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ORIGINAL RESEARCH ARTICLE

Enhancing HMA properties with polypropylene-based face mask integration: A qualitative comparison of wet mixing and dry mixing techniques

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ABSTRACT

In the wake of the emergence and widespread dissemination of the COVID-19 coronavirus, scientifically identified as SARSCoV-2, the utilization of medical equipment, specifically tri-layered polypropylene (PP)-based face masks, has experienced significant proliferation. The extensive adoption of single-use polymer-based face masks has raised notable environmental concerns, given their extended degradation period of up to 480 years and their substantial threat to ecosystems, particularly aquatic organisms, due to pervasive littering practices. Hence, this study is dedicated to assessing the influence of incorporating polypropylene (PP)-based face masks into asphalt formulations. The incorporation of PP-based face masks into asphalt was executed at three distinct weight percentages, employing both dry and wet mixing techniques. Comprehensive performance evaluations were carried out utilizing the Marshall test, indirect tensile fatigue test, and Hamburg wheel tracking rutting experiments and the best value for each. Remarkably, augmenting the PP content yielded improvements in both fatigue life and rutting resistance of the asphalt mixtures, and the maximum improvement was recorded at 0.3% replacement. Notably, asphalt specimens prepared using dry mixing techniques outperformed their wet mixing counterparts, demonstrating superior cohesion attributes.

Keywords: polypropylene; mask; fiber; bitumen; asphalt; fatigue life; rutting resistance; polymer; plastic; stability; flow; bridging

1. Introduction

The coronavirus (SARSCoV-2) appeared on the globe in early 2020, and by 11 March 2021, a public health emergency of international concern was declared by WHO (World Health Organization) due to the rapid spread of the pandemic[1]. Due to the contagious nature of the virus, personal protection equipment, i.e., gloves, medical masks, and goggles, was declared mandatory by all international organizations as well as governments. According to an estimate by WHO, 76 million safety gloves, 89 million medical masks, and 1.6 million goggles were consumed globally in 2020 to prevent the pandemic from spreading[2]. Also, a tremendous compound annual growth of 20% is projected in the production of facial masks between 2020 and 2025[3]. Only China

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exported a staggering amount of 200 billion masks to other countries in the year 2020[3–5]. Even after the control of COVID-19, face masks remained relevant due to increased air pollution and deteriorating air quality[6].

No doubt, face masks are the need of the time, but no one can undermine the fact that they pose a great threat to the environment due to their disposable nature[7]. Even if disposed of properly into dustbins and landfills, they still find their way to public places due to their reduced weight. Donning abandoned masks and littering face masks in parking lots, neighborhood streets, sidewalks, and parks may result in social, environmental, and animal difficulties[7–9]. Especially, wind and increased rainfall can lead them to seas and oceans, which can harm the ecosystem and marine life[10]. Only in 2020, 1.56 billion facemasks entered the ocean[11]. Reports even say that in the future, the number of facemasks in the ocean will be even greater than the number of jellyfish[12].

Currently, the main notable techniques for recycling single-use masks include high-temperature incineration, landfill collection, and recycling through mechanical and chemical processes[13]. Combustion requires a high amount of energy for the breakdown of the polymers. Added to this, combustion results in the emission of toxic gases, which lead to environmental pollution. On the other hand, in a landfill, microorganisms are employed for the breakdown of polymers, which is not only time taking but also results in further soil pollution. In the mechanical recycling method, waste masks are pulverized using a mechanical recycling procedure to yield low-grade goods for further use. Melt processing is used to blend waste masks with polymers or inorganic fillers, which is also energy intensive. Chemical recycling involves converting large molecular polymers into tiny molecular compounds using chemical processes such as pyrolysis or gasification, then reconstituting them to generate new materials. This is also a very complicated procedure. As a result, the utilization of conventional recycling and treatment technologies for discarded face masks does not yield ecological or economic advantages. Composition-wise, the three-ply facial masks are made of polypropylene (blown and spun-bonded) fabric[14]. A single-use face mask may take up to 450 years to degrade[10]. Therefore, we need to look for more advanced and sustainable methods for the disposal of used facemasks so that environmental disruptions can be controlled. Since the construction industry is highly impacted by this issue, it can also be a potential solution to this matter.

Generally, plastic has been incorporated into nearly every aspect of construction, i.e., in masonry infills[14,15], as artificial aggregates in concrete[4,16], as filler[5,17], and as an additive in asphalt as well[18,19]. The use of virgin polymers to enhance the properties of bitumen is a very old method but is still not adopted because virgin polymers are very expensive. Therefore, the use of polymer wastes in HMA (hot mix asphalt) is considered a good option in terms of waste disposal as well as the enhancement of the properties of asphalt[20]. A considerable amount of research has been done on the topic of the addition of polypropylene in HMA. Othman et al.[21] used PP as a coating for asphalt and studied its impact on the long-term aging of HMA. It was observed that the coating of PP not only reduced the aging effect on HMA but also increased the tensile strength and fracture energy under both aged and unaged conditions. Hamedi et al.[22] employed PP as an antistripping additive in HMA and found that it enhanced the resistance of asphalt mixtures in both wet and dry conditions. Goli et al.[23] also studied the impact of PP (facemask) on the various physio-mechanical properties of hot mix asphalt and concluded that the addition of PP enhanced the indirect tensile strength as well as fatigue resistance of the hot mix asphalt. He concluded that the mechanical properties of the HMA were enhanced due to the increased cohesion between the material and the protective layer it formed around the material that prevented water absorption.

Unlike previous studies that only focused on the mix design of plastic-modified asphalt, this research dives into the uncharted research area by studying the impact of different mixing techniques that can be adopted for asphalt formation on the properties of polymer-modified asphalt as well.

Firstly, the new masks were obtained from a local supplier since the municipal authorities did not allow us to collect used face masks because of health concerns. A testing scheme was proposed to categorize control samples into four categories. The first category was HMA without any additions. Then, the face masks were processed into 1 cm-sized PP before being mixed with hot mix asphalt (HMA) at varying percentages of 0% (control sample), 0.1%, 0.2%, and 0.3%, using wet as well as dry mixing.

Finally, the rutting resistance and fatigue life were measured and compared for all four types of control samples. Such a comparative analysis provided valuable insights into the most effective and efficient approach for integrating plastic masks into asphalt, along with revelations about the impact of an increase in PP content on the mechanical properties, thereby aiding future engineering projects in making informed decisions.

2. Materials and methodology

For this study, base bitumen of 60/70 penetration grade was selected because of its widespread use in the local industry of Pakistan. As well as its adequate performance in the climate conditions of Pakistan. The bitumen was procured from the outlet of Total Parco Pakistan Ltd., situated in Islamabad. **Figure 1** illustrates the overall flow of the research project. **Table 1** presents the test matrix followed for preparing test samples for each performance evaluation. Binder standardization tests were performed on bitumen as per specifications, and their results are illustrated in **Table 2**. As previously stated, three-ply polypropylene-based surgical masks obtained from a local vendor were cut into PPs with a maximum length of 1 cm. Fine and coarse aggregates were taken from Taxila Querry in Pakistan for this study. Several aggregate quality control and standardization tests were performed to evaluate the index qualities of chosen aggregates and their conformance to the standard standards. The water absorption test, impact value test, specific gravity, Los Angeles abrasion, and aggregate shape test were among the tests performed, and the results of the tests are illustrated in **Table 3**. Additionally, the aggregates were graded to meet the Gradation-B standard set by the Pakistan National Highway Authority (NHA) for use in asphaltic wearing courses. The optimum bitumen content (OBC), or the required bitumen amount for each mixture, was determined using the Marshall mix design standard procedure. Subsequently, samples for performance testing of controlled and modified asphalt were prepared using both wet and dry mixing techniques, adhering to their respective standards.

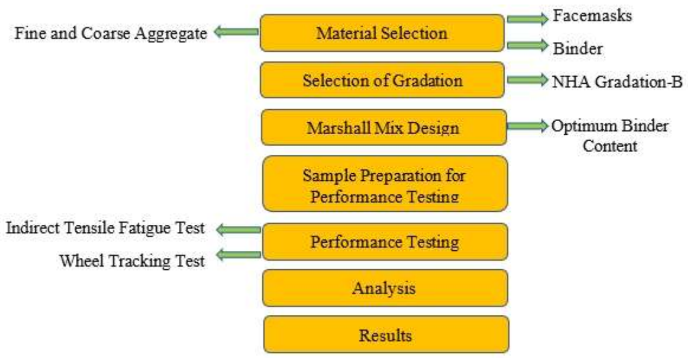

Figure 1. Research methodology flowchart.

Table 1. Test matrix for performance tests.

Sr. No.	Additive %	ITFT	Hamburg wheel tracking test
1	0	3 + 0 + 0	3 + 0 + 0
2	0.1	0 + 3 + 3	0 + 3 + 3
3	0.2	0 + 3 + 3	0 + 3 + 3
	Total	15	15

Table 2. Standardization tests of bitumen.

Test description	Specification	Result	Limits
Penetration test at 25 (°C)	AASHTO T 49-03	66	60–70
Flash point (°C)	ASTM D 92	235	280
Fire point (°C)	ASTM D 92	251	320
Specific gravity	ASTM D 70	1.03	35–45 °C
Softening point (°C)	AASHTO T 53	48.2	>100 cm
Ductility test (cm)	AASHTO T 51-00	>100	0.97–1.02

Table 3. Standardization tests of aggregate.

Test description	Specification reference		Result	Limits
Elongation index (EI)	ASTM D 4791		3.578%	≤15%
Flakiness index (FI)	ASTM D 4791		12.9%	≤15%
Aggregate absorption	Fine agg.	ASTM C 127	2.45%	≤3%
	Coarse agg.		0.73%	≤3%
Impact value	BS 812		17%	≤30%
Los Angles abrasion	AASHTO T96		22%	≤45%
Specific gravity	Fine agg.	ASTM C 128	2.61	–
	Coarse agg.	ASTM C 127	2.63	–

The study employed three distinct categories of asphalt mixes for testing purposes, as shown in **Table 4**. Firstly, the control group consisted of virgin asphalt with 0% mask PPs, providing a baseline. Secondly, PP-modified asphalt with wet mixing included 0%, 0.1%, and 0.2% mask PPs, demonstrating the impact of wet mixing. Lastly, PP-modified asphalt with dry mixing incorporated 0%, 0.1%, and 0.2% mask PPs, showcasing the effects of dry mixing. These categories allowed for a comprehensive evaluation of mask waste's influence on asphalt performance under varying conditions, as referred to in **Figure 2**.

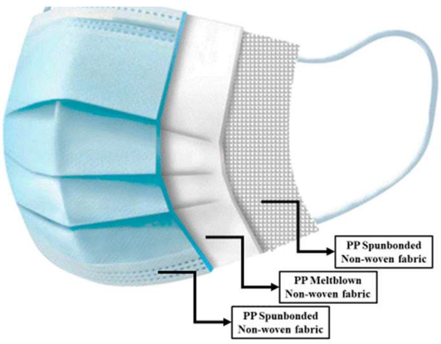

Figure 2. Structural composition of a standard face mask

Table 4. Types of mix designs studied.

S. No.	HMA mix types	Mixing technique	Composition
1	Virgin asphalt	–	0% mask PPs
2	PP-modified asphalt	Wet mixing	0%, 0.1%, and 0.2% replacement of bitumen by mask PPs
3	PP-modified asphalt	Dry mixing	0%, 0.1%, and 0.2% replacement of bitumen by mask PPs

2.1. Virgin HMA sample preparation

In accordance with the ASTM D 6927 specifications, 1200 g of HMA samples were made. Initially, the aggregate and virgin bitumen were heated in an oven up to 110 ℃, mixed to a temperature of 160 ℃, and then compacted into cylindrical samples by applying 75 blows on each side at 135 ℃. Similarly, 6 kg of samples were cast for the Hamburg wheel tracking test according to the specifications of ASTM 324. Controlled HMA samples were created to evaluate qualities later while keeping this in mind. The number of controlled samples prepared is shown in **Table 1**.

2.2. PP-modified HMA sample preparation by wet mixing technique

Wet mixing of asphalt is a technique in which additives are introduced in bitumen that has been heated to elevated temperatures, followed by mixing with hot aggregates. The plastic (PET, PP) or rubber (pyrolytic carbon black) modifiers are added in powdered or shredded form to the heated bitumen. The heated bitumen is blended simultaneously to ensure uniform mixing of additives. For this study, multiple HMA samples were prepared by heating aggregate and bitumen separately in an oven up to 110 ℃. The binder was heated to 160 ℃, where the shredded face mask samples were added to the heated bitumen. The bitumen was blended with shredded face mask samples to ensure uniform distribution of PP in bitumen. Then, the aggregates and PP-modified bitumen were mixed thoroughly at 160 ℃. Lastly, the samples were compressed in cylindrical form by means of giving 75 blows to each side at 135 ℃. ASTM D 6927 standard procedure was followed for the preparation of samples for the ITFT (indirect tensile fatigue test) test. Also, 6 kg samples were prepared as per ASTM 324 for the Hamburg wheel tracking test. A gyratory compactor was used for the preparation of samples for this test. A diamond cutter was used to cut samples into the dimensions specified by the standard testing procedure for the Hamburg wheel tracking test. **Table 1** displays PP-modified HMA samples made using the wet mixing method.

2.3. PP-modified HMA sample preparation by dry mixing technique

The dry mixing technique relies on introducing additives in powdered or shredded form to aggregates that have been heated in advance. The additives are blended mechanically with hot aggregates to ensure thorough and uniform mixing. Lastly, the heated bitumen is introduced into the mix. In order to prepare samples for assessing dry mixing technique, aggregates were first heated to 260 ℃. The face mask samples were shredded up to a nominal length of 1 cm. The shredded face masks were added to the heated aggregates, and they were blended to ensure uniform distribution of PP in the mixture. The mix was cooled down to 160 ℃ subsequently. The bitumen was separately heated in an oven to 110 ℃. Then the heated bitumen was added to the preheated aggregate mix at a temperature of 160 ℃. Once the bitumen was thoroughly mixed with aggregate and PP, the blend was given 75 blows to its each side to compress it in the form of cylinders. This process was performed at 135 ℃. Also, the 6 kg samples for the Hamburg wheel test were prepared by mixing heated aggregates coated with polymers and bitumen, followed by compaction using the Gyratory compactor. **Table 1** shows the samples created for each test using dry mixing technique.

2.4. Marshall mix design for OBC determination

The ASTM D 6927 Marshall mix design standard was utilized for the controlled HMA samples. The technique proposed by the National Asphalt Pavement Association was used to determine the optimum bitumen content (OBC). HMA samples with various bitumen contents of 3.5%, 4.0%, 4.5%, and 5.0% were made according to the procedure. A total of 1200 g of cylindrical HMA sample with a diameter of 4" and a height of 2.5" was prepared at a mixing temperature of 160 ℃ and compacted at 135 ℃ with 75 blows on each side of the sample. Finally, volumetric parameters of Marshall samples were computed and presented in **Figure**

3, including voids in mineral aggregate (VMA, %), voids filled with asphalt (VFA, %), air voids (AV, %) flow (mm), and stability (kN).

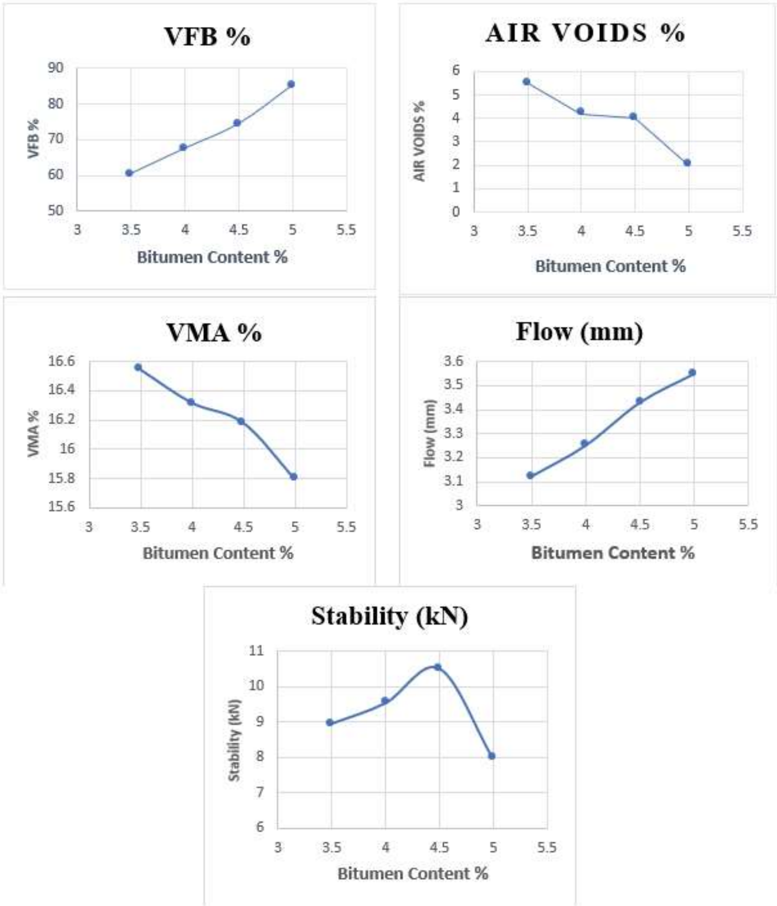

Figure 3. Marshall mix design volumetric properties.

Following the guidelines of the National Asphalt Pavement Association, OBC was interpolated against 4% AV, which turned out to be 4.1%. The remaining volumetric parameters were likewise measured against 4% AV. The volumetric properties of HMA samples at OBC are summarized in **Table 5**.

Table 5. Volumetric properties of HMA at OBC.

Sr. No.	Property	Value
1	Flow	2.896 mm
2	Stability	12.465
3	VMA	13.937
4	VFA	71.921

3. Results and discussion

3.1. Indirect tensile fatigue test (ITFT)

In accordance with standard EN 12697-24, ITFT was performed to assess fatigue life in terms of cyclic loading in a stress-controlled universal testing machine (UTM). The load was applied vertically, causing a horizontal tensile stress distribution along the vertical plane. According to EN 12697-24, the sample had measurements of 51 mm ± 1 mm in thickness and 100 ± 3 mm in diameter and the aggregates were below 25 mm diameter. Before testing, samples were kept in a temperature-controlled chamber for 4 h at 25 °C with a loading time of 0.1 s and a rest period of 0.4 s. **Figure 4** depicts the ITFT's device diagram and load assembly. The tests were conducted at a temperature of 25 °C. When the sample cracked, the test was over, and the machine shut off. **Figure 5(c)** depicts a broken sample after the loading cycles have been completed. Finally, the number of cycles leading to failure was recorded. The number of fatigue cycles was found to rise considerably as the PP % increased. At a PP (polypropylene) content of 0.3%, the asphalt mixture exhibited the highest fatigue life, with a recorded 19,000 loading cycles for dry mixing and 18,200 loading cycles for wet mixing. In contrast, the asphalt mixture without any PP content (0%) exhibited significantly lower fatigue life, with only 4150 loading cycles for wet mixing and 4350 for dry mixing. These findings indicate that the inclusion of PP fiber from masks resulted in a substantial threefold enhancement in pavement performance, as evidenced by the increased fatigue life. Increased PP content led to increased cohesiveness within the sample, and PPs functioned as a bridge between the asphalt content and reduced the chances of surface cracking. Also, the findings in this article are consistent with the experiments conducted by Goli et al.[23].

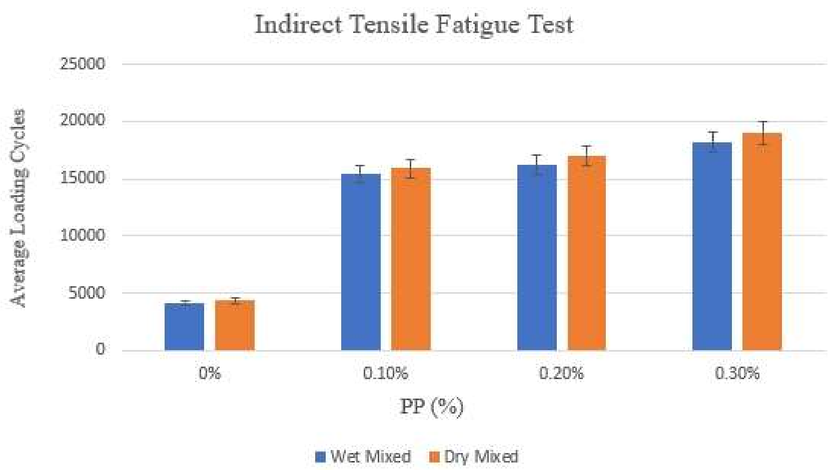

Figure 4. Indirect tensile strength test results.

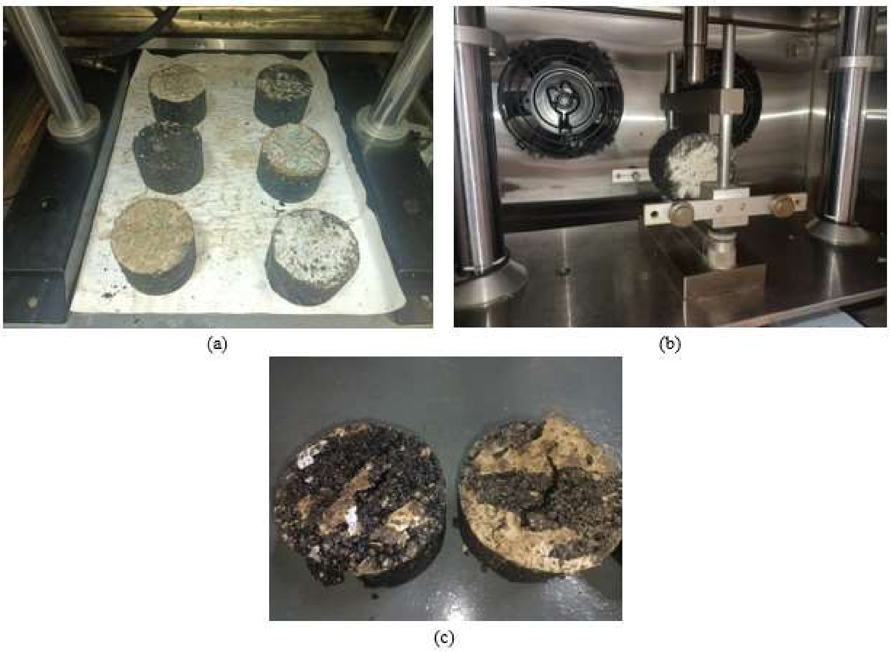

Figure 5. Indirect tensile fatigue test: **(a)** samples prepared for ITFT; **(b)** samples placed in ITFT apparatus; **(c)** cracked samples after the test was performed.

Furthermore, samples created using the wet mixing approach had greater fatigue resistance than those formed using the dry mixing technique. This is most likely due to the PP-improved dispersion in wet mixing technique as compared to dry mixing technique. Agha et al.[24] also concluded that wet-mixed samples have better endurance against fatigue than dry-mixed samples.

3.2. Hamburg wheel tracking test

The Hamburg wheel tracking test is used to gauge an asphalt surface's resistance to rutting. In other words, this test is used to estimate the amount of deformation caused by repetitive loads on asphalt. The authors considered that it was important to assess the rutting resistance of the PP-modified asphalt since rutting is a significant problem in the southern peripheries of Pakistan, where the pavements are subjected to heavy service loads and high temperatures. For this test, samples weighing 6 kg were prepared per ASTM T 324's requirements. Using a diamond cutter, the samples were divided into two equal pieces and then put into the assembly. About 10,000 passes of the samples were conducted under dry circumstances at 25 °C. Both samples' average rut depths were discovered to be minimal or accurate. **Figure 6** provides an illustration of the testing procedure for the Hamburg wheel tracking test for the samples under investigation.

Figure 6. Hamburg wheel test: **(a)** samples prepared for Hamburg wheel test; **(b)** samples placed in wheel tracking apparatus; **(c)** results recorded for samples; **(d)** deformed samples at the end of test.

The rutting depth reduces as the mask PP content increases in wet mixed as well as dry mixed samples. The rutting resistance of PP-modified samples was observed to be higher than that of virgin asphalt as shown in **Figure 7**. This accounts for the improved resistance to permanent deformation in terms of rutting caused by the addition of polymers. The best results recorded were 0.52 mm for wet mixing and 0.58 mm for dry mixing for samples having 0.3% mask PP. The rutting depth for wet and dry mixing at 0% PP content measured 8.1 mm and 7.9 mm, respectively. These results indicate that the inclusion of PP fiber from masks led to a significant enhancement in pavement performance in terms of rutting resistance as well. The decrease in rutting depth is due to the network formed by the polymers in the asphalt matrix. This network helps in efficient load transfer, which leads to the reduction of permanent deformations. Secondly, the polymers impart additional flexibility to the asphalt, which also enhances its rutting resistance.

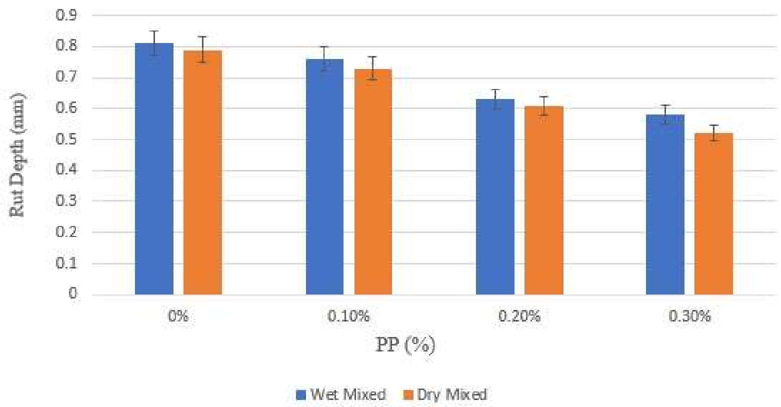

Figure 7. Hamburg wheel tracking test.

Also, the samples formed by the wet mixing technique had more rutting resistance than those formed with the dry mixing method. This is because of the enhanced workability and better dispersion of the ingredients in the asphalt mix. Also, the wet mixing technique allows lower mixing temperatures as compared to the dry mixing technique, which helps preserve the properties of the asphaltic concrete and prevent premature hardening.

4. Conclusion

In summary, this research has systematically assessed the performance of asphalt modified with single-use mask-derived polypropylene (PP) in terms of indirect tensile strength, rutting resistance, stability, and flow properties. In regions characterized by adverse weather conditions and high traffic volume, pavements are susceptible to rutting and damage over time. The primary objective of this article was twofold: to propose a safe and sustainable approach for the disposal of face masks and, concurrently, to enhance the durability and functionality of pavements. This study also investigated the influence of different mixing methods, specifically wet and dry mixing, on pavement performance. By doing so, it was aimed at understanding how the choice of mixing method impacts the overall effectiveness of the modified asphalt. It was observed that the PP-modified asphalt imparted desirable characteristics to asphalt, resulting in better performance than controlled virgin samples.

- The best results for ITFT, Hamburg wheel test, and Marshall flow and stability were recorded at 0.3% (wet mixing).

Incorporating 0.3% PP (polypropylene) content resulted in the highest fatigue life, with 19,000 loading cycles for dry mixing and 18,200 loading cycles for wet mixing, whereas at 0% PP content, significantly lower fatigue life was observed, with only 4150 loading cycles for wet mixing and 4350 for dry mixing.

- For rutting depth, at 0.3% PP content, the best results were achieved, with depths of 0.52 mm for wet mixing and 0.58 mm for dry mixing. In contrast, at 0% PP content, the rutting depths measured 8.1 mm and 7.9 mm for wet and dry mixing, respectively. These findings underscore the substantial improvement in pavement performance associated with the inclusion of 0.3% mask-derived PP content.
- The increase in polymer content enhanced the performance of asphalt because of the network generated by polymers in the asphalt matrix, which helped in efficient load transfer and reduced surface cracking. Also, polymers imparted additional flexibility to the asphalt, which reduced permanent deformations.
- The wet mixing technique outperformed dry mixing because of the better dispersion of ingredients.

Data availability

No data was used for the research described in the article.

Author contributions

Conceptualization, SAK, ZWS and MAK; methodology AH; validation, AH and MAM; formal analysis MAM; investigation, SAK, FH and ZWS; resources, MAK and MAM; writing—original draft preparation, SAK and ZWS; writing—review and editing, SAK, MAM and AH; visualization, SAK and ZWS; supervision, AH; project administration, AH and MAM. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

PP	Polypropylene
PSE	Personal safety equipment
WHO	World Health Organization
HMA	Hot mix asphalt
ITFT	Indirect tensile fatigue test
UTM	Universal testing machine

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