

## SUGGESTING A SIMPLE DESIGN METHOD FOR COLD RECYCLED ASPHALT MIXES WITH ASPHALT EMULSION

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**Abstract.** Although there are typical and well-known standard methods for designing hot mix asphalt in the world, there is no unique design method for cold recycled asphalt mixes. The current methods are mainly local or even dependent on technology owners due to the diversity of materials and qualitative control limitations. Currently, most of the design methods are based on 4 inch mold. The major problem of these methods is that in the mix design, the effect of aggregates larger than 25 mm is neglected, while this size of aggregates is used in the recycling projects. Therefore, there is a significant difference between in-situ and laboratory mix behaviors. So, 6-inch mold is used. In this study, a simple mix design has been obtained for reclaimed asphalt pavements (RAP) considering the different amount of emulsified asphalt, Portland cement, three gradations, moisture contents, temperatures, and curing times. For this reason, 315 samples were prepared. The results show that the mixes with aggregates larger than 25 mm have a significant difference with 25 mm and smaller aggregates sizes in terms of mechanical properties and moisture susceptibility. Therefore, 6-inch molds should be used for RAP materials that are larger than 25 mm in the mix design.

**Keywords:** cold recycling, mix design, reclaimed asphalt pavement (RAP), emulsified asphalt, curing condition, performance tests.

### Introduction

Asphalt pavements recycling, using cold and hot methods, is one of the most effective rehabilitation and reclamation methods (Ma *et al.* 2016). The recycling process refers to reusing the existing pavement materials which have reached the end of their service life. Among the available technics, cold in-place recycling (CIR) is an option with environmental and economic benefits. It can perform the process of modification and reuse of top layers aggregates easily through one passage of advanced machinery without causing any damage to its subgrade. Nowadays, there are various codes to design of cold recycled mixes in different countries based on experience and research. However, there is no unique standard or approved method for mix design, structural design, laboratory evaluation method and quality control characteristics for CIR (Apeageyi, Diefender 2013, Asphalt Recycling and Reclaiming Association 2001, 2004; Bessa *et al.* 2016; Cox, Howard 2015; Du 2015; Kavussi, Modarres 2010; Kim 2007; Lee 2003; Martinez-Echevarria *et al.* 2012; Tebaldi *et al.* 2014). Different institutions includ-

ing the Joint Committee of AASHTO<sup>1</sup>-AGC<sup>2</sup>-ARTBA<sup>3</sup>, AI<sup>4</sup> and ARRA<sup>5</sup> have presented general methods for designing CIR mixes based on hot mix asphalt (HMA) design methods. Most of the recent mix design methods are based on a series of parameters and characteristics (Marshal resistance, uniaxial compressive strength, indirect tensile strength (ITS), resilient modulus, etc.) along with estimating of their limits and values (Asphalt Recycling and Reclaiming Association 2004; Kavussi, Modarres 2010; Kim 2007; Suleiman 2002). And the optimum value of each constituent and mix design are specified.

Recently, in the majority of cases, 4-inch molds are used in recycled pavements mix design (whether in recycling with foamed asphalt or with emulsified asphalt). The mix design is based on Superpave or Marshal tests,

<sup>1</sup>American Association of State Highway and Transportation Officials

<sup>2</sup>Associated General Contractors of America

<sup>3</sup>American Road and Transportation Builders Association

<sup>4</sup>Asphalt Institute

<sup>5</sup>Asphalt Recycling and Reclaiming Association

bulk and theoretical maximum specific gravity, air voids, and resistance to fatigue and rutting. The first step of these methods is the assessment of pavement condition and evaluation of recycled aggregates (including gradation, the amount of asphalt of RAP materials, etc.), and then laboratory samples are prepared to estimate the optimum amount of additives (water and emulsified asphalt) (Cox, Howard 2015).

Due to the usage of 4-inch molds, grains larger than 25 mm are separated from aggregates. Therefore, mix design is changed into a mix with different gradation and thus with different characteristics from those that constructed in the field. Considering the significance of cold recycling as an economical modification technic for old pavements, use of a design method based on gradation close to field conditions is necessary. In addition, those methods not only have shortcoming in aggregate gradation but also the calculation of other properties such as specific gravity is based on old and common tests which are not able to well reflect the behavior and properties of the recycled mixes. As a result, this study deals with the introduction of a simple mix design method based on performance tests. It also evaluates the effect of gradation on the properties of these mixes.

The objective of this research is to develop a simple mix design for cold in-place recycling with emulsified asphalt through reviewing former studies. To accomplish this objective, the following tasks are performed:

- Review and comparison of previous research on mix design methods;
- Suggesting a simple mix design method for cold recycled mixes based on performance tests;
- Investigation of the effect of gradation and maximum size of RAP materials on resistance properties of cold recycled mixes;
- Investigation and comparison of the use of 4 and 6-inch molds in the mix design.

## 1. Literature review

Currently, there is no unique and universal mix design method for cold in-place recycling. Although these design methods are similar in their steps, Lots of procedures are made and modified by different agencies, countries and factories based on past experiences and laboratory tests (Asphalt Recycling and Reclaiming Association 2004; Cox, Howard 2015; Bessa *et al.* 2016).

The most important methods that exist are as follows: AASHTO, California, Chevron, US Army Corps of Engineers, Illinois, Mississippi, Kansas, Iowa, Montana, Oregon, Pennsylvania, New Mexico, Nevada, Texas, Virginia, New York, Spain, Purdue and AI (AASHTO 1998; Cox, Howard 2015).

In most methods, the primary steps of designing (i.e. collection of RAP, aggregate gradation, RAP characteristics, ...) is similar so the focus of this research is on the parameters that make the methods different. The main parameters are presented as follows.

### 1.1. Recycling agent and chemical additives

Based on previous research, it has been recognized that emulsified asphalt has the greatest usage in pavement recycling as the primary binder in multiple component binder (MCB) systems (Cox, Howard 2015). And in different types of emulsified asphalt, medium setting (MS) emulsions (commonly high float anionic type) have the greatest application in the cold in-place recycling process (Lee, Kim 2010; Kim 2007).

In MCB systems, in addition to emulsified asphalt, the usage of Portland cement, hydrated lime and fly ash are common (Cox, Howard 2015). Use of chemical additive not only decrease the amount of asphalt but also improves the mechanical properties (such as indirect tensile strength, ...) of the mix (Du 2015; Kavussi, Modarres 2010; Niazi, Jalili 2009). Many researches have proved that portland cement has greater effects on mix properties than other chemical additives and it is generally added 1% to 3% by mass to the mix (Bessa *et al.* 2016; Bocci *et al.* 2014; Cox, Howard 2015; Du 2015; Iwański, Chomicz-Kowalska 2016; Miro *et al.* 2000; Niazi, Jalili 2009).

### 1.2. Preparation of laboratory samples

Comparing the previous studies have shown that application of Superpave gyratory compactor (SGC) in designing and preparing of laboratory samples is more effective and useful than using other compactors (Cox, Howard 2015; Cross 2003). However, in many methods and countries, considering technological and financial limitations, Marshal hammer is used instead of the SGC (Bessa *et al.* 2014; California Department of Transportation 2005; Cross *et al.* 2010; Du 2015; Kavussi, Modarres 2010; Virginia Department of Transportation 2014). However, it should be noted that in many of existing design methods, both 50 blows of marshall compaction (AASHTO 1998) and 75 blows of Marshall compaction is used to compact laboratory samples (Apeageyi, Diefender 2013; Bessa *et al.* 2014; California Department of Transportation 2005; Cross *et al.* 2010; Du 2015; Iwański, Chomicz-Kowalska 2016; Lee *et al.* 2002; Virginia Department of Transportation 2014). In sample preparation, both 4 and 6 inch molds have been used, but in 6-inch molds to eliminate pore water pressure, voided molds are used.

### 1.3. Determination of the optimum amount of water and emulsified asphalt

Currently, in new mix design methods, total liquid content (TLC) is used in the design of cold recycled mixes (Bou Jove *et al.* 2004; Cox, Howard 2013; Fiser, Varas 2004; Miro *et al.* 2004). The procedure is the same as proctor compaction test and optimum amount of TLC is selected based on maximum bulk specific gravity test. In this method, according to same role of water and emulsified asphalt on the level of compaction, all of the samples were prepared by water and compacted with Marshall hammer. Then, based on specified parameters, the

optimum amount of water and emulsified asphalt is selected. Several parameters are involved in selecting of optimum cold recycled mixes in new methods. And the most common of them are as follows: bulk specific gravity, rutting resistance, raveling, fatigue, moisture damage and thermal cracks (Cox, Howard 2015). The mentioned tests are the best to reflect the behavior and performance characteristics of the mix. But the shortage of the advanced equipment in laboratories made it impossible to perform all of them. So, nowadays each design methods use their own procedures and testing programs. But the most popular, simple and comprehensive test that reflects many characteristics of the cold recycling mixes is indirect tensile strength test. So, many researchers had taken the advantage of this test (Apeageyi, Diefender 2013; Cross 1999; Dudley *et al.* 1987; Kavussi, Modarres 2010; Marcandali da Silva *et al.* 2013; Kim *et al.* 2011; Niazi, Jalili 2009; Yan *et al.* 2009). Another parameter that can be achieved by the ITS test is tensile strength ratio (TSR) and it reflects the moisture susceptibility of the recycled mixes. There are different opinion about TSR value and it ranges between 0.5 and 0.75 in different design methods. However, the common and rational ratio in different codes is the minimum of 0.7 (California 2005; Cross *et al.* 2010; Illinois Department of Transportation 2012; Iowa Department of Transportation 2008; Kansas Department of Transportation 2014; Lane, Kazmievowski 2005; Montana Department of Transportation 2015; Texas Department of Transportation 2004; Virginia Department of Transportation 2014).

#### 1.4. Performance tests

The past research in evaluation of asphalt mixes showed that the total area under the stress-strain curve in ITS test up to the sample's failure has a good relationship with the resistance of the mixes to fatigue cracking (Christensen, Bonaquist 2002; Cox, Howard 2015; Koh, Roque 2010; Kim, Wen 2002; Roque *et al.* 2004; Transportation Research Board 2004; Zhang *et al.* 2001).

Currently, there are many standardized laboratory tests to predict pavement layers rutting potentials. Some of the most common tests used include: Asphalt Mixture Performance Tester (AMPT), Hamburg Wheel Tracking Tester (HLWT), Asphalt Pavement Analyzer (APA), PURWheel (PW), French Rutting Tester (FRT), Static Creep Test (Cox, Howard 2015; Kandhal, Cooley 2003). Although the loaded wheel tester (LWT) type of devices are the common tests and providing a more realistic evaluation of the mix, they are so expensive. In recent decades, static creep test has been used as a basic test for evaluation of rutting resistance in hot mix asphalt. Various researchers have proposed different methods for performing this test.

## 2. Methodology and laboratory experiments

According to different design methods of cold recycled mixes, the following steps were done.

### 2.1. Collection of RAP materials

In this research, the required RAP materials were collected from eastbound of the Tehran's Azadegan highway. The asphalt pavement has been crushed by a milling machine with a width of 1 m, with the cutting depth of 10 cm.

### 2.2. Determination of RAP materials gradation

After collecting and transporting the RAP materials to the laboratory, sampling of RAP materials was done according to the ASTM D75M (2014).

### 2.3. Determination of RAP materials Characteristics

The properties studied in this section include determination of the percentage of asphalt according to the ASTM D6307 (2016) and gradation of extracted RAP materials according to the ASTM C136 (2014).

### 2.4. Proper Selection of aggregate gradation

Based on previous studies, the need for further research in this area seem to be required (Frigio *et al.* 2015; Vislavičius, Sivilevičius 2013). So, three different dense gradations (with the maximum aggregate size of 19, 25 and 37.5 mm) have been examined based on a report of federal highway administration (FHWA). The resulting cumulative gradations are shown in Table 1.

### 2.5. Selection of the suitable type of emulsified asphalt and chemical additive

In this paper, due to lack of access to high float anionic medium setting emulsion, medium setting cationic emulsion has been used and 2% Portland cement (that suggested in a research by Niazi and Jalili (2009)) is used to improve the initial mechanical properties of the recycled mix.

### 2.6. Performing classic and Superpave tests on asphalt emulsion residues

After determination of the type of asphalt emulsion, the asphalt residue was separated according to ASTM D244 (2009) instruction. And then classic (penetration, softening point, ductility) and Superpave (resistance to fatigue using Dynamic Shear Rheometer (DSR) and resistance to thermal cracks using Bending Beam Rheometer (BBR)) tests according to the related ASTM instructions were performed to determine its performance grading (PG).

### 2.7. Preparation of laboratory samples

In this research Marshall hammer has been used as a simple and more accessible compaction methods. And two compaction levels (50 and 75 blows) and comparison of the results from specific gravity and performance properties of the samples has been done. 4-inch molds have been used for the maximum aggregate size of 19 and 25 mm and 6-inch molds have been used for the maximum aggregate size of 37.5 mm. Due to eliminate the

Table 1. Detailed proportions of three RAP gradations

sieve size (mm)	percent passing of existing RAP	maximum aggregate size of					
		19 mm		25 mm		37.5 mm	
		percent passing of RAP materials by removing aggregates larger than 19 mm	selected gradation	percent passing of RAP materials by removing aggregates larger than 25 mm	selected gradation	percent passing of RAP materials by removing aggregates larger than 37.5 mm	selected gradation
50	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	99.5	100.0	100.0	100.0	100.0	100.0	100.0
25	97.2	100.0	100.0	100.0	100.0	97.6	96.0
19	91.5	100.0	100.0	94.1	94.0	91.9	90.0
12.5	82.4	90.0	90.0	84.8	85.0	82.8	79.0
9.5	74.6	81.0	81.0	76.3	76.0	74.5	70.0
4.75	50.7	55.4	55.4	52.1	52.0	50.9	47.0
2.36	28.4	31.1	38.0	29.2	33.0	28.6	29.0
1.18	14.4	15.7	25.0	14.8	22.0	14.5	19.0
0.6	6.5	7.1	17.0	6.7	16.0	6.6	13.0
0.3	3.8	4.2	12.0	3.9	11.0	3.8	9.0
0.15	1.2	1.3	8.0	1.2	7.0	1.2	6.0
0.075	0.4	0.5	5.0	0.4	4.0	0.4	3.0
Pan	0	0	0	0	0	0	0
*percent of added virgin aggregates		9.8		9.3		10.9	

\* It should be noted that:

- 1 – New aggregates (nearly 10%) was added to the RAP to satisfy the gradation requirement, due to the lack of fine aggregates in the RAP materials.
- 2 – For the studied gradations (19, 25, 37.5 mm), nearly the same amount of new aggregates and parallel aggregate gradation curves is chosen. So, better comparison and evaluation of mixes properties is expected.

pore water pressure in 6-inch molds, voided molds similar to those constructed by Pine Co., was used.

According to the former studies, in this research the blending process consists of mixing the RAP materials with chemical additive (Portland cement) at the specified amount. Then mixing with water for 60 seconds and at last mixing with emulsified asphalt for another 60 seconds.

## 2.8. Determination of the required total liquid content (TLC)

In this research, this parameter has been used to determine the optimum amount of water and emulsified asphalt. The procedure is the same as proctor compaction test with the exception that the Marshall hammer is used for compaction.

## 2.9. Determination of the optimum amount of water and emulsified asphalt based on selected tests

According to different new design methods and the existing equipment, in this research, bulk and theoretical maximum specific gravity, ITS in dry and saturated conditions have been used in design of recycled mixes. Calculating the optimum amount of water and emulsified asphalt of

the recycled mix has been done based on the following tests:

1. Bulk Specific Gravity according to AASHTO T331 with vacuum sealed specimens.
2. ITS of the samples according to AASHTO T283 with partial curing (to simulate the mix after compaction in field).
3. ITS of the samples according to AASHTO T283 with final curing in dry and saturated conditions (to simulate the long-term strength of the mix) and calculation of tensile strength ratio (TSR).

Note:

In ITS test, two loading strips was mounted on Marshall stability load frame to calculate the tensile strength of cylindrical specimens in vertical diametric plane. Then, the indirect tensile strength of the specimens calculated according to Eqn (1):

$$ITS = \frac{2000 P_{max}}{\pi d t}, \quad (1)$$

where: *ITS* – indirect tensile strength, kPa;  $P_{max}$  – peak load, N; *d* – diameter of the specimen, mm; *t* – thickness of the specimen, mm (Kavussi, Modarres 2010).

### 2.10. Investigation of laboratory mixes behavior in terms of fatigue resistance

With regard to the past research, the ITS test and the plot of stress-strain curve of its data is used to examine the fatigue behavior in recycled mixes with different gradation.

### 2.11. Evaluation and comparison of rutting resistance

Based on previous studies, static creep test is selected for evaluation of rutting resistance. Since the recycled layer is commonly used as a base in pavement structure, thus the amount of stress exerted to this layer is lower than to the top layers. Thus, in order to investigate the rutting behavior of recycled mixes with different gradations and considering the lower quality of these mixes (compared with hot mix asphalt), DD-185 instruction by British Standard Institute has been used.

## 3. Results and discussions

### 3.1. Determination of required TLC

By determination of grading limits, laboratory samples were prepared and the amount of required liquid agent through different compaction energies has been done. According to same role of water and emulsified asphalt on the level of compaction, all of samples were prepared by water and compacted with Marshall hammer. The summary of the results is provided in Table 2.

Data obtained from the optimum liquid content determination test shows that:

1. The optimum amount of liquid agent of the samples have a significant difference in different compaction energies (50 and 75 compaction blows) in the studied gradations by nearly 9%.
2. Investigating the amount of air voids reveal that the selected gradations of 19 and 25 mm have been suitable, meeting the minimum requirements for preparation of recycled base layer (around 14%), while the 37.5 mm gradation has a low specific gravity and a high amount of air voids by nearly 17%.
3. Based on the results obtained from this section along with the significance of the bulk specific gravity and

the amount of air voids in the performance of asphalt mixes, the use of 75 compaction blows is chosen for the rest of the work.

### 3.2. Determination of the optimum amount of emulsified asphalt and water

By determining the optimum liquid content in each gradation, the optimum amount of water and emulsified asphalt should be determined. At this step, by keeping the TLC constant, the amount of water and emulsified asphalt is changed, and samples are prepared with different amount of liquid agent. The tests included ITS in partial and final curing along with moisture susceptibility test.

#### 3.2.1. ITS test in partial curing

Considering the passage of traffic stream over the recycled pavement, after a short period of time of its construction, the cohesive strength of cold recycled mixes is known as one of its important characteristics (Kim *et al.* 2011; Sebaaly *et al.* 2004). So, ITS test in the short term stage has been conducted to examine the cohesion values.

In this method, for partial curing, at first, the samples were subject to 60 °C in an oven for 6 hours. Then, they are kept for another 12 hours at the room temperature. Finally, they were removed from the molds and then tested (AASHTO 1998; Lee *et al.* 2002). The test results are shown in Table 3.

Analysis of the data in Table 3, reveals that:

1. In 19 and 25 mm gradations, in initial mixing water of 2%, the maximum tensile strength has been obtained. Therefore, it can be stated that the mix with 2% of initial water will probably have the best strength to raveling under traffic stream.
2. In 37.5 mm gradation, no certain trend can be observed among the tensile strength and amount of water, and a great discrepancy is seen between the parameters. This can be due to the low quality and Inhomogeneity of the samples in this group, which is itself dependent on large gradation and improper physical characteristics of the mix (e.g. low bulk specific gravity, high air voids, etc.) as it can be seen in variation analysis data shown in Table 3.

Table 2. The results of optimum liquid content for the studied gradations

Number of compaction blows	maximum aggregate size of								
	19 mm			25 mm			37.5 mm *		
	Bulk specific gravity (gr/cm <sup>3</sup> )	Optimum liquid (%)	Average air voids (%)	Bulk specific gravity (gr/cm <sup>3</sup> )	Optimum liquid (%)	Average air voids (%)	Bulk specific gravity (gr/cm <sup>3</sup> )	Optimum liquid (%)	Average air voids (%)
50	2.054	5.8	15.8	2.024	5.5	15.9	**		
75	2.089	5.3	13.6	2.073	5	14	1.983	4.3	17.3

Notes:

\* The number of compaction blows in the 6-inch molds has been obtained according to the same compaction energy of the mix in relation with the 4-inch molds.

\*\* due to the incompetency of 50 blows compaction method, in the 37.5 mm gradation the equivalent compaction of 50 blows, was not conducted.

Table 3. Indirect tensile strength of 19, 25 and 37.5 mm gradations in partial curing

19 mm TLC= 5.3%				25 mm TLC= 5%				37.5 mm TLC= 4.3%			
4-inch mold								6-inch mold			
Sample	Initial mixing water (%)	emulsified asphalt (%)	Average ITS (kPa)	Sample	Initial mixing water (%)	emulsified asphalt (%)	Average ITS (kPa)	Sample	Initial mixing water (%)	emulsified asphalt (%)	Average ITS (kPa)
1	1.5	3.8	212.5	1	1.5	3.5	177.6	1	1.5	2.8	108.5
2	1.5	3.8		2	1.5	3.5		2	1.5	2.8	
3	1.5	3.8		3	1.5	3.5		3	1.5	2.8	
4	2	3.3	222.4	4	2	3	213.7	4	2	2.3	89.1
5	2	3.3		5	2	3		5	2	2.3	
6	2	3.3		6	2	3		6	2	2.3	
7	2.5	2.8	211.4	7	2.5	2.5	174.4	7	2.5	1.8	101.5
8	2.5	2.8		8	2.5	2.5		8	2.5	1.8	
9	2.5	2.8		9	2.5	2.5		9	2.5	1.8	
10	3	2.3	210.7	10	3	2	182.4	<i>Note:</i> for this gradation, because of low amount of TLC, the initial mixing water above 2.5% is neglected to avoid poor mix.			
11	3	2.3		11	3	2					
12	3	2.3		12	3	2					
13	3.5	1.8	208.2	13	3.5	1.5	174.5				
14	3.5	1.8		14	3.5	1.5					
15	3.5	1.8		15	3.5	1.5					

*Note:*

In order to investigate the variation of results, variation analysis was done at each testing condition:

- In 19 mm gradation, in all cases the coefficient of variation (CV) were in the range of 1.2 to 9.7%.
- In 25 mm gradation, in all cases the coefficient of variation (CV) were in the range of 1.2 to 10.9%.
- In 37.5 mm gradation, in all cases the coefficient of variation (CV) were in the range of 23.6 to 34.8%.

3. Although in hot mix asphalt, the higher the amount of asphalt, the greater the extent of cohesion, in cold recycled mixes, this phenomenon does not occur. Because the emulsified asphalt required a minimum moisture level for better dispersion and distribution in the recycled mix. In conclusion, the maximum level of tensile strength does not occur at the maximum amount of emulsion. Western US Research Institute also proved that the amount of the optimum emulsified asphalt, as well as the mechanical properties of the mix, are a function of aggregates moisture and the type of the emulsified asphalt. Therefore, it is wrong to use a constant level of water in preparation of the mix and determination of the optimum emulsion amount as it can be seen in Table 3.
4. 19 mm gradation has a greater strength compared with the 25 mm gradation. It can be due to greater homogeneity and compaction level and the lower air voids in these samples. So, if it designed well, it can be used as binder course in pavement structure.

### 3.2.2. Moisture susceptibility test after final curing

To examine the long-term behavior of recycled mixes along with their resistance to moisture damages, ITS test

in dry and saturated conditions has been used. In cold recycled mixes, one of the most important parameters in determination of the optimum amount of recycling agents is the extent of moisture susceptibility of the mixes. In mix design, the importance and the role of extent of resistance in saturated condition is greater than that of in dry condition. This is due to the fact that the majority of mixes prepared in laboratory, meet the minimum level of dry resistance, though this is not a reason for meeting the TSR limits. In this stage, the ITS test has been done on the specimens at two curing conditions:

- 3 days at 40 °C (Fu *et al.* 2009; Wirtgen 2006) and
- 2 days at 60 °C (Iowa Department of Transportation 2008; Wegman, Sabouri 2016),

where moisture susceptibility test has been performed according to AASHTO T283 (2014) instruction. The summary of the test results for optimum mixes is provided in Table 4.

According to the data in Table 4, the following results are obtained:

1. Selection of the optimum mix depends on curing conditions, so different types of curing can cause different optimum mix. It is at the same result of Kim's *et al.* (2011) article.

Table 4. The summary of indirect tensile strength in 19, 25 and 37.5 mm gradations for optimum mixes in two curing conditions

Gradation (mm)	sample curing									
	3 days at 40°C					2 days at 60°C				
	Initial mixing water (%)	Emulsified asphalt (%)	ITS in dry condition (kPa)	ITS in saturated condition (kPa)	TSR	Initial mixing water (%)	Emulsified asphalt (%)	ITS in dry condition (kPa)	ITS in saturated condition (kPa)	TSR
19	2.0	3.3	347.9	239.8	0.69	2.5	2.8	350.7	304.7	0.87
25	2.5	2.5	332.8	263.7	0.79	2	3	438.7	332.7	0.76
37.5	2.0	2.3	279.8	179.1	0.64	1.5	2.8	302.4	211.7	0.70

Note:

In order to investigate the variation of results, variation analysis was done at each testing condition (curing time and test temperature):

- In 19 mm and 25 mm gradations, in all cases the coefficient of variation (CV) were less than 15%.
- In 37.5 mm gradation, in most cases the coefficient of variation (CV) were less than 25%.

2. Although some methods are mentioned that these two curing methods are the same, the obtained data shows vice versa.
3. The time and temperature of curing of the recycled mixes affect their characteristics. Although in the same samples, the amount of temperature-days in two curing methods are constant and the duration of curing in 40 °C methods is more, it is concluded that the temperature is more important than the duration of curing. It is at the same results of Kavussi and Modarres (2010) research.
4. The results proved that by the same material, different mix design methods with different curing condition can lead to different recycled mixes with different characteristics. The same results have been reported by Martinez-Echevarria’s *et al.* (2012) research.

### 3.3. Investigation of the fatigue resistance of the prepared samples

Stress-strain curve is plotted for each of the optimum mixes based on the mentioned methods. Many Studies

show that, as the area under the curve is increased, the energy absorptivity is become more and the mix shows a better behavior against fatigue. The data is shown in Figure 1 and Table 5.

Table 5. The area under stress-strain curves in optimum samples in different curing methods (kPa)

Curing method	Gradation		
	19 mm	25 mm	37.5 mm
	The area under stress-strain curves (kPa)		
3 days at 40 °C	1.29	1.79	1.01
2 days at 60 °C	1.80	2.92	1.21

Based on Figure 1 and Table 5 the following results are obtained:

1. The recycled samples with 19, 25 and 37.5 mm gradations have shown the greatest resistance to fatigue cracks, respectively. This order exists in the two studied curing methods.
2. The value of obtained area of the samples cured at 60 °C are greater than that of the samples cured at 40 °C.

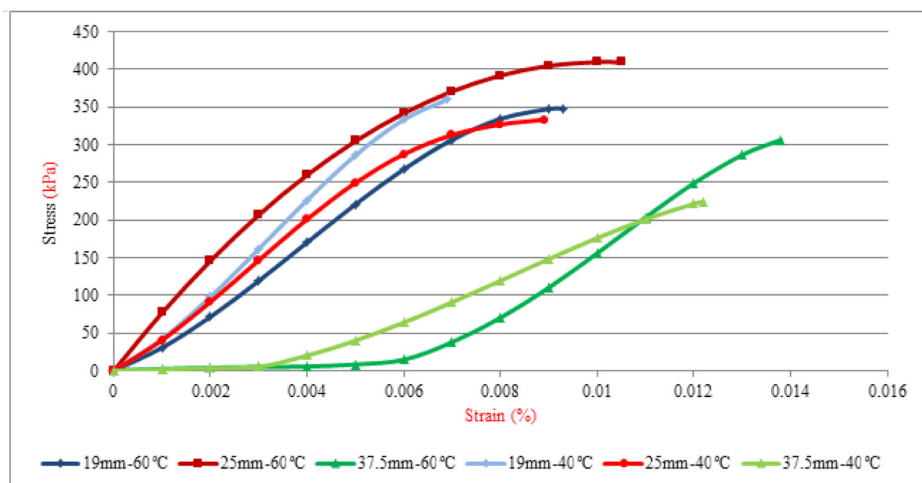


Fig. 1. Stress-strain curves for optimum samples at 40 °C and 60 °C curing

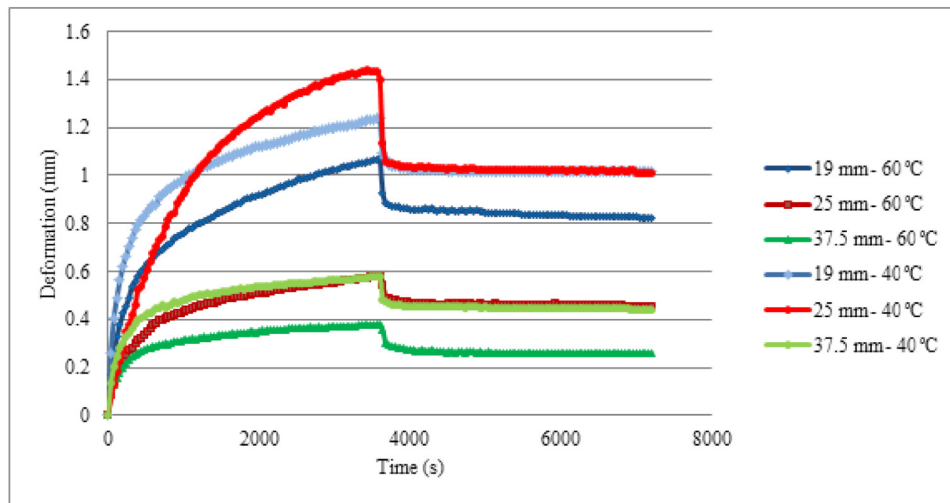


Fig. 2. Deformation of optimum mix samples under different curing methods (40 °C and 60 °C)

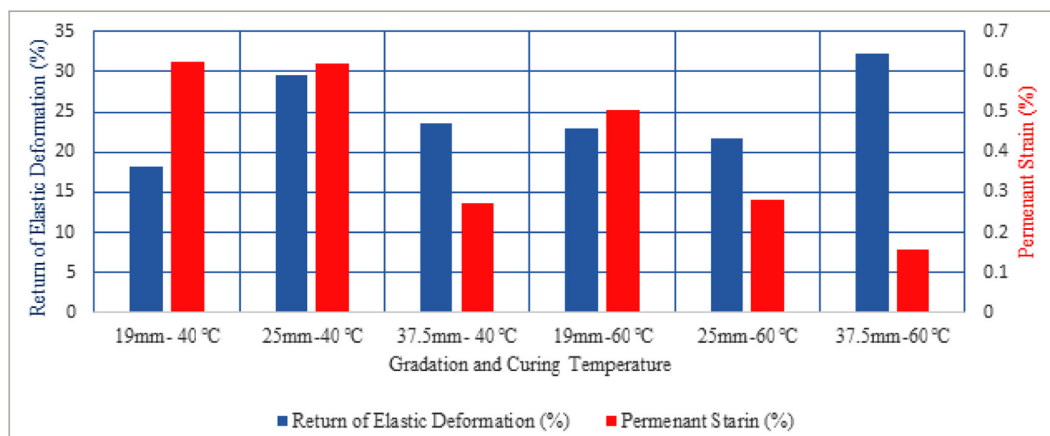


Fig. 3. Permanent strain and return of elastic deformation of recycled mix in static creep test

3. It is found that evaluation of the recycled mixes with 40 °C curing method does not reflect the final behavioral potential of these mixes. Therefore, it seems that the use of the results of 40 °C curing method caused underestimation of the recycled mixes properties and improper design of these mixes.

### 3.4. Rutting resistance evaluation of the samples

According to the results of the static creep test, the amount and time trend of deformation, permanent strain and the return rate of deformation for optimum design mixes were collected and evaluated. The results of static creep test are shown in Figure 2 and Figure 3.

Through the Figure 2, it is determined that in all types of recycled mixes, the return rate of deformation will continue until the end of the test process and complete return of deformation could not occur within 2 hours. This Figure show that the return of deformation of cured samples at 60 °C is greater than at 40 °C. This can be due to incomplete samples curing at 40 °C, the existence of more moisture and more ductility of these samples.

According to Figure 3, in 40 °C curing method, although rutting resistance of 37.5 mm gradation is greater than 19 mm and 25 mm gradations, there is no difference between rutting behavior of 19 and 25 mm gradations. In 60 °C curing method, it concluded that the rutting resistance of the samples is affected by the maximum size of aggregates that is compatible with the theoretical method. Although the 37.5 mm gradation is not the optimum mix and has more air voids rather than other samples with smaller maximum aggregate size, it has more rutting strength than others. So it can be expected that it could show better behavior if it is well designed.

### Conclusions

This study was designed to evaluate different design methods of cold recycled mixes to suggest a simple design method. The following conclusion can be drawn from the results:

- There is no consensus in the curing of recycled Mixes and most of them are following its own process.



- The use 6-inch molds is suggested when the real aggregate size of RAP materials in the field is larger than 25 mm.
- Because of the high prosity of recycled mixes, the results of specific gravity test based on the AASHTO T166 (2016) is not accurate so the use of AASHTO T331 (2013) is recommended.
- In authors suggesting method, as a simple, cheap and comprehensive test method, the ITS test is recommended to determine the optimum mix design.
- Despite of some theories that equate the two types of curing of cold recycled mixes (3 days at 40 °C and 2 days at 60 °C), those are not the same.
- Time and temperature of curing of recycled mixes affect their characteristics. Since in the same samples that cured with two types of studied curing methods the temperature-day is constant and curing time at 40 °C is higher than 60 °C therefore curing temperature has a greater role rather than time of curing.
- According to the ITS and TSR's results in different gradation, it concluded that the use of curing method of 3 days at 40 °C in mix design is not appropriate and it cannot show real and long-term behavior of recycled mixes so it can cause improper design of these mixes.
- The ITS's test results show that the selecting of optimum mix is dependent on curing conditions and different types of curing cause different optimum mixes.
- The moisture susceptibility test results show that by increasing the maximum aggregate size of the mixes the moisture susceptibility get worse.
- The rutting test results show that increasing the maximum aggregate size of the mixes improve the rutting resistance of the recycled mixes. Another important finding of this test is that despite of existence of high amount of air voids (above 14%) in the 37.5 mm gradation it has a great rutting resistance.

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