Chapter 4
Properties

4-1. General

The properties of hardened RCC are similar to those of conventionally placed mass concrete (CMC). Where differences exist, they are generally due to the lower water content in RCC, differences in void content, or slight aggregate or other material differences. The range of possible RCC properties may be wider than for CMC due to the wider range of aggregate qualities used in RCC, the use of lower cementitious material contents, and the use of significant amounts of mineral filler on some projects. The variation of RCC properties for some projects may be greater than that for CMC if greater variation exists than usual for materials quality or compaction. This chapter provides information on hardened RCC properties including strength, elastic properties, tensile strain capacity, creep, volume change, thermal properties, permeability, density, and durability. ACI 207.5R, "Roller Compacted Mass Concrete," presents additional data and information on these properties.

a. Testing. Some properties will be determined by laboratory testing and some will be assigned by the engineers. Some properties, like modulus of elasticity, creep, and, to some degree, tensile strain capacity, are difficult to estimate without testing. When thorough laboratory tests cannot be performed, the best approach is to use results of more easily performed laboratory tests in conjunction with published information in ACI documents, technical publications, and engineering handbooks for similar concrete materials and mixtures from other projects. Properties that are determined in laboratory tests should be representative of concrete mixtures containing project-specific materials. Whenever possible, material properties should be obtained from tests on core samples taken from test RCC placements made with the proposed design mixes. Variations in material properties due to scatter of test data, differences in behavior of the material between actual and that predicted by a numerical model, and expected differences between the laboratory mixture and the actual mixture used during construction can be accounted for by performing parametric studies using combinations of the upper and lower bound values of critical properties. Test data should be included in the concrete materials reports. The rapid construction time of RCC structures, and the general practice of using a 1-year-age design strength, can lead to a structure's being loaded prior to the RCC attaining the required design strength. This serves to emphasize the need for materials engineers and structural engineers to be closely involved in the selection of RCC properties.

b. Strength and elastic properties. The strength and elastic properties of RCC vary depending on the mixture components and mix proportions in much the same manner as for CMC. Aggregate quality and cementitious content are the principal factors affecting strength and elastic properties, but these properties may be as much dependent on field control of mixing and placing operations as on mixture ingredients or mixture proportions. Properties important to the seismic analysis of RCC dams include compressive strength, tensile strength, shear strength, modulus of elasticity, Poisson's ratio, and density. Except for density, all these properties are strain-rate sensitive, and the strain rates that occur during major earthquakes are on the order of 1,000 times greater than those used in standard laboratory testing.

4-2. Strength

The following sections provide information and guidance on compressive, tensile, and shear strength. Tensile strength is further subdivided into topics of direct tensile strength, lift joint direct tensile strength, splitting tensile strength, flexural strength, and dynamic tensile strength. Shear strength is subdivided into subsections on parent shear strength and lift joint shear strength. Strength of RCC is measured using the identical methods employed for CMC, with the only differences being the methods of consolidating specimens. Strength properties of RCC are heavily dependent on degree of compaction, aggregate quality, and cementitious content. RCC strength tests may be conducted using compacted specimens or specimens cored or sawn from structures or test sections. As with CMC, suitable factors should be used to account for the natural variability of not just compressive strength but tensile strength and shear strength as well. RCC differs from CMC due to the more frequent horizontal planes of weakness (construction joints) created during placement, each with tensile and shear strength generally less than that of the parent concrete. Adequate compaction is essential for all RCC. For a properly proportioned mix, compaction is often considered sufficient if the RCC has no more than 1.5 percent air voids. Five percent air voids due to incomplete compaction can result in a 30 percent loss of strength, while 20 percent air voids can produce a strength loss of 80 percent (Kaplan 1960). The more difficult an RCC mixture is to compact, the more likely it is that incomplete compaction will occur and that strength will be less than desired. In some instances, adding water to a very dry mix may produce a strength gain, because the added water increases workability and compactibility of the mix, thereby reducing air voids. Aggregates that produce high strength are not always the ideal material for RCC or CMC dams. On some projects, the use of aggregates of lower physical strength has produced RCC with desirable (high) creep rates, low elastic moduli, and good tensile strain capacity. However, the same aggregates may also produce low tensile strength and low shear properties which are important for structures in seismic areas. Caution should be exercised in using early strength results to predict long-term strength and when using marginal aggregates or other unusual materials since some materials may unexpectedly limit long-term strength properties. As in CMC, the use of significant quantities of pozzolan may result in slower strength gain but, often, higher ultimate strength. Some RCC mixtures, depending on the shape and grading of the aggregates and the degree of compaction and segregation present in the RCC, may exhibit stronger anisotropic properties than CMC. Strength tests on several RCC projects indicate that in some cases cores drilled vertically yield higher strengths than companion horizontally drilled cores (also observed in conventional concrete) (Kogan and Fedossov 1995, Dunstan 1981, Cannon 1995). In a few cases the opposite result has been observed. For conventional concrete, the anisotropic behavior is usually attributed to accumulation of bleed water under aggregate particles. For RCC, the observed anisotropic behavior may be due to the distribution and orientation of aggregate particles resulting from spreading and compacting the horizontal RCC layers. The orientation of cores can influence tensile strength results by as much as 20 percent. If tensile strength is of structural importance, drilled cores of both vertical and horizontal orientation should be tested. In at least one international RCC dam project, the anisotropic nature of the RCC strength properties was accounted for in adjustment factors for design strength (Tejada 1995). Tensile strength (also referred to as bond) and shear strength at lift joints are affected by degree of compaction, aggregate quality, and cementitious material content, but also by the lift joint preparation and condition. The chance of obtaining the desired bond and shear strength at lift joints is less likely with RCC mixtures that are too dry to be easily consolidated or with RCC mixtures that are designed with inadequate paste volume. Lift joint bond as well as shear strength, to a lesser degree, and the overall variation of these properties in a structure will generally be improved with use of a bedding mortar or concrete and rapid placement of successive lifts. The bond strength at the lift joints for properly proportioned, well-compacted RCC will approach that achieved at the prepared lift joints of CMC. The design values for joint bond and shear strength should be based on a laboratory test program that includes evaluation of joint strength using core or sawn block samples from test placements constructed under anticipated field conditions. A comprehensive laboratory test program will ensure a greater degree of certainty and, in some cases, may eliminate overly conservative or redundant design assumptions. The use of various strength properties derived from coring test pads, test sections, or actual structures must be done with care. A sufficient number of specimens must be tested to yield statistically significant results. The process of coring specimens has possible effects that must be taken into account by the materials engineer. These include the variety of strains imposed on the specimens by the coring action and by core removal. These effects are especially troublesome when extracting cores from lift joints for lift joint strength testing.

a. Compressive strength (f'_c). As with CMC, compressive strength is used as a gauge of the overall strength of RCC, as well as a gauge of other properties such as durability. It is rarely a concern for design loading; tensile strength is generally the principal concern for design. Compressive strength for RCC is measured from cylinders fabricated as described in paragraph 3-2b(2) as well as from drilled cores (ASTM C 42), with the size of the specimens determined using conventional practice with respect to aggregate size. Compressive strength can be measured during construction to monitor mixture variability, to confirm achievement of design properties, and for historical purposes. Compressive strength is primarily affected by cementitious material content, type of cementitious materials, aggregate quality and grading, and degree of compaction achieved. For well-compacted RCC mixtures, these influences are similar to those for CMC. For RCC mixtures either poorly compacted or lacking sufficient paste to fill all voids, the degree of compaction will generally control the level of strength achieved. Typical RCC compressive strength values for a wide range of projects are shown in ACI 207.5R. RCC with high-quality aggregates will produce compressive strength equal to conventional concrete. RCC, due to the use of sometimes marginal aggregates, can provide an even wider range of strength than CMC. Common RCC mixtures may produce compressive strength ranging from 6.9 MPa (1000 psi) to over 27.6 MPa (4000 psi) at 1-year age. Most RCC projects have used mixtures producing an average compressive strength between 13.8 and 20.7 MPa (2000 to 3000 psi) at 90-days to 1-year age. RCC mixtures may be designed for a minimum strength of 13.8 MPa (2000 psi) for durability reasons alone. For seismic areas, higher design compressive strength is often required in order to achieve the higher tensile and shear strength necessary. Compressive strength from cores of RCC follows the standard relationship of core strength to cylinder strength from conventional concrete (ACI 318R), but may vary more widely depending on mixture workability, compaction effectiveness, cylinder preparation methods, and other factors. Core and cylinder testing on a number of RCC dams (ACI 207.5R, McDonald and Curtis 1997) provides an overall average of core compressive strength equal to about 75 percent of the equivalent age cylinder compressive strength. On some projects where low workability RCC mixtures were used, the cylinder strengths have been lower than the core compressive strengths due to difficulty in adequately compacting test cylinders. Coefficient of variation (*V*) of RCC compressive strength specimens cast during construction has varied widely, depending primarily on the mixture workability. Coefficient of variation (*V*) is more generally used than standard deviation, due to the commonly low-strength mixtures used on dams. Like CMC, *V* tends to decrease with later ages of testing. Values of *V* reported for RCC dams (Schrader 1988, Andriolo 1995) have varied from 10 to 28 percent, with the lower values (< 20 percent) generally representing more workable mixtures. Although there has been little testing of RCC in rapid load compression, there is no reason to expect results much different from test results for conventionally placed mass concrete. Dynamic strength testing is normally performed at rapid load rates to simulate seismic loading. During seismic events, strain rates are related to the fundamental period of vibration of the dam, with the peak stress reached during a quarter cycle of vibration. For a typical gravity dam, this may mean loading the specimens to ensure failure occurs at about 75 msec, depending on the period of the structure. Results from laboratory tests on conventional concrete, indicate an approximate 30 percent increase for compressive strength of moist specimens under rapid loading conditions. The use of moist specimens for the normal load rate or "static" strength tests is critical for this test procedure. The use of dry specimens will generally increase static compressive strength but will not affect the rapid load tests. Such test results will then suggest there is no increase in strength from normal to rapid load rates.

b. Tensile strength. Tensile strength can be measured by several methods, including the direct tension method (CRD-C 164), the splitting tensile method (ASTM C 496), and the flexural test or modulus of rupture method (ASTM C 78). All tensile strength tests are age dependent, load rate dependent, and moisture content dependent. Each of these test methods produces different results, as described by Raphael (1984). The tensile strength of RCC is dependent on cementitious material content, aggregate strength and bond characteristics with the paste, degree of compaction of the mixture, and lift surface condition and treatment. The tensile strength is more dependent on aggregate bond than compressive strength, hence the relationship between the tensile strength and the compressive strength of concrete not only varies with the method of test, but also varies with the type and maximum size of aggregate. Raphael (1984) discusses the tensile and compressive strength of concrete for dams, the various test methods used for measurement, the differences in test measurements, the effects of rapid load testing, and the resulting trends in strength results. ACI 207.2R discusses tensile strength in some detail. Lift joints are the weakest locations in RCC, as in CMC, structures. Hence, the tensile strength at the lift joints is the critical tensile property for RCC. Direct tensile strength (called "bond") is the pertinent tensile test for lift joint tensile strength. Split tensile testing of horizontal cores has been used to establish joint strength; however, identification and location of the joint in the central portion of the core, for correct performance of the test, is very difficult. Prediction of tensile strength based on compressive strength is generally not particularly reliable. The ratio of tensile to compressive strength is of interest to designers, especially for smaller structures where tensile testing may not be conducted. The ratios of tensile strength to compressive strength for RCC mixtures have typically ranged from about 5 to 15 percent, depending on aggregate quality, strength, age, and test method. Cannon (1995) and others have compared these ratios and found them to be widely varying. No single equation can fit existing data, even when only one tensile test method is involved. Cannon found a trend of changing ratios with strength level, with the ratio of tensile to compressive strength decreasing as strength level increased. These ratios depend primarily on aggregate characteristics and strength level. When testing for a specific aggregate, more meaningful ratios may be obtained. As with compressive strength, core tensile strength will generally be lower than equivalent cylinder tensile strength. The ratio of core to cylinder tensile strength can vary widely depending on the tensile test method, the handling of the specimens, and the method of cylinder compaction.

(1) Direct tensile strength (f_{dt}). Direct tension test results for RCC, similar to those for CMC, are lower than for splitting tensile tests (often about 25 to 30 percent lower than splitting tensile strength) and may be assumed to represent the minimum tensile properties of concrete. Direct tension tests are more difficult to conduct for parent concrete than splitting tensile tests, are more affected by drying and microcracking of specimens, and produce higher variability test results when compared with splitting tension tests. Because of the problems involved with the direct tension test, the splitting tensile test has historically been more commonly used to evaluate the parent tensile strength of RCC mixtures. However, the direct tension test is used to evaluate the tensile strength of the lift joint, the tensile property of most interest for RCC structure design. The parent direct tensile strengths from a number of projects, using both cores and cylinders, have ranged from 3 to 9 percent of the compressive strength, with most values between 6 and 8 percent. The ratio of f_{dt} / f'_c varies with strength level and age. The relationships expressed in Tables 4-1, 4-2, and 4-3 were developed to accommodate the apparent reduction in this ratio with increasing strength. The tensile strength of parent RCC should be based on direct tensile test strengths or a maximum of 75 percent of splitting tensile strengths (Cannon 1995). If test strengths are based on wetscreening and removal of aggregates larger than 38 mm (1.5 in.), test values for the full mixture should be reduced by 10 percent.

(2) Lift joint direct tensile strength. Tables 4-1 through 4-3 present a means to determine preliminary lift joint direct tensile strengths for design from splitting tension tests conducted on the parent RCC. The factors used in these tables are based on historical data (Cannon 1995). Lift joint direct tensile strength tests should be run on cast specimens and/or cores from test placement sections to provide values for final design. As with CMC, direct tensile strength at the lift joint will generally be less than in the parent RCC. Lift joint direct tensile strength of RCC is sensitive to the maximum size of aggregates, workability of the mixture, degree of compaction, and age and condition of the lift joint surface. Due to the varying nature of lift joint strength, statistical concepts should be applied in the selection of design values for lift joint tensile strength based on the probability of attaining anticipated joint strengths with the mixtures anticipated, the method of construction, and whether bedding mortar or concrete is applied to the lift surfaces. Inadequate lift surface cleanup, segregation, or poor consolidation can drastically reduce the direct tensile strength across lift lines. Good-quality aggregates, good mixture workability and compaction effort, rapid covering of lift joints by subsequent lifts, and the use of bedding mortar are required to obtain good bond strength at the joint. The mortar bedding ensures that there is adequate paste at the lift surface boundary to provide bond and to fill any rock pockets at the lift surface. When test data are not available, Tables 4-2 and 4-3 represent a range of acceptable preliminary design values for RCC mixtures based on mixture workability, aggregate size and type, and lift joint preparation. Low values of lift joint direct tensile strength are based on natural, low-strength aggregates and unbedded lift joints. High values of lift joint direct tensile strength are based on all crushed, high-strength aggregates and bedded lifts.

(3) Splitting tensile strength (f_{st}). Splitting tensile tests are easier to perform, can be less sensitive to drying and microcracking, and can provide more consistent results than direct tensile tests. However, splitting tensile test results tend to overpredict actual tensile strengths and should be adjusted by a strength reduction factor of 0.75 (Cannon 1995) to reflect results that would be obtained from direct tensile tests. CMC splitting tensile strength typical ranges are shown in Table 4-1. RCC splitting tensile strength varies similarly as shown in Tables 4-2 and 4-3. For preliminary design, Tables 4-2 and 4-3 can be used to develop estimated RCC lift joint tensile strength from splitting tensile tests on the parent RCC. Tests should be conducted to provide values for final design, especially for critical structures. Like direct tensile strength, the ratio of splitting tensile to compressive strength varies with aggregate type, strength level, and age. In the splitting tensile test, the failure plane is normally forced to occur through a narrow area along the specimen's longitudinal axis. This is one explanation for the splitting tensile test's producing values higher than the direct tensile test.

Table 4-1
Conventional Mass Concrete (from Cannon 1995)

		Split Tensile Strength[a]			Design Lift Joint Tensile Strength	
NMSA mm (in.)	Max/Min	≤ 20.7 MPa (≤ 3000 psi)	> 20.7 MPa (> 3000 psi)	Conversion Factor[b]	≤ 20.7 MPa (≤ 3000 psi)	> 20.7 MPa (> 3000 psi)
≤75 (1.5)	Max	0.15 f'_c	0.664 $(f'_c)^{1/2}$	0.56	0.085 f'_c	0.3735 $(f'_c)^{1/2}$
	Min	0.10 f'_c	0.498 $(f'_c)^{1/2}$	0.56	0.055 f'_c	0.2822 $(f'_c)^{1/2}$
> 75 (1.5)	Max	0.15 f'_c	0.664 $(f'_c)^{1/2}$	0.50	0.075 f'_c	0.332 $(f'_c)^{1/2}$
	Min	0.10 f'_c	0.498 $(f'_c)^{1/2}$	0.50	0.050 f'_c	0.249 $(f'_c)^{1/2}$

[a] Splitting tensile strength of parent material (cylinders).
[b] Includes factors for conversion to direct tensile of 0.80, for joint strength and probable percent of bonded joint of 0.70, and of 0.90 for NMSA >75 mm (1.5 in.).

Table 4-2
Roller Compacted Concrete, Workable Consistency ≤ 30 Seconds Vebe Vibration (Cannon 1995)

NMSA mm (in.)	Use Bedding Mortar? Y	N	Max/Min	Split Tensile Strength[a] ≤ 24.1 MPa (≤ 3500 psi)	> 24.1 MPa (> 3500 psi)	Conversion Factor[b]	Design Lift Joint Tensile Strength ≤ 24.1 MPa (≤ 3500 psi)	> 24.1 MPa (> 3500 psi)
≤ 75 (1.5)	-	-	Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.53	0.090 f'_c	0.3735 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.53	0.040 f'_c	0.2407 $(f'_c)^{1/2}$
> 75 (1.5)	Y		Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.47	0.080 f'_c	0.3320 $(f'_c)^{1/2}$
	Y		Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.47	0.040 f'_c	0.2158 $(f'_c)^{1/2}$

[a] Splitting tensile strength of parent material (cylinders).
[b] Includes factors for conversion to direct tensile of 0.75, for joint strength and probable percent of bonded joint of 0.70, and 0.90 for NMSA 75 mm (1.5 in.).

Table 4-3
Roller Compacted Concrete, Less Workable Consistency > 30 Seconds Vebe Vibration (Cannon 1995)

NMSA mm (in.)	Use Bedding Mortar? Y	N	Max/Min	Split Tensile Strength[a] ≤ 24.1 MPa (≤ 3500 psi)	> 24.1 Mpa (> 3500 psi)	Conversion Factor[b]	Design Lift Joint Tensile Strength ≤ 24.1 MPa (≤ 3500 psi)	> 24.1 MPa (> 3500 psi)
≤ 75 (1.5)	Y		Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.35	0.060 f'_c	0.2490 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.35	0.030 f'_c	0.1577 $(f'_c)^{1/2}$
> 75 (1.5)	Y		Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.32	0.055 f'_c	0.2241 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.32	0.025 f'_c	0.1411 $(f'_c)^{1/2}$
≤75 (1.5)		N	Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.18	0.030 f'_c	0.1245 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.18	0.015 f'_c	0.0830 $(f'_c)^{1/2}$
> 75 (1.5)		N	Max	0.17 f'_c	0.7055 $(f'_c)^{1/2}$	0.16	0.025 f'_c	0.1162 $(f'_c)^{1/2}$
			Min	0.08 f'_c	0.4565 $(f'_c)^{1/2}$	0.16	0.015 f'_c	0.0747 $(f'_c)^{1/2}$

[a] Splitting tensile strength of parent material (cylinders).
[b] Includes factors for conversion to direct tensile of 0.75, for joint strength and probable percent of bonded joint of 0.70, of 0.90 for NMSA >75 mm (1.5 in.), and for bedding mortar (0.67 if bedding mortar is used, 0.33 if not used).

(4) Flexural strength. Flexural strength, or modulus of rupture, is a measure of tensile strength. Although flexural strength can be applied directly in analysis as described by Raphael (1984), it is seldom measured due to the difficulty in casting specimens with mass concrete and especially with RCC. In addition, the flexural strength does not evaluate the tensile strength at lift joints, which is the critical tensile strength property for RCC dams. Hence, flexural strength is generally not used in analyses for RCC dam structures. The variation of this test is higher than other tensile tests and higher than that of compressive strength. Some flexural strength beam specimens have been sawn from test sections, but this requires substantial effort and time, with results that may be difficult to interpret. Available RCC data indicate that the Raphael (1984) relationship of flexural to compressive strength is valid for RCC as well (Hess 1995; Omran, Nayak, and Jain 1995). This relationship may be used for planning purposes where necessary, but should be confirmed by testing for significant structures.

(5) Dynamic tensile strength. Although there has been little testing of RCC in rapid load tension, there is no reason to expect results much different from test results for conventionally placed mass concrete. Raphael (1984) discusses the effects of dynamic loading on the tensile strength of concrete. Like compressive strength, tensile strength of concrete is strain-rate sensitive. High strain-rate testing produces tensile strengths at least 50 percent higher than those produced during tensile strength testing where the strain rate is very slow. For this reason, the dynamic tensile strength of RCC is considered equivalent to the direct tensile strength multiplied by a factor of 1.50 (Cannon 1995, Raphael 1984). This adjustment factor

applies to both the tensile strength of the parent material and to the tensile strength at the lift joints, whether tested in direct tension, splitting tension, or modulus of rupture. As with compressive strength specimens, the use of moist specimens for the normal load strength tests is critical for this test procedure.

c. Shear strength. Shear strength is one of the most important concrete properties for RCC dams and is generally represented by a Mohr envelope relationship of a combination of cohesion (bond) and frictional resistance:

$$S = c + \sigma \tan \phi \qquad (4\text{-}1)$$

where

S = shear strength, MPa (psi)

c = cohesion , MPa (psi)

σ = normal or confining stress, MPa (psi)

ϕ = friction angle, deg

CRD-C 90, “Method of Test for Transverse Shear Strength Confined, Single or Double Plane,” can be used to measure this property on cast specimens or drilled cores, for parent RCC and at lift joints, with tests conducted usually at a minimum of three confining pressures. The upper confining pressure selected for dams should represent at least the maximum height of the structure. The shear strength along lift surfaces is always less than the parent concrete. Therefore, as for tensile strength, the strength at lift surfaces will govern the design. Shear strength of the parent or lift joint RCC can be developed from cylinders cast in the laboratory, from blocks of RCC sawn or cored from test sections, or from cores extracted from the RCC structure. For preliminary design, values of parent shear strength can be developed from historical data or tests and then modified to represent lift joint shear strength. Final design shear strength parameters for important structures, such as moderate to high dams or dams in high seismic zones, should be developed from laboratory testing of cores from test sections. Use of “over-design factors” to account for the natural variation of strength results should be applied to shear strength, as are routinely used for compressive strength. Until specific data are available for shear strength test variation, normal coefficient of variation used for compressive strength may be applied.

(1) Parent shear strength. Cohesion varies with the mixture proportions, especially the amount of paste and cementitious content, and with age. The friction angle is primarily dependent on aggregate type and shape and is relatively independent of factors affecting cohesion. Generally, the friction angle does not change significantly with mixture proportions or age. Shear strength properties for RCC are similar to those for CMC. Values of cohesion for the parent RCC have ranged from as little as 0.5 MPa (75 psi) and less to over 4.1 MPa (600 psi) (McLean and Pierce 1988). Values of c / f_c' for workable parent RCC mixtures have ranged up to 20 percent of the compressive strength. Mixtures with Vebe consistency times greater than 30 sec may have cohesion values under 10 percent of the parent compressive strength. RCC friction angles have varied from 40 to 60 deg.

(2) Lift joint shear strength (from cores). The shear strength at the lift joints is generally the critical value for design. RCC shear strength for lift joints can be lower than for CMC and may be more variable on some projects. Cohesion varies a great deal from lift surface to lift surface, while the shear friction angle is usually quite consistent. Cohesion generally varies based on the amount of paste, cementitious content, and lift joint preparation and exposure. Cohesion can be improved by correcting these problems and by application of a bedding mortar or concrete. Shear friction angle is relatively unaffected by factors affecting cohesion and is more dependent on the aggregate type and shape. McLean and Pierce (1988) found that use of ϕ = 45 deg for preliminary design was generally conservative, while use of $c = 0.1\ f_c'$ was unconservative, due partly to the natural variation of all strength properties. For unbedded lift joints, c / f_c' has varied from 0.03 to 0.06. For bedded lift joints, c / f_c' has varied from 0.09 to 0.15. Friction angle for bedded and unbedded lift joints has been essentially unchanged. Evaluation of shear strength from cores requires caution when interpreting results since joint core recovery can vary dramatically depending on drilling and extraction procedures. Core specimens tested are invariably the best samples, while unbonded or poorly bonded RCC generally debonds during coring or extraction and is not tested further. Hence, the percent

joint recovery in a core testing program must be considered when evaluating test results and determining RCC lift joint shear strength design properties. This can be done by reducing the cohesion by a suitable factor representing the percent bonded lifts based on the percent bonded lift joint recovery, similar to that applied for the determination of lift joint direct tensile strength (bond). Bonded lift joint recovery has varied from 2 to 38 percent for projects with unbedded lift joints, while bonded lift joint recovery for projects with bedded joints has varied from 65 to 85 percent. A preliminary design value of c = 0.05 f_c' is recommended for lift joint surfaces that are to receive a mortar bedding; otherwise, a value of 0 should be assumed. A value of ϕ = 45 deg can be assumed for preliminary design or for small projects, for both parent and lift joint shear strength. Design values should also take into account the expected percentage of the joint which will be adequately bonded, as indicated by the testing of cores from test sections and later from the completed structure. Assumed values must be verified for final design by tests performed on samples prepared in the lab and on cores taken from test fills. At a number of RCC projects, joint shear tests, at different confining pressures, have been performed on a series of large blocks of the total RCC mixture cut from test placements compacted with walk-behind rollers or small to full-scale roller compactors. Shear strength under rapid loading may or may not behave like rapid load tensile strength. Until testing of RCC shear specimens under dynamic loading conditions has been accomplished, designers should use values of shear strength conducted using the normal load rate.

4-3. Elastic Properties

a. Modulus of elasticity (E). The modulus of elasticity is defined as the ratio of normal stress to corresponding strain below the proportional limit. For practical purposes, only the deformation which occurs during loading is considered to contribute to the strain in calculating the normal load rate modulus of elasticity (also called “static” or “instantaneous” modulus). Subsequent strain due to sustained loading is referred to as creep. Properly proportioned and consolidated RCC should provide a modulus of elasticity equal to or greater than that of CMC of equal compressive strength made with similar materials. E is dependent on age, strength, and aggregate type, and the same modulus-strength relationships used for CMC may be used for RCC. The modulus of elasticity is determined according to ASTM C 469 (CRD-C 19), “Standard Test Method For Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression,” or CRD-C 166, “Standard Test Method for Static Modulus of Elasticity in Tension,” which are both procedures for a chord modulus. Three methods of modulus measurement are seen in the literature (chord, secant, and tangent). Hence, for critical analyses, the engineer may need to determine which method has been used when using published data. Generally the differences between the methods are small compared to the overall variations in material properties and uncertainties in analysis. The modulus of elasticity may exhibit some anisotropic behavior due to the coarse aggregate particle alignment; however, the effects on the modulus will be small and can generally be ignored. To model the time dependency of the modulus of elasticity, tests should span the duration of analysis. Test ages of 1, 3, 7, 28, 90, 180, and possibly 365 days, as well as the design age, may be considered.

(1) Modulus of elasticity of CMC is about 6.9 GPa (1×10^6 psi) at 1 day and ranges from about 21 to 38 GPa (3 to 5.5×10^6 psi) at 28 days and from about 30 to 47 GPa (4.3 to 6.8×10^6 psi) at 1 year. Lower quality aggregates have been successfully used in RCC, often resulting in very low E at all ages. Hence, RCC values of E tend to have a wider range than for CMC. A low modulus of elasticity is generally beneficial in reducing apparent stress and strain in the structure. Low-strength mixtures will generally produce low moduli.

(2) Tensile E_c is assumed to be equal to the compressive E_c. For critical seismic structures, this assumption should be evaluated more closely, since the stress/strain relationship becomes nonlinear after concrete stresses reach approximately 60 percent of the peak stress (Raphael 1984). In compression this does not cause a problem because, in general, concrete compressive stresses, even during a major earthquake, are quite low with respect to the peak stress or ultimate capacity. In tension, it is a different matter since tensile stress can approach and exceed the peak tensile stress capacity of the concrete, and, in some cases, cracking will occur. For critical projects in seismic areas, the static and dynamic modulus should be determined by testing, using the range of materials and mixtures expected to be used. For rapid strain-rate loading, the dynamic modulus of elasticity may be 15 percent higher than the static modulus (Bruhwiler 1990, Hess 1992).

(3) Sustained modulus of elasticity (E_{sus}) includes the results of creep and can be obtained directly from creep tests by dividing the sustained load on the test specimen by the total deformation. ACI 207.1R and ACI 207.4R include values of static and E_{sus} for CMC. E_{sus} for tests conducted on specimens loaded at early ages for a period of one year will be about 2/3 that of the static E. E_{sus} for tests conducted on specimens loaded at 90 days or later ages for a period of 1 year will be a slightly higher percentage of the static E.

(4) ACI formulas for the modulus are not based on mass concrete mixtures and are generally not accurate estimates of mass concrete modulus. The static modulus of elasticity, in the absence of testing, for planning purposes only, may be assumed equal to the following formula (ACI 318R). Many CMC and RCC tests have indicated modulus values higher than the ACI formula predicts. Because most structural analyses use the modulus to calculate values of stress from strain, the use of the ACI modulus formula may be unconservative for some projects. Caution should be exercised in the use of this formula for critical projects, and actual test results should be used for final design.

$$E = 57{,}000 \ (f_c')^{1/2} \tag{4-2}$$

where E = static modulus of elasticity, psi × 10^6, and f_c' = static compressive strength, psi.
Preliminary design studies may assume the modulus of elasticity to be increased by 15 percent for seismic load conditions and reduced by one third for long-time load conditions where creep effects are important.

b. Poisson's ratio. Poisson's ratio is defined as the ratio of the lateral to the longitudinal strain resulting from a uniformly distributed axial stress and is determined according to ASTM C 469. Poisson's ratio for RCC is the same as for CMC. For static loads, most values range between 0.17 and 0.22, with 0.20 recommended when testing has not been performed. Poisson's ratio is also strain-rate sensitive and the static value may be reduced by up to 30 percent when evaluating stresses due to seismic loads (Bruhwiler 1990). This should be confirmed by testing for critical projects where this property may significantly affect design results. Some testing has suggested that Poisson's ratio is not significantly sensitive to the strain rates normally considered for mass concrete dams (Hess 1992).

4-4. Creep

Creep is defined as time-dependent deformation (strain) due to sustained load. Specific creep is creep under unit stress, or strain per MPa (psi). Creep from long-term loading results in an increase in strain, but at a continually decreasing rate, under a state of constant stress. Creep is dependent on the material properties and proportions, is closely related to the modulus of elasticity and compressive strength of the concrete, and is thus a function of the age of the concrete at loading. Concrete with a high modulus of elasticity and high strength will generally have relatively low creep. Low strength, low moduli mixtures have larger creep values. Higher creep properties are generally desirable to slowly relieve stress and strain buildup due to foundation restraint and thermal and exterior loadings. Creep is determined according to ASTM C 512, "Standard Test Method For Creep of Concrete in Compression." Creep tests for mass concrete should always be conducted with sealed specimens to avoid drying shrinkage effects. The test method recommends five ages of loading between 2 days and a year to fully define creep behavior. ASTM C 512 represents creep by the following formula. The first part of the formula, (1/E), represents the initial elastic strain from loading, and the second part represents the long-term effects of creep after loading:

$$\epsilon = (1/E) + F(K) \ln (t + 1) \tag{4-3}$$

where

ϵ = specific creep , or total strain per MPa (psi)

E = static modulus of elasticity, MPa (psi)

$F(K)$ = creep rate

t = time after loading, days

Creep values for a number of RCC projects are reported in ACI 207.5R. *F(K)* values for RCC have ranged from 1.5 to 29 millionths per MPa (0.01 to 0.2 millionths per psi), with the higher numbers corresponding to lower compressive strength mixtures. For significant structures, creep tests should be conducted using the materials, proportions, and loading ages applicable to the structure. The effects of creep can also be considered by using the sustained modulus of elasticity of the concrete measured during the period of loading (ACI 224R, ACI 207.1R).

4-5. Tensile Strain Capacity

Tensile strain capacity (TSC) is the change in length per unit length that can be sustained in concrete prior to cracking. Tensile strains can be developed by external loads as well as by volume changes induced through drying, reduction in temperature, and autogenous shrinkage. TSC is dependent on time and rate of loading, type of aggregate, and aggregate shape characteristics (angular as produced by crushing versus natural rounded) and is strongly dependent on strength. Tensile strain capacity is determined according to CRD-C 71. The Corps of Engineers introduced TSC testing of concrete several decades ago to provide a basis for evaluating crack potential for strain-based thermal studies of MCS (Houghton 1976). This property is also used to compare different aggregates and different concrete mix proportions in MCS. TSC is determined in a series of tests that include normal and slow loading of beams. The slow-load test was designed to simulate the strain conditions in a mass concrete structure during long-term cooling. Normal load rate tests were designed to simulate strain conditions near the surface of a mass concrete structure where cooling occurs more rapidly. The test method requires a minimum of three beams for each test, and, generally, a minimum of three tests is recommended for each test set to allow for variation in the test results. A TSC test series usually contains a suite of rapid- and slow-load tests to failure typically initiated at 3, 7, 28, and/or other ages. The differences in TSC capacity from the slow and normal load rate beams provide an indication of the cumulative creep strain during the slow-load test. The strains measured in the slow-load beam test containing both elastic and creep strains are expressed in millionths (1×10^{-6} mm/mm (in./in.)). Houghton (1976) previously described the test procedure for normal load rate tensile strain capacity (TSC_n) and use of the data. TSC test results can vary widely. Use of test results for the specific materials and mixtures to be used in an MCS should be used whenever possible. Typical ranges of TSC for CMC and RCC are shown in Table 4-4. Ratios of CMC slow load TSC to normal load rate TSC tested at the same age as the slow load specimen ranges, from 1.0 to 2.0 and an average of 1.4. This average is relatively insensitive to age. ACI 207.5R provides TSC values for some RCC projects.

Table 4-4
Typical TSC Ranges (millionths)

TSC load rate - Age of loading	CMC	RCC[a]
Slow load rate - 7 to 90 days	88 – 237	--
Normal load rate - 7 days	40-105	20-140
Normal load rate - 90 days	73 –136	--

[a] (Hess 1995, Andriolo 1995)

4-6. Volume Change

a. Drying shrinkage. Drying shrinkage is governed primarily by the water content of the mixture and the characteristics of the aggregate. RCC drying shrinkage is similar to or lower than that of CMC due to the lower water content of these mixtures. Drying shrinkage is tested according to ASTM C 157, "Length Change of Hardened Hydraulic-Cement Mortar and Concrete." The effects of drying shrinkage are generally ignored for analysis of MCS, since the interior of MCS generally remains moist, except for possible application to surface cracking.

b. Autogenous volume change. Autogenous volume change, commonly called "autogenous shrinkage," is a decrease in volume of the concrete due to hydration of the cementitious materials without the concrete gaining or losing moisture. This type of volume change occurs in the interior of a large mass of concrete and can be a significant factor. It is primarily related to the material properties and proportions in the mixture and especially the type of aggregate. Autogenous shrinkage occurs over a much longer time than drying shrinkage. Although no specific test method exists, autogenous shrinkage can be determined on sealed creep cylinder specimens with no load applied in accordance with ASTM C 512, "Standard Test Method For Creep of Concrete in Compression," or from sealed "rapid load" beams fabricated for tensile strain capacity tests. Autogenous volume change cannot be reliably predicted without laboratory testing. Unusual behavior has been occasionally observed with this property, including essentially zero values, as well as positive values denoting expansion. The effects of this property can generally be ignored for small, shorter length structures.

4-7. Thermal Properties

Thermal properties for CMC and RCC are generally similar and are discussed in EM 1110-2-2000. Scanlon and McDonald (1994) describe thermal properties, test methods, ranges of test values and significance of these properties, including coefficient of thermal expansion, adiabatic temperature rise, specific heat, thermal diffusivity, and thermal conductance. The actual property values can vary significantly depending on aggregate, cement and pozzolan type, and content. For this reason, testing the full mixture is recommended. Thermal properties are seldom employed to make final selection of materials for detailed study. These properties are normally determined for the concrete materials selected for use (selection based on other factors). There may be exceptions to this general rule for some large projects where there is a variety of available aggregate sources from which to choose. For these projects, the selection of aggregates based on thermal properties like coefficient of thermal expansion may yield significant cost reductions. ACI reports 207.1R, 207.4R and 207.5R and many WES reports provide a wide range of laboratory determined concrete thermal properties. If likely aggregate sources are known, an improved estimate of thermal properties can be made based on the aggregate rock type and previous testing of CMC or RCC mixtures made with similar aggregate. The coefficient of thermal expansion is usually slightly smaller for RCC (because of higher aggregate content) than for conventional concrete. The coefficient of thermal expansion for CMC and RCC varies between 7 and 14 millionths per °C (4 and 8 millionths per °F). A value of 9 millionths per °C (5 millionths per °F) can be used for preliminary RCC design studies. The ratio of TSC/coefficient of thermal expansion is a rough indicator of the temperature drop required to produce cracking and can be used to compare the ability of various materials combinations (particularly aggregates) to resist thermal cracking.

4-8. Permeability

Permeability of the RCC mass and of the horizontal lift surfaces are key elements for hydraulic RCC structures. The permeability of RCC is largely controlled by mixture proportioning, placement method, use of bedding mortar on lift surfaces, and the degree of compaction. Concrete with low permeability generally has a low water-cementitious material ratio, is well mixed and consolidated, is proportioned with adequate paste and mortar to sufficiently fill all voids, and has been properly cured to allow for the continued hydration of cement. High cementitious material content mixtures have lower permeability than low cementitious material content mixtures. RCC permeability, particularly for lift joints, is discussed in Chapter 5, Design and Construction Considerations. Permeability of RCC cylinders and cores can be tested using CRD-C 163, "Test Method for Water Permeability of Concrete Using Triaxial Cell." This test method produces a value of intrinsic permeability (k) which must be converted to the more commonly used coefficient of permeability (K) using the formula in the test method. In general, an unjointed mass of RCC proportioned with sufficient paste will have permeability values similar to CMC. Test values for well-compacted, workable RCC mixtures typically range from 1.5 to 150×10^{-8} mm/sec (0.3 to 30×10^{-9} ft/min). Measured RCC permeability values have a very large range (Dunstan 1988) because of the wide range of mixtures used and the wide range of density achieved in structures and test specimens due to the use of cores and cylinder specimens and the variety of permeability tests used.

4-9. Density

Density is defined as mass per unit volume and is determined according to CRD-C 23. Density of RCC depends primarily on aggregate density and the degree of compaction. Typical values of density for CMC range from 2240 to 2560 kg/m^3 (140 to 160 lb/ft^3). The lack of entrained air and lower water content of many RCC mixtures result in a slightly higher density when compared to conventional air-entrained mass concrete made with the same aggregate. For some projects in seismic areas, density plays a significant role in structural design and on cost.

4-10. Durability

RCC, like CMC, is subject to potential deterioration due to the effects of abrasion/erosion, freezing and thawing, and other factors such as alkali-silica reaction expansion and sulfate attack. Chapter 8, Performance, discusses historic performance of RCC hydraulic structures subject to deterioration from some of these factors. Water-cementitious material ratio guidance for conventional concrete is given in EM 1110-2-2000, including maximum permissible water-cementitious material ratios for various anticipated structure exposure conditions. Due to the nature of RCC these water-cementitious material ratios cannot be applied easily to RCC but should be followed whenever possible.

a. Abrasion/erosion resistance. Abrasion/erosion resistance is primarily governed by compressive strength of the RCC and quality of the aggregate. ASTM C 1138, "Standard Test Method for Abrasion Resistance of Concrete (Underwater Method)," has been used to evaluate the erosion resistance of both conventional concrete and RCC. This procedure results in values of concrete volume (or average depth) loss at 12-hr increments up to conclusion of the test at 72 hr. Abrasion-erosion percent loss after 72 hr (ASTM C 1138) can be expected to range from about 3 to 15 percent (higher values for lower strength mixtures) for workable RCC mixtures with good to excellent quality aggregates. Sufficient data and field experience with high velocity flows over RCC is not yet available to provide guidance on correlation of test results to field performance. A variety of other observational tests have been run on RCC (Schrader and Stefanakos 1995) to evaluate resistance to abrasion/erosion. These have generally confirmed good to excellent RCC resistance for moderate to high velocity flows. RCC mixtures with a low water-cementitious material ratio and large-size aggregates are expected to provide erosion resistance equal to a conventional concrete with similar ingredients.

b. Resistance to freezing and thawing. RCC mixtures do not normally have intentionally entrained air and consequently will not have a high resistance to freezing and thawing in a critically saturated moisture condition. However, many examples of good field performance exist for RCC that is not critically saturated. RCC subjected to ASTM C 666, Procedure A, "Standard Test Method for Resistance of Concrete to Rapid Freezing and Thawing," typically performs poorly. Air-entraining admixtures are available and have been used to successfully entrain air in RCC mixes in the laboratory and on a few RCC projects. Entrained air has been successfully incorporated in RCC mixtures for Zintel Canyon Dam, Nickajack Dam, Santa Cruz Dam, Lake Robertson Dam, and others, as well as in a number of test sections. For workable RCC mixtures, laboratory investigations and field applications have shown certain air-entraining admixtures can effectively establish an air-void system with good performance, even when subjected to ASTM C 666 testing. Most RCC mixtures require a high dosage of air-entraining admixture to be effective, and percentages of air entrained in RCC will usually be more variable when compared with CMC.