

Improvement of pavement engineering properties with calcium carbide residue (CCR) as filler in Stone Mastic Asphalt

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ABSTRACT

Characteristics of pavement material are crucial factors in improving the stability and durability of asphalt pavement due to the poor performance of traditional asphalts. Reusing industrial waste in asphalt concrete production can address these concerns, reduce environmental problems and preserve resources. There have been few studies on the effects of using industrial waste materials on Stone Mastic Asphalt (SMA) properties. This paper examines the impact of Calcium Carbide Residue (CCR) as a filler in SMA. The study evaluates control samples, those with Rock Powder (RP) and Ordinary Portland Cement (OPC) filler, and those with CCR using Marshall stability (MS) and Indirect Tensile Strength (ITS_{dry} and ITS_{sat}) tests. Results show positive effects of CCR and RP on asphalt sample strength. The highest MS, MQ, and TSR values were observed in samples containing CCR80 % + RP20 %. These indices increased 45 %, 35 %, and 51 %, respectively, compared to control samples. The alkaline CCR material forms strong bonds with acidic bitumen, producing asphalt more resistant by 97 % compared to control samples. SMA modified with CCR + RP was also found to be less sensitive to water damage than traditional SMA with RP or OPC filler. The rough texture of CCR may positively affect the strength and durability of asphalt mixtures against moisture damage. Using CCR as a filler in SMA can enhance pavement engineering properties, reduce production costs and environmental problems, and develop sustainable asphalt mixtures for practical application. The main novelty of this research is the use of CCR and RP combination in SMA mixtures.

1. Introduction

Currently, the accumulation of solid waste is among the foremost challenges in the urban management of many countries [1–3]. Governments worldwide are grappling with the issue of environmental conservation due to its profound impact on daily life. The escalating cost of raw minerals, environmental concerns, and the gradual depletion of natural resources have prompted researchers and scientific authorities in this field to seek appropriate methods of recycling wastes and by-products as efficient alternatives to conventional construction materials [4–6].

Around 95 % of the world's roads are made of flexible pavement using bituminous mixtures [7], making it the preferred pavement structure globally. Asphalt binders, mineral aggregates, and fillers are the main components of these mixtures. Particles in asphalt mixture that

pass through a 63 µm sieve are fillers and mineral grains that makeup 5–10 % of the aggregate by weight in the whole mixture [8]. Traffic patterns and climatic conditions have reduced the operational life of asphalt concrete [9,10]. As a result, it is essential to find solutions to improve the efficiency and durability of asphalt structures for economic reasons and to enhance road transportation safety. One issue that can cause premature damage to the upper layers of asphalt is the loss of adhesion between stone materials, particularly hydrophilic materials, and bitumen, referred to as stripping [11,12].

Numerous studies have been conducted on the effect of mineral fillers in asphalt mixtures, indicating that they enhance the bond between bitumen and aggregate, thereby reducing the optimal bitumen amount required [13]. The pavement mixture's performance and durability depend on the fillers' physical and chemical properties. Fillers increase density, stability, and resistance to fatigue, moisture

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susceptibility, rutting, ageing, and low-temperature cracking [14]. Filler texture, shape, porosity, size, specific gravity, and size distribution affect pavement performance. Mineralogy and active clay content also affect pavement durability and resistance to various distresses [15–17]. As a result, filler selection and characterization can extend pavement life and lower maintenance costs. Cardon et al. [18] recommended that using an appropriate filler could enhance pavement functionality and reduce costs. Kim et al. [19,20] also found that mineral fillers could enhance asphalt mixture characteristics, including roughness, moisture sensitivity, and rutting resistance.

Recent research has explored using various industrial waste materials to modify asphalt and bitumen to reduce economic costs [21–23]. Here, various methods have been recommended and assessed to enhance the efficiency of asphalt structures, reinforcing the SMA by incorporating CCR [24,25]. Raad et al. [26] asserted that CCR could be utilized as a filler in Hot Mix Asphalt (HMA), which improves thermal resistance compared to RP-stabilized asphalt. Al-Dossary et al. [25] investigate the potential use of CCR and sulfonic acid dilution as a geopolymer stabilizer to improve the performance of road base materials. The authors conducted laboratory experiments to evaluate the road base materials' mechanical properties, compaction characteristics, and durability. The results indicated that the geopolymer stabilizer significantly improved the road base material's mechanical strength and durability and reduced its water absorption and swelling characteristics.

Zhao et al. [27] discussed the properties of different waste solid materials and their potential as substitutes for conventional construction materials in pavement applications. The manuscript reviewed various studies investigating waste materials such as reclaimed asphalt pavement (RAP), steel slag, waste glass, and plastic waste in pavement construction. The study suggested that using these waste materials, including reduced environmental impact, could be a cost-effective and environmentally friendly approach to enhance the performance of road base materials.

Dulaimiet al. [28] conducted laboratory experiments to evaluate the mechanical properties of the asphalt emulsion mixtures, including MS, ITS, and resilient modulus. The results indicated that the new cementitious material improved the mechanical properties of the cold asphalt emulsion mixtures and could be used as a substitute for conventional cementitious materials in pavement construction. Pourabbas et al. [29] conducted another research on different types of bitumen modifiers. The research involved MS and ITS tests in the first phase and SP, PI, and tension tests in the second phase, which were implemented on the bitumen. They found that the simultaneous use of recycled glass powder (RGP) and styrene butadiene styrene (SBS), styrene-butadiene rubber (SBR), and Crumb Rubber (CR) polymers can effectively extend the service life of the asphalt. Adding CR and RGP increased the MS of SMA, improving asphalt performance. Moreover, the addition of CR increased the SP of bitumen, which enhanced the asphalt's flexibility due to the main characteristic of rubber.

Muniandy et al. [30] studied the modification of bitumen properties using Cellulose Oil Palm Fiber (COPF) and Ethylene Vinyl Acetate (EVA). COPF, widely available in Malaysia, was used in this research as a stabilizer, while EVA was used as a traditional modifier in addition to COPF. The results showed that cracks have a direct relationship with fatigue strength. The samples stabilized by COPF had the most miniature fatigue life and more micro-cracks than those stabilized by EVA. The combination of EVA with pure bitumen increased the physical properties of bitumen, such as permeability and softening point, while decreasing ageing and viscosity. In addition, the EVA-stabilized samples had the most extended fatigue life and the most petite crack length, area, and density. Using polymeric materials improves the performance of asphalt, but using residuals is a priority due to environmental and stable development issues.

The ITS test in saturated mode is a frequently used test to detect bitumen ageing during the service life of roads. Asphalt cracks caused by moisture decrease the service life, and the ITS test in saturated mode is

used to detect bitumen ageing and strength against this damage. Climatic conditions are different in any region, which is effective on the thickness of the pavement layer. The ITS test in saturated mode can help in designing the thickness of pavement layers and detecting/preventing cracks caused by water. Using the results of this test decreases the pavement and maintenance costs of asphalt while increasing the useful life of pavement layers [31], which led us to use this test as well.

Hamed et al. [32] researched using RP, Calcium Carbide (CC), hydrated lime, OPC, and two types of bitumen, 60/70 and 85/100, to modify the asphalt mixture. The ITS test outcomes in the dry mode indicated that using hydrated lime and CC led to an increase in the ITS in a dry way. It was observed that hydrated lime had the most significant impact on ITS for bitumen 60/70, whereas CC had the most significant effect on bitumen 85/100. On the other hand, using OPC resulted in a reduction of ITS. Furthermore, the results of the TSR test illustrated that including hydrated lime and CC enhanced the strength of samples against moisture. Specifically, the value of TSR for the samples stabilized by hydrated lime and CC showed an increase of 33 % and 30 %, respectively, compared to the control samples. Therefore, it can be concluded that hydrated lime is more effective than CC regarding TSR. These findings are consistent with other studies that have explored the use of different materials as modifiers for asphalt mixtures. The use of waste polyamide, recycled glass powder, cellulose oil palm fibre, CCR, and waste PET fibres [33–36] have also been shown to improve the performance and durability of asphalt mixtures against various types of damage. Incorporating these materials into asphalt pavement systems can lead to more sustainable and cost-effective infrastructure solutions.

The depletion of natural resources is a major concern, particularly due to the increased demand for civil infrastructure. To address this issue, finding an alternative source of materials is necessary, and recycling industrial waste materials is a promising solution. By utilizing industrial waste materials to meet the technical demands for enhancing the properties of bitumen and asphalt, we can achieve positive economic effects by reducing costs and contributing to a more environmentally friendly approach. One such waste material is CCR, generated as a by-product of acetylene gas production. In 2014, around 1.4 t of waste calcium carbide was generated from global acetylene gas production, which is expected to increase by 5.1 % annually [37]. Preparing and grading calcium carbide is considerably less expensive than ordinary Portland cement. Due to the rising cost of traditional fillers, reusing waste and by-product materials is recommended to reduce production costs, improve properties, and reduce environmental impact. This paper examines the potential use of CCR as a filler material in SMA asphalt and its effect on pavement engineering properties. Although research conducted on HMA asphalts has shown well that using CCR as a waste filler reduces the manufacturing costs of asphalt mixtures and enhances the mix's performance against different distressed, research on the effects of using this filler in improving the characteristics of the SMA asphalt mixture is very limited. The available information in this regard seems insufficient. Therefore, this study aims to investigate using CCR as a raw material to add to an SMA asphalt mixture. This study aimed to enhance SMA asphalt's behavioural, durability, and resistance properties. To achieve this, industrial waste materials like calcium carbide residue were utilized instead of conventional polymer modifiers.

2. Materials and methods

2.1. Bitumen

The present study utilized bitumen with penetration grade 60/70 produced in the Isfahan refinery. Penetration grade 60/70 bitumen is commonly used in road construction and infrastructure projects [38]. This type of bitumen is characterized by its physical properties, including its penetration value, softening point, ductility, flash point, and solubility [39,40], presented in Table 1.

Table 1

The characteristics of bitumen 60/70.

Test	Value
Solubility	Between 99.0 % and 99.5 %
Ductility	Between 100 and 200 cm
Density	1.017 in 25°
Softening point	Min: 43° Max: 51°
Penetration value	Between 60 and 70 decimillimeters
Flash point	More than 230 °C

2.2. Stone materials

Choosing the right materials for asphalt production and considering factors such as cost and quality are essential for creating durable and long-lasting pavement [41]. Thus, the crushed granite aggregate was selected for its durability and suitability in producing bituminous mixtures. The granite aggregates possess common attributes such as hardness, cleanliness, and a well-suited shape. Additionally, they exhibit excellent resistance to rutting, making them a favoured and widely chosen option within the industry. The mechanical characteristics of the used aggregate are presented in Table 2. To ensure the quality of the materials, the stone materials were procured from a reliable source, the Majidiyeh manufacturing of Municipality located on Kalat road of Mashhad City, and graded according to BS EN 933-1 and FHWA-SA-95-060 recommendations [42,43]. Fig. 1 displays the consumable materials' granulation diagram and the permissible regulation ranges.

Various tests were conducted to ensure the quality of the aggregate materials used in the research. The Atterberg Limit tests (AASHTO-T89 [44]) were performed to determine the plastic and liquid limits of the materials. The Sand Equivalent test (AASHTO-T176 [44]) was conducted to measure the level of clay-like materials in the aggregates. The Flakiness and Elongation Index test (BS-812 [45]) was performed to determine the shape and size of the materials. Additionally, the weight loss of the materials due to abrasion was determined using the Los Angeles Abrasion test (AASHTO-T96 [46]) and against Sodium Sulfate (AASHTO-T104 [47]). The percentage of fractured particles in the coarse aggregate was determined using the ASTM-D5821 test [48]. The organic impurity percentage of the filler was determined using the AASHTO-T21 test [49]. Finally, the effect of water on the bitumen cover of the materials was tested using the ASTM-D4625 [50] method. These tests ensured that the properties of the aggregate materials were accurately determined and suitable for use in the research. The properties of aggregate materials are shown in Table 3.

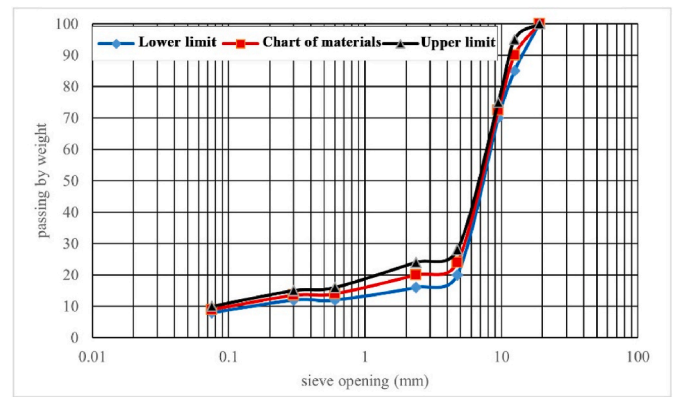
2.3. Additives

The research on bituminous mixtures also involved using fillers, namely CCR, OPC (type 2), and RP. CCR was chosen due to its potential to modify bitumen and asphalt properties in an environmentally and economically friendly manner. The CCR powder was produced by powdering CCR in a planetary mill, and the resulting powder was used in

Table 2

Grading of the materials used was based on the recommendations of BS EN 933-1 and FHWA-SA-95-060.

Screen size (mm)	Max/min limits	Passed percentage
19	100	100
12.5	85–95	90
9.5	Max 75	72.5
4.75	20–28	24
2.36	16–24	20
0.6	12–16	14
0.3	12–15	13.5
0.075	8–10	9

**Fig. 1.** The SMA gap gradation implemented.

the tests after passing through screen no. 200 (0.075 mm). Table 4 presents the chemical properties of CCR and OPC (type 2) used in the study. Also, the physical properties of used OPC are given in Table 5.

2.4. Asphalt samples

Three samples were created for each test using 1200 g of material based on the grain size distribution in Table 2 to prepare samples for testing. The materials were then placed in an oven and heated for 24 h at a temperature of 160–170 °C. After grading the materials, 15 samples of SMA were made with varying percentages of bitumen to determine the optimal percentage. The bitumen percentage was determined to be 6 % after analyzing the results. Bitumen was heated to 130°C and mixed with the aggregate samples at a temperature of 170°C. A filler with a temperature of 170°C was then added to the mixture and blended for 10–15 min to ensure all aggregates were covered by bitumen. Throughout the blending process, the mixture's temperature was monitored and kept within the range of 140°C–163°C using a digital thermometer. Once the blending process was complete, the prepared asphalt was poured into a Marshall mold and hit by a Marshall hammer to simulate medium traffic with 50 hits to each side of the sample. The molds and upper container were heated, and the bottom and top of the mold, as well as the surface of the hammer, were lubricated before pouring the asphalt to ensure easy removal of the sample (ASTM D5581-07 A [53]).

2.4.1. The ITS test in dry and saturated modes

The ITS test, as described in ASTM D-4123 [27], is a widely used method for assessing the tensile properties of asphalt concrete. The results obtained from this test can be used as an indicator of the pavement's resistance against cracking. In this test, a diagonal plate is placed between two loading blades and pressure forces are applied, resulting in a uniform tensile stress that acts vertically along the loading direction. The sample is then broken along the loading plate due to being divided into two parts. The test is insensitive to surface irregularities, and variations in the test results are negligible. The Poisson ratio used in this research was 0.35, and horizontal deformations were calculated. The test is performed at a temperature of 25°C, and variations in force and movement are recorded until the point of failure. The failure force and deformation of the samples at the failure point are measured and recorded. The ITS of the sample is calculated using equation (1).

$$ITS = \frac{P \times 2000}{\pi \times D \times t} \quad (1)$$

Where ITS is the indirect tensile strength in N/mm², P is the final load at the failure point in N, D is the sample diameter in mm, and T is the sample thickness in mm. Maintenance and testing conditions of dry and saturated ITS samples are different, which are discussed as follows.

Table 3

Results of the stone materials quality test.

Properties		Test results			Method test
		Coarse mixture	Sand 0-6	Materials filler	
Sand equivalent		–	60	–	AASHTO-T176 [44]
Weight loss by Los Angles Abrasion test	Grading type	C	–	–	AASHTO-T96 [46]
	Cycle No.	500	–	–	
	Abrasion %	24	–	–	
Atterberg Limit	Plastic range	–	Non-plastic	Non-plastic	AASHTO-T89 [51]
	Plastic limit	–	–	–	
	Liquid limit	–	Indeterminable	Indeterminable	
Crack percentage on screen no.4	In one front	–	–	–	ASTM D5821-13 [48]
	In two fronts	76	–	–	
Corner percentage of fine aggregates by method A		43	–	–	ASTM D5821-13 [48]
Flakiness and Elongation percentage	Elongation	12	–	–	BSI BS-812 [52].
	Flakiness	11	–	–	
Weight loss against Sodium Sulfate	Coarse	–	1	–	AASHTO-T104 [47]
	Fine	1	–	–	
Organic impurity percentage of the filler	–	–	–	Less than standard limits	AASHTO-T21 [49]
Water effect on bitumen cover of the materials	Bitumen cover >95 %	–	–	–	–

Table 4

Chemical properties of CCR and OPC type 2.

Chemical Composition	CCR (%)	OPC Type 2 (%)
SiO ₂	6.48	21.6
Al ₂ O ₃	2.56	4.4
CaO	70.79	–
Fe ₂ O ₃	3.24	3.8
MgO	0.668	4
SO ₃	0.66	2
K ₂ O	7.92	–
C3A	–	5.2
LoI	–	0.71

Table 5

Physical Properties of OPC Type 2: test Results and Standard Limits.

Property/Test Description	Standard Limit	Test Results
Blaine - Area Surface Specific (cm ² /gr)	Min 2800	3150
Autoclave Expansion Test (%)	Max 0.8	0.04
Initial Setting Time (min)	Min 45	150
Final Setting Time (min)	Max 360	210
UCS (kg/cm ²) - 3 Days	Min 100	326
UCS (kg/cm ²) - 7 Days	Min 175	451
UCS (kg/cm ²) - 28 Days	Min 315	470

2.4.2. Investigating moisture sensitivity according to the ITS results

The AASHTO T-283 [54] standard method is commonly used to determine the moisture sensitivity of asphalt mixtures. Compacted samples with an air content of 7 ± 1 % are first cured under standard conditions and then vacuumed to a saturated level of 55 %–80 %. The samples are placed in a plastic pocket containing 10 mL of water and stored in a refrigerator at -18 °C for 16 h, followed by immersion in a water bath at 60 °C for 24 h. The samples are then subjected to an ITS test at a constant loading rate of 50 mm/min, and the required force for fracturing the samples is measured according to AASHTO T-283 [54]. The tensile strength ratio (TSR), which indicates the strength of the samples against moisture, is calculated using equation (2) [26,28]. A higher TSR value represents greater moisture damage resistance, with a minimum TSR of 75 %.

$$TSR = \frac{ITS_{sat}}{ITS_{dry}} \quad (2)$$

2.4.3. Asphalt tests

The asphalt testing process consisted of three distinct phases. In the first phase, 15 Marshall samples were created to determine the optimal bitumen percentage. Following the implementation of several tests, the

optimal ratio of bitumen was found to be 6 %. In the second phase, 153 asphalt samples were produced using different combinations of additives (CCR, RP, and OPC) at the optimal bitumen percentage. These samples were further divided into three combination types (I, II, and III) with varying proportions of the additives. All fillers used in the research were less than 75 μ m and passed through the No. 200 (75 μ m) sieve. Specifically, 51 samples were tested in the Marshall test, 51 samples were tested in the ITS test in dry mode, and an additional 51 samples were tested in the ITS test in saturated mode. Table 6 provides an overview of the different combinations of filler used in the samples stabilized by RP, CCR, and OPC.

2.4.4. Determination of optimal bitumen

The optimal bitumen percentage was determined following the ASTM D7369-20 standard [55], whereby the percentage of bitumen resulting in 4 % voids in the mixture was considered optimal). To evaluate the properties of each sample, measurements were taken for specific weight, voids, liquidity, Voids in the Mineral Aggregate (VMA), and voids filled with aggregate (VFA), and the results are presented in Table 7. These findings are relevant for inclusion in an article.

The special properties of asphalt concrete at different percentages of bitumen were evaluated using various parameters. The G_{mb} indicates the real special weight of asphalt concrete, VTM (voids in the total mix)

Table 6

Combinations of filler used in the samples stabilized by RP, CCR, and OPC.

Bitumen Sign	Combination Type (I)	Combination Type (II)	Combination Type (III)
1	CCR 100 %	Control	Control
2	RP 100 %	RP 100 %	RP 80 % + OPC 10 %
3	CCR 80 % + RP 20 %	RP 80 %	RP 60 % + OPC 20 % + CCR 10 %
4	CCR 60 % + RP 40 %	RP 50 % + OPC 50 %	RP 40 % + OPC 30 % + CCR 30 %
5	CCR 50 % + RP 50 %	RP 40 % + OPC 60 %	RP 20 % + OPC 40 % + CCR 40 %
6	CCR 40 % + RP 60 %	–	–
7	CCR 30 % + RP 70 %	–	–
8	CCR 20 % + RP 80 %	–	–
9	CCR 10 % + RP 90 %	–	–

Note: RP + CCR represents the combination of rubber powder and cement kiln dust, RP + OPC represents the combination of rubber powder and ordinary Portland cement, and RP + OPC + CCR represents the combination of rubber powder, cement kiln dust, and ordinary Portland cement.

Table 7

Parameters of optimal bitumen percentage: Evaluating Gmb, Gsb, Gmm, VTM, VMA, VFA, stability, and flow.

Bitumen percentage	G _{mb}	G _{sb}	G _{mm}	VTM (%)	VMA (%)	VFA (%)	Stability (kg)	Flow (0.25 mm)
5	2350	2698	2517	6.64	17.25	61.46	474	1.88
5.5	2364	2698	2498	5.36	17.19	68.80	560	2.08
6	2386	2698	2479	3.91	17	76.99	603	2.2
6.5	2382	2698	2460	3.05	17.34	82.36	646	2.26
7	2380	2698	2441	2.53	17.96	85.91	653	2.35

indicates the voids present in asphalt concrete, Flow represents the liquidity of asphalt concrete, VMA (voids in mineral aggregate) reflects the void percentage of stone materials, Stability indicates the MS of asphalt concrete, and VFA (voids filled aggregate) indicates the percentage of filled asphalt concrete voids (Fig. 2). Using graphs of density, MS, sample deformation, air percentage of the mixture, air percentage between stone materials, and percentage of voids filled by bitumen, the optimal percentage of bitumen was selected as 6 %. Table 8 was then used to control the optimal bitumen percentage.

3. Results analysis

This section examines the impact of various fillers on the properties of asphalt mixture using in-vitro testing. Marshall samples were created with different fillers, and the results of the MS, ITSdry, and ITSsat tests

Table 8

Marshall mix design Criteria.

Description	Average Traffic		Test Method
	Min	max	
No. Of hits to both sides of the sample	50	50	AASHTO -T245 [29]
Sample stability (kg)	550	–	AASHTO -T245 [29]
VMA	17	–	MS-2 magazine: Asphalt Institute
VTM	4	–	MS-2 magazine: Asphalt Institute

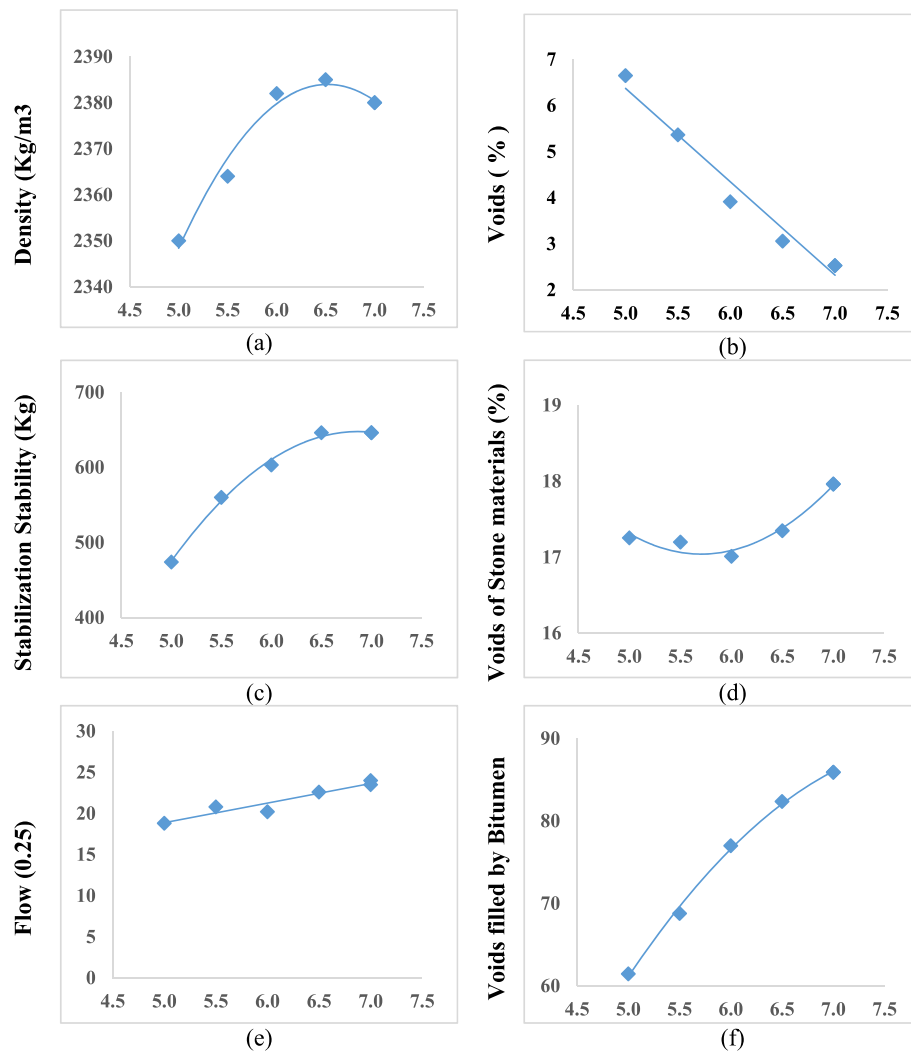


Fig. 2. Variations curves of asphalt mixtures quantities with different percentages of bitumen. Fitting are based on the least squares error for multiple regressions and trends for density (a), air voids(b), stability (c), VMA (d), flow (e), and VFA (f).

were compiled in a chart. The findings from these tests and the Marshall stability/flow index (MQ) and TSR ratios were analyzed. MQ index a significant parameter in determining the mixture's resistance against shear stress, rutting, and permanent deformation. A higher MQ index indicates a more challenging and stable mixture, which can better withstand permanent deformations. Additionally, the MQ index is used as an indicator to measure the stability of materials against permanent deformations during pavement maintenance [56,57].

3.1. Marshall test of original samples

This study aimed to investigate the effects of filler varieties on the properties of asphalt mixtures in vitro. Marshall samples were prepared with different fillers based on the optimal bitumen percentage determined earlier. The results of MS and ITS_{dry} and ITS_{sat} tests were presented as charts. The study focused on the RP and OPC-stabilized asphalt samples, and these samples' MS, flow and MQ index were compared with the control sample. The addition of RP and OPC enhances the MS of SMA. As depicted in Fig. 3, Table 9, it is shown that the sample stabilized with RP40 % + OPC60 % has the highest MS, and the asphalt stability increased by 21 % compared to the control sample. The rough surface texture and alkaline CCR material forms strong bonds with acidic bitumen, producing asphalt more resistant [58,59].

The flow of the RP40 % + OPC60 % sample increased by 75 % compared to the control sample, indicating greater flexibility. The findings of this study are consistent with the previous research conducted by Aljassar et al. [60] and Jony et al. [61], which showed that using RP and OPC improves the MS and flow of the asphalt.

Table 10 illustrates the impact of CCR and RP on MS, flow, and MQ index. The addition of RP and CCR enhances the MS of SMA. As depicted in Fig. 4, the CCR80 % + RP20 % combination exhibits the highest asphalt stability with a 45 % increase in MS and a 7.2 % increase in flow compared to the control sample. However, according to the results obtained by Isa et al. [62], the rise in CCR content initially enhances MS but ultimately reduces the MS after passing the optimal percentage. This reduction in stability can be attributed to the accumulation of particles resulting from excess CCR content, which reduces the porosity of the sample and, thus, MS. The mixtures containing CCR have less flow than those containing OPC due to the high reactivity of CCR particles, which harden the mixture.

Table 11 presents the effect of using a combination of CCR, RP, and OPC on the MS and flow of the asphalt. The highest MS was obtained from the combination of RP20 % + OPC40 % + CCR40 %, which increased MS by 27 % compared to the control sample (Fig. 5). The strong bonding between the alkaline CCR material and the acidic bitumen enhances the overall strength of the asphalt, making it more resistant to wear and tear [63]. Both RP and OPC had similar effects on MS, but OPC had a greater effect on increasing MS [60]. As shown in Fig. 5, increasing the OPC and

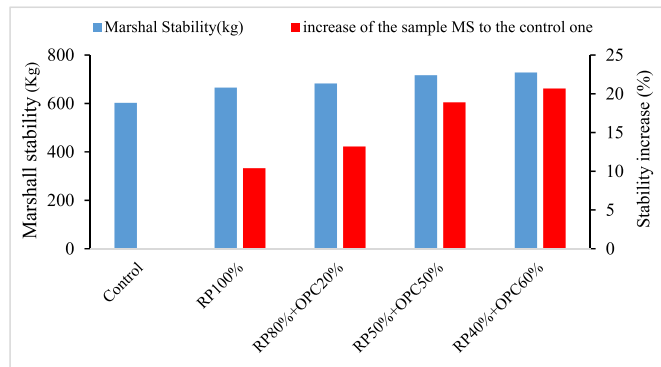


Fig. 3. MS and percentage of stability increase for RP and OPC-stabilized samples compared to the control sample.

Table 9

MS and MQ index of the samples stabilized by RP and OPC.

Samples	Marshall Stability Average (kg)	Flow Average (mm)	MQ (kg/mm)
Control	603	4.3	140.2
RP100 %	666	5.06	131.6
RP80 % + OPC20 %	683	6.38	107.05
RP50 % + OPC50 %	717	7.19	99.72
RP40 % + OPC60 %	728	7.5	97.06

Table 10

MS and MQ index of the samples stabilized by RP and CCR.

Samples	Marshall Stability Average (kg)	Flow Average (mm)	MQ (kg/mm)
Control	603	4.3	140.2
RP100 %	666	5.1	131.6
CCR100 %	839	4.9	171.2
CCR80 % + RP20 %	874	4.6	189.6
CCR60 % + RP40 %	824	4.9	167.78
CCR50 % + RP50 %	791	5	159.47
CCR40 % + RP60 %	786	5.0	155.95
CCR30 % + RP70 %	783	5.2	149.71
CCR20 % + RP80 %	718	5.3	135.47
CCR10 % + RP90 %	707	5.9	119.22

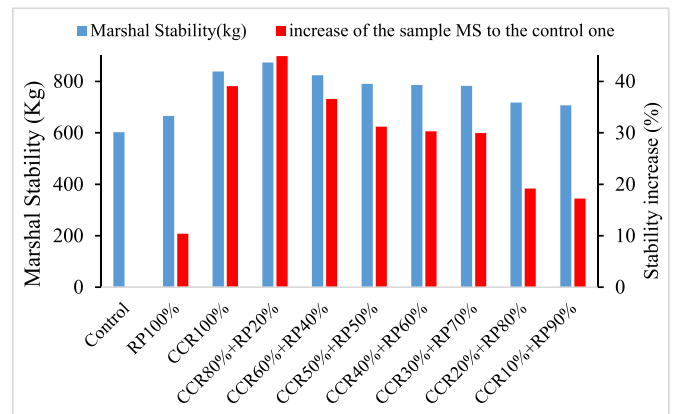


Fig. 4. MS and percentage of stability increase compared to the control sample for the samples stabilized by RP and CCR.

Table 11

MS and MQ index of the samples stabilized by RP, OPC and CCR.

Samples	Marshall Stability Average	Flow Average	MQ (kg/mm)
Control	603	4.3	140.2
RP80 % + OPC10 % + CCR10 %	731	5.49	133.15
RP60 % + OPC20 % + CCR20 %	744	5.42	137.26
RP40 % + OPC30 % + CCR30 %	758	5.21	145.48
RP20 % + OPC40 % + CCR40 %	764	5.16	148.02

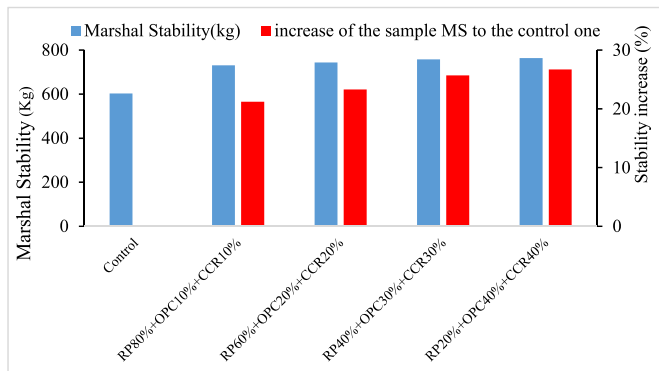


Fig. 5. MS and percentage of stability increase compared to the control sample for the samples stabilized by RP and CCR.

CCR content increased in MS. The flow of the RP20 % + OPC40 % + CCR40 % sample was 20 % higher than that of the control sample. However, as shown in Table 11, increased CCR content decreased the extra flow. Excessive flow can lead to rutting and bleeding during heavy traffic [64]. Using CCR can prevent rutting at high temperatures, making the asphalt more stable in hot environments. Furthermore, CCR is an environmentally friendly and cost-effective material [24]. Even though Pourabbas et al.'s [29] achieved superior results, with SBR and SBS polymers effectively preventing rutting, CCR demonstrates more cost-effectiveness than the aforementioned polymer.

In Fig. 6, the priority of all samples based on MS is displayed, with the CCR80 % + RP20 % sample having the highest MS and the control sample (natural filler passed through screen no.200) having the least. This figure also indicates that using any additives (CCR, RP, and OPC) increases MS compared to the control sample. The study utilized three additives (CCR, RP, and OPC) to stabilize SMA, and the results demonstrate that CCR increases MS more than RP and OPC. However, the MS decreases with an extra addition of CCR (CCR100 %) due to particle accumulation, which can be attributed to many pores in the grading of mineral stones in a mixture. The study findings reveal that using CCR improves MS and hardness.

The application conditions for asphalt differ across regions, with some areas demanding greater stability and others prioritizing flexibility. Fig. 7 offers a comprehensive qualitative analysis of various additives and ranks all samples using the MQ index. This index serves as a dependable standard for assessing the stability, hardness, and softness of materials in response to shear stress and enduring deformations provides an appropriate qualitative overview of the different additives based on the MQ index [38]. Result shows that the CCR80 % + RP20 % combination had the highest MQ, increasing by 35 % compared to the control sample due to increasing MS values, obtained positive CCR and RP filler

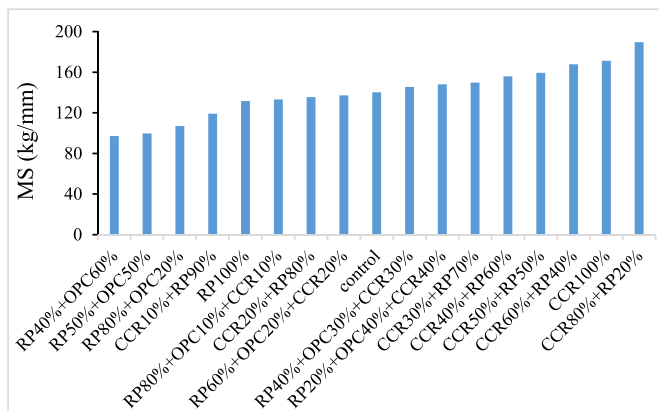


Fig. 6. Priority based on MS.

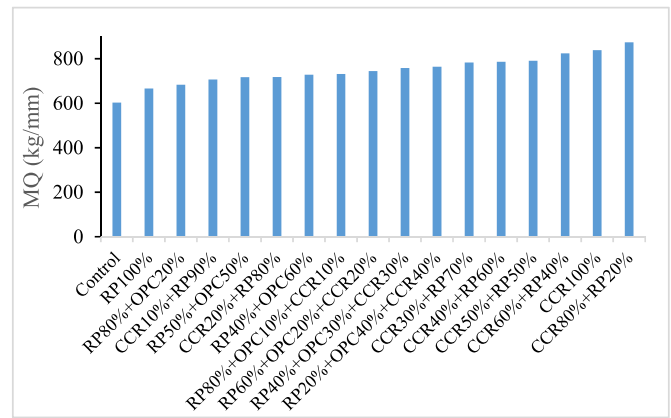


Fig. 7. Priority based on MQ.

on The use of this combination in SMA can enhance asphalt stability against shear stresses and permanent deformations during heavy traffic. On the other hand, the RP40 % + OPC60 % sample had the least MQ. The diagram depicts the effect of each additive (CCR, RP, and OPC) in different percentages on the stability and flexibility of the sample. For instance, the CCR80 % + RP20 % sample is more stable and less flexible than the RP40 % + OPC60 % sample.

3.2. Analysis of ITS test results in dry and saturated modes

Figs. 8–10 depict the charts of ITS_{dry} values and their percentage increase in proportion to the control sample for RP + OPC, RP + CCR, and RP + CCR + OPC additives, respectively. Based on the results in Fig. 8, using RP filler enhances the ITS_{dry} of the samples more than OPC. However, replacing some RP with OPC reduces the ITS_{dry} of the samples. The positive effect of using RP + CCR on the ITS values is demonstrated in Figure Fig. 9 Fig. 10. The addition of CCR + RP increases the ITS_{dry} in almost all samples, with the samples containing CCR + RP having higher ITS_{dry} than those containing RP + OPC and RP + OPC + CCR. Using CCR increases ITS_{dry}, and the CCR20 % + RP80 % samples show the highest ITS_{dry}, which increased by 40 % compared to the control sample. Figs. 8 and 10 show that replacing OPC reduces ITS_{dry}, which is consistent with the results of the study conducted by Hamed et al. [32]. However, studies indicate that CCR produced in acetylene manufacture is toxic to the surrounding ecosystem due to its harmful components such as calcium hydroxide, strontium, and inorganic polycyclic aromatic hydrocarbons [65]. The common method of CCR disposal is landfill, which can cause problems such as water contamination and soil saturation by harmful and alkaline compounds with pH levels higher than 12 [66,67]. Therefore, finding new ways to

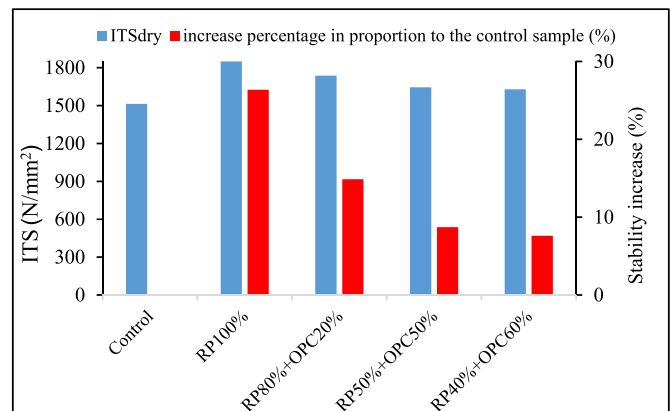


Fig. 8. The ITS_{dry} for RP + OPC-stabilized samples.

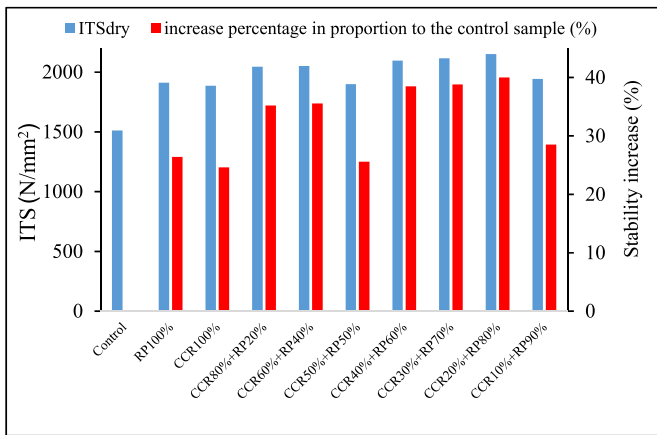


Fig. 9. The ITSdry for CCR + RP-stabilized samples.

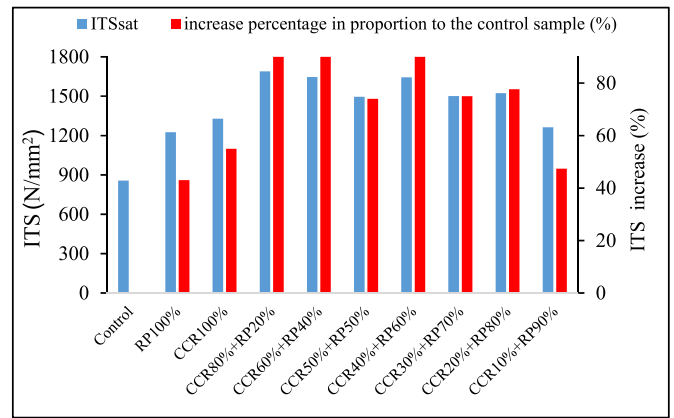


Fig. 12. ITSsat for RP + CCR-stabilized samples.

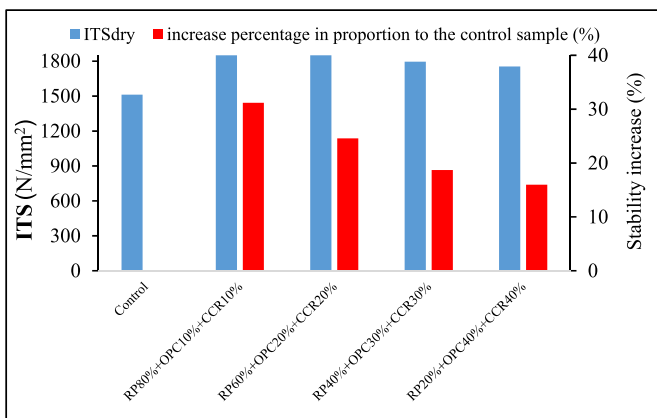


Fig. 10. The ITSdry for RP + CCR + OPC-stabilized samples.

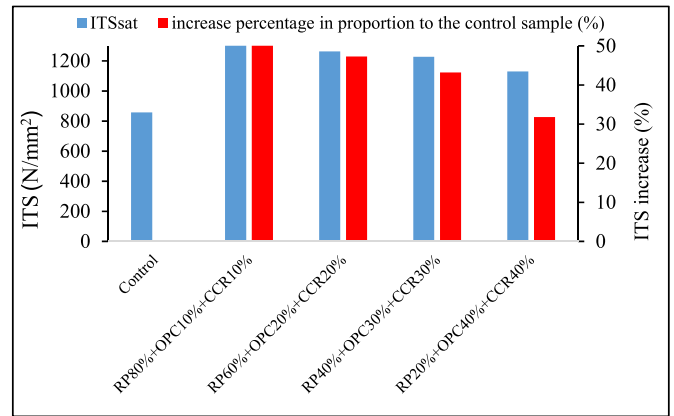


Fig. 13. ITSsat for RP + CCR + OPC-stabilized samples.

use CCR efficiently is crucial.

Fig. 11 shows a 45 % increase in ITSsat when RP is used as a filler compared to the control sample, but replacing OPC with RP damages the stability of stabilized samples against saturation and freezing. This finding is consistent with previous studies that have shown the positive effect of RP on improving ITSsat in asphalt mixtures [68,69]. As a result, RP can positively impact the ITSsat of asphalt mixtures when used as a filler. Still, caution is needed when replacing OPC with RP to avoid negative effects on the stability of the mixtures.

Figs. 12 and 13 show that in addition to numerous environmental advantages, using CCR as a filler has significant technical effects on the

stability behaviour of asphalt samples. Therefore, CCR can be used as a bitumen stabilizer or stabilizing filler. They also demonstrate that adding CCR and RP to the asphalt mixture increases the ITSsat in most samples. The ITSsat of the samples containing CCR + RP was higher than those containing RP + OPC and RP + OPC + CCR. The combination of CCR, RP, and OPC resulted in higher ITSsat than the RP + OPC combination, highlighting the prominent effect of CCR on increasing ITSsat. The use of RP + CCR improved the results significantly, and the highest ITSsat was observed in the CCR80 % + RP20 % samples. In this sample, the ITSsat was 1689 N/mm², while it was 857 N/mm² in the control sample, indicating a 97 % increase in ITSsat compared to the control sample.

The presence of moisture in pavement systems is one of the leading causes of pavement failure, making it one of the most critical factors damaging flexible pavements. If water is not immediately removed before damaging the pavement or if the stability of asphalt is low against moisture, the pavement's service life will decrease. To investigate the sensitivity rate of asphalt against moisture, one of the methods used is the TSR, which examines the adhesion rate of bitumen to aggregates in the presence of water. A low TSR can cause aggregates to detach from the bitumen over time, resulting in stripping along the road surface. According to AASHTO T283 regulations [54], the TSR should not be less than 75 %. The moisture sensitivity rate of asphalt mixtures is affected by variables such as the type and properties of materials and grading, bitumen hardness, type of filler used, and mixture properties such as permeability and voids. However, using appropriate fillers such as CCR and RP can significantly decrease the asphalt moisture sensitivity and increase its stability against stripping, as shown in Fig. 14 Fig. 15 and Fig. 16. The increase rate of TSR in the samples containing CCR + RP is

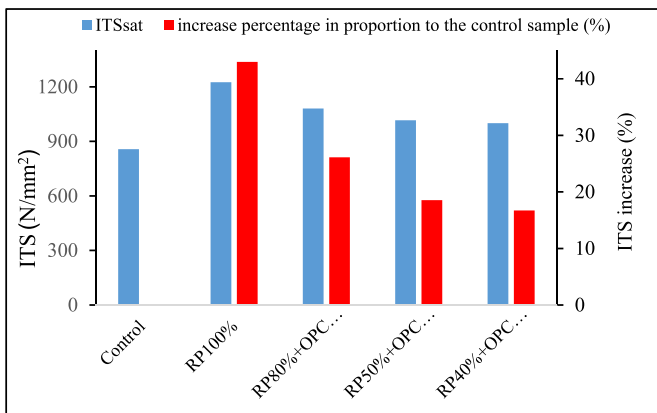


Fig. 11. ITSsat for RP + OPC-stabilized samples.

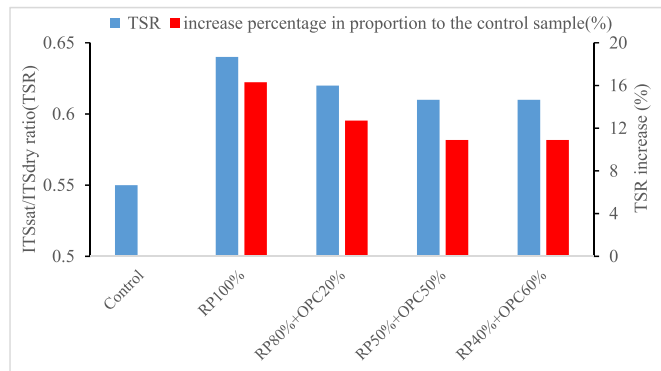


Fig. 14. The TSR of RP + OPC-stabilized samples.

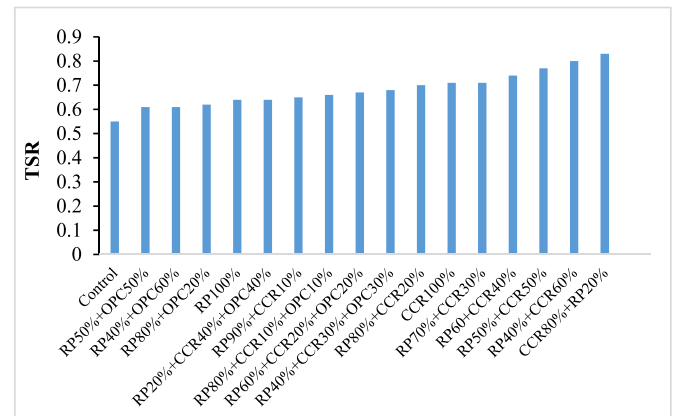


Fig. 17. TSR-based priority of samples.

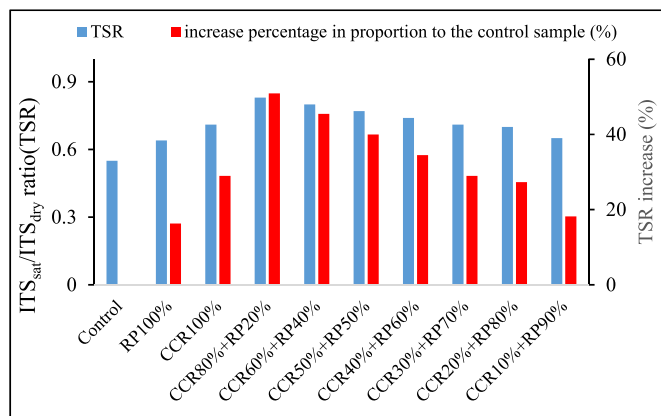


Fig. 15. The TSR of RP + CCR-stabilized samples.

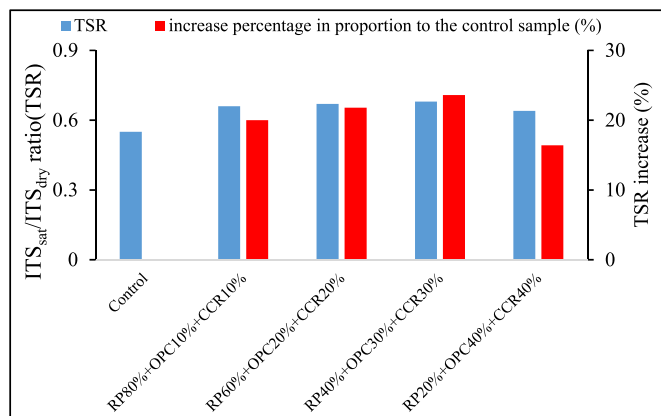


Fig. 16. The TSR of RP + CCR + OPC-stabilized samples.

more than the samples containing RP + OPC and RP + OPC + CCR, indicating a reduction in moisture sensitivity. The highest TSR was observed in the CCR80 % + RP20 % samples, which showed a 51 % increase compared to the control samples.

Based on Fig. 17, the sample with the highest TSR value, indicating the highest stability against moisture, is the CCR80 % + RP20 % sample, while the control sample has the lowest TSR value. As shown in Fig. 17, the addition of CCR, RP, and OPC to asphalt mixtures can reduce sensitivity to moisture and improve asphalt stability against common field issues like cracking and stripping. Nevertheless, the most favorable outcome is observed in the CCR + RP stabilized sample.

4. Conclusion

This study investigated the effectiveness of three different additives (CCR, RP, and OPC) in enhancing the stability of SMA asphalt mixtures. According to the findings, the following points summarize the outcomes:

- The Marshall stability (MS) of the traditional varieties was less than that of the RP + CCR-stabilized combinations. The best result was obtained from the CCR80 % + RP20 % mixture, which increased the MS by 45 % compared to the control sample. RP + CCR was a better compound for increasing MS than other compounds, such as RP + OPC and RP + OPC + CCR.
- Using CCR as an additive in asphalt increases its stability and reduces disposal costs, leading to added value. Moreover, the effectiveness rate of CCR was higher than that of RP's, and the RP's effectiveness was higher than that of OPC in increasing MS. The findings indicated that using RP + OPC increased the softness and flexibility of asphalt. While increasing MS reduces the softness of asphalt, increasing softness reduces stability, increasing the rutting depth during heavy traffic. However, the stabilized asphalt samples containing RP and CCR showed increased MS and softness, increasing stability and flexibility.
- Using an acceptable and proper combination of CCR additive remarkably increased MS and reduced asphalt thickness and the expenses incurred for pavement implementation.
- The CCR + RP compound remarkably increased the ITS of asphalt samples. In the ITS test in dry and saturated mode, the stability of the sample containing CCR80 % + RP20 % increased by 97 % and 40 % compared to the control sample, respectively, with an average increase of about 69 %. There was a direct relationship between asphalt ITS and bitumen adhesion, making the ITS test an executive test to evaluate the adhesion rate of asphalt mixtures.
- The increase in ITS in dry and saturated modes can be a criterion for the samples' stability against stripping. The samples containing RP + CCR, especially those containing RP20 % + CCR80 %, showed appropriate stability against stripping.
- Furthermore, the increase in Total Resilient Strain (TSR) values showed a reduction in moisture sensitivity and increased stability of asphalt against moisture damage. The RP20 % + CCR80 % sample had a 51 % increase in TSR, offering its noticeable stability against harmful damage from moisture.
- Using stabilized samples with increased adhesion reduced sensitivity against permanent temperature variations, making it appropriate for use in regions with high-temperature variations daily or annually. Although CCR + RP-stabilized mixtures had a high tensile strength during failure under static loading, the stabilized mixtures could bear higher strains before cracking.

- Additionally, using RP + CCR reduces the production costs of stabilized asphalt, helps return CCR to the production cycle, and reduces disposal costs, which has positive environmental effects.
- This research serves as a preliminary exploration of a novel filler combination. However, additional advanced asphalt performance testing, such as fatigue test, wheel tracking test and an detail microscopic studies are necessary.

Credit authors statement

Peyman Zangoeeinia: Investigation, Methodology, Visualisation, Resources, Formal analysis, Validation, Writing – original draft. Danial Moazami: Data curation, Conceptualization, Methodology, Project administration, Investigation, Writing – initial draft, Supervision. Meysam Pourabbas Bilondib: Data curation, Methodology, Review & editing, Supervision. Mojtaba Zaresefat: Review & editing, Data curation, Visualisation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mojtaba Zaresefat reports article publishing charges was provided by Utrecht University. Mojtaba Zaresefat reports a relationship with Utrecht University that includes:

Data availability

Data will be made available on request.

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