Primljen / Received: 12.2.2023.
Ispravljen / Corrected: 20.4.2023.
Prihvaćen / Accepted: 30.4.2023.
Dostupno online / Available online: 10.9.2023.

Utilising cellulose fibre in stone mastic asphalt

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Research Paper

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In this study, the optimum amount of cellulose fibre (CF) use was evaluated to better understand its influence on the volumetric design parameters of stone mastic asphalt (SMA) with polymer-modified bitumen (PMB). SMA-PMB specimens were manufactured, and their primary volumetric properties were compared with those of the respective SMA-PMB mixtures without CF. The results revealed that the addition of CF as a stabilising agent increased the optimal binder content, voids in the mineral aggregate, and voids filled with binder but decreased air voids and bulk specific gravity. The results suggest that the utilisation of CF, along with an increased optimum binder content, slightly increased the primary manufacturing cost of SMAs.

Key words:
cellulose fibre, stabilizer, stone mastic asphalt, volumetric design

Prethodno priopćenje

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Upotreba vlakana celuloze u splitmastiksasfaltu

U ovom istraživanju su utvrđene optimalne količine vlakana celuloze (engl. *cellulose fibre* - CF) kako bi se bolje razumio njihov utjecaj na volumetrijske projektne parametre splitmastiksasfalta (engl. *stone mastic asphalt* - SMA) s bitumenom modificiranim polimerom (engl. *polymer-modified bitumen* - PMB). Proizvedeni su uzorci SMA-PMB, a njihova primarna volumetrijska svojstva uspoređene su s onima u mješavinama SMA-PMB bez vlakana celuloze (CF). Rezultati su otkrili da je dodavanjem CF-a kao stabilizirajućeg aditiva došlo do povećanja optimalnog udjela veziva, šupljina u agregatu minerala te udio šupljina ispunjen vezivom, ali je došlo do smanjenja udjela šupljina i specifične mase. Rezultati pokazuju da upotreba CF-a, zajedno s povećanim optimalnim udjelom veziva neznatno povećavaju primarne troškove proizvodnje SMA.

Ključne riječi:
vlakna celuloze, stabilizator, splitmastiksasfalt, volumetrijski projekt

1. Introduction

In addition to economic development and growth, global transportation has consistently increased over the past few decades. The unprecedented increase in both passenger and freight transport demands necessitated the construction of additional highways, which are still the most accessible and widely used modes of transportation worldwide compared to other transport modes such as airways, railways, coastal and other multidisciplinary modes. The construction of durable highways with flexible pavements consisting of superimposed asphalt courses requires a large amount of funding from the government. In addition to the initial cost of construction, a substantial amount of funds, which is sometimes overlooked, is periodically allocated for the operation, preservation, maintenance, repair, and rehabilitation of pavements that are already open for service [1, 2]. Hence, with the overall costs, designing flawless pavement structures is considered a priority in engineering as one of the most important public assets.

More recently, asphalt roads paved with conventional bituminous materials have fulfilled the required technical specifications and have previously sustained well under axle loads. However, with higher tyre pressures and increasing axle loads owing to the increasing number of heavy-duty vehicles, ordinary pavements with limited strength have failed to perform under all types of loading and thermal conditions [3, 4]. Early detrimental deteriorations such as rutting and low-temperature and fatigue cracking that emerge in these pavements ultimately result in premature failures. Thus, the occurrence of these failures has promoted research in pavement technology to explore methods of improving pure bitumen and straight asphalt.

Polymer modification is commonly performed to enhance the rheological properties of pure bitumen. The most common polymers include styrene-butadiene rubber (SBR), styrene-butadiene-styrene (SBS), and polyethylene (PE). Owing to the repeated chains of small molecules, these polymers make bitumen stiffer, more rut-resistant, and less susceptible to temperature, which increases its performance under heavy vehicle traffic and hot weather conditions [5, 6]. Furthermore, polymer modifiers help softer binders maintain their workability and flexibility against low-temperature cracking under cold conditions [5]. Other prominent properties following polymer modification include increase in strength, adhesion, cohesion, and resistance to permanent deformation and fatigue.

Depending on the aggregate gradation, asphalt mixtures can be categorised into two main groups: standard hot-mix asphalt (HMA) and stone mastic asphalt (SMA) [7]. SMA, a gap graded mixture (70–80 % coarse aggregates, 8–12 % filler, 6–7 % bitumen), was initially pioneered in Germany in the early 1960s and has subsequently gained wide application throughout Europe, Australia, Japan, the USA, and other parts of the world [8, 9]. Compared with conventional HMA, using SMA mixtures has its advantages and disadvantages. Owing to their large coarse aggregate fraction and solid skeleton structure, SMA mixtures offer the advantages of outstanding durability, increased skidding resistance, improved performance against reflective cracks, fatigue, and rutting, reduced traffic-related noise pollution, and decreased hydroplaning. However, the inclusion of relatively excessive bitumen in SMA causes some disadvantages, such as higher initial production costs and binder drainage problems [10]. The use of higher amounts of bitumen was attributed to the presence of a relatively large content of coarse aggregate and mineral filler. Therefore, maintaining the binder around the aggregates in SMAs is essential for preventing water penetration and moisture damage. The use of various recycled fillers, particularly class C fly ash, has been reported to significantly improve the resistance to moisture damage [11, 12]. Numerous studies have attempted to overcome the problem of separation and drain-down of binders in SMAs, and scholars have reached a consensus on using polymer-modified bitumen (PMB) and/or the addition of stabilising agents. Although common PMBs have been claimed to replace stabilising agents, owing to their thermodynamic incompatibility and limited performance when used alone in SMA, they fail to adequately withstand destructive pavement distress, particularly cracking, rutting, and moisture damage [13–15]. However, it has been shown that using stabilisers in SMA leads to thickened and bulked bitumen, restrained drainage, fortified bituminous mortar, a more homogeneous structure, and a substantial increase in the overall performance of the mixture [16-18].

Considering the potential benefits of using polymers and stabilisers conjunctively, this study aims to evaluate the impact of a stabilising agent on the design properties of SMA with PMB. To achieve this objective, the most common volumetric parameters, including the total air voids, voids in the mineral aggregate, voids filled with bitumen, bulk specific gravity, and optimum bitumen amount, were determined. Furthermore, a comparative cost analysis was performed regarding the effect of introducing the stabilising agent.

2. Literature review

Mineral and cellulose fibres (CFs) are the most commonly employed stabilising agents in SMA production to prevent and minimise binder drainage while hauling and laying of the bituminous mixtures. They are generally added in the range of 0.3–0.4 %, depending on the nature of the fibres and their shapes. To date, a growing number of studies have been conducted with the goal of developing cheaper, abundant, sustainable, and eco-friendly materials as fortifying additives for SMA. Correspondingly, a wide range of organic, synthetic, waste, and natural materials have been tested to assess their feasibility for SMA production.

Rockwool as a mineral fibre and polyester as an organic fibre have been proven to reinforce the performance of

SMA by filling the voids and increasing the stone-on-the-stone connection. The optimal binder amount was greater for the SMA mixtures with polyester than for those with rockwool [9]. Kofteci emphasised that the incorporation of 4 % pumice as a mineral fibre into an SMA mixture would provide a favourable performance in asphalt pavements [19]. In a performance-focused study, the use of 3 % ceramic fibre was proposed to improve the rutting performance of SMA [20]. García-Travé et al. examined the viability of introducing reclaimed geomembranes into SMA to identify cost-effective stabilising agents [21]. The test results proved that, owing to its polymer and fibre content, the geomembrane waste in the bitumen phase enhanced the SMA mixture performance in terms of improved resistance to moisture damage and rutting and alleviated drainage-related problems in the binder. To address the soaring burden of cigarette butt (CB) disposal, encapsulated CBs have been included in large-scale asphalt projects. The observed improvements in stability, resilient modulus, and bitumen drain-off resistance suggest CBs as promising substitutes for both virgin CFs and coarse aggregates in SMAs [7, 22]. Putman and Amirkhanian investigated the possibility of incorporating waste fibres into SMA [23]. From a performance perspective, SMA with carpet fibres and waste tyres have exhibited increased toughness, promising moisture susceptibility, and permanent deformation resistance. Furthermore, the mixtures with tyre and carpet fibres were observed to have 0.1 and 0.45 % lower optimum bitumen content, respectively, than SMAs with CFs. In another study, Oner and Ozdas reported that using textile waste instead of CFs in SMA mixtures increases the Marshall stability and decreases binder drainage, cost of asphalt pavement, and environmental pollution [24].
Recycling natural fibres is considered to be an environment-friendly method for producing SMA mixtures. From this perspective, various fibres have been tested as stabilising agents. In one study, banana fibres (at a fixed 0.3 % amount) of 15–20 mm in length resulted in an evidently prolonged fatigue life of SMA mixtures and an increase in their rutting performance [25]. However, this scenario was reversed when coconut and jute fibres were used. The SMA with the coconut fibres exhibited a shorter fatigue life owing to its lower cracking resistance, and the SMA with the jute fibre was found to be more vulnerable to permanent deformation owing to its low values of accumulated deformation in the dynamic creep test [26, 27]. Other prominent examples of natural fibres tested were coir [28], sisal [29], corn stalk [30] and palm oil [31].
A recent study reported that aged cellulose fibres decrease the high-temperature performance as well as cracking and fatigue resistance of bituminous mortar, which ultimately constitutes a potential barrier for mitigating SMA reclamation and reuse [32]. Concerning this issue, an investigation into the possibility of manufacturing an SMA mixture without fibres concluded that employing rubber (end-of-life tyres) in SBS-modified bitumen would have a pronounced effect on SMA performance [33]. The results of the water sensitivity, indirect tensile strength, binder drainage, and permanent deformation tests confirmed the hypothesis that the conjunctive effect of rubber and SBS modification promotes an economical SMA production without the need for cellulose fibres.

3. Materials and method

3.1. Bitumen and its modification

A neat conventional binder with a penetration grade of 50/70, supplied by Turkey's Oil Refineries Corporation, was used in this study. SBR, a typical synthetic rubber, was used for the bitumen modification. To determine the optimum amount of this modifying agent, two different amounts of SBR (8 % and 10 % by binder weight) were added to the pure bitumen. After adding SBR to pure B50/70 binder in a uniform distribution, bitumen modification was performed using a digital electro-mechanic mixer at a constant mixing temperature of 160 °C and a constant mixing speed of 1000 rotations (rpm) for 1 h. To prevent or minimise the binder aging, evaporation, volatilisation, and oxidation that may occur while mixing and to obtain a constant-temperature mixing environment, the mixer was covered with a cap; moreover, any contact with ambient air was prevented during the mixing period. After the modification process was completed, the rubber-modified binders were labelled with various codes and placed in closed storage containers away from hot temperatures and ultraviolet rays.
To emulate the short-term aging of the modified bitumen during storage, transfer to the asphalt plant, mixing with the aggregate in the plant, transfer of the produced asphaltic mixture to the workplace, paving in layers, and compaction, the samples were subjected to the rolling thin-film oven test (RTFOT) according to EN 12607-1 standards [34]. To simulate the long-term aging of the modified bitumen in asphalt-paved roads that are already in service, a pressure aging vessel (PAV) test, in accordance with EN 14769 standards, was conducted on the modified binder samples that were previously aged with RTFOT [35].
The most commonly used conventional and rheological binder tests (penetration, softening point, elastic recovery, flash and fire point, specific gravity, storage stability, mass change, dynamic shear rheometer, and bending beam rheometer) were performed to evaluate the technical properties of the modified bitumen specimens at the unaged, short-term aged, and long-term aged stages. The tests, their pertinent standards, and the obtained results are listed in Table 1.
Following the experiments conducted with the unaged, RTFOT-aged and RTFOT+PAV-aged bitumen involving 8 % and 10 % SBR content, no significant difference was observed between the traditional and the rheological properties of the modified samples. Therefore, for this study, it was concluded that modification with 8 % SBR would be economically more

Table 1. Engineering properties of modified binders

Test	Standard	Unit	B50/70 8 % SBR	B50/70 10 % SBR
Penetration (25 °C, 100 g, 5 sec)	EN 1426 [36]	0.1 mm	33	30
Softening Point Temperature	EN 1427 [37]	°C	65.9	69.8
Elastic Recovery (25 °C)	EN 13398 [38]	%	63.3	76.3
Flash and Fire Point	EN ISO 2592 [39]	°C	241	242
Specific Gravity (Distilled Water, 25 °C)	EN 15326 [40]	-	1.047	1.052
Dynamic Shear Rheometer (G*/sinδ > 1 kPa)	EN 14770 [41]	°C	92.7	97.9
Storage Stability	EN 13399 [42]			
Differences in Softening Point Temperature	EN 1427 [37]	°C	4.8	4.5
Differences in Penetration	EN 1426 [36]	0.1 mm	11	10
Rolling Thin Film Oven Test	EN 12607-1 [34]			
Mass Change	EN 12607-1 [34]	%	0.48	0.49
Increase in Softening Point Temperature	EN 1427 [37]	°C	12.4	11.8
Retained Penetration	EN 1426 [36]	%	87.9	93.3
Dynamic Shear Rheometer (G*/sinδ > 2.2 kPa)	EN 14770 [41]	°C	95.5	100.8
Rolling Thin Film Oven Test + Pressure Aging Vessel	EN 14769 [35]			
Dynamic Shear Rheometer (G*sinδ < 5000 kPa)	EN 14770 [41]	°C	19.5	19.7
Bending Beam Rheometer (S ≤ 300 MPa, m ≥ 0.300)	EN 14771 [43]	°C	-12	-12

cost-effective. Furthermore, 8 % SBR modification was considered to ensure less usage of the polymer and thus less energy consumption and gas emission during mixing to obtain a homogeneous binder. It also demonstrated increased compatibility between the bitumen and polymer phases, and reduced storage stability.

3.2. Aggregate gradation and properties

In this paper, crushed basalt stones were used as coarse and fine aggregates, and triturated basalt stone dust was used as a mineral filler. They were obtained from the Harput stone quarry located in Turkey's eastern city of Elazig. The gradation of the aggregate is crucial for the aggregate surface area, and when combined with the binder amount and absorption, they play a significant role in determining the amount of free bitumen that can coat the aggregates in the SMA [44]. Figure 1 illustrates the upper and lower gradation limits recommended by Turkey's General Directorate of Highways (KGM) for SMA design; the gradation selected in this study is in the middle of these limits [45]. The maximum particle size of the SMA was 19 mm (0.74 inch).
To form stone-to-stone contact structures, high-quality aggregates with superior physical and mechanical properties should be utilised in SMA production. The main characteristics of the aggregates (coarse and fine) and mineral fillers used in this study (Los Angeles abrasion value, flakiness index, soundness, stripping resistance, specific gravity, methylene blue value, and water absorption) are listed in Table 2. The results confirmed that the selected aggregates met the technical specifications required by KGM and were acceptable for SMA production [45].

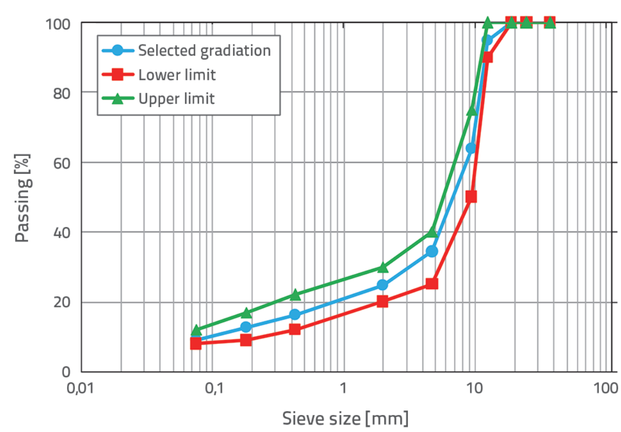

Figure 1. Particle-size distribution of the gradations

Table 2. Physical properties of aggregates (coarse and fine) and mineral filler

Property	Unit	Result	Method	Specification
Coarse aggregate				
Los Angeles abrasion value	[%]	12	ASTM C131 [46]	≤ 25
Flakiness index	[%]	11	BS EN 933-3 [47]	≤ 20
$MgSO_4$ soundness	[%]	4.1	ASTM C88 [48]	≤ 14
Stripping resistance	[%]	60-65	ASTM D1664 [49]	≥ 60
Bulk specific gravity	-	2.855	ASTM C127 [50]	-
Apparent specific gravity	-	2.911	ASTM C127 [50]	-
Water absorption	[%]	0.674	ASTM C127 [50]	≤ 2
Fine aggregate				
Methylene blue value	[g/kg]	1.0	ASTM C1777 [51]	≤ 1.5
Bulk specific gravity	-	2.808	ASTM C128 [52]	-
Apparent specific gravity	-	2.901	ASTM C128 [52]	-
Water absorption	[%]	1.142	ASTM C128 [52]	≤ 2
Mineral filler				
Apparent specific gravity	-	2.730	ASTM D854 [53]	-

3.3. Stabilizer and its properties

This study utilised commercial CF (Enfalt Fibrocel) with a percentage of 0.35 % (by weight of SMA manufactured with B50/70+8%SBR). CF is an organic fibre sourced from chemically processed natural wood. It is mainly composed of cellulose, hemicellulose, lignin, and other impurities [32]. The fundamental engineering properties of the CF used in this study are presented in Table 3.

Table 3. Main characteristics of CF (Enfalt Fibrocel)

Property	Unit	Value
Shape	-	Granular
pH value	[5 g/100 ml]	7,5 ± 1 %
Average pellet diameter	[mm]	7
Average pellet length	[mm]	2
Density	[kg/m^3]	450
Thermal endurance	[°C]	> 250
Ash content	[%]	18
Oil absorption	-	5 ± 1 times of fibre weight
Water absorption	[%]	5

In batch-mixing asphalt plants, the fibre is typically added through a separate inlet directly into the weigh hopper above the pugmill, whereas in drum-mixing asphalt plants, separate fibre-feeding equipment is run to integrate loose fibre by blowing it into the drum. In this study, CFs were directly added to the SMA mixture under loose conditions by a dry process (a method of mixing fibres with aggregates and then adding a binder).

4. SMA specimen preparation

In this study, SMA mixtures were manufactured at 145 °C in conformance with the Marshall mixture design method as detailed in ASMT D6926 [54]. Compared with the standard HMA mixtures, less effort is required for SMA mixtures to achieve the desired in situ compaction degree [55]. Considering that over-compression is limited in terms of achieving a noticeable increase in density and is also likely to crush the aggregates, 50 blows were applied to each side of each mixture during compaction. To fairly compare the volumetric characteristics of the SMA with and without CF, the main sources (aggregate, filler, and modified bitumen) and the selected gradation curve were maintained as constants in the mixture design. Five binder (B50/70 + 8% SBR) contents at 0.5 % increments (5.0 %, 5.5 %, 6.0 %, 6.5 %, and 7.0 %) were used to produce both types of SMA mixtures. Three replicate samples were prepared for each binder level; therefore, 30 (15 × 2) Marshall briquettes were designed separately for the SMA with and without CF.

5. Effect of fibre on SMA design parameters

Air voids (AV) in a compacted asphalt specimen refer to the total volume of small air spaces between coated aggregate grains. Because the tendency of the binder flow is mostly dependent on the presence of small air pockets, AV is considered as the main volumetric parameter to determine the optimum binder amount in the SMA. A low number of AV makes SMA-paved roads susceptible to bleeding, whereas excessive AV can exacerbate the penetration of air and water into the asphalt mixture [56]. Considering its direct effect on maintaining stability and durability, it is generally suggested that AV should be in the range of 2–4 % for proper SMA design.

The effect of CF on the level of AV was evaluated for each bitumen amount, and the results are displayed in Figure 2. Regardless of CF utilisation, increasing the amount of binder in the mixtures causes a drastic decrease in the AV values. The AVs of both types of SMAs with 5 %, 5.5 %, and 6 % binder content failed to remain within the desired range. As can be deduced from the same figure, the integration of CF yields a cardinal increase in the AV of the SMA mixture with 6.5 % binder content (AV of 2.63 % and 3.43 % for SMA without and with CF, respectively.). This finding has also been corroborated by previous research [25, 57] reporting that a higher AV is closely related to greater bitumen absorption and consequently to an increase in the aggregate surface area covered by bitumen caused by the addition of CF.

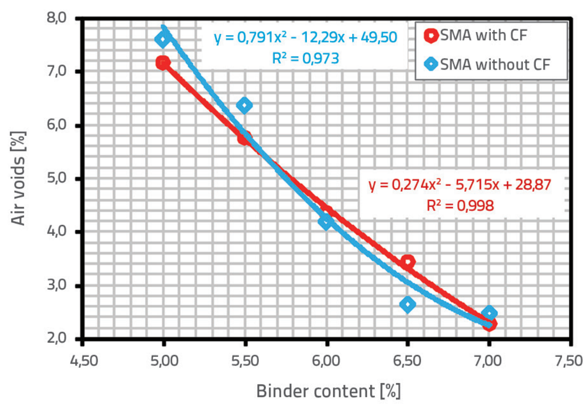

Figure 2. Results of air voids (AV) content

Consisting of AV and effective bitumen content (not occupied by aggregates), the voids in mineral aggregate (VMA) are associated with the total volume of the intergranular void space between the aggregate particles [58]. In most cases, a minimum VMA of 16 % is recommended to provide sufficient accommodation for bitumen and AV components in SMA mixtures. Figure 3 displays the changes in VMA as a function of the binder amount, which also indicates that the inclusion of CF to control SMA mixture first decreases the VMA at low bitumen levels and then substantially increases the VMA with increasing bitumen content. The resulting increase is attributed to the homogenous effect of CF on the rubber-modified bitumen. By increasing the percentage of air-void spaces in the bituminous mastic of the SMA, CF partially prevents coarse aggregates from making contact with each other, which ultimately allows the formation of more interspaces available for fine aggregates. These findings were consistent with those of previous studies [59–61]. Although a higher VMA makes SMA a cracking-resistant mixture under cyclic loading, excessive VMA may result in the utilisation of a redundant amount of binder, leading to incremental costs and stability problems in SMA mixtures.

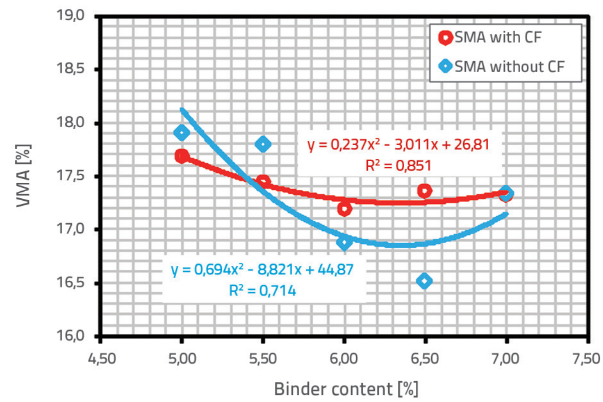

Figure 3. Results of voids in mineral aggregate (VMA)

Voids filled with binder (VFB) are the percentage of the volume of VMA occupied by the bituminous binder. VFB is inversely proportional to AV; when AV decreases, VFB increases. In the case of a particularly low AV content, the VFB acts in a compensatory manner to prevent asphalt mixtures from rutting and shoving under heavy traffic loads. Figure 4 shows the variation in the VFB values of the respective base SMA and SMA with CF over the bitumen range. As expected, increasing the binder content in both SMA mixtures causes an apparent increase in the VFB values. The VFB values of SMA with CF are 59.5 %, 67 %, 74.7 %, 80.2 %, and 86.9 % at the respective binder contents. When compared with the control mixture, the VFB content was found to be 0.5 % and 3.8 % lower for the SMA mixtures with CF at 6.0 % and 6.5 % binder levels, respectively. Although the introduction of CF seems to cause a slight decrease in VFB at relatively higher binder contents, the general trend of the almost superimposed curves confirms that the VFB values of both mixtures agree.

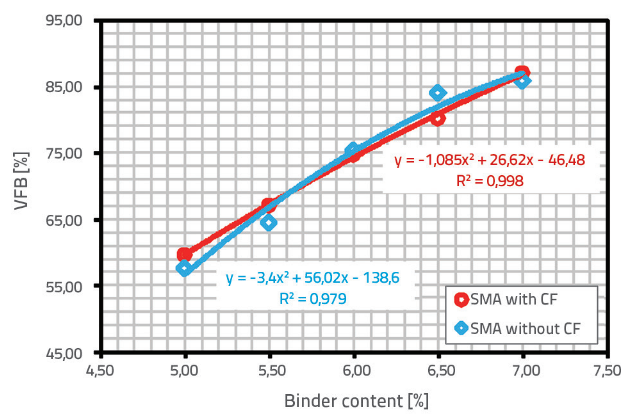

Figure 4. Results of voids filled with binder (VFB)

Bulk specific gravity (BSG) is the ratio of the mass in air of a unit volume of a permeable mixture (consisting of both permeable and impermeable voids normal to the mixture) at a given temperature to the mass in air (of equal density) of an equal volume of gas-free distilled water at a given temperature. To calculate the weight per unit volume of the compacted SMA mixture, the BSG is essential for converting weight measurements to volumes [58]. The BSG values for each SMA mixture were evaluated, and the pertinent curves are plotted in Figure 5. The concave shape of the curve drawn for the control mixture indicates that the BSG values first increased and then decreased with increasing binder content. The almost linear curve of the SMA with CF indicates that the BSG values tend to increase continuously as the bitumen level increases in the mixture. Owing to the presence of fibres, the curve of SMA with CF was drawn below that of the control mixture, and small differences in BSG were observed at higher bitumen contents. Reductions of 0.008 and 0.023 in the BSG were observed at bitumen levels of 6 % and 6.5 %, respectively. This decrease is attributed to the CF, which prevents the coarse aggregates from touching each other, thereby constituting more space in the SMA mixture. Conversely, a previous study by Brown and Manglorkar concluded that the utilisation of mineral fibres did not result in a reduction in density [62].

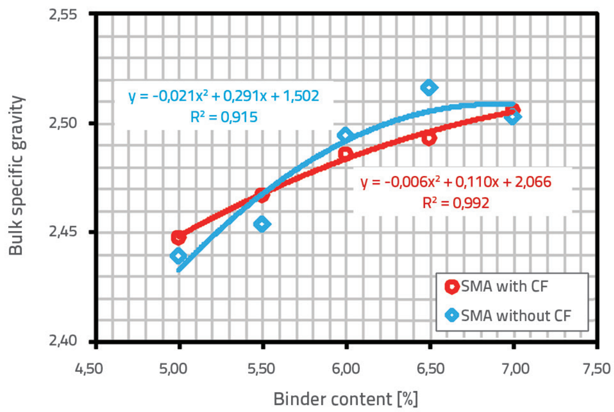

Figure 5. Results of bulk specific gravity (BSG)

In the Marshall graphs, the optimal binder content (OBC) was determined to be 6.5 % and 6.6 % by weight of the aggregate for the SMA mixtures without and with CF, respectively. At each OBC, the ultimate volumetric design parameters of both SMA mixtures (AV, VMA, VFB, and BSG) assessed in this study were obtained from the corresponding plots. The properties of each type of mixture are summarised in Table 4.

When the OBC at 6.5 % was used for the SMA mixture without CF, its AV, VMA, VFB, and BSG were 3.07 %, 16.9 %, 81.8 %, and 2.505, respectively. CF incorporation, along with a relatively high amount of OBC in the SMA, causes a reduction in the AV and BSG values and an increase in the VMA and VFB values. As shown in Table 4, the AV value, which should be in the range of 2–4 % according to technical specifications, was found to be 3.01 % for the SMA with CF. This proves that using CF resulted in a desirable AV value in the SMA. The imperceptible decrease in the SMA density can be attributed to the increase in the amount of bituminous binder and the effect of CF particles by providing more interspace between the aggregate particles. A higher VMA value in the SMA owing to CF indicates increased binder content, specifically, increased film thickness, which ensures an increased effective bitumen volume while maintaining voids and improved durability while maintaining rut resistance. The VFB value increased from 81.8 % to 82.5 %, which may be due to the conversion effect of CF on the percentage of absorbed PMB in the SMA. With the respective OBC, the most important volumetric properties (AV, VMA, and VFB) of the SMA with CF meet the specific technical requirements; thus, the addition of CF as a stabilising agent is considered an appropriate approach in SMA design.

Table 4. Volumetric design properties of SMA mixtures

Parameter	SMA without CF	SMA with CF	Specification
OBC	6.5 %	6.6 %	min. 5.8 %
AV	3.07 %	3.01 %	2 % - 4 %
VMA	16.9 %	17.2 %	min. 16 %
VFB	81.8 %	82.5 %	75 % - 85 %
BSG	2.505	2.500	-

OBC - optimal binder content, AV - air voids,
VMA - voids in mineral aggregate, VFB - voids filled with binder,
BSG - bulk specific gravity

6. Cost analysis

The monetary effect of introducing CF was studied by calculating the total cost required to manufacture a 1-ton SMA mixture. The amount of each ingredient in this study (aggregate, filler, and modified bitumen) was based on the SMA design parameters. The average unit price of each component (including shipping costs) and the production cost of the SMA for 2021 were obtained from KGM. The average hauling distances for the aggregates and filler, base bitumen, and SBR and CF were approximately 30 km, 260 km, and 1250 km, respectively. It is a fact that bitumen price is heavily affected not only by the market demand but also by the seasonal peak consumption. The most recent price of base B50/70 bitumen in Turkey is approximately 556 $/t (including taxes and shipping). The overall costs for the base SMA and SMA with CF are given in Table 5 in detail.

The results of the cost analysis clearly indicate that SMA with CF is more expensive than the respective control SMA mixture. The inclusion of CF and a relatively higher amount of binder utilisation are evidently the primary reasons for the cost increase. Considering the 1-ton SMA production, the addition of 0.35 % CF as a stabiliser resulted in a cost increase of almost $0.9. According to the EAPA report (Asphalt in Figures, 2020), approximately 32 million tons of bituminous mixtures were

Table 5. Comparison of costs of SMA without CF and SMA with CF

Description	SMA Without CF			SMA With CF		
	Quantity [t]	Unit price [$/t]	Cost [$]	Quantity [t]	Unit price [$/t]	Cost [$]
Aggregate (19–9.5 mm)	0.3366	5.17	1.74	0.3362	5.17	1.74
Aggregate (9.5–4.75 mm)	0.2767	5.48	1.52	0.2764	5.48	1.52
Aggregate (4.75–0.075 mm)	0.2356	5.67	1.34	0.2353	5.67	1.34
Mineral Filler	0.0860	6.03	0.52	0.0859	6.03	0.52
B50/70 Binder	0.0650	556.34	36.16	0.0660	556.34	36.72
SBR Modifier	0.0052	1989.86	10.35	0.0052	1989.86	10.51
Bitumen Modification	0.0650	25.83	1.68	0.0660	25.84	1.71
CF Stabilizing Agent				0.0002	546.19	0.13
SMA Production	1.0000	4.31	4.31	1.0000	4.31	4.31
Total Cost ($/t)			57.62			58.50

produced in Turkey in 2020 [63]. Five million tons of these total paving materials were supposed to be allocated for paving with the SMA mixture, suggesting that the annual overall cost increase in SMA production could amplify to 4.5 million USD in Turkey when CF is added. However, this initial cost increase can be tolerated, considering that the application of SMA with CF results in relatively thinner layers, longer performance life, and lower maintenance costs.

7. Conclusions

As a gap-graded and densely compacted mixture, stone mastic asphalt (SMA) is commonly used as a wear layer for pavements with heavy traffic loads owing to its superior performance resulting from its outstanding bituminous mastic and dense framework structure. Owing to its open-graded mix design, SMA requires some type of fibre which will adsorb and stabilise the binder to avoid the drainage of bitumen through the air voids of the mixture. This study aimed to gauge the impact of 0.35 % cellulose fibre (CF) content on the volumetric design of SMA with polymer-modified bitumen (PMB, B50/70+8 %SBR). Based on the test results of this study, the following conclusions were drawn.

- CF incorporation into the SMA with PMB caused a 0.1 % increase (from 6.5 % to 6.6 %) in binder utilisation, which is a controversial issue affecting the initial cost.
- CF utilisation along with a considerable increase in the optimal binder content increased the cost of the 1-ton SMA by 1.5 %.
- With a favourable AV value, using CF allows SMA-paved roads to expand and contract safely under changing traffic loads and temperatures without any bleeding or flushing on the pavement surface.
- CF ensures an increase in VMA, which ultimately promotes an improvement in SMA performance owing to increased durability, lower sensitivity to variations in binder content, more flexibility, and increased resistance to low-temperature shrinkage cracking.
- Compared with the respective control mixtures, SMA with CF showed a slight increase (0.7 %) in the VFB value, which is reasonable according to the technical specifications.
- By forming more space to overcome the binder drainage problem, CF inclusion leads to an insignificant reduction in the SMA mixture density.

In summary, cellulose fibre is considered as a backbone to stabilise SMA, particularly in terms of preventing and/or mitigating the draining of bituminous binders from the mixture. However, because of their higher costs, future studies should focus on more cost-saving, sustainable, abundant, and eco-friendly alternative reinforcing additives for SMA production.

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