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Proportioning RCCP mixes under hot weather conditions for a specified tensile strength

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Abstract

The work presented in this paper introduces the use of roller-compacted concrete pavements (RCCPs) as a substitute to the traditional asphalt concrete pavements that suffer from severe rutting and cracking due to heavy loading and hot weather which prevail in most of the Middle East countries. A soil compaction method (Kneading compaction) was used in this research to simulate compaction in the field. The variables affecting the mix proportioning of RCCP in hot weather have been evaluated and discussed. The variables included in this research were cement content, aggregate-to-cement ratio, water-to-cement (W/C) ratio, and degree of compaction. The effects of these variables on the density, tensile, and compressive strengths have been studied. Various plots and tables showing the interrelations between the studied variables were included in the paper.

Results showed that under hot weather conditions, slight alterations in material proportions should be made to arrive at the required properties of RCCP mixes. A W/C ratio of 0.45 has been found to produce the optimum density and tensile strength for concrete in hot weather under the conditions of the experiments. One of the major findings was that the main factor that controlled most of the fresh and hardened properties is the cement content. Another important factor is that, unlike normal concrete, lowering the W/C ratio below an optimum value may not result in increase in the strength. Based on the results, simple relationships and equations have been obtained to predict the tensile strength of RCCP using the proportions of the mix. In addition, it has been found that a simple relationship, similar to the one presented in the ACI 325.10 state-of-the-art report, exists between the compressive and the tensile strength of concrete. The equation is presented in the simple form:

$$f_{ct} = \frac{2}{3}\sqrt{f_{cu}}$$

Based on the extensive study, the paper proposed a method of mix design that is suitable for RCCP in the Middle East. However, the method can be extended for other situations.

Keywords: Concrete; Mix design; Roller-compacted concrete

1. Introduction

Roller-compacted concrete (RCC) is that concrete which is laid and compacted by heavy equipment that are used in the road construction industry. It has been considered, probably, as the most important development in concrete dam technology in the past quarter century [1]. According to the ACI 325.10R, roller-compacted concrete pavement (RCCP) is defined as a relatively stiff mixture of aggregates, cementitious materials, and water, which is compacted by vibratory rollers. Such definition implies that concrete should be of extremely low consistency and workability [2]. The use of RCC for pavements is relatively a new technology and is still under development. However, early trials have proven the success of the use of RCCP, which encouraged engineers to apply it in various fields. Anderson [3] reported a form of RCC as early as the 1930s. The first application in North America was in 1942 when U.S. Army Corps of Engineers constructed a runway at Yakima, WA [2]. The first highly publicized RCCP was constructed in Canada

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in 1976 at the log-sorting yard at Caycuse on Vancouver Island, British Columbia by the British Colombia Forest Company (BCFP), where 4 acres of RCCP were constructed and then was doubled in the 1978 expansion [4]. Following this success, several projects utilizing RCCP were constructed in America, Spain, Australia, and elsewhere [2,4–8].

Asphalt and rigid pavements in some highways and expressways in the Middle East region have suffered extensive pavement problems characterized by severe wheel path rutting and corrosion of steel reinforcement, which was attributed to [9–13]:

(a) the increase in the number of heavily loaded trucks using the road network,
(b) the prevailing very high ambient temperatures, and
(c) the highly corrosive environment and the geomorphic factors along the seaboards.

Due to the previous problems, RCCP is thought to be an alternative to the traditional pavements. This thought was encouraged by the good performance of RCC and RCCP in different environments [1–8]. It has been shown that RCCP will have the following advantages when compared with traditional pavements [1–15]:

(a) Compared with traditional Portland cement concrete (PCC):
1. It has a flexural strength equivalent to that of PCC.
2. Reduced time of construction.
3. Easy construction.
4. Reduce construction and maintenance costs.

(b) Compared with asphalt concrete:
1. About 25% higher flexural strength than central-mixed cement-treated bases (CTB).
2. High resistance for abrasion.
3. It does not need a protective layer; however, a protective layer can be used in future after possible deterioration of the wearing surface.
4. Higher resistance to fuel and hydraulic spills.
5. Better resistance for high temperatures.
6. Can reduce up to one third of construction and maintenance costs.

According to the ACI 305R [16], hot weather is defined as the combination of many conditions that tend to impair the quality of freshly mixed or hardened concrete by accelerating the rate of moisture loss and rate of cement hydration. These conditions are (1) high ambient temperature, (2) high concrete temperature, (3) low relative humidity, (4) high wind velocity, and (5) solar radiation. All the previous factors are available in most of the Middle East countries, and hence, concrete suffers during its lifetime. As an example of the severity of the problem, Fig. 1a and b shows the prevailing temperature and humidity in Kuwait, which is one of the Middle East countries [17]. It is quite clear from the plot that during summer, high temperatures are always accompanied by very low humidity. Under such conditions, it is expected that any concrete constructed in hot weather, including RCCP, requires special attention and mix proportioning before being used. The problem becomes more difficult when local materials are used, because many of these materials are not "specificationally perfect" when compared with international specifications and standards. As no special mix proportioning of the concrete for RCCP in hot weather is available, the authors in this paper tried to produce special guidelines that aimed at finding the optimum mix proportioning of RCCP under hot weather conditions using local materials.

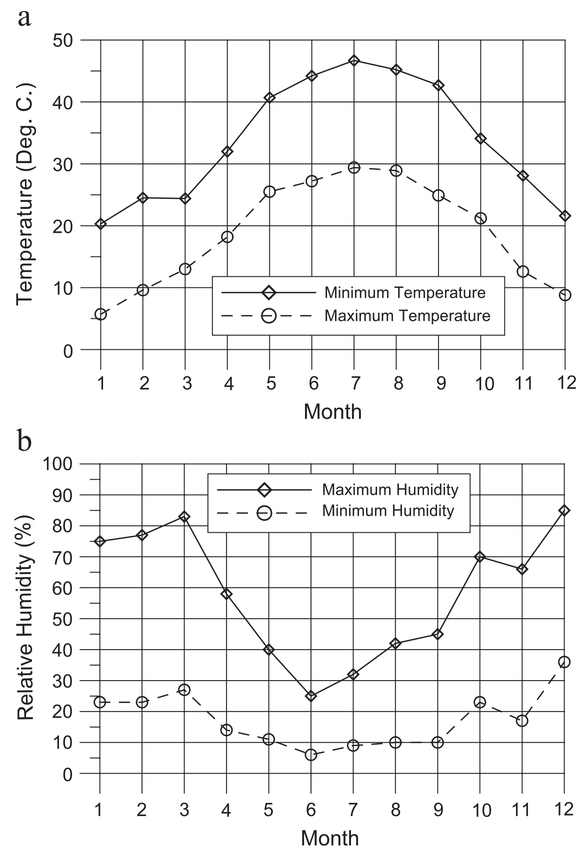

Fig. 1. (a) Monthly distribution of air temperature in Kuwait. (b) Monthly distribution of humidity in Kuwait.

2. Materials

The materials that are generally used in RCCP mixes are as follows:

2.1. Cementitious materials

RCCP mixes contain Portland cement of any type as the main cementitious material depending on the environment and the prevailing conditions in the site [2]. However, blended hydraulic cements and cements containing pozzolans or granulated blast furnace slags can also be used. Previous practice [2] showed that most RCCP made to date have been constructed using Type I or Type II Portland cement and Class F or Class C fly ash. However, the use of sulfate-resisting Portland cement alone can be used if the base soil contains high amounts of sulfates as the case in the Gulf region [13].

Past experience showed that cement content, not its type, played the major role in deciding the proportions needed in the mixture. A cement content of about 10–16% is usually expected in the mixes [2]. However, the usual ratio of the weight of the cementitious material to the total weight of aggregate should be in the range of 12–14% [14]. Moreover, in certain conditions where high-quality concrete is required, this value may reach 19% [10]. Virtually, such amount approaches the amount required for normal concrete and hence will end with uneconomic design. Furthermore, the cement content can be reduced to 6–8% for the bottom lift of a multiple-lift construction. In this study, the aim was to obtain the appropriate mix proportioning for RCCP that will be constructed in one lift under hot weather conditions.

In practice, fly ash contents in the range of 15–20% of the total volume of cementitious material are usually used [3,4,6]. Furthermore, RCCP mixtures can be made without the use of pozzolans [2,3,13]. Due to the fact that higher cement contents may result in temperature problems in hot weather due to the higher heat of hydration expected to evolve during concreting, in this study, the amount of cement was restricted to 12–15% and no pozzolan was used in the mixes. In addition, lower values of cement contents may result in durability problems especially in the environment of the Middle East.

2.2. Water and water-to-cement ratio

As with traditional concrete, drinking water is recommended for RCCP. However, for normal concrete, seawater can be used in special cases if concrete is not reinforced or there are no durability problems [18].

In RCCP mixes, the used water content should result in concrete of very low consistency (zero-slump concrete). Therefore, as outlined in ASTM D558 [19], it is quite suitable to treat RCCP mixes as soil cement rather than concrete and thus establish a relationship between the moisture content of the mix and its density for an applied compactive effort. ACI 325.10 state-of-the-art report supports this recommendation [2]. The authors used the Kneading compaction method in this study to simulate the effect of roller compactors that are usually used in compacting RCCP mixes.

In RCCP mixes, Abrams and Jacksha [8] suggested a water-to-cement (W/C) ratio in the range of 0.30–0.40. However, this ratio, which might suit cold and normal weather, was found to be narrow in hot weather [13]. Therefore, a range of 0.30–0.50 was selected and used in this study. Experiments by Al-Abul Wahhab et al. [13] reinforced this choice.

2.3. Aggregates

The aggregates comprise approximately 75–85% of the volume of an RCCP mixture and therefore have a significant effect both on fresh and hardened concrete [1,3]. Therefore, the used aggregate should have the following basic properties:

1. Aggregates should have good mechanical properties (strength, elasticity, abrasion resistance, etc.) to withstand the heavy machinery during construction and after hardening.
2. Aggregates should have good physical properties. In hot weather, the thermal properties become more important.
3. As with normal concrete, aggregates should be free of harmful substances or ingredients. ASTM aggregate testing methods and specifications, such as ASTM C33 [20], can be used in this respect. However, aggregates that do not meet certain specification can still be used provided that the design criteria are met.
4. Grading of aggregates plays a major role in determining the properties of both fresh and hardened concrete. Special gradation limits have been suggested by ACI 325.10R. The grading limits can be met by careful choice of coarse aggregate-to-fine aggregate (CA/FA) ratio. Furthermore, the use of aggregate fractions finer than 75 μm (# 200 sieve), if nonplastic, may be beneficial to reduce fine aggregate voids.

Based on the fact that RCCP concrete has low water content and hence may segregate, nominal maximum size of aggregate is limited to 22 mm (7/8 in.). In addition, it is recommended that crushed aggregate forms two thirds of the total aggregates [7]. However, ACI 325.10 report does not support the two-third recommendation and states that any good quality type of aggregates (natural, crushed, or any combination) can be successfully used in RCCP mixes; however, better quality can be attained using crushed aggregate. To attain good quality of the mixes, the authors incorporated the recommendation of Jofre et al. [7] and ACI [2] and made sure that at least two thirds of the used aggregate were crushed aggregate.

In addition, to reduce segregation possibility, RCCP concrete mixtures should contain higher amounts of fines when compared with normal concrete. ACI 325.10 [2] report limited the nominal maximum size of aggregate to 20 mm (3/4 in.). Therefore, in this research, the nominal maximum size of aggregate was limited to the standard size of 20 mm.

3. Experimental program

The experimental program has been designed to fulfill the following points:

1. take into account the interrelations between the various variables affecting mix design,
2. obtain the variable, or variables, that optimally control(s) the fresh and hardened properties of the finished RCC concrete for pavements, namely, rollability, density and strength, and,
3. obtain values that are statistically acceptable.

To fulfill the previous points, the following has been considered:

1. Because ACI 325.10 suggests two methods of mix proportioning for RCCP mixes, either by using the consistency tests or by using soil compaction methods, it has been decided to use the latter one in this study.
2. Based on previous discussion about used cementitious materials, it has been decided to use cement with no pozzolans. However, pozzolans will be introduced in the mix in a future research.
3. Aggregates that follow international standards were used. In this respect, special attention has been given to ASTM C33 [20] and requirements of the ACI 207.5R.
4. Based on previous studies [6,13,14], it has been decided that the principal factors controlling the quality of concrete are the W/C ratio, the total aggregate-to-cement ratio (TA/C), the CA/FA ratio, the cement content, and degree of compaction (rollability). To cover the possible practical ranges of the various variables, the following has been adopted in the study:
   (a) Cement contents 12–15% have been introduced. This value corresponds to about 250–315 kg/m^3 of concrete.
   (b) Five levels of W/C ratios (0.30, 0.35, 0.40, 0.45, and 0.50) have been incorporated in the study.
   (c) Four levels of TA/C ratios (5.40, 5.8, 6.4, and 7.0) have been incorporated.
   (d) Two levels of CA/FA (1.0 and 1.40) have been used.
   (e) Three compactive efforts have been incorporated, as will be discussed later.
   (f) A nominal maximum size of aggregate of 20 mm has been used.
5. For the sake of obtaining significant and reliable results, a factorial experiment was designed to explore the effect of the variables on rollability, density, and strength.

The first step of design started by testing both the coarse and fine aggregates according to ASTM standard test methods, then comparing the results with ASTM C33 [20]. The test results, as well as the ASTM C33 requirements, are shown in Table 1. The aggregate grading, as well as ACI 325.10R and the Canadian suggested limits are shown in Fig. 2. Fig. 2 shows that although the used aggregate falls a little bit outside the ACI 325.10 suggested limits, it falls within the Canadian limits [13]. The results shown in Table 1 and Fig. 2 indicate that the aggregate is of good quality and can be used for RCCP.

The samples were prepared and mixed using a Hobart mixer having a capacity of 0.012 m^3. The Ronny Anderson method [3,5] was used to measure rollability (ability to roll or compact the zero-slump concrete with reasonable effort whilst maintaining its homogeneity without segregation). Of course, all the factors mentioned before affect the rollability of the mixes. It is a fact in RCC that very dry mixes are difficult to roll in the field and mixes with higher degrees of workability cannot sustain the load in the site.

There is no standardized method to prepare test specimens for RCC. In addition, conventional concrete specimen fabrication procedures, such as those standardized by ASTM, cannot be used to fabricate RCCP test specimens due to the stiff consistency [2,5,13]. Therefore, it has been decided to use the California Kneading Compactor to compact the test specimens. The Kneading compactor was calibrated to attain the suitable pressure for achieving the highest density with minimal degradation; this pres-

Table 1
Properties of the used aggregate

Aggregate type	Property	Test results	ASTM limit	ASTM test
Coarse	Grading	3/4 in. maximum size grading specified in literature	–	C 136
		Bulk specific gravity (oven dry basis) = 2.613	–	
	Specific gravity	Bulk specific gravity o(SSD basis) = 2.646	–	C 127
		Apparent specific gravity = 2.702	–	
	Absorption	24 h = 1.26%	–	C 127
	Abrasion loss	23.25%	40%	C 131
	Presence of clay lumps and friable particles	0.74%	3% to 10%	C 142
	Soundness	0.58%	12%	C 88
Fine	Grading	Fine modulus = 1.46	2.3–3.1	C 136
		Bulk specific gravity (oven dry basis) = 2.614	–	
	Specific gravity	Bulk specific gravity o(SSD basis) = 2.634	–	C 128
		Apparent specific gravity = 2.667	–	
	Absorption	24 h = 0.77%	–	C 128
	Presence of clay lumps and friable particles	#8 = 0.45% and #16 = 0.18%	3%	C 142
	Soundness	1.38%	10%	C 88

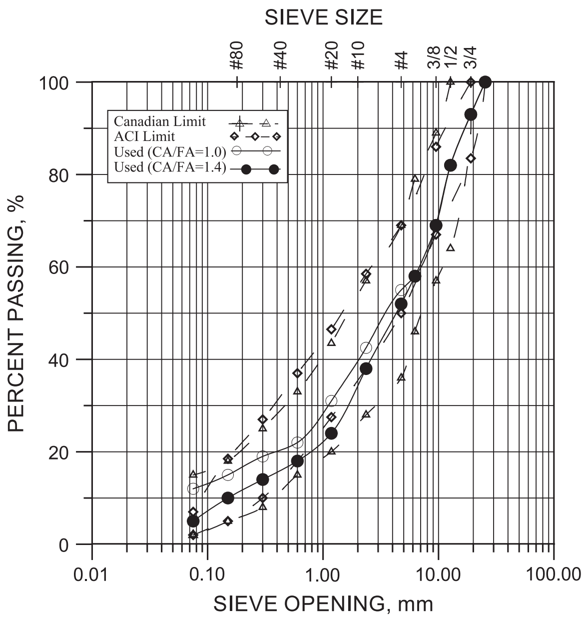

Fig. 2. Grain size distribution of the used materials.

sure was found to be 1.55 MPa (225 psi). This value has been adopted for compacting all specimens in the study.

Beams of size 400 × 100 × 100 mm (16 × 4 × 4 in.) were cast for each RCCP mix. These beams were subjected to three compactive efforts corresponding to 50, 100, and 150 tamps at the specified foot pressure of 1.55 MPa. Initial consolidation was attained by subjecting the samples to a static load of 620 kPa (90 psi) before placing the molds in the Kneading compactor. The static load did not only constitute the initial compaction but also was considered important for obtaining a relatively flat-finished beam surface. The specimens were then covered with wet burlap for 24 h before transferring them to a water bath, where they were kept under standard conditions as per ASTM C192 [21]. Specimens were kept for 28 days and then tested for flexural strength according to ASTM C 683 [22]. Furthermore, 100 × 100 × 100 mm cubes were sawed from the beams and then tested for compressive strength at the same age.

4. Results and discussion

To study the interrelation of the variables, tensile strength was plotted against W/C ratio as shown in Fig. 3. Fig. 3 is plotted for a cement content of 14%. Similar plots to Fig. 3 have been drawn for the other used cement contents. From the plots, the following observations can be obtained:

1. Tensile strength increased with the increase in W/C ratio until it reached an optimum value at W/C ratio of about 0.45 then it started decreasing. It is well known [18] that strength of normal concrete reduces when W/C ratio increases. However, this was not true for RCCP. In all the tested samples, this was only applicable when W/C ratio exceeded 0.45. Therefore, it was concluded that when the water contents were low, it was difficult to produce full compaction of the mix. Previous studies [23] showed that insufficient compaction of stiff concrete resulted in large amounts of entrapped air and hence severe reduction in the strength was observed.
2. Irrespective of all the studied variables, W/C ratio of 0.45 always produced the optimum tensile strength. This led to the conclusion that the use of other values would not lead to the optimal mix. To support this conclusion, further analysis has been performed, as will be shown later.
3. The cement content (%) was the major factor influencing the tensile strength.
4. For the same W/C ratio, the flexural strength increased with the increase in the CA/FA ratio.

Based on finding number (3), plots similar to Fig. 4 were generated to depict the effect of cement content on the tensile strength. Statistical analysis of the results showed that simple linear relationships existed between tensile strength and cement content, and the tensile strength can be expressed in the following form:

$$\text{Tensile Strength } (f_t) = A \times \text{Cement Content } (\%) + B \quad (1)$$

where A and B are regression constants.

The coefficients of determination (R^2) values for the different mixes are shown in Table 2. It is clear from the

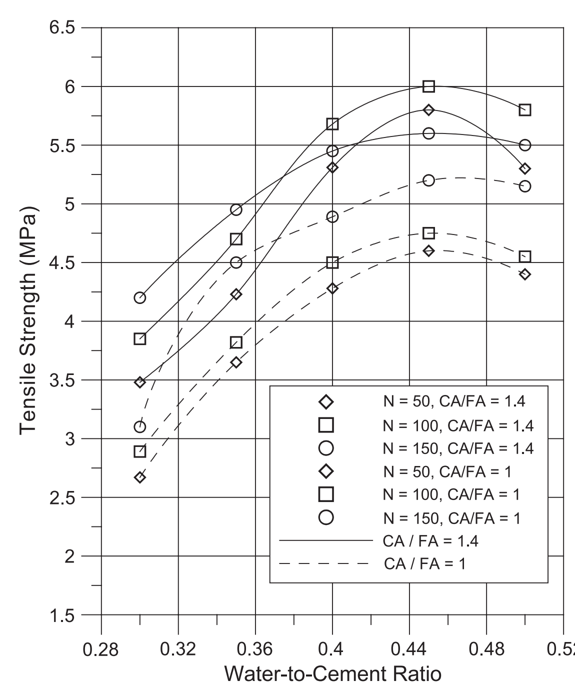

Fig. 3. Variation of tensile strength with W/C ratio for RCCP mixes having cement content of 14%.

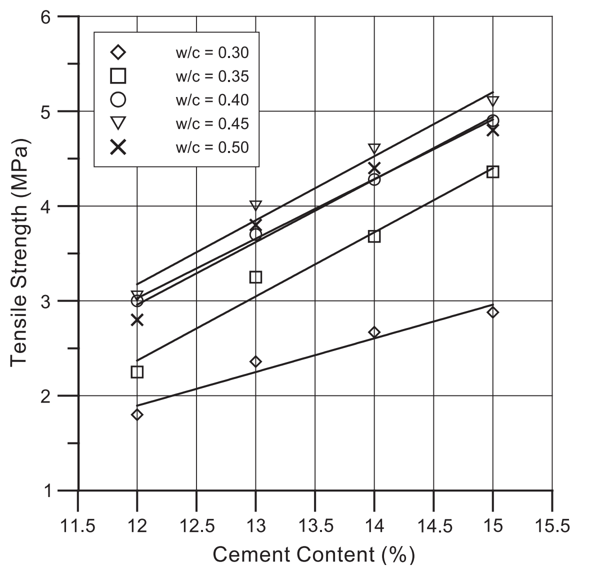

Fig. 4. Relationship between cement content and tensile strength for $N=50$ and CA/FA = 1.

table that, except for two cases, at a W/C ratio of 0.30, linearity between the variables is dominant.

Statistical analysis of the variables have been carried out and showed that the tensile strength of RCCP can significantly and reliably be predicted using the following relationship [13]:

$$f_t = 7.44 - 1.18\ (\mathrm{TA/C}) + 1.81 \times \sin\left[\left(\frac{\mathrm{W/C} - 0.30}{0.15}\right) \times \frac{\pi}{2}\right] + 1.94(\mathrm{CA/FA}) + 0.0059\ \mathrm{N} \quad (2)$$

The coefficient of determination for this model was found to be 95%.

Simple partial differentiation of the previous equation with respect to W/C and equating it to zero shows that the optimum value is obtained when W/C = 0.45. This finding is consistent with the previous presented results and with all the plots. Therefore, it is recommended to use W/C ratio of 0.45 in RCCP mixes in hot weather provided that the material grading is within the limits shown in Fig. 2

Table 2
Coefficient of determination (R^2) values of the best-fit lines in Fig. 4

W/C ratio	R^2					
	CA/FA = 1.0			CA/FA = 1.4		
	$N=50$	$N=100$	$N=150$	$N=50$	$N=100$	$N=150$
W/C = 0.30	.9918	.9986	.9722	.9520	.7390	.7384
W/C = 0.35	.9930	.9775	.9978	.9747	.9743	.9484
W/C = 0.40	.9524	.9860	.9376	.9985	.9739	.9733
W/C = 0.45	.9705	.9744	.9596	.9770	.9625	.9675
W/C = 0.50	.9891	.9346	0.9331	.9595	.9529	.9672

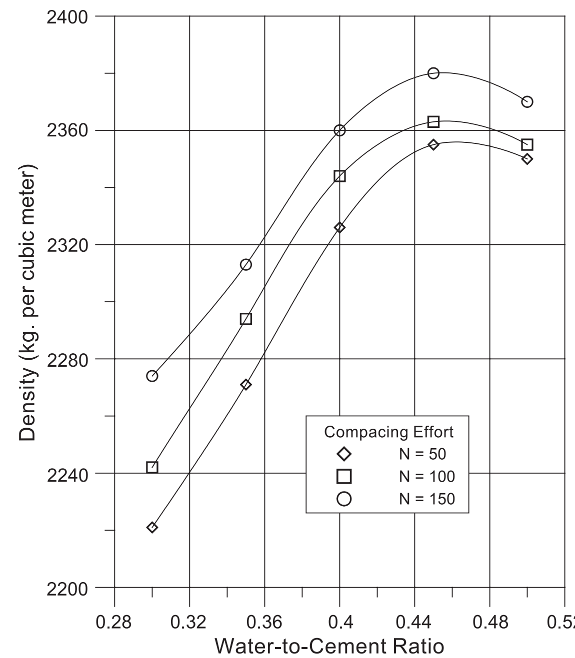

Fig. 5. Variation of density with W/C ratio for RCCP mixes having cement content of 14%.

and that the CA/FA, the TA/C, and cement content values are within the used ranges in this research.

Fig. 5 shows the relationship between W/C ratio and density for cement content of 14%. Again, the optimum density was obtained at W/C ratio of 0.45 irrespective of the other variables.

Furthermore, the strength-to-density ratio was calculated and plotted in Fig. 6 for cement content of 14%. The highest

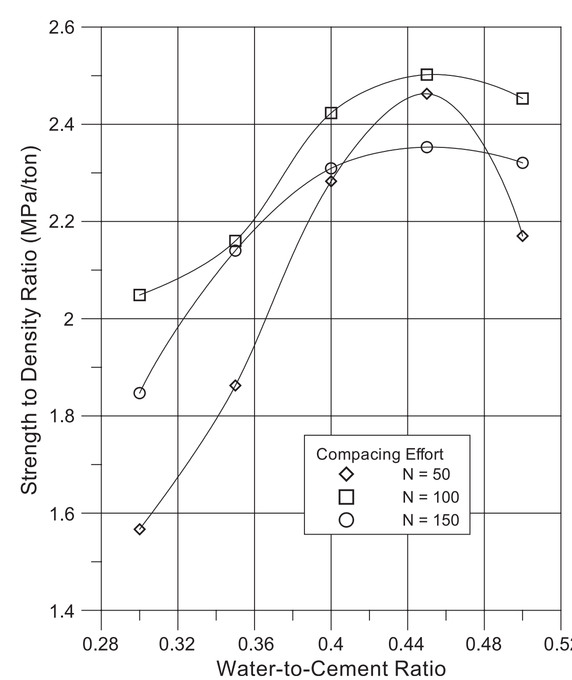

Fig. 6. Variation of strength-to-density ratio with W/C ratio for RCCP mixes having 14% cement content and CA/FA = 1.4.

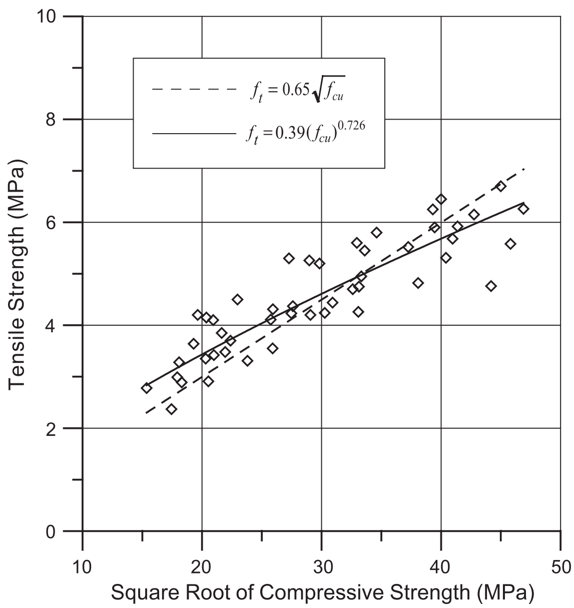

Fig. 7. Relationship between the tensile strength and the compressive strength for RCCP samples.

values were obtained for W/C ratio of about 0.45, which supported the conclusion that the optimum density and strength were obtained at W/C ratio of 0.45 irrespective of the other variables.

It has been considered an acceptable practice, for normal concrete, to relate the tensile strength of concrete (f_t) to its compressive strength (f_c). A number of empirical formulas relating f_t and f_c have been suggested. Many of these formulas are of the type represented in the following format: [18,24–30].

$$f_t = C(f_c)^n \tag{3}$$

where C is a constant and n is a constant representing the power of the equation. In literature, reported n values ranged between 1/2 and 3/4 [18,24–30].

ACI 325.10 [2] suggested a similar relationship for RCCP mixes in the form:

$$f_t = 0.75 \text{ to } 0.82\sqrt{f_c} \tag{4}$$

where f_c is the cylindrical strength of concrete in MPa.

To obtain the relationship for prepared RCCP mixes, the tensile strength of the tested beams were plotted against the compressive strength as shown in Fig. 7. The following simple relationship was obtained:

$$f_t = 0.65\sqrt{f_{cu}} \tag{5}$$

where f_{cu} is cube compressive strength of concrete.

The R^2 of this model was found to be .977. Comparing the used constant value (0.65) with that suggested by ACI, and assuming that the cylinder strength is about 0.80 of the cube strength, it can be concluded that the obtained constant value is slightly lower than the value suggested by the ACI (0.67–0.73) if f_c is the cube strength. However, a better estimate of the tensile strength can be obtained when the equation is put in the form:

$$f_t = 0.39(f_{cu})^{0.726} \tag{6}$$

Eq. (5) is considered much easier to use and memorize by practicing engineers (simply, two-thirds square-root of the strength).

5. Steps of mix design

The following paragraph summarizes the steps that can be followed in order to arrive to an estimate of the proportions of an RCCP mix for a specified tensile strength:

5.1. Step 1: Determine the target design strength (f_{design})

The well-known relationship design strength = characterestic strength + margin can be applied to determine the design strength of RCCP. In mathematical terms, the relationship can be written as follows:

$$f_{design} = f_{char} + ks \tag{7}$$

where f_{design} = design strength of concrete (MPa), f_{char} = characteristic strength of concrete (MPa), s = standard deviation, and, k = a statistical constant, which depends on the percentage defective of the tested samples and on the importance of the constructed road. It also depends on the previous knowledge and experience, if available. However, if such knowledge is not available, the authors suggest the values given in Table 3 according to the road type. Furthermore, engineers can assign other values for the factor k if their experience in their regions requires modification of this value.

To obtain a representative value for the standard deviation, the tensile strength was plotted against the standard deviation of the tested samples, as shown in Fig. 8a. No distinct relationship between the two variables was obtained. This finding was similar to that obtained by Lane [31] for normal concrete. However, when the tensile strength is plotted against the ratio of the standard deviation to the measured strength, a boundary can be

Table 3
Statistical constant (k) for Eq. (7)

Type of road	Percentage defective	k
Main highways, express roads, and heavily loaded roads	5	1.65
Roads of medium use and loads	10	1.28
Secondary and rural roads	15	1.04

observed, as shown in Fig. 8b. The value obtained from this boundary can be used to obtain the standard deviation if no previous data is available.

5.2. Step 2: Determine the required W/C ratio

The suitable W/C ratio is the one that would result in the optimum strength and in the optimum density. Under the conditions of the experiment, this value has been found to be 0.45. In addition, this value is suitable for durability requirements as outlined in ACI 211.1 [32]. Therefore, it is recommended to start with this value under hot weather conditions.

5.3. Step 3: Determine the required cement content and the CA/FA ratio

Fig. 9 shows the relationship between the cement content and the tensile strength of concrete for different degrees of compaction. It is quite clear that the engineer can choose among different alternatives. The best choice is the one that would probably attain the required strength with the minimum cost. Two major factors control the economy of the mix design: the cement content and the compaction effort. Of course, mixes that cannot withstand the minimum compactive effort are rejected. From Fig. 9, the cement content can be determined for two possible CA/FA ratios for each degree of compaction. The conditions of the site and the cost and availability of coarse and fine aggregates would guide the engineer for the best possible choice or choices. It is advisable that more than one choice be tried if any doubt exists about effectiveness of a certain choice. Note that when CA/FA is 1.4, practically no benefit is obtained by increasing the compactive effort from 100 to 150 blows. It is worth pointing out that every 1% cement content corresponds to a cement weight of about 21 kg/m^3 of concrete [2]. Hence, an approximate estimate of the weight of cement can be obtained.

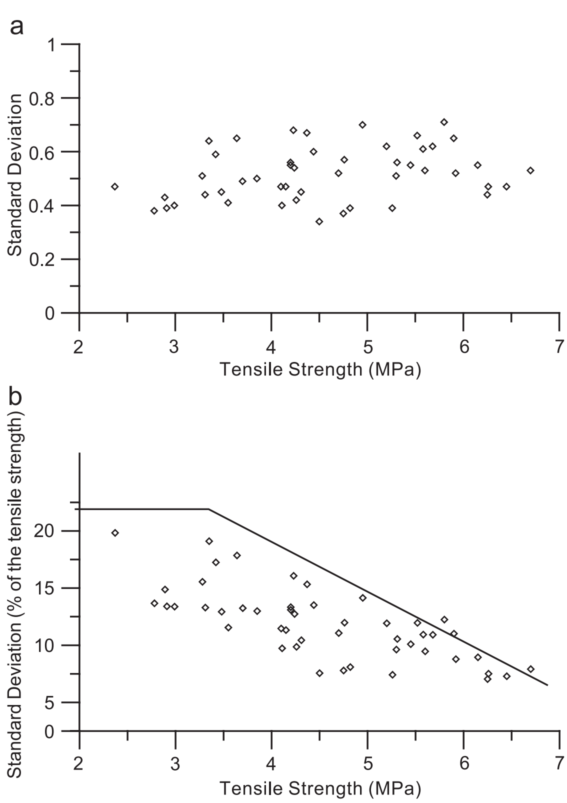

Fig. 8. (a) Relationship between tensile strength and standard deviation. (b) Relationship between tensile strength and ratio of standard deviation to the tensile strength.

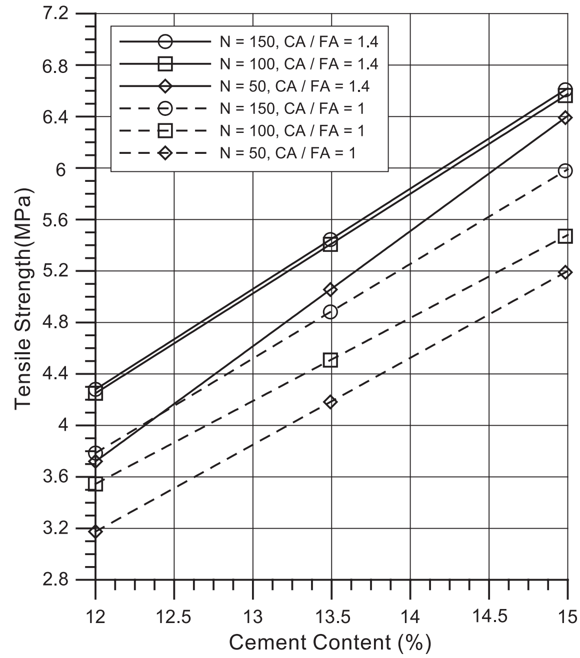

Fig. 9. Relationship between cement content and tensile strength for W/C = 0.45.

If the compressive strength is specified instead of the tensile strength, then an estimate of the tensile strength can be obtained using Eq. (5).

From the same plot (Fig. 9), the engineer can decide on the value of CA/FA and the compactive effort.

5.4. Step 4: Estimate of the water content

Once the cement content has been determined from Step 3, then the water content can be calculated using the relationship:

water content = cement content times water-to-cement ratio

The W/C ratio is taken as 0.45, as was shown in Step 2.

5.5. Step 5: Estimate the density of RCCP

The density of RCCP can be estimated using Fig. 10. The figure shows the relationship between the cement

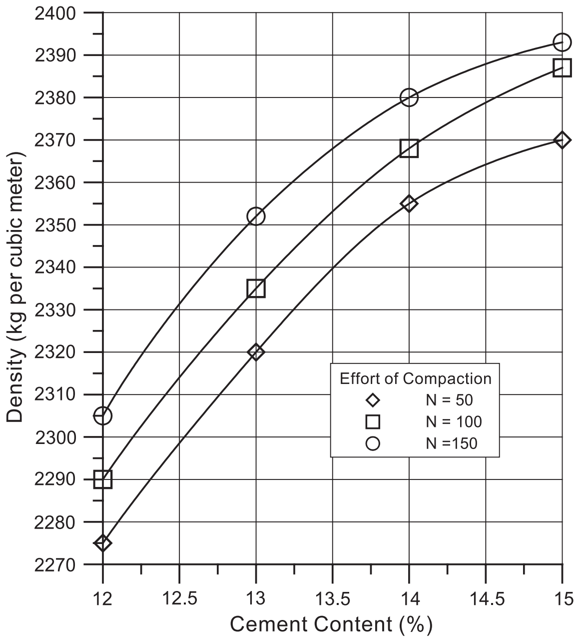

Fig. 10. Relationship between cement content and density of RCCP.

content and the optimum density of all the mixes prepared using W/C ratio of 0.45. The estimated density can be easily obtained by entering the plot with the cement content obtained from Step 3.

5.6. Step 6: Estimate of coarse and fine aggregate contents

The total aggregate content can be obtained using the simple relationship: Density of Concrete = Summation of all ingredients, expressed as the weights per cubic meter of finished concrete. Hence, the amount of the total aggregate will be the density obtained from Step 5 minus the sum of the cement content obtained from Step 3 and the water content obtained from Step 4.

Once the total aggregate is obtained, both the fine and coarse aggregate contents can be calculated using the ratio obtained from Step 3.

5.7. Step 7: Trial mixes

When all the ingredients have been determined, special mixes should be prepared and tested for the required properties. From experimental trials carried by the authors, it is advisable to start with three mixes, the first one contains the cement content obtained from the previous steps, and two other mixes with cement contents ± 0.5 from the selected percentage. In all the three mixes, the water should be added gradually to attain the required rollability. In addition, the three mixes should be prepared and tested for fresh density. The mix that satisfies rollability and optimum density should be selected for further trials. The yield and proportions should be adjusted in the same way as for normal concrete. ACI 211.1 [32] is considered quite suitable in this respect.

6. Conclusions and recommendations

In view of the research results, the following conclusions and recommendations can be obtained:

1. Slightly higher water contents and hence W/C ratios are required for RCCP mixes in hot weather when compared to those in normal and cold weathers. A W/C ratio of 0.40–0.50 seems to be more suitable in hot weather than the common 0.30–0.40 in normal and cold weather.
2. RCCP mixes can be successfully proportioned using a soil compaction method. In this respect, the optimum density is considered the objective of the mix design.
3. Both the optimum density and the optimum tensile strength were obtained when the W/C ratio is 0.45. In addition, the strength to density ratio was the highest for this W/C ratio.
4. A simple estimate of the tensile strength of concrete can be obtained when the proportions of the mix are known (Eq. (2)).
5. Simple linear relationships exist between the cement content and the tensile strength as shown in Fig. 4 and Eq. (2).
6. For high ratios of CA/FA, no increase in density is expected beyond a compaction effort of 100 tamps.
7. Both coarse and fine aggregates should be carefully chosen and proportioned to meet the necessary properties and grading. The use of standard specifications and international experience is quite suitable in that respect.
8. A simple relationship between the compressive strength of concrete and its tensile strength can be obtained and used for RCCP. The equation is, somewhat, similar to the one shown in ACI 325.10 state-of-the-art report. However, the strength was slightly lower than the estimated value from the ACI report.
9. RCCP can be used in hot weather to replace traditional pavements in certain conditions where wheel track rutting is expected.
10. Unlike normal concrete, lowering the W/C ratio below the optimum would not result in increase in the strength of concrete.
11. The cement content plays the major rule in controlling the properties of fresh and hardened concrete.
12. The proposed method of RCCP mix design in this research is restricted to the conditions of the experiment (C, cement content, is 12–15%; CA/FA 1–1.4; TA/C = 5.4–7). In addition, the materials should be, somehow, similar to those presented in this paper. Therefore, the method can be recommended, generally, in the Middle East and particularly in the Gulf region.

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