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Laboratory investigation of portland cement concrete containing recycled asphalt pavements

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Abstract

Recycled asphalt pavement (RAP) is the removed and/or reprocessed pavement material containing asphalt and aggregate. The use of RAP in asphalt pavement has become a common practice in the construction of new, and reconstruction of old, hot mix asphalt (HMA) pavements. But little research has been done to examine the potential of incorporating RAP into concrete. Since RAP contains asphalt, it is very likely that the toughness of concrete made with RAP could be improved. In the present study, the mechanical properties of RAP-incorporated Portland cement concrete were investigated through laboratory experiments. Two types of RAP (coarse and fine RAP) materials were considered. The results from this study indicated that RAP could be incorporated into Portland cement concrete without any modification to the conventional equipment or procedures. Without any treatment, there was a systematic reduction in the compressive and split tensile strengths with the incorporation RAP in concrete. Notably, the energy absorbing toughness for the RAP incorporated concrete has been significantly improved.

Keywords: Portland cement; Concrete; Recycled asphalt

1. Introduction

The use of recycled materials in Portland cement concrete (PCC) has become more and more popular in recent years. Most recycled materials applied in PCC are used to replace coarse aggregates (such as crushed PCC), fine aggregates (such as crushed waste glass), or act as cementitious additives (such as granulated blast furnace slag and fly-ash, etc.) [1–5].

When using recycled materials in PCC, it is desirable that the properties of the concrete can also be improved. Plain PCC, while typically having high strength, generally possesses very low post failure toughness, which may cause abrupt failure of structures and short pavement life. Partially replacing coarse or fine aggregates in PCC with waste rubber tires greatly improves the toughness and energy absorbing capability of PCC. However, both compressive and tensile strength have been significantly decreased [6–10]. Thus, the applications of waste tire modified PCC have been limited to non-structural areas.

On the other hand, reclaimed or recycled asphalt pavements (RAP) have been routinely used in the construction of pavement granular bases and hot-mix asphalt concrete. RAP is the removed and/or processed asphalt pavement materials containing both aged asphalt and aggregates. Typical RAP materials contain both coarse and fine aggregates. The asphalt coated on the surface of the aggregates typically forms a film with a thickness between six to nine microns. Every year, the US highway industry generates over 100 million tons of RAP through the rehabilitation and reconstruction of existing highways. The use of RAP in PCC, though seems to be a viable solution to improve the toughness, has received little attention by research communities.

As a composite, the performance of concrete can be improved for high toughness and crack resistance by systematically tailoring the concrete microstructure via modern concrete fracture mechanics [11]. In concrete made

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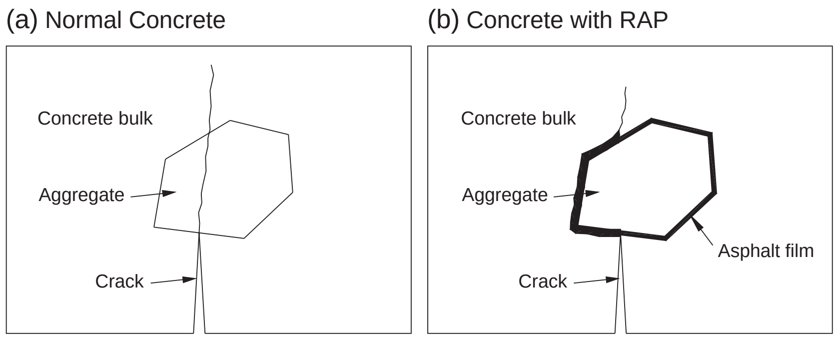

Fig. 1. Crack propagation in concrete and concrete with RAP.

with RAP, asphalt forms a thin film at the interface of cement mortar and aggregate, which can be used to arrest crack propagation, Fig. 1. Thus, crack develops around rather than go through aggregate particle, during which more energy can be dissipated. This is likely to be the toughness improvement of concrete made with aggregates coated with emulsified asphalt [12].

The objective of the present study was to explore the potential of using RAP in Portland cement concrete to enhance its toughness and reduce its chances of brittle failure.

2. Laboratory experiment

Laboratory experiment was carried out to investigate the material characteristics of PCC incorporated with RAP. Two types of RAP (coarse and fine) materials were considered to replace the fresh aggregates from the control PCC mixture. Instead of using real RAP from highway, laboratory fabricated RAP materials were prepared for this study. Compressive and split tensile strength tests were employed to evaluate the mechanical properties of hardened concrete at the curing time of 3, 7, 14 and 28 days.

2.1. Materials

Commercially available Type I Portland cement conforming ASTM C150 was used in this study. The density of the cement was 3150 kg/m^3.

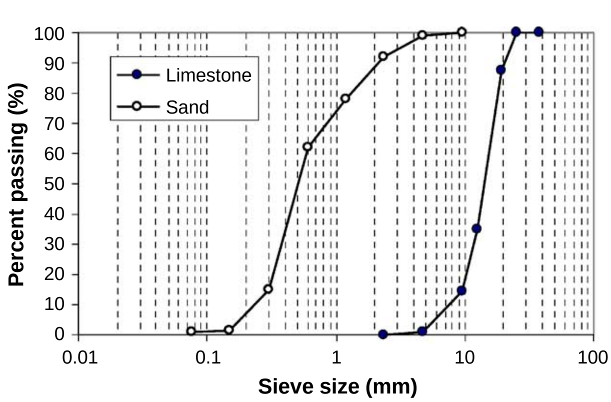

Fig. 2. Gradations of limestone and sand.

The coarse aggregates selected in this study were No.57 limestone with nominal maximum size of 19mm. The saturated dry density and absorption were 2790 kg/m^3 and 0.49%[13], respectively. The gradation curve of limestone is shown in Fig. 2.

The fine aggregates used in the laboratory study were natural Ohio River sand with a fineness modulus of 2.45 and a saturated dry density and absorption of 2600 kg/m^3 and 1.4%[14], respectively. The gradation curve of sand is also shown in Fig. 2.

2.2. RAP preparation

In order to evaluate the performance of concrete made with and without RAP, laboratory-made RAP materials rather than the actual RAP from pavements were used. The amount of asphalt was first calculated such that the asphalt film around the aggregate particle was 8 μm. The aggregates were then super-heated in a forced draft oven prior to being mixed with asphalt cement (PG64-22) in the laboratory using a mechanical mixer. After mixing, the artificial RAP mixture was subjected to an aging process for a period of 12 h at 120 °C. Laboratory-made RAP was obtained after the separation with No. 4 sieve (4.75 mm). Coarse RAP consisted of asphalt-coated aggregates retained on No. 4 sieve and fine RAP materials were those passing No. 4 sieve. Except for the difference in size, coarse and fine RAP are actually the same materials.

2.3. Mixture proportions

In order to investigate the different effects of asphalt-coated coarse and fine aggregates on the properties of concrete, four groups of concrete mixtures were prepared in this study as shown in Tables 1 and 2.

Table 1
Mix variants and fresh concrete properties

Mix	Coarse aggregates	Fine aggregates	Air content (%)	Slump (cm)
1	Fresh	Fresh	1.60	16.5
2	RAP	Fresh	1.20	14.0
3	Fresh	RAP	2.50	7.5
4	RAP	RAP	2.00	20.0

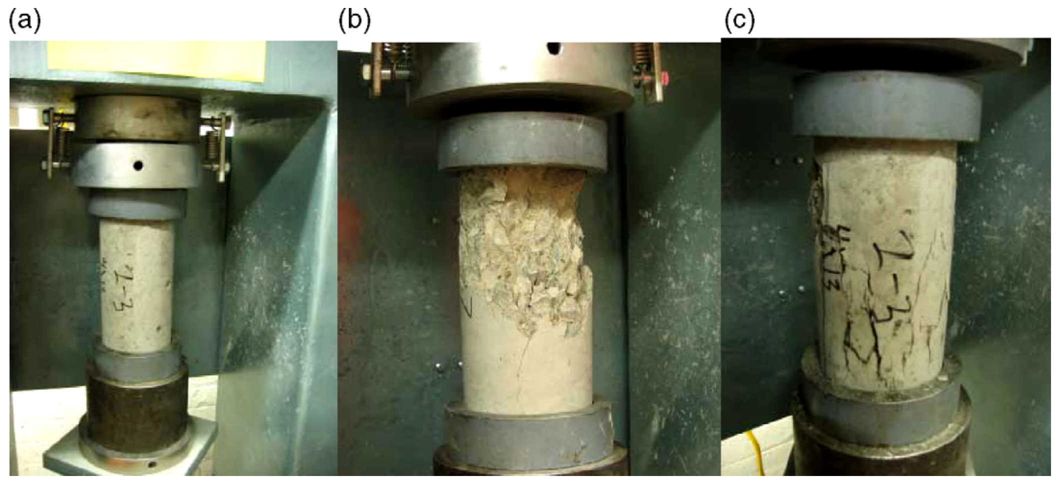

Fig. 3. Cylindrical specimens before and after compression test (a) Before test (b) Specimen without RAP after test (c) Specimen with RAP after test.

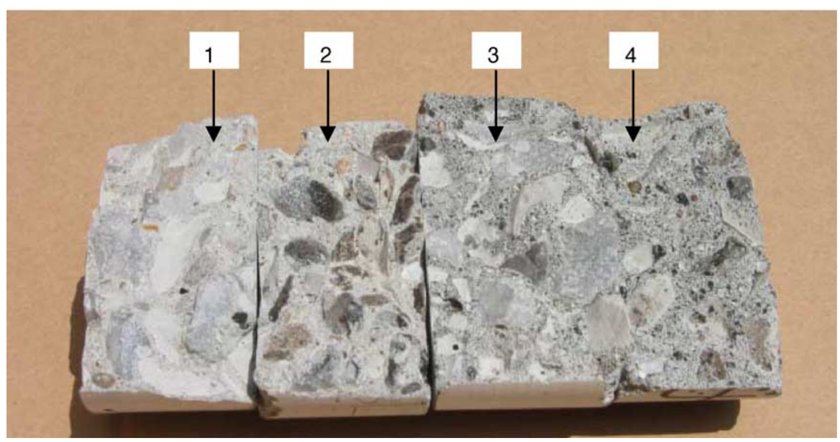

Fig. 4. Samples after split tensile strength test (labels indicate Mix no.).

2.4. Mixing and curing of concrete

Concrete mixtures were prepared using a mechanical mixer and applying standard rodding for compaction. The specimens were cured in a standard moisture curing chamber until the days of testing.

2.5. Testing procedures

∅100 × 200 mm (4 × 8 in.) cylindrical specimens were used to evaluate the compressive strength of concrete. For split tensile strength, circular specimens 100 mm in diameter by 50 mm in thickness were used. The split tension specimens were made by sawing a cylindrical specimen into 5 plates. The top and bottom plates were 25 mm thick and they were discarded to avoid the end effect. The remaining three middle plates were used to determine the split tensile strength.

The compressive strength of cylindrical specimens was measured in accordance with the ASTM C39 and AASHTO T22. Tests were performed on the specimens at 3, 7 and 28-days at 25 °C. Fig. 3 presents a specimen before and after the test.

An MTS machine was used to conduct the split tensile strength test. Fig. 4 presents split tensile test specimens

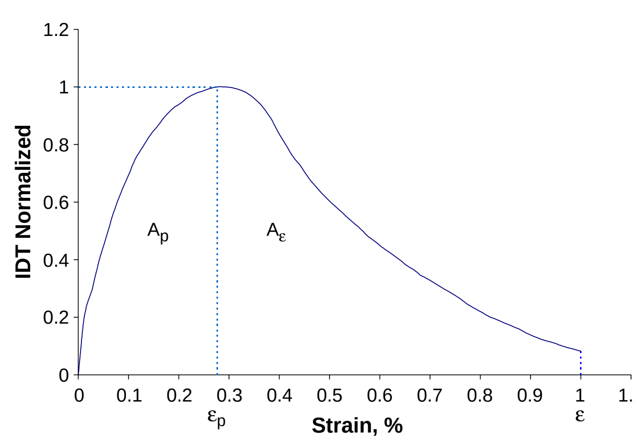

Fig. 5. Normalized IDT curve for TI calculation (after [15]).

Table 2
Laboratory mix proportions (kg/m^3)

Mix.	RAP sand[a]	RAP limestone[a]	Fresh sand[b]	Fresh limestone[b]	Cement	Water
1	/	/	646	1149	396	198
2	/	1149	646	/	396	198
3	646	/	/	1149	396	198
4	646	1149	/	/	396	198

[a] RAP sand and limestone are laboratory prepared asphalt-coated sand and limestone.
[b] Fresh sand and limestone are ordinary aggregates used in conventional concrete.

after the testing. Split tensile strength test was performed on specimens at 3, 7, 14 and 28-days at 25 °C. The loading rate was adjusted to 1.0 MPa/min according to ASTM C496.

Toughness index (TI), a parameter describing the toughness in the post-peak region, was also calculated from the indirect tensile test results. Fig. 5 presents a typical normalized indirect tensile stress and strain curve. A dimensionless indirect tensile toughness index, TI_{it} is defined as follows:

$$TI_{it} = \frac{A_{\varepsilon} - A_p}{\varepsilon - \varepsilon_p} \quad (1)$$

where TI_{it} - Toughness index, A_{ε} - Area under the normalized stress–strain curve up to strain ε, A_p - Area under the normalized stress–strain curve up to strain ε_p, ε - Strain at the point of interest, and ε_p - Strain corresponding to the peak stress.

This toughness index compares the performance of a specimen with that of an elastic perfectly plastic reference material, for which the TI remains a constant of 1. For an ideal brittle material with no post-peak load carrying capacity, the value of TI equals zero. In this study, the horizontal tensile strain was calculated from the vertical load head displacement using the theory of elasticity and Poisson's ratio for concrete was assumed to be 0.15. The values of indirect tensile toughness index were calculated up to tensile strain of 0.4%.

3. Discussion of results

3.1. Properties of fresh concrete

Table 1 presents the results of slump and air voids for fresh concrete. It can be seen that the air content of concrete with RAP was relatively close to that of control mix. However, the slump of concretes made with only coarse or fine RAP was lower than that of control concrete. This may be due to the high viscosity of asphalt binder. Surprisingly, the slump of concrete made with both coarse and fine RAP was higher than that of control mix. The reason could be probably attributed to the asphalt coating around both coarse and fine RAP so that less waster could be absorbed by the aggregates. The water absorption for fine RAP is 1.2%, which is slightly lower than that of fine aggregate. It was clear that concrete made with RAP could be mixed, cast and compacted using the same equipment and method for conventional concrete.

3.2. Properties of hardened concrete

A summary of test results regarding the compressive and split tensile strengths and strain corresponding to the peak split tensile stress of different concrete mixtures are presented in Table 3, Figs. 6 and 7.

3.2.1. Compressive strength

The results presented in Fig. 6 indicated a systematic reduction in compressive strength of concrete mixes made with RAP compared to that of control concrete. The strength of concrete made with both coarse and fine RAP

Table 3
Test results of hardened concrete

Concrete properties	Mix	Age (days)			
		3	7	14	28
Compressive strength (MPa)	1	22.0 (3.92)	29.3 (1.17)	/	37.7 (2.76)
	2	16.3 (1.29)	19.8 (1.28)	/	22.1 (1.45)
	3	14.1 (0.41)	16.2 (0.14)	/	18.8 (1.2)
	4	6.98 (0.16)	9.43 (0.48)	/	10.4 (0.52)
Split tensile strength (MPa)	1	3.01 (0.21)	3.21 (0.06)	3.23 (0.49)	3.21 (0.3)
	2	2.47 (0.17)	2.86 (0.17)	2.58 (0.37)	3.06 (0.21)
	3	2.08 (0.38)	2.26 (0.30)	2.54 (0.15)	2.54 (0.17)
	4	1.16 (0.16)	1.27 (0.12)	1.60 (0.36)	1.59 (0.14)
Strain at peak split tensile stress ($\times 10^{-3}$)	1	1.18 (0.12)	1.34 (0.28)	1.37 (0.14)	1.52 (0.04)
	2	1.15 (0.18)	1.26 (0.17)	1.32 (0.23)	1.15 (0.08)
	3	1.25 (0.13)	1.34 (0.21)	1.35 (0.11)	1.34 (0.08)
	4	1.19 (0.22)	1.65 (0.20)	1.57 (0.20)	1.56 (0.16)

Average value for three specimens, plus standard deviation (in parentheses).

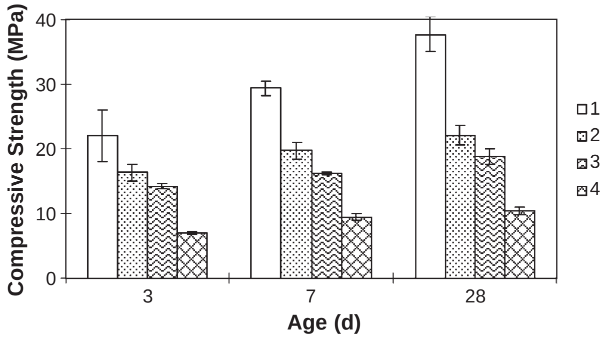

Fig. 6. Compressive strengths at different days.

decreased the most among the three RAP mixtures. The strength of the concrete with coarse RAP decreased the least. Whereas, the compressive strength reduction of concrete with fine RAP was in between the coarse RAP mix and whole (both coarse and fine) RAP mix. At 28-day, the strengths of Mix #2, #3 and #4 were 58.7%, 50% and 27.6% of that of control concrete, respectively.

As expected in this study, the reduction in strength was understandable because the asphalt film around the aggregate particle was much softer than the concrete matrix and aggregate. The presence of soft asphalt binder may have induced stress concentration and caused micro-cracking within the concrete matrix. The mechanism of such stress concentration can be found in reference [7]. Another possible reason could be the weak bonding between the asphalt film and the concrete matrix/aggregate. Based on the causes of reduction in strength, several possible methods can be proposed to mitigate the strength loss due to the incorporation of RAP, such as improving the strength and modulus of asphalt by aging, improving the bonding between asphalt and aggregate by changing the interface between them, etc.

3.2.2. Split tensile strength

Fig. 7 presents the results of split tensile strength test. The strength reduction pattern for the split tensile strength was similar to that of the compressive strength. However, the rate of strength reduction in the split tensile strength for RAP mixtures was significantly lower than that of the compressive strength. At 28-day, the split tensile strengths of Mix #2, #3,

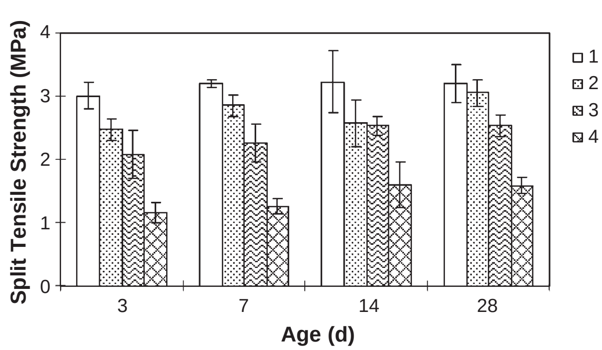

Fig. 7. Split tensile strength at different days.

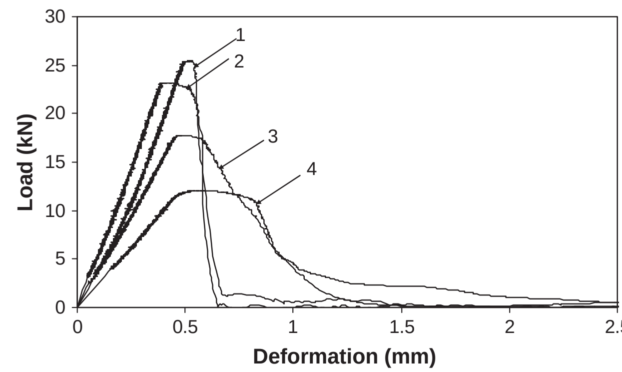

Fig. 8. Typical load-deformation curves of concrete specimens under split tensile strength test at 14 days.

and #4 were 95.3%, 79.1% and 49.5% of that of the control concrete, respectively. The split tensile strength of Mix #2 was very close to that of the control concrete.

3.2.3. Toughness

Fig. 8 presents the typical load-deformation curves of concrete specimens under split tensile strength test at 14 days. The vertical deformation was measured by using the load head displacement. It was noticed that mixtures with RAP could maintain the peak load while undergoing relatively long displacement. The increased toughness was also demonstrated by the failure mode of the specimens under compressive strength test. The specimens of concrete made with RAP did not disintegrate suddenly at failure while those of control concrete did. Only several cracks emerged on the surface of specimens of concrete with RAP at its failure (Fig. 3b).

Fig. 9 presents the calculated toughness index for the concrete mixtures under split tensile strength test at 14 and 28 days. The inclusion of RAP in concrete generally exhibited increased the toughness of the modified concrete. However, the concrete mixture with only fine RAP exhibited the similar toughness to the control mixture. Concrete mixtures with coarse RAP and whole RAP (both coarse and fine RAP) exhibited much higher energy absorption (the area between the load-deformation curve and the abscissa) than the control concrete.

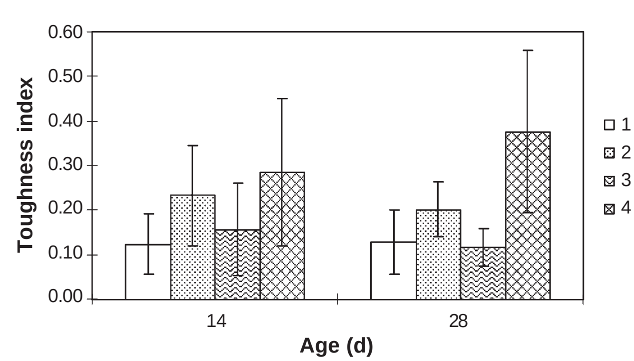

Fig. 9. Calculated toughness index from split tensile strength test to tensile strain of 0.4%.

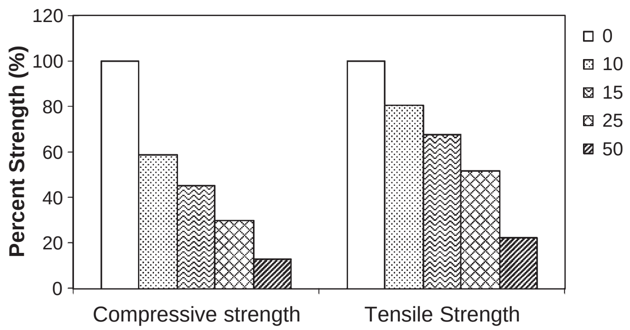

Fig. 10. Decrease in the strength of ruberized concrete (after [16]).

3.2.4. Comparison

In order to compare the findings in this study with the results of research on similar materials, Fig. 10 presents test results of concrete made with 0, 10%, 15%, 25%, 50% of aggregate volume replaced by rubber[16]. The trend of reduction in strength with the increase in the quantity of recycling materials for concrete incorporating RAP and rubber was similar. Due the much bigger difference of rubber from aggregate than RAP from aggregate, concrete with rubber exhibited greater decrease in strength than concrete with RAP. In Fig. 10, concrete with 50% of aggregate volume replaced by rubber exhibited less than 25% of the control concrete strength. Compared with rubber, RAP had better chance of replacing aggregate in concrete mix.

4. Summary and conclusion

A laboratory study has been carried out to evaluate the mechanical properties of concrete made with RAP. Based on the test results and discussion, the following conclusions can be drawn:

1. Conventional equipment and method can be used to mix, cast and cure the concrete made with RAP.
2. Concrete made with RAP exhibits a systematic reduction in both compressive and split tensile strengths.
3. Generally, the higher the content of RAP incorporated in concrete, the lower the strengths, the higher the toughness.
4. Concrete made with only coarse RAP shows the least reduction in the strength of the RAP concretes and significant increase in toughness. Thus it might be more practical to incorporate a certain portion of coarse RAP to replace coarse aggregate.
5. Concrete made with RAP had a much higher toughness than concrete without RAP, which is of practical importance for many civil engineering applications.

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