Experimental Study on Properties of Portland Cement Concrete Containing Recycled Asphalt Pavements

Baoshan Huang[1] and Xiang Shu[2]

Abstract

Although recycled asphalt pavement (RAP) are widely used in the construction of new, and reconstruction of old, hot mix asphalt (HMA) pavements, little research has been done to examine the potential of incorporating RAP into Portland cement concrete to replace virgin aggregate. Because RAP consists of aggregates coated by asphalt cement, the toughness of concrete made with RAP could be improved. In this paper, the mechanical properties of portland cement concrete containing RAP were investigated through laboratory experiments. Two types of RAP (coarse and fine RAP) materials were used to replace the equal amount of virgin coarse and/or fine aggregate. Silica fume and high-range water reducing agent (HRWRA) were also added into concrete mixtures to minimize the strength loss due to the incorporation of RAP. A total of 17 concrete batches were cast and tested for compressive and split tensile strengths, static compressive modulus of elasticity, and toughness index in accordance with ASTM standards. Test results indicated that there was a systematic reduction in the strengths and elastic modulus as well as an increase in the toughness index with the increase in RAP content. While the addition of HRWRA into the matrix improved the mechanical properties of concretes containing RAP, addition of silica fume unexpectedly did not.

Introduction

In the past few decades, ever increasing concern over solid waste and by-product materials generated in our society has spurred the recycling of these materials in Portland cement concrete pavements. Most recycled materials applied in PCC are usually 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.) (Nagataki *et al*. 2004; Craig *et al*. 1998; Swamy *et al*. 1983; Sakai *et al*. 1993; Malhotra *et al*. 2000).

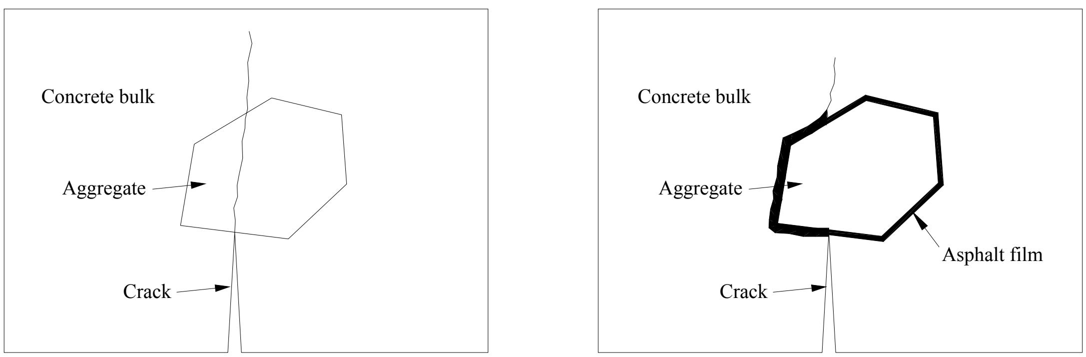
Generally, recycled materials should be used in such a manner that the expected performance will not be compromised. It is desirable that some properties of the concrete can be improved. Plain PCC, while typically having high strength, generally possesses low failure toughness, which may cause abrupt failure of structures and short in-service life of pavement. 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 (Huang *et al*. 2004; Li *et al*. 2004; Topçu 1995; Eldin

[1] Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996; PH (865)974-7713; FAX (865)974-2608; email: bhuang@utk.edu
[2] Department of Civil and Environmental Engineering, The University of Tennessee, Knoxville, TN 37996; PH (865)974-7938; FAX (865)974-2608; email: xshu@utk.edu

and Senouci 1993; Herna´ndez-Olivares *et al*. 2002). Thus, the applications of waste tire modified PCC have been limited to non-structural applications.

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 material 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, although it 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 (Li and Maalej 1996). In concrete made with RAP, asphalt forms a thin film at the interface of cement mortar and aggregate, which can be used to arrest crack propagation, Figure 1. The forming of this film is likely to be the toughness improvement of concrete made with aggregates coated with emulsified asphalt (Li *et al*. 1998).



(a) Normal Concrete **(b) Concrete with RAP**

Figure 1. Crack Propagation in Concrete and Concrete with RAP

The objective of the present study was to evaluate the feasibility and performance of Portland cement concrete incorporating RAP. The potential of using RAP in PCC to enhance its toughness and reduce its chances of brittle failure also was explored. Methods to minimize the strength loss due to the incorporation in PCC were also investigated.

Research Significance

This paper investigates the potential of using recycled asphalt pavement in Portland cement concrete. The results reported in this paper show that concrete containing RAP exhibits a systematic reduction in compressive and split tensile strength with the increasing amount of RAP while its toughness is improved. This paper also shows that it is practical to incorporate fine RAP to replace fine aggregate because of the better performance of concrete containing fine RAP than concrete containing coarse RAP.

Raw materials

Commercially available Type I Portland cement conforming to ASTM C150 was used in this study. The specific gravity of the cement was 3.15.

The coarse aggregates selected in this study were No.57 limestone with nominal maximum size of 19mm. The saturated surface-dry specific gravity and absorption were 2.79 and 0.49%, respectively. The gradation curve for the limestone is shown in Figure 2.

The fine aggregates used in the laboratory study were natural Ohio River sand with a fineness modulus of 2.45 and a saturated surface-dry specific gravity and absorption of 2.60 and 1.4%, respectively. The gradation curve of sand is also shown in Figure 2.

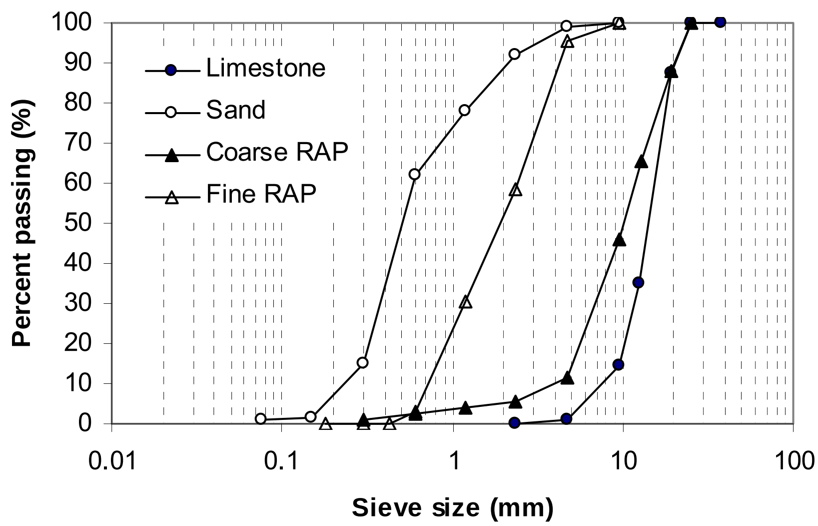


Figure 2. Gradations of aggregates and RAP

Two types of RAP (coarse and fine) were used in this current study (Figure 3). The gradation curves of coarse and fine RAP are also shown in Figure 2. The asphalt content of coarse and fine RAP are asphalt contents of coarse and fine RAP are 5.8% and 7.1%, respectively.

Silica fume powder with a specific gravity of 2.2 conforming to ASTM C 1240 was used in this laboratory investigation.

High-range water reducing agent (HRWRA) conforming to ASTM C 494 type A and F was used in this study.

In preparation of RAP-modified concrete, 10, 30, 50, 100 percent by weight of coarse or/and fine aggregate were replaced with coarse or fine RAP. 10, 20 percent by weight of cement was replaced with silica fume. The mix proportion by weight was cement: water: limestone: sand (: HRWRA) = 1: 0.50: 2.90: 1.63 (: 0.0104). When HRWRA was used, water was reduced by 23 kg/m^3 and 35 kg/m^3 for concrete mix with and without silica fume, respectively, to keep the slump with 2 – 4 cm. Concrete mixtures were prepared using a mechanical mixer and applying standard rodding for compaction. Slump test and air content test were conducted on the fresh concrete to estimate the workability of the concrete. The specimens were cured in a standard moisture curing chamber until the days of testing.

(a) Coarse RAP

(b) Fine RAP

Figure 3. RAP materials

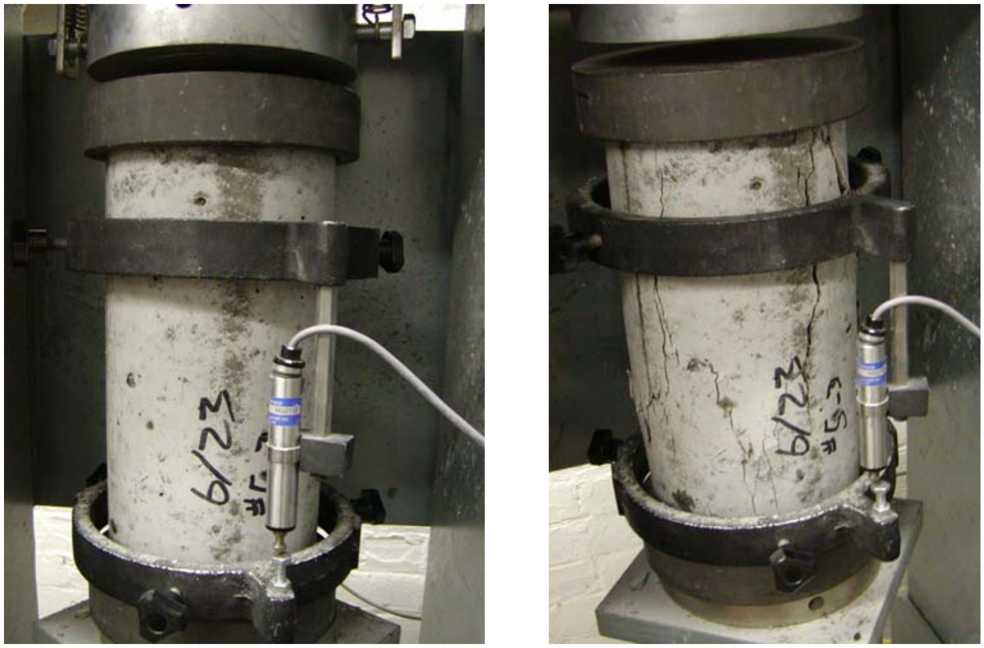
Testing Procedures

In order to investigate the effects of different factors on the performance of Portland cement concrete containing RAP, a total of 17 batches of concrete mixtures were prepared in this study. For each batch, 3 cylinder specimens were tested for the compressive strength and elastic modulus and 6 circular plate specimens cut from the cylinder specimen were tested for the indirect tensile strength and toughness index.

Specimen Size. Cylindrical specimens 150 mm diameter × 300 mm (6 × 12 in.) 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 100 × 200 mm (4 × 8 in.) 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 (Figure 4).

Figure 4. Split tensile strength test specimen

Compression Test. The compressive strength and compressive modulus of elasticity of cylindrical specimens was measured in accordance with the ASTM C39. Tests were performed on the specimens at 28 days at 25 ^{o}C. Figure 5 presents specimens before and after the test.



(a) Before test **(b) After test**

Figure 5. Cylindrical specimens before and after compression test

Split Tensile Strength Test. An MTS machine was used to conduct the split tensile strength test. Figure 6 presents a specimen under split tension test. Split tensile strength test was performed on specimens at 28 days at 25 ^{o}C. The loading rate was adjusted to 0.01 in./min so that it is close to the loading rate specified in ASTM C496.

Toughness index (TI), a parameter describing the toughening characteristics in the post-peak region, was also calculated from the indirect tensile test results. Figure 7 presents a typical normalized indirect tensile stress and strain curve. A dimensionless indirect tensile toughness index, TI is defined as follows:

$$TI = \frac{A_\varepsilon - A_p}{\varepsilon - \varepsilon_p} \qquad (1)$$

where

TI – 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 values of indirect tensile toughness index were calculated up to a tensile strain of 0.4 percent.

Figure 6. Split Tensile Strength Test Setup

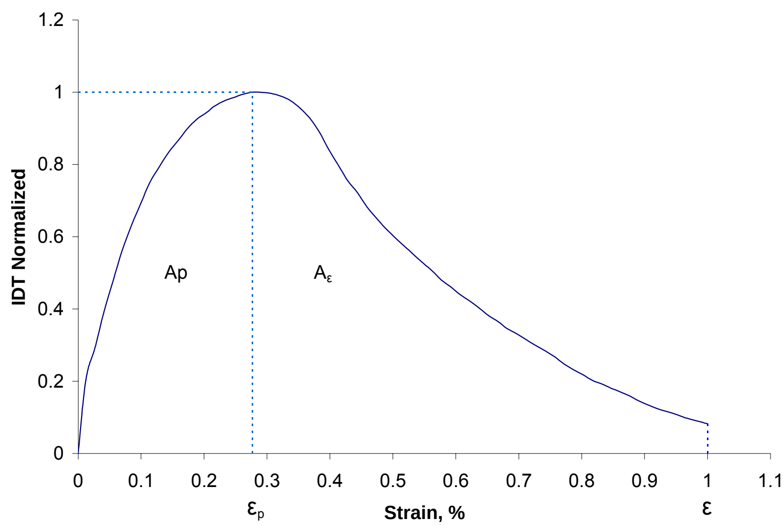
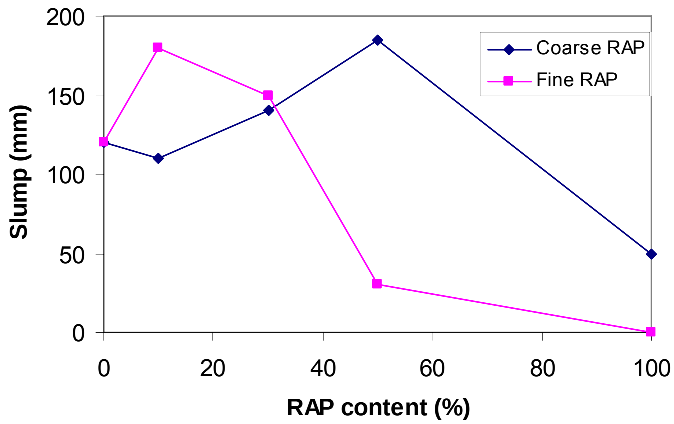


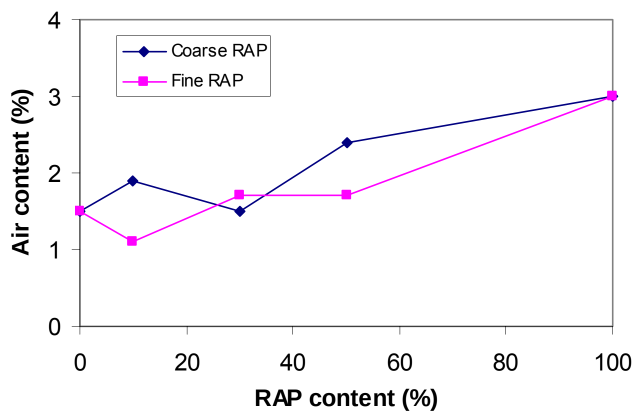
Figure 7. Normalized IDT Curve for TI Calculation (After Huang *et al*. 2004)

Discussion of Results

Effect of RAP on the workability. Slump and air content are two important parameters indicative of the workability of fresh concrete. The variations of slump and air content of the RAP-modified concrete with coarse or fine RAP content are shown in Figure 8. It was observed that at low RAP contents, slump was increased with the introduction into concrete, resulting in a better workability. However slump of concrete with higher RAP content decreased dramatically. When fine aggregate was fully substituted with fine RAP, the slump even became zero, resulting in the poor workability. Air content didn't change too much for concrete in this study. However there was a trend that concrete with high RAP content had a slightly higher air content.



(a) Slump



(b) Air content

Figure 8. Influence of RAP content on properties of fresh concrete

Effect of RAP on the toughness. The test results for toughness index of concrete containing coarse or fine RAP are shown in Fig. 9. From Fig. 9 it can be readily seen that the toughness index of concrete containing RAP is higher than that without RAP and generally the higher the RAP content, the higher the toughness index. A comparison of the toughness indices of concretes with coarse and fine RAP shows that at RAP content less than 50%, both concrete mixtures exhibited almost the same increase in the toughness index. However, at 100% RAP content, concrete containing fine RAP showed a much higher increase than did concrete with coarse RAP (Fig. 10).

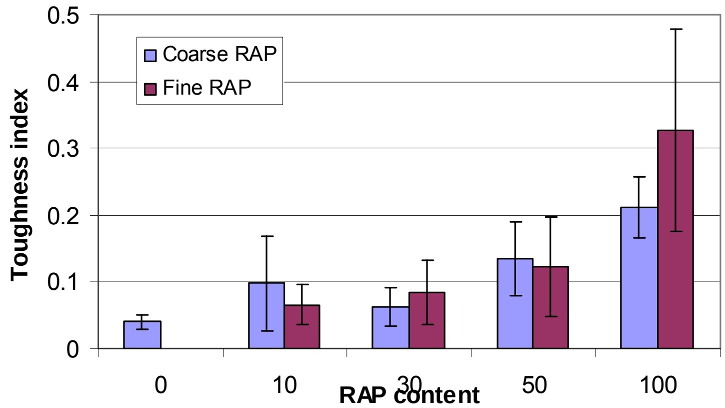


Figure 9. Variation in toughness index with RAP content

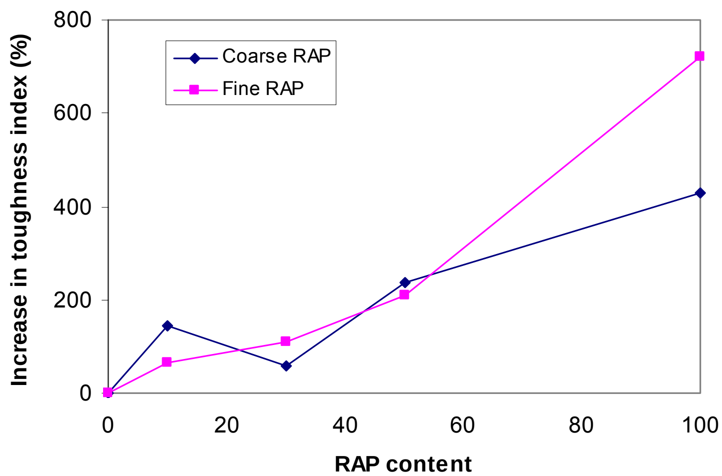
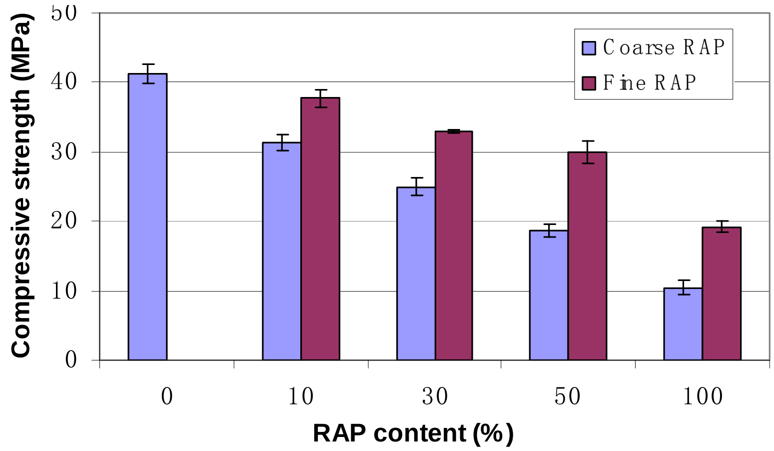
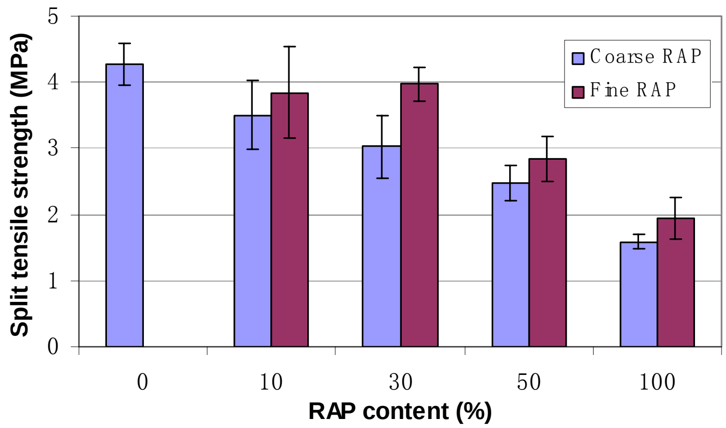


Figure 10. Percent increase in toughness index

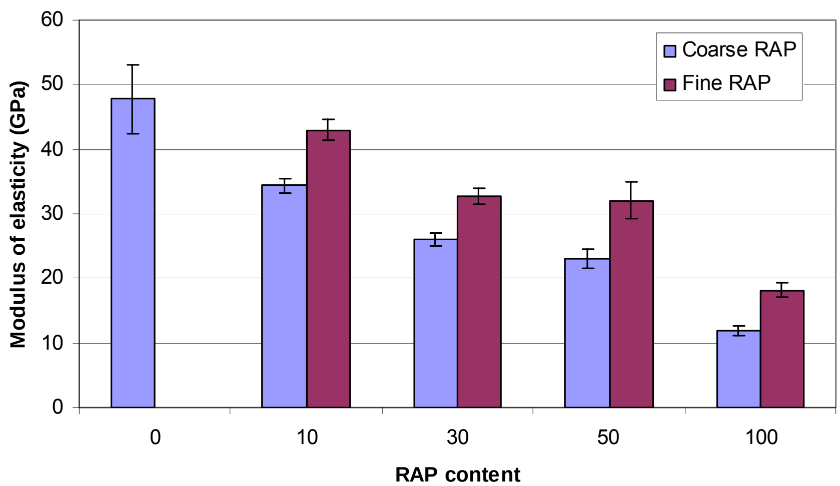
Effect of RAP on the strength and modulus. The test results for compressive and split tensile strength and modulus of elasticity are shown in Fig. 11. From Fig. 11 it can be seen that the strength and modulus of RAP-modified concrete are lower than those of the control concrete, regardless of coarse or fine RAP. The higher the RAP content, the greater the reduction in the properties. The reason for this phenomenon can be attributed to: (1) the lower modulus of asphalt film compared to aggregate and cement paste and (2) the poor bonding between aggregate and asphalt film and between asphalt film and cement paste. Due the huge difference in modulus between aggregate (cement paste) and asphalt, stress concentration will inevitably occurs between aggregate (cement) and asphalt which will cause microcracking of the concrete matrix and thus reduce the strength and modulus of the modified concrete. The difference in the properties between aggregate (cement paste) and asphalt also results in the weaker bonding between them than those between aggregate and cement paste which will further worsen the strength and modulus of elasticity.



(a) Compressive strength



(b) Split tensile strength



(c) Modulus of elasticity

Figure 11. Variation of strength and modulus with RAP content

Coarse RAP versus fine RAP. From Fig. 11, it can also be seen that concrete with coarse or fine RAP exhibited similar trend in the reduction in compressive and split tensile strength and modulus of elasticity. However the reduction degree was different. The decrease in the mechanical properties of concrete with fine RAP was smaller than that with coarse RAP. Take compressive strength for example. When half virgin coarse or fine aggregate was replaced with RAP, about 75% of the compressive strength of concrete with fine RAP was retained compared with half of the strength retained for concrete with coarse RAP. The reason could be attributed to the different RAP contents by the total aggregate weight. Concrete with fine RAP actually contains less RAP by the total aggregate weight than concrete with coarse RAP at equal coarse or fine RAP content (Fig. 12).

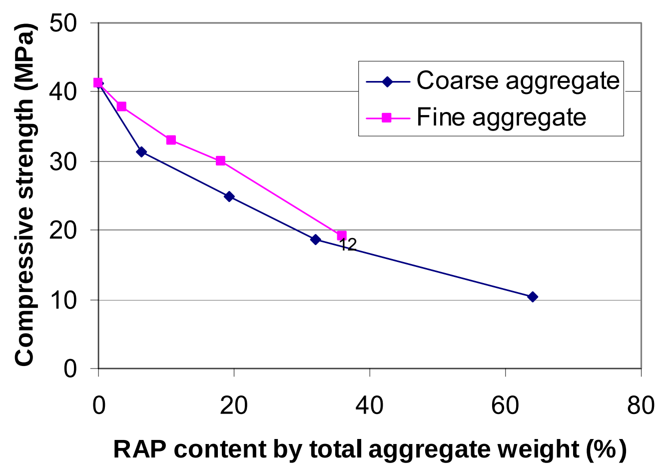
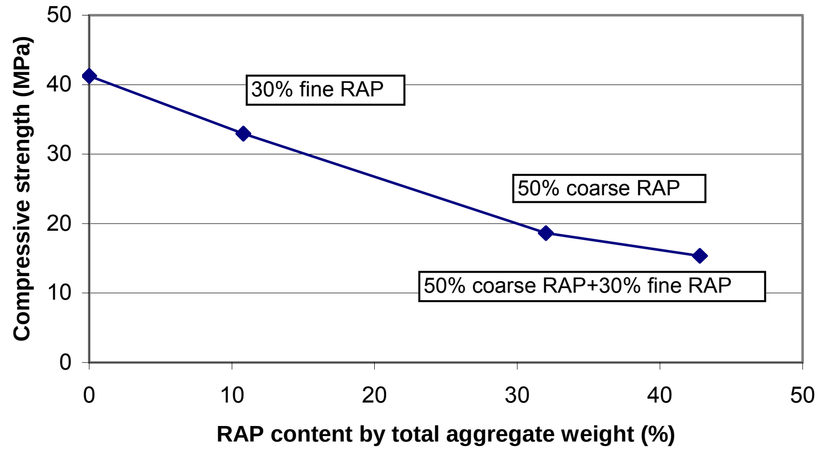
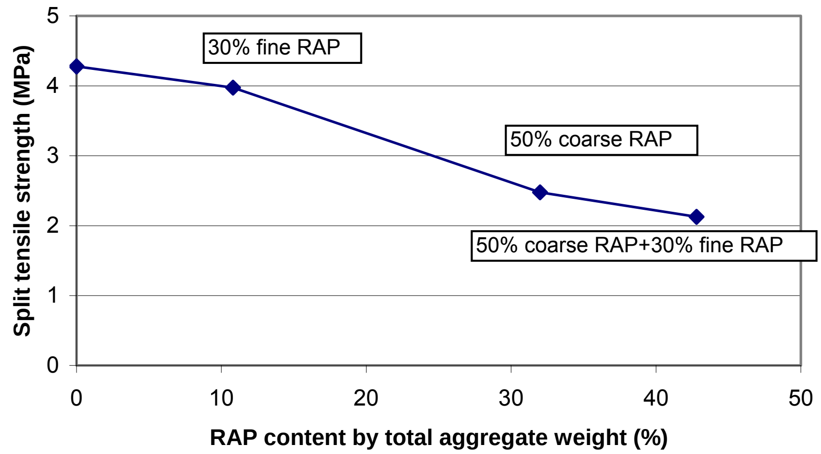


Figure 12. Variation of compressive strength with RAP content by total aggregate weight

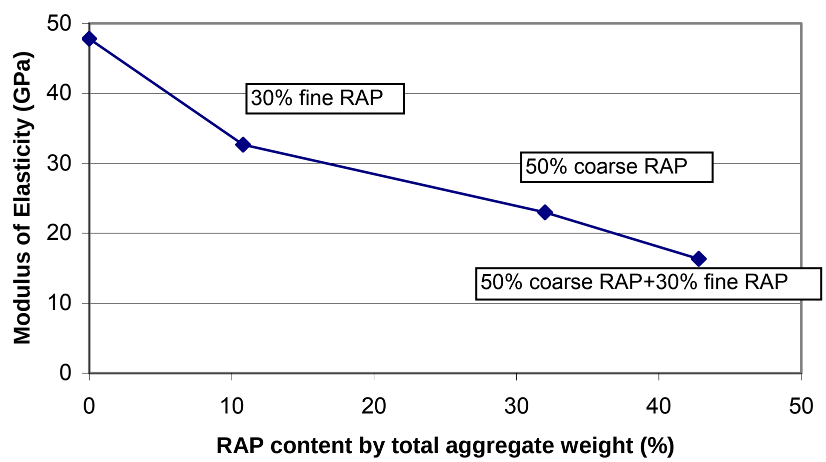
Effect of combination of coarse and fine RAP. Fig. 13 shows the influence of the combination of coarse and fine RAP on compressive and split tensile strength and modulus of elasticity. Concrete containing both coarse and fine RAP exhibited a larger decrease in the properties than concrete with only coarse or fine RAP. The higher reduction in the properties of concrete with both coarse and fine RAP is obviously attributed to the higher overall RAP content by total aggregate weight due to the combination of both coarse and fine RAP.



(a) Compressive strength



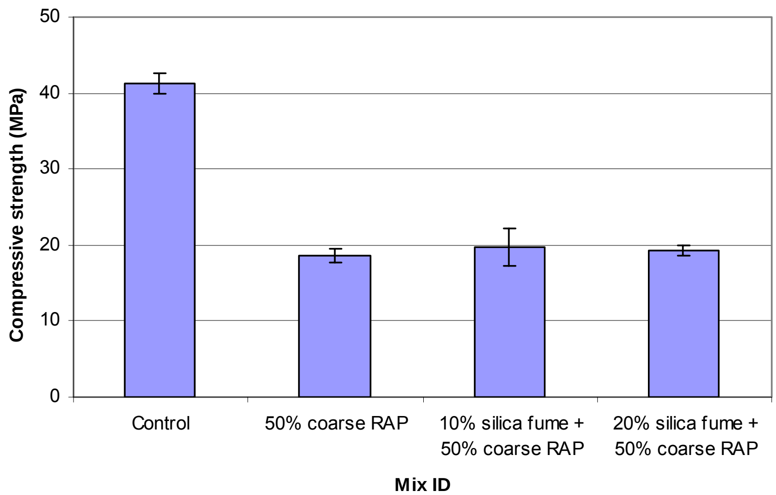
(b) Split tensile strength



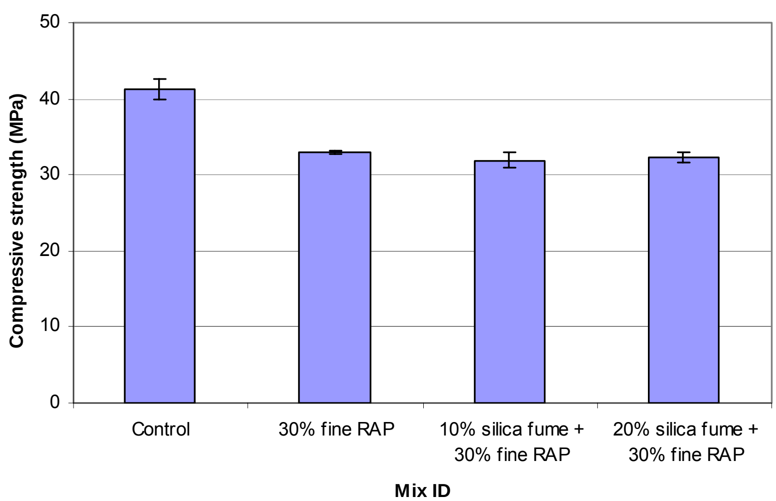
(c) Modulus of elasticity

Figure 13. Effect of combination of coarse and fine RAP on properties of concrete

Effect of silica fume. In this study, silica fume was added into the concrete to minimize the negative effects caused by the inclusion of RAP. Fig. 14 presents the compressive strengths of concretes with and without silica fume. From Fig. 14, it was observed that the compressive strength of concrete containing silica fume was only slightly higher or, in some cases, lower than that of concrete without silica fume, which indicated that the use of silica fume had no significant impact or trend on concrete strength in this study. The contribution of silica fume to the strength improvement was not as good as expected (Güneyisi *et al*. 2004). The reason for that may be attributed to the fairly short curing period of the concrete (28d) and the poor consolidation due to the low slump. It is reasonable to expect that the performance of concrete with silica fume could be improved markedly if it is subjected to a considerably longer curing period and proper consolidation. For split tensile strength and modulus of elasticity, similar phenomena were observed.



(a) Concrete mix with coarse RAP



(b) Concrete mix with fine RAP

Figure 14. Effect of silica fume on compressive strength

Effect of HRWRA. In this study, high-range water reducing agent (HRWRA) was also used to minimize the reduction in the mechanical properties concrete made with RAP. Fig. 15 shows the compressive strengths of concretes with and without HRWRA. It can be seen that HRWRA did contribute to the compressive strength improvement of concrete containing RAP. However, the effect of HRWRA on the strength gain seemed somehow decreased when combined with silica fume. Concrete with both silica fume and HRWRA did not exhibit a significant performance improvement as expected. Similar phenomena were also observed for split tensile strength and modulus of elasticity.

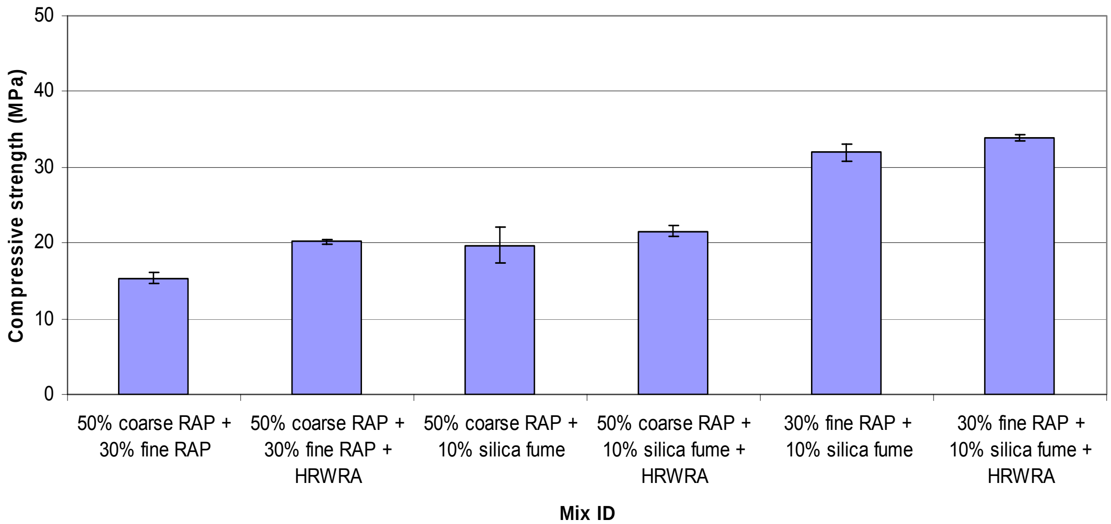


Figure 15. Effect of HRWRA on compressive strength

Summary and Conclusions

An extensive research program was experimentally carried out to investigate the potential use of RAP into concrete and to evaluate the mechanical properties of concrete made with RAP. Ways to minimize the reduction in strength and modulus of concrete due to the incorporation of RAP were also tested. Based on the test results and analyses, the following conclusions can be drawn:

1. Conventional equipment and method can be used to mix, cast and cure the concrete containing RAP.
2. At low percentages, RAP did not influence the workability of concrete much.
3. Concrete made with RAP exhibits a systematic reduction in both compressive and split tensile strength and modulus of elasticity, regardless of RAP type.
4. Generally, the higher the content of RAP incorporated in concrete, the lower the strengths and modulus of elasticity, and the higher the toughness.
5. Concrete made with RAP had a much higher toughness index than concrete without RAP, which is of practical importance for many civil engineering applications.

6. While the addition of HRWRA into the matrix improved the strength properties of concretes containing RAP, addition of silica fume did not.

Acknowledgments

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