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Optimization of Roller-Compacted Concrete for Local Application

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Recently constructed asphalt pavements in Saudi Arabia are experiencing a high level of wheel track rutting, which is mainly attributed to the high ambient pavement temperature, the high volume of loaded trucks, and the viscoelastic behavior of the asphalt pavement. One proposed solution is to use reinforced concrete rigid pavement. Because of corrosion of the reinforcement bars, a common problem in Saudi Arabia, it is better to use roller-compacted concrete (RCC) pavements. A comprehensive and rational design of RCC mixes, such as conventional concrete, is extremely complex, because it is influenced by numerous factors that depend on the sources of materials and their properties; methods of preparation, placement, compaction, and curing; and, most important, prevailing environmental conditions. Incorporation of all these factors into RCC mix design not only requires the arduous selection of appropriate proportions of the ingredients, but also inaccuracies occur in the required properties of RCC that are usually rectified by trial-and-error procedures. Effects of variation of the water to cement ratio, coarse-to-fine aggregate ratio, and total aggregate to cement ratio, on rollability, density, and strength of RCC are investigated for three compactive efforts. The main objective is to find optimum mix design proportions for locally available materials by varying the mentioned variables and to develop a model to predict the flexural strength of local mixes.

The increase in the number of heavily loaded trucks using the Saudi Arabian road network, and the country's high ambient temperatures, have resulted in wheel path rutting. One proposed solution to this problem is to use rigid pavement. However, because of humidity levels and high water-table levels (especially in the coastal areas of Saudi Arabia) and an environment that causes corrosion of reinforcement bars and dowels, roller-compacted concrete pavement (RCCP) may be an option. RCCP is a mixture of aggregates, binder, and a small amount of water, which forms a zero-slump portland cement concrete that is spread and compacted, first with an asphalt paver and then with a vibratory roller, to obtain satisfactory results. The resulting pavement is of higher strength and load-carrying capability than conventional concrete pavement. Traditional RCCP is like a central-mixed cement-treated base (CTB) or soil cement. Some major differences that exist between them are (*1,2*)

- Compressive and flexural strengths of RCCP are higher than CTB, because of the greater content of portland cement (usually 12 to 14 percent cement for RCCP and 6 to 8 percent cement for CTB.
- RCCP does not need a protective wearing surface whereas CTB needs to be covered.
- A true paver or laydown machine normally is used for placing and finishing RCCP.
- RCCP is designed to resist abrasion from traffic, to remain durable under severe weather exposure, and to have a satisfactory surface finish and straight-edge tolerance for the traffic served.

The first highly publicized RCCP was built in Canada by the British Columbia Forest Products Company on Vancouver Island at Caycuse Dry Log Sort in summer 1975. Because of the ease and simplicity of construction, and that it's possible to save one-third or more of the cost of conventional concrete pavement construction (*3*), this new technology is catching on so fast that, to date, several RCCPs have been built in other parts of Canada, the United States, Spain, Sweden, and Australia (*4–7*).

Some advantages of RCCP are its high flexural strength (25 percent higher than CTB) and its high resistance to abrasion and fuel and hydraulic spills. Tires turning in hot weather have no effect on it, and it is less affected by summer temperature. Finally, it has the advantage of reduced construction time and cost (*1–6*). However, because RCCP technology is in its infancy, standard procedures for proportioning and fabricating samples are virtually nonexistent. Commonly used procedures are based on an arbitrary selection of mix parameters. Batches are prepared using trial-and-error procedures, and adjusted to achieve the required density, rollability, and strength. Some samples have been fabricated by consolidating them on vibrating tables (*2*) and by using a modified proctor (*8*) and a Kango hammer (*5*).

This study applied factorial experiment design, which facilitates analysis of the combined effects of two or more variables and their interactions in terms of density, rollability, and strength—with a view to optimizing mix designs. Samples were fabricated using a California kneading compactor.

MATERIALS

The three main ingredients of RCCP are aggregate, portland cement, and water. The selected materials are described in the following sections.

Aggregate

Composition and variation of the aggregate is an important component of all concretes, particularly of roller-compacted concrete (RCC). Several concrete properties, such as density and surface texture, are affected by parameters such as the coarse-to-fine aggregate ratio and the coarse-to-total-aggregate ratio. If the aggregates are well proportioned, a high density and impermeable RCC is formed. RCC has a low water content and therefore is likely to segregate. To avoid segregation, maximum aggregate size should not exceed 22 mm ⅞ in.) (*9*) and should contain a high proportion of fines. However, if the pavement is to be laid in lifts, the base lift could have an aggregate size of up to 37.5 mm (1.5 in.). At least 66 percent of the aggregate should be crushed stone (*6*). Aggregate gradations used in Canada and Spain are indicated in Figure 1. The Canadian limits appear to have a wider band, although

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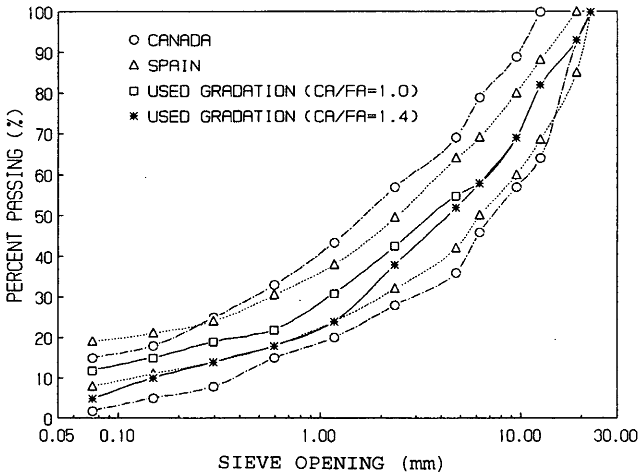

FIGURE 1 Aggregate gradations used in Canada and Spain.

they appear to have common limits, ranging from .075 to 19 mm (.003 to 0.75 in.). All gradations were chosen to minimize segregation in the mix.

In this research, coarse and fine aggregates were collected from local areas. Coarse aggregate was collected from the Al-Summan area near Riyadh. The area is potentially a large source of aggregate. The aggregate (limestone) is excavated and crushed into various sizes to have angular shape and rough texture. The fine aggregate was natural sand and was collected near Dhahran. The two aggregates were proportioned to form two gradation envelopes with different coarse-to-fine aggregate (CA/FA) ratios (Figure 1). Those gradations were chosen to fall within the specified limits shown in Figure 1 and contain enough fines to prevent segregation. The aggregate was subjected to a series of quality tests in accord with ASTM standard specifications for concrete aggregate ASTM C33. Test results and ASTM limits are presented in Table 1. Results indicate that the selected aggregate satisfies ASTM requirements.

Cement Content

Cementitious content by weight of aggregate should be between 12 and 14 percent (*2*). It may be made up of portland cement and additives such as fly ash. Because wear resistance is not a factor in the bottom lift of a multiple-lift construction, a reduction of cement content from 6 to 8 percent by weight of aggregate is recommended (*7*). In cases where sulphate exposure is not a problem, any available portland cement, (with the exception of Type III portland cement) or a combination of portland cement and pozzolan, or blended hydraulic cement with pozzolan, can be used. If sulphate exposure is a problem, Type II, Type V, or a moderate sulphate-resistant blended hydraulic cement should be used (*2*). Because sulphate attack is a major problem affecting concrete durability in the coastal areas of Saudi Arabia, ASTM Type V cement was used in all the mixes.

Water Content

Water content is proportioned in such a way that the resulting RCC has zero-slump and maximum density under compaction. The

TABLE 1 Summary of Test Results on Aggregates

Aggregate Type	Property	Test Results	ASTM Limit
Coarse	Grading	3/4" maximum size grading specified in literature	-
	Specific gravity	Bulk specific gravity oven dry basis = 2.613 Bulk specific gravity (SSD) basis = 2.646 Apparent specific gravity = 2.702	- - -
	Absorption	24-hour = 1.26%	-
	Abrasion loss	23.25%	40%
	Presence of clay lumps and friable particles	0.74%	3% to 10%
	Soundness	0.58%	12%
Fine	Grading	Fine modulus = 1.46	2.3-3.1
	Specific gravity	Bulk specific gravity oven dry basis = 2.614 Bulk specific gravity (SSD) basis = 2.634 Apparent specific gravity = 2.667	- - -
	Absorption	24-hour = 0.77%	-
	Presence of clay lumps and friable particles	#8 = 0.45% #16 = 0.18%	3%
	Soundness	1.38%	10%

method outlined in ASTM D558 (ASTM 1988h) treats RCC as soil cement instead of concrete and thus establishes a relationship between moisture and density for an applied compactive effort. Abrams and Jacksha (*10*) have suggested a water cement (W/C) ratio in the range of 0.3 to 0.4. Results of initial mix trials indicate that this range is too narrow for local aggregates. The W/C ratio range was therefore adjusted to a range of 0.3 to 0.5. In this research, potable water available from a laboratory faucet was used in all stages of testing, preparation, and curing of the concrete.

EXPERIMENTAL PROGRAM

RCC for pavements must attain a consistency similar to soil cement yet still possess some features of conventional concrete, such as strength and durability. In the design of a mix, particular attention should be given to the three most important factors controlling the quality of concrete: W/C ratio, CA/FA ratio, and total aggregate to cement ratio (TA/C).

To achieve the appropriate mix design for rollability, density, and strength (comprehensive and flexural), trials usually have to be conducted that are not only laborious but also time-consuming. One objective of this study is to investigate several mix proportions in terms of rollability, strength, and density, for three different compactive efforts.

To test for the different variables, five levels of W/C (0.3 to 0.5), four levels of TA/C (5.4 to 7.0), and two levels of CA/FA (1.0 and 1.4) were chosen, as shown in Table 2. By using these levels, a factorial experiment was designed to explore the effect of the factors on rollability, density, and flexural strength of RCC and the interactions among the factors.

Typical RCC mix proportions for four countries are shown in Table 3. The rationale behind a country's selected the mix proportions relates to a mix's strength and serviceability, the availability of constituent materials, and cost.

A Hobart electrically operated, laboratory mechanical mixer with a capacity of 0.012 m^3 (732 $in.^3$) was used to mix the ingredients for RCC. Mixing was done in batches; water was the last ingredient added. The water and other ingredients were mixed vigorously for 3 min to reduce the chance of segregation.

The Ronny Anderson method (*5*) was used to measure rollability (the ability to roll or compact the zero-slump concrete with reasonable effort while maintaining its homogeneity without segregation). In the Ronny Anderson method, 2.5 kg (5.5 lb) of RCC is placed into a cylindrical form. A 13.3-kg (20.3-lb) weight is lifted into place, and a vibrating table is run for 20 sec. The rate at which the weight sinks (the rate of compaction) may be used as a measure of rollability.

Currently there are no standard procedures for making test specimens. The authors decided to use a California kneading compactor to compact the test specimens because it is the best means of simulating construction compaction (similar to ASTM D3202-83 setup). The kneading compactor was calibrated to find a suitable foot pressure for achieving the highest density with minimal degradation. This pressure was found to be 1551 kPa (225 psi).

The RCC from each mix was cast into three 400 × 100 × 100-mm (16 × 4 × 4 in.) beams using a single layer; the beams were then subjected to three chosen compactive efforts corresponding to 50, 100, and 150 tamps, respectively, at a foot pressure of 1551 kPa (225 psi). Initial consolidation was achieved by subjecting the sample to a static load of 621 kPa (90 psi) before it was transferred to the compactor. Applying static load not only constitutes initial compaction but is also a means of obtaining a relatively flat finished beam surface.

The specimens were covered with wet burlap for 24 hr and cured for 28 days in a curing tank filled with water, per ASTM Standard C192.

RESULTS

Within the range of W/C ratios, all samples were within an acceptable range of rollability. Figures 2 to 7 show the effects of varying W/C, C, CA/FA, and number of tamps, on flexural strength and mix density. Results indicate that for the W/C ratio used, the 28-day flexural strength improves by increasing the W/C ratio to a maximum value, then it starts decreasing. This finding is attributed to the fact that, in the early stages, cement mortar acts as a filler material, filling the voids between the aggregates until all voids are filled. The same is true for density. The maximum flexural strength was 6.7 MPa (971.5 psi), corresponding to a W/C ratio of 0.45 and a CA/FA

TABLE 2 Schematic Representation of the Experimental Design

Levels of A (CA/FA)	Levels of C (TA/C)	Levels of B (W/C)				
		.3	.35	.4	.45	.50
1.4	7.0	$a_1b_1c_1$*	$a_1b_2c_1$	$a_1b_3c_1$	$a_1b_4c_1$	$a_1b_5c_1$
	6.4	$a_1b_1c_2$	$a_1b_2c_2$	$a_1b_3c_2$	$a_1b_4c_2$	$a_1b_5c_2$
	5.8	$a_1b_1c_3$	$a_1b_2c_3$	$a_1b_3c_3$	$a_1b_4c_3$	$a_1b_5c_3$
	5.4	$a_1b_1c_4$	$a_1b_2c_4$	$a_1b_3c_4$	$a_1b_4c_4$	$a_1b_5c_4$
1.0	7.0	$a_2b_1c_1$	$a_2b_2c_1$	$a_2b_3c_1$	$a_2b_4c_1$	$a_2b_5c_1$
	6.4	$a_2b_1c_2$	$a_2b_2c_2$	$a_2b_3c_2$	$a_2b_4c_2$	$a_2b_5c_2$
	5.8	$a_2b_1c_3$	$a_2b_2c_3$	$a_2b_3c_3$	$a_2b_4c_3$	$a_2b_5c_3$
	5.4	$a_2b_1c_4$	$a_2b_2c_4$	$a_2b_3c_4$	$a_2b_4c_4$	$a_2b_5c_4$

*Three samples were fabricated and tested for each cell.

TABLE 3 Typical Mix Proportions for Four Countries

CANADA		
Aggregate	3480 lb/yd^3	CA/FA = 1.86
Portland Cement Type I	448 lb/yd^3	TA/C = 6.5
Fly Ash	90 lb/yd^3	W/C = 0.35
Water	188 lb/yd^3	
Average Compressive Strength = 4570 psi (31.5 MPa) at 28 days		
SPAIN		
Gravel 10 to 30 mm	390 lb/yd^3	CA/FA = 1.38
Gravel 0 to 10 mm	2750 lb/yd^3	
Sand 0 to 5 mm	400 lb/yd^3	TA/C = 8.05
ASTM Class C Fly Ash	150 lb/yd^3	
Category P-450 Cement	290 lb/yd^3	W/C = 0.42
Water	185 lb/yd^3	
Average Compressive Strength = 2850-3560 psi (20-25 MPa) at 28 days		
SWEDEN		
Gravel 16-30 mm	573 lb/yd^3	CA/FA = 1.5
Gravel 0-16 mm	2076 lb/yd^3	
Sand 0- 5 mm	691 lb/yd^3	TA/C = 5.26
Cement	635 lb/yd^3	
Water	219 lb/yd^3	W/C = 0.34
Average Compressive Strength = 5800 psi (40 MPa) after 28 days		
U.S.A. [Portland Airport]		
Gravel	1550 lb/yd^3	CA/FA = 1.17
Sand	1700 lb/yd^3	
Cement Type I	488 lb/yd^3	TA/C = 5.35
Pozzolan (Class F)	119 lb/yd^3	
Water	260 lb/yd^3	W/C = 0.43
Average Flexural Strength = 710 psi at 28 days		
U.S.A. [Multnomah County Rd.]		
Aggregate	3309 lb/yd^3	CA/FA = 0.75
Cement-Pozzolan Type I P	550 lb/yd^3	TA/C = 6.02
Water	242 lb/yd^3	W/C = 0.44
Average Flexural Strength = 600 psi (4.1 MPa) at 28 days		

1 kg/m^3 = 1.868 lb/yd^3
CA/FA = Coarse to Fine Aggregate ratio
TA/C = Total Aggregate to Cement ratio
W/C = Water to Cement ratio

ratio of 1.4, for a mixture of 15 percent cement with 150 tamps. Flexural strength of normal concrete prepared using the same aggregate gradation at an optimum W/C ratio generates a value of 4.2 MPa (612.0 psi). That indicates an increase of about 37 percent in the flexural strength of RCC above that of normal concrete.

The total aggregate cement (TA/C) ratios used in the mixes were 5.4, 5.8, 6.4, and 7.0. For all W/C ratios, an increase in the total aggregate resulted in a decrease in strength. At lower TA/C ratios, the volume of the cement paste is greater, and it plays a greater role in improving strength. On the other hand, increasing the CA/FA ratio increases gaps between the aggregate, allowing the cement to coat the aggregate effectively. That resulted in the mixes' increased flexural strength.

To check that the studied variables (TA/C, CA/FA, and W/C) significantly affect flexural strength and density, an analysis of variance was performed on all test results. Analysis of variance determined that the source of variation due to TA/C, CA/FA, and W/C is highly significant when compared with values of *F* (variance ratios) at a 95 percent probability level (0.05 significance level). That finding indicates the underlying influence of such variables on the strength and density of RCC.

Statistical methods were used to fit a model between the obtained flexural strength of the RCC mixes and the applied variables (CA/FA, TA/C, W/C, and number of tamps). Figures 2 to 4 indicate that the relation between flexural strength and W/C ratio has the shape of a sine function, but for the other variables the relation is linear. The resulting model is

$$\text{Flexural strength} = 7.44 - 1.18\,(\text{TA/C}) + 1.81\,\text{sine}\left[\left(\frac{\text{W/C} - .3}{.15}\right) * \frac{\pi}{2}\right] + 1.94\,(\text{CA/FA}) + 0.0059\,(\text{no. of tamps}) \tag{1}$$

The model has a coefficient of determination of 95.6 percent.

A stepwise selection analysis indicates that the important variables affecting flexural strength are TA/C, W/C, CA/FA, and the

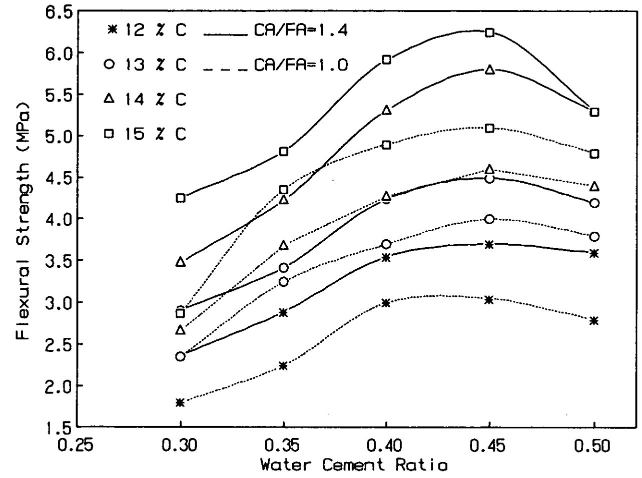

FIGURE 2 Relation between W/C ratio and flexural strength for a compaction effort of 50 tamps.

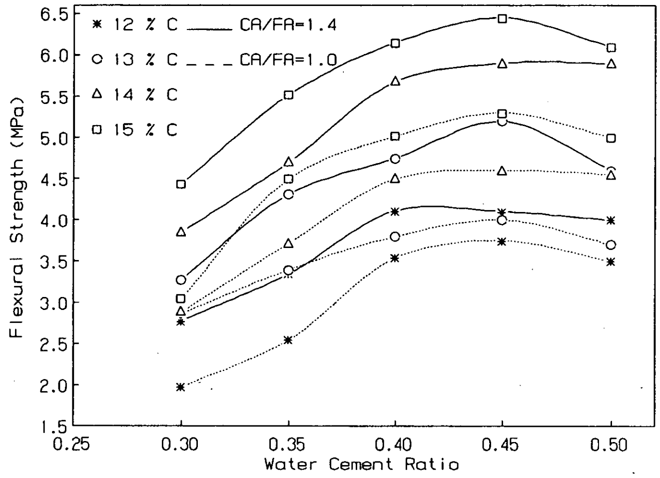

FIGURE 3 Relation between W/C ratio and flexural strength for a compaction effort of 100 tamps.

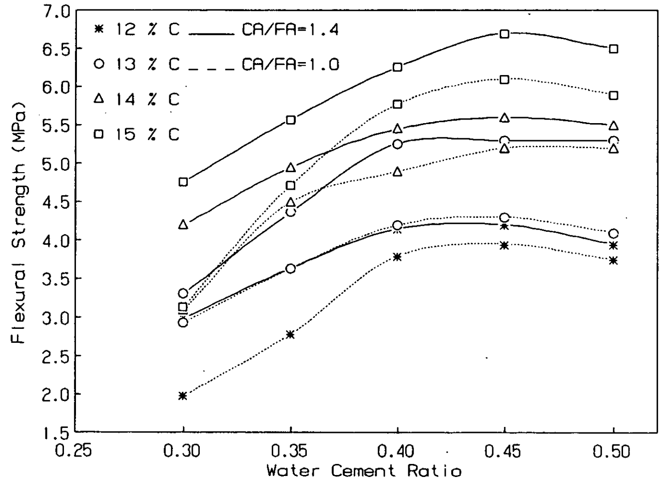

FIGURE 4 Relation between W/C ratio and flexural strength for a compaction effort of 150 tamps

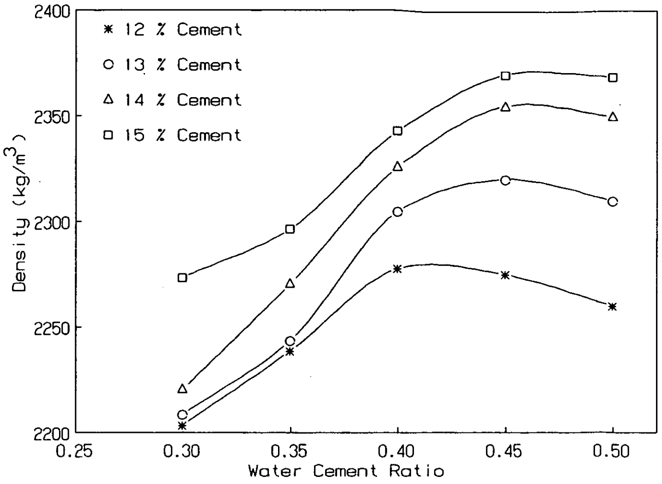

FIGURE 5 Relation between W/C ratio and density for a compaction effort of 50 tamps.

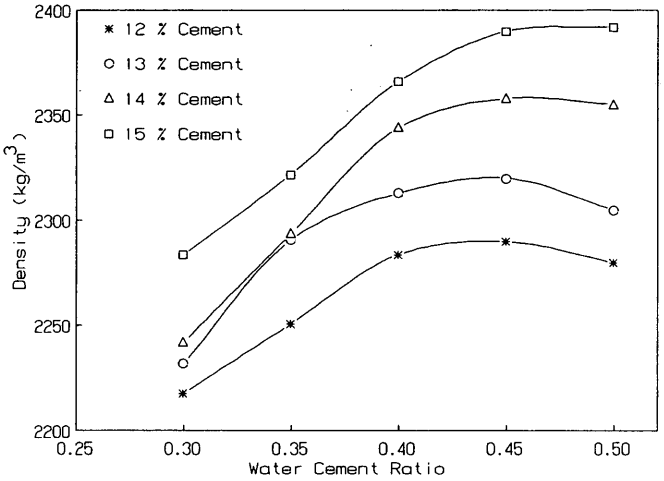

FIGURE 6 Relation between W/C ratio and density for a compaction effort of 100 tamps.

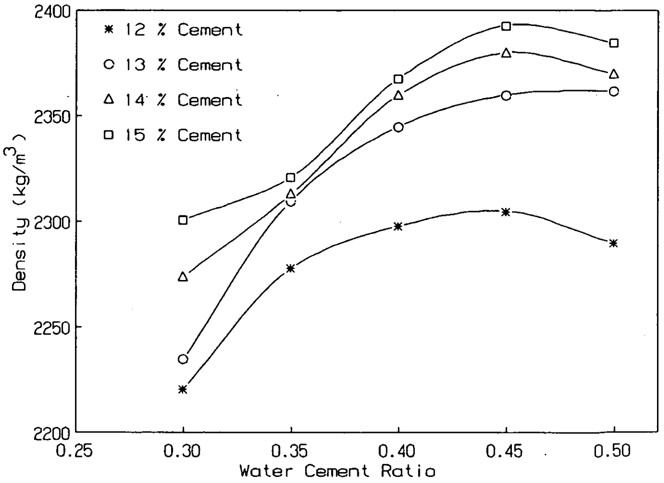

FIGURE 7 Relation between W/C ratio and density for a compaction effort of 150 tamps.

TABLE 4 Fitted Model Statistics

Stepwise Selection

Selection: Forward	Maximum steps: 500	F-to-enter: 4.00
Control: Manual	Step: 4	F-to-remove: 4.00

R-squared: .95785 Adjusted: .95638 MSE: 0.0531012 d.f.: 115

Variables in Model	Coeff.	F-Remove	Variables Not in Model	P. Corr.	F-Enter
1. TA/C	-1.18228	1160.8486			
2. W/C	1.81215	980.7224			
3. CA/FA	1.93613	338.8497			
4. TAMPS	0.00593	132.6122			

Model Fitting Results

Independent variable	coefficient	std. error	t-value	sig. level
CONSTANT	7.438022	0.256845	28.9592	0.0000
TA/C	-1.182281	0.0347	-34.0712	0.0000
W/C	1.812152	0.057866	31.3165	0.0000
CA/FA	1.936132	0.10518	18.4079	0.0000
TAMPS	0.005934	0.000515	11.5157	0.0000

R-SQ. (ADJ.) = 0.9564	SE = 0.230437	MAE = 0.185586	DurbWat = 1.297
Previously: 0.0000	0.000000	0.000000	0.000

120 observations fitted, forecast(s) computed for 0 missing val. of dep. var.

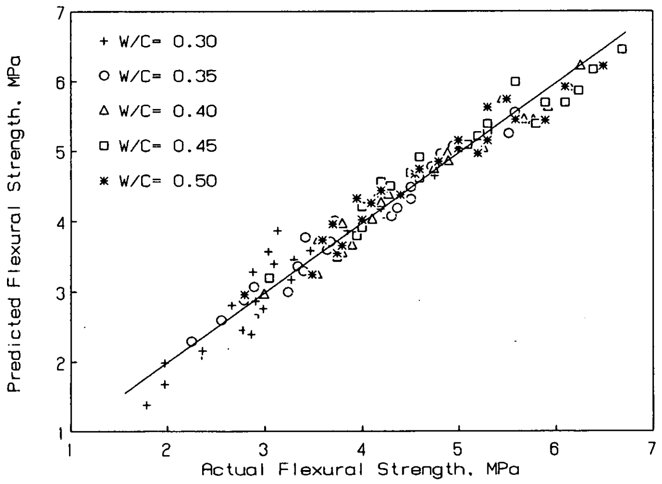

FIGURE 8 Comparison between predicted and actual flexural strength.

number of tamps, respectively. Stepwise analysis and model fitting results are shown in Table 4. The model is applicable to local materials and can be used for the ranges of all variables indicated in Table 2. Figure 8 shows the relation between measured flexural strength and the model predicted values and indicates that the predicted values are close to the measured ones.

CONCLUSIONS

- Chosen local aggregates meeting the requirements of ASTM C33 can be used for fabrication of quality RCCP.
- For the local aggregates, a W/C ratio ranging from 0.3 to 0.5 produces mixes with acceptable rollability.
- Because of its lower water content, the flexural strength RCC is about 37 percent higher than the flexural strength of normal concrete.
- Statistical analyses reveal that the effects of TA/C and CA/FA ratios on flexural strength and density are highly significant for all W/C ratios studied.
- Gain in strength between 100 and 150 tamps is not so significant to justify the effort.
- The model is descriptive of the strength data developed for these particular aggregates within the range of the experimental variables.

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