

# Effects of Crushed RAP on Free and Restrained Shrinkage of Mortars

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**Abstract:** Reclaimed asphalt pavement (RAP) is abundant substitute for natural aggregate in many areas. It is obtained by crushing of old road pavements in milling machine during rehabilitation and reconstruction process. In this study, reclaimed asphalt pavement mortars (RAPM) have been produced with different cement dosages and replacement ratios. The destructive and nondestructive tests have been conducted on specimens to determine physical and mechanical properties of RAPM. The free and restrained shrinkage tests on RAPM have been conducted to predict fractural behavior of mortars. The aim of the shrinkage tests was to delay crack formation and improve strain capacity of mortars before cracking. The results showed that RAPM exhibits lower elasticity modulus; however the tensile capacity was improved for deformation before cracking.

**Keywords :** recycling, mechanical property, mortar, cracking, shrinkage.

## 1. Introduction

The use of recycled materials in cement based composites has become more popular in recent years. Each year, 73 million tons of reclaimed asphalt pavements (RAP) have been reused. RAP is used not only for new roads, but also for roadbeds, shoulders and embankments. The U.S. highway industry generates over 100 million tons of RAP through the rehabilitation and reconstruction of existing highways. Asphalt pavements (roads, parking lots, drive-ways) are most recycled products with over 80% of the pavement removed each year being reused in various forms in the construction of new asphalt pavements. RAP is typically generated through milling a portion of the pavement structure or through full depth removal.

Waste materials have been reused instead of coarse or fine aggregates in concrete or mortars.<sup>1</sup> Generally, scientists have been studied on improvement of toughness and workability of concrete and mortars.<sup>2</sup> They proved that the replacement of waste materials as coarse or fine aggregates in concrete greatly improves the workability, toughness and energy absorbing capability.<sup>3</sup> However, compressive and tensile strengths have been decreased.<sup>4,5</sup> Asphalt forms a thin film at the interface of cement mortar and aggregate, which can be used to arrest crack propagation in concrete.<sup>6</sup> The results obtained with cement-treated materials and roller compacted concrete show that introduction of RAP in hydraulic materials leads to a decrease of splitting tensile strength

but also to a greater decrease of elastic modulus. Evolution of both properties lost interest in pavement material owing to the lower elastic modulus limits and the increase in pavement thickness due to the lower tensile strength.

The studies have presented various results obtained with concrete mixtures incorporating different amounts of RAP, and the permeability of blended RAP is similar to that of conventional granular material.<sup>7</sup> Cement based materials are brittle and sensitive to cracking due to their poor capacity for deformation and low tensile strength.<sup>8</sup> In this case, shrinkage can be improved with recycling of waste materials such as rubber of waste tires or reclaimed asphalt pavements etc. Several test methods have been used to determine free and restrained shrinkage behaviors of cement based materials. Restrained ring test has been the most popular among quality control tests for assessing the shrinkage cracking potential of cement based mixtures.<sup>9</sup>

## 2. Experimental study

### 2.1 Materials

In experiments, CEM II/B-M 32.5 R Portland cement, city network water and CEN standard sand were used in respect of TS EN 197-1, TS 1247 and TS EN 196-1, respectively. The properties of cement and chemical analysis of mixture water is given in Tables (Table 1 and Table 2). The water/cement ratio was 0.5 in mortar series. The RAP was crushed into 0-4 mm to replace with standard sand. The unit weight of the RAP varies between 1,940 and 2,300 kg/m<sup>3</sup>. However, the saturated specific weight and water absorption value of RAP were 2,530 kg/m<sup>2</sup> and 0.7%~0.8%, respectively (Table 3).

### 2.2 Experimental method

In experiments, physical and mechanical properties of RAPM

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**Table 1** Properties of CEM II/B-M 32.5 R Portland cement.

Chemical compositions (%)		Physical properties	
SiO <sub>2</sub>	31.53	Specific gravity	2.85
Al <sub>2</sub> O <sub>3</sub>	7.06	Specific surface (cm <sup>2</sup> /g)	3574
Fe <sub>2</sub> O <sub>3</sub>	3.29		
CaO	48.89	Compressive strengths (MPa)	
MgO	1.46	2 <sup>nd</sup> day	12.8
SO <sub>3</sub>	2.01	7 <sup>th</sup> day	26.9
Cl <sup>-</sup>	0.27	28 <sup>th</sup> day	42.5
LOI	4.55		

**Table 2** Properties of mixture water.

Parameters	Values
pH	6.85
Calcium (Ca) <sup>++</sup>	58 mg/l
Magnesium (Mg) <sup>++</sup>	83 mg/l
Chloride (Cl) <sup>-</sup>	46 mg/l
Sulfate (SO <sub>4</sub> ) <sup>--</sup>	45 mg/l
Vaporization	434 mg/l

**Table 3** Physical and mechanical properties of RAP.

Type of property	RAP property	Typical range of values
Physical properties	Unit weight	1,940~2,300 kg/m <sup>3</sup>
	Moisture content	Normal: up to 5% Maximum: 7~8%
	Asphalt content	Normal: 4.5~6% Maximum range: 3~7%
	Asphalt penetration	Normal: 10~80 at 25°C
	Absolute viscosity or recovered asphalt cement	Normal: 4,000~25,000 poises at 60°C
Mechanical properties	Compacted unit weight	1,600~2,000 kg/m <sup>3</sup>
	California bearing ratio	100% RAP: 20~25% 40% RAP and 60% natural aggregate: 150%

were investigated in addition to fractural behavior of ring specimens. The destructive and nondestructive tests were conducted on fresh and hardened mortars. The mixture ratios were determined due to the weight batch method. Mortars were produced with 450 g CEM II/B-M 32.5 R Portland cement per 1350 g CEN standard sand or RAP owing to replacement ratios. The water/cement ratio was kept constant at the ratio of 0.5 in all experiments. The volumetric mixture proportions and weight batch ratios of RAPM are shown in tables (Table 4 and Table 5). The RAP was used instead of sand with the replacement ratios of 0, 25, 50, 75 and 100% to produce specimens at dimensions of 40 × 40 × 160, 25 × 25 × 285 and 150 × 150 × 150 mm, furthermore ring speci-

**Table 4** Volumetric mixture proportions of RAPM.

Experimental test	Specimen number	Dimension (mm)	Volume (m <sup>3</sup> )	Total volume (m <sup>3</sup> )
Compressive strength	6	40 × 40 × 40	Obtained from flexural strength test	
Flexural strength	6	40 × 40 × 160	0.0002560	0.0015360
Modulus of elasticity	6	150 × 150 × 150	0.0033750	0.0202500
Free shrinkage	2	25 × 25 × 285	0.0001782	0.0003563
Restrained shrinkage	2	Ring	0.0043872	0.0087745

**Table 5** Mixture proportions for 1 m<sup>3</sup> RAPM.

RAP (%)	Sand (kg)	Cement (kg)	Water (kg)	RAP (kg)
0	1,760	580	290	0
25	1,320	580	290	440
50	880	580	290	880
75	440	580	290	1,320
100	0	580	290	1,760

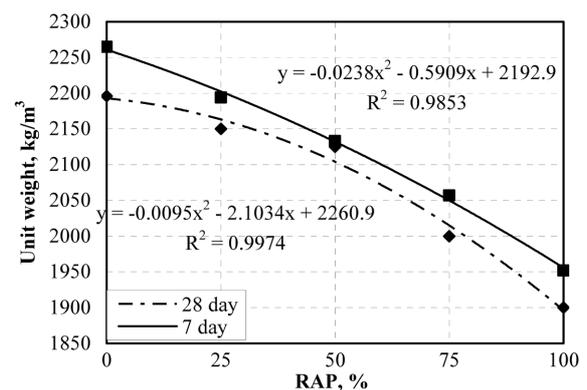
mens with 35 mm thick and 140 mm height were produced. The ring and 25 × 25 × 285 mm prismatic specimens were initially exposed to 20°C temperatures and 100% relative humidity (RH) during 24 hours. Afterward, specimens were exposed to temperature of 20°C and 50% RH for 60 days while 70 × 70 × 70, 40 × 40 × 160 and 150 × 150 × 150 mm specimens were cured at 20°C in lime saturated water for 7 and 28 days to conduct mechanical tests (ASTM C 157).

In ring tests, outer mould of ring was removed 24 hour after casting, and silicone was used to prevent drying from the upper surface of mortar ring. The crack formations were observed during 60 days, and crack widths and lengths were measured each day. The average crack openings at the top, middle and bottom of ring mortar was considered for measuring crack widths. The mechanical and physical properties of 40 × 40 × 160 and 150 × 150 × 150 mm specimens were tested at the end of the 7<sup>th</sup> and 28<sup>th</sup> days. The unit weight, ultrasound pulse velocity, compressive and flexural strengths were determined (ASTM C 349-02). Furthermore, elasticity modulus and abrasions were obtained on 150 × 150 × 150 and 70 × 70 × 70 mm prismatic specimens, respectively (ASTM C 469-02).

### 3. Results and discussion

#### 3.1 Unit weight

The hardened unit weight of RAPM decreased with the increase



**Fig. 1** Hardened unit weight of RAPM.

in RAP ratio for both 7 and 28-day specimens (Fig. 1). The unit weights of RAPM were generally lower than the control series. This behavior occurs owing to the lower unit weight of RAP compared to natural sand. However, it was observed that the decrease rate in 7-day unit weight was similar with the decrease rate in 28-day unit weight. However 13% decrease in unit weight with the 100% RAP content was observed for both 7 and 28-day specimens.

### 3.2 Ultrasound pulse velocity

The ultrasound pulse velocity was determined on  $40 \times 40 \times 160$  mm specimens. Approximately, 23% and 20% decrease in ultrasound pulse velocity were observed for 7 and 28-day specimens with the RAP content of 100%, respectively (Fig. 2). The decrease in ultrasound pulse velocity can be explained by the porous structure of RAP.

### 3.3 Compressive strength

The decreases owing to porosity and lower strength of RAP in compressive strengths were observed with the increment in RAP content (Fig. 3). The best fit curve of compressive strength was approximately linear in 7-day specimens. The decreasing slope in 28-day specimens were higher for 25% RAP content, however the rest of the RAP content were linear likewise in 7-day specimens. The decrements in compressive strengths of 7 and 28-day RAPM specimens with the 100% RAP content were approximately 60%. However RAPM with the RAP content between 25% and 75% were still adequate for various types of structures.

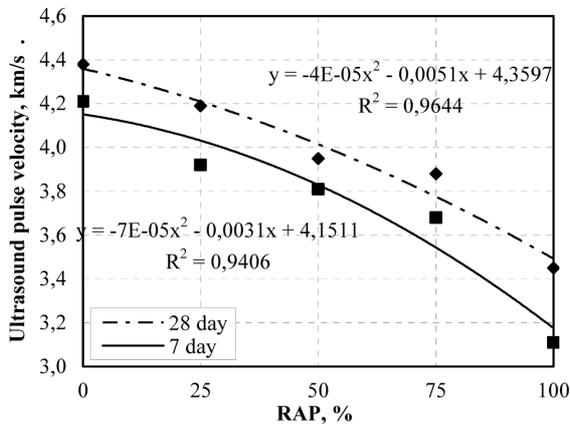


Fig. 2 Ultrasound pulse velocity of RAPM.

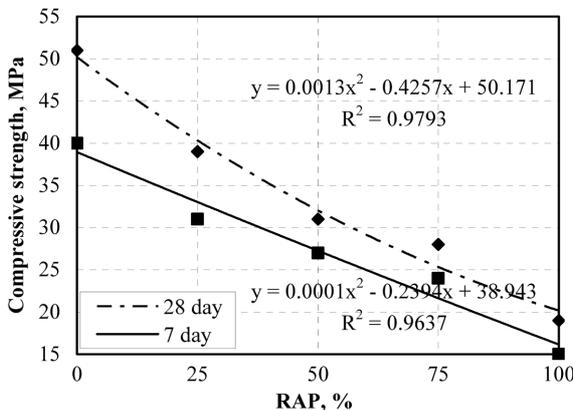


Fig. 3 Compressive strength of RAPM.

### 3.4 Flexural strength

The decrements in flexural strength were observed with the increasing RAP content (Fig. 4). Approximately, 40% decrements in flexural strengths were observed in both 7 and 28-day specimens with the RAP content of 100%, however lower replacement ratios (25~75%) were acceptable due to the results. A linear decrement for both 7 and 28-day RAPM were obtained in experiments.

### 3.5 Restrained shrinkage cracks

The aim of the ring tests was to observe and determine restrained shrinkage cracks, initial cracking time, crack length and widths. Dimensions of the ring specimens, ring test set up and restrained shrinkage cracks are shown in figures (Figs. 5 to 7). In experiments, crack widths were measured with optical binoculars. It was observed that the initial time for restrained shrinkage cracking was delayed with the increment in RAP content (Table 6). Crack

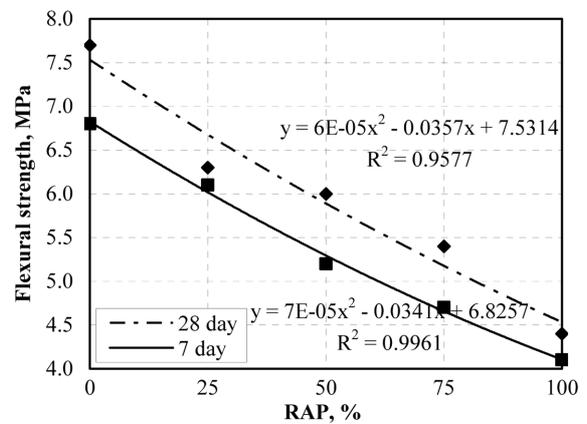


Fig. 4 Flexural strength of RAPM.

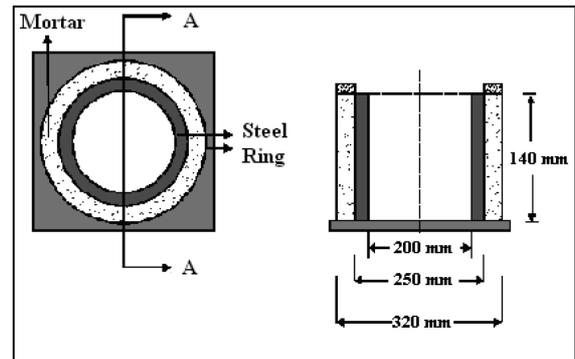


Fig. 5 Dimensions of a ring specimen.



Fig. 6 Ring test set up.



Fig. 7 Restrained shrinkage crack of RAPM 50% series.

Table 6 Restrained ring test results.

RAP (%)	0	25	50	75	100
First cracking time (day)	17	21	23	26	27
Crack number for 60 days	1	1	1	1	1
Main crack length for 60 days (mm)	140	140	140	140	140
Max. crack opening (mm)	0.70	0.47	0.39	0.32	0.17

widths were decreased and first cracking was also delayed systematically with the increment in RAP content. Approximately, 75% decrement in crack width of RAPM 100% series was observed compared to control series (Fig. 8). The highest first cracking time and lowest crack width were both observed in series of RAPM 100%. This is explained by the porous structure of RAPM (Fig. 9). This leads lower strength development and modulus of elasticity for the higher RAP content. As is known, lower compressive strength and modulus of elasticity leads a delay in crack formation and also leads lower crack width formation. The porosity is the most effective reason on delayed crack formation. However, in this study, it was proved that lower replacement ratios (25–50%)

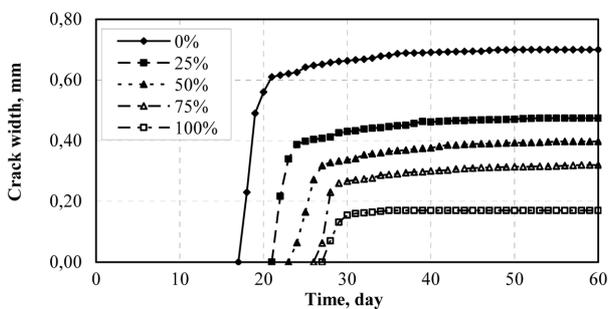


Fig. 8 Crack width of restrained shrinkage for RAPM.

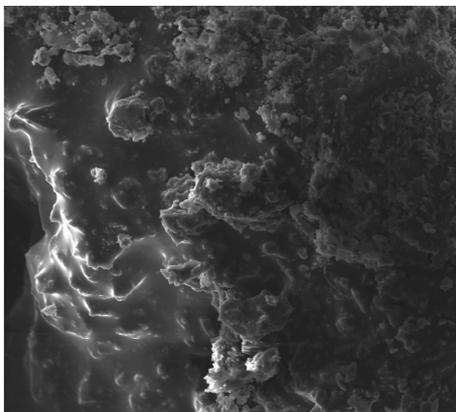


Fig. 9 Microstructure of RAPM (EHT:20.00 kV, WD: 9 mm, Mag: 591x).

of RAP were adequate for obtaining delayed crack formation due to the modulus of elasticity results and compressive strengths. The RAP contents of 50–100% were excessively high in experiments to obtain appropriate elasticity modulus, however the RAP ratios of 0-10-20-30-40-50% which have lower intervals will be preferred. Nevertheless, crack widths in all series were still lower than the crack widths of control series. This was verified with the behavior of modulus of elasticity.

The initial cracks occurred in 17<sup>th</sup>, 21<sup>st</sup>, 23<sup>rd</sup>, 26<sup>th</sup> and 27<sup>th</sup> days for the 0, 25, 50, 75 and 100% RAP content, respectively; after exposure of 20°C and relative humidity of 50%. The crack widths approximately reached to final width after 40 days for all series. However, the crack formations were faster in first 4 days after first crack. It was observed that the slope of the curves for all series were similar. In other words, first cracking delayed and final crack formation was slowed down with the increment in RAP content. However due to the results, this situation is more effective for the series of 50–100% owing to excessively porous structure compared to other series. Thus minimum crack widths were obtained in 100% RAP content. The maximum and minimum crack widths were obtained as 0.70 and 0.17 mm for control and 100% series respectively, after 60 days of exposure time. Similarly, crack lengths were also delayed with the increment in RAP content. The crack lengths reached to final length (140 mm) generally for 10 days in all series and remained constant. The measurements of crack width were all conducted on main cracks; no sub-cracks were occurred on specimens during 60 day period.

### 3.6 Free shrinkages

In experiment, similar curing conditions were applied with the restrained shrinkage test (20°C and 50% RH). Higher RAP content leads lower unit deformation due to lower water absorption capacity however; it was observed that the unit deformations in free shrinkage tests of RAPM specimens systematically increased with the increase in RAP content. Approximately 40% increment was obtained in 100% RAPM series compared to the control series. This is explained as the lower modulus of elasticity ensures less restraint in cement paste for free shrinkage. The less stiff aggregate reduces the internal strain and thus increase the elongation in free shrinkage test. Control series and 25% series were similar compared to other series (Fig. 10).

### 3.7 Modulus of elasticity

In experiments, modulus of elasticity was obtained with the

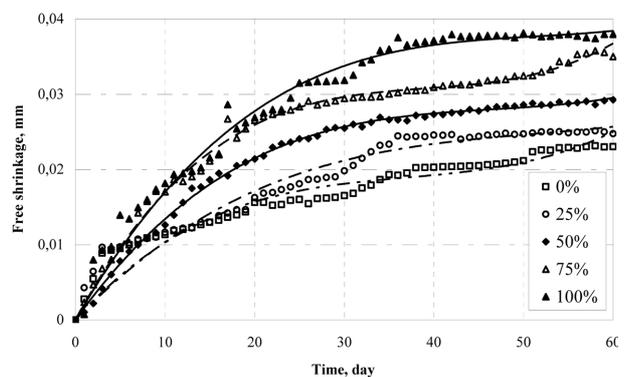


Fig. 10 Unit deformations of free shrinkage for RAPM.

tests conducted on 28-day RAPM specimens (Fig. 11). Modulus of elasticity decreased systematically with the increment in RAP content. The variations are approximately linear up to ratio of 50% RAP and polynomial after series of 50%. It was observed that the deformation values for 75~100% series were similar. However, the experimental moduli of elasticity of each specimen were higher in series of control and 25% RAP compared to other series. The lowest value was obtained in series of 100%; approximately 65% decrement was obtained in this series compared to control series. Internal restraint decreased with the decrease in compressive strength and modulus of elasticity.

### 3.8 Abrasion

The abrasion tests were conducted on 70 × 70 × 70 mm RAPM specimens by Bohme disc (TS 699). It was observed that the abrasion increased with the increase in RAP ratio (Fig. 12). The minimum and maximum abrasions were obtained as 7.0 and 8.6 cm<sup>3</sup>/50 cm<sup>2</sup> on 25 and 100% RAPM series, except control series. It was proved that the lower replacement ratios of RAP can be appropriate for several constructions.

## 4. Conclusions

The optimum RAP content for mechanical properties was obtained between 25% and 50% series. The restrained shrinkage test results of RAPM were adequate at higher RAP content despite the lower strengths. However, free shrinkage behavior was totally

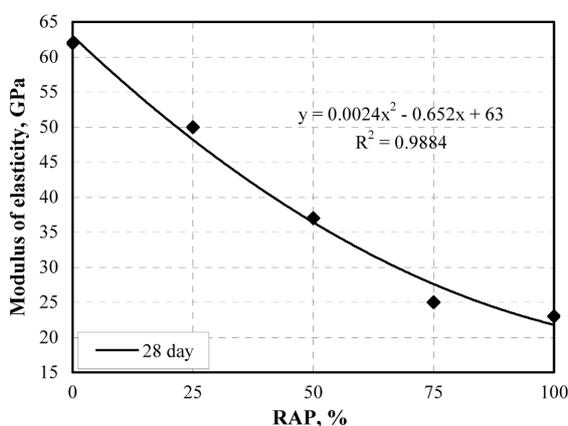


Fig. 11 Experimental modulus of elasticity for RAPM.

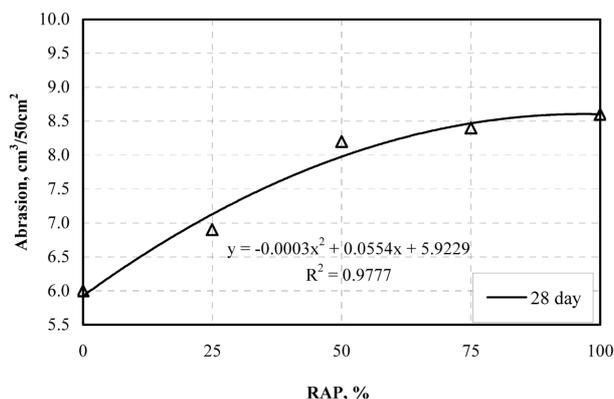


Fig. 12 Abrasion values for RAPM.

opposite of restrained shrinkage which is explained with the “lower modulus of elasticity ensures less restraint in cement paste for free shrinkage.” The crack widths are in acceptable ranges for all series due to restrained shrinkage test results. In fact, crack widths were reduced with the increase in RAP content. Nonetheless, the crack formations and first cracking were delayed. The acceleration for crack width formation was eligible for all series. In general, experimental results barely obtained with high replacement ratios of waste materials as aggregate in concrete or mortars, consequently lower ratios (up to 30~40%) are preferred in studies. However, in this study, results were obtained with both high and low replacement ratios despite remarkable decrements in strengths. The results show that incorporation of RAP modified mortars is adequate for delaying crack formation and reducing crack opening. The RAP enhances the strain capacity of mortars despite the decrease in mechanical properties. Shrinkage is the most effective reason for cracking in cement based materials. It is expected that the aggregate which is less stiff decreases the internal restraint.

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