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Drying Shrinkage of Roller-Compacted Concrete for Pavement Applications

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This paper reports the results of a laboratory investigation of the drying shrinkage of roller-compacted concrete for pavement applications. The aggregate grading and moisture content of nine RCC mixtures were varied, and the drying shrinkage measured according to the procedures described in ASTM C 157, with some modifications. The 28-day drying shrinkage results of the mixtures ranged from 8 to 33 × 10^{-5}, with an overall average of 15 × 10^{-5}. The combined effects of moisture content and aggregate grading on the drying shrinkage were statistically significant, while the individual effects of moisture content or aggregate grading were not statistically significant. A regression model for predicting the 28-day drying shrinkage of RCC from the relative aggregate grading and moisture content was developed from the data, with a multiple correlation coefficient of 67 percent. The ACI Committee 209 model for predicting the drying shrinkage of concrete with time compared favorably with the RCC drying shrinkage data.

Keywords: aggregate grading; concrete pavement cracking; drying shrinkage; optimum moisture content; roller-compacted concrete pavements.

BACKGROUND

General

Roller-compacted concrete (RCC) pavements are constructed from a zero-slump portland-cement concrete mixture that is typically mixed in a pug-mill mixer, placed with a modified asphalt-concrete paver, and compacted with rollers. By using this construction technique, in which a large amount of concrete pavement can be placed quickly with a minimum amount of labor, equipment, and no reinforcing steel or dowel bars, cost savings over conventional concrete pavements of 20 to 30 percent[1] or more have been realized. This technique for constructing pavements has been used in Canada since the mid-1970, and the United States since 1983. Most placements to date have been for applications where heavy, low-speed traffic is the primary user of the pavement.

Cracking of concrete pavements

The drying shrinkage of concrete is a key contributor to the cracking of concrete pavements in the first few days after placement. Concrete pavements generally crack within the first few days after placement as the concrete shrinks due to cooling and drying during curing and is restrained by the foundation upon which it is placed. This restraint creates tensile stresses in the concrete slab, which increase as the slab continues to shrink with time and to contract during the cooler night temperatures. These stresses will crack the slab as the tensile strength of the concrete, which develops at a somewhat slower rate, is reached. Subsequent cracks will develop in the slabs over time as the concrete is fatigued from curling, warping, and load-related stresses. For this reason, contraction joints are typically sawn in slabs at regular intervals along the length of the slab, usually within the first 24 hours, to control the location of the cracks by creating a weakened plane in the slab. Contraction joints are much easier to maintain than natural cracks, are more attractive, and their regular spacing promotes better load-transfer characteristics at the joints. Contraction joints in plain (nonreinforced) concrete slabs are typically spaced 12 to 20 ft apart, depending upon the thickness of the slab, with the longer spacings corresponding to the thicker slabs.

Contraction joints in RCC pavements

In the earlier RCC pavements, no attempt was made to saw contraction joints in the pavement, thereby allowing the RCC to develop shrinkage, contraction, and fatigue cracks at their naturally occurring locations. This was done for several reasons: the earlier applications of RCC were used for such heavy-duty applications where good appearance was considered secondary; problems with raveling of the sawcut during the cutting operation were considered excessive; the added cost of sawing joints was considered unnecessary. These natural shrinkage cracks were generally spaced 30 ft (10 m) to over 80 ft (25 m) for thicker pavements; cracks occurred at spacings of 60 to 250 ft (20 to 80 m) at a 15-in. (380 mm)

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thick intermodal shipping yard at Denver[2] and 80 to 450 ft (25 to 140 m) at an 18-in. (460 mm) thick port facility at Boston.[3] These crack spacings, much greater than would be expected for plain concrete pavements, are likely due to the lower moisture content typical of RCC mixtures, which contribute largely to a lower drying shrinkage.

As the use of RCC increased over the years, the impetus to saw contraction joints to make more attractive, easier maintained, joints became greater. Initial attempts at determining appropriate contraction joint spacings were based on trial-and-error joint spacings in RCC pavement sections.[1] It became apparent that a mechanistic model for predicting cracks in concrete slabs due to drying shrinkage and thermal contraction could help in determining the spacing of contraction joints in RCC slabs. A key component for the cracking model would be both the rate and magnitude of the drying shrinkage of the concrete.

Purpose of the research

The purpose of this research study was two-fold: to determine the magnitude of the drying shrinkage and the rate of drying shrinkage of RCC with time; and to determine and model the relative effects of the RCC composition, primarily the moisture and aggregate grading, on the drying shrinkage.

Factors influencing the drying shrinkage of concrete

The ultimate drying shrinkage of plain concrete may range from 20 to 120 × 10^{-5} for normal concrete, depending upon the properties and proportions of materials in the mixture. According to Neville,[4] the drying shrinkage of portland cement concrete depends primarily upon two variables: the initial moisture or water content of the concrete, and the volume of aggregate (or conversely the volume of paste) of the mixture. A concrete mixture containing a relatively large moisture content or water/cement ratio has the greatest potential for water loss and therefore a greater drying shrinkage than one with a low water content. Most of the volume change is due to the loss of adsorbed water; little or no shrinkage results from the loss of free water.[4] Since most of the water in concrete is contained in the paste fraction (water and cementitious materials) of the mixture, it is also obvious that a concrete with a higher paste fraction would have a higher potential for drying shrinkage. Thus, the more the paste volume is replaced by aggregate, the lower the potential exists for drying shrinkage.

The rate of shrinkage and ultimate shrinkage depends upon several factors.[4] The elastic properties of the aggregate, which offers restraint to the reduction in paste volume, directly influences the degree of shrinkage achieved for a particular mixture. The relative humidity around the concrete also greatly affects the degree of shrinkage of a concrete mixture; normal concrete exposed to 50 percent relative humidity shrinks at about twice the rate of the same mixture exposed to 80 percent relative humidity. The size and shape of the specimen also has a significant influence on the degree and rate of shrinkage.[4] Generally, the larger the specimen, the smaller the shrinkage. The effect can be quite dramatic when comparing small specimens (2 × 2 × 11-in. [51 × 51 × 280 mm]) to relatively large slabs (4 × 4 ft square, 8 in. thick [1.2 m × 1.2 m × 200 mm]). Kraai[5] reported that the larger specimen size resulted in a shrinkage of about 25 percent of that of the smaller specimen.

Since RCC pavements have been placed using similar aggregates, environmental conditions, and slab thicknesses as plain concrete, one could deduce that the drying shrinkage of RCC mixtures would be relatively small compared to typical concrete mixtures due to the relatively small water/cement ratios (0.3 to 0.4) and total moisture contents typical of RCC.[6] However, little information was found in the literature to suggest exactly what the rate or magnitude of drying shrinkage of RCC mixtures is; therefore, a laboratory study was conducted to determine approximate values of drying shrinkage for RCC, and to determine the influence of moisture content, aggregate type, and aggregate volume on the shrinkage.

RESEARCH SIGNIFICANCE

The drying shrinkage of concrete is an important parameter in mechanistic models used for predicting natural crack spacings of and determining contraction joint spacings for concrete pavements. Since RCC pavements contain a relatively low water content, it is expected that the drying shrinkage of RCC mixtures is much less than that for conventional concrete pavements. Since very little if any data on the drying shrinkage of RCC are available in the published literature, this paper will present the results of a laboratory study designed to investigate the effects of moisture content and aggregate grading or paste volume on the drying shrinkage of RCC. A multiple linear regression model used to predict the 28-day drying shrinkage of RCC based on this data will be presented, and the data will be compared to an existing model for predicting the drying shrinkage of concrete with time.

EXPERIMENTAL

Experiment design

Two factors were investigated for their influence on the drying shrinkage of RCC: the moisture content of the RCC and the volume of paste in the mixture. The moisture content is calculated by dividing the mass of water in the mixture by the mass of the dry aggregate. These parameters were selected not only because of their expected influence on the drying shrinkage, but also because of their importance in the RCC mixture proportioning and quality control process. The RCC moisture content is selected during the mixture proportioning process as that which results in the maximum wet density of an RCC sample compacted with a specified degree of energy, such as the Modified Proctor[7] compactive effort; this is

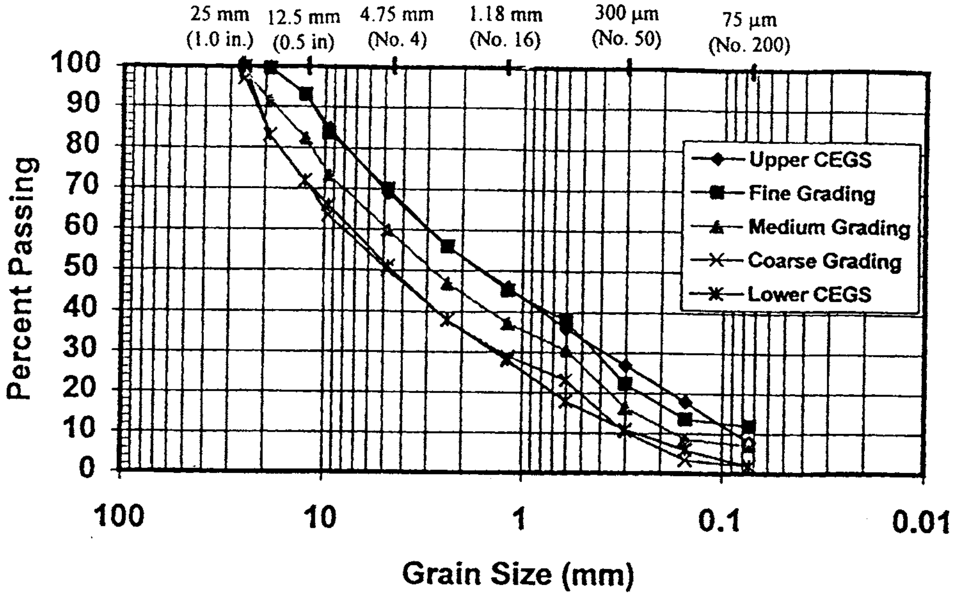

Fig. 1—"Coarse," "medium," and "fine" combined aggregate gradings for the RCC mixtures

generally referred to as the optimum moisture content. The volume of paste in an RCC mixture may be varied by changing the grading of the aggregate; in general, the coarser the aggregate grading, the more of the RCC volume is occupied by aggregate and consequently the paste content is lower. Both the RCC moisture content and aggregate grading are checked in the quality control operations of Corps of Engineers RCC projects in an effort to make them as nearly constant during the construction process as possible.

The laboratory study was designed to investigate the widest range of RCC moisture content and aggregate gradings that would yield a mixture of the proper consistency for field compaction and would meet the Corps of Engineers guide specifications (CEGS) for RCC mixtures.[8] Three moisture contents were investigated; the optimum moisture content (at maximum wet density), and a moisture content above and below the optimum, corresponding to the wettest and driest moisture contents which would be expected to yield RCC mixtures with a consistency suitable for field compaction. The wet and dry moisture contents were generally one-half percent greater than and less than the optimum moisture contents, respectively. Three aggregate gradings were also investigated. The aggregate gradings were varied from a grading close to the center of the CEGS recommended aggregate grading band (medium grading), to gradings close to the top (fine grading) and bottom (coarse grading) of the aggregate grading band. The three aggregate gradings used in the experiment are shown in Fig. 1.

To incorporate the three aggregate gradings—fine (F), medium (M), and coarse (C)—and three levels of moisture content—dry (D), optimum (O), and wet (W)—into the experiment, a 3 × 3 complete factorial experiment design was implemented. The resulting nine mixtures were designated by the letters representing the aggregate grading and moisture content in the mixture; for example, the mixture containing the fine grading and dry moisture content was designated FD. To obtain an estimate of the experimental error, each experimental condition or treatment was represent-

Table 1—RCC mixture proportions for the drying shrinkage study

Mix ID*	Batch weights, lb/yd^3 (kg/m^3) (saturated surface-dry aggregates)								W/(C+F)†	Moisture content, percent‡	Aggregate volume, percent
		Total fly ash		Aggregate							
	Cement	Fly ash	Aggregate	$^3/_4$ in.	No. 5	No. 7	Sand	Water			
FD	331.3 (197.4)	76.3 (45.5)	412.4 (245.7)	369.5 (220.1)	— —	736.5 (438.8)	1918.0 (1142.6)	190.2 (113.3)	0.23	5.7	67.9
FO	326.9 (194.7)	75.3 (44.9)	406.9 (242.4)	364.6 (217.2)	— —	726.7 (432.9)	1892.5 (1127.4)	209.7 (124.9)	0.26	6.3	67.0
FW	322.2 (191.9)	74.3 (44.3)	401.0 (238.9)	359.3 (214.1)	— —	716.3 (426.7)	1865.2 (1111.2)	230.4 (137.3)	0.29	6.9	66.0
MD	337.9 (201.3)	80.4 (47.9)	248.6 (148.1)	236.3 (140.8)	440.7 (262.5)	807.3 (480.9)	1767.8 (1053.2)	176.6 (105.2)	0.27	5.2	72.7
MO	333.2 (198.5)	79.3 (47.2)	245.2 (146.1)	233.0 (138.8)	434.7 (259.0)	796.4 (474.5)	1743.8 (1038.9)	196.6 (117.1)	0.30	5.8	71.7
MW	327.6 (195.2)	77.9 (46.4)	241.1 (143.6)	229.2 (136.5)	427.6 (254.7)	783.2 (466.6)	1714.9 (1021.6)	220.7 (131.5)	0.34	6.5	70.5
CD	342.6 (204.1)	83.2 (49.6)	70.9 (42.2)	39.4 (23.5)	911.7 (543.1)	909.0 (541.5)	1613.2 (961.1)	172.5 (102.8)	0.35	5.0	77.3
CO	336.7 (200.6)	81.8 (48.7)	69.7 (41.5)	38.8 (23.1)	896.2 (533.9)	893.6 (532.4)	1585.8 (944.7)	197.6 (117.7)	0.40	5.7	76.0
CW	331.6 (197.5)	80.6 (48.0)	68.6 (40.9)	38.1 (22.7)	882.3 (525.6)	879.8 (524.1)	1561.3 (930.1)	220.1 (131.1)	0.46	6.4	74.8

*F = Fine grading; M = Medium grading; C = Coarse grading; D = Dry moisture content; O = Optimum moisture content; W = Wet moisture content

†Includes total fly ash

‡By weight of aggregate

ed by three samples or replicates, for a total of 27 samples. The order of fabricating the drying shrinkage samples for each mixture was randomized as much as practically possible to minimize extraneous trend or pattern effects.

Materials

The proportions of each RCC mixture are given in Table 1. Type I portland cement and Class F fly ash was used in each of the mixtures. The fly ash was proportioned to replace 25 percent of the cement by volume, and to contribute to the proportion of the material finer than the 75-mm (No. 200) sieve in the aggregate. This practice is common in RCC mixtures when the aggregates contain insufficient fines to meet the aggregate grading specifications. As a result, rather high proportions of cementitious materials were contained in the mixtures, ranging from 820 lb/yd^3 (486 kg/m^3) in Mix FD to 481 lb/yd^3 (285 kg/m^3) in Mix CW.

Four different aggregate size groups were used to obtain the fine, medium, and coarse gradings used in the RCC mixtures. The three coarse aggregate size groups were crushed limestone, and the fine aggregate was a natural sand. Crushed aggregate is typically used in RCC mixtures because it results in good stability of the fresh mixture during compaction with the rollers. The total aggregate volumes were about 67, 71, and 76 percent for the fine, medium, and coarse gradings, respectively. The aggregate volumes also varied slightly for the various moisture contents, with a somewhat lower aggregate volume for the wetter mixtures. This corresponds to paste volumes of approximately 31, 27, and 22 percent, respectively, since the mixtures were assumed to contain 2 percent air by volume (Fig. 2).

The optimum moisture contents of the mixtures containing the fine-, medium-, and coarse-graded aggregates were 6.3, 5.8, and 5.7 percent, respectively. The corresponding W/(C + F) ratios ranged from 0.23 for the FD mixture to about 0.46 for the CW mixture.

Shrinkage specimens and curing conditions

The 3 × 3 11.25-in. (76 × 76 × 286-mm) drying shrinkage test specimens were fabricated and tested according to ASTM C 157 "Length Change of Hardened Cement Mortar and Concrete,"[9] with the following modifications. Each sample was fabricated by loosely filling the mold with fresh RCC to a height just above the gage studs (about half the depth of the 3-in. [76-mm] dimension). The sample was then compacted by vibrating the mold on a vibrating table with a 150 lb/ft^2 (732 kg/m^2) surcharge mass resting on top of the RCC. The RCC was vibrated until a paste was discernible at the top of the sample, usually after 30 to 90 seconds of vibration. The mold was then slightly overfilled with RCC and the concrete compacted by vibration and trimmed to form a 3-in.

Table 2—Analysis of variance (ANOVA) of 28-day drying shrinkage test results

Summary of 28-day shrinkage results (x 0.00001)

	Dry	Optimum	Wet	Total	
Fine grading					
Count	3	3	2	8	
Sum	37	49	45	131	
Average	12.33	16.33	22.50	51.17	
Variance	8.33	22.33	12.50	43.17	
Medium grading					
Count	3	3	3	9	
Sum	35	23	40	98	
Average	11.67	7.67	13.33	32.67	
Variance	0.33	2.33	9.33	12.00	
Coarse grading					
Count	3	3	3	9	
Sum	31	28	100	159	
Average	10.33	9.33	33.33	53.00	
Variance	24.33	6.33	184.33	215.00	
Total					
Count	9	9	8		
Sum	103	100	185		
Average	34.33	33.33	69.17		
Variance	33.00	31.00	206.17		

ANOVA

Source of variation	SS	df	MS	F ratio	F critical (Alpha = 0.05)
Sample	-7.26	2	-3.63	-0.08	3.55
Column	302.51	2	151.26	3.15	3.55
Interaction	879.26	4	219.82	4.57	2.93
Within	865.33	18	48.07		
Total	2039.85	26			

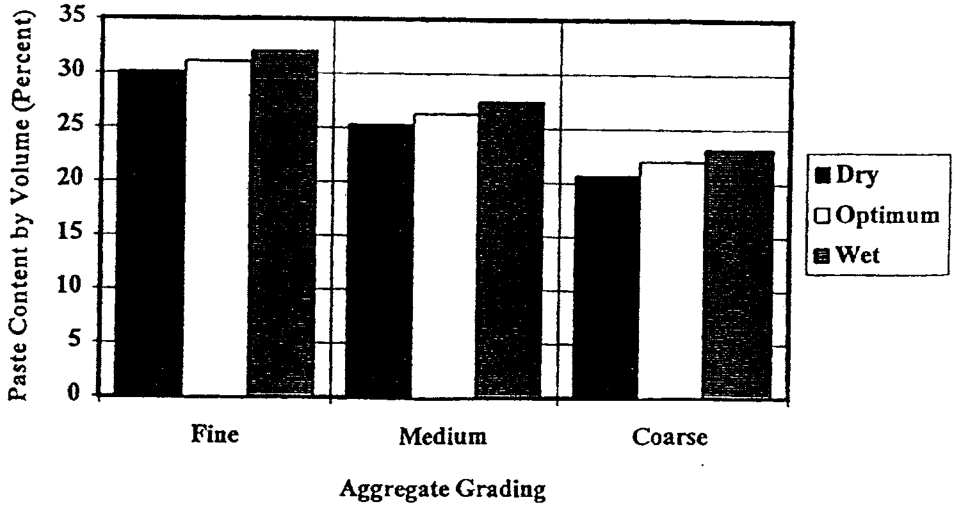

Fig. 2—Paste volumes of RCC mixtures

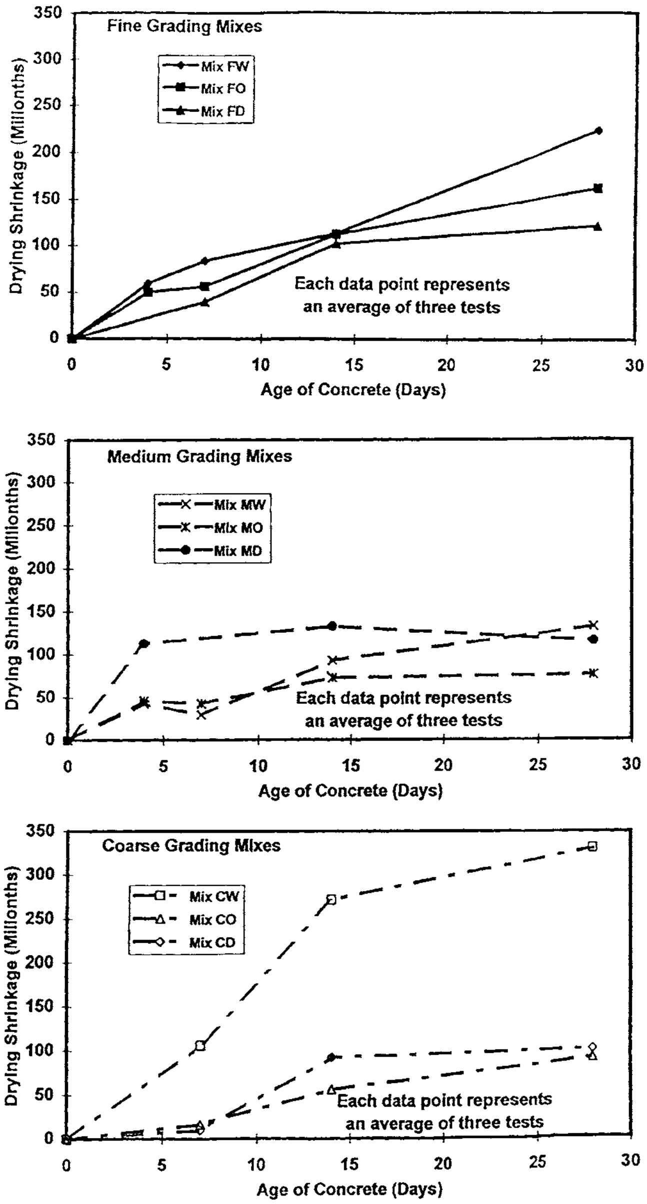

Fig. 3—Results of the RCC drying shrinkage tests

(76-mm) square cross-section. The samples were cured according to the test method (i.e. moist cure for 28 days), and then stored in air (50 percent relative humidity, 73 deg F [21 deg C]) for the duration of the testing.

RESULTS AND DISCUSSION

Drying shrinkage results

The results of the drying shrinkage tests are presented in Fig. 3. The average of the three test results of drying shrinkage for each mixture is reported for each test time (4, 7, 14, and 28 days). Most of the average 28-day shrinkage values fall in the range of 8 to 33 × 10^{-5}. The overall average is 15 × 10^{-5}, and the overall coefficient of variation is 61 percent (Fig. 4). (One of the FW samples was damaged during fabrication, so only two test result values were available for this mixture).

The average 28-day shrinkage results are plotted on a single chart in Fig. 5 for comparison. There does not appear to be a consistent trend of increasing drying shrinkage with increasing moisture content or increasing paste volume (finer grading) as might be expected, although the greatest overall shrinkage was for the CW mixture. For instance, at the optimum moisture content, the drying shrinkage decreases from a maximum to a minimum value as the aggregate grading varies from fine to coarse (decreasing paste volume), but the opposite trend occurs for the wet mixtures. This inconsistent trend behavior is apparent for each combination of moisture content and aggregate gradings.

Effect of moisture content and aggregate grading on shrinkage

To determine whether the changes in moisture content and aggregate grading had a significant effect on the drying shrinkage results, an analysis of variance (ANOVA)[10] was conducted using the 28-day data (Table 2). The ANOVA is used to test the hypothesis (the null hypothesis) that there is no significant change in the shrinkage values with changes in the moisture content or aggregate grading, or both, versus the alternative hypothesis that there is a significant change. The ANOVA makes use of the F ratio, which is calculated by dividing the mean square of the treatment (moisture content,

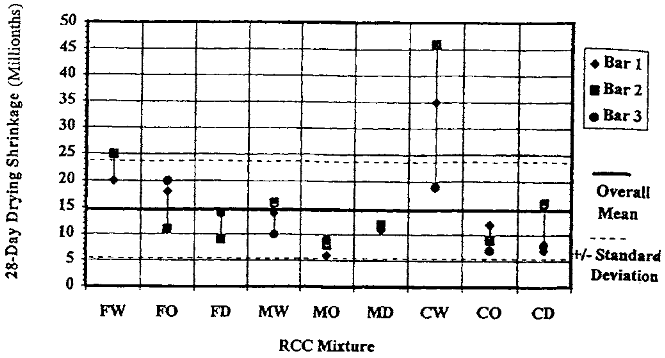

Fig. 4—28-day RCC drying shrinkage test results

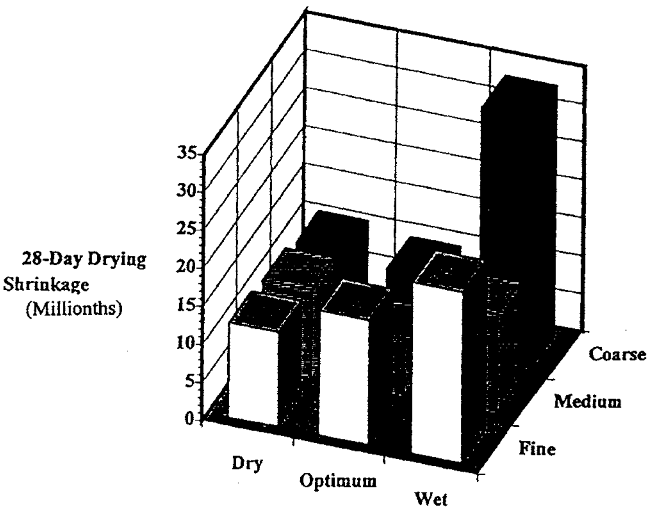

Fig. 5—Average 28-day drying shrinkage results for each RCC mixture

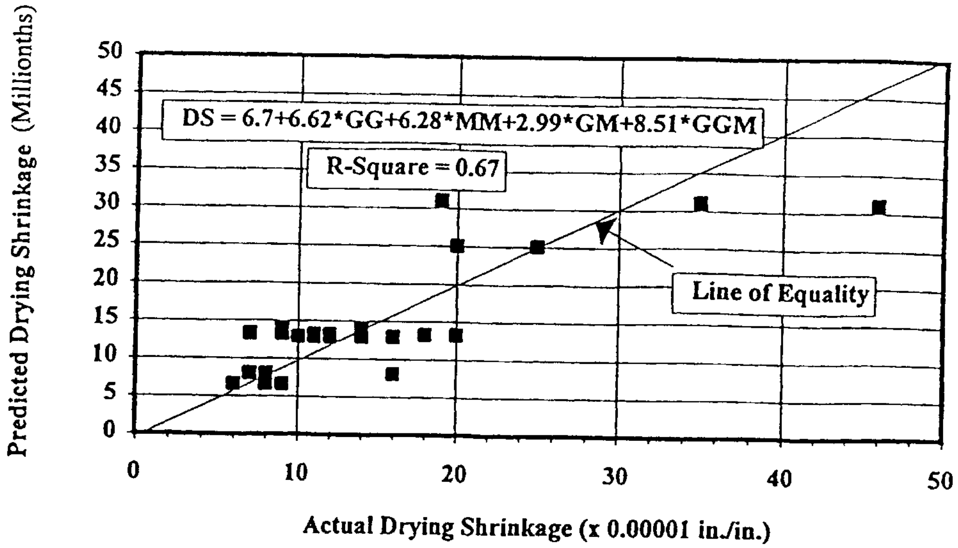

Fig. 6—Comparison of actual and predicted 28-day drying shrinkage of RCC mixtures

aggregate grading, or combination) by the mean square of the error, and comparing the result to the F distribution with degrees of freedom corresponding to those for the numerator and denominator of the F ratio, respectively. The statistic from the F distribution was chosen at the 0.05 level of significance, meaning that there is a 5 percent chance that the conclusions derived from the analysis are incorrect. The null hypothesis is rejected if the absolute value of the F ratio is greater than the F statistic.

From the results of the ANOVA, it is apparent that the null hypothesis should be rejected in the case of the separate effects of the aggregate grading or moisture content, but not for the interaction effects of the two factors. In other words, there is insufficient evidence or data to suggest that changes in the moisture content or aggregate gradings by themselves have a significant effect on the drying shrinkage, but their combined interactions do have a significant effect.

Development of regression model for moisture content and aggregate grading effects on RCC drying shrinkage

Since the ANOVA analysis suggests a relationship between the drying shrinkage and the combined effects of moisture content (M) and aggregate grading (G), a stepwise linear regression procedure[11] was used to develop a linear model that includes interactions between the two independent variables M and G. Since M and G are represented as dimensionless qualitative variables, they were assigned values of -1, 0, and 1 for the fine, medium, and coarse gradings (G) and the dry, optimum, and wet moisture contents (M), respectively. The stepwise regression procedure in the SAS computer program[12] was then used to estimate the parameters β_0 through β_9 in the third-order linear model:

$$DS = \beta_0 + \beta_1 G + \beta_2 M + \beta_3 G^2 + \beta_4 M^2 + \beta_5 GM + \beta_6 G^3 + \beta_7 G^2 M$$
$$+ \beta_8 GM^2 + \beta_9 M^3 + \varepsilon_r$$

where

DS = 28-day drying shrinkage ($\times 10^{-5}$)
β_i = parameters for variables
G = aggregate grading value (-1, 0, 1)
M = moisture content value (-1, 0, 1)
ε_r = residual error, or actual DS-predicted DS

The level of significance for the regression was set at $\alpha = 0.05$; i.e. there is a 5 percent probability that the null hypothesis $\beta_i = 0$ is falsely rejected. The final form of the equation is:

$$DS = 6.7 + 6.62G^2 + 6.28M^2 + 2.99GM + 8.51G^2M$$

The F ratio for the regression was 10.9, which is greater than the critical F statistic of 2.76 for 2 and 25 degrees of freedom. The multiple correlation coefficient (R^2), which is the percentage of the total error explained[11] by the regression, is 67 percent. Figure 6 shows the predicted DS versus the measured DS for each of the samples; the regression model appears to provide a reasonable estimate for the DS.

The results of this experiment do not take into account all the factors which affect the drying shrinkage of RCC. As mentioned previously, the drying shrinkage is also a function of the modulus of elasticity, the size of the sample, and the drying conditions, and none of these variables were analyzed in this study. However, the regression model does provide an estimate of the drying shrinkage for a particular set of materials over the range of aggregate gradings and moisture contents that might be expected to be used during the construction of an RCC pavement. The final RCC design program does allow for other values of drying shrinkage to be input if they are known.

Comparison of RCC drying shrinkage rate to ACI Committee 209 equation

Another trend of interest is the rate of drying shrinkage of RCC with time. The ACI Committee 209[13] suggests that the drying shrinkage of a concrete mixture varies with time (after 7 days) by the relationship:

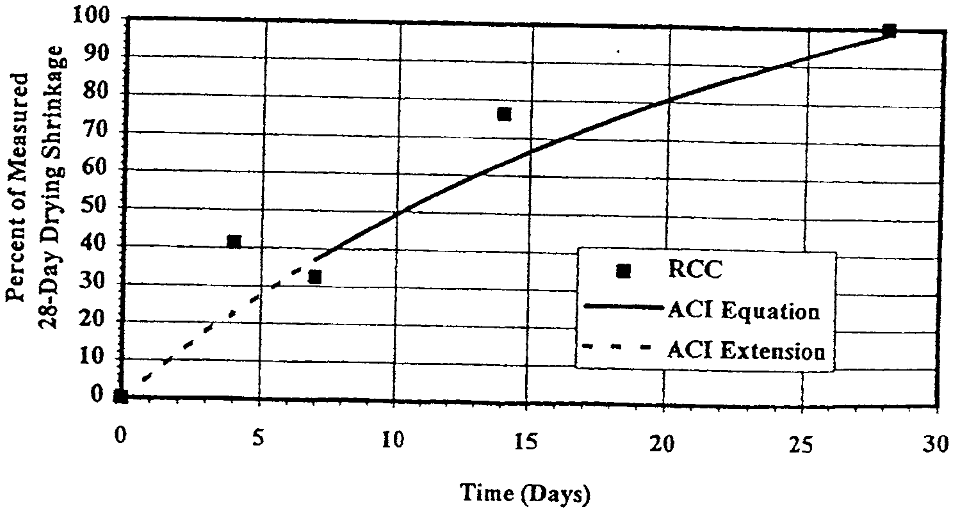

Fig. 7—Comparison of ACI Committee 209 drying shrinkage model to RCC data

$$(\varepsilon_{sh})_t = \frac{t}{35+t}(\varepsilon_{sh})_u$$

where

$(\varepsilon_{sh})_t$ = drying shrinkage of concrete at time t

t = time after end of initial wet curing (days)

$(\varepsilon_{sh})_u$ = ultimate drying shrinkage at 40 percent relative humidity (H)

The 28-day shrinkage of concrete has been estimated to be between 20 and 52 percent of the 20-year shrinkage, or about 40 percent on average.[4] If the ultimate shrinkage is assumed to occur after 20 years (which is a typical design life for concrete pavements), then the ultimate shrinkage of the RCC mixtures may be estimated by dividing the 28-day shrinkage results by 0.40. The estimated ultimate value for the drying shrinkage of the RCC mixtures is then 37×10^{-5}. This value was used in the drying shrinkage equation to compare the ACI model to the average of the 4, 7, 14, and 28 day drying shrinkage results of all nine mixtures (Fig. 7). It appears that the ACI model gives a reasonable estimate of the rate of drying shrinkage for RCC mixtures.

CONCLUSIONS

The following conclusions were reached in this study:

1. The drying shrinkage of RCC for pavement applications is relatively low compared to conventional concrete used for pavements, and for this data is on the order of 8 to 33 x 10^{-5} at 28 day's age, with an overall average of 15 x 10^{-5}.

2. The individual effects of moisture content and aggregate grading (paste volume) on the drying shrinkage of RCC were not found to be significant, but their combined effects were found to be significant.

3. The combination of aggregate grading and moisture content that resulted in the greatest 28-day shrinkage was the coarse grading, wet-of-optimum moisture content, and the smallest 28-day shrinkage was realized with the medium or mid-range grading, with the optimum moisture content.

4. A regression model which can predict the 28-day drying shrinkage of RCC from the aggregate grading and moisture content was developed from the data. The model has a multiple correlation coefficient of 67 percent.

5. The ACI Committee 209 equation for predicting the drying shrinkage of concrete results in a reasonable estimate of the rate of drying shrinkage of the RCC samples tested in this study.

RECOMMENDATIONS

Twenty-eight day drying shrinkage values of 8 to 33 × 10^{-5} should be expected when estimating the shrinkage of RCC used for pavement applications. The regression model developed in this paper may be used to estimate the drying shrinkage of RCC, provided that the assumptions on material types and proportions used in developing the model are met. However, more research is necessary to evaluate the effects of aggregate modulus of elasticity, the sample size, and various drying conditions on the drying shrinkage of RCC.

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