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Effect of using recycled coarse aggregate and recycled asphalt pavement on the properties of pervious concrete

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Abstract. This paper presents the results of a study that investigated the influence of using recycled coarse aggregate (RCA) and recycled asphalt pavement (RAP) on the properties of pervious concrete (PC). The natural aggregate (NA) was replaced by RCA and RAP in the PC with replacement levels of 0%, 20%, 40%, 60% and 80% by the total weight of NA, respectively. In addition to incorporating RAP and RCA in the same mixes with replacement levels of: (1) 20% RAP and 80% RCA; (2) 60% RAP and 40% RCA; and (3) 80% RAP and 20% RCA. Water permeability, thermal conductivity, density, porosity, void content, and compressive, splitting tensile and flexural strengths were studied in this paper. The results showed that using RCA, RAP, and (RAP-RCA) enhanced the properties of PC in general and improved the mechanical properties significantly in particular. The optimum mix was reported to be the 60% RAP and 40% RCA. Accordingly, the RAP has the potential to be used in PC in order to reduce the negative impact of RAP on the human health and environment.

Keywords: recycled coarse aggregate; recycled asphalt pavement; pervious concrete; mechanical properties; thermal conductivity

1. Introduction

Pervious concrete (PC) is different than conventional concrete (CC) because of its high porosity. This porosity permits water to pass through the pores causing reduction of runoff of storm water in addition to recharging of the groundwater. Also it improves pavement skid resistance due to rapid drainage of water. PC has been used recently in landscaping of garden and riverside paths, pedestrian walkways, parking areas, and light traffic roads. PC can be considered as a good example of sustainable construction and has a positive impact on the environment because it enhances the water quality significantly (Ferguson 2005, Tennis *et al.* 2004).

PC is made by using ordinary Portland cement (OPC) Type I with water-to-cement (w/c) ratios of 0.25-0.40 with sufficient cement coating for the coarse aggregate and with no fine aggregate. The permeability and porosity of PC varies in the range of 0.025-0.61 cm/s, and 15-25% respectively. The aggregate-to-cement ratio varies in the range of 4:1 to 12:1 and the volume of aggregates is 50-65% compared to CC which is 60-75%. The aggregate sizes are in the range of 19-19.5 mm to maintain sufficient voids and the slump of PC usually is zero. The compressive strength for PC usually ranges from 4 to 10 MPa (Chandrappa and Biligiri 2016).

Lately many researchers studied the improvement of mechanical properties, permeability, and the abrasion and freezing–thawing resistance of PC by adding many materials such as: (1) waste tire rubbers (Gesoglu *et al.* 2014, Gesoglu *et al.* 2014); (2) palm oil clinker (Ibrahim and Abdul Razak 2016); (3) crushed seashells (Nguyen *et al.* 2017); (4) oil palm kernel shell and cockleshell (Khankhaje *et al.* 2017); (5) rice husk ash and fiber (Hesami *et al.* 2014); (6) electric arc furnace slag (Yeih *et al.* 2015, Chang *et al.* 2016). Other researchers such as Osic *et al.* (2015) studied the influence of aggregate size and type on the properties of PC by using four mixtures with varied aggregate types and different proportions of 4-8 mm to 8-16 mm aggregate. The authors reported that a higher amount of small aggregate causes a higher density and flexural strength. While Brake *et al.* (2016) studied the flexural strength of low and high strength and unit weight PC. The results showed that the flexural strength depends on the size and can be predicted using Bazant size effect law.

Using Recycled coarse aggregate (RCA) to replace natural aggregate (NA) in concrete has a positive effect on environment because it reduces the landfill areas which will reduce air and water pollutions. Also, it will minimize production and consumption of NA which is considered as non-renewable natural resources. Many studies have been conducted in the last decade by many researchers on using RCA in CC (Katkhuda and Shatarat 2016, Katkhuda and

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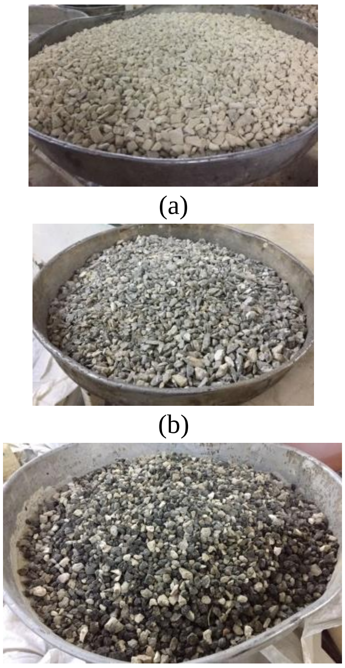
Shatarat 2017, Andre *et al.* 2014, Seo and Choi 2014, Koenders *et al.* 2014, Bravo *et al.* 2015, Yildirim *et al.* 2015, Shi *et al.* 2016, Zhang *et al.* 2015, Saravanakumar and Dhinakaran 2013, Shah *et al.* 2013), however, there are very limited research have been done on using RCA in PC (Chinchillas *et al.* 2014, Barnhouse and Srubar 2016, Zhang *et al.* 2017, Tavares and Kazmierczak 2016, Shahidan *et al.* 2017). Sriravindrarajah *et al.* (2012) replaced cement by blast furnace slag and investigated the compressive strength, void content, and water permeability of PC with RCA. The results showed that the porosity and compressive strength of PC was badly affected by the use of RCA, however, the water permeability is not affected by RCA. The authors provided an idealized mix design for PC using RCA. Zaetang *et al.* (2016) studied the total void, density, thermal conductivity, water permeability, compressive strength, and surface abrasion of PC containing recycled block concrete aggregate (RBA) and RCA. The NA was replaced by RCA and RBA at 0%, 20%, 40%, 60%, 80%, and 100% by weight. The results reported showed that RCA and RBA increased the compressive strength except for the 100% replacement and the RCA increased the surface abrasion resistance, while RBA improved the surface abrasion resistance only with 20% replacement. Guneyisi *et al.* (2016) replaced NA with RCA in PC with 25%, 50%, 75%, and 100% with w/c of 0.27 and 0.32. The authors tested for porosity, water permeability, dry density, abrasion resistance, and compressive and splitting tensile strengths. The results showed that using RCA caused a considerable increment in the permeability coefficient. However, the mechanical properties were adversely influenced up to a certain degree.

Lately, many researchers used recycled asphalt pavement (RAP) to replace coarse and fine NA in CC (Huang and Shu 2006, Erdem and Blankson 2014, Modarres and Hosseini 2014, Saride and Avirneni 2016, Brand and Roesler 2015, Okafor 2010, Bilondi 2016). RAP is usually obtained from milling old asphalt pavements. It contains coarse and fine aggregates that are coated with aged asphalt cement. RAP has a very negative effect on environment and human health because it causes air and water pollutions due to stockpiling or landfilling. To enhance the negative environmental effects of RAP; it has been re-used in concrete pavement as granular base and sub-base, in embankment or fill, and in non-structural concrete elements such as road barriers. Some researchers such as Hung *et al.* (2013) replaced coarse and fine NA with 100% RAP in laboratory to study its effect on mechanical strengths and failure behavior of concrete. The results showed that the compressive and splitting tensile strengths of RAP mixes decreased and the toughness increased compared to NA mixes. Al-Oraimi *et al.* (2009) studied the effect of replacing the NA with RAP at different percentages for (w/c) ratios of 0.45 and 0.5. The results showed that slump, modulus of elasticity and flexural and compressive strengths declined as the percentage of RAP increased. Katkhuda *et al.* (2017) investigated the enhancement of the mechanical properties of coarse and fine RAP by adding silica fume (SF) with contents of 5%, 10%, and 15% by total weight of the cement. The coarse and fine NA were replaced by RAP with replacement ratio of 20%, 40% and 60% by the total weight. The results showed that the mechanical properties decreased as the content of RAP increased, and using SF enhances the mechanical properties of RAP mixes where the optimum content of SF was found to be 10%.



(a) (b) (c)

Fig. 1 Photo of coarse aggregate used: (a) NA; (b) RCA; (c) RAP

Table 1 Properties of coarse aggregate

Property	NA	RCA	RAP
Dry-rodded density (kg/m^3)	1386	1299	1423
Bulk specific gravity (Dry)	2.335	2.251	2.368
Water absorption (%)	5.49	7.12	2.12
Los Angeles Abrasion %	38.96	40.82	28.12

Based on this literature review, there is a lack of studies on using RCA and RAP in PC because most of the studies were conducted by replacing NA with RCA and RAP in CC. The aim of this paper was to study the influence of using RCA and RAP in PC. The NA was replaced by replacement levels of 20%, 40%, 60%, and 80% by weight of NA with RCA and RAP, respectively. In addition, RAP and RCA were used in the same mixes with replacement levels of: (1) 20% RAP and 80% RCA; (2) 60% RAP and 40% RCA; and (3) 80% RAP and 20% RCA. Water permeability, thermal conductivity, density, porosity, void content, and compressive, flexural, and splitting tensile strengths were studied in this paper. This paper can be considered the first paper that studies the effects of using RAP, and (RCA and RAP) in PC.

2. Experimental program

2.1 Materials

2.1.1 Cement

The cement that was used was Ordinary Portland cement (OPC) Type I.

2.1.2 NA and RCA

Natural limestone aggregate was used as the coarse NA, while the RCA was prepared by crushing old concrete cubes specimens available in the laboratory. The type of the original aggregates in those cubes was limestone. The age of the old concrete cubes ranged from one to two years and the average cubic compressive strength was 20-25 MPa at 28 days. The concrete chunks resulted from the crushing process were broken into 4.75 and 9.5 mm sizes using a jaw crusher, and the RCA was washed, dried, and sieved to be used. Fig. 1 shows a photo of NA and RCA that were used.

The dry-rodded density, bulk specific gravity, water absorption, and Los Angeles abrasion tests were determined using ASTM C29-17, ASTM C127-15, and ASTM C131-14, respectively. Table 1 shows the properties of the NA and RCA. The specific gravity of NA and RCA was 2.335 and 2.251, respectively, and the water absorption of RCA was higher than NA as expected.

Table 1 indicates clearly that the quality of the NA aggregate is poor compared to NA used in structural concrete elements. This is acceptable since pervious concrete is intended to be used in sidewalks and concrete pavements and not in structural concrete members.

2.1.3 RAP

The RAP was obtained by crushing waste asphalt pavement rubbles that was taken from road reconstruction site. The RAP was washed, dried, and sieved to obtain 4.75 and 9.5 mm sizes. Figure 1 shows a photo of the RAP used. The dry-rodded density, bulk specific gravity, and water absorption of RAP were evaluated using the same ASTM standards that were adopted for NA and RCA. Table 1 shows the properties of the RAP. The specific gravity and water absorption were 2.368 and 2.12, respectively. The water absorption for RAP was much less compared to that for NA and RCA; this could be due to the layer of old asphalt that was coating the aggregates which prevented the absorption of water.

2.2 Mix proportions

The details of the mix proportions for the twelve PC mixes that were used in this paper are shown in Table 2. The fifteen mixes were separated by type of aggregates into four groups: (1) NA; (2) RCA; (3) RAP; and (4) (RAP and RCA). In the second and third groups, the NA was replaced by RCA and RAP with replacement levels of 20%, 40%, 60%, and 80% by weight of coarse NA, respectively. While in the fourth group the mixes were prepared by (RAP and RCA) only. The first, second, third, and fourth mixes in this group were 20% RAP-80% RCA, 60% RAP-40% RCA, and 80% RAP-20% RCA, respectively. All types of aggregates were oven dried for 24 hours before used in mixing.

The names of the mixes are shown in Table 2. The name of first group is NA which represents using natural aggregate as a control specimen. The names of second and

Fig. 2 Photo of cylindrical pervious concrete specimen using RAP

third groups consist of two parts. The first one is for the type of the mix: RCA- recycled coarse aggregate, and RAP-recycled asphalt pavement, while the second part is for the replacement levels of RCA and RAP by the weight of coarse NA, i.e., 20 = 20%, 40= 40%, 60= 60%, and 80= 80%. The names of fourth group consist of four parts. The first one is for the type of the mix: RAP and the second one is for the replacement levels of RAP by the weight of coarse NA. The third one is for the type of the mix: RCA and the fourth one is for the replacement levels of RCA by the weight of coarse NA. The w/c ratio shown in Table 2 is the effective w/c ratio.

2.3 Mixing and preparation of specimens

All concrete mixes were mixed using a mechanical mixer. The fresh mixtures were placed into two layers in the mold. Each layer was rodded 25 times by using a tamping rod. Two sizes of specimens were cast: (1) the 100×100×500 mm prism specimen that was used for flexural strength test; and (2) the 100 mm diameter and 200 mm height cylindrical specimen that was used for void content, water permeability, density, thermal conductivity, and compressive and splitting tensile strengths tests.

All specimens were demolded at the age of 24 hours and cured in a water bath at a temperature of 20℃ until the day of testing. Fig. 2 shows a photo of cylindrical PC specimen using RAP.

2.4 Testing details

2.4.1 Density and void content

Density and void content of PC were determined using ASTM C1754-12.

The density of PC was calculated by

$$\text{Density} = \frac{K\,A}{D^2\,L} \tag{1}$$

Where K is 1273240 mm^3kg/m^3g, A is the dry mass in g, D and L are the diameter and length of specimen in mm, respectively.

The void content was determined by

$$\text{Void content} = \left[1 - \left(\frac{K\left(A - B\right)}{\rho_W\,D^2\,L}\right)\right] \text{X } 100\% \tag{2}$$

Table 2 Details of mix proportions

Mix type	Cement (kg/m^3)	Water (kg/m^3)	W/C	Coarse NA (kg/m^3)	Coarse RAP (kg/m^3)	Coarse RCA (kg/m^3)
NA-0	420	147	0.35	1554	0	0
RCA-20	420	147	0.35	1243.2	0	310.8
RCA-40	420	147	0.35	932.4	0	621.6
RCA-60	420	147	0.35	621.6	0	932.4
RCA-80	420	147	0.35	310.8	0	1243.2
RAP-20	420	147	0.35	1243.2	310.8	0
RAP-40	420	147	0.35	932.4	621.6	0
RAP-60	420	147	0.35	621.6	932.4	0
RAP-80	420	147	0.35	310.8	1243.2	0
RAP-20-RCA-80	420	147	0.35	0	310.8	1243.2
RAP-60-RCA-40	420	147	0.35	0	932.4	621.6
RAP-80-RCA-20	420	147	0.35	0	1243.2	310.8

Table 3 Density, void content, porosity, and water permeability for mixes

Mix type	Density (kg/m^3)	Density Standard Error	Void Content (%)	Void Content Standard Error	Porosity	Porosity Standard Error	Water Permeability (mm/s)	Water Permeability Standard Error
NA-0	1604	15.84	47	1.64	0.32	0.0075	11.06	1.90
RCA-20	1669	20.79	41	1.89	0.29	0.0094	10.74	0.56
RCA-40	1620	6.27	43	0.49	0.30	0.0024	10.73	1.57
RCA-60	1601	7.23	43	0.32	0.30	0.0016	12.18	0.73
RCA-80	1603	4.56	41	0.74	0.29	0.0037	11.83	1.85
RAP-20	1665	7.68	38	0.66	0.27	0.0035	10.50	0.86
RAP-40	1777	7.59	28	1.02	0.22	0.0062	10.71	0.22
RAP-60	1822	16.57	23	1.11	0.19	0.0072	12.68	1.12
RAP-80	1878	59.71	21	1.06	0.18	0.0081	11.87	1.38
RAP-20-RCA-80	1635	25.27	41	10.98	0.28	0.0568	10.64	0.06
RAP-60-RCA-40	1649	17.80	37	1.67	0.27	0.0090	10.32	0.85
RAP-80-RCA-20	1620	11.71	38	0.68	0.27	0.0036	10.48	0.79

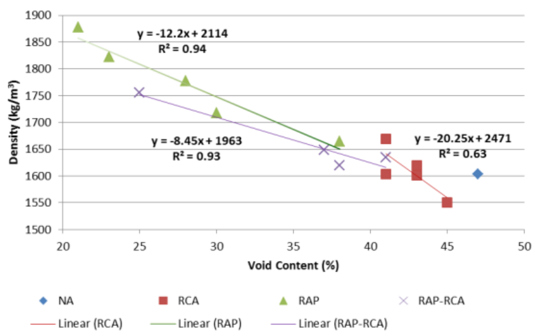


Fig. 3 Relationship between density and void content for all mixes

Where *B* is the submerged mass of the specimen in g, and ρ_w is the density of the water in Kg/m^3.

2.4.2 Water permeability

The water permeability of PC was determined by using falling head method that was adopted by Guneyisi *et al.* (2016). The cylindrical specimen was wrapped by flexible polyethylene foam membrane to prevent the leakage of water along the sides and to allow the flow of water vertically through the specimen. The time for water to flow through the specimen was reported at the initial (h_o) and the final (h_1) levels. The water permeability test was determined under the falling of head from 500 mm to 250 mm. For each specimen, three readings were reported and the average was taken. The coefficient of permeability was calculated using Darcy's low from the following equation

$$\text{Water permeability} = \left(\frac{aL}{At}\right)\ln\left(\frac{h_o}{h_1}\right) \tag{3}$$

Where a is the area of pipe in mm^2, L and A are the length and area of specimen in mm, mm^2, respectively, t is the time in seconds from h_o to h_1, h_o is the initial water level in mm, and h_1 is the final water level in mm.

2.4.3 Compressive, splitting tensile and flexural strengths

The compressive strength was conducted in accordance with ASTM C39-17. Splitting tensile strength was conducted in accordance with ASTM C496-11, and flexural strength was in accordance with ASTM C293-16. Three specimens were tested at the age of 28 days for each mix and the average of the three values was reported.

2.4.4 Thermal conductivity

The thermal conductivity of PC was determined using the cylindrical specimen with 100 mm diameter and 200 mm height at the age of 28 days using an instrument TLS-100 thermal conductivity system.

3. Results and discussions

3.1 Density, void content, and porosity

The values of density, void content, and porosity for all mixes are shown in Table 3. Also, the corresponding standard errors for each property are shown in the table. All the densities were in the range of 1601-1878 kg/m^3. These values are within the range that was done by many researchers in the literature (Chandrappa and Biligiri 2016, Zaetang 2016, Guneyisi *et al.* 2016). In general, the densities of RCA mixes were lower than the NA control mix and there was a reduction in the density with the increase of the RCA replacement level. This is due to the fact that the specific gravity of RCA was lower than that of NA. However, the densities of RAP and (RAP and RCA) mixes were higher than the NA control and the RCA mixes because the specific gravity of RAP was the highest.

The void content for the NA control mix was 47% while the void contents for the RCA mixes ranges from 41 to 43%. The void contents of the RCA mixes were very similar to the NA control mix which shows that the replacement of NA with RCA did not affect the void content

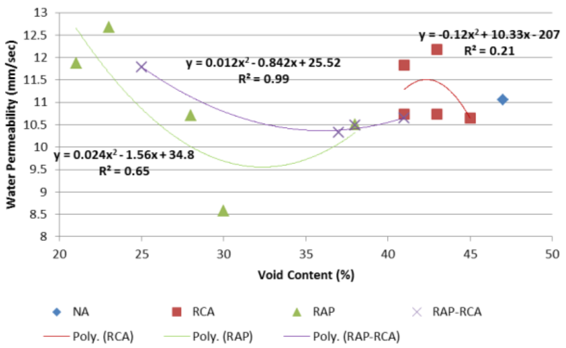


Fig. 4 Relationship between water permeability and void content for all mixes

significantly. This fact is similar to what was reported by Zaetang *et al.* (2016). However, the void contents for RAP and (RAP and RCA) mixes ranged from 21 to 38%, and 37 to 41%, respectively. These values are lower than that for the NA control mix. Accordingly, the replacement of NA with RAP affects the void content despite that the mix proportions and the aggregate sizes were the same. The reason behind this is the increase amount of asphalt that was coating aggregates which filled the voids and lowered the void contents of those mixes.

The relationship between density and void content for all mixes are shown in Fig. 3. There is a good relation between density and void content of all PC mixes. The R^2 values for RCA, RAP, and (RAP-RCA) mixes were 0.63, 0.94, and 0.93, respectively.

The porosity for the NA control mix was 0.32 while the porosity of RCA mixes ranges from 0.29 to 0.30 The porosity of the RCA mixes were very similar to the NA control mix which shows that the replacement of NA with RCA did not affect the porosity significantly. However, the porosity for RAP and (RAP and RCA) mixes ranged from 0.18 to 0.27, and 0.27 to 0.28 respectively. These values are lower than that for the NA control mix. This could be related to the coating film around RCA and RAP mixes.

3.2 Water permeability

The water permeability for all mixes is shown in Table 3. Also, the corresponding standard errors for the water permeability are shown in the table. The water permeability for all mixes ranged from 10.32 to 12.68 mm/s. These values are within the range that was done by many researchers in the literature (Chandrappa and Biligiri 2016, Zaetang 2016, Guneyisi *et al.* 2016). On average, the water permeability for RCA mixes were almost the same as the NA control mix and increased with the increase of the RCA replacement level. This increase is due to the slight increase in the void content which allows the water to pass more freely through the specimens. On the other hand, the water permeability for RAP and (RAP and RCA) mixes was slightly lower than the NA and the RCA mixes but are still acceptable. The reason behind that could be due to lower void content of those mixes which delay the movement of water through the specimens.

The relationship between water permeability and void content for all mixes are shown in Fig. 4. There is a good relation between water permeability and void content of all PC mixes. The R^2 values for RCA, RAP, and (RAP-RCA) mixes were 0.21, 0.65, and 0.99, respectively.

3.3 Compressive strength

The results of the compressive strength at 28 days for all PC mixes are shown in Table 4 and Fig. 5. Also, the corresponding standard errors for the compressive strength are shown in the table. It can be seen that replacing the NA with RCA, RAP, and (RAP and RCA) enhanced the compressive strength of PC significantly. The strength of the RCA mixes increased in the range of 36.36 to 54.54% compared to the NA mix. The optimum strength was for the RCA-40 mix and the compressive strength decreased as the replacement level of RCA increased. These results are similar to what was reported by Zaetang *et al.* (2016). They concluded that: (1) replacing NA with RCA improved the compressive strength; (2) the optimum strength was achieved for 60% replacement level; and (3) the compressive strength reduced upon increasing replacement of RCA above optimum.

Regarding the influence of using the RAP mixes; the compressive strength of those mixes showed better enhancement. The strength of the RAP mixes increased in the range of 45.94 to 201.58% compared to the NA control mix. The optimum strength was for the RAP-80 mix and the compressive strength increased as the replacement level of RAP increased. On the other hand, the optimum increase in the compressive strength was for (RAP and RCA) mixes. The increase was in the range of 76.28 to 248.62% compared to the NA mix. RAP-80-RCA-20 mix showed a decrease in the compressive strength compared to the other two mixes in its group. This could be due to the low content of RCA in this combined mix. Accordingly, the optimum strength was reported to be for the RAP-60-RCA-40 mix which was 8.82 MPa. This mix is considered the most optimum one among the twelve mixes.

The increase in the strength for the RAP and the (RAP and RCA) mixes was due to the high toughness of recycled asphalt aggregates. In PC the cement paste layer is quite thin and the old asphalt is coating the aggregates providing a thin film at the interface of aggregate and cement mortar. This will cause the crack propagation to develop around the aggregate rather than through it causing more energy to be dissipated and enhancement in the toughness of the RAP mixes (Huang *et al.* 2006).

3.4 Splitting tensile strength

The results of splitting tensile strength at 28 days for all PC mixes are shown in Table 4 and Fig. 6. Also, the corresponding standard errors for the splitting tensile strength are shown in the table. It can be reported that replacing the NA with RCA, RAP, and (RAP and RCA) enhanced the splitting tensile strength of PC significantly. The strength of the RCA mixes increased compared to the NA mix. The optimum strength was for the RCA-20 mix and the strength decreased as the replacement level of RCA increased. These results are similar to what was reported by

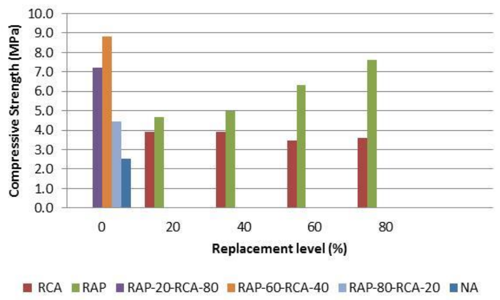


Fig. 5 Compressive strength at 28 days for all mixes

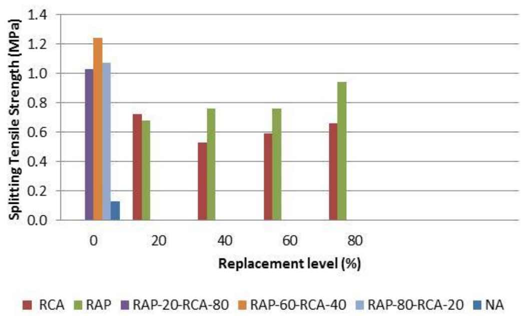


Fig. 6 Splitting tensile strength at 28 days for all mixes

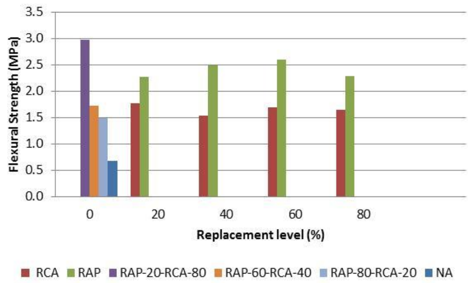


Fig. 7 Flexural strength at 28 days for all mixes

Zaetang *et al.* (2016) and Guneyisi *et al.* (2016). It can be noted from the results that the decrease was irregular especially for the RCA-80 mix. This could be due to some errors in the splitting tensile test for this mix.

Regarding the effect of using the RAP mixes; the splitting tensile strength of those mixes showed better improvement. The optimum strength was for the RAP-80 mix and the splitting tensile strength increased as the replacement level of RAP increased. On the other hand, the optimum increase in the splitting tensile strength was for (RAP and RCA) mixes. RAP-80-RCA-20 mix showed a decrease in the splitting tensile strength compared to the other two mixes in its group. This could be due to the low content of RCA in this combined mix. Accordingly, the optimum strength was reported to be for the RAP-60-RCA-40 mix which was 1.24 MPa. This mix is still considered the most optimum one among all mixes.

3.5 Flexural strength

The results of flexural strength at 28 days for all PC mixes are shown in Table 4 and Fig. 7. Also, the corresponding standard errors for the flexural strength are shown in the table. Again, it can be said that replacing the NA with RCA, RAP, and (RAP and RCA) improved the flexural strength of PC significantly. The strength of the RCA mixes increased compared to the NA mix. The optimum strength was for the RCA-20 mix and the flexural strength decreased as the replacement level of RCA increased. These results are similar to what was reported by Zaetang *et al.* (2016). It can be noted from the results that the decrease was irregular for the RCA-40 mix. This could be due to some errors in the flexural strength test for this mix.

Regarding the influence of using the RAP mixes; the flexural strength of those mixes showed better improvement. The flexural strength increased as the replacement level of RAP increased. Only the flexural strength of RAP-80 mix showed a decrease in strength compared to the other mixes in its group. Accordingly, the optimum strength was for the RAP-60 mix

On the other hand, the optimum increase in the flexural strength was for (RAP and RCA) mixes. The optimum strength was reported to be for the RAP-20-RCA-80 mix which was 2.97 MPa.

3.6 Thermal conductivity

The results of thermal conductivity for all PC mixes are shown in Table 4. The thermal conductivity of the NA control mix was 0.764 W/m K. The thermal conductivity of the RCA mixes was low compared to the NA control mix. These results are similar to what was reported by Zaetang *et al.* (2016). The thermal conductivity of the RCA mixes ranged from 0.546-0.93 W/m K. Regarding the effect of using the RAP mixes; the thermal conductivity of those mixes showed higher values; it ranged from 0.812-0.912 W/m K. While for the (RAP-RCA) mixes it ranged from 0.782-0.992 W/m K.

The thermal conductivity of PC is usually lower than CC. For CC it is usually ranges between 0.98 and 1.46 W/m K (Zaetang *et al.* 2016).

4. Conclusions

This paper presented a study addressing the effects of using recycled coarse aggregate (RCA), recycled asphalt pavement (RAP), and (RAP and RCA) on the properties of pervious concrete (PC). Based on the test results, the following conclusions were drawn:

1. The densities of RCA mixes were lower than the PC natural aggregate (NA) control mix and there was a reduction in the density with the increase of the RCA replacement level. However, the densities of RAP and (RAP and RCA) mixes were higher than the NA control mix.

2. The replacement of NA with RCA did not affect the void content significantly. However, the replacement of NA with RAP and (RAP and RCA) affected the void content by lowering them compared to the NA control mix.

3. The water permeability for RCA mixes were almost the same as the NA control mix and increased with the increase of the RCA replacement level. On the other hand, the water permeability for RAP and (RAP and RCA) mixes

Table 4 Compressive, splitting tensile, flexural strengths and thermal conductivity for mixes

Mix type	Compressive strength (MPa)	Compressive strength Standard Error	Splitting Tensile Strength (MPa)	Splitting Tensile Strength Standard Error	Flexural Strength (MPa)	Flexural Strength Standard Error	Thermal conductivity (W/m K)	Thermal conductivity Standard Error
NA-0	2.53	0.022	0.13	0.0056	0.69	0.0406	0.764	0.0151
RCA-20	3.91	0.160	0.72	0.0215	1.78	0.0122	0.546	0.1813
RCA-40	3.91	0.160	0.53	0.0202	1.54	0.0537	0.608	0.0412
RCA-60	3.45	0.040	0.59	0.0271	1.70	0.0107	0.636	0.0110
RCA-80	3.60	0.086	0.66	0.0209	1.65	0.0146	0.930	0.0031
RAP-20	4.68	0.055	0.68	0.0279	2.28	0.0428	0.841	0.0081
RAP-40	4.98	0.005	0.76	0.0237	2.49	0.1050	0.889	0.0003
RAP-60	6.32	0.048	0.76	0.0376	2.61	0.0558	0.912	0.0012
RAP-80	7.63	0.349	0.94	0.0102	2.29	0.0361	0.812	0.0116
RAP-20-RCA-80	7.22	0.479	1.03	0.0256	2.97	0.0455	0.992	0.0015
RAP-60-RCA-40	8.82	0.235	1.24	0.0208	1.73	0.0368	0.926	0.0200
RAP-80-RCA-20	4.46	0.122	1.07	0.0139	1.50	0.0203	0.782	0.0172

was slightly lower than the NA and the RCA mixes.

4. Replacing the NA with RCA, RAP, and (RAP and RCA) enhanced the compressive strength of PC significantly. The compressive strength decreased as the replacement level of RCA increased and increased as the replacement level of RAP increased. The optimum strength was reported to be for the RAP-60-RCA-40 mix which was 8.82 MPa.

5. Replacing the NA with RCA, RAP, and (RAP and RCA) enhanced the splitting tensile strength of PC significantly. The splitting tensile strength decreased as the replacement level of RCA increased and increased as the replacement level of RAP increased. The optimum strength was reported to be for the RAP-60-RCA-40 mix which was 1.24 MPa.

6. Replacing the NA with RCA, RAP, and (RAP and RCA) enhanced the flexural strength of PC significantly. The flexural strength decreased as the replacement level of RCA increased and increased as the replacement level of RAP increased. The optimum strength was reported to be for the RAP-20-RCA-80 mix.

7. The thermal conductivity of the RCA mixes was low compared to the NA control mix. While it was higher for the RAP mixes.

Accordingly, it is recommended that the RAP and RCA can be used in the previous concrete in order to reduce the negative impact on human health and the environment.

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