Evaluation of the Mechanical Properties of the cement treated Cold-in-Place Recycled Asphalt Mixtures

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Abstract:

Cold-in-place recycling (CIR) is an environmentally sustainable alternative for preservation of asphalt pavements. A major disadvantage of this practice is the lower strength of the cold-in-place mixtures. Addition of cement into this type of mixture is a method for increasing its bearing capacity. The effect of cement content on the mechanical properties of the cold-in-place recycled asphalt mixtures has been investigated in laboratory. Different percentages of cement have been added to the recycled asphalt mixtures mixed with an optimum percentage of emulsified bitumen and moisture, and the indirect tensile strength, resilient modulus, dynamic stiffness and fatigue life have been measured. Due to the problem of fabrication of beam specimens, traditionally, the fatigue behavior of cold-in-place recycled mixtures has been investigated using dynamic indirect tensile loading. In this research, a method has been developed for making fatigue beams of the mixture. It is found that the fatigue life, dynamic stiffness, indirect tensile strength and resilient modulus of the mixtures increase with increasing cement content.

Keywords: Cold-in-place recycled asphalt mixtures, cement, fatigue, resilient modulus, dynamic stiffness.

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1. Introduction

Cold asphalt mixture is a type of bituminous material which is normally made by mixing cold aggregates with emulsified asphalt and water. Low energy consumption, lower environmental impact, less occupational hazards for operators, lower costs and more resistance against cracking thanks to their higher flexibility are considered as the main advantages of cold mix asphalts, which make them more appropriate than the conventional hot mix asphalts in some applications [Gomez-Meijide et al. 2015]. However, they suffer from some disadvantages such as low early life strength, higher air voids content after compaction and long curing times before being able to carry the traffic, which has restricted their application to the pavement with low traffic volume or in lower pavement layers. There are different technologies for making cold mix asphalt, in which the aggregate source, mixing equipment, type of binder or additives may vary. A more common type of cold mix asphalt is that made by reclaimed asphalt, which is even more environmentally sustainable than those made of natural aggregates. Cold in place recycling (CIR) is a method of pavement rehabilitation that uses 100% of reclaimed asphalt pavement materials [Gao et al. 2015]. The asphalt pavement recycling has been considered as a maintenance alternative since the oil crisis in 1970s. Reusing the existing asphalt mixtures in the pavement layers by adding a small amount of new materials would be much cheaper than a new construction. In addition to the cost effectiveness, asphalt recycling is an effective way for protecting the environment. There are two methods of asphalt recycling, namely, hot recycling, in which the reclaimed asphalt pavement (RAP) is heated before laying and compaction, and cold recycling, in which the asphaltic mixtures are milled, crushed and mixed with new materials and additives, laid and compacted in ambient or slightly elevated temperatures. The two typical forms of cold recycling are cold central plant recycling (CCPR) and cold in-place recycling (CIR). Agencies using cold recycled asphaltic mixtures have different mix design procedures; however, most of them involve the application of foamed or emulsified asphalt with chemical recycling additives [ARRA, 2001].

Application of emulsified asphalt has shown to be satisfactory in cold-in-place recycling [Thomas, Kadrams and Huffman, 2000; Rogge et al. 1992]. However, premature distresses, such as excessive permanent deformation and fatigue cracking have been observed in some of the cold-in-place projects [Cross and Young, 1997; Asphalt Institute, 1997; Thomas, Kadrams and Huffman, 2000]. Therefore, additives, such as cement, fly ash, silica fume, rice husk ash, and quick lime have been considered for improving the mixtures against these distresses [Issa et al., 2001; Cross, 2008; Niazi and Jalili, 2009] .Some studies have investigated using cement and polymer modified emulsified asphalt for improving the properties of durability, resistance to cracking and moisture damage susceptibility [Issa et al., 2001; O'Leary and Williams, 1992; Niazi and Jalili, 2009; Behnood et al., 2015; Kavussi and Modarres, 2010a and 2010b].

The performance of the cold-in-place recycled asphalt mixtures can be related to some of their properties, which can be evaluated in laboratory. Among these properties, the resilient modulus of the mixtures can be related to the low temperature cracking. The mixtures with a higher resilient modulus are more susceptible to thermal cracking. Resilient modulus is usually measured by the dynamic indirect tensile test, in which the specimen is subjected to few number of haversine loading pulses, with the amplitude of 10 to 50% of the indirect tensile strength, and the resilient modulus is calculated by measuring the resilient deformation of the specimen along its diameter. Another property which is directly related to the alligator cracking is fatigue, which is described by fatigue life, measured by a number of test methods. Similar to hot mix asphalt (HMA), one of the most common distresses in cold recycled pavement is the fatigue racking. The cracking resistance of asphalt mixture in the lab is highly related to its fatigue performance in the field. However, limited studies have been conducted in the past on the fatigue behavior of cold recycled mixes in the lab. In previous research some field processed cold recycled samples were evaluated in the asphalt pavement analyzer (APA) fatigue test and they exhibited lower fatigue values compared with HMA [Tarefdar et al. 2006]. In other research the fatigue properties of cold recycled mixes with foamed or emulsified asphalt were compared through indirect tensile fatigue test [Yan et al. 2010]. Efforts were also paid to find out the effects of cement content on fatigue property of cold recycled mixtures.

Researchers have been trying to compensate the weakness of cold in place asphalt mixtures by modifying the emulsified bitumen or incorporating additives such as cement, quick lime, coal waste (ash), silica fume or fly ash into the mixtures [O'Leary and Williams, 1992; Oruc et al., 2007; Thanaya, 2007; Rotherforda et al. 2014; Chavez-Valencia, 2007, Ameri and Behnood, 2011; Cross and Young, 1997; Niazi and Jalili, 2009; Al-Hdabi et al., 2013; Modarres and Ayar, 2014; Kim and Lee, 2012, Behnood et al. 2015, Gao et al. 2016]. Different factors such as cost, performance, and climate condition should be considered when choosing the appropriate type of additive [Modarres and Ayar, 2014]. It has been found that the type of additive is a main factor in improvement of the mixture properties [Behnood et al. 2015]. Proper selection of the materials to be added to the RAP plays a vital role on the performance of the final product [Cross et al. 1997; Asphalt Institute, 1997; Thomas, Kadrams and Huffman, 2000]. One of the most common additives is Portland cement. The main objectives of using cement in asphaltic mixtures containing emulsified asphalt have been improvement of resistance against initial deformations, reducing curing time and increasing the setting time of the mixture. However, use of cement may affect the other properties of the mixtures, including stability, indirect tensile strength, resistance against permanent deformation, resistance against fatigue and thermal cracking, moisture damage etc. Addition of cement to the mixture reduces its flexibility and makes it more susceptible to cracking [Asphalt Institute, 1986].[Issa et al. 2001] investigated the effects of using different cement contents on some properties of cold asphalt mixtures containing different emulsified asphalt contents and cured in dry and saturated conditions. They found that the stability of the mixtures, measured by Hveen stabilometer increased with increasing cement content. They also found that the effect of cement on the stability is more pronounced on the mixtures cured in saturated conditions. It was also found that the moisture damage is reduced by increasing cement content. They measured the indirect tensile strength and the strain level at failure and found that the indirect tensile strength increases and the strain at failure decreases with increasing cement content. [Niazi and Jalili, 2009] found that the density and Marshall stability of cold in place recycled asphalt mixtures increases, and the air voids content and flow decreases with increasing cement content. They also found that the resilient modulus of the mixture increases with increasing cement content. Confirming previous studies, they also found that the moisture damage of cold asphalt mixtures decreases with the addition of cement. Their results also showed that the resistance against permanent deformation increases with increasing cement content. Using digital camera [Gao et al. 2016] found that the addition of cement to the cold recycled asphalt mixture increases the resistance against fatigue cracking. [Kavussi and Modarres 2010a, 2010b] investigated the fatigue behavior of the cold-in-place recycled asphalt mixtures over a range of temperatures and cement contents using indirect tensile fatigue tests. They found that the rate of variation of the fatigue life with tensile strain decreases with increasing the cement content and decreasing the temperature. [Modarres et al. 2011] found that, by increasing the cement content and resilient modulus, the slope of the fatigue line was decreased, indicating that changing the characteristics of mixes from a typical asphalt mixture to cement treated material [Modarres et al. 2011, Yan et al. 2010] investigated the tensile strength, stiffness modulus and fatigue properties of recycled asphalt mixtures treated with cement and emulsified and foamed asphalt. They found that the stiffness decreases with increasing temperature and stress levels, and the mixtures with emulsified asphalt showed a higher fatigue life at high stress levels than those with foamed asphalt. The fatigue behavior of the cold-in-place recycled asphalt mixtures using the beam fatigue test has not been investigated, because of the problem of breaking the samples when the beams are cut from roller compacted slabs [Jinhai et al. 2010; Lesuerer et al. 2008].

This study attempts to investigate some of the mechanical properties, such as the indirect tensile strength, resilient modulus and beam fatigue behavior of the cold-in-place recycled asphalt mixtures containing cement.

2. Materials

The reclaimed asphalt concrete mixture used in this research was obtained from the milled asphalt concrete of the surface layer of Mashhad-Shandiz Road in the north east of Iran. The gradation of the mixture was determined following [ASTM C136, 2010] standard test method. Figure 1 shows the gradation of the mixture.

The moisture content of the mixture was also measured to be 0.305%. The moisture content was obtained by dividing the RAP into four fractions and taking a 1000gr sample from each, drying in oven for 1 hour and weighing. The moisture content was obtained by averaging the four values. Then, the bitumen content of the mixtures was measured using a centrifuge equipment and gasoline as solvent. The bitumen content was 5.62%. After determination of the bitumen content of the mixture, the density and water absorption of the coarse and fine aggregates were determined. The densities for the coarse, fine and filler were, respectively 2.49, 2.52 and 2.12, and the water absorption of the coarse and fine aggregates was, respectively, 1.81 and 1.91.

Selection of the type of bitumen, in terms of compatibility with the aggregates, is an important issue. Therefore, two types of emulsified bitumen, a slow setting (CSS-1h) and a medium setting (CMS-1), were used to evaluate their compatibility with the RAP. The compatibility was evaluated based on the visual inspection of the particles coated by bitumen. It was seen that the CSS-1h coats more than 95% of the aggregates surface, and was selected for this study. Table 1 shows the properties of the css-1h emulsified bitumen used in this study.

3. Mix Design

The main objective of mixture design in cold-in-place recycled asphalt concrete is to determine the percentages of different constituents for obtaining a mixture with the properties of a new asphalt concrete [Asphalt Institute, 1986]. There are different methods for mixture design of cold-in-place recycled asphalt concrete [Rogge et al. 1992; Asphalt Institute, 1986]. The modified Marshall method is commonly used in Iran and has also been used in this study, which is described as follows.

Marshall specimens with 3% of moisture content, at 5 different percentages of emulsified bitumen, from 2.5 to 4.5%, with 0.5% increment, were made. In order to have the mixture similar to that compacted in filed, the Marshall specimens were made using Superpave gyratory compactor. The number of gyrations, vertical stress level and the angle of gyration for compacting the specimens, were selected to be 60, 600kPa, and 1.25˚, respectively. After compaction, the specimens were cured at 40˚C for a duration of 6 hours, succeeded by curing at room temperature for 24 hours. Then,

Table 1. Properties of emulsified bitumen

Test	Standard Method	Specification limits		CSS-1h
		minimum	maximum	
Sybolt-Furol Viscosity in 25˚C (sec)	ASTM D2170 (2003)	20	100	40
Sybolt-Furol Viscosity in 50˚C (sec)	ASTM D2170 (2009)	-	-	-
Stability (Settlement after 24 hrs.) %	ASTM D244 (2011)	-	1	1
Percentage of set bitumen (Cement Mixing Test)	ASTM D6935 (2012)	-	2	2
Residual bitumen %	ASTM D6997 (2012)	57	-	60
Water content%	ASTM D6997 (2012)	-	43	35
Emulsifier content %	-	-	-	1
Solvent %	ASTM D6997 (2012)	-	-	3
Acid Clorhidric %	-	-	-	1
Penetration of the residual bitumen	ASTM D5 (2006)	40	90	65

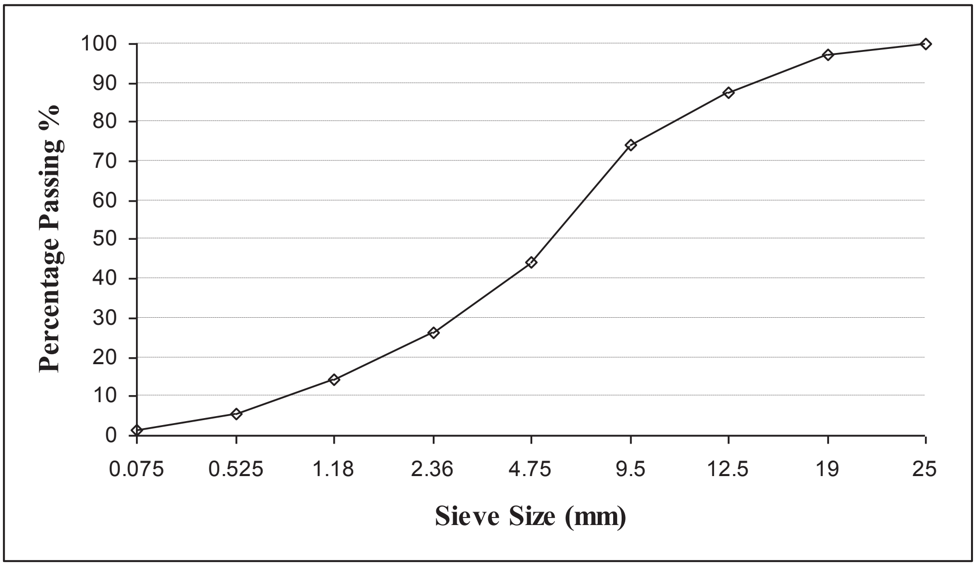


Figure 1. Gradation of the RAP

the specimens were removed from molds, and cured at room temperature for 48 hours. Then, the bulk density of the specimens were measured using [ASTM D 2726, 2006], and the maximum theoretical density of the mixtures was measured using[ASTM D2041, 2041], and the air voids content of the specimens was calculated. Then, the Marshall stability of the specimens was measured. Figure 2 shows the variation of the bulk density, Marshall Stability, flow and air voids content with emulsified asphalt content. Based on the results of Marshall Stability, density and air voids content, the optimum bitumen content was determined to be 3.4%. Using the optimum bitumen content and different moisture contents, Marshall specimens were made with different cement contents, and, similar to the determination of optimum emulsified asphalt content, based on the density, air voids content, Marshall stability and flow, the optimum moisture content for the mixtures was determined. Table 2 shows the optimum moisture content of the mixtures with different cement contents.

Table 2. The optimum moisture content values

Cement content %	Optimum moisture content %
0	3.7
1	4
2	4.5
3	5

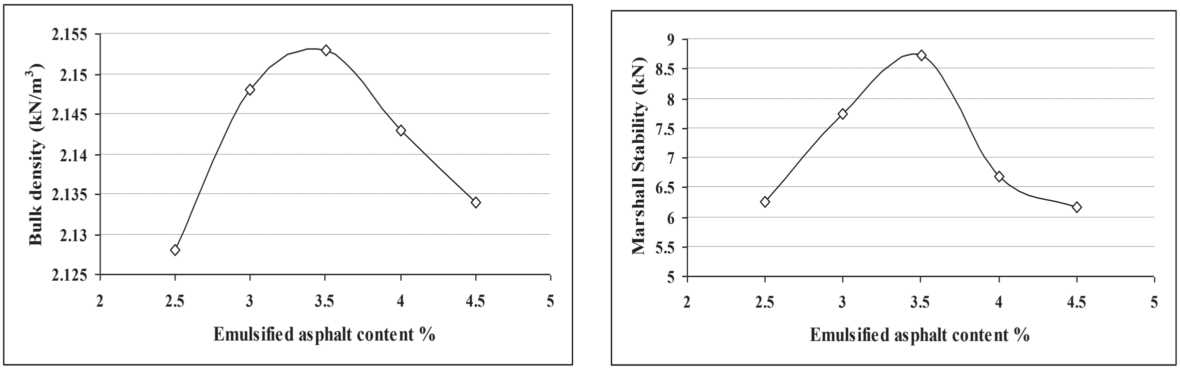
For the fatigue, indirect tensile and resilient modulus tests, three different cement contents of 1, 2 and 3% were added to the mixture in dry condition, and, then the optimum moisture content was added and mixed by laboratory mixer, and then the optimum emulsified bitumen was added and mixed.

4. Tests

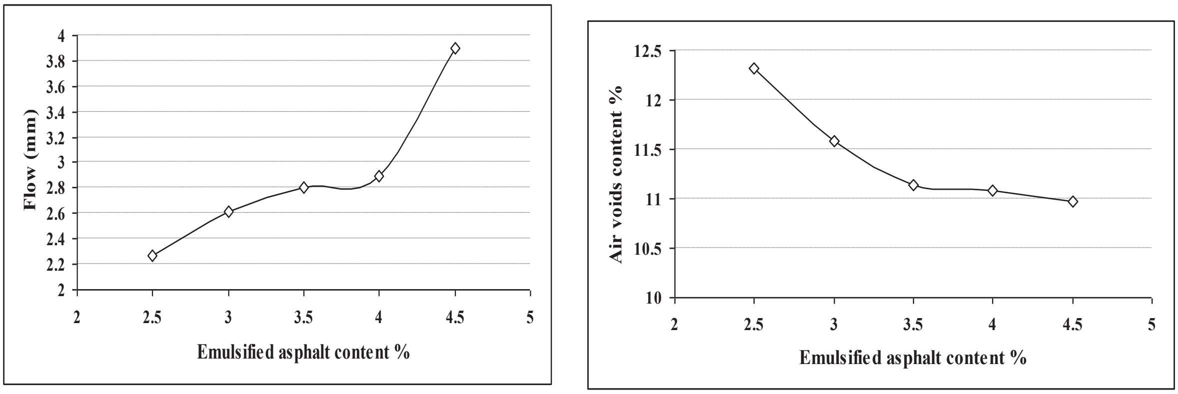
In order to investigate the effects of cement on the cold-in-place recycled asphalt concrete, a testing program, including indirect tensile, resilient modulus and fatigue tests, over a range of conditions, was planned. The testing methods and the results are described in the following sections.

4.1 Indirect Tensile Tests

The indirect tensile strength tests were conducted following ASTM D6931 (2007) standard test method. The specimens required for the indirect tensile tests were made in a similar method and dimensions as those for the Marshall stability test. The specimens were stored in a water bath set at 40˚C, for 40 minutes, before testing. Then, using Marshall loading frame, the specimens were loaded diametrically, at a constant rate of 50mm/min until failure. The maximum force required for failing the specimen was monitored, and, the tensile strength of the mixtures was calculated using Equation (1).



a) Marshall stability b) Marshall stability



c) Flow d) Air voids content

Figure 2. Variation of bulk density, Marshall Stability, flow and air voids content with emulsified asphalt content

$$S_t = \frac{2P}{\pi t D} \tag{1}$$

Where S_t is the indirect tensile strength in kPa, D is the specimen diameter (m), t is the thickness of specimen (m) and P is the load require for failing the specimen (kN). For each cement content, three replicate specimens were made and tested, and the results were averaged.

4.2 Resilient Modulus Tests

Resilient modulus is a parameter, which is widely used for characterizing asphalt mixture behavior, and many pavement design methods require that as an input data. The resilient modulus is the elastic modulus of the materials in the multilayer elastic analysis of pavement.

There are different methods for determination of the resilient modulus of asphaltic mixtures. The dynamic indirect tensile test, because of a better simulation of the stress state at the bottom of the asphaltic layer under wheel load, has been used in this research.

The resilient modulus of the mixtures was determined using the ASTM D4123 (2003) standard test method. Specimens were made similar to those for the Marshall and indirect tensile tests, 4in. in diameter and 2.5 in. in thickness. Based on the ASTM D4123 and AASHTO T3194, it has been suggested that the applied load be from 10 to 50% of the indirect tensile strength. Specimens were made of the mixtures, containing the optimum bitumen and moisture content without cement and with three different cement contents of 1, 2 and 3%. Three specimens were made for each condition. The tests were conducted at three temperatures of 5, 20 and 40˚C. Using a Universal Testing Machine (UTM-14p), haversine loading pulses with a 0.1 sec. of loading time, and 0.9 sec. of rest time were applied on the specimens. 100 loading cycles were applied for conditioning and the main loads were applied considering the ratio of 10 to 50% of the indirect tensile strength, suggested by standards. The resilient modulus of the mixtures was determined using Equation (2).

$$M_r = \frac{P(\mu + 0.27)}{t\delta_h} \qquad (2)$$

Where, M_r is the resilient modulus (MPa), P is the maximum dynamic load (N), μ is the Poisson's ratio, t is the thickness of specimen (mm), and δ_h is the horizontal resilient deformation of specimen (mm).

4.3 Fatigue Tests

Fatigue tests were conducted on rectangular beam specimens, following SHRP-M009 standard method. Based on SHRP-M009, the samples are cut from slab compacted by a roller compactor. However, because of the high air voids content in the cold recycled asphalt mixtures used in this study, cutting is difficult and results in occurrence of cracks in the beams. Therefore, a new set up method was developed for fabricating the beam specimens with standard dimensions of 381±6.35mm in length, 60±6.35mm in width and 50±6.35mm in height. In this method, molds with the standard dimensions were made (Figure 3(a)), and a roller was made for compacting the mixtures in the molds (Figure 3(b)). A plate was placed on the roller to allow for applying the same load as the standard roller. The number of passes of the roller, and the load level were tried to be identical for making all specimens. The mixture required for making each beam was estimated to be 1220gr. The RAP was stored in 60˚C for one hour, and, after dry mixing with cement, the required water and emulsified bitumen was added and mixed thoroughly, and placed in the mold and compacted by roller. All the specimens were cured in 40˚C for 12 hours.

The fatigue tests were conducted at three stress levels of 150, 175 and 200kPa at 20˚C. Test condition was replicated 3 times with each stress level and cement content. The bulk density of the samples was determined before fatigue tests, to ensure that the air voids content conforms to the range suggested by SHRP M009 standard method. Table 3 shows the bulk density and air voids content of the mixture with different cement content. The values in Table 3 are the average of 3 measurements in each condition. It can be seen that the air voids decreases slightly by increasing the cement content.

The fatigue tests were conducted by four-point bending method, using UTM-14P equipment. The specimens were placed in the temperature controlled cabinet set at 20˚C for 6 hours, before commencing the loading. The fatigue tests in this study were conducted in a stress controlled state, at a frequency of 10Hz, and continued until the specimen failure. The specimens were loaded cyclically with two concentrated loads, P/2, at one-third distances from the beam ends, which produces a uniform bending in the central third of the specimen. The initial dynamic stiffness of the specimens, at the loading cycle number of 50 was calculated by the software on the computer connected to the loading equipment. The fatigue life of the specimens was also monitored by the software after failing the specimen.

(a) Molds for making beam specimens *(b)roller for compacting the specimens*

Figure 3. Mold and roller for fabricating the specimens

Figure 3. Mold and roller for fabricating the specimens

Cement content %	Bulk density (gr/cm^3)	Air voids %
0	2.129	12.27
1	2.131	11.88
2	2.141	11.40
3	2.144	11.11

5. Tests Results Analysis and Discussion

Figure 4 shows the variation of the indirect tensile strength with the cement content. As can be seen, the indirect tensile strength of the mixtures increases with increasing the cement content. Two modes of failure were observed in the specimens, some failed with developing cracks along the diameter of the specimen, with triangular pieces in the vicinity of the loading strip, and the others failed with excessive deformation near the loading strip and cracking in the central section of the specimen.

Figure 5 shows the resilient modulus test results. As can be seen, the resilient modulus of the mixtures increases with increasing cement content, and decreases with increasing temperature. The addition of cement to the mixture results in a cementation effect which increases the bond between aggregate particles and the stiffness. Moreover, decreasing temperature results in the stiffening of the bitumen and increasing the stiffness. In addition, Figure 5 also shows that the rate of variation of the resilient modulus with cement content increases with decreasing temperature, indicating that the share of cement in the stiffness of the mixtures at low temperature is more important. At higher temperatures, because of the softening of bitumen, the stiffness is more dependent on the bitumen mortar, which cannot be significantly improved by addition of cement.

Figure 6 shows the variation of the initial dynamic stiffness with the stress level. As can be seen, the initial dynamic stiffness decreases with increasing the stress level. Results indicate that the stiffness of the cold-in-place recycled asphalt mixture with and without cement is stress dependent, with a higher sensitivity to the stress level for the mixtures without cement and 1% of cement content. Over the range of cement contents used in this research, it can be seen that the stiffness increases with increasing the cement content.

Figure 7 shows the variation of fatigue life of the mixtures with different cement contents versus stress level. As can be seen, over the range of stress levels applied in this research, the fatigue life decreases with increasing the stress level, with a higher fatigue life for the mixtures with higher cement content, which is attributed to the higher stiffness of the mixtures with

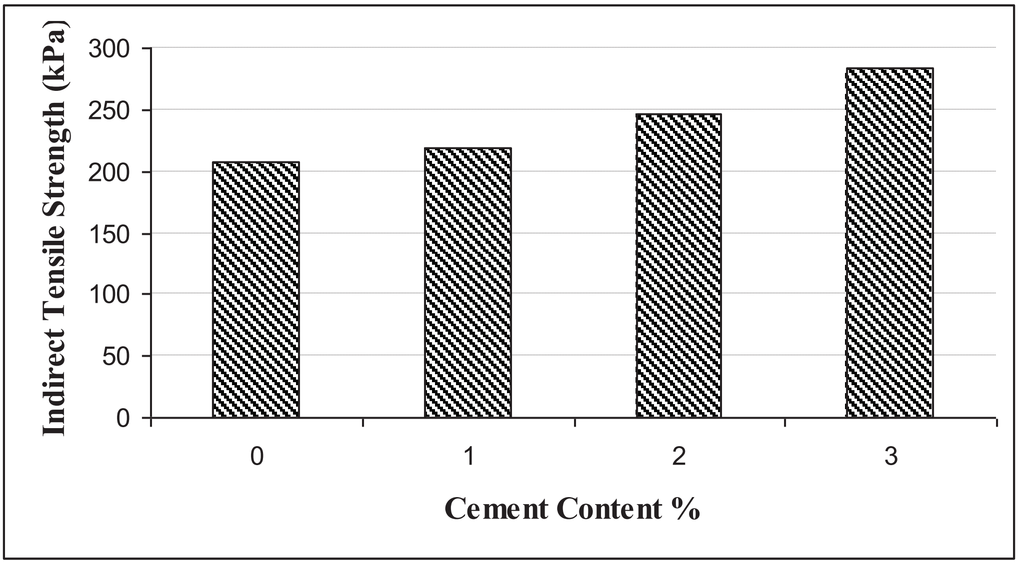


Figure 4. Indirect tensile strength of the cement stabilized recycled asphalt versus asphalt content

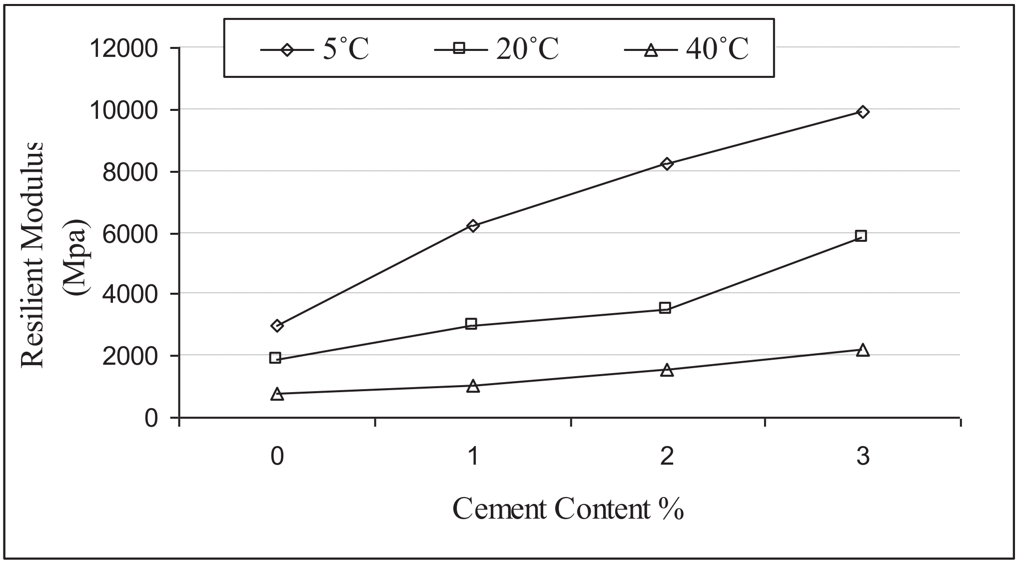


Figure 5. Resilient modulus of the mixtures versus cement content

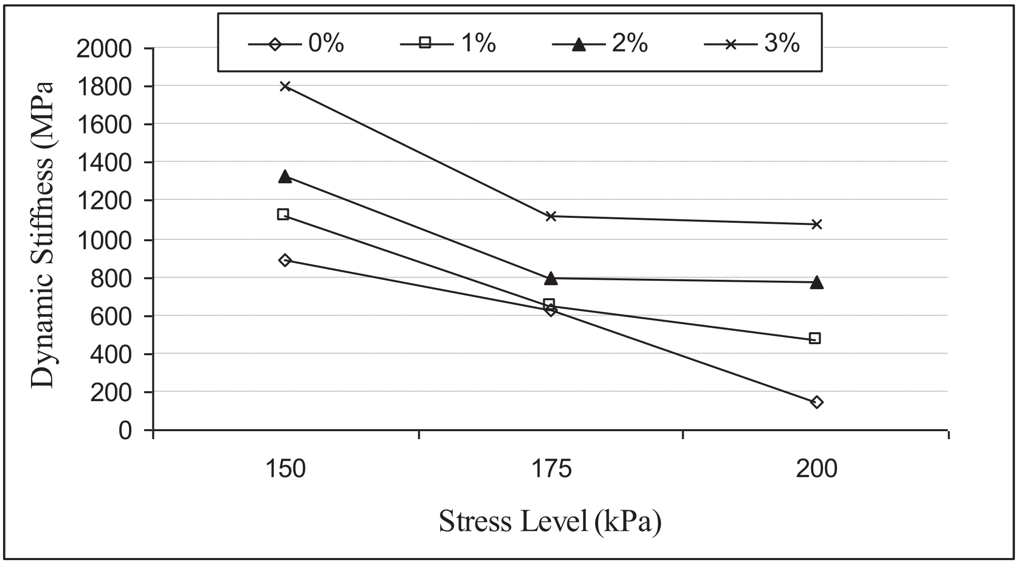


Figure 6. Variation of the dynamic stiffness versus stress level for the mixtures

higher cement content. At a constant stress level, a lower strain level may be induced in the mixture with a higher stiffness, resulting in a higher fatigue life. It can also be seen from Figure 7 that the mixtures with higher cement content have a lower rate of reduction of fatigue life with increasing stress level. This is consistent with the finding of [Brown et al. 2000], who found that the slope of the variation of strain level versus fatigue life is steeper for the mixtures containing higher cement content. However, because of the lower slope of the mixtures containing higher cement content, it is predicted that, at stress levels, far lower than those utilized in this study, the fatigue life of the mixtures with higher cement content is less than those with lower cement content. Kavussi also found a point, at which, the lines of the variation of strain level with fatigue life of the mixtures containing different cement contents intersect. By fitting the fatigue model developed by [Monismith et al. 1995] (Equation 3) to the test results, the constant a and b were determined for the mixtures which are shown in Table 4, as well as correlation coefficient R2.

$$N_f = a\sigma^{b} \tag{3}$$

Table 4. Constants a and b

Constant	Cement content %			
	0	1	2	3
a	6×10^{29}	2×10^{27}	3×10^{25}	4×10^{16}
b	-11.48	-10.16	-9.045	-4.785
R^2	0.979	0.9013	0.9215	0.9434

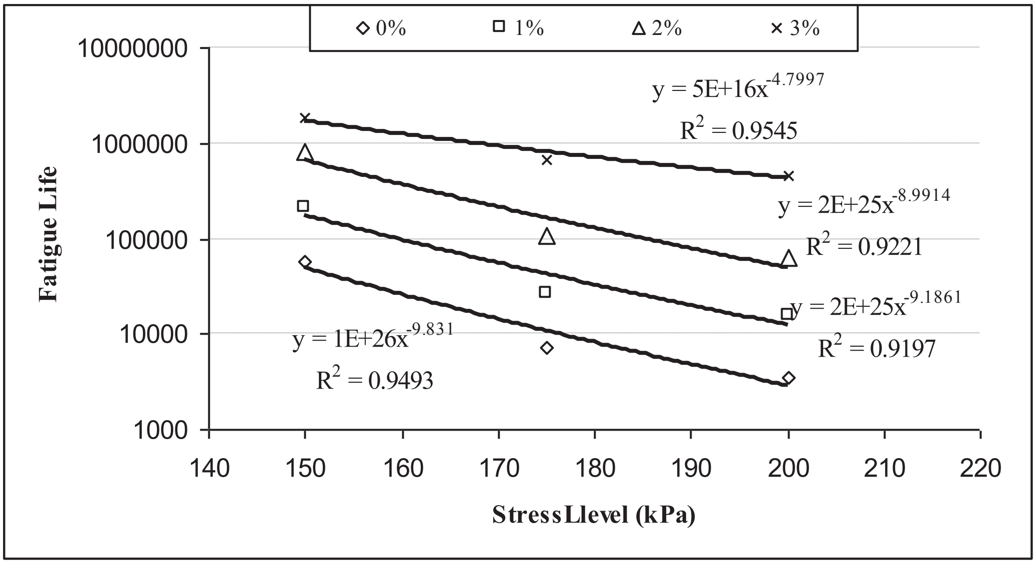


Figure 7. Variation of the fatigue life versus stress level for the mixtures with different cement contents

6. Conclusions

Experiments were conducted on the specimens made from reclaimed asphalt concrete mixed with an optimum emulsified bitumen and moisture content, and various cement contents. The following conclusions can be drawn from this study.

- The indirect tensile strength of the mixtures increases with increasing cement content.
- The resilient modulus of the mixtures increases with increasing the cement content and decreasing temperature.
- The dynamic stiffness of the mixtures decreases with increasing the stress level, with different rate of reduction for different cement contents. However, the variation of the stiffness with the stress level is not significant beyond 175kPa.
- The bending stiffness of the cement treated recycled asphalt mixtures decreases with increasing stress level. Therefore, the stiffness of these mixtures is highly dependent on the applied stress level.
- The fatigue life of the cement treated recycled asphalt mixtures depends on the applied stress level, with a considerable reduction in fatigue life with increasing the stress level. This can be explained by the accelerated breaking of the bond between bitumen and aggregate particles and formation and propagation of cracks in the mixtures by increasing the stress level. However, increasing the cement content decreases the sensitivity of the fatigue life to the stress level, with a slight variation of the fatigue life with the stress level for the mixture with 3% of cement content.

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