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Research Article

Potential Use of Volcanic Ash as Filler Material in Hot Mix Asphalt

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Road construction often focuses on the use of conventional materials. Due to the depletion of these conventional materials, this cannot be always true. To overcome such problems, several alternative construction materials have been proposed as sustainable solutions. Thus, this study has investigated the potential use of volcanic ash (VA) as an alternative filler material in hot mix asphalt. The investigation has used laboratory scale and purposive sampling method for sample collection. The plastic index and specific gravity of volcano ash are 0.92% and 2.44, respectively. The chemical composition analysis indicated that VA is a class-N pozzolana material. Maximum stability of 11.38 kN was obtained at full replacement of volcano ash. The tensile strength ratio of the mix at full replacement of CSD and volcanic ash is 82% and 98%, respectively. From the fatigue resistance analysis, the probable failure of pavement constructed with the mixture containing VA could be improved from 16600 to 14400. Due to its rough surface, VA has better bonding ability with bitumen compared to CSD. The mix prepared from VA has less deformation tendency than that prepared from CSD.

1. Introduction

To attain high quality and extended service life, the demands of hot mix asphalt (HMA) for high thermal stability, low-thermal crack resistance, and water stability have been steadily growing with the fast growth of the economy, science, and technology [1]. Numerous additives, including both organic and inert, were utilized in bitumen mixes to address these issues [2–4]. Organic additives have several drawbacks, including high cost, sophisticated operation, and challenging manufacturing procedures, all of which limited their application [5]. Inert additives were viewed as mineral fillers, which had an impact on their distribution in bitumen and the reactivity at the filler-asphalt interface. In reality, inert additives might increase the bondage between bitumen and aggregates, which would enhance the quality of the bitumen binder [6, 7]. Furthermore, the modified bitumen containing inert components possessed properties like simple manufacturing method, cheap cost, and superior quality, all of which are in line with China's specifications [8].

Fly ash and limestone dust were commonly employed in roadway construction as typical inorganic materials. Despite limestone being the most often used material in road construction, studies have indicated that it is only available as mineral filler in bitumen [9, 10]. Franesqui et al. [11] discovered that asphalt rubber compositions comprising high-porosity marginal volcano pebbles had stronger resistance to moisture susceptibility. Due to the complicated terrain and high porosity of volcanic ash, Liu et al. [12] discovered that a solid packing-SBS-binder system generated inside mastic might further improve the mechanical characteristics of styrene-butadiene-styrene (SBS) improved mixes. Liu et al. [13] investigated four types of mixes with nano-scale VA mineral fillers, demonstrating that the form of the sustainable cyclical strain graph is free from loading magnitude and particle structure.

The authors in [14, 15] studied the road performance of VA asphalt glue and found that natural VA could greatly increase the superior thermal resistance of asphalt mixtures and the low-thermal resistance of bituminous glue.

Furthermore, Hu et al. and Qureshi et al. [16, 17] demonstrated that fine volcanic ash may be used as a filler additive for asphalt mix, considerably improving HMA quality and lowering construction costs. Kong et al. [18] investigated the effects of several hybrid aggregate types on the design of asphalt enhanced base mixtures. Hybrid aggregate alters the volumetric characteristics of hybrid bitumen mixes, according to the studies. The physical qualities of bitumen coated base can be improved by using alkaline coarse particles or coarse aggregates with greater surface roughness.

VA is the outcome of a volcano outburst which majorly contains minerals Si, Al, Mg, and Ca. Moreover, many heavy metals such as Cu, Mn, V, Zn, Zr, and Fe [19–21] were discovered as constituents of VA which are dangerous to life [22]. VA particles have diverse forms and microporous architectures, which are generated in high-thermal and high-pressure circumstances at the moment of volcanic eruptions [23–25].

As per Yong and Dupre's formula, which stated that the wetting impact of bitumen may be improved by greater roughness of the filler's area [26], these features allow more sufficient wetting of bitumen binder onto volcanic ash than traditional mineral dust packing. Also, because of the harmful chemical composition of volcanic ash, the physiochemical adsorptions of bitumen by volcanic ash are stronger than those of packing material. The presence of interparticle and interparticle pores on the surface of VA indicates that VA has a high potential bitumen adsorption area. Because of this, volcanic ash reacts strongly with bitumen binder compared to standard packing dust [14]. Volcanic ash's micro or nanoporous nature makes it a good candidate for collaborating with polymeric additives. Other studies looked into using granular volcanic ash instead of fine aggregate in mix design to improve the creep and fatigue resistance of HMA [27].

The major goal of this research was to examine VA as a filler ingredient in asphalt concrete production. The materials were evaluated for Marshall properties, dynamic creep, fatigue resistance, and moisture resistance using neat bitumen, VA filler, and CSD conventional filler. The impact of VA particle characteristics on the interaction between VA and neat bitumen binder was further investigated by examining morphology, porosity, and physical properties of fine fillers using SEM analysis and N_2 adsorption/desorption experiments. It should be emphasized that the possible use of VA as a filler material in the mix was chosen as the primary research topic, allowing the impact of VA fillers on the mechanical characteristics of mixes to be adequately demonstrated.

2. Materials and Experimental Setup

Figure 1 shows the framework of activities undertaken in this study. The materials like bitumen with penetration grade of 60/70, CSD, and VA were used in this investigation. In order to clearly show its effect on the volumetric properties and performance of asphalt mixtures, the volcanic ash was added to the mix from 0–100 in 10% differences.

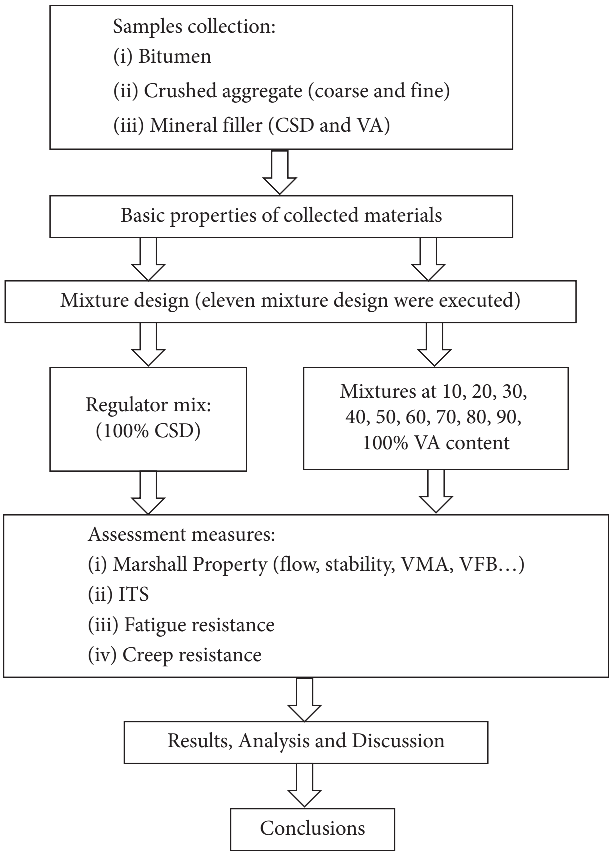


Figure 1: Framework of activities.

2.1. Properties of Materials

2.1.1. Bitumen. Since it is widely used in Ethiopia, bitumen with a penetration grade of 60/70 has been used as binding material. Quality control tests were done on the bitumen, and results are presented in Table 1.

2.1.2. Aggregate. Because it is widely available in Ethiopia and widely used in asphalt concrete production, crushed basalt rock was used as coarse and fine aggregates in this study. The nominal maximum aggregate size (NMAS) used to prepare the mixture is 19.0 mm. The basic properties of aggregate used in this research are presented in Table 2.

2.1.3. Mineral Fillers. In this study, CSD and volcanic ash were used as filler materials. CSD (as control) and volcanic ash (as additive) were taken from the Ethiopian Roads Authority (ERA) of Jimma district and Wanchi found at Woliso, Oromia, respectively. These two mineral fillings were ground with a grinder to a particle size of less than 75 μm. Using silicate analysis, the major and trace chemicals of volcanic ash were identified and are presented in Table 3. Further analysis with X-ray fractionation (XRF) revealed that Si is mostly found in the form of SiO_2, whereas Al, Fe, Ca, Mg, K, Na, and Mn are found in the form of Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, Na_2O, and MnO, respectively. As shown in the table, the VA contains more types of dense

Table 1: Bitumen quality test results.

Property test	Test method	Result	Specification
Penetration (25°C, 0.1 mm)	AASHTO T-49	65.1	60–70
Ductility (25°C, cm)	AASHTO T-51	108	≥50
Softening point (°C)	AASHTO T-53	47.2	46–56
Specific gravity (25°C)	ASTM D-70	1.018	1.01–1.06
Flash point (°C)	ASTM D-92	320	≥232

Table 2: Basic properties of aggregate.

Property test	Test method	Result	Specification
Water absorption (%)	AASHTO T-85	1.4	<2
Sand equivalent (%)	AASHTO T-176-186	75.6	>40
Flakiness index (%)	BS-812, part 105	23	<35
Aggregate crushing value (%)	BS-812, part 110	14.9	<25
Los Angeles abrasion (%)	AASHTO T-96	11.58	<35
Aggregate impact value	BS-812, part 112	8.06	<25

Table 3: Chemical compositions of volcanic ash.

Composition	Content (%)
SiO_2	55.2
Al_2O_3	20.85
Fe_2O_3	5.48
CaO	1.9
MgO	0.42
Na_2O	5.46
K_2O	2.12
MnO	0.18
P_2O_5	0.1
TiO_2	0.18
H_2O	2.21
LOI	5.24

Table 4: Physical properties of mineral fillers.

Property test	Test method	Result		Specification
		CSD	VA	
600 μm	ASTM D242	100	100	100
300 μm		100	96	95–100
75 μm		100	83.3	70–100
Plastic index	BS 1377	NP	0.92	≤4
Gsa	ASTM D 854	2.68	2.44	—

metals and more oxides than the mineral powder, which increases their reaction and adhesion with asphalt binder. The results of grade, plastic index, and apparent specific gravity of crushed rock dust and volcanic ash are presented in Table 4. The resulting plasticity index of volcanic ash is 0.92% which is less than 4%, indicating that it is non-plastic. The combined mixture of silica (SiO_2), aluminum (Al_2O_3), and iron oxide (Fe_2O_3) greater than 70% shows that the material is class-N pozzolana. The result of loss on ignition is less than 10% which shows that the material is not sensitive to weather action. The moisture content of volcano ash is 2.21% which is less than 3%. Hence, it indicates that this material does not significantly affect the aggregate intergranular bondage of HMA.

2.1.4. Characterization of Mineral Fillers. Small quantity of fine CSD and VA was used to characterize their grain characteristics by using LPSA. Sludge porosity was characterized by the BET N-isotherm method using automated specific surface area and micropore analysis. The morphology of VA was detected using SEM. Mineral filler specimen for scanning electron microscope imaging was prepared by dispersing a thin layer of the powder on a piece of conductive tape and sputtering coated with gold. The scanning electron microscope images of the filler were acquired with a field emission scanning electron microscope in secondary electron mode.

2.2. Experimental Setup

2.2.1. Mixture Design. Although Marshall mixture design in favor of advanced pavement is challenging in some developing countries, Marshall Standard ASTM D1559 was applied in this study as equipment such as Superpave Gyratory Compactor is not available in Ethiopia. In this study, volcanic ash was added to the crushed stone dust at a difference of 10%. Seventy-five blows on each side of the 101.6 mm specimens were applied following the Marshall requirement for heavy traffic. The mixing and compaction temperatures were 1602°C and 1452°C, respectively. Five BC percentages were used in each mix design. Three samples were prepared at each BC percentage. The prepared samples were subjected to bulk specific gravity and stability-flow tests. The density void analysis was then performed, and the results were shown graphically. At each volcanic ash addition, the OBC of 4% air voids was derived and used to estimate the Marshall stability, density, bitumen-filled void (VFB), and corresponding mineral aggregate void (VMA).

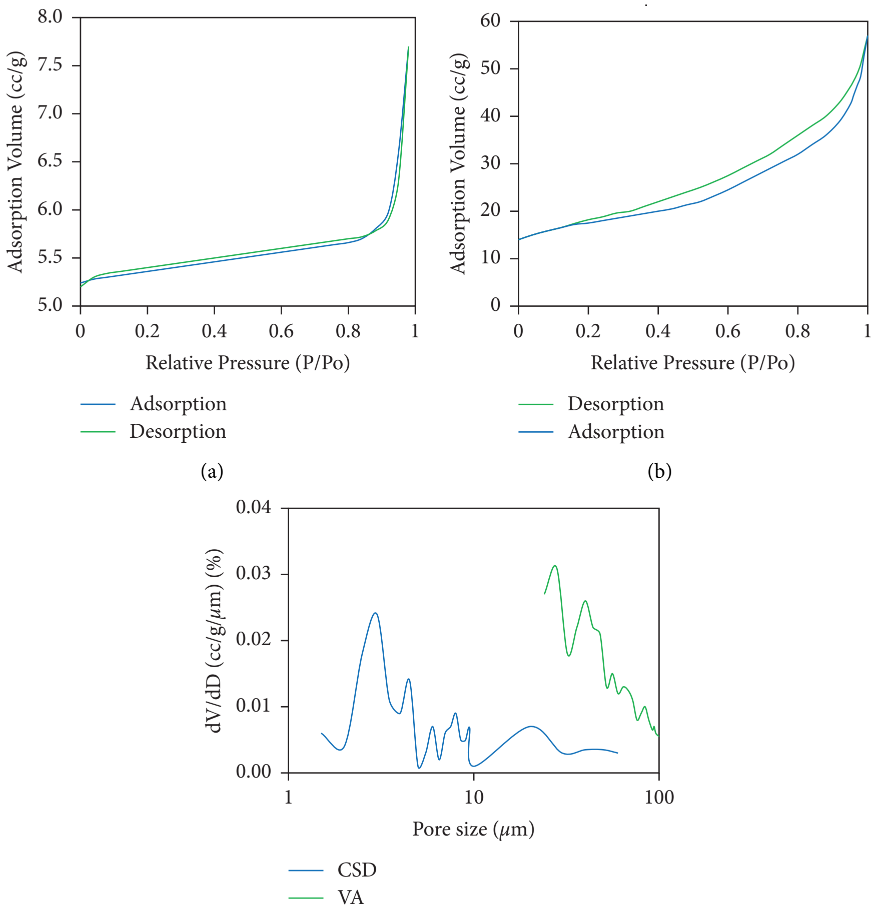
All mixtures were tested at their optimum bitumen content using various tests to evaluate field performances such as Marshall stability, density, VFB, and VMA. The traditional examination processes are not adequate to give serious examination of paving mixture. Thus, the implementation of supplementary advanced paving mix experiments is essential to examine useful mix properties. This contains moisture susceptibility, fatigue resistance, and creep resistance. Therefore, the results from this experiment were useful as further testing criteria. In every stage of VA addition, sufficient specimens were made to assess the characteristics described earlier.

3. Results and Discussion

3.1. Physical Properties of Mineral Fillers. The physical properties of the mineral fillers are described in Table 5. The identified porosity using N adsorption isotherms is shown in Figure 2. As confirmed in Table 5, the bulk specific surface area and mass specific surface area of CSD are much smaller than those of VA, suggesting that VA has a much larger

Table 5: Physical properties of CSD and VA.

Filler	CSD	VA
Mean grain size (μm)	1.976	1.864
Size (μm)/ratio of the governing grains	2.169/96.36%	1.886/94.54%
Bulk specific surface area (m^2/cc)	3.64	113.92
Mass specific surface area (m^2/g)	1.49	39.62
Apparent density (g/cc)	2.68	2.44



(a)

(b)

(c)

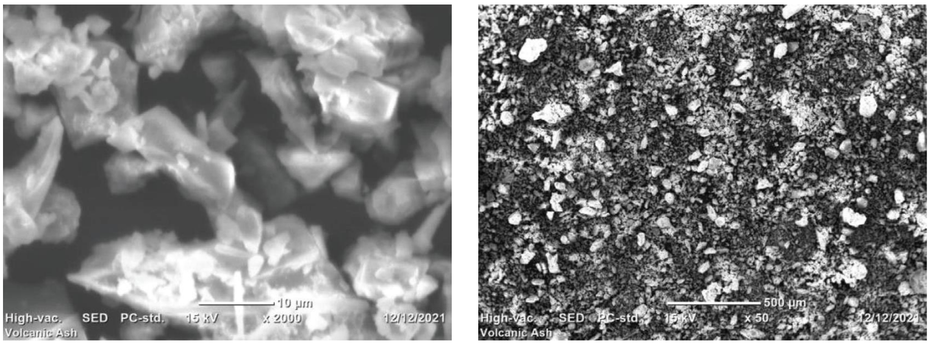
Figure 2: N adsorption isotherm of (a) CSD and (b) VA and (c) their pore size.

surface area that can be wetted by bitumen than CSD. Because the ingredients were grinded by a grinder, the mineral fillers have uniform size. The governing particle diameters of CSD and VA are 2.169 μm and 1.886 μm, respectively.

The N classic adsorption isotherm is used to identify whether the material is four-type isotherms or two-type isotherms [28]. Based on the adsorption isotherms analysis, this study identified VA to type four isotherms and CSD to type two isotherms as shown in Figures 2(a) and 2(b), respectively. The type two isotherms are most repeatedly obtained as adsorption happened on non-porous particles or particles with a size greater than the diameter of micro-pores. The Type Four isotherms mostly occur on porous adsorbents with pores between 1.5×10^{-3} and 0.1 μm.

3.2. Scanning Electron Microscopy of Volcanic Ash. As shown in Figure 3, the VA particle has an irregular blocky shape as determined by scanning electron microscopy. The bowl shape of VA particles was created by grinding the porous section of coarser particles as shown in Figure 3(b). Small spherical nodules cover the top of VA with some finely dispersed collections embedded. The nodules on the VA surface may be due to the relatively large number of micropores, which helps them to interact with the bitumen molecular chains. Furthermore, VA nodules were smaller and more dispersed than those of CSD, indicating that VA has a higher specific area as shown in Table 5.

3.3. Impact of Volcanic Ash on Unit Weight. The impact of VA mineral filler content on specimen unit weight is illustrated in Figure 4. Since the density of hot mix asphalt



(a) (b)

Figure 3: The SEM image particle distribution of volcanic ash.

sample containing volcanic ash mineral is smaller than that made with sole CSD, it appears that the specific gravity of volcanic ash is smaller as compared to that of CSD.

3.4. Impact of Volcanic Ash on VMA and VFB. Because it shows the space that is required to accommodate the net volume of bitumen and the volume of AVs needed in the mixture, evaluating VMA is imperative. The smallest VMA is required to attain a sufficient bitumen film around aggregate particles, which results in resilient flexible pavement. If the density of aggregate gradation is high, then the VMA is found to be too low which causes the bitumen to have a thin film and makes the mix nonresilient. Thus, saving in bitumen content by reducing VMA is counterproductive and harmful to pavement quality (Asphalt Institute, 2001). In this research, the impact of VA addition on VMA was assessed and values are presented in Figure 5. The results showed that as VA content increased, VMA also increased. This impact might be ascribed to the existence of vesicles in VA particles. These vesicles are exposed to increase the VMA in the mix. The relation between the VA and VFB of the mix is shown in Figure 6. As shown in the graph, when the amount of VA increases, the VFB decreases. The reason for this decrease in VMA may also be attributed to the fact that the amount of VA increased at a greater rate than that of CSD.

3.5. Impact of Volcanic Ash on Stability and Flow. As predicted, the addition of the volcanic ash filler has affected the performance of the HMA. The relation between Marshall stability and volcanic ash content is shown in Figure 7. The general trend shows that as the amount of VA increases, so does the stability. This may happen due to the pore property of VA which indicates that it has lower strength as compared to that of CSD. Although the stability increased with increasing the amount of VA in the mix, the stability of the mix which contains 100% VA filler is within the limits of Marshall criteria for heavy traffic. As shown in Figure 8, the HMA density increased with increasing amount of volcanic ash, mainly due to the increase in bitumen content with increasing ash content. Although flow increased with increasing amount of VA, flow at every increasing level of VA was also within the range of the heavy traffic Marshall criteria of 2–3.5 mm.

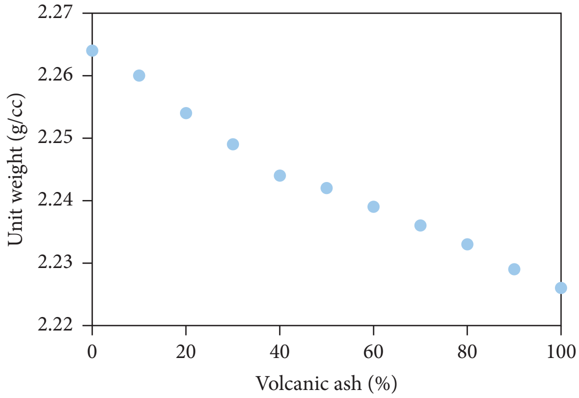


Figure 4: Impact of VA on the density of HMA.

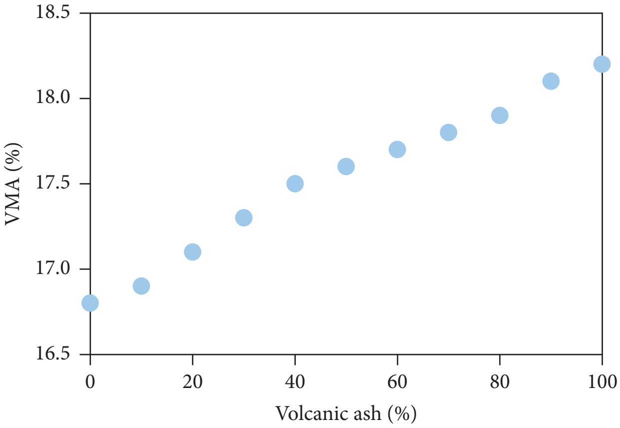


Figure 5: Impact of VA content on Marshall VMA of HMA.

3.6. Moisture Susceptibility of HMA. The moisture susceptibility of unconditioned and conditioned specimens is shown in Figure 9. This study proved that the tensile strength (TS) property of the conditioned mixture is lower than that of the unconditioned one. The presence of water may cause a reduction in interaction between bitumen and

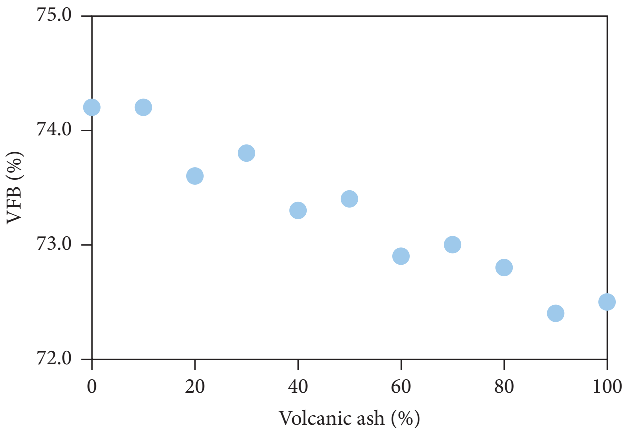


FIGURE 6: Impact of VA content on Marshall VFB of HMA.

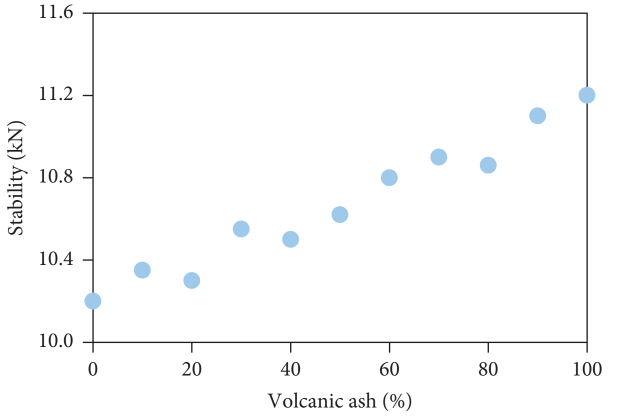


FIGURE 7: Impact of VA content on Marshall stability of HMA.

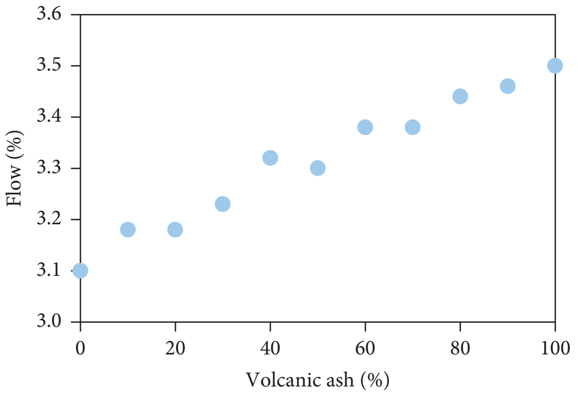


FIGURE 8: Impact of VA content on Marshall flow of HMA.

aggregate, which lessens the resistance of asphalt mixtures with vehicle loads. Additionally, the reduction in tensile strength of VA containing mixtures due to moisture presence in it is not significantly higher than that of stone dust filler mixtures. The results indicate that the mixture prepared with volcanic ash gives higher tensile strength ratio compared to conventional crushed stone. VA strengthens the bondage between asphalt and aggregate, preventing water from repelling asphalt from the surface of aggregate. Figure 10 shows the tensile strength

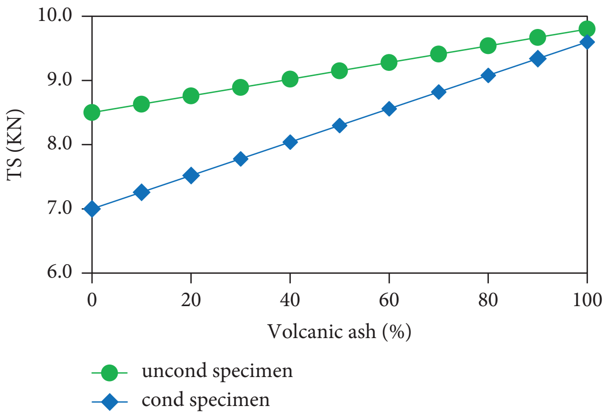


FIGURE 9: Impact of VA content on tensile strength of HMA.

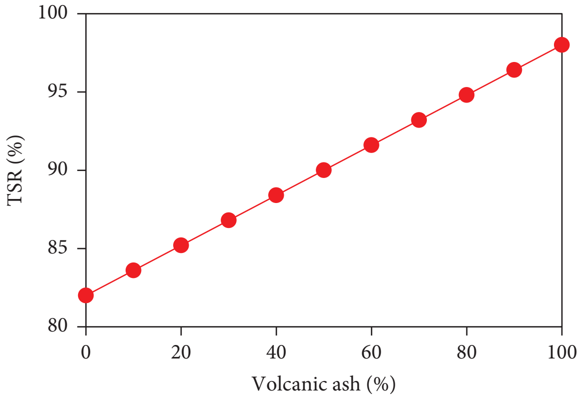


FIGURE 10: Impact of VA content on tensile strength ratio of HMA.

ratio (TSR) experiments at different amounts of VA. It also indicated that VA significantly enhanced the yield of conditioned and unconditioned specimens, resulting in a stronger resistance to moisture susceptibility. The result of TSR for mixtures containing VA is relatively greater than 80%. Consequently, adding VA into the mix as a filler resulted in an excellent TSR, which means that VA avoids the possibility of pavement failure due to moisture.

3.7. Fatigue Resistance. Fatigue is the crucial failure challenge in the flexible pavements which are familiar with recurrent traffic loads. The fatigue resistance of an asphalt concrete mix is its ability to withstand this recurrent loading without fracture. Fatigue in asphalt concrete pavements starts at the bottom of the layer and propagates to the surface of the pavement. As shown in Figure 11, the addition of VA continuously enhanced the fatigue life up to its full replacement as compared with that of CSD. The reason behind the improvement in fatigue life with a mix containing VA may be due to the existence of vesicles in VA particles.

3.8. Creep Deformation. A correlation between load repetitions and strain of mixture containing VA is shown in Figure 12. The figure reveals that as the amount of VA in the mix increases, the strength decreases. VA positively

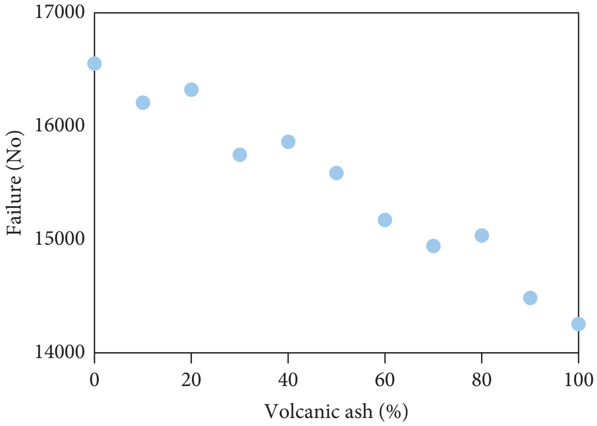


Figure 11: Impact of volcanic ash on the failure of the mix under repetition of load.

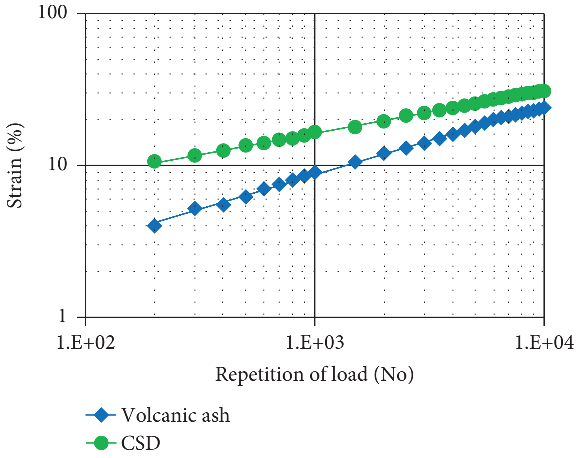


Figure 12: Impact of volcanic ash content on creep deformation.

influences the creep properties of HMA, and this might happen due to roughness of VA particles which enhances the bonding capacity of the mix [29]. In addition, the creep stiffness result showed that creep stiffness increased with the increase in the amount of VA. Creep stiffness is the ratio between the stress and the axial strain which indicates the resistance of the HMA to creep.

4. Conclusions

The study showed that the results of plasticity index and specific gravity of volcanic ash were 0.92% and 2.44, respectively. According to the chemical analysis, the combined result of silica, aluminum, and iron oxide is 81.51%. The study illustrated that the observed losses due to ignition and moisture presence in volcanic ash are 5.24% and 2.21%, respectively. Depending on the result of chemical test, the volcanic ash is classified as class-N pozzolana. The addition of volcanic ash to the HMA as filler has positively improved the performance of volumetric properties of mixture. The use of volcanic ash alone as a filler in the production of hot asphalt mixtures increased the maximum stability of the mixture to 11.38 kN. The use of only volcanic ash as filler allows the asphalt mixture to have a higher moisture resistance when it is produced from the optimal bitumen content. Compared to CSD, it also showed that asphalt concrete mixes containing basalt aggregates and volcanic ash fillers would have better creep/slippage, fatigue, and stripping resistance.

Data Availability

The data used to support the findings of the study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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