

Enhancement of High-temperature Rheological Performance of WMA Mastics Modified by Spray Dryer Absorber (SDA) Powders

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Abstract:

For many years, coal combustion by-products (CCPs) have been broadly used as a replacement for portland cement in the production of different types of concrete; in embankments and soil stabilization; however, use of these materials in the pavement industry has been very limited, and few research studies have been conducted in this area.

Spray dryer absorber (SDA) materials are a type of CCPs that are derived from flue-gas desulfurization of coal-fired power plants. The current study explores the effect of the incorporation of SDA materials on the high-temperature rheological performance of warm mix asphalt (WMA) mastics. To do this, SDA material and dolomite powder (as a reference filler) were first investigated in terms of different physical and chemical properties, including particle size distribution, specific gravity, Rigden voids, morphological properties, X-Ray diffraction (XRD), and X-Ray fluorescence (XRF). The fillers were then incorporated in PG 58-28 asphalt binder with 5, 15, and 25% replacement of the asphalt binder by volume, making a total of six asphalt mastics.

The high-temperature performance of SDA-based mastics was evaluated using a dynamic shear rheometer (DSR) machine and compared with that of dolomite-based mastics. The rheological properties were assessed by performing temperature sweep tests for complex modulus (G^*), phase angle (δ), multiple stress creep (J_{nr}) at different loading levels, and aging resistance tests.

The experimental results indicate that SDA-based mastics have higher resistance to permanent deformation and higher rutting resistance and show better performance in terms of aging compared to the reference dolomite-based mastics with similar filler volume concentrations.

Based on the results, it can be concluded that the incorporation of SDA powders in asphalt binders can pave the way to achieving a sustainable, long-lasting, cost-effective, flexible pavement.

Introduction

Spray dryer absorber (SDA) material, also known as spray dryer ash, is a byproduct of coal combustion and flue gas scrubbing processes that has self-cementing properties similar to those of class C fly ash (Atadero et al., 2011). Flue-gas desulfurization (FGD) systems have been used to limit the release of sulfur dioxide (SO_2) from coal-fired power plants since the late 1960s. The solids produced by FGD systems represent the second-largest coal combustion product (CCP) stream by volume. The solids produced by FGD systems represent the second-largest coal combustion product (CCP) stream by volume (K. J. Ladwig & Blythe, 2017).

The SDA solid is a mixture of calcium-sulfite hemihydrate, gypsum, excess slaked lime, and calcium carbonate. In systems where fly ash is not pre-collected, the solids collected in the particulate control device after the SDA unit contain 72% fly ash, 15% calcium sulfite, 9% gypsum, 1% unreacted lime, and 3% water (EPRI, 2007). These percentages vary with the sulfur and ash concentrations in the coal-fired and with the percentage of SO_2 removal achieved. The solids generally produce a high pH when wetted due to the excess slaked lime and the alkaline nature of the fly ash when the process is applied to western coal (EPRI, 2015).

Spray dryer ash is produced in far smaller quantities than fly ash in the US. In 2020, the production of 2.8 million tons of dry products was reported. The dry product collected from the SDA is mostly landfilled, with less than 5% used, primarily in agriculture and waste stabilization applications. On the other hand, 65% of produced fly ash in the U.S. was utilized, according to the American coal ash association, ACCA (ACCA, 2021). Furthermore, the Electric Power Research Institute estimates much higher annual production rates for SDA material than ACCA: between 3.3 and 3.8 million tons, projected to grow to 14 million tons by 2025 as more plants are required to reduce airborne sulfur emissions (EPRI, 2007). Thus, the need for more beneficial applications of this material is critical.

There has been a lot of attention paid to the use of fly ash in the asphalt industry (Sobolev et al., 2014), (Wozuk et al., 2019) (Ramme et al., 2016.) ; however, limited studies have been conducted on using SDA as a filler in flexible pavement (Bautista et al., 2015) (Bautista et al., 2015) . Fillers are described as particles less than 0.075 mm in size. Despite their small size, fillers play a pivotal role in the mechanical performance of asphalt mixes; they contribute to the stiffening of the asphalt binder as suspended particles in the binder but provide a denser packing by increasing the contact points between the coarse and fine aggregates within the mix (Cloutier et al., 2021). The general role of the pavement structure is to transfer the applied vehicle loads with desirable performance and sufficient tolerance (Norouzi et al., 2022).

In the current study, the incorporation of SDA powder into warm-mix asphalt binder is explored and compared to the performance of asphalt binder containing reference dolomite filler. First, the chemical, physical and morphological properties of both filler materials are characterized, then the fillers were added to asphalt binders with 5%, 15%, and 25% by volume replacement of bitumen to form asphalt mastics, making a total of 6 mastics. The rheological response of asphalt mastics is evaluated in terms of complex modulus and phase angle at different temperatures, rutting resistance, and aging resistance.

Materials and Specimen Fabrication

PG58-28 bitumen was used for this study. The binder was warm-mix modified by the addition of 0.5% (by mass of binder) of Evotherm admixture per manufacturer guidelines. Evotherm would help to reduce the mixing temperature and compaction effort of asphalt concrete as required for warm mix asphalt (WMA) (Farahi et al., 2021). Dolomite (DL) dust, which is a conventional filler for the pavement industry in the state of Wisconsin, was used as a reference filler, and spray dryer absorber (SDA) ash, provided by Weston, was used as a reactive powder. The fillers were added to asphalt binders at 5%, 15%, and 25% replacement by volume of the binder to make the asphalt mastics. Approved Wisconsin DOT job mix formula (JMF) suggests that dolomite dust be used as 1% by weight of total aggregates for asphalt mixtures. This amount is tailored to make the particle size distribution of aggregates in the asphalt mixture matrix look similar to the 0.45 power curve, so the maximum density line where the particles fit together in the densest possible arrangement can be achieved. In the current study, filler incorporation is assumed as a part of the binder phase rather than as an aggregate component. Totally six mastics were made, and the rheological performance of SDA-based mastics was compared to those of reference DL-based mastics.

Results and Discussions

Physical Properties of Fillers

The particle size distribution of powders, including D_{10} (the diameter with a percent passing 10%), D_{50} (a diameter with a percent passing 50%), and D_{90} (a diameter with a percent passing 90%), are reported in Table 1. This Table also reports the investigated fillers' specific gravity and Rigden voids.

Table 1: Physical properties of fillers

Filler properties	DL	SDA
D_{10} (μm)	4.52	1.01
D_{50} (μm)	38.10	6.06
D_{90} (μm)	141	192
Rigden voids (%)	26.80	41.71
Specific gravity (g/cm^3)	2.85	2.63

As noted in Table 1, SDA ash is fine-graded with higher Rigden voids; hence it has a larger specific surface and packing degree, making the SDA-based mastics prone to have a higher stiffness compared to DL-based mastics.

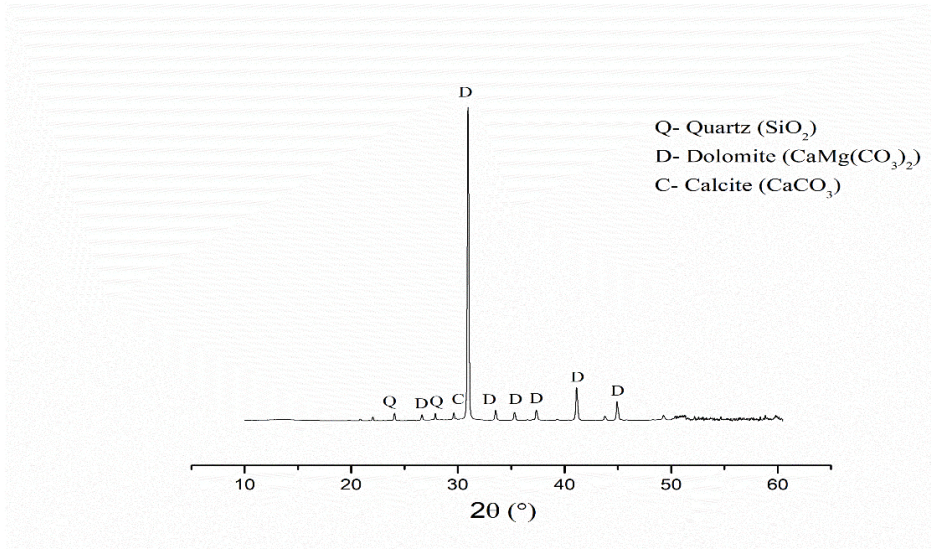
Chemical Properties of Fillers

The XRF results of the investigated fillers are reported in Table 2. It can be noted that in DL, CaO is the main chemical oxide composition, followed by SiO_2 , while in SDA, CaO and SiO_2 are the main constituent oxides, followed by Al_2O_3 . Alkalinity of a given filler is mostly affected by CaO+ SiO_2 content. In this regard, DL dust is more alkali active compared to SDA powder.

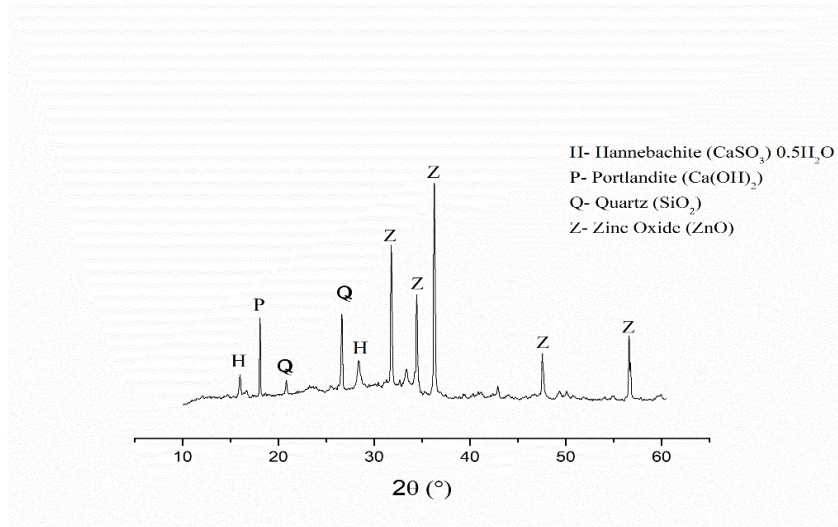
Table 2: Chemical composition of fillers (% by weight)

Compound		CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	SO ₃	MgO	Loss on Ignition
Filler	DL	57.82	12.77	3.16	2.05	2.71	2.61	1.82
	SDA	28.15	27.22	14.99	4.91	14.05	4	1.13

The XRD patterns of the mineral phases present in DL and SDA fillers are shown in Figures 1 and 2, respectively. In mineral composition of DL dust, dolomite is the dominant phase, while the dominant phase in SDA powder is Zinc Oxide, accompanied by quartz.



(a)



(b)

Figure 1: XRD pattern of a) DL dust and b) SDA powder

Morphological Characteristics

Scanning electron microscope (SEM) imaging of DL and SDA fillers is indicated in Figure 2. It can be observed that DL dust consists of angular shape particles, while SDA powder is mostly made of individual spherical particles.

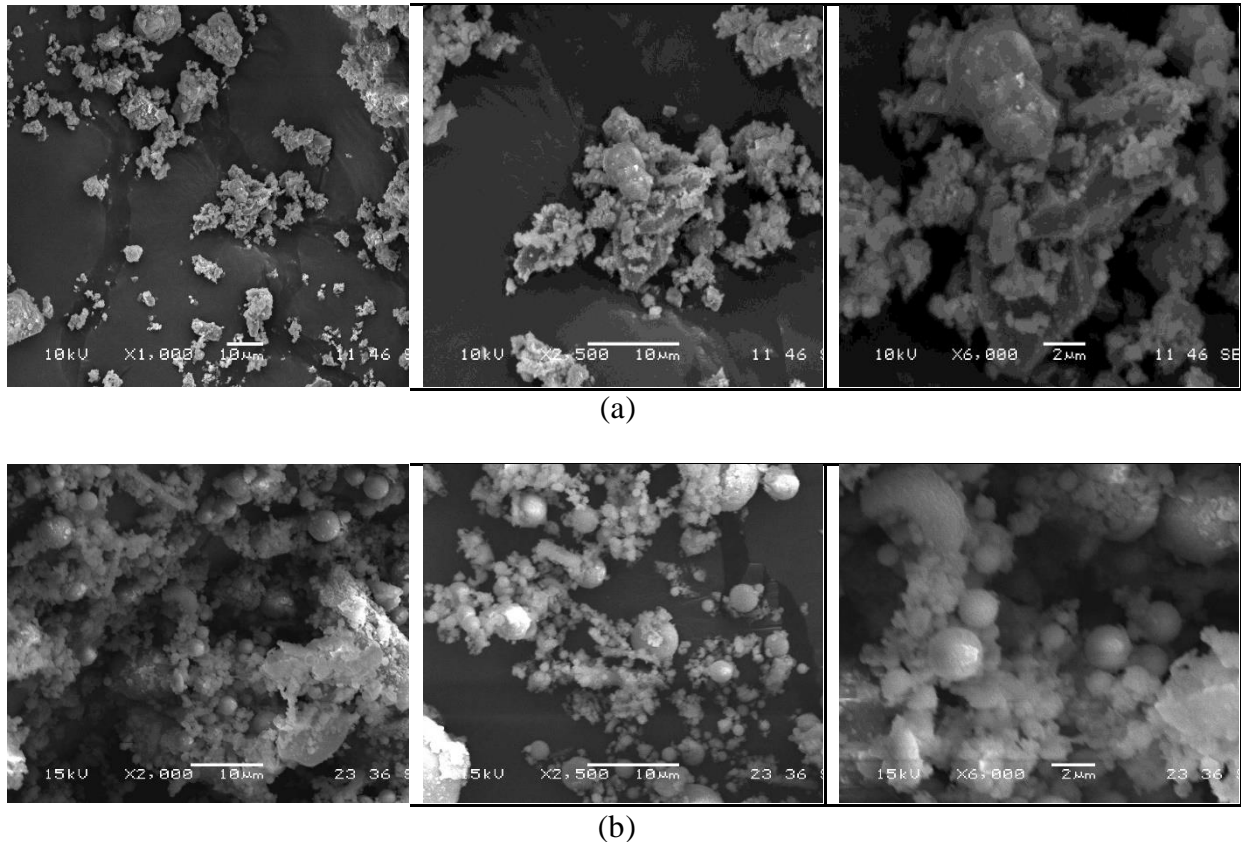


Figure 2: SEM images of a) dolomite and b) SDA particles at zoom levels of 1000X, 2500X, and 6000X (left to right)

Rheological Performance

Complex Modulus (G^) and Phase Angle (δ)*

The complex shear modulus (G^*) can be defined as the ratio of maximum shear stress to corresponding shear strain for a given mastic. The larger value of G^* indicates that the material can better resist permanent deformations. Phase angle (δ) is the angle between the recoverable and non-recoverable deformations. For purely elastic materials, the phase angle is zero, while for In Newtonian liquids, the phase angle is 90 degrees. Viscoelastic materials, like asphalt mastics, exhibit phase angles between 0 and 90 degrees. The temperature-sweep test was performed on unaged mastics to better understand the rheological response of the mastics in a wide variety of temperatures, ranging from 40°C to 88°C. The results of the abovementioned test are demonstrated

in Figure 3. It can be observed that reducing temperature and increasing the filler dosage will lead to an increased G^* for all investigated mastics. Further, it is demonstrated that increased temperature will make the mastic exhibit a more viscous response. Compared to DL-based mastics, SDA-based mastics showed superior performance in terms of G^* value since their complex modulus is higher than that of DL-based mastics in a similar temperature and filler content. On the other hand, no pattern can be found to relate the type of incorporated filler to the phase angle of the mastics. However, it can be observed that as the temperature increased, the effect of filler content on the phase angle became less significant. Overall, it is noted that the type and dosage of fillers had a negligible effect on the phase angle values.

None-recoverable Compliance (J_{nr})

The multiple stress & recovery (MSCR) testing was performed at the high PG temperature (58°C) to evaluate non-recoverable compliance (J_{nr}) of the short-term aged mastics. J_{nr} is a parameter that evaluates the accumulated deformation of a mastic that prevents the return to its original shape. Lower J_{nr} denotes higher rutting resistance. The MSCR test was performed at 0.1Pa and 3.2Pa loading levels, and the test results are demonstrated in Figure 4. As can be observed in Figure 5, by increasing the filler content, J_{nr} would reduce. Further, SDA-based mastics had lower J_{nr} values at both loading levels when 15% and 25% of bitumen were replaced by fillers, comparing the DL-based mastics. This means that these mastics showed a better performance in terms of the resistance of the material against rutting deformation.

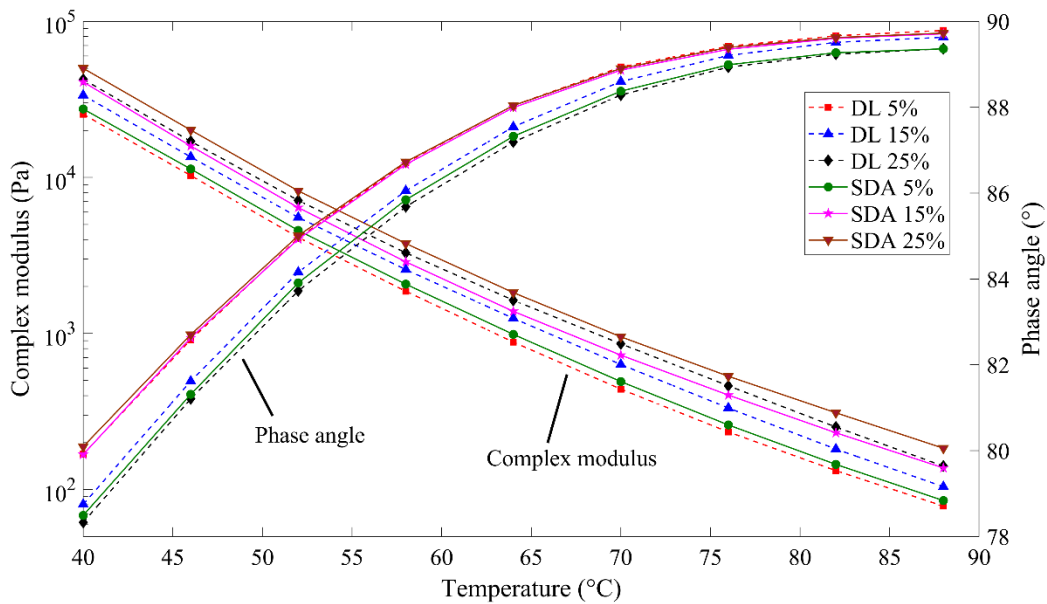


Figure 3: Complex modulus and phase angle changes of mastics with temperature

Aging Index

The aging index is defined as the susceptibility of a given material to aging. Here, the aging index of investigated mastics was calculated based on unaged and short-term aged complex modulus measured at 58°C using Eq. (1). This parameter was adopted in another research (Das & Singh, 2017). A higher aging index indicates smaller resistance against aging and vice versa.

$$\text{Aging index} = \frac{G_{\text{short-term aged}}^*}{G_{\text{unaged}}^*} \quad (1)$$

The results for the aging index of the mastics are demonstrated in Figure 5. As can be observed in the figure, SDA-based mastics had a smaller aging index at all filler volume concentrations compared to DL-based mastics. Hence, it can be concluded that the incorporation of SDA powder into asphalt binder can improve the resistance of mastics against aging.

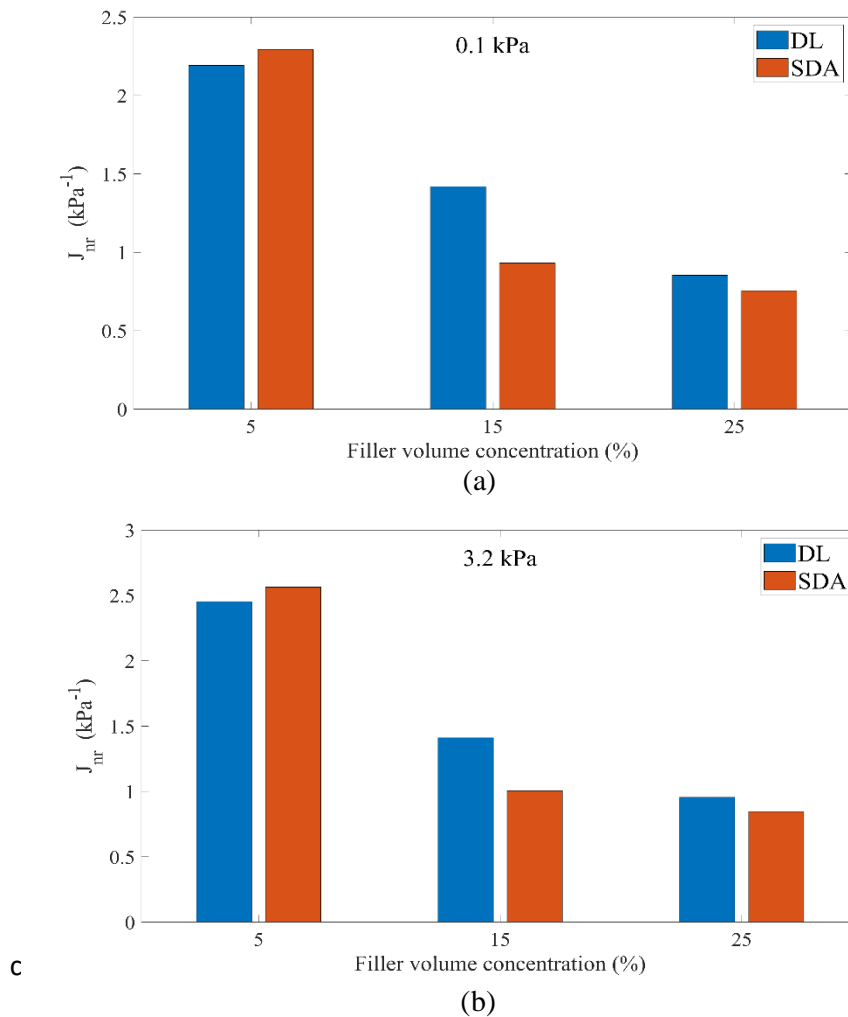


Figure 4: J_{nr} values of investigated mastics at a) 0.1 kPa and b) 3.2 kPa loading level

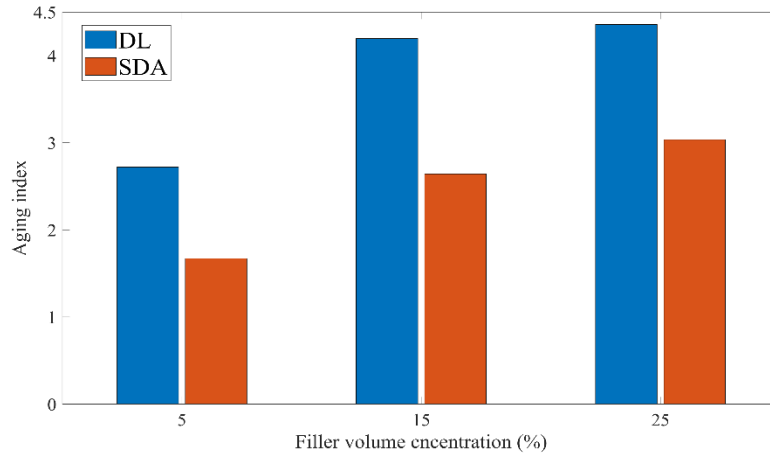


Figure 5: Aging index of investigated mastics

Conclusions:

In the current study, the effect of the incorporation of spray dryer absorber (SDA) ash on the high-temperature rheological performance of war-mix asphalt (WMA) mastics was explored. To do this, the physical, chemical, and morphological properties of SDA and dolomite (DL) dust, as the reference filler, were investigated, and then they were added to WMA binder at filler volume concentrations of 5, 15, and 25%, and their rheological response was compared. Based on the results, the following conclusions are drawn:

- 1- Physical characteristics of the investigated fillers, including Rigden voids and particle size, had a significant effect on the rheological performance of the mastics; however, the effect of chemical and morphological properties on the high-temperature performance of the given mastics could not be determined.
- 2- Incorporation of SDA into asphalt binder resulted in a higher complex modulus in a wide range of temperatures than DL-based mastics, with similar filler content. However, it did not affect the phase angle significantly.
- 3- SDA-based mastics had higher rutting resistance than their corresponding DL-based ones in terms of J_{nr} value in the case of increased filler content. This means that asphalt containing SDA powder can have higher resistance against distress at high temperatures.
- 4- SDA-based mastics had larger resistance against aging than the reference DL-based mastic with the same filler content; hence the asphalt materials containing SDA are prone to have extended service life.

SDA is a cheap byproduct material, so the use of SDA in asphalt not only solves landfill issues but also provides a cost-effective, long-lasting, and environmentally friendly flexible pavement.

Acknowledgments

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