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# Construction Techniques for Roller-Compacted Concrete

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## ABSTRACT

Roller-compacted concrete (RCC) is a new material that uses a construction technique that applies the material property theories of both soil mechanics and concrete. The resulting product is a construction material with the strength characteristic of conventional concrete. Because RCC is a new material, the construction process for its placement is in a state of trial and adjustment; however, a unique feature of RCC is the use of standard earthmoving equipment for transportation, placement, and compaction. Earthmoving equipment reduces the labor-intensive process necessary for conventional concrete placement. The RCC mix is placed in a solid (no vertical joints) horizontal layer across the total placement area. No cure time is necessary between layers.

In 1970 Raphael presented the idea of a new construction material that would exist between conventional concrete and earth fill (1, pp. 221-247). With the equipment and techniques of an earth embankment project, a structure would be constructed with this new material in a continuous-cycle-type operation. The completed structure would, however, develop the strength and material characteristics of conventional concrete. The material would be an intermedium substance having the advantages of both earth fill and conventional concrete; therefore, a more economical structure or project could be achieved through reductions in materials, labor, and time (1).

These ideas become realities with the introduction of zero-slump concrete. The new construction material

is known as roller-compacted concrete (RCC), roll-concrete, or rolled concrete. As actual project experience is gained, the construction process for RCC is being developed, modified, and adjusted. Projects to date have been approached by applying new ideas to previous earthwork or concrete construction techniques. Engineers around the world have gained experience on a first generation of RCC projects and are beginning to report the results of their field experimentation with RCC placement techniques on those projects (2-5). This paper is a state-of-the-art review of the construction processes used for RCC construction.

## MATERIAL FUNDAMENTALS

Materials play an important part in dictating construction processes. RCC construction techniques for mixing, transporting, and placement are controlled

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primarily by material characteristics in relation to moisture retention, segregation, and compaction.

In the wet stage, RCC exhibits the material handling properties of a moist, granular soil; standard earthmoving equipment can be used for transportation, placement, and compaction. The term "wet" is used here instead of "plastic," as would be expected with concrete construction, because the no-slump concrete (RCC) does not react during placement operations as a plastic mix. After the RCC hardens, it is a concrete with the physical properties of conventional concrete and a finished appearance similar to that of conventional concrete (6).

#### Strength Characteristics

The density of RCC is developed through vibratory compaction. The resulting final strength is based on the percent composition of materials, the type and gradation of the aggregates, and the percent of optimum density obtained. The required RCC strength is specified for each individual project. The design strength is based on the structural use of the RCC: as a massive material with relatively low strength in a gravity structure where the compressive strength of the material is not a controlling factor; as a high-strength material with low mass in paving applications for high loadings; or somewhere in between, as a material with an average mass and strength. Higher-strength RCC requires a greater degree of control during the construction process and limits the selection of materials and equipment.

Gary N. Reeves of Freese and Nichols, Inc., and Lewis B. Yates of Trinity Engineering Testing Corporation approach RCC strength and mix quality using standard soil mechanics methods and theory; that is, as unit dry density increases, the material's strength will also increase and permeability will decrease (4). They develop a Proctor-type curve of dry density versus moisture using the project's proposed aggregates. This project- and aggregate-specific curve then provides the information necessary for controlling field placement operations. After placement, the RCC is cured and treated as conventional concrete.

Both the U.S. Army Corps of Engineers (7-9) and the U.S. Bureau of Reclamation (4-10) view RCC more as a concrete material in terms of design and field construction control. However, these two federal agencies each use slightly different approaches and techniques (11).

At Upper Stillwater Dam, the Bureau plans to use processed aggregates and high cementitious materials to provide bond strength without extensive joint cleanup. In planning Elm Creek Dam, the Corps is looking at increasing the amount of mortar to aid in attaining bond. This will be accomplished by the addition of portland cement, pozzolan, and more fines in the aggregate (12).

#### Aggregate Requirements

Generally, the specification requirements for the aggregates in RCC are not as strict as those for aggregates used in conventional concrete. Because heavy rollers, common to earth or rock construction, are utilized to densify RCC, aggregate gradation is not as important to achieving desired density as is slumpable concrete production (11). If mass, not strength, is the controlling characteristic, then a wide gradation range for aggregate selection exists. Many aggregates can be utilized directly from their bank or pit-run condition without special processing, thereby lowering project cost. Washing of aggregates

to remove fines is not always necessary. The controlling factor as to the amount of acceptable fines in a given situation is their plasticity. Some studies have shown that fines in RCC can improve both strength and compactibility (8,12). Material excavated during site preparation, which would otherwise be wasted, can often be used as RCC aggregate (Figure 1).



FIGURE 1 Three-hopper layout used to blend one site-mined sand and two imported aggregates for RCC pugmill production.

The larger rock-fill type of construction equipment allows the use of large-size aggregates. A rule of thumb for aggregate size selection is that the maximum size should not exceed one-third of the thickness of the layer of RCC being placed. Segregation problems, associated with loading, transporting, and unloading the RCC, increase with larger-size aggregate. Segregation can be reduced by partial remixing during spreading operations. This remixing is accomplished when the material is "knocked down" and contoured to the correct lift thickness (3,13,14). Rock ladders (4,15) and drop pipes (16) have been used to avoid segregation.

#### CONSTRUCTION

The construction process for RCC is based on a three-step cycle that results in continuous placement of the RCC mix. The cycle consists of production, transportation to the site, and spreading and compaction. Continuous placement means that one RCC layer is placed immediately on the preceding layer.

#### Production

Because continuous placement eliminates the delay due to curing time between layers or segments or both, as required by conventional concrete, a greater demand is placed on mixing-plant production capability, availability, and efficiency. Most concrete plants cannot produce a sufficient volume of RCC. This problem can be solved by enlarging the plant, utilizing more than one plant, or a combination of enlarging and multiple plants. The use of more than one plant provides a safety factor. If an individual plant breaks down, RCC can still be produced, ensuring that placement operations are not interrupted. With the use of holding hoppers for temporary storage, both continuous and noncontinuous batch-type

plants can provide a sufficient volume of material for continuous placement.

Pugmill-type plants have been the project norm (Figure 2). Standard conventional concrete central plants have been utilized only on a limited basis because of the performance problems associated with the lower consistency characteristic of zero-slump concrete. Contractors are beginning to investigate other plants in order to be competitive by utilizing equipment already in their possession.



FIGURE 2 Continuous-mix pugmill plant mixing RCC and loading into dump trucks.

Some mixing-plant experimentation is being performed by Tyger Construction Company, Inc., on their Upper Stillwater Project. Tyger has a Noble 600 batch plant with two 8-yd<sup>3</sup> tilt mixers and a Noble 600 modified to accept two 4-yd<sup>3</sup> high-intensity spiral-flow mixers on the project (4).

Mix-in-place techniques are not applicable because RCC is a controlled-mix product.

#### Transportation

The wet RCC can be transported from the plant by conveyor system (4); large buckets, the 8-yd size that is common in conventional concrete (1); or standard earthmoving haul units (4,14,17). Buckets are hauled on flatbed trucks or railway cars to the construction site, where they are swung into position by use of a crane. The haul route can be fixed for the duration of the project because the crane provides mobility at the job site (13). On small construction projects where space is severely limited, the use of buckets or a conveyor system is advantageous (15). The Shimajigawa Dam project in Japan used 12-yd<sup>3</sup> skip cars running down tracks laid on the right abutment (18). Even on projects of limited extent, the use of haul units may still be required because of other factors that dictate a distant batch-plant location.

On many of the projects completed to date, various earthmoving haul units have been utilized: scrapers (17), rear dump trucks (17,18), and wheel loaders (16). The number of haul units will be controlled by the batch-plant output and haul-unit cycle time. Because of the height of fall during placement, segregation sometimes occurs when rear dump trucks are used (Figure 3) (14,19). Because of the zero-slump characteristics of RCC, vibrators can be added



FIGURE 3 Euclid R-22 end dump used to transport RCC.

to rear dump trucks to smooth material flow and reduce buildup in the bed.

The utilization of scrapers provides better control of layer thickness during placement. This reduces the time necessary for the knock-down equipment to finish preparing the layer for compaction. Scrapers having positive displacement systems cause the RCC to flow from the haul unit with no substantial buildup occurring in the unit.

No impurities can be tracked onto the RCC. This requires that provisions be made for keeping haul-unit tires clean or for cleaning the tires before a machine enters the RCC area. Special haul-road surfacings, such as washed gravel or clean sand that will not adhere to tires, can be used to control surface contamination. Special wheel-cleaning spray systems have been used on two projects (20,21). Another solution is to keep the haul units on the RCC surface during loading. The Japanese did this at Shimajigawa by using skip cars to deliver the mix to the dump trucks on the dam (18). At Middle Fork Dam, a wheel loader stayed on the dam and was fed by a rock ladder initially. As the dam gained height above the pugmill elevation, feeding of the loader was handled by a radial stacker (15). A good maintenance program is also necessary in order to prevent equipment oil leaks or fuel spills from contaminating the RCC.

Travel in the RCC area should be in one direction, that is, a single entrance into and a separate exit from the area. One-directional travel across the RCC area prevents the haul units from interfering with the placement equipment. This helps to provide a continuous flow of the mix and steady production.

#### Spreading

Like earth embankment fills, RCC is placed at a specified layer thickness. The most common specified thickness in the United States has been 1 ft. Each layer is a continuous sheet over the total RCC area of the structure. Because the layers are placed over the total area, there are no vertical joints. In Japan, a built-up lift technique has been used in which a 1.6- to 2.3-ft lift is created by spreading several thin (6- to 8-in.) layers and then compacting the thick lift. This procedure is reported to have helped in reducing segregation (22).

It is advantageous to limit internal structural elements. One method of handling interior structural

elements is to place sand in the required space during the RCC placement. Such areas can be excavated after placement of the RCC is complete. This allows interior structural elements to be built following RCC activities.

Either a wheeled or a track bulldozer or a grader or both are used to knock down and spread the RCC. Early studies recommended the use of rubber-tired equipment for three reasons (13):

1. It was thought that the RCC would build up to a greater extent on tracks than on wheels;
2. There was concern about tracks scarring the RCC surface; and
3. Wheeled tractors are generally heavier, thereby providing more initial compaction.

Recently constructed projects have utilized track-type tractors (Figure 4) for the following reasons:

1. Experience has shown that buildup on tracks does not occur;
2. Wheeled tractors can spin, causing indentions in the RCC layer and increased segregation; and
3. The benefit of initial compaction does not speed the placement operation because the spreading operation is generally the controlling laydown cycle element (23).



FIGURE 4 John Deere 450 track-type tractor used to spread dump-truck-delivered RCC.

A custom-built spreader box mounted on a heavy shovel was used to control the lift placement on the Galesville Dam project in Oregon. Dump trucks hauled the RCC and dumped the mix into the box for spreading (20).

Water trucks or hose spray systems are often employed to maintain a wet surface until the placement of another layer. A wet surface must be maintained in order to achieve bonding between layers (23).

#### Compaction

Vibrator compaction rollers (Figure 5) are used to achieve mix density. Because most towed vibratory rollers are designed to turn in one direction only, operation on the RCC in reverse direction will tear up the semicompacted layer and material will stick to the roller. For maneuverability, the use of a



FIGURE 5 Vibrator roller used to compact RCC.

self-propelled vibratory roller allows both forward and reverse travel without adverse effects to the RCC layer (13).

#### CONSTRUCTION CONTROL

Control over the mixing operation of RCC is maintained by obtaining samples at set intervals from the batch plant and testing for water and cement content. At Willow Creek Dam, a set of three samples was run during each shift of operation (24).

One of the best controls is the experience of the operator as he learns to judge the consistency of the material by sight (13). In most concrete operations, complaints concern the question of adding more water, but with RCC the roller operators complain when the mix is too wet. A wet mix results in difficulty in rolling. A seemingly crude but accurate test for proper moisture content is the reaction of the vibratory roller to the RCC. An indicator of the optimum moisture content is when a wave just begins to show in front of the vibratory roller (23).

Control of compaction is maintained by in-place density tests using a nuclear density meter or by specifications that require a certain number of passes for a specified roller weight. If a nuclear device is used for density testing, the reading must be taken before the cement hydration and initial set can affect the results. The time frame for consistent results is from 30 to 40 min after mix batching (4).

One roller can usually compact for several knock-down machines. On projects completed to date, compaction time has not been critical. Control on these past projects was by a specified number of passes of a roller with a specified weight. When compaction time becomes a critical factor, nuclear density meters can be used for individual layer density control. This permits almost instant feedback as to roller effectiveness (19). Excessive rolling will add to construction cost and result in decreased dry density and strength (4).

Cores and samples can be collected for compressive strength and other tests. However, construction of the RCC will often be completed or have progressed considerably before the results of such tests are available. The RCC construction process is fast; therefore the use of cores and samples is inadequate for field monitoring. However, they do provide the historical data for evaluating the final product.



## FACING FINISHES

The vertical face of the RCC can be finished in several ways. Facing systems that have been used are (a) natural, uncured slope; (b) high-strength-concrete slipformed curb; and (c) concrete panel.

### Natural Facing

RCC can be compacted to within several inches of the vertical edge by use of light rollers. The top RCC layer is cured by a conventional concrete method in order to achieve maximum strength. During continuous operations, curing between layers is not necessary because each successive layer serves to retain the moisture in the previous layer; maximum strength is thereby obtained and a curing operation is eliminated. If the outside vertical face is left with no protection, a foot or so of the exposed side will lose moisture to the atmosphere. This exposed area will have a reduced strength, but the dried portion protects the interior mass of the RCC from further loss of moisture, and the strength lost at the edges does not affect the overall strength of the structure.

### Curb

Low-slump, high-strength concrete can be used in slipform pavers to form curbs. The exact makeup of the curb concrete will depend on its structural purpose. If the curb's purpose is to provide both a form for the RCC mix and freeze-thaw protection, conventional concrete is appropriate (10).

The RCC can be compacted against the completed curbs. Vertical expansion joints must be included because the curbs are designed like conventional concrete. The slipforming can be a continuous operation. The slipform machine can be guided by a wire or by laser control systems. The curbs are raised 2 to 3 ft at a time in a continuous process along the vertical edge of the RCC layers. Construction of the curb precedes the placing of the RCC layers by 1 or 2 ft vertically. The curb is usually "green" (still in the curing process) when a layer of RCC is compacted against it. This creates some bonding of the two materials and helps to form a solid structure. Curing for the curb facing and the last layer of the RCC must be provided (19).

### Panel

Precast concrete panels have been used to form a vertical face. A modified version of the system patented by Reinforced Earth was used on one project. The RCC layers must gain sufficient strength to retain the preset bolts to which the framing is attached before additional panels are added. To prevent buildup of pressure behind them, the panels are not sealed (8).

## COLD JOINTS

The concept of continuous placement of the RCC layers exists in theory only. Shutdowns of the RCC operation will occur, but these should be minimized. Shutdowns or delays will result in the forming of a cold joint, which occurs when there is a time lapse between the placement of layers and the layer just placed is allowed to dry out to a point where bonding with a new

layer would not occur. The creation of bonding between such layers often requires a special treatment.

The treatment of cold joints between RCC layers is dependent on the condition (clean or dirty and percent water content) of the old or cold RCC surface layer. The common approach is to sandblast the old surface clean, if necessary, and then to wet the surface and apply a 3-in.-thick rich RCC layer. The rich mix has a higher water and cement content and a smaller maximum aggregate size. The 3-in. rich layer plus the next 12-in. layer of RCC are compacted as one mass. Other cold surface treatments consist of water only, dry cement only, water-cement slurry, and water-cement-sand mixtures (Figure 6). The normal continuous cycle can be resumed once this cold surface bonding is effected.



FIGURE 6 Laborer wetting a sand-cement cold-joint mixture (note limited RCC buildup in upper corner of truck bed).

## CONCLUSION

Continuity and therefore efficiency are dependent on the design of the RCC construction process to produce a succession of operations. The three parts of the total cycle--production, transportation, and spreading and compaction--must complement one another and be synchronized. Project conditions will dictate specific equipment selection. Selection of the size and number of haul units is based on haul-cycle time and the volume of RCC being utilized per unit of time in the placement area. The mixing plant must be capable of producing a sufficient volume of RCC so that the haul units are not delayed in supplying the placement operation. A delay in any part of the total cycle produces a delay in all the other parts of the cycle (6). The adaption of standard construction equipment and processes to RCC construction has proved that RCC is a construction material that offers savings in both money and project duration.

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