concrete INFORMATION

Bonding Roller-Compacted Concrete Layers

Roller-compacted concrete (RCC) can be defined as a no-slump concrete compacted by vibratory roller. It differs from conventional concrete principally in its drier consistency, which is similar to that of damp gravel. For effective consolidation, RCC must be dry enough to support the weight of large external compaction equipment yet wet enough to permit adequate distribution of the paste binder throughout the mass during the mixing and compaction process. Materials that fall into the basic definition of RCC include rollcrete; dry, lean concrete; and certain coarse-grained soil-cement, for example, cement-treated aggregate.

The conventional method of concrete gravity-dam construction consists of casting the concrete in a series of blocks or monoliths. Concrete is placed in continuous multiple layers 18 to 20 in. thick to a final lift height of 5 to 10 ft. As concrete sets, subsidence of the heavy materials causes excess water to separate from the mixture and rise to the surface. The rising water, known as "bleeding" or "water gain," may also carry lighter, fine deleterious particles to the surface. In some cases, a film called "laitance" forms on the surface. This laitance, which tends to reduce the bonding of a subsequent lift to the concrete below, must be completely removed.

A common method of achieving adequate bond for conventional mass concrete is to clean the concrete surface by wet sandblasting or by high-pressure air or water-jet blasting (7000 to 10,000 psi pressure) as shown in Fig. 1. To avoid loosening aggregate and removing too much good material, the cleaning operation is performed after initial concrete set, which is typically one to three hours depending on temperature and other factors that effect the rate of hardening. The surface is cleaned again just prior to placing the next lift to remove any contaminants or carbonate deposits that may have developed following initial cleanup. With high-pressure equipment, cleanup may be accomplished in one operation just prior to placing the subsequent lift, provided there is no excessive delay between the two placements.[1]

In most cases only surface cleanup is required for adequate bonding. When more than surface cleanup is required, as in the case of structural concrete, a bedding layer is applied to the concrete surface just prior to placing the next lift. The bedding generally consists of a thin layer of mortar having the same proportions as the concrete but with the coarse aggregate removed.[2]

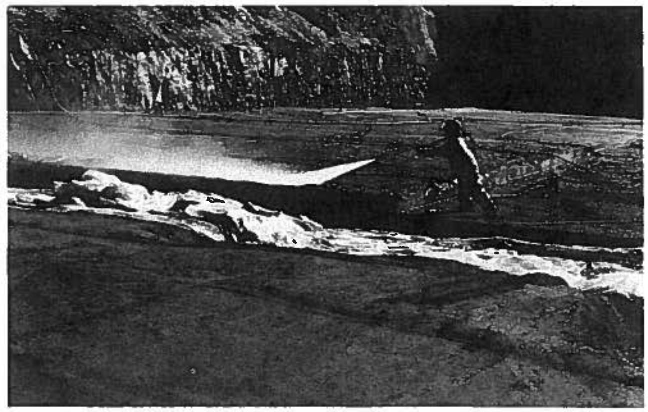


Fig. 1. Water jet blasting surface of conventional concrete foundation leveling pad prior to RCC placement at Upper Stillwater Dam, Utah.

Typical roller-compacted concrete dam construction consists of placing and compacting the material in long, continuous horizontal lifts one to two feet thick. This method of construction can create up to 10 times more horizontal lift surfaces than in conventional mass concrete. With the drier consistency of RCC mixtures, there is little or no surface water gain during concrete setting. Thus, no weak laitance film at the surface is produced. For some high paste content mixes, it is not unusual for full consolidation of the RCC to bring paste to the surface. This paste, if properly cured, does not have to be removed prior to placement of the next lift.

Design

Concrete gravity dams are designed essentially for stability against overturning and sliding. Shear strength along the interface between RCC layers is an influencing factor, especially on higher dams and those with steep downstream slopes. Compressive strength is generally not a controlling factor except for its influence on shear strength and for very high dams where compressive stresses may be large.

Earthquakes impart accelerations to dams, which may tend to increase horizontal loads while decreasing the effective weight of the structure. In seismic areas allowance for earthquake effects must therefore be made in the design. It is beyond the scope of this publication, however, to address the effects of dynamic loadings on dams.

Seepage is also a major design consideration. While some seepage may be tolerated without affecting the safety of the dam, excessive seepage can create problems. Methods to minimize seepage include high-paste RCC mixtures, adequate bonding of joints, and use of watertight upstream facing elements.

Overturning

For stability against overturning, gravity sections are generally sized for compression over the entire base. In the stability analysis, uplift pressure at the base and along lift joints is usually taken as varying from full hydrostatic pressure at the upstream face to some ratio of the difference between headwater and tailwater pressures at the foundation drains. If the vertical stress at the upstream edge of any horizontal section, computed without uplift, exceeds the uplift pressure at that point, the dam is considered safe against overturning. Fig. 2 shows the relationship of base width to dam height requirements as affected by foundation drain location. The figure assumes one-third of the uplift pressure occurs at the drains after allowing for a linear uplift pressure drop from headwater to tailwater.[3]

When stability against overturning controls design, the volume requirements are dependent upon dam shape as well as location of foundation drains. The optimum design consists of a triangular-shape dam with a vertical or nearly vertical upstream face and a foundation drainage system located approximately one-fourth of the base length from the upstream face.[3]

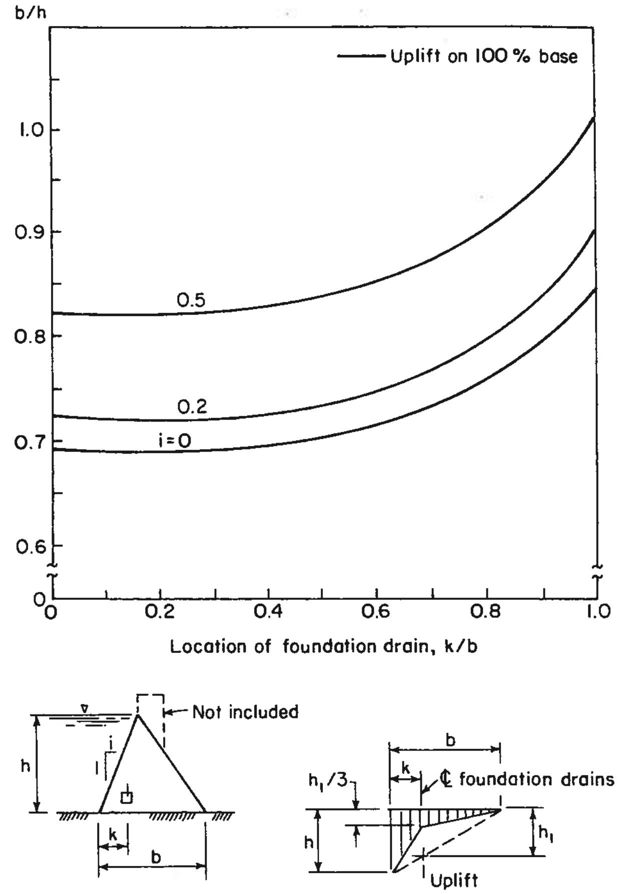


Fig. 2. Stability against overturning full base in compression—b/h versus k/b (Reference 3).

Sliding

Resistance to sliding within a concrete section relates to the shear strength of concrete and is based on the bond strength (cohesion) of the concrete, the compressive stress on the potential failure plane, and the coefficient of internal friction in the concrete. The ratio of resisting to driving forces along any section of a concrete dam can be expressed by the following equation:

$$Q = \frac{CA + (\Sigma W - U)\tan\varphi}{\Sigma H}$$

where

Q = shear friction factor of safety at section
C = cohesion per unit area
A = area of section considered
ΣW = resultant vertical force above section
U = total uplift force on horizontal section
tanφ = coefficient of internal friction
ΣH = resultant horizontal driving force above section

The shear friction factor may vary depending on the size and importance of the structure and loading conditions during operation. The U.S. Bureau of Reclamation (USBR) design criteria provides for three major loading conditions: "usual" or normal, which occurs most of the time; "unusual," which occurs during occasional flooding; and "extreme," which combines the usual load with earthquake loading. The minimum shear friction factor (Q) for each condition is 3.0, 2.0, and 1.0, respectively.[4]

The coefficient of friction for concrete along a joint depends upon the roughness and soundness of the hardened base concrete surface and on the ability of the paste in the covering layer to interlock into the pore structure of the hardened concrete. A typical value for concrete sliding on a relatively smooth concrete surface is 0.7 ($\varphi = 34°$). Where intimate contact of the two surfaces is assured, a value of 1.0 ($\varphi = 45°$) is generally assumed.[5]

A cohesion value for concrete is determined from direct shear tests under varying confining pressures. Table 1 gives shear strength tests results from various projects.

A relationship between shear friction factor and cohesion requirements for varying upstream slopes and coefficients of internal friction are given in Fig. 3. The figure discounts entirely the effectiveness of foundation drains to reduce uplift and increase sliding resistance; therefore, the required cohesion values can be considered conservative. Comparing Fig. 3 with the values obtained for cohesion and friction angles in Table 1, it would

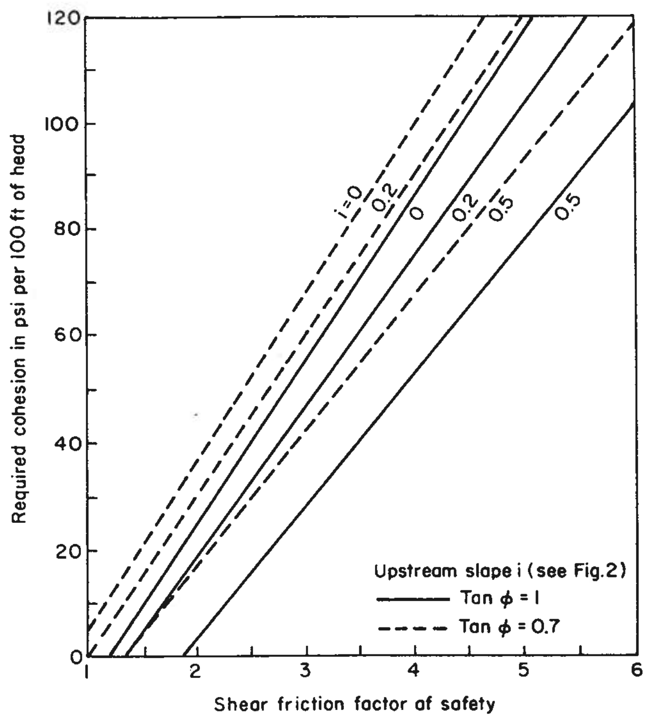


Fig. 3. Cohesion requirements for stability against sliding (Reference 3).

appear that adequate friction factors can be obtained with minimal effort.

Seepage

Dams are not expected to be totally impermeable to the flow of water. Most concrete dams have galleries with a system of internal and foundation drains to collect and dispose of the seepage. Experience has shown that seepage will significantly decrease within the first couple of years of operation due primarily to autogenous healing and siltation of the cracks and joints. Although seepage is normally not a problem, too much seepage may produce excessive uplift pressure not accounted for in the design; permit the loss of excessive amounts of water that would otherwise be used for power production, irrigation, or water supply; create a maintenance problem involving collection and disposal; cause internal erosion of the structure; or create freeze-thaw durability problems along the downstream face.

The permeability of a concrete mass is largely dependent upon the entrapped air void system and therefore is almost totally controlled by mixture proportioning and degree of compaction. When there is sufficient paste to minimize air void space between aggregates and adequate compaction to fully consolidate the mass, the RCC should be relatively impervious. The importance of cementitious content on permeability is shown in Fig. 4. The data include permeability along joints as well as through the mass. In the case of Willow Creek, where poor joint bonding has been reported,[7] a high permeability along an unbonded joint can contribute significantly to total permeability. Bonding RCC joints will obviously reduce permeability. Test results from a USBR/PCA study[8] showed permeabilities of bonded joints varied from 1×10^{-2} to 30 ft per year.

In addition to bonding RCC joints, seepage can be minimized by other methods including the use of conventional concrete upstream facing with sealed vertical joints or installation of a watertight membrane liner at the upstream face. If seepage rather than stability is the overriding factor, consideration may be given to use of a bedding mix between each layer along a narrow strip adjacent to the upstream face. This partial bonding should not be considered in the stability analysis but can be very effective in reducing seepage.

Table 1. Shear Strength Properties Along Untreated Joints

Project	MSA, in.	Cement, lb/cu yd	Fly ash, lb/cu yd	Test age, days	Friction angle, degrees	Tan φ	Cohesion, psi	Comments
Upper Stillwater	2	182	210	28	47	1.07	220	Lab specimens; confining pressures varied from 50 to 200 psi for all mixes
				90	49	1.15	376	
				365	47	1.07	497	
	2	121	269	28	47	1.07	136	
				90	58	1.60	241	
				365	71	2.90	355	
	2	129	286	28	42	0.90	235	
				90	59	1.66	281	
				365	46	1.04	575	
Willow Creek	3	80	32	35	44	0.97	114	Field test from actual project; joint maturity of 1600°F-hour
				90	48	1.11	132	
	3	175	80	35	54	1.38	174	
				90	54	1.38	202	
Elk Creek (1982)	3	94	38	90	53	1.33	130	Field test section; joint maturity of 112°F-hour
					52	1.28	100	Joint maturity of 318°F-hour
					44	0.97	110	Joint maturity of 3168°F-hour
Galesville	3	74	51	90	43	0.93	82	Lab specimens; joint maturity of 500°F-hour
Copperfield	2	134	50	46	48	1.11	8	Field test from actual projects

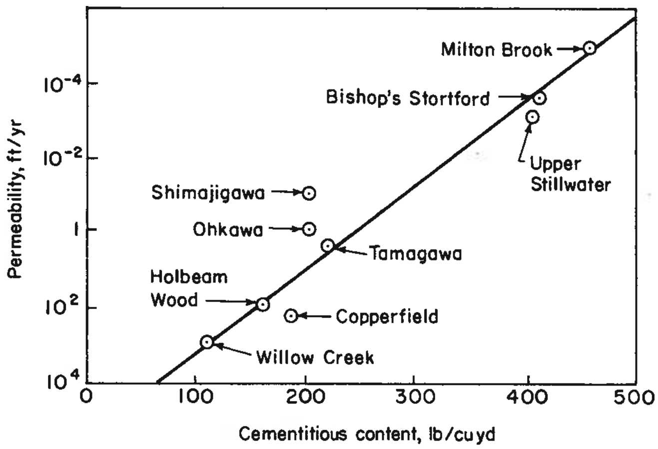


Fig. 4. Relationship between in-place permeability and cementitious content (Reference 6).

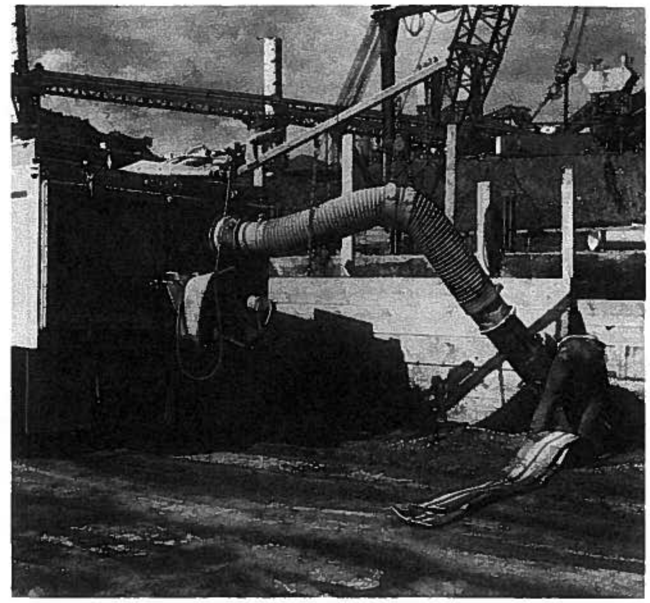


Fig. 5. Vacuum truck removing loose material from RCC surface at Elk Creek Dam, Oregon (courtesy of U.S. Army Corps of Engineers, Portland, Oregon).

Methods of Bonding

The principal factors that control bonding of one layer of concrete to another are

1. Condition of the surface to be bonded
2. Time delay between placements
3. Moldability of the covering concrete
4. Degree of compaction (consolidation).

As previously mentioned, bonding conventional mass concrete generally consists of simply cleaning the hardened concrete surface to remove laitance and any loose material prior to placing the subsequent layer. The fresh concrete is thoroughly consolidated with internal vibrators to full depth to assure adequate distribution of paste into voids along the surface of the hardened concrete below.

An RCC mix contains less paste and is drier than conventional mass concrete. It is compacted (consolidated) by external means through the use of vibratory rollers. The consistency and methods of construction of RCC often do not provide sufficient excess paste to adequately fill voids along the surface of the hardened concrete below. Consequently, complete bonding of untreated RCC lifts is questionable. The following presents information on various methods for achieving adequate bond between layers.

Surface Condition

As with conventional concrete, the RCC surface should be kept continuously moist but not overwatered. In addition to the obvious benefits of moist curing, studies[8,9] have shown that moist curing improves bonding, especially at later ages. Excessive surface moisture, however, is detrimental to bond development.

Although laitance is not expected to develop, all loose or contaminated material must be removed prior to placing the subsequent lift. Surface cleaning by high-pressure jet blasting with air or water is acceptable; however, tests at Galesville and Elk Creek Dams indicated that sandblasting actually reduced bond strength. Use of vacuum equipment, as shown in Fig. 5, is very effective in removing loose material and excess water without disturbing the surface. At Willow Creek Dam, the lack of bonding and permeability between layers has been attributed to a poor surface condition. Equipment used to haul the RCC from the batch plant to the placement area would routinely track mud, silt, and fine noncementitious debris onto the completed RCC from access ramps. In addition, the sharp turning action and constant movement of the hauling equipment over a completed layer would cause tearing and rutting of the surface. The condition was made worse by repeated rewetting with a water truck. This constant traffic over a wet surface resulted in the development of a thin layer of disturbed, damp, fine material with little or no cement value.[7]

To eliminate the problem of tracking mud and other loose material onto the placement area, the use of conveyor belts to transport RCC from the batch plant to the placement area, as shown in Fig. 6, has become standard practice on most large dam projects. Other equipment for hauling, spreading, and compacting the RCC are permanently assigned to the placement area to prevent them from bringing contaminant material onto the fill. Whether or not conveyor belts are used, it is important the surface be properly maintained and cleaned prior to placing a cover layer.

Joint Maturity

There is a correlation between bond strength and time delay between placements. Other factors including temperature, curing conditions, and actual RCC mix design including use of set retarders and high fly ash mixes will influence the bond strength of untreated joints.

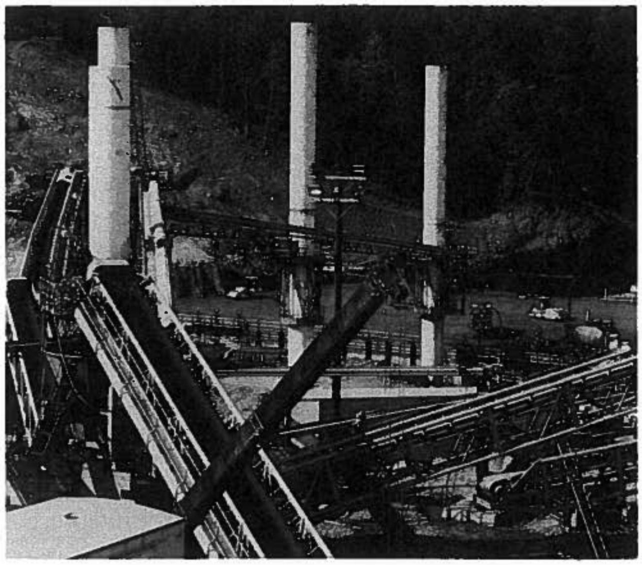


Fig. 6. Conveyor belt system at Elk Creek Dam in Oregon. Placement area in background.

When an RCC lift is covered with an additional lift before it reaches initial set, it is considered a fresh or plastic joint and should provide a strong, watertight joint. Beyond this point, a "cold joint" begins to develop, resulting in loss of bond strength and increase in seepage. Once a cold joint develops, a bedding layer may be required to achieve the required bond strength as well as watertightness.

Common practice is to express the development of a cold joint or joint maturity in terms of average surface temperature and time of exposure. For example, if an RCC lift is exposed for 10 hours at an average temperature of 60°F the joint maturity is 600°F-hour (60°F × 10 hours). There is no distinct value that will apply for all situations. For example, a dry, lean mix RCC constructed in an arid environment would require a lower joint maturity value than a wet, high-paste volume RCC constructed under humid conditions. In general, limits for joint maturity have ranged from 350 to 1600°F-hour. Examples of projects that specified joint maturity values include Willow Creek Dam (1600°F-hour), Galesville Dam, Oregon (500°F-hour), and Stagecoach Dam, Colorado (500°F-hour).

An alternative method, especially for small projects, is to eliminate the temperature factor and express the joint maturity in terms of time only. No matter which method is used, the designer should establish a joint maturity criteria based on field or laboratory studies. In the absence of these studies, a conservative value should be chosen.

High-Paste RCC

Adequate paste is necessary to achieve satisfactory bond between successive lifts. This is especially important following initial set of the lower lift. Once the lower lift has completely hardened, bond is dependent on the interlocking of the paste of the covering mix into the pore structure of the sound paste of the lower lift. Studies[10,11] have shown poor bond developed between lifts of mixtures that were very dry or contained relatively low amounts of cementitious material.

The flowability or consistency of an RCC mixture is determined by use of a modified Vebe apparatus. The apparatus described in Reference 12 consists of a one-third cubic foot metal container attached to a Vebe vibratory table (Fig. 7). A loose RCC sample is placed in the container under a 50-lb surcharge and then vibrated until consolidated. When the sample becomes fully consolidated, a ring of mortar will form around the circumference of the surcharge. The time it takes for this ring to form is called the "Vebe time" and usually ranges from 15 to 40 seconds. Factors that influence the Vebe time include water, sand, and cementitious material content; size and texture of coarse aggregate; and type and quantity of fines. At the USBR Upper Stillwater Dam in Utah the Vebe time ranged from 15 to 30 seconds. The Corps of Engineers at Elk Creek Dam in Oregon, which has a 3-in. MSA and a higher minus No. 200 fines content than Upper Stillwater, used a Vebe time of approximately 10 seconds with a 27.5-lb surcharge. Some mixtures, however, do not consolidate well in the Vebe test including very stiff mixtures, mixtures with paste volumes near the minimum voids content of the aggregates, or those with a very high plastic fines content.

According to ACI 207.5, a minimum paste to mortar ratio by volume of 0.38 has generally been found suitable for interior mass mixtures. A high-paste RCC will

Fig. 7. Vebe apparatus with 50-lb surcharge (courtesy of U.S. Bureau of Reclamation).

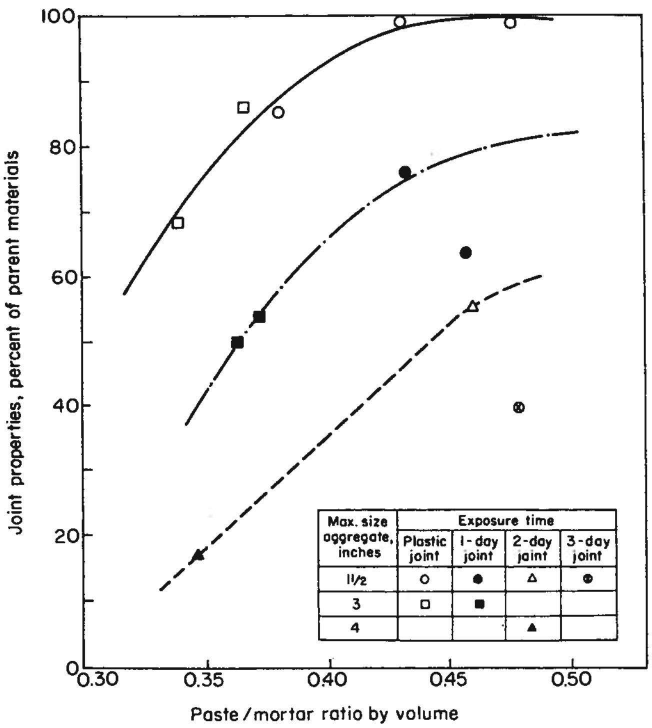


Fig. 8. Relationship between RCC bonding and paste/mortar ratio (Reference 13).

contain more paste than is required to sufficiently fill all voids and coat all particles of aggregates. Fig. 8 provides test results from a Construction Industry Research and Information Association (CIRIA) study[13] showing the benefits of increased paste-mortar ratios on bond strength. Most high-paste mixtures contain a large quantity of pozzolans, which effectively serve to limit the heat of hydration within the compacted mass. Although high-paste mixtures tend to provide better bond, the designer must also consider other factors including thermal effects, drying shrinkage, and additional cost for the higher cementitious content mixtures.

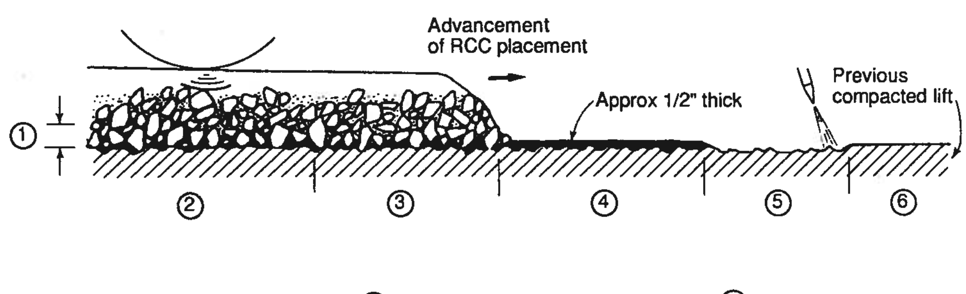
A possible concern of high-paste mixtures occurs during hauling and compaction operations when excess moisture, trapped in the mixture, occasionally causes rutting and weaving of the RCC surface. In soils this spongy condition would imply the presence of excess pore pressure. If pore pressure is not relieved in soils work, it will contribute directly to a reduction in shear strength. In concrete the excessive moisture will dissipate with hydration of the cement and should have little adverse effect on strength.

Bedding Mixtures

In lieu of high-paste RCC mixtures, satisfactory bond at horizontal joints can be assured by utilization of a bedding mixture of either concrete or mortar. Fig. 9 illustrates how the proper placement of a mortar bedding mix can effectively fill voids in both the base and cover layer and "glue" the layers together.

Several RCC projects have used bedding mixtures consisting of highly sanded ¾-in. MSA concrete containing a water reducer and set retarder. Cement contents have ranged from 400 to 500 lb per cubic yard. A slump of 4 to 7 in. is normally specified with the bedding mix placed approximately 1 in. thick. Other projects use the upstream facing concrete mix for bedding purposes. During placement of the facing element, a thin layer of concrete is spread four to eight feet back from the face. This method provides for seepage control but should not be considered in any stability analysis.

In the Japanese RCD method of construction, the compacted lifts are thicker than those commonly used in the United States. To minimize segregation and facilitate compaction, a bulldozer spreads out the concrete in thinner layers prior to compaction. After spreading four or five thinner layers, the concrete is thoroughly compacted by vibratory rollers to a finished lift height of two to three feet. The finished compacted horizontal surface is then handled similarly to joint treatment of conventional mass concrete dams. After the surface is cleaned, a one-half to 2-in.-thick mortar layer is broomed or screeded (Fig. 10) onto the hardened layer just prior to placing the RCC cover layer. The mortar typically



① Maximum penetration of bedding mortar into RCC is approximately 1-1/2 inches

② Compacted RCC – Bedding mortar squeezed up into RCC by vibration action. No remaining voids

③ Noncompacted RCC, some voids remaining

④ Bedding mortar, fills in depressions and irregularities

⑤ Cleaned surface

⑥ Nontreated surface

Fig. 9. Procedure used at Elk Creek Dam, Oregon, to treat horizontal joints (Reference 14).

Fig. 10. Spreading mortar bedding layer onto RCC surface at Elk Creek Dam, Oregon (courtesy of U.S. Army Corps of Engineers, Portland, Oregon).

consists of equal portions of sand and cement with enough water to produce a creamy consistency. Disadvantages to mortar beddings are that they may be more expensive, dry out faster, and have higher shrinkage potential than concrete bedding mixtures.

Dry cement and cement-water slurry have been effectively used to bond horizontal layers of soil-cement stairstep slope protection. Test results[9] showed adequate bonding at an application rate of 0.36 lb of cement (dry or slurry form) per square yard of surface area, although higher rates of approximately 1 lb per square yard are recommended in the field. However, considering the normally coarser aggregates in RCC, the use of dry cement or cement-water slurry may not be as effective as concrete or mortar beddings.

Table 2 summarizes two studies to evaluate the effectiveness of various bonding techniques. The USBR conducted a laboratory test program[11] with two mixes containing cementitious material contents (cement plus fly ash) of 150 and 300 lb per cubic yard, respectively. In general, bond-strength values of untreated joints decreased with increases in the time interval between placement of successive layers. Also the 300 lb per cubic yard mixture had higher strengths than the 150 lb per cubic yard mixture. All bedding mixtures were effective in improving bond; however, the sliding friction angles for most joint ages and treatment methods were somewhat lower than the 45° value normally assumed for RCC.

In the USBR/PCA study,[8] a test section was constructed (Fig. 11) to evaluate variables including RCC mixtures, joint maturity, water content of mix, interface treatment, and curing conditions. Test results indicate that for lean mixes (150 lb/cu yd cement), joint interface treatment is necessary to assure effective bonding of RCC layers. Only one joint out of a possible 48 was recovered intact without treatment whereas 43 and 42 were recovered with mortar and bedding concrete treatment, respectively. For richer mixes with 300 lb/cu yd (cement + fly ash), approximately one half of the joints were recovered intact without treatment, and almost all joints were intact for both mortar and bedding concrete. For the six-hour untreated joints, bonding was effective for approximately one-half of the joints regardless of moisture content or curing condition. For the 48-hour untreated joints, the lower moisture content had only two out of a possible 12 cores recovered intact, and the higher moisture content had eight out of 12 recovered intact.

Fig. 11. U.S. Bureau of Reclamation/Portland Cement Association joint research project on bonding successive layers of roller-compacted concrete.

Summary

There are many acceptable methods for obtaining adequate bonding between layers including rapid placement, high-paste RCC, and concrete and mortar beddings. No single method may be right for all situations. In some cases, a combination of methods may be appropriate, as in the Japanese RCD method, which uses relatively high paste RCC mixtures and mortar beddings.

Before deciding on the type of bonding technique, the designer must first determine bonding requirements. Most RCC dams are designed with vertical upstream and 0.7 to 1 or flatter downstream slopes. The typical dam includes a relatively impermeable concrete face and a foundation and internal drainage system. If the structure performs as intended, the dam should have adequate safety against overturning and sliding with minimum bonding of joints. If seepage is a concern, the designer may choose to use a bedding mix only adjacent to the upstream facing. In this case the bedding mix is spread from abutment to abutment 4 to 8 ft behind the upstream face rather than over the entire lift. It is important to note not all situations require fully bonded horizontal joints. To minimize cost and time associated with bonding techniques, the designer should use reasonable judgment in developing appropriate bonding criteria.

Table 2. Joint Bond Strength

Joint* designation	Tensile strength, psi	Bond** failure, Y/N	Cohesion, psi	Friction angle, degrees	Tan φ	Comments
8-0	60	N-PL	100	45	1.00	Laboratory study; 75 lb cement + 75 lb fly ash; 90-day test age
24-0	45	N-PL	110	35	0.70	
72-0	55	Y	40	39	0.81	
24-S	65	N-PL	190	39	0.81	
24-M	45	N-PL	170	38	0.78	
24-SB	65	N-PL	100	35	0.70	
24-DC	60	Y	140	44	0.97	
24-B	60	Y	160	40	0.84	
8-0	195	N-P	410	44	0.97	Laboratory study; 150 lb cement + 150 lb fly ash; 90-day test age
24-0	180	N-P	450	41	0.87	
72-0	180	Y	380	41	0.87	
24-S	200	N-P	420	42	0.90	
24-M	210	N-P	480	46	1.04	
24-SB	175	N-P	330	40	0.84	
24-DC	195	Y	440	40	0.84	
6-0	NR	—	—	—	—	Test section; 150 lb cement, 75- to-105-day test age; wet cured
48-0	NR	—	—	—	—	
6-M	70	N-P	—	—	—	
48-M	90	N-P	—	—	—	
6-B	60	Y	—	—	—	
48-B	60	Y	—	—	—	
6-0	NR	—	—	—	—	Test section; 150 lb cement + 150 lb fly ash; 75- to-105-day test age; wet cured
48-0	NR	—	—	—	—	
6-M	85	Y	—	—	—	
48-M	175	N-P	—	—	—	
6-B	135	N-P	—	—	—	
48-B	180	Y	—	—	—	

*Age (hours)—surface condition 0—no treatment, S—slurry, M—mortar, SB—sandblast, DC—dry cement, B—bedding concrete,
**Bond failure at joint NR—recovered core disbonded at joint, PL—plate failure, P—parent material failure.

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