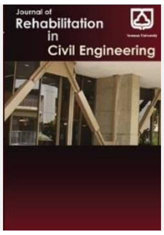

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Optimizing the Amount of Multicomponent Polymer Fibers in RAP Mixtures Based on the BMD Criteria

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ABSTRACT

As the final part of a pavement, asphalt mixtures are aimed to ensure the road users' safety and comfort and any defect in them can disturb the users. They usually consist of bitumen, aggregates and air (as main components) plus a wide range of additives, among which fibers are more important and attract the attention of researchers because they overcome the tensile weakness of asphalt mixtures and improve their performance features. This research has used multicomponent fibers to modify the properties of asphalt mixtures containing reclaimed asphalt pavement overhauled by waste, engine-oil rejuvenator, and applied the balanced mix-design method to optimize the materials. The dynamic creep test, Illinois Flexibility Index (IFI), indirect tensile strength (ITS), and tensile strength ratio (TSR) were utilized to evaluate the mixtures' performance. The findings revealed that the incorporation of multi-component polymer fibers improved the rutting resistance of asphalt mixtures by up to 70%, whereas the addition of waste oil decreased rutting resistance by up to 1.5%. Furthermore, the highest IFI values were recorded for the specimens containing waste oil. However, the rejuvenator exhibited a negligible effect on the TSR values. Considering the Balanced Mix Design (BMD) criteria, two mixtures containing 40% reclaimed asphalt pavement (RAP), 0.75% rejuvenator, and 0.8% or 1.2% multi-component fibers were identified as the optimum mixtures in this study.

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1. Introduction

A major part of the road quality depends on its pavement quality, and since asphalt mixtures form a large part of the pavement, their proper quality can play a significant role in saving the maintenance costs.[1] Asphalt mixtures consist mainly of bitumen and aggregates, any change in the properties of which can change the mixture's final properties [2]. In recent years, different additives, fibers, and aggregate substitutes have also been used, besides the main components, to improve the performance features and the environmental benefits resulting from the use of these materials [3,4]. Although the latter can create such challenges as additional costs and improper fiber dispersion, the challenges can be ignored if their benefits are considered as well.

Using fibers is a new and effective method of improving the asphalt pavement's performance and durability because fibers improve the asphalt mixtures' mechanical and resistance features, reduce cracking and, hence, increase the pavement's useful life. Fibers can, depending on their type, length and other features, increase the asphalt mixture's tensile and shear strengths, reduce thermal cracks, increase resistance to permanent deformation, improve the stability and integrity, and increase the durability and useful life [5–8].

There are some methods to reduce the mentioned challenges (increased costs, etc.); for instance, since reclaimed asphalt pavement contain bitumen, their use has many environmental merits and reduces costs. Recycled Asphalt Pavement (RAP) chips are materials removed from old asphalts and used again in the production of new asphalts after they are recycled. Using RAP materials in asphalt mixtures is an effective and sustainable solution of reducing costs, preserving natural resources, and improving the performance features of new pavements. Like many other materials, RAP too has some challenges, the most serious one of which is perhaps the bitumen loss due to aging or other environmental factors, and some related studies have suggested using rejuvenators to solve this problem [9–11].

This is why various researches have discussed the use of fibers, RAP and different rejuvenators in asphalt mixtures; for instance, Wi´sniewski et al. [12] used aramid fibers to improve the functional features of asphalt mixtures and realized that there was some limited improvement. Among researchers that have studied the effects of the fibers' physical features (type, length and content) on the performance and properties of asphalt mixtures, Fucheng et al. [13] showed that the optimum 0.4 kg by wt. 6 mm-long basalt fibers were the preferred type because they improved the engineering properties such as the water sensitivity, high-temperature stability and low-temperature crack resistance. From a practical point of view, these results can be valuable for engineers and specialists.

Different researchers have investigated the RAP usage in asphalt mixtures from different views. For instance, Yang et al.[14] have reported that using up to 42% RAP in asphalt mixtures can reduce the earth energy/heat by 20% compared to no-RAP mixtures. Ghabchi et al. (2016) added 0, 25 and 40% RAP to asphalt mixtures and found that their rutting performance and moisture sensitivity were improved, but the results were somewhat different for the fatigue life; up to 25% (by wt.) RAP improved the fatigue performance/life of the mixture, but more RAPs made the performance weaker than the control design. Adding any amount of RAP reduced the low-temperature performance and thermal cracking sensitivity [15].

Various researches have studied the low-/medium-temperatures cracking, moisture sensitivity, fatigue, rutting, Marshall Resistance, etc. of asphalt mixtures [16–18], but there was no special weighting (in terms of importance) on the functional features before introducing the balanced mix-design method. Besides academic researchers, various contractors and asphalt-mixture-manufacturing agencies have also used different tests to verify the resistance of asphalt mixtures against existing types of damage, but no common agreement has been made on choosing different tests and proper requirements to check the performance of asphalt mixtures. According to the recent studies, since good-performance asphalt mixture should resist rutting and cracking (2 common pavement failures), balanced mix-design (BMD) method requires that the proper design should be selected based on multiple investigations on the best performance against rutting and cracking. Some researchers have also found that besides these two functional features, examining the moisture sensitivity is also very effective; therefore, in the past few years, these three items have been used by various researchers and institutions to provide the optimal mix-design using the BMD method [19,20].

On this same basis, this research has investigated and optimized the amount of the multicomponent polymer fibers in asphalt mixtures with/without PAR, and used the waste motor-oil in some samples, as an environmental rejuvenator, to find the amount of the bitumen in PAR.

2. Experimental procedure

2.1. Aggregate materials

aggregate materials used in this research (Table 1) are limestone obtained from the mines in the southeast of Tehran.

Table 1. Characteristics of aggregate materials.

Explanation	Results	Test standard	
		AASHTO	ASTM
Maximum wear (%) (Los Angeles method)	20	T96	
Specific gravity (gr/cm3)	2.654	T85	
Minimum breakage on two sides (%) (on Sieve No. 4)	98		D5821
Maximum water absorption (%) (coarse aggregates)	0.8	T85	
Maximum water absorption (%) (fine aggregates)	1.4	T84	

Using aggregate materials to make asphalt mixes requires aggregate gradation and weighting. The gradation of aggregates used in this research and their upper and lower limits, specified by the Iran Highway Asphalt Paving Code, are shown in Figure 1; their maximum nominal size is 12.5 mm.

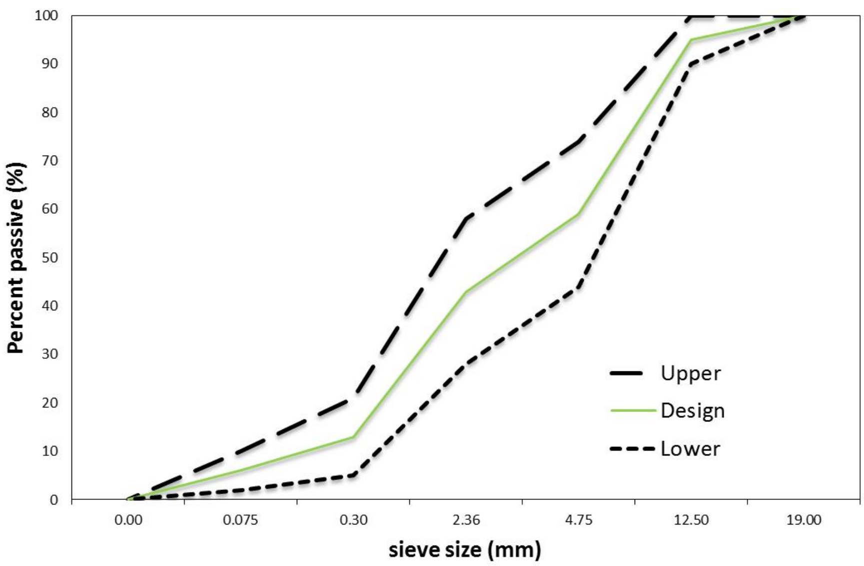

Fig. 1. Granulation curve of the aggregate materials*.

* The aggregate gradation was designed in accordance with the gradation illustrated in Figure 1.

2.2. RAP

The RAP used in this research (Table 2) has been taken from South Tehran Highway, and as the user company has announced, the gradation of its aggregate materials is in accordance with those of the present research.

In this study, 40% reclaimed asphalt pavement (RAP) was utilized, as RAP is a recycled material whose increased use in asphalt mixtures can significantly enhance the environmental benefits of the design. However, it is essential to ensure that higher RAP contents do not adversely affect the performance properties of the mixture. Previous studies have shown that incorporating up to 40% RAP with a rejuvenator can improve properties such as rutting resistance and dynamic modulus. Nevertheless, increasing the RAP content beyond 40% necessitates the application of High-RAP technologies and careful consideration of potential reductions in certain performance parameters, such as dynamic modulus [21–23].

Table 2. RAP characteristics.

Taken from	South Tehran Highway
Stored in	Open pit of aggregate materials
Additive	None
Pavement life	5 years
Withdrawal-to-use period	3 months
Amount of bitumen	4.7%

2.3. Rejuvenator

This research has used a certain, nature-friendly, recycled, motor-oil rejuvenator (Table 3); the motor-oil was obtained from a specific car that used it for several months under a constant mileage. To reduce errors, the engine worked with no problems during the time the car used the engine oil.

The primary reason for selecting this rejuvenator is its low cost and wide availability. The second reason is its proven ability to effectively restore the properties of aged asphalt binder through the use of waste motor oil, as reported in previous studies [24–26]. According to earlier research, the maximum reported dosage of waste motor oil as a rejuvenator has been up to 3% by weight of RAP, while the optimum dosage can be less than 1.5% [27,28]. In addition, to provide a more comprehensive evaluation, an intermediate dosage of 0.75% by weight of RAP was also investigated in this study.

Table 3. Rejuvenator properties.

Property	Amount
Specific weight	0.916
Viscosity (at 135° C)	280
Flash point (°C)	225

2.4. Multicomponent fibers

This research has used multicomponent polymer fibers (Figure 2 & Table 4) to reinforce the asphalt mixtures. The fibers were added when the bitumen and aggregates were mixed so that they were spread uniformly (through visual control) in the mixture.

The multi-component fibers used in this study consist of two soluble constituents, both of which are polymers. In the presence of a rejuvenator—which typically reduces the flow number (rutting resistance)

[29–31]. their incorporation into asphalt mixtures containing RAP and a rejuvenator can be particularly beneficial. Additionally, the insoluble components of these fibers can enhance tensile strength and improve cracking resistance. Based on previous studies, a maximum fiber content of 1.2% by weight of binder was adopted in this study [32].To further evaluate the influence of these fibers, two additional dosages of 0.4% and 0.8% by weight of binder were also investigated.

Fig. 2. Multicomponent polymer fibers*.

*These fibers consist of five different components, which are also illustrated in the figure.

Table 4. Features of multicomponent fibers.

Feature	Multicomponent
color	White, yellow, beige
length	19 (mm)
density	1.44 (gr/cm^3)
melting point	450 (°C)
Tensile strength	3100 (MPa)

2.5. Bitumen

This research has used PG64-22 bitumen (Table 5), the optimum amount of which, by the Superpave method, was 4.8% for the control design. This amount was considered constant in all samples.

Table 5. Bitumen specifications.

Standard	Test	Results
ASTM D-36	Softening point	47°C
ASTM D-5	Penetration (at 25°C)	67 deci mm
ASTM D-92	Ignition	304°C
ASTM D-113	Ductility (at 25°C)	> 100 CM
ASTM D-70	Bitumen specific weight	1.045 gr/cm^3

3. Methods

First, the aggregate materials were kept in the mixing temperature for 16 hours and then the bitumen, aggregates and fibers were mixed. In RAP samples, the required RAP was placed for 2 hours at the same temperature, and then the waste engine-oil (research rejuvenator) was added to the RAP sample and mixed. The combination was then kept for 15 min at the mixing temperature to be ready to be added to the aggregates.

To determine the optimal amount of the needed materials and evaluate the functional behavior of the asphalt mixtures, the samples were tested by the dynamic creep, indirect tensile strength and indirect tensile crack tests based on the Illinois Flexibility Index Test (IFIT). The samples have different names (Table 6) based on the materials used.

Table 6. Naming of the samples.

No.	Name	% Fiber	% Rejuvenator	% RAP
1	AC	0	0	0
2	F4	0.4	0	0
3	F8	0.8	0	0
4	F12	1.2	0	0
5	R40	0	0	40
6	R40F4	0.4	0	40
7	R40F8	0.8	0	40
8	R40F12	1.2	0	40
9	R40W7.5	0	0.75	40
10	R40W7.5F4	0.4	0.75	40
11	R40W7.5F8	0.8	0.75	40
12	R40W7.5F12	1.2	0.75	40
13	R40W15	0	1.5	40
14	R40W15F4	0.4	1.5	40
15	R40W15F8	0.8	1.5	40
16	R40W15F12	1.2	1.5	40

3.1. BMD method

Considering the variety of materials used in asphalt mixtures, lack of enough tests and functional methods in the normal mix-designs, and complexity of the Superpave mix-design levels, asphalt mixtures need new mix-designs. This means that using recycled materials and new technologies to produce asphalt mixtures is challenging the conventional design/mix-design methods.

Recent research has demonstrated that a robust approach to accurately characterizing the performance of asphalt mixtures should simultaneously evaluate their resistance to two primary forms of distress: rutting and fatigue cracking. Accordingly, the selection of an optimal mix design is guided by these performance indicators, a principle underpinning the Balanced Mix Design (BMD) methodology. Rutting is predominantly governed by the high-temperature deformation resistance of asphalt mixtures, whereas fatigue cracking is largely influenced by their intermediate-temperature performance and the propagation of cracks within the mixture.

Although rutting and cracking are among the main asphalt pavement failures, moisture damage too is another failure BMD can evaluate in the mix-design. This research has used the dynamic creep test, the indirect tensile test, and the IFIT to check the rutting, moisture sensitivity and medium-temperature fatigue cracking, respectively.

In using the BMD method, the most important issue is the minimum value (threshold) considered for the output of each test (Table 7); if the test output is higher than the threshold, it is acceptable and if it does not reach the threshold, it is not acceptable by the BMD approach.

Table 7. Thresholds for the tests.

No.	Test	Output	Threshold
1	Dynamic creep	FN	740 [33]
2	Moisture sensitivity	TSR	80 [34]
3	Indirect tensile crack	FI	8 [35]

3.2. Indirect tensile test

Indirect tensile test is used to determine the tensile strength and stiffness of asphalt mixtures according to AASHTO T283, its output is the indirect tensile strength (ITS), and it is either conditioned or unconditioned. All the samples used in this test were 100 mm in diameter and had empty spaces in the 6-8% range (in this research, 7±0.5%). Before the tests, the conditioned samples were saturated 55-80%, kept at -18°C for 16 hrs, 60°C for 24 hrs, and 25°C for 120 min, and the unconditioned samples were kept at 25°C for 120 min. Finally, both sample groups were subjected to a constant strain loading of 50 mm/min to create a relatively uniform tensile stress in the load application vertical diameter plane [36].

The indirect tensile strength is obtained by the following relationship.

$$ITS = \frac{P \times 2000}{\pi \times t \times D} \tag{1}$$

where D is the sample diameter (mm), t is its thickness (mm), P is the maximum load applied to it (KN) and ITS is the indirect tensile strength. Finally, for each group, 3 repetitions were averaged to find the sample's indirect tensile strength.

However, the main parameter of this test is the sample moisture sensitivity (TSR) found by dividing the conditioned and unconditioned indirect tensile strengths as a percentage.

3.3. Dynamic creep test

One method to measure the permanent deformation of asphalt mixtures is to apply several thousand load-repetitions through an iterative load test and record the permanent displacements as a function of the loading cycles. To this end, this research has used the dynamic creep test based on the AS2891 standard and has considered the Flow Number (FN) as a criterion to rate the asphalt mixture resistance versus permanent deformations.

According to the mentioned standard, the samples of this test were 100 mm in diameter and 50 mm in height, with 5% empty space. They were first kept at 50°C for 5 hrs and then tested under the UTM25 device by applying a 400KPa haversine load; loading took 0.5 sec and unloading took 1.5 sec. Finally, FN (test output) was found as the number of cycles needed to enter the beginning of the third region in the cumulative strain curve 4 [37].

3.4. Illinois flexibility index test (IFIT)

To evaluate and compare the medium-temperature cracking in asphalt mixtures containing additives and reinforcements, this research has used the IFIT at 25°C (AASHTO TP124).

To this end, the main compressed cylinder was first cut by a gyratory compression machine to yield SCB samples with 7±1% empty space, 75 mm in radius, 50 mm in thickness, and 160 mm in height. Since each cylinder gave 4 test samples, one was used for each mix-design; each sample had, in its middle, a groove 2.25 mm-thick and 15 ±1 mm-long.

The samples were first kept at 25 ± 0.5°C for 2 hrs and then subjected to a 50 mm/min static load. After failure, the test stopped and the flexibility index (FI) was found using the AASHTO TP124 [38] relations.

4. Results and discussion

4.1. Indirect tension

Results of the indirect tensile and moisture sensitivity tests (TSR) are shown in, respectively, Figures 3 and 4. In asphalt mixtures, fracture toughness and "ITS" are directly related and an increase in the former increases the latter. These results are also related to the mixture stiffness, which varies with additives, and any increase or decrease in stiffness also changes the value of ITS. Results of the indirect tensile tests of the research samples (Figure 3) show that this test should be done for both wet and dry indirect tensile strengths.

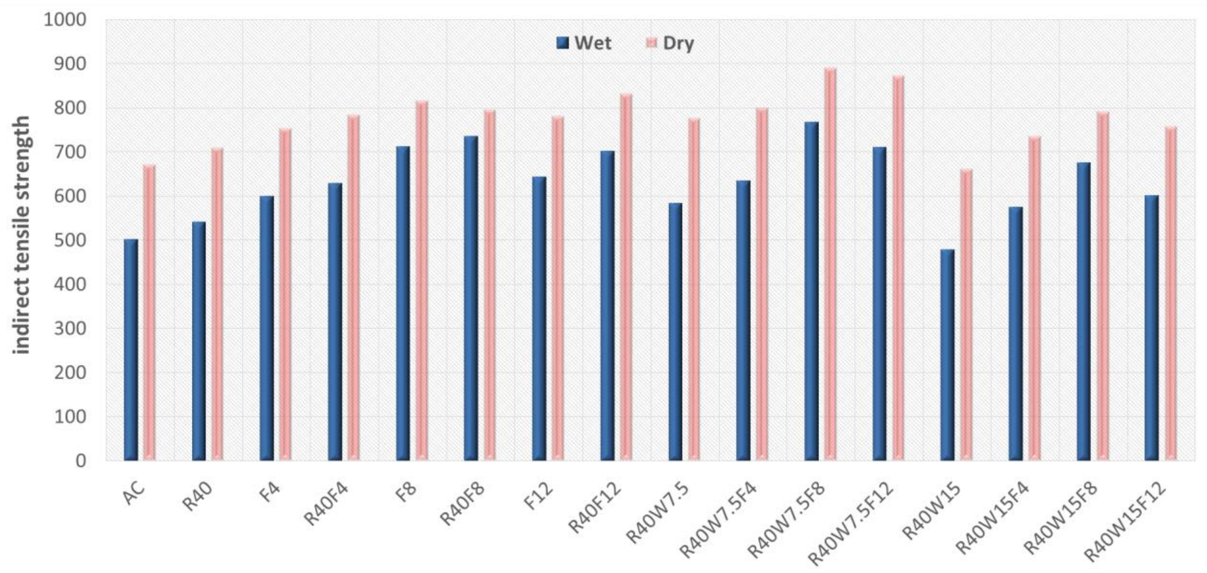

Fig. 3. Indirect tensile test results.

The results of the wet and dry indirect tensile strength tests are presented in this figure.

The dry-condition test results demonstrate that incorporating reclaimed asphalt pavement (RAP), due to the increased stiffness imparted to the mixture, results in approximately a 10% improvement in indirect tensile strength (ITS). This improvement becomes substantially greater with higher dosages of multi-component fibers. As shown in the corresponding graph, the highest dry ITS values are observed in specimens containing 0.8% and 1.2% multi-component fibers, exhibiting increases of approximately 25% and 20%, respectively, compared to the control. In contrast, the addition of a rejuvenator initially decreases the dry ITS. This reduction is negligible in specimens with 0.75% rejuvenator but becomes pronounced in those with 1.5% rejuvenator.

As illustrated in Figure 3, the incorporation of reclaimed asphalt pavement (RAP) increases the indirect tensile strength (ITS) under wet conditions, similar to the dry condition; however, this increase is marginal, being less than 10% compared to the control sample. Previous studies have also reported an enhancement in the ITS of asphalt mixtures with 40% RAP, attributing this to the hard binder present in RAP and the corresponding increase in the stiffness modulus of the asphalt mixture in specimens containing 40% RAP [39].

In contrast, the addition of fibers exhibits a considerably more pronounced effect compared to other additives investigated in this study. The results clearly show that all specimens containing multi-component fibers possess substantially higher wet ITS values than their respective counterparts, with the improvement becoming more significant as the fiber content increases. For example, the R40F12 specimen demonstrates more than a 40% improvement over the control, whereas the R40 specimen exhibits less than a 10% increase. Similarly to the dry condition, the inclusion of 0.75% rejuvenator yields more reasonable results compared to the addition of 1.5% rejuvenator.

Another ITS result is TSR, which equals the wet ITS divided by the dry ITS (in percent), and represents the sample moisture sensitivity. TSR results of the samples are shown in Figure 4, and its minimum value is 80% according to the standard.

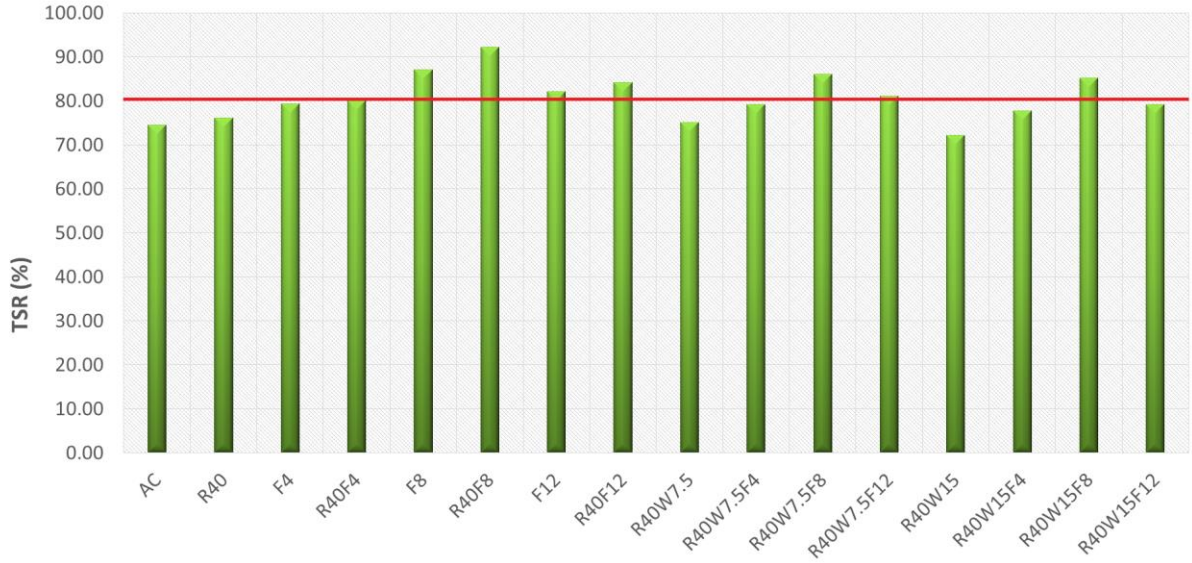

Fig. 4. TSR results*.

* The TSR results are presented in this figure, along with the minimum acceptable range as specified in Table 7.

As shown, the greatest effect in improving the moisture sensitivity occurred at 0.8% multicomponent fibers. As samples containing this amount of fibers in all research situations (with/without different percent rejuvenator, with/without RAP) yielded the best results. As illustrated in Figure 4, the R40F8 mixture achieved the highest TSR value, with an improvement exceeding 25% compared to the control specimen. This substantial enhancement highlights the positive contribution of multi-component fibers in improving moisture resistance. Based solely on the TSR criterion, the optimum fiber content can therefore be identified as 0.8% by weight of the aggregate.

In contrast, the incorporation of reclaimed asphalt pavement (RAP) exhibited only a marginal influence on TSR, yielding less than a 5% improvement relative to the control mixture. This finding suggests that the contribution of RAP to moisture susceptibility resistance is negligible under the tested conditions.

Furthermore, the addition of a rejuvenator at a dosage of 0.75% by weight resulted in a moisture susceptibility performance essentially equivalent to that of the control specimen. However, increasing the rejuvenator dosage to 1.5% led to an approximate 10% reduction in TSR compared with the equivalent mixture, indicating that excessive rejuvenator content may compromise the moisture resistance of asphalt mixtures.

4.2. Dynamic creep test

In this research, the dynamic creep test, as one of the functional tests proposed in BMD, evaluated the asphalt mixture rutting performance, and its results in the current research are presented in Figure 5.

Dynamic creep test results are worth considering from different angles. The first angle is the effects of adding RAP. According to the results, RAPs highly improve the asphalt mixtures' performance features; the increase in the ductility number is almost 100% and similar researches have also confirmed this increase [20][40] it can be concluded, therefore, that the tests' conditions/processes were standard and accurate enough. The second angle is the effects of adding multicomponent fibers. As mentioned before, 4 different percent fibers are used in this research, and results show that increasing these fibers increases the ductility number, but the increase lacks a constant rhythm; increasing fibers makes the ductility number to have a slower ascending slope. For example, the mixtures containing 0.4% and 1.2% fibers exhibited improvements of approximately 40% and 90%, respectively, compared to the control specimen. The results described so far can perhaps enable a suitable comparison between samples with and without RAP and fibers; RAPs have more significant effects than fibers on the ductility number due, maybe, to the increased stiffness of the RAP mixture. Comparing 0 and 40% RAP samples with those containing fibers reveals that adding RAP and increasing fibers make the ductility number to have a slower ascending slope compared to no-RAP samples, which is acceptable considering the significant increase in the ductility number due to adding RAPs. The third angle is the effects of adding 0, 0.75 and 1.5% waste engine-oil rejuvenator. Comparisons showed that using rejuvenator reduced the ductility number, which is an innovative part of this research because the increased value due to the addition of RAP is fully lost by adding the rejuvenator. Here, multicomponent fibers can clearly create differences by increasing the ductility number compared to previous researches. As indicated by the performance results of the mixtures incorporating fibers, reclaimed asphalt pavement (RAP), and rejuvenator, increasing the rejuvenator content led to a pronounced reduction in the flow number, indicating a deterioration in rutting resistance. Nevertheless, the inclusion of fibers effectively mitigated a substantial portion of this reduction. Specifically, the R40W7.5F12 mixture exhibited an improvement exceeding 50% in flow number compared with the R40W7.5 mixture, underscoring the significant role of fibers in restoring the mechanical stability of asphalt mixtures containing higher rejuvenator dosages.

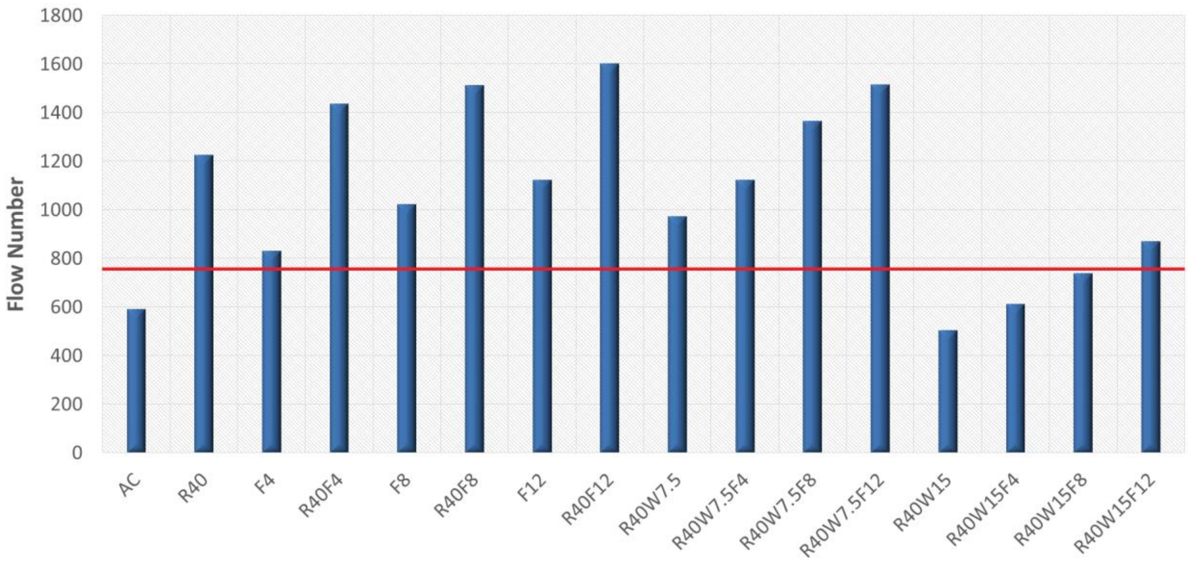

Fig. 5. Dynamic creep test results*.

* The results of the Dynamic Creep test are presented in this figure, together with the minimum acceptable range as specified in Table 7.

4.3. Illinois flexibility index test (IEIT)

The most reliable, common test to check the medium-temperature cracking behavior is the IEIT, which is also approved by the equilibrium mix-design method, like the indirect tensile crack test, to check the cracking resistance (reference: Fatemi paper). The outputs of this test are examined under the FI title, the value of which indicates the overall capacity of asphalt mixtures against the medium-temperature cracking. In general, since higher-FI mixtures show a longer-term resistance to crack propagation under tensile loads, this index can be used to rank the strength of different asphalt mixtures under the tensile loads-induced fatigue cracks [41].

In Figure 6 that presents the results of this test on the research samples, each result is the average of 3 results for the same sample.

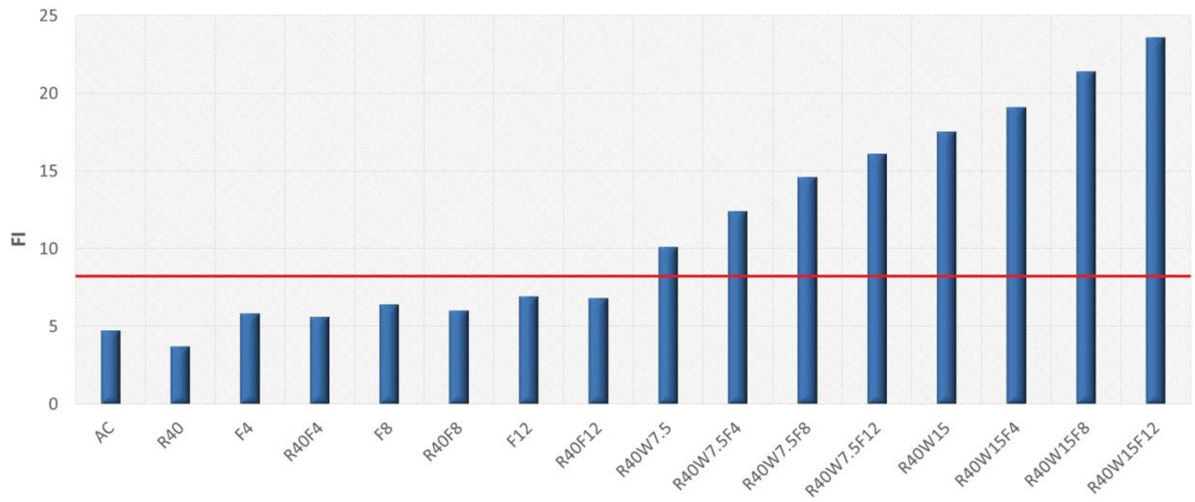

Fig. 6. IFIT results*.

* The FI parameter results are presented in this figure, along with the minimum acceptable range as specified in Table 7.

As evidenced by the results, the incorporation of reclaimed asphalt pavement (RAP) without any additives led to a marked reduction—approximately 20% compared to the control specimen—in the Illinois Flexibility Index (I-FIT). In contrast, the addition of fibers significantly increased the I-FIT value. Among the fiber-only mixtures (i.e., without rejuvenator or RAP), the highest increase was observed in the specimen containing 1.2% fibers, which exhibited an improvement exceeding 45% relative to the control. This enhancement, however, became noticeable only at lower fiber contents when RAP was incorporated, and was negligible at higher fiber dosages.

For mixtures containing rejuvenator, the combined use of rejuvenator and fibers further increased the I-FIT, thereby improving the mixture's resistance to intermediate-temperature fatigue cracking. The effect of the rejuvenator became more pronounced as its dosage increased from 0.75% to 1.5%, with the influence of fibers also becoming more evident. The highest I-FIT value was obtained for the specimen containing 1.2% fibers and 1.5% rejuvenator, which showed more than a threefold improvement over the control specimen. Moreover, this result was distinctly higher than that of the specimen with 0.8% fibers, suggesting a synergistic effect between the rejuvenator and fibers in enhancing cracking resistance.

4.4. Determining the optimal values based on the BMD method

As stated in Section 3, since this approach first determines the functional tests related to each failure, this research used the dynamic creep test, with the ductility number as output, to check the rutting, the indirect tensile test and TSR index to check the moisture sensitivity, and the IFIT, with FI as output, to check the fatigue cracking. Next, the research mix-designs were selected based on such additives as RAP, multicomponent fibers, and the waste motor-oil rejuvenator, some samples were made and tested for each mix-design according to the related standard, and, finally, the minimum outputs were found based on the past researches; Table 8 lists the outputs of the research samples.

In the *Mixture Name* section, the specimens are color-coded into three categories: green indicates mixtures that satisfied all three BMD requirements; yellow denotes mixtures that failed to meet at least one requirement; and red represents mixtures that did not satisfy the requirements in two or more tests.

Table 8. Balanced mix-design.

No.	Mixture name	TSR	FI	Creep
1	AC	74.44	4.7	590
2	R40	76.10	3.7	1224
3	F4	79.34	5.8	830
4	R40F4	80.10	5.6	1436
5	F8	87.10	6.4	1021
6	R40F8	92.12	6	1512
7	F12	82.12	6.9	1123
8	R40F12	84.15	6.8	1601
9	R40W7.5	75.10	10.1	971
10	R40W7.5F4	79.12	12.4	1123
11	R40W7.5F8	86.12	14.6	1364
12	R40W7.5F12	81.12	16.1	1513
13	R40W15	72.10	17.5	502
14	R40W15F4	77.78	19.1	612
15	R40W15F8	85.12	21.4	737
16	R40W15F12	79.12	23.6	868

As shown, the outputs failed to yield the corresponding test minimum are colored, names of mix-designs that have obtained at least one case less than the minimum are yellow, and those that have obtained more than one case are red.

Figure 7 shows the 3-D mix-designs of Table 8.

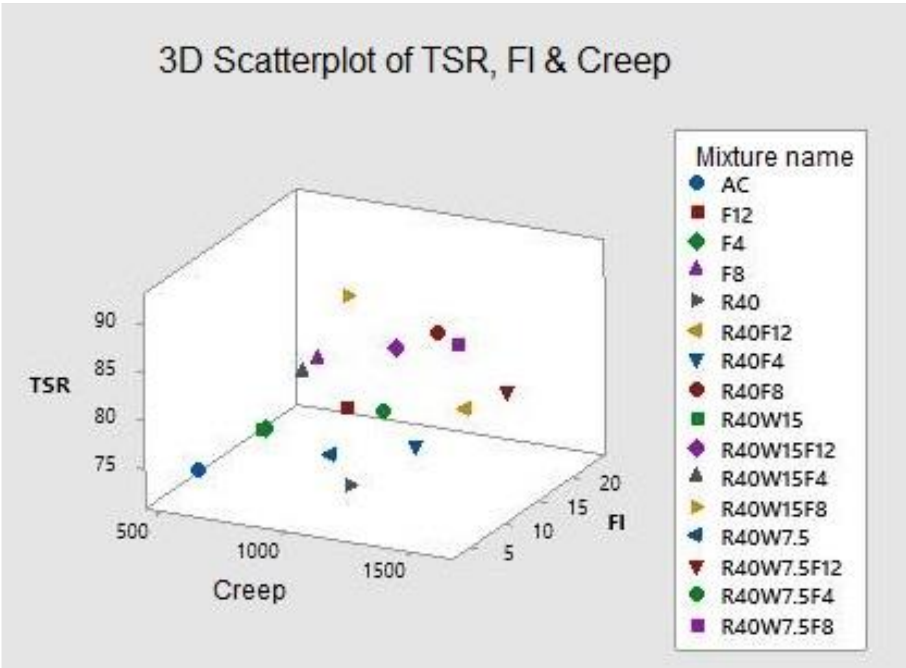

Fig. 7. 3-D balanced mix-designs*.

*In the BMD approach, the simultaneous evaluation of three parameters—TSR, Creep, and FI—is employed to determine the optimal mix design, with these parameters illustrated in this figure.

According to the results, since two samples containing 0.8 and 1.2% fibers, 40% RAP, and 0.75% rejuvenator have met the minimum requirements of the balanced mix-design method, they have been introduced as the final candidates of this research. In fact, among all the evaluated specimens, only these two mixtures achieved results exceeding the required thresholds in all three tests specified by the BMD procedure.

5. Conclusions

This research used RAP and waste motor-oil rejuvenator (2 recycled materials), and covered their weak points through the use of multicomponent fibers.

The working and optimal amounts of these additives were determined by the balance mix design method, where first 3 main failure types - rutting, cracking and moisture sensitivity - were determined and then the tests related to each failure - dynamic creep test to determine rutting, indirect tension test and TSR to determine the moisture sensitivity and the Illinois Flexibility Index Test (IFIT) to determine the medium-temperature fatigue cracking- were selected. Next, standard samples of each test were made by the gyratory compaction device and then the samples were evaluated. The optimal samples were finally selected using the desirable optimal minimum values of the balanced mix-design method.

Accordingly:

1. The dynamic creep test results showed that: i) RAP increased the mixture stiffness and, hence, increased the ductility number considerably, ii) the RAP-multicomponent fibers combination increased the ductility number, and iii) rejuvenator reduced the ductility number significantly.

2. The Illinois flexibility index test results showed that: i) adding RAP reduced this index, ii) adding fibers compensated for a part of this decrease, iii) adding rejuvenator increased this index, and iv) the highest percentage fiber-rejuvenator combination highly increased this index.

3. The indirect tensile test results showed that: i) adding RAP and multicomponent fibers increased the asphalt mixture tensile strength and ii) adding rejuvenator reduced the indirect tensile strength.

4. The moisture sensitivity test results showed that: i) adding multicomponent fibers highly increased the TSR, ii) rejuvenator reduced the TSR, and iii) RAP increased the TSR slightly.

5. Based on the balanced mix-design method, and considering the minimum values for each test, 2 asphalt samples containing 0.8 and 1.2% fibers (by wt. of the mixture), 40% RAP (by wt. of aggregate materials), and 0.75% rejuvenator (by wt. of the RAP bitumen) provided the best results.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Mahmoud Reza Keymanesh: Conceptualization; Formal analysis; Methodology; Project administration; Supervision; Validation; Writing – original draft.

Amin Jafari: Conceptualization; Formal analysis; Investigation; Methodology; Resources; Software; Validation; Visualization; Writing – original draft; Writing – review & editing.

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