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Laboratory Investigation on the Fresh, Mechanical, and Durability Properties of Roller Compacted Concrete Pavement Containing Reclaimed Asphalt Pavement Aggregates

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Abstract

The present study evaluates the potential and suitability of different fractions of reclaimed asphalt pavement (RAP) for roller compacted concrete pavement (RCCP) mixes. Natural coarse and fine aggregates were replaced, partially and in combination, by coarse RAP, fine RAP, and combined RAP for preparation of RCCP mixes. The considered properties to determine the optimum RAP fraction and its proportion for RCCP were fresh density and water demand, compressive strength, flexural strength, split tensile strength, porosity, water absorption, abrasion resistance, and performance in aggressive environments of chloride- and sulfate-rich ions. It was observed that inclusions of all the fractions of RAP considered could reduce the strength related properties of RCCP mixes significantly at all curing ages. However, fine RAP mixes were found to exhibit better strength properties than coarse RAP and combined RAP mixes. It was also observed that none of the RAP mixes could achieve the recommended compressive strength criterion of 27.6 MPa, however, they exhibited enough flexural strength to replace a fraction of conventional aggregates, individually or in combination, for construction using RCCP. In fact, 50% coarse and 50% fine RAP mixes had higher flexural strength than the target laboratory mean strength of 4.3 MPa. Similarly, these mixes were found to have sufficient abrasion resistance and could be included in RCCP (surface course) to be constructed in areas having high concentrations of chloride and sulfate ions. Additionally, the results also indicated that higher proportions of fine RAP may be suggested for RCCP mixes to be laid in sulfatic environments.

Roller compacted concrete pavement (RCCP or RCC pavement) is a zero-slump concrete mixture placed with asphalt pavers and compacted using drum/rubber-tired vibratory rollers (*1–8*). Over the years, RCCP has been widely used for low structural applications such as for parking lots, ports, military facilities, highway shoulders, and base course layer of pavements (*1, 2, 5*). However, with recent advances in the field of pavement engineering, its low cement requirement, and relatively rapid construction compared with other traditional concrete mixes, RCCP is now being popularly used as a surface course layer provided with a thin bituminous coating of 50 mm (1.96 in.) thickness (to ensure a good riding surface) for different highway applications (*1*). The recommended compressive strength for RCCP mixes to be used as a surface course layer of pavements is 27.6 MPa [4003.04 pounds per square inch (psi)] as specified by the American Concrete Institute (ACI) (*1*). With proper mixture proportioning (well-graded aggregates and adequate quantities of cement and water) followed by dense compaction, RCCP mixes have been observed to achieve strength properties comparable to those of conventional concrete mixes (*1, 4, 5*).

In the last few decades, because of rapid urbanization, sustainability has become the most important criterion for all civil engineering applications. Several countries have imposed a ban on quarrying activities causing

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disturbance to the natural topography. This condition has compelled highway authorities to look for alternative sources of aggregates which are not only reliable, economical, and eco-friendly but also abundantly available (*9–13*). One such abundantly available recycled aggregate is reclaimed asphalt pavement (RAP) (*14, 15*). RAP is the milled/demolished material from an existing bituminous pavement, removed for various maintenance and rehabilitation activities (*10, 12, 16–19*). In the United States alone, in 2015 more than 85.1 million tons of RAP is reported to have remained unused even after its effective utilization for different bituminous pavement applications (*10*). A similar or even higher percentage of unused RAP may be assumed in India, since the road densities of both the countries are nearly equal and there is lack of confidence among Indian engineers to utilize RAP even for lower layers of pavement.

Utilization of RAP for cement concrete pavements has several pros and cons. Advantages generally associated with RAP include the elimination of RAP disposal problems, reduction in greenhouse gas emissions, less consumption of natural aggregates, and lower transportation costs (*10–12*). However, the main hurdle observed by highway agencies to enact the use of RAP for cement concrete pavements is the lack and unavailability of proper documentation and codal provisions (*11*). Another obstacle faced in using RAP for cement concrete pavements is the formation of a weak interfacial transition zone (ITZ) between the RAP surface and cementitious mortar matrix (*9–13, 20–25*). In addition to asphalt coating, agglomerated particles in RAP have also been reported to reduce the strength properties by as much as 70% compared with the control mix (*22, 26*). Most authors have recommended utilizing only the coarser fraction of RAP up to a proportion of 50%, and have recommended against including any proportion of fine RAP for cement concrete mixes (*9, 11, 12, 21, 25, 27, 28*). This is because of the coarseness and gap-graded nature of fine RAP aggregates (*12*). On the other hand, only a handful of studies pertaining to RAP-inclusive RCCP mixes are available to date. Like cement concrete pavements, incorporation of RAP for the production of RCC pavements is also restricted to a proportion of 50% (*7, 29*). Since RAP aggregates have a lower specific gravity and density, their inclusion in RCCP mixes considerably reduces the compactness and density of fresh mixes, which in turn has a great negative effect on the hardened properties (*7*). All the above-mentioned factors (asphalt, agglomerated particles, weak ITZ, lower specific gravity and density) greatly contribute to reducing the potential of RAP for use in RCCP mixes.

Apart from the mechanical properties of cement concrete pavements, concrete durability is also equally important. Low concrete durability has been considered as one of the main reasons for the premature deterioration of concrete structures (*12, 30*). Concrete pavements are often constructed in aggressive environments (especially marine) which are prone to severe attack by chloride and sulfate ions (*12, 30*), Hence the suitability of recycled aggregates, especially RAP, which generally imparts porosity to mixes (*7, 12, 30)* and thus could accelerate the transportation of aggressive ions within the microstructure of pavements, shall be evaluated very cautiously.

Research Objectives and Significance

A limited number of studies have been conducted to evaluate the suitability of RAP for RCCP mixes. Of these, studies pertaining to the determination of the optimum replacement level of natural fine by fine RAP are very scarce. Furthermore, all the previous studies evaluated the optimum replacement level of RAP for RCCP mixes, giving most emphasis on fresh and mechanical properties only. The present study is a comprehensive investigation taken up to evaluate the optimum replacement level of both the fractions of conventional natural aggregates by coarse RAP and fine RAP (individually and in combination), respectively, based upon various fresh, mechanical, and durability properties. It is anticipated that the results of the present study would help the relevant authorities in deciding the optimum fraction of RAP along with its optimum proportion for preparation of RCCP mixes to be used either as base course or surface course of pavements and also the suitability of these mixes in aggressive environments with sulfate- and chloride-rich ions.

Materials and Experimental Program

Materials and Mix Design

Portland cement Grade 43 was used throughout the study for preparation of RCCP mixes. Natural coarse and fine aggregates used in the present investigation were provided by a local supplier. Similarly, the RAP considered in the study was provided by a local contractor. The stated RAP was fractionated into coarse and fine fractions by sieving on 4.75 mm (0.187 in.) Indian Standard (IS) sieve. The specific gravity and water absorption of the natural coarse and natural fine and coarse RAP and fine RAP aggregates were determined in accordance with IS: 2386 (*31*) and the values were found to be 2.63 and 2.59 and 0.65% and 0.81% for natural coarse and fine aggregates, respectively, whereas lower values were observed for coarse and fine RAP aggregates with values of 2.41 and 2.26 and 0.40% and 0.59% respectively. The asphalt content in coarse and fine RAP was found to be 3.22% and 7.5%, respectively, when determined in accordance with ASTM D2172 (*32*). The particle size

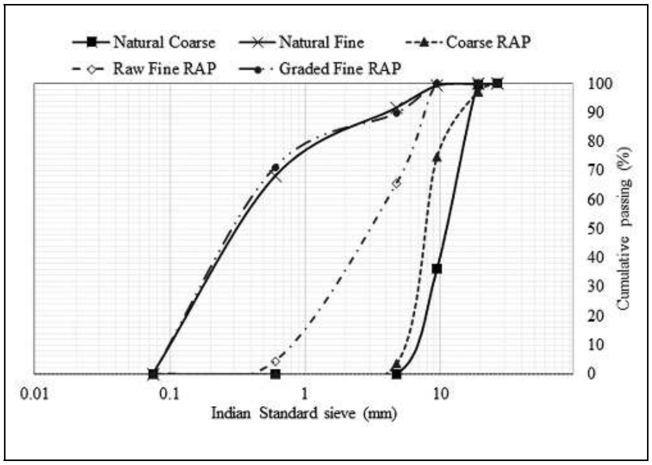

Figure 1. Particle size distribution of natural and RAP aggregates.
Note: 1 mm = 0.039 in.

distribution of all the considered aggregates is presented in Figure 1. Fine RAP, as can be seen in Figure 1, was found to be relatively coarser than the natural fine, whereas coarse RAP was observed to be slightly finer than the considered coarse natural aggregates, findings which are in agreement with most of the studies (*10, 12, 28*). Similarly, the considered fine RAP was highly gap-graded in nature owing to lack of particles finer than 600 μm (#30) IS sieve and therefore it was decided to fill these gaps with the introduction of natural fine aggregates (finer than 600 μm [#30]) to increase the suitability of fine RAP for RCCP mixes. The resultant fine RAP (30% fine RAP and 70% natural fine) was found to have nearly the same particle size distribution as that of considered natural fine aggregates (Figure 1).

The mix design for all the considered mixes was carried out in accordance with IRC: SP:68 (*33*) guidelines. For the control RCCP mix, the quantity of natural coarse and natural fine aggregates was 962.5 kg/m^3 (60.08 lb/ft^3) and 787.5 kg/m^3 (49.16 lb/ft^3), respectively. Thereafter, the considered natural aggregates were partly and fully replaced (by mass) by individual fractions of coarse RAP (RC mixes), fine RAP (RF mixes) and combined RAP (RAP mixes) aggregates in the proportions of 50% and 100% for the productions of RCCP mixes. The quantity of Portland cement in all the considered mixes was kept constant at 350 kg/m^3 (21.84 lb/ft^3). All the considered mixes were prepared at their respective optimum moisture content values (Table 1).

Experimental Program

The RCCP mix design is based on the optimum moisture content (OMC) corresponding to its maximum dry density (MDD) values carried out in accordance with ASTM D1557 (*34*). All the mixes were prepared at their respective OMC values. Compaction of the specimens was carried out in three equal layers with the help of a standard compacting hammer. A total of 63 cubical specimens of size 150 mm (5.91 in.) were prepared and tested in accordance with IS: 516 (*35*) for determination of compressive strength at seven, 28, and 90 days of curing. A further 42 prismatic specimens of size 100 mm × 100 mm × 500 mm (3.9 × 3.9 × 19.7 in.) were prepared and tested in accordance with IS:516 (*35*) to evaluate the flexural strength of the hardened RCCP mixes at seven and 28 days of curing. Similarly, 42 cylindrical specimens of size 100 mm × 200 mm (3.9 × 7.9 in.) were cast and tested in accordance with IS:5816 (*36*) for determining the split tensile strength of the mixes at seven and 28 days of normal curing. ASTM C642 (*37*) procedure was adopted to determine the density, water absorption, and total permeable voids of the hardened RCCP mixes at 28 days of curing. It should be noted that the recommended temperature (110 ± 5ºC [230 ± 9ºF]) and duration (24 hours) for completely drying the specimens for the determination of total porosity and water absorption were changed to 48 ± 2ºC (118.4 ± 3.6ºF) and eight days (until the difference between successive readings is less than 0.5%) respectively (*38*). This was done to ensure that the asphalt present around the RAP aggregates did not flow under high oven drying temperature and subsequently affect the results (*38*).

The performance evaluation of the considered RCCP mixes in the aggressive environments of sulfate and chloride ions was assessed in accordance with ASTM C267 (*39*) guidelines. The test was simulated in laboratory conditions using hydrochloric acid (HCl) and sulfuric acid (H_2SO_4) solutions of 1.5% concentration each. The acidic solutions were renewed after every 14 days to maintain a constant acidic concentration level throughout the study. A total of 63 cubical specimens of size 100 mm were prepared and cured for 28 days (in normal curing tank) after which three specimens from each RCCP mix were kept in individual acid solution tanks. Subsequently, another set of three specimens were tested for compressive strength at 28 days of normal curing. The initial weight of the test specimens in saturated surface dried (SSD) condition was noted (SSD1) before placing them in solution tanks. After 63 days of exposure to the acidic environment, the specimens were taken out from the solution tanks, washed with tap water, cleaned with a cotton cloth, and the SSD weight was noted as SSD2. Thereafter, the compressive strength of these specimens was measured in accordance with IS:516 guidelines (*34*). The difference in mass of the specimens before and after exposure (SSD1 and SSD2) to the acidic environments is termed as the loss in mass of the specimens. Similarly, the difference between the compressive

Table 1. Fresh and Hardened Properties of RCCP Mixes

Mix	OMC (%)	MDD (kg/m^3)	Compressive strength (MPa)						Flexural strength (MPa)				Split tensile strength (MPa)			
			7 days		28 days		90 days		7 days		28 days		7 days		28 days	
			X	σ	X	σ	X	σ	X	σ	X	σ	X	σ	X	σ
Control	6.19	2242	21	1.36	38	0.98	42	0.13	3.8	0.12	5.4	0.46	3.2	0.39	3.6	0.31
50RC	6.95	2231	16	1.90	25	1.57	26	1.15	**3.7***	0.07	4.6	0.03	1.7	0.31	2.1	0.19
100RC	5.89	2193	14	1.51	15	1.45	17	3.24	3.1	0.15	3.7	0.09	1.6	0.08	1.7	0.23
50RF	6.81	2220	24	0.37	28	5.04	35	3.65	3.5	0.09	4.7	0.07	2.5	0.20	2.6	0.18
100RF	6.06	2185	19	2.46	24	1.23	29	6.04	**3.4***	0.49	4.6	0.35	1.9	0.39	2.5	0.19
50RAP	6.43	2156	17	0.27	20	1.00	21	0.04	3.4	0.08	4	0.45	2	0.29	2.2	0.25
100RAP	5.92	2129	11	1.48	12	1.08	12	1.81	3	0.05	3.4	0.13	1.4	0.05	1.6	0.04

Note: OMC = optimum moisture content; MDD = maximum dry density; RCCP = roller compacted concrete pavement; 50RC = mix containing 50% coarse RAP; 100RC = 100% coarse RAP; 50RF = 50% fine RAP; 100RF = 100% fine RAP; 50RAP = 50% coarse and fine RAP; 100RAP = 100% coarse and fine RAP; RAP = reclaimed asphalt pavement; 1 kg/m^3 = 0.062 lb/ft^3; 1 MPa = 145.038 pounds per square inch (psi); X = average; σ = standard deviation.
*Numbers in bold have a mean which is not statistically different from the control mix with 95% confidence.

strength is denoted as the loss in the strength of the mixes after the acid attack.

Concrete pavements are subjected to wear and tear because of abrasive forces caused by vehicular movements (*40*). This wear and tear reduces the functional performance of the pavements and thus its evaluation is necessary if RCCP is to be used as a surface layer of pavement. ASTM C1747 (*41*) procedure was adopted to determine the Cantabro abrasion loss of the RCCP mixes. A total of 42 cubical specimens of size 100 mm (3.9 in.) were prepared for the determination of the abrasion resistance of the considered mixes. The Los-Angeles abrasion machine was used for determining the Cantabro abrasion loss. After 28 and 90 days of curing, three specimens from each RCCP mix were taken out from the curing tank and their initial weight was noted down and subsequently, the specimens were kept in the Los-Angeles abrasion machine (without steel balls) and rotated at about 33 rpm for 15 minutes. After 500 revolutions, the specimens were removed from the machine, cleaned for any loose particles, and their mass was recorded. The difference between the initial mass and final mass of the specimens before and after abrasion is termed the Cantabro abrasion loss.

Results and Discussion

Fresh Properties

The effect of inclusions of different fractions of RAP on the OMC and MDD of the considered RCCP mixes are summarized in Table 1. It was observed that, despite lower water absorption of individual RAP fractions than the considered natural aggregates, the water demand of the lower RAP proportion mixes (50%) was higher than the control mix. To the contrary, high RAP mixes exhibited lower OMC values than the low RAP mixes and even lower than the control mix containing natural aggregates. The reduction in OMC on the incorporation of RAP may be attributed to the lower water absorption of the considered RAP fractions than the considered natural aggregates. The reason for the higher water demand of low RAP mixes is not known, however, the presence of agglomerated particles may be held responsible to some extent (*42*). As far as the effect of RAP on the workability of the fresh mixes is concerned, all the considered mixes were observed to be workable in nature. However, this condition may or may not be true for other RAP materials. The smoothly textured asphalt coating is generally hydrophobic in nature, and thus could result in bleeding and segregation, as reported by several authors (*42–44*). Nevertheless, this condition could be resolved by either increasing the fine content or by increasing the Portland cement quantity (*43, 44*). Additionally, inclusions of RAP aggregates may result in less compactive effort owing to the combined effect of smooth texturing and slightly rounded morphology than the rough textured and angular conventional nature aggregates. However, these statements need to be validated by conducting laboratory and field trials.

It was observed that inclusions of any fraction of RAP could reduce the MDD of the considered RCCP mixes. The reduction in MDD was found to be profound for combined RAP mixes (RAP), followed by fine RAP (RF) and coarse RAP (RC) mixes. This reduction in MDD on the incorporation of RAP is because of the fact that RAP aggregates are lighter than natural aggregates as depicted by their lower specific gravity value. Nevertheless, a maximum of 5% reduction in MDD was noted for the 100RAP mix (compared with the control mix) which may be considered as comparable with that of the control mix.

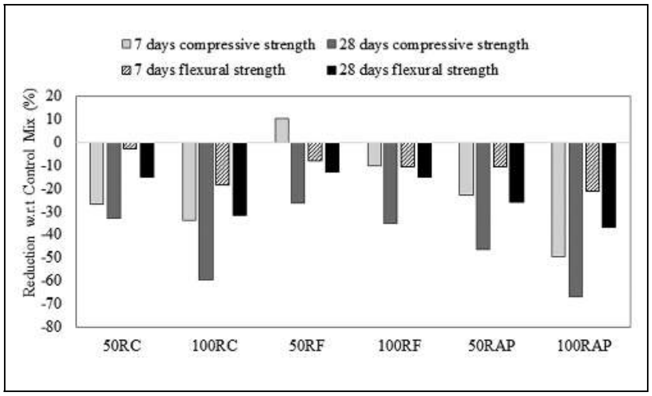

Figure 2. Reduction in strength of considered RAP mixes compared with control mix.

Compressive Strength

The results of testing the compressive strength of hardened RCCP mix at seven, 28, and 90 days of curing are summarized in Table 1. Consistent with the available literature, incorporation of different fractions of RAP reduced the compressive strength of RCCP mixes considerably at all curing ages (except 50RF at seven days) both experimentally and statistically (t-test comparing the RAP mixes with the control mix at 95% confidence level). Moreover, as the percentage incorporation of individual RAP fraction increases, the compressive strength tends to decrease linearly. This reduction in strength is because of the presence of asphalt coating around the aggregates which creates a hindrance in bonding formation between the surface of the aggregate with that of cementitious mortar matrix (*11, 12, 20, 22, 26*). However, contrary to the published studies, the reduction in strength was found to be higher in coarse RAP mixes compared with fine RAP RCCP mixes. For instance, the reductions compared with the control mix for 50RC and 100RC mixes were observed to be 33% and 59%, respectively, whereas only 26% and 35% strength reduction was found for 50RF and 100RF mixes, respectively, at 28 days of curing. A similar reduction trend was noted at other curing ages. The greater reduction in strength for coarse RAP mixes compared with fine RAP mixes despite the lower concentration of asphalt coating is possibly because of the higher percentage of RAP in RC mixes (50% and 100%). For fine RAP mixes, owing to gap-graded particle size distribution, fine natural was introduced (as discussed in the experimental program) which limited the percentage of fine RAP to 15% and 30% in 50RF and 100RF mixes, respectively. Interestingly, the fresh densities of RC mixes (Table 1) were higher than the fine RAP mixes and yet the compressive strength of RC mixes was lower than that of RF mixes, at all curing ages. This is contrary to the general perception that higher MDD will always lead to better strength properties. This unnatural behavior may again be attributed to the presence of a lower percentage of asphalt-coated aggregates in RF mixes compared with RC mixes which contributed to the formation of relatively better mortar matrix, and thus better bonding with the surface of the natural aggregate. This is further supported by the compressive strength results of these mixes at 28 and 90 days curing where it can be clearly seen that the strength development in RC mixes is very low ($<13\%$) compared with RF mixes ($>20\%$).

The minimum recommended strength of 27.6 MPa (4003.04 psi) at 28 days of curing for construction of RCC pavements (as a surface layer) as specified by ACI (*1*) was not found to be achieved by any of the considered RAP mixes, except the 50RF mix. However, the stated mix cannot be confidently suggested for preparation of RCCP mixes since the difference between the achieved and minimum stipulated value is minimal.

Flexural Strength

As with the compressive strength results, incorporation of fine RAP was found to have a less negative effect on the flexural strength of RCCP mixes, followed by coarse RAP and total RAP fractions (Table 1). However, the percentage reduction compared with the control mix was noted to be significantly lower (Figure 2). For instance, the percentage flexural strength reduction for 100RC, 100RF and 100RAP at 28 days was noted be around 31%, 15%, and 37%, respectively, whereas the same mixes had 59%, 35%, and 67% lower compressive strength compared with the control mix at 28 days, respectively. This finding is of utmost importance to pavement engineers since RCC pavements are designed based upon 28 days flexural strength results rather than compressive strength. It can be seen in Table 1 that, except 100RAP mix, all the considered mixes had flexural strength greater than the stipulated field flexural strength of 3.67 MPa (532.28 psi) at 28 days of age. Except the 100RC and 100RAP mixes, all the RAP mixes exhibited greater flexural strength (experimentally as well as statistically) than the target laboratory mean strength of 4.3 MPa (623.66 psi) which clearly demonstrates the suitability of RAP for pavement applications. Based upon the results, it can be stated that 50% of RAP content, individually as well as in combination, may be included for the preparation of RCCP mixes.

Split Tensile Strength

Consistent with the compressive and flexural strength results, inclusions of all the RAP fractions resulted in lowering the split tensile strength of RCCP mixes at both

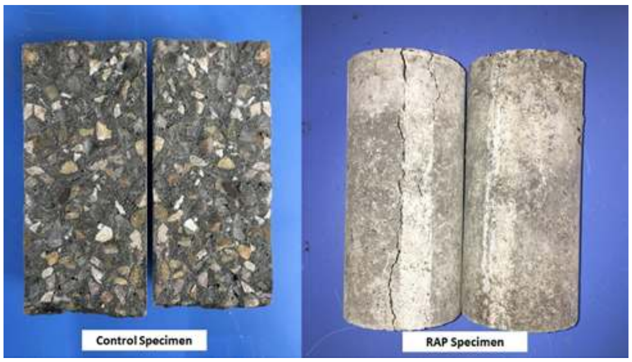

Figure 3. Split specimens after failure.

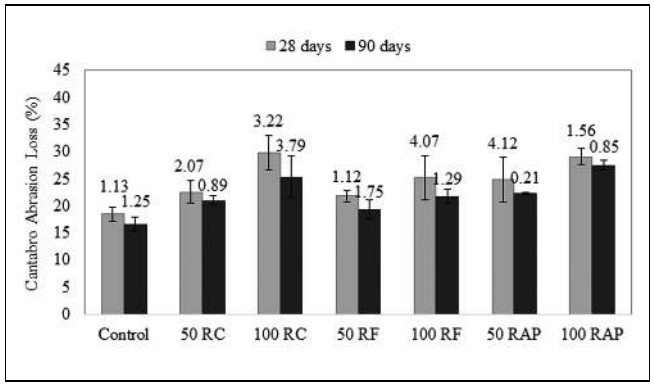

Figure 4. Cantabro abrasion loss of the RCCP mixes.
Note: Error bars represent standard deviation.

curing ages. RF mixes had the lowest reduction in split tensile strength compared with the control mix, followed by a nearly comparable performance by coarse RAP and total RAP mixes at both curing ages.

It was observed that the RAP specimens could sustain the loading even after the failure of the specimens and this may be attributed to the presence of asphalt coating around the aggregates which may have increased the toughness of the concrete mixes (*5, 11, 22, 27, 29*). The split tensile specimens of 100% RAP mix did not even split into two halves (Figure 3) as the control mix specimens did (Figure 3), clearly suggesting that inclusion of RAP fractions would certainly enhance the load carrying capacity of RCC pavements post-failure. This condition, in turn, could be expected to increase the functional life of the RCC pavements. This phenomenon is of greater importance especially in hilly terrain in India, where frequent repairs are generally required after every monsoon season, and provision of such remedial measures is relatively harder as well as costlier owing to the harsh terrain in such areas. Based on the above findings and the results of mechanical properties testing, replacement of traditional natural aggregates by RAP fractions (individual or combined) in a proportion of 50% may be suggested for RCC pavements. This combination of aggregates would not only provide requisite strength properties with increased residual value, but also offer several other economic and environmental benefits such as: less consumption of natural aggregates, reduced transportation costs (because of on-the-spot utilization of RAP aggregates), elimination of RAP disposal problems, reduction in greenhouse gases emissions, and so forth (*10, 24*). However, prior to suggesting this optimum proportion of RAP for RCCP pavements, especially to be situated in higher temperature differential zones, shrinkage and warping properties need to be considered, and joint spacings determined accordingly. The usual joint spacing for RCCP pavements is generally kept between 6.1 m (20 ft) and 9.1 m (30 ft). For RCCP mixes containing 50% RAP (optimum for the present case) the same stipulation may be followed, as several authors have reported near insignificant effects on the shrinkage behavior of concrete mixes containing RAP (*25, 45*). However, this suggestion needs to be validated via laboratory, field investigation, or both.

Cantabro Abrasion Loss

When used as the surface slab of pavements, RCCP mixes are expected to offer significant resistance to the wear and tear caused by high speed and heavily loaded moving vehicles (*40*). In the case of hilly terrains, frequent skidding and slipping are common and thus the abrasion resistance of the surface slab becomes of utmost importance. The percentage loss in mass of the considered mixes after abrasion testing (28 and 90 days) is depicted in Figure 4. As expected, the control mix was found to have the lowest percentage abrasion loss, whereas all the RAP mixes suffered a significant loss in mass after exposure to abrasion conditions. It was also observed that, with the increase in the RAP proportions included, the abrasion resistance tended to reduce considerably. Both the individual fractions of RAP (RC and RF mixes) were found to exhibit nearly similar abrasion resistance at lower proportions; however, a significant difference in percentage abrasion loss was noted between 100RC and 100RF mixes at both the testing ages. While the percentage reduction in abrasion resistance for 100RF mix was less than 35%, more than 50% reduction in abrasion resistance was observed for 100RC mix as compared to the control mix. As far as the abrasion resistance of the combined mixes is concerned, nearly 35% and 60% higher loss in mass was found for 50RAP and 100RAP mixes, respectively, compared with the control mix at both curing ages. These results reduce the potential of RAP inclusion when RCCP is to be used as a surface/wearing course of pavements. Nevertheless,

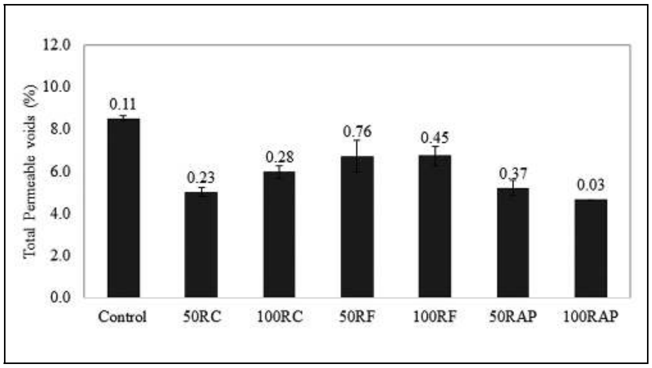

Figure 5. Total permeable voids of the RCCP mixes.
Note: Error bars represent standard deviation.

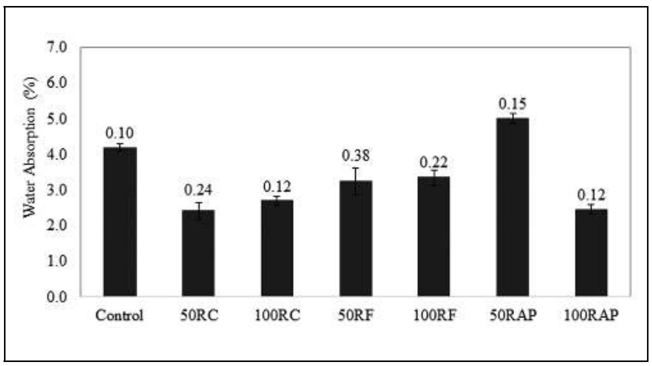

Figure 6. Water absorption of the RCCP mixes.
Note: Error bars represent standard deviation.

50RC and 50RF mixes may be suggested for RCC pavements since these mixes had sufficient resistance to wear and tear as shown by the results. It was also observed that the trend in abrasion resistance of the considered mixes is almost similar to the trend observed for considered strength related properties. Strong linear relationships with high values of coefficient of determination were found to exist between the abrasion loss and the compressive/flexural strength of the considered RCCP mixes at different curing ages. These relations show that the potential of including RAP in RCCP mixes to be used as a surface layer of pavements may be increased by increasing the strength related properties. One of the best ways to increase the strength related properties of RAP inclusive mixes is by increasing the quantity of Portland cement (*43, 44*):

$$Y = -0.46X + 35.22; \mathrm{R2} = 0.92 \quad (1)$$

$$Y = -0.34X + 30.75; R2 = 0.95 \quad (2)$$

$$Y = -5.54X + 48.57; R2 = 0.89 \quad (3)$$

where Y is abrasion loss in %, X in Equations 1 and 2 is the value of compressive strength at 28 and 90 days of curing respectively, and in Equation 3, X is the value of flexural strength at 28 days of curing.

Porosity and Water Absorption

The effect of incorporation of individual/combined fractions of RAP on the total porosity and water absorption of the considered RCCP mixes at 28 and 90 days of curing age is illustrated in Figures 5 and 6. Unexpectedly, inclusion of both the fractions of RAP was found to reduce the total porosity and thus the water absorption of the considered RCCP mixes considerably, at both curing ages. For instance, the concentration of total permeable voids in the control mix was 8.5% which is approximately 70% and 27% higher than the voids present in 50RC and 50RF mixes, respectively. Similarly, 100RC and 100RF mixes exhibited around 30% and 21% lower porosity values than the control mix, whereas more than 40% reduction in the porosity values was noted for combined fraction mixes (50RAP and 100RAP) compared with the control mix. A similar trend in the water absorption values was noted when natural aggregates were replaced, partially or in combination, by the considered RAP fractions. Mixes of 100RC, 100RF, and 100RAP had around 36%, 20%, and 41% lower water absorption values than the control mix. Since the considered mixes were oven dried at lower temperature and for longer durations than the codal provision—to minimize the negative effect of flowing of asphalt at higher temperature (*38*)—, the reduction in the total porosity and water absorption capacity of RCCP mixes containing RAP fractions may be attributed to the hydrophobic and soft textured nature of asphalt-coated aggregates which facilitated better workability (*12, 42*) and thus better compactness of the mixes was achieved than the control mix containing rough textured natural aggregates. Moreover, the relatively finer gradation of RAP aggregates compared with the considered conventional aggregates (both coarse and fine) may also be held responsible for the lower porosity and thus lower water absorption of the RAP inclusive RCCP mixes. The results of the statistical analysis also confirmed that the considered fractions of RAP had statistically reduced the porosity of the RCCP mixes.

Resistance to Aggressive Ions

The loss in mass (in percentage) of the specimens after exposure to chloride and sulfate attack is depicted in Figure 7. As expected, the loss in mass of all the considered RCCP mixes was higher when subjected to sulfate attack. This is because of the fact that sulfate is responsible for both physical as well as chemical attack (*30*). Complete surface deterioration (scaling) was observed

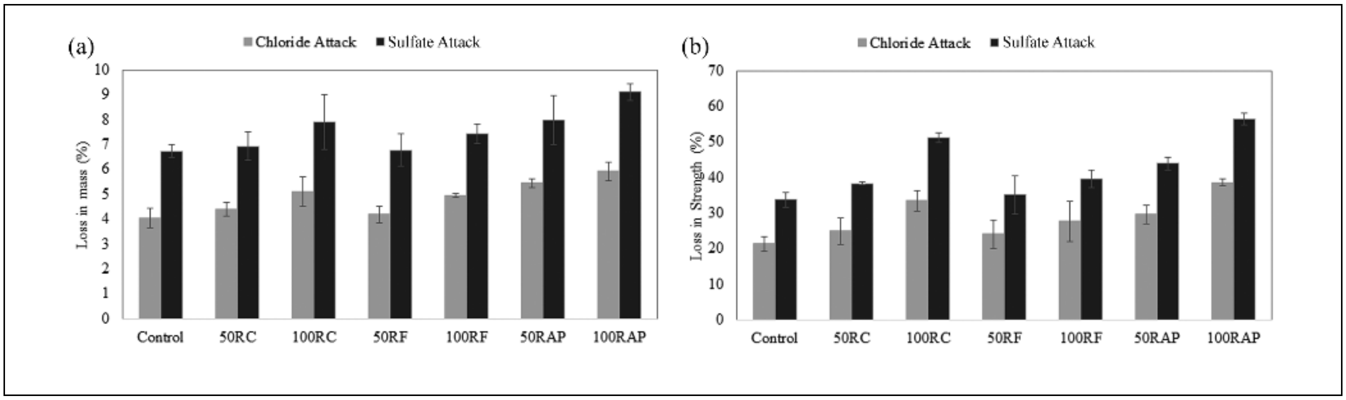

Figure 7. RAP mixes after exposure to aggressive environments: (*a*) loss in mass; (*b*) loss in strength.

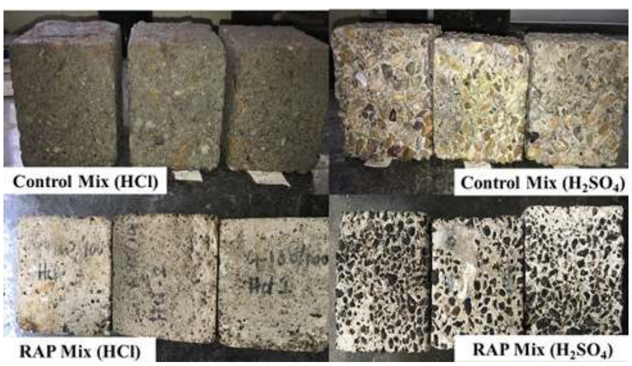

Figure 8. Specimens of control mix and RAP mix after exposure to attack by chloride and sulfate.

for the specimens kept in sulfate solution, whereas specimens placed in chloride solution nearly retained their shape and surface characteristics (Figure 8). The control mix, as expected, had the highest resistance to both the attacks, whereas RAP mixes suffered a dramatic loss of mass when subjected to aggressive ions of sulfate and chlorides. The higher loss of mass in RAP mixes may be because of the higher interconnectivity between the pores which allowed easy ingress of sulfate and chloride ions within the microstructure of the specimens and thus subsequent leaching of calcium sulfate and calcium chloride salts from the specimens into the acid solution (*12, 30*). However, lower proportion individual RAP fraction mixes exhibited resistance to both the attacks comparable with that of the control mix. For instance, 50RC and 50RF mixes suffered 4.39% and 4.18% and 6.93% and 6.77% loss of mass in chloride and sulfate solutions, respectively, which were only ˜3% higher than that of the control mix (except 50RC which had 9% higher mass loss in chloride solution). This finding clearly suggests that 50% of traditional natural aggregates may be replaced by any fraction of RAP (coarse/fine) for the preparation of RCCP mixes to be used in sulfate- or chloride-rich surroundings. On the other hand, since both the combined fraction mixes (50RAP and 100RAP) showed significant deterioration in both the acid solutions, combined utilization of coarse and fine RAP should not be recommended.

It was also observed that the performance of RAP mixes was better in a sulfate-rich environment than that in a chloride solution. For instance, all the considered RAP mixes suffered $<20\%$ higher loss of mass than the control mix (except 100RAP) in the sulfate-rich environment, whereas $>20\%$ higher loss was noted compared with the control mix (except 50RC and 50RF) when these mixes were subjected to chloride attack. This finding certainly suggests including a higher fraction of RAP in RCCP mixes which are to be placed in a sulfate-rich environment than those in chloride-rich surroundings. Moreover, the results also encourage the inclusion of higher proportions of fine RAP for RCC pavements to be constructed in the vicinity of sulfate-rich environments since the 100RF mix only had less than 10% higher mass loss than the control mix when subjected to a sulfate solution.

A similar trend in the values of percentage loss in compressive strength was noted for all the considered mixes when subjected to sulfate and chloride attack. Lower proportion individual RAP mixes had $<15\%$ lower strength loss compared with the control mix, whereas combined fraction mixes had the greatest loss in strength when subjected to sulfate and chloride solutions. Similarly, the loss in strength in sulfate solution was found to be lower than that in chloride solution. However, compared with the loss in mass, the loss in compressive strength associated with the considered RAP mixes, compared with the control mix, was significantly higher. For instance, the difference between the percentage strength loss and mass loss (compared with the control mix) was noted to be 30% and 34%, 7% and 7%, and 34% and 32% for 100RC, 100RF, and

100RAP mixes when subjected to chloride and sulfate attack, respectively. These results further lower the potential and suitability of RAP aggregates for RCC pavements to be constructed in the vicinity of aggressive ions. Nevertheless, 50RC and 50RF mixes may be suggested for these areas since the difference between the aforementioned parameters was less than 10% and, moreover, the stated mixes exhibited performance nearly comparable with that of control mix in both the solutions of aggressive ions.

Conclusions

The present study evaluates the optimum fraction (coarse/fine/combined) of RAP along with its optimum proportion (50%/100%) for RCCP, or RCC pavements, based upon several fresh, mechanical, and durability properties. The main inferences that have been drawn from the present study are:

- An inconsistent trend was observed in the values of OMC of the considered RCCP mixes when natural aggregates were replaced, partially or in combination, by different fractions of considered RAP. However, the MD of the RCCP mixes was found to be in a decreasing trend with the increase in the proportion of RAP aggregates. Coarse RAP mixes exhibited higher MDD values, followed by fine RAP and combined RAP mixes.
- Incorporation of any fraction of RAP could reduce the compressive, flexural, and split tensile strength of RCCP mixes significantly at all curing ages. However, fine RAP mixes were found to have better strength properties than the coarse RAP and combined RAP fraction mixes. Additionally, it was found that inclusions of RAP would have a lower negative effect on the flexural strength values than the compressive strength at all curing ages. None of the considered RAP mixes could achieve the recommended compressive strength criterion of 27.6 MPa (4003.04 psi) for constructions of RCC pavements at 28 days of curing age, however, all the mixes had higher flexural strength than the stipulated value of 3.6 MPa (532.28 psi). Based on the results, partial replacement of conventional natural aggregates in a proportion of 50% by either fraction of RAP (coarse or fine) may be suggested for RCC pavements (for the base course) since these mixes had even higher flexural strength than the recommended target laboratory mean strength of 4.3 MPa (623.66 psi).
- A fraction of 50% of natural aggregates can be replaced by either fraction of RAP (coarse or fine) for the RCCP mixes to be used as a surface course layer of pavements since these mixes had sufficient resistance to abrasion caused by moving vehicles. Different strong linear relations were found to exist between abrasion resistance and compressive/flexural strength values, showing that the stated proportion of RAP may be increased by improving the strength related properties.
- RAP mixes, owing to their lower porosities than the control mix, were found to have lower water absorption capacities. However, when subjected to sulfate- and chloride-rich environments, the mixes suffered a drastic loss in mass and compressive strength compared with the control mix. These results lower the suitability of RAP for RCC pavements to be constructed in aggressive environments of sulfate- and chloride-rich ions. Nevertheless, 50% of natural aggregates can be replaced by any fraction of RAP (coarse/fine) for these areas as the associated mass loss and compressive strength loss was relatively lower. Moreover, the results also encourage the inclusion of higher proportions of fine RAP for surroundings rich in sulfate ions, but not for those rich in chloride.

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Author Contributions

The authors confirm contribution to the paper as follows: study concept: GDRRN, SD, SS; laboratory experimental program: SD, SS; analysis and interpretation of results: SD, SS, GDRRN; draft manuscript preparation: SD, SS, GDRRN. All the authors reviewed the results and approved the final version of the manuscript.

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