift placed.

5.2.5 Overall Lift Quality

After the completion of an RCC lift and prior to the placement of the next lift, the quality of the surface must be maintained. A moist surface should be maintained with addition of water to promote proper curing of the RCC. Rock pockets should be removed to reduce the potential for seepage along the lift lines. The lift surface should be cleaned of ponded water, spillage from conveyors and any other loose materials which would prevent the RCC from bonding or contaminate the new RCC. In some instances, a layer of fine dust develops on the RCC surface. The surface can be prepared using high pressure air and/or water, taking care not to undercut the RCC (only exposing its top surface). In most cases, it is advisable to conduct a final cleaning of the surface with compressed air within 15 to 30 minutes of spreading of the next lift of RCC.

5.2.6 Placement of Facing Concrete

Facing concrete for RCC dams has historically been placed either prior to the placement of the RCC or after placement of the RCC depending on the required design. The interface between the facing concrete and RCC will have varying properties of density, permeability and strength, ranging from very poor to good, depending on the workability of the facing concrete and RCC, and the degree of effort in the consolidation and compaction of the materials. Typically, the facing concrete and the exposed edge of RCC are not consolidated/compacted until after placement of both materials. After the facing concrete and RCC adjacent to each other are placed, the concrete is consolidated using an immersion vibrator and the RCC is compacted using a large, smooth drum vibratory roller. A jumping jack type compactor is also used in areas close to forms and in tight areas. After placement and compaction of the RCC, it is suggested that the facing concrete/RCC interface be revibrated to additionally intermingle the two materials to promote a good bond.

The degree and variability of quality at this interface zone can be improved by providing confinement during consolidation/compaction. When the facing is placed first, it is best to provide lateral restraint and vibrate the conventional concrete prior to the placement of the RCC. When the RCC is placed first, it is best to compact the RCC against a restrained surface and then place and vibrate the facing concrete. This will allow for an improved bond between the facing and RCC.

5.2.7 Removal of RCC and Subsequent Surface Preparation

The need for the removal of RCC can result from the occurrence of several conditions including but not limited to the following:

- Moisture content out of specification – either too wet or too dry
- Rain, groundwater, or surface water contamination of uncompacted RCC
- Exceedence of time limitation before compaction
- Freezing of the RCC

- Error in mixing plant operation (lack of cement or flyash in the RCC mix)
- Severe segregation of mix during placement
- Contamination of the RCC lift surface that cannot be removed by the method described previously for cleaning cold joints
- Contamination of the uncompacted RCC or compacted lift surface with diesel fuel or other contaminant including curing compound
- Moderate compaction

All of these conditions will involve the removal of the affected area of the uncompacted lift or the surface area of a compacted lift if in the judgement of the Engineer that the design criteria or the projects performance will be compromised.

The removal of RCC should be done by hand or with a dozer or loader depending on the quantity removed, and should expose fully compacted RCC. Loose RCC should then be blown from the lift surface using compressed air and/or water. Lift surface treatment should be performed in accordance with the specifications prior to subsequent RCC placement (see Figure 5.5). If the RCC lift surface needs to be removed due to contamination (by diesel fuel or such), the contaminated area should be removed using hand tools, or if a large area exists, a dozer or loader could be used. The depth and lateral limits of removal will need to be determined by the inspector. Care needs to be taken such that all loose aggregate is removed (potential weakened plane) prior to the placement of the next lift. If the affected area is rejected due to moisture or density problems, the affected area should be removed to the full depth of that lift. If due to surface contamination or damage that the depth of removal should be determined by the extent of the damage. Any replacement lifts should be not less than 6 inches in compacted thickness.

When RCC freezes, as with conventional concrete, its long-term strength is reduced. If RCC is allowed to freeze, the RCC lift should be removed to at least the depth of the frozen portion of the lift. Removal of the compacted RCC should be as above and the depth should be determined based on field conditions.

5.2.8 On-Site Laboratory Requirements

Often it is advantageous, but not always necessary to have a materials testing laboratory on the project site or at the batch plant site. For small projects, it is advantageous to do bulk materials testing off-site at an existing testing laboratory. For larger projects working multiple shifts, it is recommended that an on-site laboratory, with a dedicated staff, be established.

Typical laboratory equipment will consist of:
Rotap Sieve Shaker (sieves: 1_, 1, _ and 3/8 –inch, #4, #8, #16, #30, #50, #100, #200 and pan)
Drying Oven, 220 volt
Vibrating Hammer (ASTM C1435)
Mold Sleeve (ASTM C1435)
Type A Cylinder Molds
Wheel barrel
Slump Cone
Air Pot
Concrete Thermometer

Additional field laboratory equipment could include:
Vebe vibrating table
12-ft by 12-ft by 6-inch thick concrete slab with roof for outdoor testing
Curing tanks with immersion type testers capable of maintaining water at 73^{o} Fahrenheit
Gibson Model TM-3 Test Master with 3-inch, 2-inch, 1_-inch, _-inch, _-inch, 3/8-inch and No. 4 screen trap.
Microwave Oven (750 watt minimum)
Concrete compression testing machine
Exhaust hood for capping cylinders
Galvanized sample pans (24-inch x 24-inch x 3-inch)
Aluminum sample pans (11-inch x 17-inch x 1_ inch)
Air compressor with 150 cubic feet per minute capacity at 150 psi
Ingersoll-Rand Tamper with 5_-inch tamping force

5.2.9 Lift Thickness Tolerances

Lift thickness tolerances can be as much as ±15 percent of the lift thickness, or about 1.5 in (38mm) for a 12-in thick (300mm) lift. The potential problem with a greater than specified lift thickness is that the required density may not be achieved throughout the entire lift, especially at the bottom. Thin lifts are more susceptible to breakage because of reduced section modulus and should be terminated before the thickness gets below 6 in (150 mm), which can occur where RCC intersects with a rising foundation. The remaining area can then be filled with the next lift. If necessary, the grade can be re-established by placing two, 8-inch lifts in lieu of a 4-inch lift followed by a 12-inch lift.

5.2.10 RCC Mix Design Responsibility

The responsibility for conventional concrete mix designs on most projects is assigned to the contractor. Mix design procedures for RCC are still evolving and the resulting properties are not as uniformly predictable as they are for conventional concrete. Consequently, at this time it is recommended that Owner/Engineer maintain this responsibility. The Owner should retain an engineer experienced with the design of RCC mixes to achieve the best results for the intended project.

6.0 REFERENCES

ACI 207.5, Roller Compacted Mass Concrete.

ACI 211.1, Standard Practice for Selecting Proportions for Normal, Heavyweight Concrete and Mass Concrete.

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APPENDIX A
FORMS

This appendix contains several data recording and calculation sample forms that can be used as part of a RCC Quality Control program. The data type and general format is compatible with some typical equipment used for RCC projects. However, the project specific RCC quality control program must be customized to match specific equipment, plant control systems and definitions. The forms included in this appendix include:

Form 1a	Batch Plant RCC Mix Evaluation
Form 1b	Shift Batch Plant Summary
Form 1c	Continuous-Flow Plant RCC Mix Evaluation
Form 1d	Shift Continuous-Flow Plant Summary
Form 2	RCC Aggregate Moisture Data
Form 3	RCC Lift Summary
Form 4	Summary of In-place Density and Moisture Content
Form 5	RCC Compressive Strength Test Results
Form 6	Summary of RCC Test Data
Form 7	RCC Shift Summary
Form 8	Material Placement Quantities
Form 9	Cement and Pozzolan Quantity Balance

In general, a good approach for data recording and data reduction is to facilitate easy raw data entry, and automated data reduction. This approach serves to minimize the potential for calculation errors. Computer based spreadsheets, and linkage of common data in a workbook format, can further increase efficiency while minimizing errors. The spreadsheets described herein have been utilized on numerous RCC projects to date. A description of each of the forms and their general use is presented below. In order to facilitate easy usage of the forms, shaded columns/cells are used to indicate areas for raw data input into the form. The remaining cells are generally cells that contain data calculated using formulas and/or links to cells in other worksheets in a workbook.

Form 1a: The batch plant summary form is used to evaluate mixture proportioning data from a plant that measures each constituent. The mixture proportions from the plant, usually weight based, are input into the form. A spreadsheet program can then be used to convert the data to mixture proportions for comparison with the specified design mix, and to calculate the water content for correlation with field measurements. The computer spreadsheet can also be prepared that reduces the data from multiple batches, on each page.

Form 1b and 1d: These forms are similar to Forms 1a and 1c, except that the RCC mixture proportioning is evaluated over a longer interval, such as for a complete lift or shift. This type of evaluation can be used for developing an understanding of the average placement condition, for comparison with the range of individual batches, or time intervals, for the project.

Form 1c: This form is used for continuous flow type mixing plants and is similar to the setup of form 1a. In a continuous flow type plant, measurement of the constituent consists of volumetric and/or weight measurements that are recorded at selected time intervals (usually ranging between 3 minutes and 10 minutes). Volume measurements are usually correlated to an equivalent weight during plant calibration.

Form 2: This form is used to record the moisture content of the aggregate from the stockpiles that is communicated to the plant operators for mixing plant proportioning, and for analysis of the RCC actually produced.

Form 3: During RCC construction, various observations and test results should be recorded. This form provides and example.

Form 4: Compaction control usually consists of measurement of the wet density and comparison with a minimum required percent compaction. Form 4 is a density summary control form showing the results of a moving average of the wet density.

Form 5: Cylinders of RCC are usually prepared for evaluation of the compressive strength of the RCC produced by the mixing plant. In order to evaluate the compressive strength tests results, the wet density of the cylinders should be measured and recorded. The water:cement ratio of the RCC mix that represents the cylinders should also be calculated from the plant records.

Form 6: Comparison of the field test results, RCC mix data (mixing plant records) and compressive strength data is valuable for summarizing and evaluating the project RCC quality. Form 6 summarizes mixing data, field test data, and RCC cylinder test density on one form.

Form 7: This form summarizes the RCC quantity produced during a shift and waste quantities if applicable, and the average mix proportions.

Form 8: This form summarizes various products placed during a shift or by lift or day.

Form 9: An important part of a QC program for RCC is evaluation of the cement (and pozzolan, if used) used for RCC, in comparison with the plant records. By evaluating the RCC plant records with cement deliveries, an independent check of the cement content can also be made. Form 9 provides an example material balance summary.

FORM 1a
BATCH PLANT RCC MIX EVALUATION
(6 cu yd batch)

Date			Batched Weights (pounds)						Calculated Water Content (pounds) and Water:Cement Ratio			
1/1/00	Time		C. Agg.[1]	F. Agg.[1]	Add Water[1]	Cement[1]	Pozzolan[1]	Total Batch	Water in Agg.[5]	Total Water[6]	Free Water[7]	W/C Ratio[8]
Time batched	9:40 a.m.		11980	8835	1280	2100	0	24195	712.3	1992.3	1680.5	0.80
											Water Content[9] =	8.97%
Stockpile Moisture									Comments:			
Coarse agg.[2]	1.60%	Net Dry[3]	11791	8311	N/A	2100	0					
Fine agg.[2]	6.30%	Calc. %[4]	58.66	41.34	N/A	10.45	0					
Design Mix Proportions			58.65%	41.35%	N/A	10.45%	0.00%		Material Data:		C. Agg.	F. Agg.
										Absorption	0.60%	2.90%

Notes:

[1] Readings obtained from batch plant

[2] Fine and Coarse Agg. moisture are based on the stockpile moisture contents

[3] Net Dry = Batched weights divided by 1 + the moisture content of the constituent

[4] Proportion of each constituent as a percentage of the total dry weight of the aggregate

[5] Water in Agg. = (C. Agg. batched weight - Net Dry C. Agg.) + (F. Agg. batched weight - Net Dry Fine Agg.)

[6] Total Water = Add Water + Water in Agg.

[7] Free Water = Excess water in the mixture (i.e., total water less absorbed water in aggregate)
= Total Water - (Net Dry C. Agg. x Absorption) - (Net Dry F. Agg. x Absorption)

[8] W/C Ratio = Free Water / (Cement + Pozzolan)

[9] Water Content = Total Water / (Net Dry C. Agg. + Net Dry F. Agg. + Cement + Pozzolan)

FORM 1b
SHIFT BATCH PLANT SUMMARY

Date		Actual Batch Plant Readings (tons)							Calculated Water Content and Product Produced (tons) and Water:Cement Ratio				
1/1/00	Time		C. Agg.[1]	F. Agg.[1]	Add Water[1]	Cement[1]	Pozzolan[1]	Belt[2]	Water in Agg.[7]	Total Produced[8]	Total Water[9]	Free Water[10]	W/C Ratio[11]
Time, final reading	5:00 p.m.		1188.0	876.8	127.2	208.0	0.0	2398.0	70.7	2400.0	197.9	166.9	0.80
Time, initial reading	8:30 a.m.		0.0	0.0	0.0	0.0	0.0	0.0				Water Content[12]=	8.99%
Stockpile Moisture		Net Mat.[4]	1188.0	876.8	127.2	208.0	0.0	2398.0				Belt Weight/Total Produced[13]=	99.9%
Coarse agg.[3]	1.60%	Net Dry[5]	1169.3	824.8	N/A	208.0	0.0		Comments:				
Fine agg.[3]	6.30%	Calc. %[6]	58.64	41.36	N/A	10.43	0						
Design Mix Proportions			58.65%	41.35%	N/A	10.45%	0.00%		Material Data:			C. Agg.	F. Agg.
											Absorption	0.60%	2.90%

Notes:

[1] Readings obtained from batch plant

[2] Some plants have a belt (totalizer) scale for the combined weight of the mixture that can differ from the sum of individual readings

[3] Fine and Coarse Agg. moisture are based on the stockpile moisture contents

[4] Net Mat. = the difference between the final and initial plant readings over a duration of time

[5] Net Dry = Batched weights divided by 1 + the moisture content of the constituent

[6] Proportion of each constituent as a percentage of the total dry weight of the aggregate

[7] Water in Agg. = (C. Agg batched weight - Net Dry C. Agg.) + (F. Agg. batched weight - Net Dry F. Agg.)

[8] Total Produced = Calculated total run weight = Net Mat. (C. Agg. + F. Agg. + Add Water + Cement + Pozzolan + Add Water)

[9] Total Water = Add Water + Water in Agg.

[10] Free Water = Excess water in the mixture (i.e., total water less absorbed water in aggregate)
= Total Water - (Net Dry C. Agg. x Absorption) - (Net Dry F. Agg. x Absorption)

[11] W/C Ratio = Free Water / (Cement + Pozzolan)

[12] Water Content = Total Water / (Net Dry C. Agg. + Net Dry F. Agg.+ Cement + Pozzolan)

[13] Belt totalizer reading to the sum of the batched weight of each constituent

FORM 1c
CONTINUOUS-FLOW PLANT RCC MIX EVALUATION

Date		Actual Plant Readings (tons)							Calculated Water Content and Product Produced (tons) and Water:Cement Ratio				
1/1/00	Time	Total Agg.[1]	C. Agg.[2]	F. Agg.[2]	Add Water[1]	Cement[1]	Pozzolan[1]	Belt[3]	Water in Agg.[8]	Total Produced[9]	Total Water[10]	Free Water[11]	W/C Ratio[12]
Time, final reading	9:40 a.m.	43.00	24.73	18.28	2.64	4.34	0.00	49.95	1.47	49.98	4.11	3.47	0.80
Time, initial reading	9:30 a.m.	0.00	0.00	0.00	0.00	0.00	0.00	0.00				Water Content[13]=	8.97%
Stockpile Moisture	Net Mat.[5]	43.00	24.73	18.28	2.64	4.34	0.00	49.95				Belt Weight/Total Produced[14]=	99.9%
Coarse agg.[4]	1.60%	Net Dry[6]	24.34	17.19	N/A	4.34	0.00		Comments:				
Fine agg.[4]	6.30%	Calc. %[7]	58.60	41.40	N/A	10.45	0.00						
Design Mix Proportions			58.65%	41.35%	N/A	10.45%	0.00%		Material Data:			C. Agg.	F. Agg.
											Absorption	0.60%	2.90%
											Percent Feed Rate	57.50%	42.50%

Notes:

1. Readings obtained from plant at selected time intervals
2. Some plants measure the total aggregate feed weight. Individual aggregate weights can be estimated based on the percent feed rate for each gate
3. Some plants have a belt (totalizer) scale for the combined weight of the mixture that can differ from the sum of individual readings
4. Fine and Coarse Agg. moisture are based on the stockpile moisture contents
5. Net Mat. = the difference between the final and initial plant readings over time
6. Net Dry = Batched weights divided by 1 + the moisture content of the constituent
7. Proportion of each constituent as a percentage of the total dry weight of the aggregate
8. Water in Agg. = (C. Agg. batched weight - Net Dry C. Agg.) + (F. Agg. batched weight - Net Dry F. Agg.)
9. Total Produced = Calculated total run weight = Net Mat. (C. Agg. + F. Agg. + Add Water + Cement + Pozzolan)
10. Total Water = Add Water + Water in Agg.
11. Free Water = Excess water in the mixture (i.e., total water less absorbed water in aggregate)
    = Total Water - (Net Dry C. Agg. x Absorption) - (Net Dry F. Agg. x Absorption)
12. W/C Ratio = Free Water / (Cement + Pozzolan)
13. Water Content = Total Water / (Net Dry C. Agg. + Net Dry F. Agg. + Cement + Pozzolan)
14. Belt totalizer reading to the sum of the batched weight of each constituent

FORM 1d
SHIFT CONTINUOUS-FLOW PLANT SUMMARY

Date		Actual Plant Readings (tons)							Calculated Water Content and Product Produced (tons) and Water:Cement Ratio				
1/1/00	Time	Total Agg.[1]	C. Agg.[2]	F. Agg.[2]	Add Water[1]	Cement[1]	Pozzolan[1]	Belt[3]	Water in Agg.[8]	Total Produced[9]	Total Water[10]	Free Water[11]	W/C Ratio[12]
Time, final reading	2:00 p.m.	1133.48	651.75	481.73	66.69	111.78	0.00	1304.60	36.79	1245.90	101.75	85.65	0.80
Time, initial reading	7:15 a.m.	58.97	33.91	25.06	1.73	5.35	0.00	66.70				Water Content[13]=	8.89%
Stockpile Moisture	Net Mat.[5]	1074.51	617.84	456.67	64.96	106.43	0.00	1237.90				Belt Weight/Total Produced[14]=	99.4%
Coarse agg.[4]	1.60%	Net Dry[6]	608.11	429.60	N/A	106.43	0.00		Comments:				
Fine agg.[4]	6.30%	Calc. %[7]	58.60	41.40	N/A	10.26	0.00						
Design Mix Proportions			58.65%	41.35%	N/A	10.45%	0.00%		Material Data:			C. Agg.	F. Agg.
											Absorption	0.60%	2.90%
											Percent Feed Rate	57.50%	42.50%

Notes:

[1] Readings obtained from plant at selected time intervals

[2] Some plants measure the total aggregate feed weight. Individual aggregate weights can be estimated based on the percent feed rate for each gate

[3] Some plants have a belt (totalizer) scale for the combined weight of the mixture which can differ from the sum of individual readings

[4] Fine and Coarse Agg. moisture are based on the stockpile moisture contents

[5] Net Mat. = the difference between the final and initial plant readings over a duration of time

[6] Net Dry = Batched weights divided by 1 + the moisture content of the constituent

[7] Proportion of each constituent as a percentage of the total dry weight of the aggregate

[8] Water in Agg. = (C. Agg. batched weight - Net Dry C. Agg.) + (F. Agg. batched weight - Net Dry F. Agg.)

[9] Total Produced = Calculated total run weight = Net Mat. (C.Agg. + F.Agg. + Add Water + Cement + Pozzolan)

[10] Total Water = Add Water + Water in Agg.

[11] Free Water = Excess water in the mixture (i.e., total water less absorbed water in aggregate)
= Total Water - (Net Dry C. Agg. x Absorption) - (Net Dry F. Agg. x Absorption)

[12] W/C Ratio = Free Water / (Cement + Pozzolan)

[13] Water Content = Total Water / (Net Dry C. Agg. + Net Dry F. Agg.+ Cement + Pozzolan)

[14] Belt totalizer reading to the sum of the batched weight of each constituent

FORM 2
RCC AGGREGATE MOISTURE DATA

Date	Shift	RCC Mix Design[1]	Moisture Content Test Results[2]						Fine Aggregate Average Total MC[3]	Coarse Aggregate Average Total MC[3]	Weighted Avg. of Total MC[4]
			Fine Aggregate			Coarse Aggregate					
			1	2	3	1	2	3			
1/1/00	Plant start	1	6.60%	6.40%	5.80%	1.70%	1.65%	1.70%	6.27%	1.68%	3.60%
1/2/00	Test pad	1	6.40%	6.60%	6.10%	1.70%	1.50%	1.60%	6.37%	1.60%	3.60%
1/3/00	Test pad	1	5.70%	6.40%	6.70%	1.45%	1.60%	1.50%	6.27%	1.52%	3.51%
Average									**6.30%**	**1.60%**	**3.57%**

Notes:

[1] Material proportions for RCC mix designs

Mix No.	Coarse Agg.	Fine Agg.
1	58.1%	41.9%

[2] Moisture contents obtained from material stockpiles

[3] Arithmetic average of test results

[4] Weighted average of total MC (moisture content) of the fine and coarse aggregate based on the material proportions

FORM 3

RCC LIFT SUMMARY

PROJECT NAME/LOCATION: RCC Project

PROJECT NO.: 100

DATE: 1/1/00 and 1/2/00

PREPARED BY: RCC Inspector

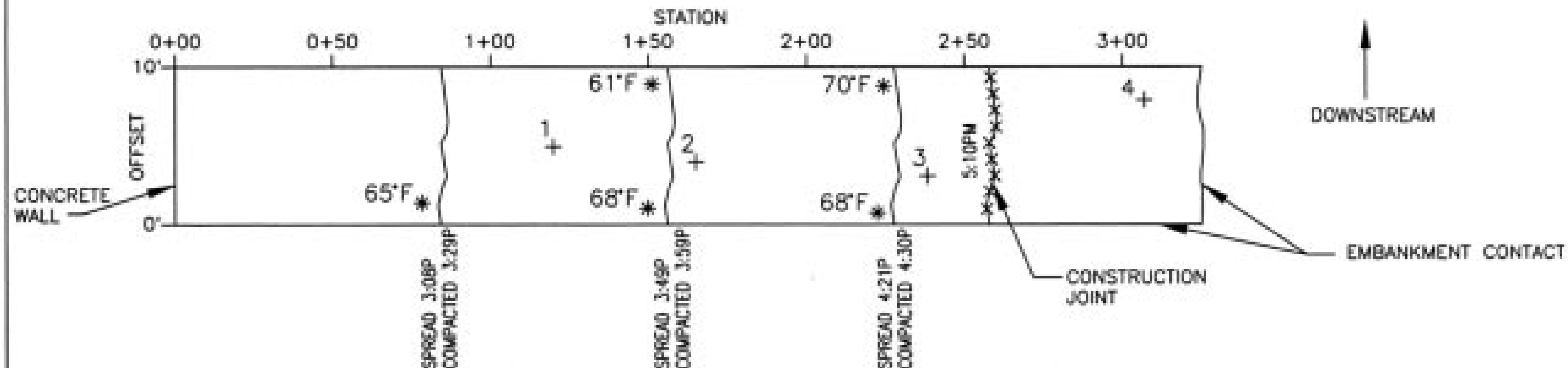
LIFT NO./ELEVATION: 1/El. 1110

WEATHER CONDITIONS: Sunny to partly cloudy, low to moderate wind

1 PM – 83°F 4 PM – 87°F

2 PM – 85°F 5 PM – 85°F

3 PM – 89°F



TEST NO.	1	2	3	4	
STATION	1+20	1+65	2+40	3+07	
OFFSET (FT)	5	4	3	8	
GAUGE NO.	00103	00103	00103	00103	
MOISTURE CONTENT	9.3	9.1	9.0	8.6	
WET DENSITY	146.1	149.5	146.7	149.1	
PROBE DEPTH	12"	12"	12"	10"	
COMMENTS					

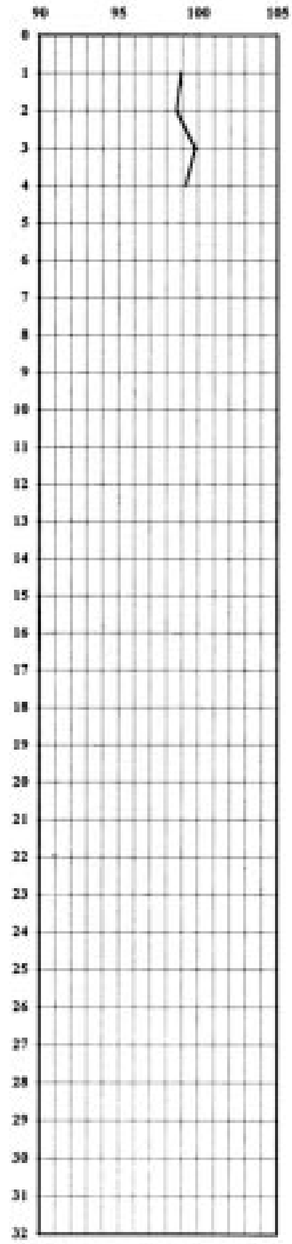
DESCRIBE LIFT TREATMENT, JOINT MATURITY, AND TEMPERATURE MEASUREMENTS

FORM 4

SUMMARY OF IN-PLACE RCC DENSITY TEST & MOISTURE CONTENT TEST RESULTS
Project Name: RCC Project

Test No.	Date Tested	Test Location: Station & Offset		Lift No. / Elevation	Specified Control Wet Density (pcf)	Test Depth (in.)	Wet Density (pcf)	% Moisture	% Relative Compaction	Required Relative Compaction
1	1/1/00	1+20	5'	1	149.3	12	146.1	9.3	97.9	99%
2	1/1/00	1+65	4'	1	149.3	12	149.5	9.1	100.1	99%
3	1/1/00	2+40	3'	1	149.3	12	146.7	9.0	98.3	99%
4	1/2/00	3+07	8'	1	149.3	10	149.1	8.6	99.9	99%

Moving Average Summary (Density Results)



FORM 5
RCC COMPRESSIVE STRENGTH TEST RESULTS

Cylinder Set No.	Shift	Date Made	Cylinder W/C	Avg. Cyl. Density	Avg. Results (psi)	
					7 day	28 day
R1	D	1/1/00	0.82	149.6	1973	3053
R2	D	1/2/00	0.73	149.1	2100	3113
R3	N	1/2/00	0.78	148.9	1970	2988
R4	D	1/3/00	0.80	149.9	1773	2700
R5	N	1/3/00	0.77	149.9	2008	3140
R6	N	1/4/00	0.75	150.2	2163	3188
R7	N	1/4/00	0.83	147.5	1888	3150

FORM 6
SUMMARY OF RCC TEST DATA

Date	Shift	Set No.	Measurements from Fill[1]: Average wet density on fill (per cu ft)	Measurements from Fill[1]: Average mst. on fill (%)	Calculated from Plant Records: Combined agg. mst. (%)[2]	Calculated from Plant Records: Avg. total water (%)[3]	Calculated from Plant Records: Avg. cement and pozzolan (%)[3]	Calculated from Plant Records: Avg. shift W/C ratio[3]	Based on Field Test Cylinders: Cylinder W/C ratio[4]	Based on Field Test Cylinders: Avg. cyl. Density[5] (per cu ft)	Compressive strength[5]: 7 day (psi)	Compressive strength[5]: 28 day (psi)
1/1/00	D	R1	146.1	9.20	3.60	8.97	10.45	0.78	0.82	149.6	1973	3053
1/2/00	D	R2	149.5	8.55	3.60	8.85	10.50	0.78	0.73	149.1	2100	3113
1/2/00	N	R3	146.7	8.20	3.51	9.20	10.10	0.82	0.78	148.9	1970	2988
1/3/00	D	R4	149.1	8.20	3.68	9.09	9.90	0.84	0.80	149.9	1773	2700
1/4/00	N	R5	147.4	9.00	3.55	8.75	10.60	0.82	0.77	149.9	2008	3140
1/5/00	N	R6	147.3	8.30	3.70	8.80	10.40	0.80	0.75	150.2	2163	3188
1/6/00	N	R7	148.2	8.50	3.45	9.05	10.70	0.85	0.83	147.5	1888	3050
Average			**147.8**	**8.56**	**3.58**	**8.96**	**10.38**	**0.81**	**0.78**	**149.3**	**1982**	**3033**

Notes:

[1] Readings obtained from nuclear density gauge tests on the RCC fill
[2] Combined aggregate moisture content based on shift or daily weighted average (Form 2 - RCC Aggregate Moisture Data)
[3] Average from Shift Plant Summary Form (Form 1b or 1d)
[4] Cylinder W/C ratio is calculated using Plant RCC Mix Evaluation (Form 1a or 1c) for RCC produced during the sampling interval
[5] Data obtained from RCC Compressive Strength Test Results (Form 5)

FORM 7
RCC SHIFT SUMMARY

Date	Shift	Average Mix Proportions - lb per cu yd[1]					Approx. Quantity Produced	Estimated Quantity Wasted	Approx. Quantity Placed	Comments
		C. Agg. (Dry)	F. Agg. (Dry)	Total Water	Cement	Pozzolan				
		lb	lb	lb	lb	lb	cu yd	cu yd	cu yd	
1/1/00	D	1,965.4	1,385.5	332.8	349.6	0.0	1,190	0	1,190	
Design Mix Prportions		1,965.2	1,384.8	332.0	350.0	0.0	1	N/A	N/A	

Note:

[1] Based on batch plant records (see Shift Batch Plant Summary Form 1b). The quantities produced by the batch plant are converted to absolute volumes using the specific gravity of the constituents. The total volume of RCC produced was calculated assuming 2 % entrapped air.

FORM 8
MATERIAL PLACEMENT QUANTITIES

Date	Shift	Lift Number	RCC Quantity (cu yd)	Sum (cu yd)	Facing Concrete (cu yd)	Sum (cu yd)	Bedding Concrete (cu yd)	Sum (cu yd)
1/1/00	day	1,2	150	150	0	0	33	33
1/2/00	day	3	112	262	0	0	24	57
1/2/00	night	4,5	452	714	0	0	58	115

FORM 9
CEMENT AND POZZOLAN
QUANTITY BALANCE

Date	Shift	RCC Quantity Produced (tons)	Cement Used - RCC Plant Records		Cement Delivery									
			Daily (tons)	Cumulative (tons)	Plant Silo	Storage 1 (tons)	Total in Storage (tons)	Change in Storage (tons)	Delivered (tons)	Net Used (tons)	Cumulative Used (tons)	Delivered vs. Plant Usage %	Avg. Cement Content %
1/1/00	day		0	0	81.9	115.5	197.5						
1/2/00	day	2,398	208.3	208.3	80.5	62.5	143	-54.4	153.9	208.3	208.3	100	8.69
1/2/00	night	1,199	104.2	312.5	41.9	112	153.9	10.9	115.1	104.2	312.5	100	8.69
1/3/00	day	575	50.4	362.9	78.8	107	185.8	31.9	82.3	50.4	362.9	100	8.77

Date	Shift	RCC Quantity Produced (tons)	Pozzolan Used - RCC Plant Records		Pozzolan Delivery								
			Daily (tons)	Cumulative (tons)	Plant Silo (tons)	Storage 2 (tons)	Total in Storage (tons)	Change in Storage (tons)	Delivered (tons)	Net Used (tons)	Cumulative Used (tons)	Delivered vs. Plant Usage %	Avg. Pozz. Content %
1/1/00			0	0	80.5	120	200.5						
1/2/00	day	2,398	119	119	80	66.1	146.1	-54.4	64.6	119	119	100	4.96
1/2/00	night	1,199	52.1	171.1	75	54.9	129.9	-16.2	35.9	52.1	171.1	100	4.35
1/3/00	day	575	25	196.1	80	108.9	188.9	59	84	25	196.1	100	4.35

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

Selected Conversion Factors to SI Units

To Convert	Into	Multiply by
Inch (in.)	Millimeter (mm)	25.4
Foot (ft)	Meter (m)	0.3048
Square foot (sq ft)	Square meter (sq m)	0.0929
Square yard (sq yd)	Square meter (sq m)	0.8361
Cubic foot (cu ft)	Cubic meter (cu m)	0.02832
Cubic yard (cu yd)	Cubic meter (cu m)	0.7646
Pound (lb)	Kilogram (kg)	0.4536
Ton (2,000 lb)	Kilogram (kg)	907.185
Gallon (U.S.)	Cubic meter (cu m)	0.003785
Pound per square inch (psi)	Kilopascal (kPa)	6.8948
Pound per cubic foot (lb/cu ft)	Kilogram per cubic meter (kg/cu m)	16.0185
Pound per cubic yard (lb/cu yd)	Kilogram per cubic meter (kg/cu m)	0.5933
Gallon per minute (gpm)	Liter per second (l/s)	0.06309
Degree Fahrenheit (°F)	Degree Celsius (°C)	5/9 (°F-32)

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