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RESEARCH ARTICLE

Evaluation of rubberised asphalt mixture including natural Zeolite as a warm mix asphalt (WMA) additive

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ABSTRACT
One of the ways to modify bitumen and asphalt mixture characteristics is to use recycled Crumb Rubber (CR). Although using CR improves the mechanical properties of asphalt mixtures and rheological behavior of bituminous binders, it increases binder viscosity. Warm Mix Asphalt (WMA) is a practical technology to ameliorate the disadvantage of Rubberized-Asphalt (RA) mixtures. This study aimed to investigate the effect of zeolite as a WMA additive on Hot Mix Asphalt (HMA) and RA mixtures. These modifiers' effect on the properties of asphalt mixtures and binders was studied utilizing different tests such as resilient modulus, indirect tensile fatigue, dynamic creep, moisture susceptibility (TSR and RMR), and rotational viscosity (RV). The findings indicate that the addition of zeolite and CR improved mechanical properties. 16% CR along with 6% zeolite is the optimum dosage to enhance durability. Moreover, the addition of CR to mixtures without zeolite decreased the TSR, RMR, and workability of mixtures, while zeolite increased the durability and workability of HMA and RA mixtures. The cost-effective analysis results also indicated that not only does the simultaneous proper use of zeolite and CR decreases energy consumption, but it also decreases the production cost of modified asphalt mixture.

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KEYWORDS
Warm mix asphalt; crumb rubber; natural zeolite; fatigue resistance; dynamic creep; resilient modulus; moisture susceptibility

1. Introduction

Inadequate quality of materials used in the manufacture of asphalt mixtures and improper design lead to distresses such as rutting, fatigue and thermal cracking, and moisture susceptibility in asphalt mixtures (Zhang and Kevern 2021). In the last decades, the asphalt industry applied several ways to modify asphalt mixtures/binders and mitigate the above-mentioned challenges, including Crumb Rubber (CR) (Zheng et al. 2021), WMA additives (Yousefi et al. 2020a, 2020b), polymers (Habbouche et al. 2020; Sadeghian et al. 2019), anti-stripping agents (Ameri et al. 2021), and recycling agent (Haghshenas et al. 2021; Yousefi et al. 2021).

The newest technology available for road surface construction is crumb-rubber modified asphalt. It is recognised as a green technology because it saves energy, improves human health, reduces resource depletion, protects the ecosystem, and reduces pavement noise (Wang et al. 2018b; Farina et al. 2017). CR improves mechanical properties of asphalt mixture and binder such as rheological behaviour of binder (Liu et al. 2009), fatigue cracking (Wang et al. 2013), rutting resistance (Kök and Çolak 2011; Lee et al. 2008), reflective and thermal cracking of asphalt pavements (Yildirim 2007), and pavements skid resistance (Huang et al. 2007; Lo Presti 2013). Rubberised Asphalt (RA) needs higher mixing and compaction temperature, while creating additional difficulties, such as reduced workability and pumping ability, higher viscosity, and reduced storage stability (Bindu et al. 2020; Memon et al. 2021) as well as resulting in more energy consumption and higher construction cost (Yengejeh et al. 2020; Jahanbakhsh et al. 2020).

Due to the substantial amount of energy used and greenhouse gases (GHG) emissions in the preparation of hot mix asphalt, the usage of Warm Mix Asphalt (WMA) has grown in popularity among pavement engineers (HMA). The application of WMA technologies in manufacturing asphalt mixture results in less energy used for material heating, less air pollution, less aging of asphalt binder, a more extended construction season, and lower production costs (Hettiarachchi et al. 2019; Guo et al. 2020; Zhao et al. 2013). Overall, there are three categories of WMA technology, namely organic, chemical additives, and foaming process (Rubio et al. 2012).

The majority of studies have been orchestrated upon WMA technology with chemical additives. For example, Evotherm (a chemical WMA additive) has reduced HMA mixing temperature. Typical plant mixing temperatures for HMA production ranges between 140 and 150 °C. In contrast, the temperature range for WMA technology with chemical additives is between 120 and 130 °C (Silva et al. 2010a). Test results on WMA mixtures containing Evotherm showed that the resilient modulus of these mixtures is higher than their control HMA mixes with no Evotherm. Furthermore, the Asphalt Pavement Analyzer (APA) rutting test results demonstrated that Evotherm mixtures have less rutting potential than the control HMA mixtures (Hurley and Prowell 2005). In another study, Rodríguez-Alloza et al. used four types of organic WMA additives: Sasobit, Asphaltan A, Asphaltan B, and Licomont BS 100 to assess and compare their potential effects on binder modified with 20% CR. They found that for the optimum content of these additives, their effectiveness is additive type-

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dependent. The mixing temperature for blending aggregates with the modified binder containing these WMA additives (i.e. Sasobit, Asphaltan A, Asphaltan B, and Licomont BS 100) may be reduced by 10°C, 7°C, 4°C, and 2°C respectively (Rodríguez-Alloza et al. 2014). Synthetic and natural zeolite are placed under the asphalt foaming category. They are classified into water-based and water-containing groups (Rubio et al. 2012; Woszuk et al. 2017). Because of the crystallized structure of the zeolite, it can preserve 18–21% water released in temperatures higher than the boiling temperature of the water. The binder's foaming process occurs with the release of water, causing a reduced production temperature (Rubio et al. 2012; Kristjansdottir 2006). According to Topal investigations, zeolite lowered mixing and compaction temperatures. Evaluation of mechanical properties showed that zeolite increased Indirect Tensile Stiffness Moduli (ITSM), fatigue life, and rutting resistance of asphalt mixtures (Topal et al. 2014). Vaiana et al. studied the effects of the foaming process on the workability of asphalt mixtures containing zeolite. They concluded that the release of water from zeolite is time and temperature-dependent. The time at which the foaming process begins is known as reaction time. They fabricated samples of the mixture containing 0.3% zeolite (by weight of aggregates) and prepared them in three different conditions. The first samples was compacted by Marshall Hammer immediately after mixing, and the second and third group were compacted after being stored in an oven for 1 and 2 h, respectively. It was found that the foaming process occurred in the second group (1 h of storage). Foaming vanishes after 2 h of storage in the oven. Moreover, the air void in the second group of samples was the lowest. The results demonstrated that the second group's Indirect Tensile Strength Moduli (ITSM) was higher than the control HMA mixture. Finally, it was concluded that one hour of storage time was a desirable reaction time for the zeolite to release water and produce foam (Vaiana et al. 2013).

Furthermore, Goh and You used synthetic zeolite with 0.3% and 0.5% based on the weight of the mixtures. Resilient modulus (M_r) and dynamic modulus (E^*) tests were carried out on the mixtures. By adding zeolite, both M_r and E^* were increased (Goh and You 2008). Malladi et al. investigated moisture susceptibility on Advera (kind of synthetic zeolite), Foamer, and Sasobit. Results showed that Advera and Foamer did not pass the minimum requirement of 85% for Tensile Strength Ratio (TSR), while Sasobite and HMA exceeded the minimum criteria (Malladi et al. 2015). Another research study found that the use of synthetic zeolite reduces TSR values, validating Malladi et al. research (Malladi et al. 2015), although natural zeolite improved the TSR value (Şengöz et al. 2013). Hence it was concluded that the use of natural zeolite in the mix improves the moisture susceptibility of the mixture better than synthetic zeolite. Shafabakhsh et al. conducted an experimental study for evaluating propagation of reflective cracking in asphalt pavements. Natural zeolite and hydrated lime were added to RA. RA mixtures, including these additives, were used in asphalt concrete overlay and sand asphalt interlayer. It was concluded that the fatigue life of modified mixtures was higher than that of the control mixture, and the highest fatigue life belonged to mixtures containing CR and 5% zeolite (Shafabakhsh and Ahmadi 2019).

Numerous studies have been evaluated the performance of CR blended WMA mixture/binders (Ma et al. 2017; Lushinga et al. 2020; Ameri et al. 2020a, 2020b; Gui et al. 2021; Yazdipanah et al. 2021; Yang et al. 2017; Wang et al. 2012, 2018a, 2020a, 2020b, 2020c; Yu et al. 2020a, 2020b). According to these previous studies, CR could cause lower workability, lower pumping potential, increment binder viscosity, and mixing and compaction temperature. On the other hand, the use of WMA additives in asphalt binders can reduce the viscosity of the modified binders, resulting in lower production temperatures and energy consumption. Considering the additives' characteristics, it was hypothesised that the addition of zeolite into the CR-modified asphalt binders could potentially neutralise the problems associated with the use of CR, such as poor workability and pumping potentially. Additionally, to the best of the authors' knowledge, although previous researchers have explored the effects of zeolite and CR on the performance of asphalt mixture separately, the impact of using both simultaneous has not been addressed.

2. Research objectives and scope

The primary goal of this study is to determine the effect of various percentages of zeolite (i.e. 0%, 2%, 4%, and 6%) on the viscosity of asphalt binder and mechanical characteristics of the CR-modified asphalt mixtures, including three different content of CR (i.e. 0%, 8%, and 16%). This study takes two approaches to this goal: first, evaluating the effect of different content of CR on the mechanical performance of asphalt mixture and viscosity of neat asphalt binder. Second, the assessment of the coupled impact of zeolite and CR on the mechanical performance of asphalt mixture and viscosity of neat asphalt binder. The mechanical properties of HMA and RA mixtures containing various contents of zeolite are evaluated through the mechanical test such as indirect tensile resilient modulus test, indirect tensile fatigue test, dynamic creep test, and moisture susceptibility test. Furthermore, the viscosity of CR-modified asphalt binders containing various contents of zeolite has been compared and analyzed with the base binder via the rotational viscosity (RV) test. The experimental plan of this research is illustrated in Figure 1.

3. Materials and methods

3.1. Neat asphalt binder and virgin aggregate

This study used a virgin binder Pen 60–70 (equivalent to PG 64-22) supplied by Jey-Oil Refinery Tehran, Iran. The specifications of the base binder are presented in Table 1.

The asphalt mixtures in this study were made using limestone aggregates with a nominal maximum aggregate size (NMAS) of 12.5 mm, which were sourced from the Boomehen mine near Tehran, Iran. The aggregates' gradation is based on the No. 4 gradation of Iran's highway asphalt paving code (code1003), which meets the ASTM criteria for dense graded aggregates. Figure 2 depicts the gradation of the mixed aggregates.

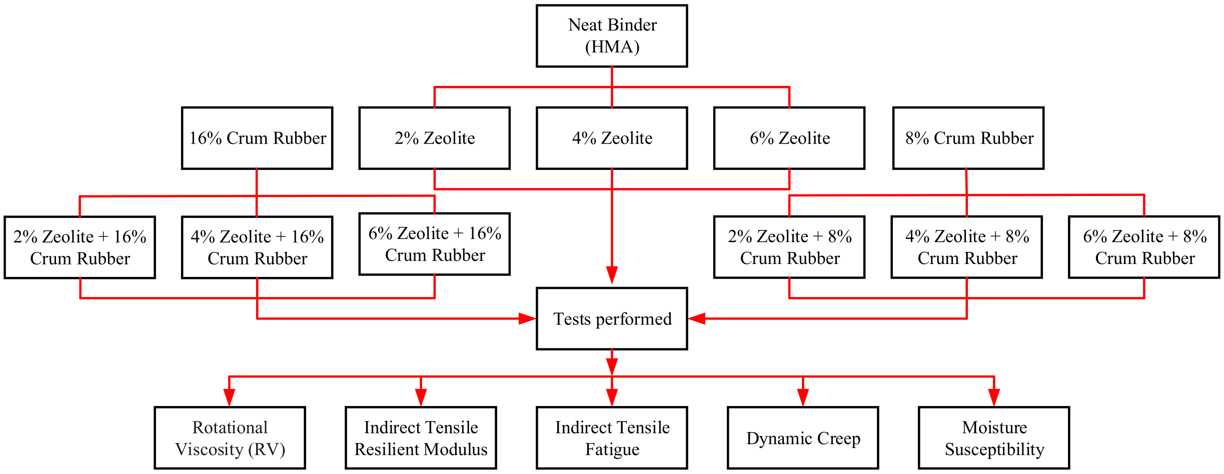


Figure 1. Flowchart of Experimental design in this study.

The mineralogical characteristics and engineering characteristics of the aggregates utilised in this study are shown in Tables 2 and 3, respectively.

3.2. Crumb rubber

The Crumb Rubber manufactured by grinding waste tires at an ambient temperature was supplied by the Sepidan Lastic Company. Crumb rubber with a maximum size of 0.595 mm (30 mesh size) was utilised to make asphalt mixes. The physical properties of CR used in this study are shown in Table 4.

3.3. Warm mix additive (Zeolite)

The word ‘ Zeolite’ is derived from a Greek word ‘ζειυ,’ which means boiling stone since it releases water which makes it seem like it is boiling (Ghobarkar et al. 2003). Naturally, zeolites are microporous, hydrated aluminosilicate minerals with a porous structure. They are formed from interconnected tetrahedral of alumina (AlO_4) and silica (SiO_4) (Grace and Grace n.d.). The zeolite used in this research study was supplied by an Iranian company that is economically effective because it is produced inside the country. It forms a white to reddish powder. 2%, 4%, and 6% doses of zeolite, respectively, are utilised as a part of the binder content. Physicochemical properties of naural zeolite used in this study are shown in Table 5 and 6. Also, the pictorial presentation of the natural zeolite are presented in the Figure 3.

Table 1. Specifications of the AC 60/70 base bitumen.

Test	Standard	Result	Standard range Min	Standard range Max
Penetration (0.1 mm) (100 g, 5s, 25°C)	ASTM D5	66	60	70
Softening point (°C)	ASTM D36	49.4	46	–
Density (60°F, Kg/M3)	ASTM D3289	1017	1010	1060
flash point (°C)	ASTM D92	334	232	–
Ductility (cm) (25 °C, 5 cm/min)	ASTM D113	>100	100	–
Solubility in TCE wt%	ASTM D2042	99.94	99	–

4. Sample preparation

8% and 16% of CR were utilised in this investigation, based on the authors’ previous experimental work and other results (Kök and Çolak 2011; Ameri et al. 2017). The mixtures were blended for 60 min at a shear speed of 6000 rpm at 180 °C using a high-shear mixer (Yengejeh et al. 2020).

The Marshall Mix Design method was used to mix asphalt mixtures, which was conducted on cylindrical samples (10.16 cm in diameter and 6.35 cm thick) by compaction utilising 75 blows on each side. The following standard methods were used to compress and test Marshall samples: bulk specific gravity (ASTM D2726) and stability and flow test (ASTM D1559). For each test, three experimental samples were utilised (Marshall stability and flow, indirect tensile strength, resilient modulus test, fatigue test, dynamic creep, and moisture susceptibility). The value of 5.3% was obtained as the amount of optimum asphalt binder.

Additional samples were fabricated using Superpave Gyratory Compactor (SGC) in cylindrical molds (10.16 cm in diameter) to reach 4% air void and 7% air void. Totally, 216 asphalt mixtures (144 samples with 7% air void and 72 samples with 4% air void) were fabricated with 12 different binders to conduct the experiments in this research study.

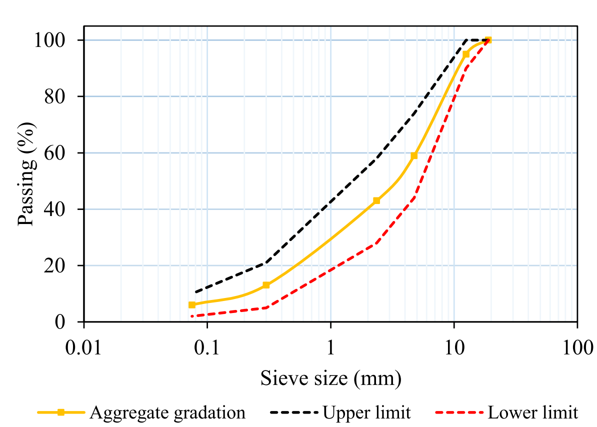


Figure 2. The gradation of used aggregates.

Table 2. Mineralogical properties of used aggregates.

element	TiO_2	Sr	MnO	Fe_2O_3	CaO	K_2O	SO_3	P_2O_5	SiO_2	Al_2O_3	MgO	Na_2O
content (%)	0.909	1.596	2.794	15.106	0.174	0.182	0.629	77.495	1.116	<<	<<	<<

Table 3. Physical and engineering properties of aggregates.

Property		Test value
Coarse aggregates		
Los Angeles abrasion (%) (AASHTO T96)	Grading type	C
	Number of cycles	500
	Abrasion	23
Sodium Sulfate soundness (AASHTO-T104) (%)		0.1
Flat and elongated particles (ASTM-D4791) (%)		0.3
Fractured particles in Coarse aggregate (ASTM-D5821) (%)		100
Fine aggregates		
Atterberg limits(AASHTO-T89,90)	PI	NP
	PL	–
	LL	Indefinable
Sodium Sulfate soundness (AASHTO-T104) (%)		1.0
Fine aggregate angularity (ASTM C 1252) (%)		43
Sand Equivalent (AASHTO-T176) (%)		84
Filler		
Atterberg limits (AASHTO-T89,90)	PI	NP
	PL	–
	LL	Indefinable

Table 4. Physical properties of crumb rubber.

Properties	Result
Ingredients	Processed rubber Carbon, sulfur
Physical State	Solid
Color	Dark
Specific gravity	Mild rubber
Bulk density	1.10-1.15
Ph values	0.35 g/cm3
melting point	N/A
Solubility	Insoluble

5. Testing procedures

This section provides the testing procedures used to evaluate the impact of zeolite and Crumb Rubber on the viscosity and mechanical performance of asphalt mixture.

5.1. Rotational viscosity (RV)

The viscosity of the binders at high temperatures was measured using the Brookfield Rotational Viscometer (BRV). To identify the proper production temperature for each specimen, the viscosity of various binders must be evaluated at different temperatures. According to NCHRP Reports 648 and 458, three distinct techniques were used to determine the viscosity of asphalt binders and assess their workability during mixing and compaction: the Equiviscous method, the zero shear viscosity (ZSV) method, and the simplified-zero shear viscosity (S-ZSV) method. Detailed information about the sample preparation and the test procedure of this method can be found in Ameri et al. (2020b). According to Superior performing asphalt pavements (Superpave), to achieve acceptable pumping ability during production and construction, the viscosity of modified and unmodified binders at 135°C should be less than 3 Pa.s. This research tested the modified binders' viscosity at three different (i.e. 135°C, 150°C, and 165°C) temperatures. After measuring the viscosity of the blended binders, the mixing and compaction temperatures were determined in accordance with AASHTO T316.

Table 6. Physical properties of zeolite.

Properties	Result
Surface area (m^2/g)	7.7
Water absorption (%)	18.5
Porosity size	0.32
Apparent density (g/cc)	0.730
Loss of ignition (%)	15.13

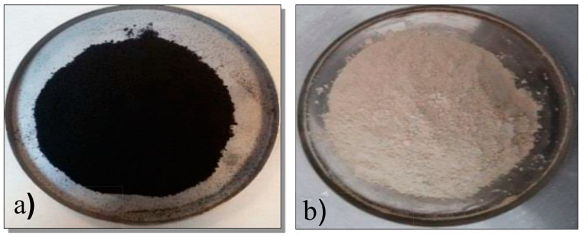


Figure 3. Pictorial presentation of the additives used in this study: (a) Crumb rubber, (b) Zeolite.

5.2. Indirect tensile resilient modulus

The indirect tensile resilient modulus test was conducted with the universal testing machine (UTM) to measure asphalt mixtures' resilient modulus (Mr). M_r is the ratio of deviator stress over recoverable strain (Ali Zangena 2019). The test was conducted based on ASTM D4123. Resilient modulus is a critical factor in designing asphalt layers. In this test, three specimens with 4% air void were used for each type of asphalt mixture. Before initiating the test, samples have been put in a chamber for 24 h to reach 25°C. M_r was measured while a 400N haversine load with 1 Hz frequency was applied to the specimen. Loading cycle width was 0.1 s followed by a rest period of 0.9 s.; all specimens were conditioned with 50 repetitions before testing. The average resilient modulus of specimens was reported as the test result. The sample in the UTM is shown in Figure 4. The resilient modulus was determined using the following equation:

$$M_r = \frac{P}{H.t} * (0.27 + v) \tag{1}$$

Table 5. Chemical structure of used natural zeolite.

Ingredient	Na_2O	K_2O	MgO	CaO	Al_2O_3	Fe_2O_3	SiO_2	LOI
Percent	0.75	0.07	0.69	2.32	11.55	1.25	64.51	18.86

Figure 4. Sample under load in UTM to conduct resilient modulus test.

Where the vertical load (N) is called P, while the mean amplitude of the horizontal deformations obtained from the previous three applications of the load pulse (mm) is labelled H, also, the mean thickness of the test sample (mm) is denoted by t, and the Poisson's ratio v is assumed to be 0.35.

5.3. Indirect tensile fatigue test (IDT fatigue)

The indirect tensile fatigue test can be done in both constant stress and strain mode. In constant stress mode, the strain will be increased when the stress is held constant (Arabani et al. 2010). The IDT fatigue test was conducted in constant stress mode by applying 300 KPa haversine signal loading. The loading cycle width was 0.1 s followed by a rest period of 0.4 s. the deformation of specimens was monitored by LVDTs. Before the IDT fatigue test, specimens were conditioned at 25°C for 24 h in the UTM device environmental chamber. Afterward, the specimens were loaded under cyclic fatigue load to failure. The loading cycle where the specimens failed was measured and reported as the mixture fatigue life (Al-Khateeb and Ghuzlan 2014).

5.4. Dynamic creep

Dynamic creep was used to determine the resistance of specimens to permanent deformation. The test was performed at 50°C. Haversine loading with 400 KPa compressive stresses and 20 KPa seating stress was applied to mixtures in which the loading cycle width was 0.5s followed by a rest period of 1.5s, and LDVTs measured the strains during the test. For evaluation and comparison of results, the model proposed by Zhou was used (Zhou et al. 2004). This model is fitted to the test results by using the solver tool in Excel software and presented in Figure 5. This model has distinct regions for the creep response, namely primary region, secondary region, and territory region. The first region has a strain accumulation rate that drops off over time. The strain rate is constant in the second region, but it increases as a function of time in the tertiary creep region. The FN is defined as the number of load cycles at which tertiary flow starts or the number of load cycles at which the slope of the curve of accumulated permanent strain against load cycles is lowest (Figure 5). The test was terminated at 6% accumulated strain because all the mixtures reached the territory region. In addition, the slope of the second stage represents the rate of increase of accumulated strain. The greater the slope, the lower the resistance to rutting. The formulations of Zhou models is demonstrated as follows (Zhou et al. 2004):

Primary stage:

$$N \le N_{ps};\ \varepsilon_p = aN^b;\ \varepsilon_{ps} = aN_{ps}^b \tag{2}$$

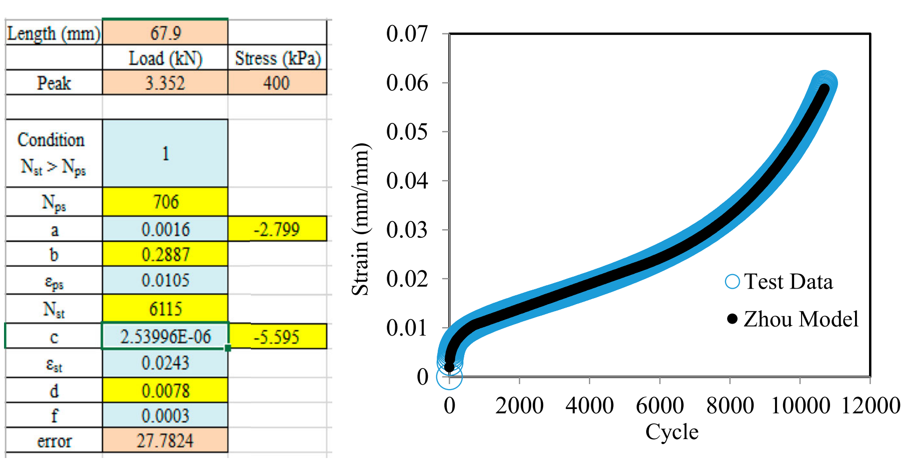
Secondary stage:

$$N_{ps} \le N \le N_{st};\ \ \varepsilon_p = \varepsilon_{ps} + c(N - N_{ps});\ \ \varepsilon_{st} = \varepsilon_{ps} + c(N_{st} - N_{ps}) \tag{3}$$

Territory stage:

$$N \ge N_{st};\ \ \varepsilon_p = \ \varepsilon_{st} + d(e^{f(N - N_{st})} - 1) \tag{4}$$

Where a and b are material constant; and $N_{ps}$is the number of load repetitions corresponding to the initiation of the secondary region, c is material constant; N_{st}or FN is the number of load repetitions corresponding to the initiation of the tertiary



Length (mm)	67.9	
	Load (kN)	Stress (kPa)
Peak	3.352	400
Condition $N_{st} > N_{ps}$	1	
N_{ps}	706	
a	0.0016	-2.799
b	0.2887	
ε_{ps}	0.0105	
N_{st}	6115	
c	2.53996E-06	-5.595
ε_{st}	0.0243	
d	0.0078	
f	0.0003	
error	27.7824	

Figure 5. Fitting the Zhou model on dynamic creep test results in Excel software.

stage; and ε_{ps} is the permanent strain corresponding to the initiation of the secondary region, d and f are material constants; and ε_{st} is permanent strain corresponding to the initiation of the tertiary stage.

5.5. Moisture susceptibility (TSR and RMR test)

Asphalt pavements are exposed to various distresses of which is stripping that is caused by moisture (Sobhi et al. 2020a). Moisture can damage asphalt mixtures through loss of cohesion and adhesion. Adhesion loss occurs because water gets between the bitumen and the aggregate and removes the asphalt film from aggregates. The loss of cohesion is due to the softening of asphalt concrete mastic (Ameri et al. 2021; Moghadas Nejad et al. 2012). In this research, two different methods, namely Tensile Strength Ratio (TSR) and Resilient Modulus Ratio (RMR), have been used to estimate the moisture susceptibility of asphalt mixtures.

5.6. Tensile Strength ratio (TSR)

The effect of water on decreasing the strength of asphalt mixtures is one of the more essential issues which needs to be evaluated for moisture sensitivity (Sobhi et al. 2020a; Moghadas Nejad et al. 2012; Silva et al. 2010b). The ratio of Indirect Tensile Stress of conditioned specimens (specimens were saturated with water) over that of unconditioned (dry specimens) specimens is called TSR, which is a criterion to measure water susceptibility of asphalt mixtures according to AASHTO T283 (Modified Lottman test). For each type of binder, six specimens were fabricated to an air void level of 7 ± 0.5% using SGC; three were prepared for the conditioned state and the remainder for the unconditioned state. The conditioned specimens were vacuumed in a vacuum device to reach 70–80% saturation. Then, specimens were transferred to a freezer set at -18°C and stored for 16 h. Afterward, the frozen samples were immersed in 60°C water for 24 h. Finally, samples were placed in 25°C water for two hours before testing. The unconditioned samples were also placed in 25°C water for two hours before testing. Equation (5) was used to calculate the tensile strength of asphalt mixtures (TRB 2000):

$$\mathrm{ITS} = \frac{2000\ \mathrm{P}}{\pi.\ \mathrm{D.\ t}} \tag{5}$$

Where ITS is Indirect Tensile Stress (KPa), P is the maximum load (N), t is the thickness of the sample (mm), D is the sample diameter (mm). The Tensile Strength Ratio (TSR) of the mixtures was calculated using equation (6) (Gorkem and Sengoz 2009):

$$\mathrm{TSR} = \frac{\mathrm{ITS\ conditioned}}{\mathrm{ITS\ unconditioned}} \times 100 \tag{6}$$

Where $\mathrm{ITS}_{\mathrm{conditioned}}$ is the average of indirect tensile strength of three conditioned specimens, and $\mathrm{ITS}_{\mathrm{unconditioned}}$ is the average value of indirect tensile strength of the unconditioned specimens.

5.7. Resilient Modulus Ratio (RMR)

Resilient modulus (M_r) is an important parameter for evaluating the stiffness of the mixtures. It is the ratio of deviator stress over resilient strain at a specific temperature and load (Yousefi et al. 2020a). RMR is the ratio of resilient modulus of the conditioned sample over the unconditioned sample in accordance with ASTM D4123. The conditioned and unconditioned samples were prepared following the AASHTO T283. UTM was used to conduct the test. The test was conducted similar to the resilient modulus test described in section 3.1 except for the sample preparation. The samples were prepared with 7% air void. 70% RMR is considered the least acceptable value against water susceptibility of the mixtures (Ameri et al. 2021; Heinicke and Vinson 1988; Lottman 1978). Resilient Modulus Ratio (RMR) was obtained by the following equation:

$$\mathrm{RMR} = \frac{Mr_{conditioned}}{Mr_{unconditioned}} \times 100 \tag{7}$$

6. Results and discussion

6.1. Rotational viscosity (RV)

The viscosity values and mix temperature range for modified asphalt binder at three temperatures are shown in Table 7. As shown in Table 7, with the addition of the CR to the asphalt binder, the viscosity of the modified binder slightly increased, which some other studies agree with these results (Behnood et al. 2020; Loderer et al. 2018; Jeong et al. 2010). With increasing the CR content, the increase of viscosity value is more. Also, Table 7 indicated that the viscosity value decreased with increasing the viscosity test temperature. Likewise, the rotational viscosity test results show that the use of zeolite reduced the viscosity of the modified asphalt binder. With increasing the use content, this increase is more significant. Therefore, adding zeolite can improve the workability of the modified asphalt binder. The range of mixing and compaction temperature of base and modified asphalt binder also indicated that the mixing and compaction of modified asphalt binder increased by adding the CR and increasing the CR content. However, the use of zeolite can decrease the negative effect of CR on the workability and pumping property of modified asphalt binder and decrease the mixing and compaction

Table 7. Viscosity values and mix temperature range for modified asphalt binder.

Binder	Rotational viscosity (mPa.s)			Temperature range (°C)	
	135°C	150°C	165°C	Mixing	Compaction
Neat	304	193	140	152–162	134–141
CR0-Z2	275	179	114	147–155	132–138
CR0-Z4	252	158	112	144–153	128–135
CR0-Z6	228	146	107	141–150	124–131
CR8-Z0	2919	1424	824	165–169	149–153
CR8-Z2	2317	1255	686	161–165	145–149
CR8-Z4	1518	940	550	154–158	136–140
CR8-Z6	1296	699	462	148–151	131–134
CR16-Z0	3615	2027	1102	175–179	157–161
CR16-Z2	3160	1667	992	171–175	153–157
CR16-Z4	2472	1422	814	166–170	148–152
CR16-Z6	2098	1075	677	159–163	143–146

temperature of modified asphalt binders so that the coupled use of CR and zeolite (CR8-Z6) can decrease the mixing and compaction temperature of asphalt mixture lower than the base binder.

6.2. Indirect tensile resilient modulus

Resilient modulus is a significant parameter to analyze the response of asphalt mixtures to determine layer thickness (Sobhi et al. 2020b). Figure 6 shows the results of the resilient modulus test. As can be seen, addition of zeolite increases the M_r value of HMA, which validates the results obtained from previous research (Yousefi et al. 2020a; Topal et al. 2014). In general, adding CR to the asphalt mixture also increases the Mr value, as seen in other studies (Ameri et al. 2020b; Behroozikhah et al. 2017). It can be seen that the values of M_r and stiffness for all the mixtures containing zeolite is greater than that of their control mixtures, and this result is in line with previously reported findings (Yousefi et al. 2020a; Topal et al. 2014; Goh and You 2008; Tafti et al. 2016; Valdes-Vidal et al. 2018; Woszuk and Franus 2016). As the content of zeolite increase from 0% to 6%, the M_r values of HMA, CR8, and CR16 mixture is increased by 16%, 24.6%, and 19.5%, respectively.

According to AASHTO Guide for the Design of Pavement Structures (1993), the strength parameter of asphalt layers depends on the M_r value of the asphalt mixture. The larger the M_r values, the higher the strength of the asphalt layers. The test results show that the CR16-Z6 mixture has the maximum M_r value, while HMA exhibited the lowest M_r. It seems that the enhancement of stiffness of asphalt binder by the addition of CR and Zeolite leads to increasing the resilient modulus for all modified mixtures. The increase in stiffness can be due to two reasons. The first reason is the better coating of aggregates with virgin bitumen and RA due to the reduction of viscosity by zeolite because it releases water at the corresponding mixing and compaction temperature. The second reason is the function of zeolite as filler in the mixture. The resilient modulus was evaluated at medium temperature, and zeolite released water at a higher temperature, so at 25°C, it acts as filler. In this way, it increases the stiffness in the asphalt mixture. Although in terms of rutting resistance, a higher resilient modulus at high temperatures is preferred, at low temperature, the AASHTO flexible pavement design handbook states that asphalt mixtures with higher resilient modulus above 3100 MPa are more susceptible to thermal and fatigue cracking (AASHTO 1993). Except for the HMA, CR0-Z2, and CR0-Z4, the resilience modulus of the modified asphalt mixtures was more than 3100 MPa, indicating that the modified mixtures are stiffer than the conventional HMA mixture (Figure 6). As a result, these stiff mixtures are advised for use in the temperate regions and topcoat's upper layer, which is not subjected to excessive tensile stress (Imaninasab 2016; Pasandín and Pérez 2013; Shen and Du 2005).

6.3. Indirect tensile fatigue test

Fatigue cracking is crucial distress that occurs at intermediate temperatures. In this study fatigue test was conducted in the controlled stress mode. When a vertical crack at the centre of the sample (entire diameter length of the sample) occurs, it represents the fact that the specimen has collapsed (Al-Khateeb and Ghuzlan 2014). The loading cycle leading to cracks was considered as fatigue life (N_f) (Abo-Qudais and Shatnawi 2007). Figure 7 shows the results of the indirect tensile fatigue test. Mixtures containing zeolite could withstand higher fatigue life as compared to their reference mixtures (Topal et al. 2014; Shafabakhsh and Ahmadi 2019). The results are the same as those of other researchers that mixtures containing zeolite can tolerate higher loading cycle than HMA (Topal et al. 2014). The addition of zeolite from 0% up to 6% in HMA, CR8, and CR16 mixtures increased fatigue life by 57.5%, 46.2%, 84.5% respectively. It seems that zeolite in CR16 mixtures had a better performance in fatigue resistance than HMA and CR8 mixtures. CR16-Z6 mixture was the better combination of CR and zeolite to resist fatigue cracking. The results showed that the addition of CR and zeolite have improved the fatigue life of asphalt mixtures. According to straight relation between resilient modulus and fatigue resistance in constant stress mode, it can be concluded that, increasing stiffness leads to an increase of fatigue life at a stress level of 300 kPa.

6.3. Dynamic creep test

Rutting happens more often when the temperature is high, and loads are placed repeatedly. Dynamic creep test enables the assessment of the asphalt mixture's permanent deformation potential (Kök and Çolak 2011; Ziari et al. 2021). In this study, three specimens were used, and the average test results

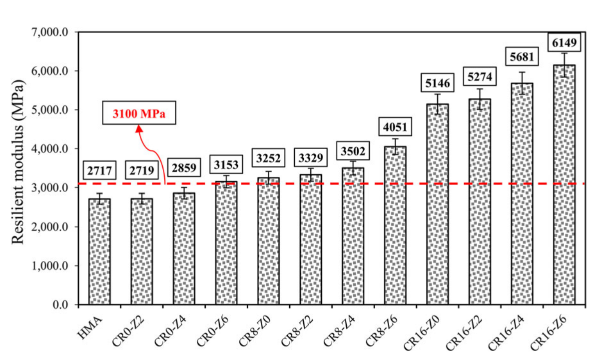


Figure 6. Results of the resilient modulus test for different mixtures.

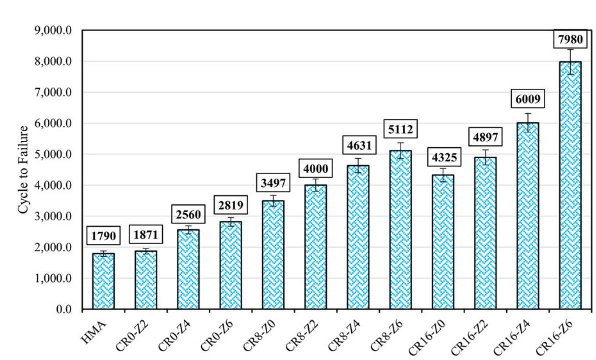


Figure 7. Indirect tensile fatigue test results.

were used to obtain the rutting potentials of the mixtures. Figure 8 shows the flow number of each type of asphalt binder. As depicted in the figure, the higher the crumb rubber content, the higher the value of the FN. The considerable positive effect of Zeolite on the rutting resistance of the mixtures is revealed when the FN of the mixture containing zeolite is compared with the FN other mixtures without zeolite, which was similar to the reported results by other researchers (Topal et al. 2014; Valdes-Vidal et al. 2018; Woszuk and Franus 2016; Sanchez-Alonso et al. 2013; Ahmadzadegan and Sarkar 2021). Increasing the amount of zeolite from 0% up to 6% led to an increase in the FN value of HMA, CR8, and CR16 mixtures by 38.1%, 47.0%, and 61.3%, respectively. The highest FN belongs to CR16-Z6, while the lowest value belongs to the control mixture (i.e. HMA). It can be concluded that the increase in resistance to permanent deformations is due to the increase in stiffness of asphalt mixtures. Figure 9 shows the accumulated strain versus load cycle for all the samples.

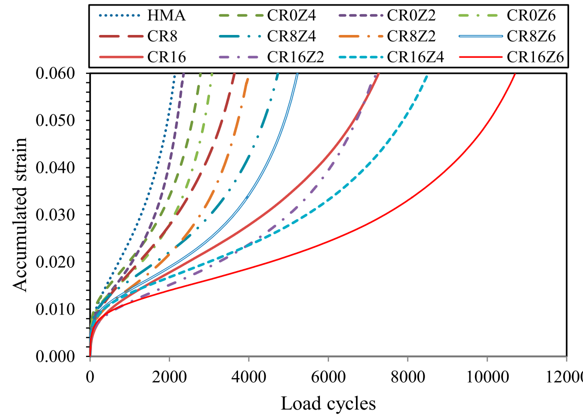


Figure 9. Accumulated strain versus load cycle.

7. Moisture susceptibility (TSR and RMR tests)

7.1. Tensile Strength Ratio (TSR)

The TSR test was conducted to evaluate the moisture susceptibility of asphalt mixtures. The higher TSR ratio indicates mixtures with better resistance to moisture damage (Xiao and Amirkhanian 2009). ITS values were measured for all the conditioned and unconditioned mixtures and are presented in Figure 10. According to AASHTO T283, a minimum TSR value of 80% is desirable. In addition, according to the SCDOT[1] standard, asphalt mixtures must have a minimum ITS value of 448 KPa in the conditioned state. The freeze–thaw cycle leads to a reduction in ITS values of the mixtures. As shown in Figure 10, by adding CR, the ITS $_{\text{unconditioned}}$ has increased while the ITS $_{\text{conditioned}}$ decreased. In contrast to CR, adding zeolite increased the ITS values for both conditioned and unconditioned samples. These results are similar to the findings of previous research, which concluded that using natural zeolite in HMA increased the ITS value of HMA in the conditioned specimens (Şengöz et al. 2013; Woszuk and Franus 2016; Ahmadzadegan and Sarkar 2021) Figure 10 shows that all of the samples had the minimum $ITS_{\text{conditioned}}$ value of 448 KPa except for the CR16-Z0, which fails to meet the minimum. Moreover, the CR16-Z6 has the maximum $ITS_{\text{unconditioned}}$ value, whereas the CR0-Z6 has the greatest value of $ITS_{\text{conditioned}}$.

Figure 11 shows that modified HMA mixture with zeolite increased the TSR value, which can validate similar findings derived from another study (Şengöz et al. 2013; Woszuk and Franus 2016). Also, the results indicated that the addition of 0% up to 6% zeolite in HMA would increase the TSR values of HMA, CR8, and CR16 mixtures by 7.3%, 8.5%, 5.8%, respectively. Furthermore, the results indicate that by using CR alone (without zeolite), TSR value decreased, and none of the mixtures met the minimum TSR value.

7.2. Resilient Modulus Ratio (RMR)

RMR is another index for evaluating the strength of asphalt mixtures against moisture. Resilient modulus test has been conducted on both unconditioned and conditioned samples after one freeze–thaw cycle. RMR values are shown in Figure 12. As shown in Figure 12, the addition of CR led to a decrease in the RMR values, which were similar to the TSR results, but zeolite enhanced RMR values. All of the mixtures met the 70% criterion except for CR16-Z0 and CR16-Z2 mixtures. CR0-Z6 Mixture has the highest RMR value, while the lowest value belongs to the CR16-Z0 mixture. The results also indicate that the RMR index is more susceptible to the presence of moisture than the TSR index. Figure 13 demonstrates the relationship between TSR and RMR values. It can be observed that there is a good correlation between TSR and RMR, which similar findings have been reported in previous studies (Ameri

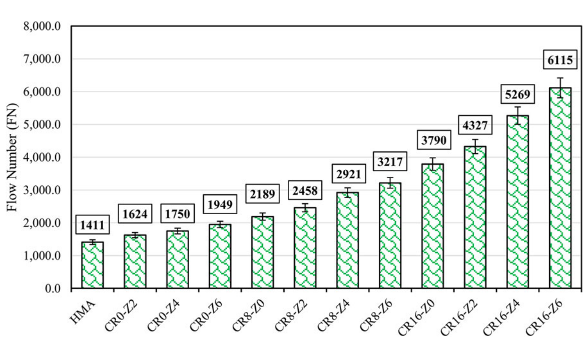


Figure 8. Flow Number values.

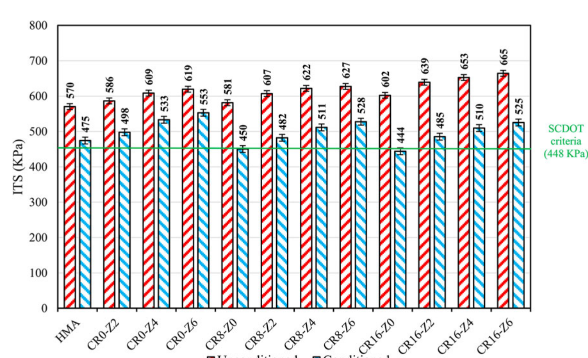


Figure 10. ITS results for dry and wet conditions.

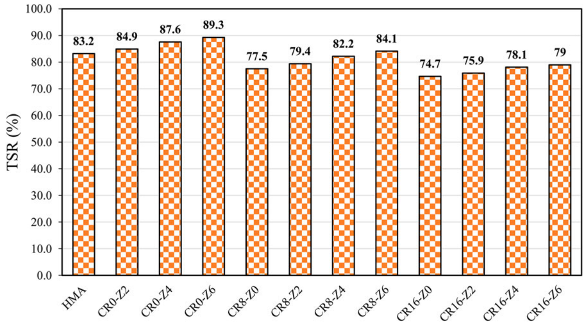


Figure 11. Tensile strength ratio of asphalt mixes with and without modifiers.

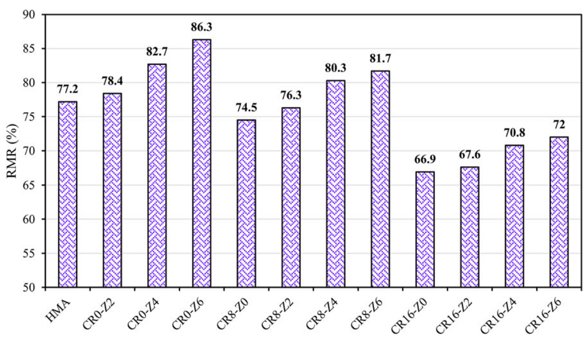


Figure 12. Control and modified asphalt mixes test results for RMR.

et al. 2021; Arbabpour Bidgoli et al. 2020; Bagampadde et al. 2006).

7. Cost-effectiveness analysis

7.1. Energy consumption

In this study, an analysis was performed to compare different mixtures from an energy consumption point of view. For this purpose, following a previous survey of the energy consumption of asphalt mixtures (Almeida-Costa and Benta 2016), the energy used to heat the mixture (i.e. Q) is calculated as:

$$Q = (m_a.c_a + m_b c_b)\Delta T \tag{8}$$

where m_a and m_b are, respectively, the masses of aggregate and

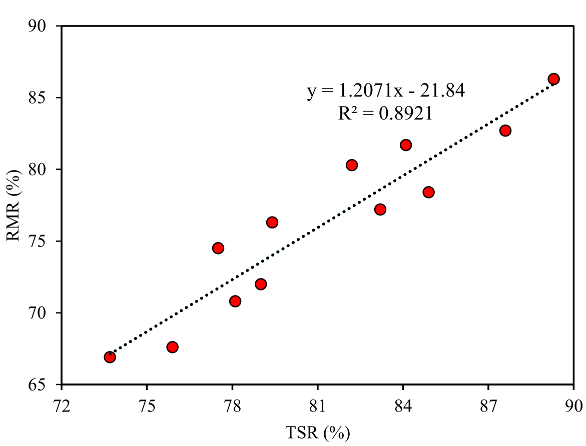


Figure 13. TSR and RMR relationship.

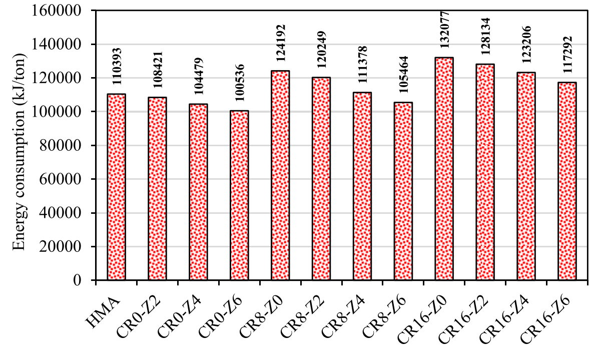


Figure 14. Energy consumption per ton of mixture (kJ/ton).

binder; c_b and c_a are, respectively, the specific heat capacities of aggregate and binder; and ΔT is the difference between the mixing temperature and ambient temperature (which is assumed to be 25°C). For the mixing temperature, the average of the mixing temperatures given in Table 7 was used. The specific heat capacities of aggregate and binder were assumed as 920.5 and 2093.4 J/(kg/°C), respectively (Almeida-Costa and Benta 2016).

The energy consumption values of different asphalt mixtures are shown in Figure 14. The results demonstrate two things. First, increasing the CR content in the modified asphalt mixture due to the increased compaction and mixing temperature increased the energy consumption. Second, by modifying the asphalt binder with zeolite, the energy consumption of the modified asphalt binder slightly decreased. The highest energy consumption is associated with the mixture containing CR without zeolite, while the lowest is related to the mixture containing 6% zeolite without CR. Furthermore, the results also indicated that the simultaneous proper use of zeolite and CR decreased the energy consumption of the asphalt mixture even lower than the base asphalt mixture.

Based on the cost of materials used in the asphalt mixture, a cost-effectiveness analysis also was conducted to compare the production cost of various asphalt mixtures. The authentic unit pricing of materials is gathered from the Company's offer price and international studies (Jahanbakhsh et al. 2020; Zaumanis et al. 2014). Aggregate, neat asphalt binder, CR, and zeolite were priced at 19.8, 704, 420, and 120 USD/

Table 8. Cost-effective analysis.

Mixture Type	Cost per ton of material (USD)				Cost per ton of mixture (USD)
	AC 60/70 ($704/ton)	CR ($420/ton)	Zeolite ($400/ton)	Aggregate ($19.8/ton)	
Neat	39.40	0.00	0.00	18.69	58.1
CR0-Z2	38.61	0.00	0.13	18.69	57.8
CR0-Z4	37.82	0.00	0.27	18.69	57.4
CR0-Z6	37.04	0.00	0.40	18.69	57.1
CR8-Z0	36.25	1.88	0.00	18.69	56.8
CR8-Z2	35.46	1.88	0.13	18.69	56.5
CR8-Z4	34.67	1.88	0.27	18.69	56.1
CR8-Z6	33.88	1.88	0.40	18.69	55.8
CR16-Z0	38.77	0.38	0.00	18.69	57.8
CR16-Z2	37.98	0.38	0.13	18.69	57.5
CR16-Z4	37.19	0.38	0.27	18.69	57.2
CR16-Z6	36.41	0.38	0.40	18.69	56.8

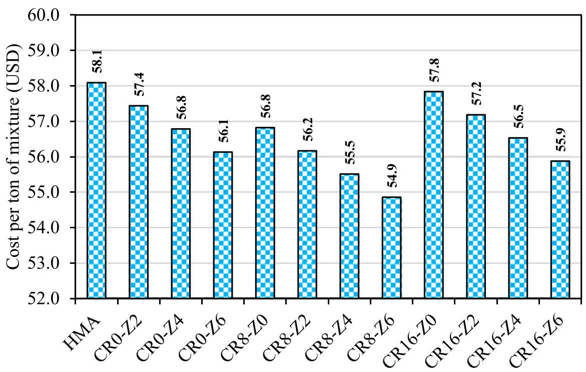


Figure 15. The production cost of different asphalt mixture.

ton, respectively. Table 8 and Figure 15 show the cost per ton of different asphalt mixtures. As expected, replacing the asphalt binder with additives (CR and zeolite), which has a lower price than the virgin binder, decreases the production cost per ton of modified asphalt mixtures. The cost–benefit analysis results indicated that not only does the simultaneous use of zeolite and CR decrease energy consumption, but it also decreases the production cost of modified asphalt minder. The highest energy consumption is associated with the mixture without zeolite and CR, while the lowest energy consumption is related to the mixture containing 6% zeolite and 8% CR.

8 Concluding remarks

In this research study, CR and zeolite were used individually and also combined to modify properties of 60/70 penetration grade bitumen and evaluate mechanical properties of asphalt mixtures produced with these modified binders. For this purpose, 0%, 8%, and 16% of CR and 0%, 2%, 4%, and 6% of zeolite have been used. Indirect resilient modulus, indirect tensile fatigue, dynamic creep tests and TSR, and RMR moisture susceptibility tests were conducted to evaluate the properties of asphalt mixtures. The following conclusions were drawn based on the limited laboratory test results obtained in this research study.

- The addition of CR increased the resilient modulus, especially for 16% CR. Also, this trend was repeated by the addition of zeolite. CR16-Z6 with 2.26 times that of the neat binder had the maximum resilient modulus.
- The fatigue life of the mixture containing 16% CR was 2.42 times more than HMA, and the mixture containing 6% zeolite was 1.58 times that of HMA. Finally, CR16-Z6 mixture had the highest fatigue life, 4.46 times more than HMA.
- FN of CR0-Z6, CR16-Z0, and CR16-Z6 were 1.38, 2.69, and 4.33 times more than HMA, respectively.
- The last step was evaluating moisture susceptibility by employing two methods (TSR and RMR). Rubberised asphalt mixtures had greater sensitivity to moisture. Because natural zeolite had moisture in its structure, it was predicted to increase moisture sensitivity. However, contrary to expectations, the addition of 2%, 4%, and 6% zeolite significantly improved moisture susceptibility in all mixtures. This indicates that natural zeolite diminishes the moisture susceptibility of asphalt mixtures. Another interesting result was the higher sensitivity of RMR compared to TSR results to moisture.
- According to the observations and favourable results, it can be deducted that using zeolite along with CR will improve mechanical characteristics. In addition, the presence of zeolite reduced mixing and compaction temperatures in HMA and rubberised mixtures. The cheapness and availability of these two additives are two other good reasons for justifying the use of this combination in asphalt pavement. Finally, the optimal content of 16% CR along with 6% of natural zeolite is recommended.
- The cost-effectiveness analysis and energy consumption values of various asphalt mixtures revealed that all of the mixtures produced in this study are cost-effective because low-cost refined materials are replaced with expensive virgin materials. CR8-Z6 may save cost-effectiveness and energy consumption by 5.5% and 5%, respectively.

Note

1. South Carolina Department of Transportation

Disclosure statement

No potential conflict of interest was reported by the author(s).

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