Site Assessment of Surface Texture and Skid Resistance by Varying the Grit Parameters of an SMA

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Abstract: For the safe operation of vehicles, pavement should provide adequate skid resistance, which can be achieved by using high polishing–resistant aggregate in wearing courses. However, supplying high-quality aggregate is not always feasible due to high transportation costs. For this reason, a method called *gritting* was adapted to meet the Highway Technical Specification (HTS) of Turkey in 2013. According to the method, for certain parts of the country, the wearing course can be constructed with local aggregates that have minimum polished stone value (PSV) of 40 (PSV ≥ 40), but, in this case, the surface must be covered with a high polishing–resistant aggregate (PSV ≥ 50), after the rollers' first pass. The objective of this study was to improve the present gritting method by investigating the effect of grit parameters on pavement performance under real traffic conditions. In this regard, during its construction, the wearing course of O-51 Highway was gritted with different aggregate types (slags and natural), sizes (1–3; 1–5 mm), spreading amount (1.5; 2; 2.5 kg/m^2), and spreading time (before and after the first pass of a roller) on eight test sections. Then, the macrotexture and skid resistance performance of these sections were evaluated under real traffic and environmental conditions for longer than 4 years. Changes in surface texture and skid resistance with respect to traffic were determined for each section. The results showed that higher skid resistance values were obtained at the sections gritted with metallurgical slags. Additionally, the sections gritted with 1–5 mm aggregates had better skid resistance than those gritted with 1–3 mm, while the change in mean texture depths were not very significant. **DOI: 10.1061/JPEODX.0000369.**

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Introduction

In 2019, the General Directorate of Highways of Turkey reported more than 45,000 traffic accidents, a major part (71%) of which occurred on state highways. Due to these traffic accidents, about 3,000 people were killed and hundreds of thousands were injured (GDH 2020a), while the economic loss was estimated at about USD 10 million (Ergin et al. 2020). When traffic accident data are analyzed, human error, at 89.5%, is the leading factor among the other traffic accident causes. At least one factor associated with road and road environment (i.e., weather, defects on roadway geometry and pavement surface) contributes to approximately one-third of the traffic accidents (Uz and Gökalp 2017a). Although human errors are the dominating factor of traffic accidents, traffic/highway engineers mainly concentrate on road-related factors, over which they have more control and responsibility. Road surfaces deteriorate over time due to traffic loadings and environmental conditions. Cracking, rutting, potholes, raveling, roughness, polishing, and bleeding are the typical pavement distresses, and all of these distresses cause loss of surface texture and skid resistance (Miller and Bellinger 2014). Subsequently, these two phenomena are detailed and the role of aggregate properties is investigated in light of the literature.

Pavement surface texture can be classified under four categories, depending on its wavelength: (1) microtexture (≤0.5 mm), (2) macrotexture (0.5–50 mm), (3) megatexture (50–500 mm), and (4) unevenness or roughness (0.5–50 m) (Flintsch et al. 2003; Prowell and Hanson 2005; Uz and Gökalp 2017a). The skid resistance of the pavement is very much affected by microtexture. Macrotexture ensures quick drainage of water from the pavement surface and influences tire/road contact, noise levels, and skid resistance. On the other hand, roughness affects both vehicle dynamics and ride quality (Cossale et al. 2013; Fisco and Sezen 2013). Numerous methods have been developed to assess the surface texture of pavements, and they can be grouped as portable/vehicle-mounted or static/dynamic according to their operating and measuring principles. Sand patch and outflow meter tests are static but portable, and are known as volumetric methods because the principle is based on the surface texture volume measurement. On the other hand, circular texture meter and vehicle-mounted laser profilometer have dynamic operating principles and are used to evaluate the mean profile depth of a road section (Flintsch et al. 2003; Gökalp and Uz 2017b).

Skid resistance is developed when the wheel prevents rotating along the pavement surface; it is one of the most important indicators of traffic safety. Skid resistance of a pavement depends on a wide variety of factors such as surface texture, material properties, type of pavement, and traffic (Luce et al. 2007; Mahboob Kanafi et al. 2015; Wang et al. 2015). Skid resistance of a pavement decreases with repetitions of traffic and increases the risk of skidding of vehicles, especially on wet surfaces. Skidding of vehicles is a common factor in traffic accidents and often results in human injury and death (Do and Cerezo 2015; Gökalp and Uz 2017a; Kogbara et al. 2016; Mataei et al. 2016; Nataadmadja et al. 2015; Sarsam and Al Shareef 2015). Therefore, it is vital to understand

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the factors affecting skid resistance of pavement to reduce the frequency of this type of traffic accident. Standard methods used for evaluating pavement resistance to skidding include the dynamic friction tester, British pendulum tester, and locked-wheel skid resistance tester (Saito et al. 1996).

Rough and tough aggregates provide better polishing resistance. Therefore, the polishing characteristics of aggregates should be evaluated with laboratory tests before choosing them for pavement wearing courses (Bessa et al. 2014; Hofko et al. 2012). Natural aggregates have different physical and mechanical characteristics due to their formation processes. Sedimentary rocks, for example, have low mechanical properties such as low abrasion, fragmentation, weathering, and polishing resistance. On the other hand, magmatic origin aggregates, such as basalt, have better properties than sedimentary rocks (Andriani and Walsh 2002; Esfahani et al. 2019; Figueroa Madero et al. 2014; Koohmishi and Palassi 2016; Krutilová and Přikryl 2015; Ugur et al. 2010).

The world's growing population requires more transport infrastructure and increases the demand for construction materials, mainly aggregates. To meet this demand, natural rock resources have been used for many years. The use of alternative resources in civil engineering facilities has long been an area of interest and has been investigated by many researchers due to depletion of natural resources and sustainability concerns (Faleschini et al. 2015; Gökalp and Uz 2019; Parrot et al. 2009; Vasudevan et al. 2012; Yüksel 2017). The aim of these efforts is to substitute natural resources with the alternative materials without sacrificing the performance of the structure. Scholars investigated the physical and chemical characteristics of metallurgical slags and their influence on the environment (Jiang et al. 2018; Mihok et al. 2006; Motz and Geiseler 2001; Pasetto et al. 2017; Wang and Suraneni 2019; Ziaee et al. 2015). Studies on the use of slags in highway pavements showed that their technical properties meet the requirements of relevant material specifications, and they are classified as inert or nonhazardous materials, which makes them an environmentally friendly material. Possible uses of slags at different pavement applications, including maintenance, overlaying, and surface coatings, have been investigated by many researchers (Anastasiou et al. 2015; El-Assaly and Ellis 2001; Kresta 2014; Murari et al. 2015; Roth and Eklund 2003). Gritting application, a kind of surface coating method, is generally used to improve the early surface texture and skid resistance of the pavement. There is very limited literature about gritting application; some of these works are presented in brief in the following section.

Background on Gritting Application

Gritting application has been studied in the literature and specified in technical specifications of some countries. Here, we present earlier studies and current specifications dealt with the gritting applications.

Halligan (2006) investigated the early-life skid resistance of stone mastic asphalt (SMA) and dense-graded asphalt (DGA) with and without the gritting application. The author analyzed four different SMA and DGA mixtures and their early-life skid resistance performance. The author concluded that using gritting on the pavement surface improved skid resistance and accelerated the wear process of the binder from the surface.

McHale et al. (2010) investigated the performance of gritting application on SMA pavements by means of skid resistance and surface texture. This study used 1–2.85 mm quartz-dolerite aggregate mix for gritting the SMA pavement surface between the second and the third rolling with 1 kg/m^2. Measurements were taken at the end of the 3rd, 6th, and 10th months using different test methods. Lower surface texture was observed on the gritted section, and the researchers attributed this finding to the gritting material, which filled the surface texture. On the other hand, the skid resistance of the gritted sections were measured to be higher than that of nongritted sections. Moreover, a decrease in friction coefficient was observed at the 6th month, at about half of the first measurement.

Baran and Lowe (2011) investigated usability of the gritting application on SMA pavement to improve skid resistance performance in early and long-term durations. Gritting was applied on newly built SMA road sections that were located in different parts of Queensland. The aggregate used for gritting was a mix that contained at least 70% quartz, 0.075–2.36 mm in size. The observations lasted about 4 years, and the authors' conclusions were as follows: (1) performance of the gritting application can vary, depending on the road type, traffic, and environmental and climatic conditions; and (2) a significant reduction was observed in skid resistance within a short period.

The Alabama Department of Transportation (ALDT) developed the specification for stone skeleton asphalt (SSA), which has similar performance characteristics to typical SMA mixtures. However, permeability was found to be a potential problem with SSA. To overcome this problem, two possible solutions were recommended: (1) contributing the smaller maximum aggregate size to SSA mixtures; and (2) implementing gritting, which is used on the SMA mixes in Germany on SSA surfaces. Although the two solutions were recommended, the gritting application was preferred due to advantages such as reducing permeability of pavement, improving skid resistance in early life without loss of structural or functional performance, and increasing service life of the pavement (Hurley and Prowell 2008).

Asphalt constructions working group members under the German Roads and Transportation Research Association (GRTRA) specified a regulation, German designation: ZTV Asphalt-StB 2007. According to the regulation, aggregates used as gritting material for surface of the SMA must have a minimum polishing value (PSV) of 48 or 51, depending on the respective usage. The application is made with crushed aggregate in two alternative ways, first a 1/3-mm grain size with 0.5 to 1.0 kg/m^2 with spreading rate, and the second is 2/5-mm grain size with 1.0 to 2.0 kg/m^2. The grit material should be applied to the surface layer while it is still hot so that it can be pressed down by the roller, and the unbound grit material must be removed after construction (GRTRA 2007).

The Highway Agency of Western Australia (MRWA 2010) specified the gritting method for increasing the early life of skid resistance of the SMA pavements. The nominal aggregate size is 3 mm, and the aggregates with the amount of 1.5–2.0 kg/m^2 are spread out to the surface just before final compaction Moreover, the types of the aggregate to be used in this method are identified as black granite from Barossa Quarries, South Australia, and grey calcined bauxite from Guyana.

Problem Statement and Objective

Turkey is rich in limestone resources due to its geological structure. Mechanical properties of the limestone, such as fragmentation, abrasion, and polishing resistance, are lower than the other rock types. The required PSV for coarse aggregate of the asphalt concrete (AC) and the SMA wearing course is a minimum of 50 PSV, and the recommended aggregate origin is igneous rock. However, it is not easy to supply these types of aggregate in some parts of the country. Therefore, the General Directorate of Highways (GDH) of Turkey allows using different types of aggregate for the construction of AC and SMA pavement wearing courses with PSV of at least 40. However, contractors have been forced to implement a

Table 1. Physical and mechanical characteristics of aggregates

Test methods	Unit	Standard	Aggregates					HTS	
			LS	BS	RBCA	EAFS	FERS	SMA	Chip seals
Abrasion resistance	%	EN 1097-1	21.3	10.41	11.3	9.5	7.6	≤20	≤25
Fragmentation resistance	%	EN 1097-2	16.2	12.04	17.5	22.9	16.5	≤25	≤30
Water absorption	%	EN 1097-6	0.2	2.00	0.9	1.8	1.1	≤2.0	≤2.5
Polishing resistance	PSV	EN 1097-8	43.2	61.00	57.9	76.1	61.7	≥50[a] ≥40[b]	≥40 ≥40
Weathering resistance	%	EN 1367-2	3.0	6.85	6.2	2.3	6.1	≤14	≤18
Vialit plate test	%	EN 12272-3	3	2	3	4	2	N/A	≤10
Nicholson stripping	%	EN 12697-11	80–85	60–65	60–65	55–60	85–90	≥60	≥60
Flakiness index	%	EN 933-3	18.1	10.9	17.9	8.1	10.4	≤20	≤20
Friable particle values	%	ASTM C142	0.8	0.5	0.4	0.2	0.2	≤0.3	≤0.3

[a]Required limit values as construction of SMA without gritting application.
[b]Required limit values as construction of SMA with gritting application.

specific application called gritting, according to the Highway Technical Specification (HTS,) to provide high skid resistance for driving safety on Turkish roads. In this case, the pavement surface must be gritted with high-quality material during its construction. The grit method in HTS requires spreading 1–3 mm of igneous aggregate (PSV ≥ 50) to the pavement surface between the first and the second roller passes in the amount of 1.5–2.0 kg/m^2 (HTS 2013).

Considering the previous studies and technical specifications of other countries, the aim of the gritting application is not to increase the low skid resistance of the roads built with low polishing resistant aggregates, but to break down the mastic part of the SMA surface to provide early-life higher skid resistance. In this respect, our research is original and innovative. There were three main questions that needed to be answered within the scope of this study. (1) Is it possible to use slags as aggregate in gritting application? (2) How do the construction parameters, including aggregate type, size, amount, and application time, affect the SMA wearing course layer's skid resistance performance and surface texture? (3) Is it possible to develop alternative applications to the suggested one for better skid resistance performance?

To answer to these questions, eight test sections (300 m each) with alternative grit parameters were constructed over a 2,550-m long segment of the O-51 highway and evaluated under actual traffic and the environmental conditions. A 150-m section of the road was left without gritting to observe the polishing process of the SMA constructed with limestone aggregate and to understand the change in surface texture and skid resistance, especially in early stages. Surface texture and skid resistance performances were evaluated with different test methods for more than 4 years. The British pendulum tester, dynamic friction tester, and locked-wheel tester were used to evaluate skid resistance performance. The sand patch test and the vehicle-mounted laser profilometer methods were used to determine changes in surface texture. Field observations were made between 2016 and 2021 for the 15 nonuniform time intervals. The changes in skid resistance performance and surface texture of test sections were evaluated on the basis of traffic loadings that converted to equivalent single axle load (ESAL) to provide a single and standard units for traffic count. The variations in the skid resistance and surface texture with respect to total ESAL were analyzed, and life-span estimations for each test section were determined considering threshold values for different test methods.

Materials and Characterizations

The materials used in this study were supplied from different sources. Limestone (LS) aggregate was utilized to construct the SMA pavement. Four types of aggregates, basalt (BS), river basin crushed aggregate (RBCA), electrical arc furnace steel slag (EAFS), and ferrochromium slag (FERS) were used for the gritting application. Physical and mechanical properties of the aggregates were determined according to EN 1097-1 (European Standards 2011), EN 1097-2 (European Standards 2020b), EN 1097-6 (European Standards 2013), EN 1097-8 (European Standards 2020c), EN 1367-2 (European Standards 2009), EN 12272-3 (European Standards 2003), EN 12697-11 (European Standards 2020a), EN 933-3 (European Standards 2012), ASTM C142 (ASTM 2012a) and the results were checked with the requirements of HTS of Turkey (Table 1). It can be clearly seen in Table 1 that all physical and mechanical characteristics of the aggregates provided the specified limitations. Like polishing resistance, fragmentation resistance of LS is much lower than the magmatic aggregates. The polishing resistance of slags, especially in EAF, was observed to be higher than the natural aggregates.

The chemical content of an aggregate varies according to its origin, and it is effective on adhesion between bitumen and aggregate and durability of asphalt aggregate bonding systems (Cala et al. 2019). The X-ray fluorescence (XRF) method was implemented according to EN 15309 standard (CEN 2012) on each aggregate to determine their chemical compounds, and the results are given in Table 2.

From the data presented in Table 2, it can be seen that chemical compounds of the aggregates vary due to their origin and/or manufacturing process. CaO and SO_2 are the two most important chemical compounds of geological formation of the natural rocks, and they are the main components of LS and BS, respectively. RBCA consists of sedimentary and magmatic rock formations. In addition to CaO and SiO_2 compounds, Fe_2O_3 was the other chemical compound of EAF slag. Finally, SiO_2, MgO, and Al_2O_3 were determined to be the main chemical compounds that form the FER slag.

Each formation of the aggregates has different surface textures at the micro level, which is quite decisive for the skid resistance (Wang et al. 2017). Moreover, the surface texture of aggregate at the

Table 2. Chemical compound of each aggregate

Aggregate	Chemical compound composition (% by weight)					
	LoI	CaO	Fe_2O_3	SiO_2	Al_2O_3	MgO
LS	47.20	48.90	0.01	0.90	0.20	0.30
RBCA	28.90	31.00	7.40	22.7	5.60	4.10
BS	5.60	8.50	6.00	49.9	18.10	3.30
EAFS	17.50	25.60	28.70	5.80	5.80	1.70
FERS	22.00	4.50	1.40	14.9	14.90	10.60

Note: CaO = calcium oxide; SiO_2 = silicon dioxide; Fe_2O_3 = ferric oxide; MgO = magnesia; Al_2O_3 = alumina; and LOI = loss of ignition.

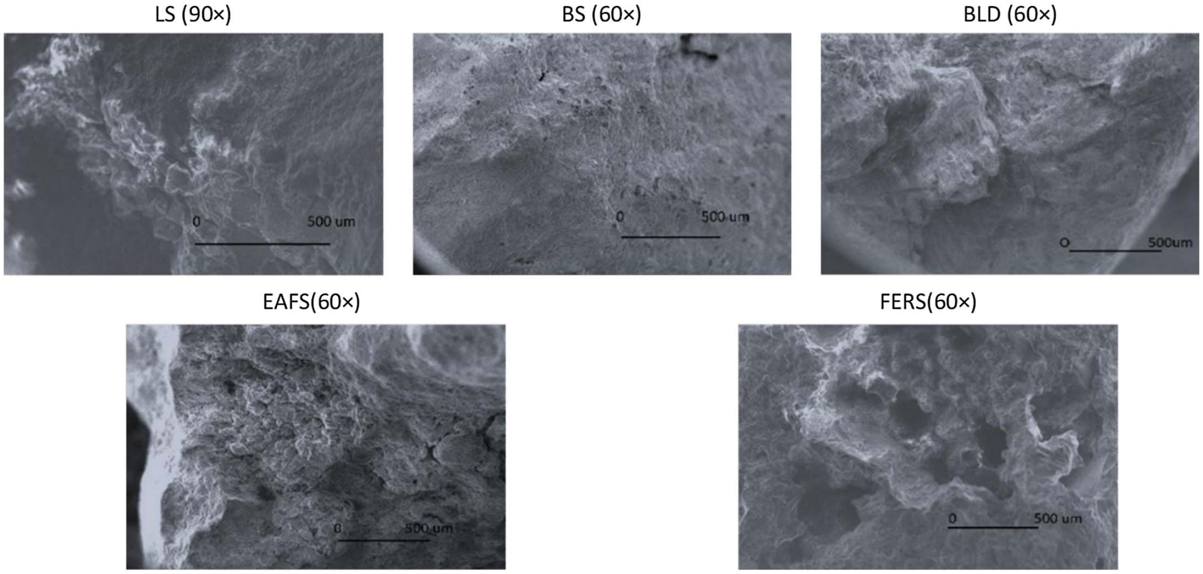

Fig. 1. SEM images taken from surface of the aggregates.

microlevel was monitored with scanning electron microscopy (SEM), and the images taken from their surface are presented in Fig. 1.

The SEM images presented in Fig. 1 show that LS has the smoothest surface texture among the others, while slags have the roughest. This case is compatible with the polishing resistance properties of the aggregates, the slags of which have higher polishing resistance and the others have lower polishing resistance than slags. This was also highlighted from the studies done by Ergin et al. (2020), Gökalp et al. (2018), and Uz and Gökalp (2017b). Therefore, slags were chosen as grit materials in this study due to their superior properties.

Slags may contain heavy chemical compounds such as chromium, barium, vanadium, and molybdenum, which are hazardous to life. Therefore, it is important to determine the environmental effect of the slags before using them. Because of this concern, a leaching test was conducted on the slags according to EN 12457-2 standard (CEN 2004) to determine heavy chemical compounds within the slags. The solutes of leached slags were analyzed with inductive coupled argon plasma mass spectrometry (ICP-MS) and their determined concentrations of heavy chemical compounds were compared with the waste disposal regulation (WDR) limits specified for Turkey (Table 3).

Table 3. Leaching test results

Parameters	EAFS (mg/L)	FERS (mg/L)	Waste regulations (mg/L) Inert
As	0.0007	0.0001	≤0.05
Ba	0.0580	<0.0004	≤2
Cd	<0.0001	<0.0001	≤0.004
Cr	0.0062	0.0073	≤0.05
Cu	0.0015	0.0003	≤0.2
Hg	0.0009	<0.0001	≤0.001
Mo	0.0099	0.0002	≤0.05
Ni	0.0007	0.0005	≤0.04
Pb	0.0002	0.0001	≤0.05
Sb	0.0091	0.0035	≤0.006
Se	0.0007	<0.0001	≤0.01
Zn	0.0271	<0.0001	≤0.4
Cl	63.2	73.1	≤80
F	0.6	0.7	≤1
SO_4	11	82	≤100

The results of ICP-MS analyses presented in Table 3 reveal that the concentration of heavy chemical compounds of the two slags remained within the WDR limits for inert materials. Therefore, using these two slags for gritting applications is not expected to be detrimental to the environment.

Test Methods

Skid resistance and surface texture of the SMA pavement constructed throughout the study were evaluated with a series of standard test methods including the British pendulum tester, dynamic friction tester, lock-wheel skid resistance tester, sand-patch test, and vehicle-mounted laser profilometer. These test methods are described briefly next.

British Pendulum Tester

The BPT is a kind of low-speed test method that generates results generally corresponding to speeds between 10 and 20 km/h, and the result of the test is reported as the British pendulum number (BPN). The details of the operating principles of the test can be found in the study by Gökalp and Uz (2017a). During the field measurements, the ASTM E303 standard method was followed (ASTM 2012c).

Dynamic Friction Tester

The DFT is a method used to measure the frictional properties of pavement surfaces. Like the BPT, it can be conducted either in the field or in the laboratory. Compared with the BPT, the DFT can determine friction characteristics at higher speeds ranging between 10 and 80 km/h. Details on the operating principle of this device and the followed method can found in the study by Rado and Kane (2014). Throughout this study, the DFT tests were performed on the test sections according to the ASTM E1911 (ASTM 2009).

Lock-Wheel Skid Resistance Tester

The LWSRT is a commonly used system to measure the skid resistance of a road. The steady-state friction force is utilized by the test method on a locked test wheel as it is dragged over a wetted surface under vertical load and speed. Details about the operating principle of this test can be found in the study by Andriejauskasa et al. (2014). The LWSRT was conducted at 64 km/h on pavement surface according to the ASTM E274 standard, and the results are reported as the skid number (SN) (ASTM 2015).

Sand Patch Test

The SPT is a volumetric-based measurement method commonly used for measuring the mean texture depth of pavement surface. Details on the principles and apparatus of this test can be found in the study by Uz and Gökalp (2017a). ASTM E965-12 was followed (ASTM 2012b) in this study for measuring the surface texture depth.

Vehicle-Mounted Laser Profilometer

The VMLP can be used for determining the surface texture, longitudinal-transverse profile, International Roughness Index values, and rutting measurements. The VMLP consists of six inclined lasers, 11 vertical lasers, an inertial motion sensor, and two accelerometers. Photographs can be taken from road surface with a high-resolution camera, and the locations of the photographs can be plotted on a map with the satellite-connected computer system. The VMLP has a special software to report the desired properties of the surface according to the data taken from the sensors and lasers (Ünal et al. 2021).

Gritting Application Process

The following six steps were taken to identify the gritting application process. (1) Supply the aggregates with desired properties and transfer them to the site; (2) adjust head angle of spreader and speed of the roller; (3) check the aggregate quantity after adjusting the spreader; (4) Construct the SMA pavement; (5) grit the SMA surface according to selected parameters; and (6) complete the compaction of the surface layer. To visualize each step during the construction of the SMA pavement and gritting application, photos taken from the construction site are shown in Fig. 2.

In the light of earlier studies, regulations (GRTRA 2007; McHale et al. 2010; MRWA 2010; Baran and Lowe 2011; HTS 2013), preliminary laboratory-based assessment, and in the window of the GDH technical staff, various grit parameters, including aggregate type, size, amount, and spreading time, were determined. The details and the coding system of gritted and nongritted test sections are presented in Table 4.

Field Testing Procedure and Data Processing

Here, the details about the construction site, the process of data gathering and processing, and testing procedures we used in the field measurements are presented.

Site Description

The test sections were constructed on the O-51 highway between the kilometers of 28 + 500 and 31 + 050 that numerated by General

Fig. 2. Photographs taken during gritting application on working sites: (a) stockpiled gritting aggregate; (b) preparing the laying area; (c) adjusting spreader; (d) determining the spreading rate of aggregate; (e) construction of the SMA; (f) gritting application; (g) compaction of the gritted sections-1; (h) compaction of the gritted sections-2; and (i) general view of construction site. (Images by İslam Gökalp.)

Table 4. Details of test sections

Test section #	Aggregates type	Size (mm)	Spreading time	Amount (kg/m^2)	Trial section length (m)	Code of test sections
SMA	LS	—	—	—	150	SMA
1[a]	BS	1-3	After first rolling	1.5	300	BS.1-3.AFR.1.5
2	BS	1-3	After paver	2.0	300	BS.1-3.AP.2.0
3	FERS	1-3	After first rolling	2.0	300	FERS.1-3.AFR.2.0
4	EAFS	1-3	After paver	2.0	300	EAFS.1-3.AP.2.0
5	EAFS	1-5	After paver	2.5	300	EAFS.1-5.AP.2.5
6	FERS	1-5	After paver	2.5	300	FERS.1-5.AP.2.5
7	RBCA	1-3	After first rolling	2.0	300	RBCA.1-3.AFR.2.0
8	RBCA	1-5	After paver	2.5	300	RBCA.1-5.AP.2.5

Note: RBCA/BS.1-5/1-3.AP/AFR.2.5/2.0, where RBCA/BS refers to aggregate type, 1-5/1-3 refers to aggregate grain size (mm), AP/AFR refers to application time, and 2.5/2.0 refers to aggregate spreading rate (kg/m^2).
[a]Gritting application required according to HTS of Turkey.

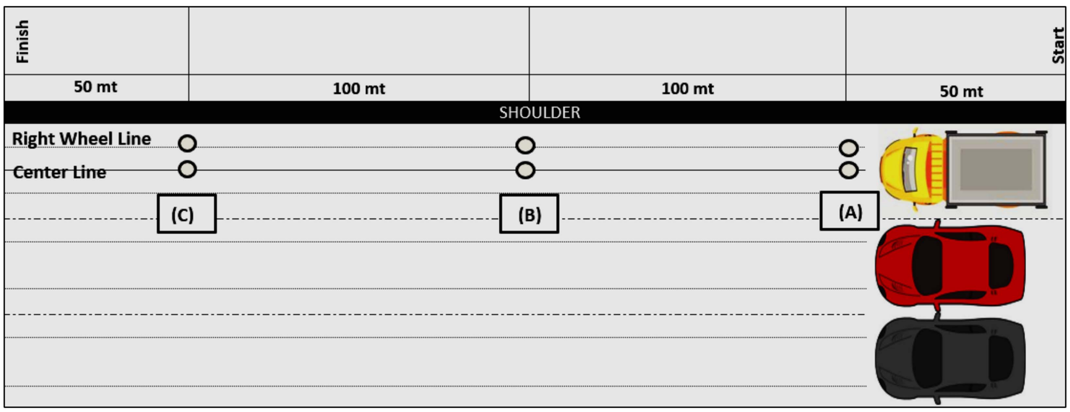

Fig. 3. Schematic representation of the measurement points.

Directorate of Highway of Turkey. The geometric standards of the road are very high. There are three traffic lanes in each direction, where the width of traffic lanes and shoulders are 3.75 and 2 m, respectively. There are no horizontal or vertical curves on the test sections, and the grade elevation is about 1.0%. It is important to highlight that the gritting application was done on the right carriage of the highway.

Skid resistance and texture measurements were done at three different locations in each test section. Two measurement points were determined by considering the wheel track and wander effect of vehicles at each test location. To evaluate skid resistance performance and to follow changes in the mean texture depth of the test sections under real traffic conditions, the observations were done on the right traffic lane. We selected the right traffic lane for the following reasons: (1) lower speed of heavy vehicles, which causes longer duration of contact between wheel and road surface; (2) occurrence of the worst loading conditions due to heavyweight vehicles; and (3) to ensure safe conditions for the test operators while they took measurements on the pavement.

The first measurement was taken on a point 90 cm away from the shoulder marking line that refers to the right-hand wheel track of vehicles, and the second was 1.70 m apart to correspond to the approximate midpostion of wheel tracks. Moreover, the tests based on the BPT, DFT, and SPT were repeated at least three times and the arithmetic means of A, B, and C points were reported. On the other hand, the LWSRT- and VMLP-based measurements were taken for the right lane of the highway three times throughout the test section length. Fig. 3 represents the positions of all the test points at each test section.

Data Processing

The main objective of this study was to evaluate skid resistance and surface texture performance of the SMA wearing course, which was gritted with different grit parameters, under actual traffic loadings. To achieve this aim, the surface properties of test sections were observed for more than 4 years, and the annual average daily traffic (AADT) values were determined and used to identify the changes in surface properties with respect to traffic. The individual lightweight and heavyweight AADT values for the O-51 highway were published by GDH of Turkey (GDH 2020b), and those values were used to estimate the cumulative traffic load in the right traffic lane. The traffic on the highway was assumed to be equally distributed in each direction (directional distribution factor, $f_D = 0.50$) and lane distribution factors (f_L) for the right traffic lane were selected according to the recommendations of GDH as 0.90 and 0.1 for the heavyweight and lightweight traffic, respectively. The AADT values and calculated daily traffic volumes for the right traffic lane in each year are given in Table 5. To represent the traffic within a single and standard unit, the ESAL approach was used based on the GDH of Turkey specifications, in which the calculated ESAL values are given in Table 6. Finally, the data for cumulative ESAL values corresponding to the date of measurements were determined and are presented in Table 7.

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Table 5. AADT for the SMA-constructed road in one direction

Years	Type of vehicle: Automobile	Medium-load commercial vehicle	Bus	Lorry	Truck	AADT total
2016	9,948	985	444	1,784	48	13,209
2017	10,492	1,051	412	1,642	62	13,658
2018	11,890	1,331	475	2,106	70	15,872
2019	12,120	1,400	453	2,184	66	16,224

Results and Discussion

In this part of the study, results of the skid resistance and the surface texture/profile depths are presented. Moreover, a subsection on life-span analysis is presented according to the thresholds defined for traffic safety.

Skid Resistance Results

Results of the BPT test are presented in Fig. 4, and those of the DFT are presented in Fig. 5. Then, results of the LWSRT are presented in Fig. 6. The logarithmic functions were used to represent the change trend of skid resistance for each test section considering cumulative ESAL values.

All the skid resistance measurement results presented in Figs. 4, 5, and 6 revealed that the proposed gritting application with code BS.1-3.AFR.1.5 in HTS exhibits lower performance compared with the alternative applications. Among the gritted sections, slag-based ones showed better performance than those constructed with natural aggregates. Numerically, the BPT results of the gritted sections were between approximately 80 and 60 (BPN), whereas the DFT results were determined to be between 0.6 and 0.3 (μ). On the other hand, the SN values found for the gritted sections were between 65 and 30 SN. It is clear that different test methods give different results. The differences in results can be linked with the working principles of the skid resistance measurement devices; the DFT and the BPT were conducted directly on the test points, but the LWSRT was performed on a road surface selected randomly by the operator within the test section (Chu et al. 2019; Ergin et al. 2020). So, normal-wearing processes of the SMA (initial increase in the short term) were observed to be better with the test methods applied on the same point at every field visit. Moreover, the data presented in the figures also indicate that the SMA constructed without gritting has the lowest skid resistance due to construction

Table 7. Data for total ESAL corresponding to measurement

Order	Date of measurement	Duration between consecutive measurements (days)	Duration from opening to traffic (days)	Total ESAL (10^6)
1[VMD]	November 9, 2016	14[a]	14	0.078
2[PD]	November 10, 2016	15	15	0.083
3[PD]	December 15, 2016	35	50	0.278
4[VMD]	March 9, 2017	120	134	0.720
5[PD]	March 16, 2016	91	141	0.756
6[PD]	May 22, 2017	67	208	1.104
7[VMD]	May 30, 2017	82	216	1.146
8[VMD]	September 27, 2017	120	336	1.769
9[PD]	November 9, 2017	171	379	1.992
10[PD+VMD]	February 28, 2018	111	490	2.645
12[PD]	June 26, 2018	118	608	3.412
13[VMD]	July 17, 2018	139	626	3.548
14[PD+VMD]	March 19, 2019	266	874	5.148
15[PDb]	January 23, 2021	676	1,550	9.618

Note: VMD = measurements with vehicle-mounted devices; and PD = measurements with portable devices.
[a]Time between first measurement and the date of opening of the road to traffic, which was October 26, 2016.
[b]Measurement only with DFT.

Table 6. Annual average daily basis data for ESAL

Vehicle group	AADT	Lane distribution factor	Vehicle equivalence factor	Average daily basis (ESAL)	Cumulative daily basis data (ESAL)
Automobile	9,948	0,20	0,0006	1	5,552 for the year 2016
MLCV	985	0,20	0,6	118	
Bus	444	0,80	3,2	1,135	
Lorry	1,784	0,80	2,9	4,139	
Truck	48	0,80	4,1	158	
Automobile	10,492	0,20	0,0006	1	5,194 for the year 2017
MLCV	1,051	0,20	0,6	126	
Bus	412	0,80	3,2	1,054	
Lorry	1,642	0,80	2,9	3,809	
Truck	62	0,80	4,1	204	
Automobile	11,890	0,20	0,0006	1	6,493 for the year 2018
MLCV	1,331	0,20	0,6	160	
Bus	475	0,80	3,2	1,215	
Lorry	2,106	0,80	2,9	4,886	
Truck	70	0,80	4,1	231	
Automobile	12,120	0,20	0,0006	1	6,613 for the year 2019
MLCV	1,400	0,20	0,6	168	
Bus	453	0,80	3,2	1,160	
Lorry	2,184	0,80	2,9	5,066	
Truck	66	0,80	4,1	217	

Note: MLCV = medium load commercial vehicle.

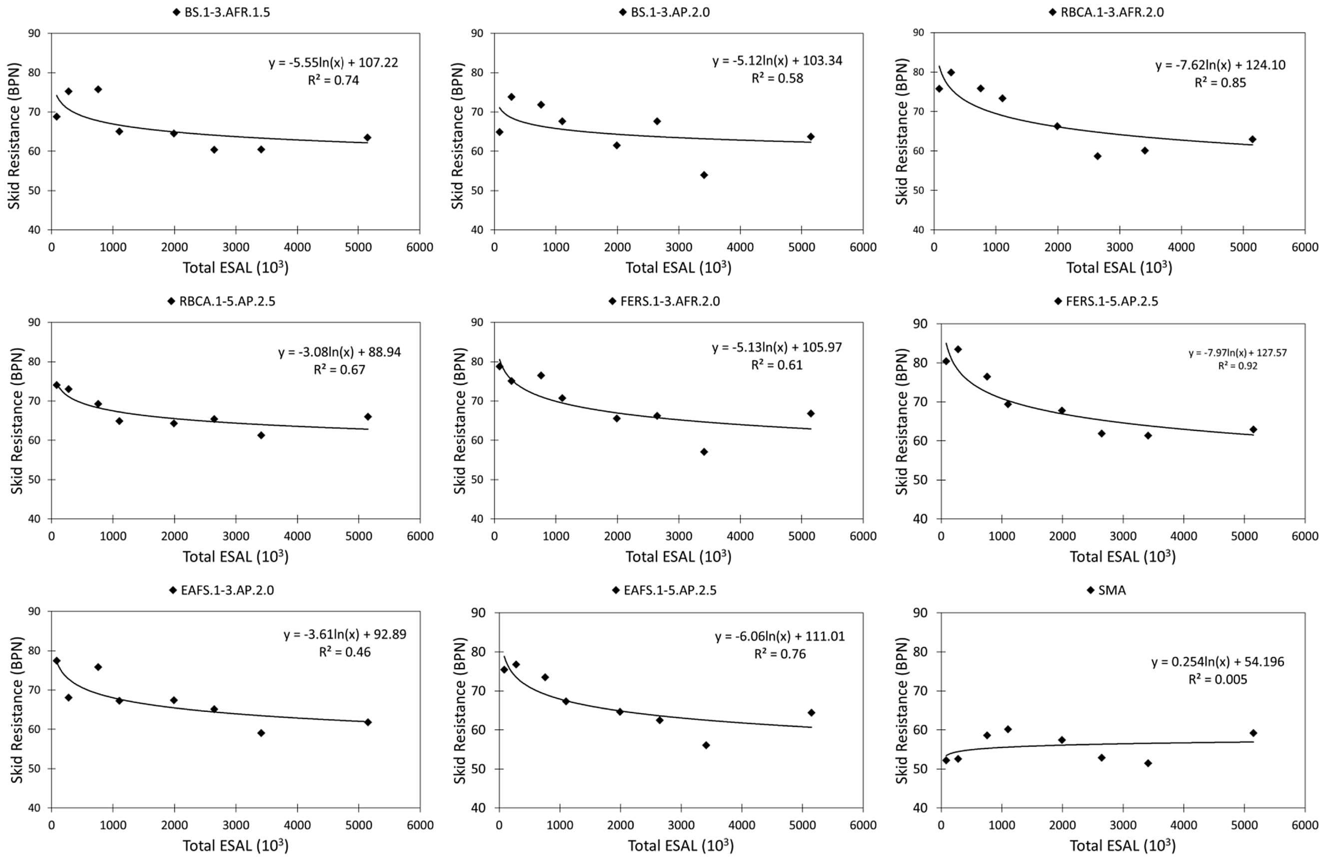

Fig. 4. Skid resistance results based on the BPT.

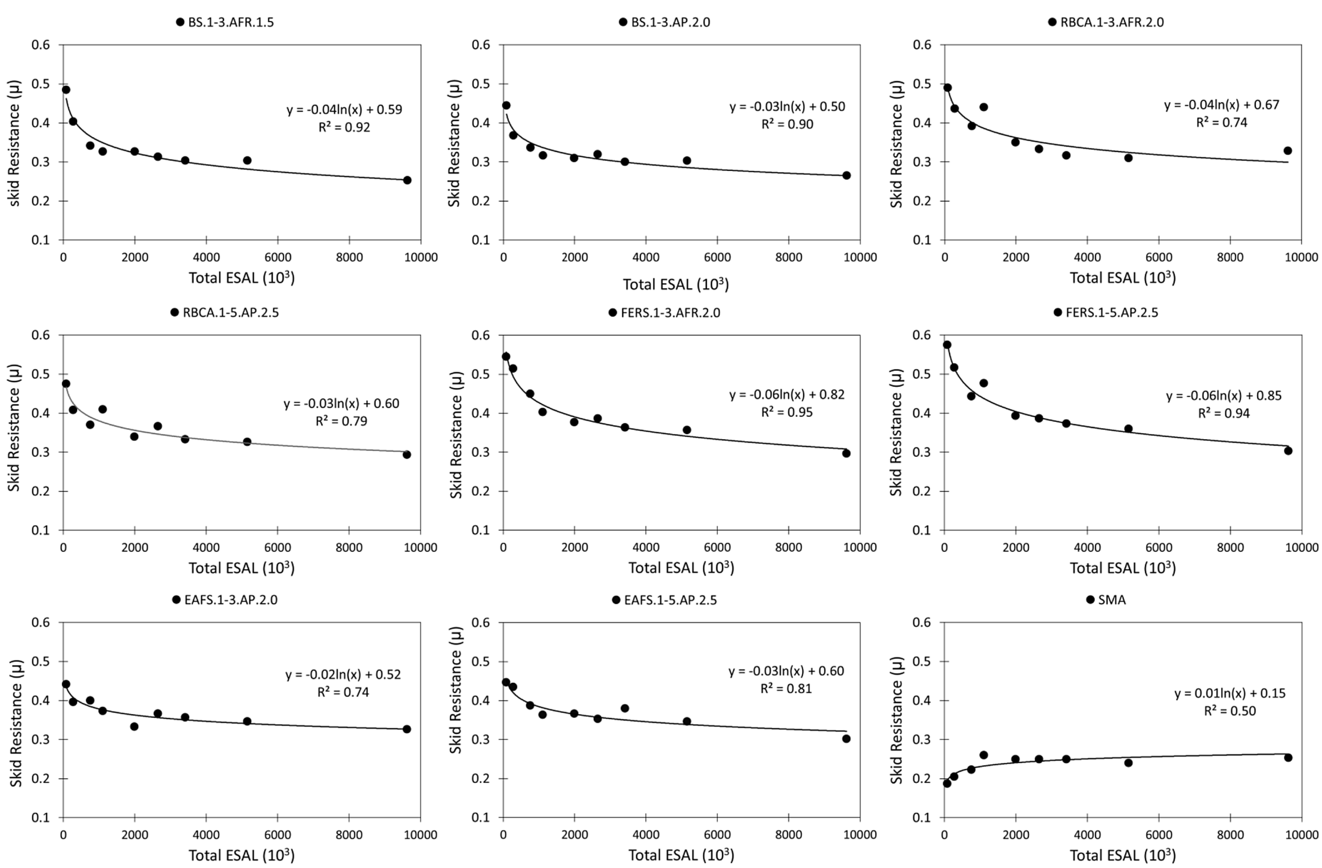

Fig. 5. Skid resistance results based on the DFT.

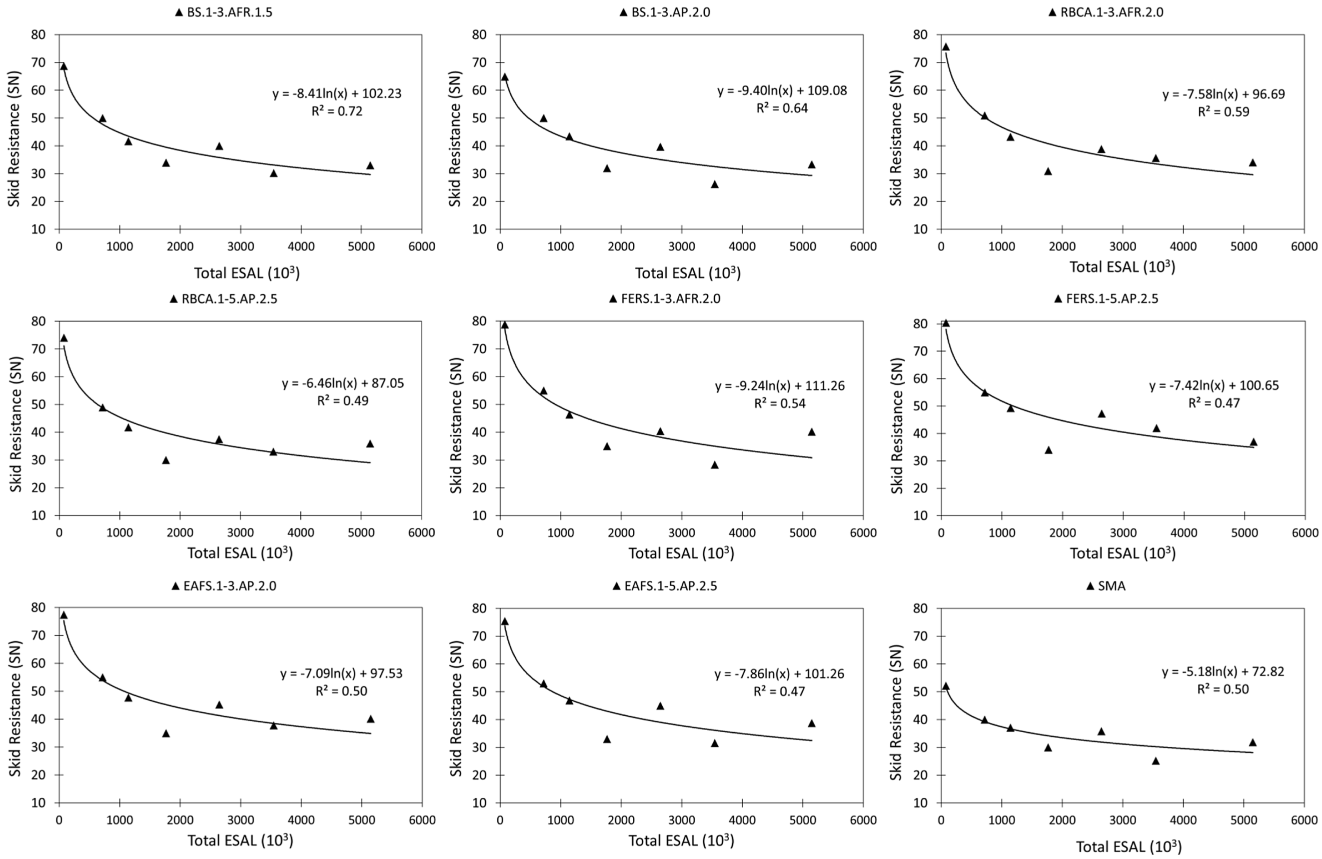

Fig. 6. Skid resistance results based on the LWSRT.

with low polishing resistance of the aggregate. This case can be seen for the BPT, for which the range of BPN is between 50 and 60, that of the DFT is between 0.2 and 0.3 (μ), and finally, that of the LWSRT is between 50 and 20 SN. However, this result can be improved significantly with gritting application, which is the main objective of the current study.

Surface Texture/Profile Depth Results

Surface texture depth was measured with two different methods. The first is the SPT and the second is the VMLP. The results of field measurements with these two methods are presented in Fig. 7.

As can be seen from Fig. 7, mean texture depth ranges between 1.6 and 0.9 mm. On the other hand, mean profile depth was determined to be between 1.0 and 0.5 mm. The threshold value for SPT is 0.8 mm, and 0.4 mm for VMLP (Fernandes and Neves 2014; Papageorgiou and Mouratidis 2014). It is clear from the figures that the texture/profile depth of the test sections did not reach the mentioned threshold values. Moreover, it is difficult to identify a regular decrease or increase in texture depth, so the lifecycle analysis was done only for skid resistance.

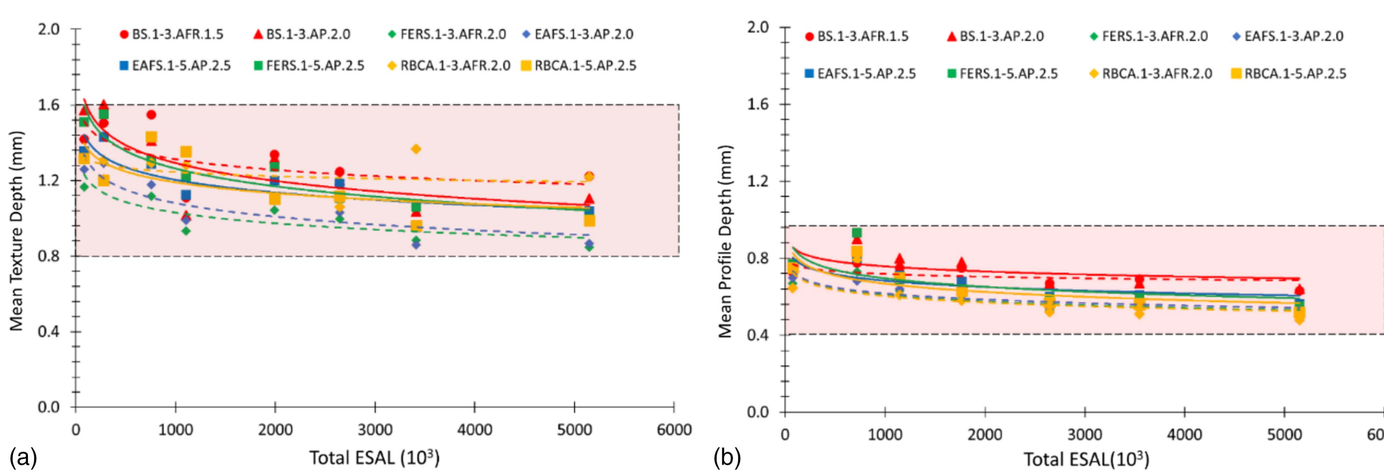

Fig. 7. Mean texture/profile depth measurement results: (a) SPT; and (b) VMLP.

Table 8. Expected lifespan of gritted sections regarding total ESAL (10^6)

Order	Test sections	BPN_{55}	$DFT_{0.30}$	SN_{30}
1[a]	BS.1-3.AFR.1.5	12.2	1.4	5.4
2	BS.1-3.AP.2.0	12.6	0.8	4.5
3	RBCA.1-3.AFR.2.0	8.8	10.4	6.6
4	RBCA.1-5.AP.2.5	61.0	22.0	6.8
5	FERS.1-3.AFR.2.0	20.7	5.8	6.6
6	FERS.1-5.AP.2.5	9.0	9.6	13.7
7	EAFS.1-3.AP.2.0	36.2	59.9	13.7
8	EAFS.1-5.AP.2.5	10.4	22.0	8.7

[a]Gritting application required according to HTS of Turkey.

Lifespan Analysis

The limit value for the BPT suggested by the transportation agency referencing the related standard is 55 BPN (BPN_{55}) (Msallam et al. 2017). Values below BPN_{55} are considered high risk for a road section. The risk of traffic accidents due to loss of skid resistance is found to be low at friction coefficient between 0.30 and 0.42, with the DFT method. However, the risk of accident due to the adequate skid resistance significantly increases as the friction coefficient drops below 0.30 (Bellopede et al. 2016). The limit value of the skid resistance measured with the LWSRT has been suggested to be 30 SN (SN_{30}) by Runkle and Mahone (1977), Fwa (2017), and the government of the United Kingdom (Hall et al. 2001) for risk level. The logarithmic functions used to estimate the lifespan of gritted test sections were determined based on cumulative traffic, which was simplified with the ESAL approach and presented in Table 8.

As seen from Table 8, different test methods obtained different lifespans. The difference is high in some test sections but low in others. For example, lifespan ESAL found with the BPN test results range between 8.8 (10^6) for RBCA.1-3.AFR.2.0 and 61.0 (10^6) for RBCA.1-5.AP.2.5 (10^6), but the ESALs for the DFT measurement results are between 0.8 (10^6) for BS.1-3.AP.2.0 and 59.9 (10^6) for EAFS.1-3.AP.2.0. Finally, the ESALs referring to lifespan for gritted sections are between 4.5(10^6) for BS.1-3.AP.2.0 and 13.7 (10^6) for FERS.1-5.AP.2.5 and EAFS.1-3.AP.2.0 as evaluated for the LWSRT. Overall, the lifespan analysis showed that the section constructed with the proposed gritting application has the lowest skid resistance performance and lifespan. However, almost all other alternatives showed better skid resistance performance and longer lifespan compared with the proposed one. It is clear that the gritting applications made with slags were found to be the best in terms of skid resistance and longer lifespan.

Summary and Conclusion

Due to the difficulty in obtaining high polishing resistance aggregate, especially in some parts of Turkey, the GDH has proposed gritting application within the HTS in 2013. The proposed application requires use of 1–3 mm magmatic-origin aggregate with a PSV higher than 50. Gritting aggregate should be spread over the paved surface after the first rolling in the amount of $1.5/2.0\ \mathrm{kg/m^2}$. The specification dictates using one type of aggregate, gradation, and spreading rate, which may not always be the best option. This study aimed to improve the proposed gritting method by investigating skid resistance performance of a newly constructed SMA gritted with numerous aggregate-based grit parameters. The effect of grit parameters applied on the SMA surface was analyzed under real traffic conditions in terms of skid resistance and surface texture. In this regard, during its construction, the wearing course of the O-51 highway was gritted with different construction parameters and eight test sections were created. The skid resistance performances and the changes in surface texture of these test sections were evaluated under actual traffic and environmental conditions for more than 4 years. Consequently, the following conclusions can be drawn from this study:

1. Slags were identified as inert material, so they will not harm the environment. Additionally, they provide all the material specification requirements of HTS specified for coarse aggregates.
2. The alternative gritting applications showed better skid resistance performance than the proposed one. Among the alternatives, slag-based ones were the best considering skid resistance performance.
3. Gritting applications with 1–5 mm grain size exhibited better skid resistance performance when spread directly after the paver.
4. The aggregate spreading rate is the least effective parameter among the others, but aggregates with higher unit weight, such as slags, would best be applied on the surface at the highest rate.
5. Using slags in gritting applications is a novel approach and provides an environmentally friendly and economical solution to their disposal problem. Additionally, their high resistance to polishing will reduce the risk of skidding-type traffic accidents and thereby save lives.
6. Different test methods tend to provide different lifespan durations for the same sections. These variations are linked to the differences in the measurement principles of the test methods used.
7. The DFT was found to be the most effective method among all those used in the study. The DFT offers the opporutnity to observe the same point on the pavement surface and its operating conditions are independent of the operator.

Overall, when grit materials covered the pavement surface, a significant decrease in the rate of oxidation occurs due to environmental conditions. This increases pavement life and skid resistance performance of the pavement at early life, and reduces pavement cracking, while improving surface texture. It can be highlighted that the existing gritting application can be improved with various grit parameters including aggregate type, grain size, and amount of the application.

Data Availability Statement

No data, models, or code were generated or used during the study.

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