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Laboratory investigation on added-value application of the COVID-19 disposable mask in hot mix asphalt (HMA)

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HIGHLIGHTS

- Added-value application of the COVID-19 disposable mask in hot mix asphalt (HMA) was investigated.
- Waste cooking oil (WCO) was introduced to improve the ductility of mask fiber (MF) modified asphalt.
- The physical-rheological property tests were performed to screen out the best combination of MF + WCO.
- The composite modified asphalt of MF5% + WCO3% was identified as the best combination.
- The HMA performance evaluation tests were performed to validate the modification efficiency.

ABSTRACT

The outbreak of the COVID-19 pandemic has stimulated the demand for disposable masks to an unprecedented level, which also poses a significant risk to the natural environment from the improper treatment or disposal of waste masks. To lower such an environmental risk and maximize the added value of the waste masks, this paper proposed to recycle the waste mask fiber (MF) in combination with the waste cooking oil (WCO) for hot mix asphalt (HMA) application. A series of MF + WCO modified asphalt binders were first designed and fabricated. Their performance properties were then systematically measured. The physical-rheological test results showed that the incorporation of MF can significantly improve the high-temperature rutting resistance performance of asphalt binder. However, it may also lower the asphalt’s low-temperature anti-cracking performance. The addition of WCO was found to compensate for this low-temperature performance loss effectively, and the MF5% + WCO3% was identified as the best combination. The Fourier transform infrared (FTIR) spectroscopy test results revealed that the asphalt modified by the MF + WCO involved only a physical modification. The performance test results indicated that the high-temperature permanent deformation resistance and low-temperature anti-cracking of MF5% + WCO3% modified HMA was greatly enhanced, while its moisture stability was slightly reduced but still met the specification requirement. The environmental benefit assessments proved that recycling the waste masks for asphalt paving can provide an enormous added value to pavement engineering in terms of carbon emission reduction and land resource saving.
1. Introduction

Due to the COVID-19 pandemic, there has been a surge in demand for personal protective equipment, especially disposable masks (Janik et al., 2021). This is because wearing a disposable mask can efficiently prevent COVID-19 infection (Bae et al., 2021), which has been a mandatory countermeasure in many countries and regions (Ho et al., 2020). Driven by this huge demand, the global manufacturing of masks has increased to unprecedented levels. For example, the daily production of masks in China has increased to 14.8 million since February 2020 (J.J. Liu et al., 2021). Globally, up to 129 billion masks are produced each month (Sabarian et al., 2021). Another statistic shows that the supply of masks is growing at an annual growth rate of 20 % (Ilyas et al., 2020), and this trend may continue in the future.

Since masks are disposable personal protective equipment, if they are not recycled and reused in a sustainable way, the discarded masks will seriously pollute the natural environment and encroach on land resources (Yang et al., 2022). This is because masks are easily scattered by wind or rain, even when they have been collected in garbage cans or landfills, as illustrated in Fig. 1. Eventually, these discarded masks will be found in rivers or oceans (Wang et al., 2021). According to estimates, every year, nearly 0.15–0.29 million tons of waste masks go into oceans, posing a potential threat to the survival of marine life (Chowdhury et al., 2021). At present, the disposal methods for discarded masks mainly include high-temperature incinerating and landfillsing (Topal and Topal, 2021). However, high-temperature incineration will aggravate not only global warming but also produce toxic gases to exacerbate environmental pollution (G.Y. Xu et al., 2021). The use of landfill disposal will cause secondary pollution to the soil, and the natural decomposition of waste masks often needs a very long time, even up to hundreds of years (Silva et al., 2021; Do Thi et al., 2021). To address the environmental challenges posed by discarded masks, researchers have been diligently promoting the resourceful reuse of waste masks based on sustainability principles. One such typical reuse avenue is to recycle waste masks in large-scale civil projects, especially in pavement construction (Wang et al., 2022).

Essentially, the major component of waste masks is polypropylene (PP) fiber, which is proven to have the capability to improve certain properties of the asphalt binder and the associated hot mix asphalt (HMA). For instance, Yu et al. developed modified asphalt by utilizing the PP plastic powder to replace conventional SBS modified asphalt (Yu et al., 2014). The experimental results showed that the high-temperature performance and moisture stability of the PP modified HMA were comparable to those of the SBS modified HMA. Meanwhile, the life cycle assessment (LCA) analysis identified that the PP modified HMA was a type of clean production with high economic and environmental impacts. Nekhoroshev et al. found that with the modification of PP, the thermo-oxidative aging resistance, adhesion to aggregates, and heat resistance of the asphalt binder can be significantly enhanced (Nekhoroshev et al., 2017). Qadir added PP fibers as an additive to the HMA with the aim of improving the rutting resistance (Qadir, 2014). The test results showed that the incorporation of PP increased the Marshall stability of the conventional HMA by almost 25 %, and the PP fibers were found to be effective against rutting deformation at high temperatures by increasing the indirect tensile strength. Due to these promising findings, some more efforts have been devoted to incorporating the waste masks directly into the asphalt or the HMA in different forms, such as squares and powders. For example, Yalcin et al. fabricated the waste mask fibers (MF) modified asphalt and SBS modified asphalt at five different mix ratios and measured their physical-rheological properties (Yalcin et al., 2022). It was experimentally observed that the softening point and viscosity of the base asphalt were increased while the penetration was reduced prominently by the MF. In addition, Wang et al. incorporated the waste MF into the HMA to improve its high-temperature permanent deformation resistance (Wang et al., 2022). The pavement performance evaluation revealed that the strength and stiffness of MF modified HMA increased significantly. When the MF content was increased from 0 % to 1.5 %, the rutting depth was decreased accordingly from 3.0 mm to 0.93 mm. Based on 4 different dosages and 2 different sizes of MF, a total of 6 modified HMAs were fabricated by Goli et al., and their performance properties were systematically measured (Goli and Sadeghi, 2022). The measurement results showed that the MF had the capability to improve the fatigue life, high-temperature permanent deformation resistance, and moisture stability of the HMA.

Evidently, the above-presented studies have shown the feasibility of recycling and reusing waste masks in the asphalt and the associated HMA. In addition, a consensus has been reached that the MF can enhance the elasticity of the asphalt, therefore improving the high-temperature permanent deformation resistance of the HMA. However, most of the studies focus mainly on the high-temperature performance improvement of the HMA through the incorporation of the MF but pay very little attention to its potentially detrimental effects on the low-temperature anti-cracking resistance. Normally, fiber modified asphalt has poor ductility at low temperatures due to the adsorption of asphalt light components by the fiber (Wu et al., 2022). The poor ductility of the fiber modified asphalt may further reduce the low-temperature anti-cracking resistance of HMA (Qadir, 2014). In this regard, the low-temperature performance of the asphalt and the associated HMA may be decreased with the incorporation of the MF, which is against the original intention of improving the overall performance of the HMA. A satisfactory asphalt modification should at least be able to ensure a balance between the high and low-temperature performance properties of asphalt binder (Kumar and Garg, 2011). To compensate for the adverse effects of fibers, some light oils (such as bio-oils, waste engine oils, or waste cooking oils) have been developed to improve the low-temperature performance of asphalt binder, and HMA (Lv et al., 2020a, 2020b; Liu et al., 2018; Zaboor et al., 2021), which will also be attempted to improve the low-temperature performance of the MF modified HMA.

2. Objective and scope

This study aims to explore the added-value application of the COVID-19 disposable masks in the hot mix asphalt (HMA) for dual purposes: (1) providing a sustainable way to consume the huge number of disposable waste masks under the current COVID-19 pandemic so as to reduce the environmental pollution; and (2) improving the performance of the asphalt and the HMA through an efficient asphalt modification treatment. It is worth mentioning that waste cooking oil (WCO) will be selected to compensate for the detrimental effects of waste masks on the low-temperature performance of asphalt binders. The findings are anticipated to open a new avenue for promoting the sustainable development of pavement engineering. The structure of this paper is organized as follows. The experimental work will be first presented, including the raw materials used, the modified asphalt binder and HMA fabricated, and a description of the physical-rheological property test methods. This will be followed by a discussion of test results, along with a conclusion section.

3. Materials and experiments

3.1. Raw test materials

The #70 base asphalt provided by Hubei Jiaotou Zhiyuan New Material Technology Co., Ltd. (located in Hubei Province, China) was selected as the binder material, whose physical properties are listed in Table 1. The COVID-19 disposable masks were collected from the trash bin. As shown in Fig. 2, before being used as the asphalt modifier, they need to be treated properly with the following steps involved:

1) Placing the waste masks in the oven at 60 °C for at least 1 h for the purpose of disinfection;
2) Removing the medical part and cotton thread of the waste masks;
3) Cutting the waste masks into fragments with a size of around 3 cm in length and 3 cm in width;
4) Transferring the mask fragments into a crusher to crush for 5 min to obtain the waste mask fibers.
The waste cooking oil (WCO) used in this study was recycled from the Logistics Service Center of Huazhong University of Science and Technology. Note that before using it to modify the asphalt binder, the WCO was heated at 160 °C for 30 min to ensure the complete removal of water residue.

### 3.2. Fabrication of the MF + WCO modified asphalt

The fabrication of MF + WCO modified asphalt is detailed in Fig. 3. First, the #70 base asphalt was heated at 135 °C for 30 min to make it fluid freely. Then, the heating temperature was increased to 165 °C, and the MF was blended with the base asphalt at 3 different mixing ratios, namely 3 %, 5 %, and 7 %, by the weight of the base asphalt. Accordingly, the modified asphalt binders are labeled as MF3%, MF5%, and MF7%. Subsequently, the 3 types of MF modified asphalt binder were fabricated by shearing and stirring at 300 rmp for 15 min with the aid of shearing equipment. After that, the heating temperature was raised up to 175 °C, and the WCO was added to the MF modified asphalt at 4 different dosages (WCO1%, WCO2%, WCO3%, and WCO4% by the weight of base asphalt). Finally, a total of 6 types of MF + WCO modified asphalt were fabricated by shearing and stirring the asphalt binders at 175 °C and 1000rmp for another 30 min, which is labeled as MF3% + WCO1%, MF3% + WCO2%, MF5% + WCO2%, MF5% + WCO3%, MF7% + WCO3%, and MF7% + WCO4%, respectively. A series of physical-rheological property tests were then designed and conducted on the 10 asphalt binders, including the 9 modified asphalt binders plus the unmodified #70 base asphalt. The aim was to screen out the modified asphalt binder with the best performance. More details related to the physical-rheological property tests will be presented in the following sections.

The reasons for selecting the above-mentioned dosages of MF and WCO can be summarized as follows:

1. To maximize the utilization rate of the MF, the MF was added into the asphalt binder with increasing dosage. When raising the MF dosage higher than 7 %, some MFs were found to be insoluble in the asphalt binder. Thus, the upper limit of the MF dosage was determined to be 7 %.
2. With the incorporation of the MF, the ductility of the asphalt binder drops sharply, verifying that the MF has the tendency to dramatically lower the low-temperature performance of the asphalt binder. Thus, it is necessary to incorporate the WCO to improve its low-temperature performance. The maximum dosage of the WCO was determined as 3 % since the addition of MF7% + WCO4% makes the asphalt binder even softer than the #70 base asphalt. The relevant test results will be given in Figs. 10 and 11.

Based on the determined upper dosage limits of the MF and WCO, a total of 9 representative combinations of the MF + WCO were designed for the asphalt modification, as summarized in Table 2, in which the MF7% + WCO4% is also included for comparison. The best combination of the MF + WCO will be then identified according to the following testing sequence:

1. The physical property tests (i.e., penetration, softening point, and ductility) will be first carried out to determine the best combination candidates of the MF + WCO;
2. The rheological property tests, including the temperature performance grade (PG) test, Brookfield rotary viscosity test, frequency sweep test, multiple stress creep recovery (MSCR) test, bending beam rheometer (BBR) test, and linear amplitude sweep (LAS) test, will be conducted to further identify the best combination from the combination

### Table 1

**Conventional properties of #70 base asphalt.**

| Physical properties | Test results | Test methods (JTG E20-2011) | Requirements (JTG F40-2004) |
|---------------------|-------------|------------------------------|-----------------------------|
| Penetration in 0.1 mm (25 °C, 100 g, 5 s) | 73.7 | JTG E20 T0604 | 60–80 |
| Penetration index (PI) | −1.18 | JTG E20 T0604 | −1.5±1.0 |
| Softening point (°C) | 47.1 | JTG E20 T0606 | ≥46 |
| Ductility (5 cm/min, 10 °C) (cm) | 23.8 | JTG E20 T0605 | ≥20 |
| Solubility (%) | 99.85 | JTG E20 T0607 | ≥99.5 |
| Dynamic viscosity at 60 °C (Pa·s) | 198 | JTG E20 T0620 | ≥180 |
| Flashpoint (°C) | 325 | JTG E20 T0911 | ≥260 |
| Rolling thin film oven test mass loss (163 °C, 5 h) (%) | 0.05 | JTG E20 T0610 | −0.8±0.8 |

Fig. 1. Waste masks in the natural environment.

Fig. 2. Preparation of the mask fibers.

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The Fourier transform infrared (FTIR) spectroscopy test will be then conducted to unveil the modification mechanism of the MF + WCO;

4) The multiple stress creep recovery (MSCR) test specified in ASTM D7405 is a routine test method used for measuring the rutting resistance of asphalt binder at high temperatures. In this study, the MSCR test was performed at 64 °C. In the MSCR test, the samples were subjected to 10 cycles of creep stress (1.0 s per cycle) and recovery (9.0 s per cycle) at two different loading amplitudes. Subsequently, the frequency sweep tests were conducted on the asphalt binders at temperatures from 10 to 70 °C with a gradient of 10 °C. In this test, the applied strain was controlled within the viscoelastic strain range, and the frequency ranged from 0.001 Hz to 10,000 Hz. Based on the raw test data obtained, the Christensen Anderson and Marasteau (CAM) model was selected to establish the master curve of complex modulus and phase angle at the reference temperature of 40 °C. More details concerning the CAM model can be found elsewhere. (Yussoff et al., 2010).

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stress levels, namely 0.1 MPa and 3.2 MPa. Nonrecoverable creep compliance ($J_{nr0.1}$ and $J_{nr3.2}$) and elastic recovery ($R_{0.1}$ and $R_{3.2}$) acquired from the MSCR testing results were then used to assess the high-temperature performance of asphalt binders. In general, a higher $R$ with a lower $J_{nr}$ value means the smaller permanent deformation of asphalt pavements accumulated under repeat traffic loadings at high temperatures, which indicates the asphalt binder has a higher rutting resistance potential (Lv et al., 2020b; H.Q. Liu et al., 2021).

5) **Bending Beam Rheometer (BBR) test:** The BBR tests specified in AASHTO T 313 are usually conducted to assess the low-temperature creep performance of the asphalt binder. In this research, the BBR tests were conducted on the base and modified asphalt binders at $-6^\circ$C, $-12^\circ$C, $-18^\circ$C, and $-24^\circ$C. The low-temperature cracking resistance of the asphalt binders can be identified by measuring the creep stiffness ($S$) and creep rate (m-values). To ensure adequate low-temperature cracking resistance, $S \leq 300$ MPa and $m \geq 0.3$ usually need to be satisfied according to the AASHTO M320.

6) **Linear amplitude sweep (LAS) test:** The LAS test documented in AASHTO TP 101 was performed to determine the fatigue life of base and modified asphalt binders at 25 °C. LAS is an oscillatory strain sweep test that contains the following two steps. In the first step, frequency sweeping was carried out to obtain the linear viscoelastic properties of the asphalt binder.
properties of asphalt binders. In the second step, the damage characteristics of asphalt binders were captured by applying a linear amplitude sweeping with strain levels ranging from 0.1 % to 30 % (H. Xu et al., 2021). Evidently, the higher fatigue life of asphalt binders indicates the better fatigue resistance of the asphalt binder.

3.4.3. Fourier transform infrared (FTIR) spectroscopy test
The FTIR spectroscopy test is typically used to characterize the chemical structure changes of the asphalt binder. In this research, the FTIR equipment (Nicolet iS50R, Thermo Scientific Co., LTD, USA) was used to identify the change in the functional groups and chemical bonds after the MF and WCO were incorporated into the base asphalt. During the testing, the prepared samples were tested at the wavenumbers ranging from 400 cm\(^{-1}\) to 4000 cm\(^{-1}\) with the instrument resolution of superior to 0.09 cm\(^{-1}\), and each test contains 180 scans.

3.4.4. Hot mix asphalt performance tests
1) **Flow number test:** Rutting is one of the major distresses of asphalt pavements occurring in summer, which is caused by repeated traffic loadings at high temperatures (Xi et al., 2021). To explore the effect of MF + WCO on the rutting resistance of the asphalt pavement, the flow number test was conducted on the HMA samples at 60 °C. In this test, the Dynamic Testing System (DTS) was employed to conduct the flow number test on the asphalt mixture cylindrical samples with 150 mm in height and 100 mm in diameter. The schematic diagram of the flow number test is exhibited in Fig. 8. Normally, a higher flow number value indicates the higher rutting resistance of the HMA. More details related to the flow number test can be found in H.Q. Liu et al., 2020.

2) **Three-point bending test:** Low-temperature cracking is another typical type of pavement distress that usually occurs in winter, which is attributed to the excessive repeated shrinkage tensile stress (Chen et al., 2022). In this section, the three-point bending test specified in JTG E20-2011-T 0715 was used to quantify the effect of MF + WCO on the low-temperature anti-cracking of the HMA. Prior to the test, the #70 base asphalt and MF + WCO modified asphalt mixture beams with a size of 250 mm * 30 mm * 35 mm (length * width * height) were fabricated, as shown in Fig. 9. The low-temperature anti-cracking was evaluated by measuring the flexural-tensile strength (R\(_{fb}\)), maximum flexural-tensile strain (\(\varepsilon_{fb}\)), and flexural stiffness modulus (S\(_B\)) of the asphalt mixture beams at −10 °C. Referring to K. Liu et al., 2020, the higher values of R\(_{fb}\) and S\(_B\) and the lower value of \(\varepsilon_{fb}\) reflect the better low-temperature cracking resistance performance of HMA.

3) **Freeze-thaw splitting test:** The freeze-thaw splitting test specified in JTG E20-2011-T 0729 was selected to assess the effect of MF + WCO on the moisture stability of HMA. The moisture stability of #70 base asphalt and MF + WCO modified HMA was evaluated by calculating the tensile strength ratio TSR of the standard Marshall samples (63.5 mm in height and 101.5 mm in diameter) before and after the freeze-thaw cycle (−18 ± 2 °C freezing for 16 ± 1 h and 60 ± 0.5 °C thawing for 24 h). In general, the larger TSR value corresponds to the better moisture stability of HMA (Xu et al., 2022).

4. Results and discussion

4.1. Physical property test results

The physical property test results of the MF-modified asphalt are summarized in Fig. 10. Evidently, when the MF is added to the base asphalt, the penetration decreases dramatically while the softening point value increases significantly. As depicted in Fig. 10(a), the penetration of #70 base asphalt is 73.7 dmm. However, the penetration of MF7% decreased sharply to 32.3 dmm by 128 %. In addition, in Fig. 10(b), the softening point of MF7% (60.6 °C) is increased by 28.7 % in comparison with the
The remarkable changes in these two physical properties demonstrate that the addition of MF enhances the elasticity of the asphalt binder, which is further beneficial to the high-temperature rutting resistance improvement of the asphalt and the associated HMA. However, when compared with the ductility of base asphalt (23.8 mm), the ductility of MF7% dramatically drops to as low as 3.5 cm, which is far below the specification requirement of JTG F40-2004. This attributes to the fact that the addition of MFs consumes and absorbs a larger number of light components in the asphalt binder, causing the ductility to decrease largely. This finding agrees with those reported in the previous studies (Wu et al., 2022; Qadir, 2014). The mentioned difference also reveals that the incorporation of MF will significantly increase the risk of low-temperature cracking of the asphalt and the associated HMA, further demonstrating the necessity of introducing the WCO into the MF modified asphalt for the improvement of its low-temperature performance.

The physical property test results of the MF + WCO modified asphalt are exhibited in Fig. 11. Obviously, the WCO can greatly improve the ductility of MF modified asphalt. For example, the ductility of MF7% + WCO4% is increased from 3.5 mm to 16.4 mm in comparison with the MF7%, which demonstrates the low-temperature ductility of asphalt binder is significantly improved by the WCO. This phenomenon can be explained by the fact that WCO is a light oil consisting of a large number of small fatty acid molecules (Ren et al., 2022). Apparently, the addition of WCO can provide some light components for the MF modified asphalt, thus improving its fluidity and low-temperature performance, and the same analysis results were also observed in previous studies (Lv et al., 2020a, 2020b; Liu et al., 2018; Zahoor et al., 2021). However, the penetration of MF7% + WCO4% is increased as high as 89.7 dmm, which is even greater than that of base asphalt (73.7 dmm), indicating that the excessive dosage of WCO adversely decreases the high-temperature permanent deformation resistance. Thus, the dosage of WCO has to be controlled below 5% so as to ensure the satisfactory high-temperature performance of the asphalt binder. Overall, it can be inferred from Fig. 11 that the modified asphalt binders of MF3% + WCO2% and MF5% + WCO3% have the best physical property performance in terms of penetration, softening point, and ductility. These two asphalt binders can be screened out as the best combination candidates, of which rheological properties will be tested and compared in the next subsection.

4.2. Rheological property test results

1) Temperature performance grade (PG): The PG test results of base asphalt, MF3% + WCO2%, and MF5% + WCO3% are exhibited in Fig. 12. The PG grades of base asphalt, MF3% + WCO2%, and MF5% + WCO3% are PG 64–26, PG 64–30, and PG 70–26, respectively. Evidently, in comparison with the base asphalt, the low-temperature performance of MF3% + WCO2% is improved, while the high-temperature performance of MF5% + WCO3% is enhanced. When MF and WCO are used as modifiers added into the asphalt binder simultaneously, the relative content of WCO in MF3% + WCO2% (WCO /
(MF + WCO = 40 %) is greater than that of in MF5% + WCO3% (WCO / (MF + WCO) = 37.5 %). In the MF3% + WCO2%, the content of WCO is higher, which is beneficial to improve the fluidity of the asphalt binder, resulting in a better low-temperature performance (Kumar and Garg, 2011). On the contrary, the MF5% + WCO3% contains a relatively higher content of MF, which can rise the elasticity of the asphalt binder, making the high-temperature performance of the asphalt binder better than the MF3% + WCO2%. The finding agrees with those reported in the previous study of Qadir, i.e., the high-temperature performance of the asphalt binder can be highly enhanced by adding fibers (Qadir, 2014).

2) Brookfield rotary viscosity: The viscosity test results of base asphalt, MF3% + WCO2%, and MF5% + WCO3% are summarized in Fig. 13. As the test temperature increases, the viscosity of all asphalt binders decreases to varying degrees. Besides, regardless of the test temperature investigated, MF3% + WCO2% shows the lowest viscosity among the three types of asphalt binder. This is plausible because the content of WCO in MF3% + WCO2% is relatively higher, which facilitates the flow of asphalt binder at high temperatures. As for the MF5% + WCO3%, its viscosity is almost identical to the base asphalt, demonstrating that the detrimental effect of MF on viscosity is adequately compensated by the 3 % of WCO.

3) Master curves of complex modulus and phase angle: The master curves (i.e., complex shear modulus & phase angle) of base asphalt, MF3% + WCO2%, and MF5% + WCO3% are exhibited in Fig. 14. It can be easily observed that the addition of MF results in an upward shift of complex shear modulus and a downward shift of phase angle in the most frequency range, indicating that the addition of MF has the capability of improving the elastic properties of the asphalt binder. In addition, in most cases, the MF5% + WCO3% has a relatively higher complex shear modulus value and a relatively lower phase angle value than the MF3% + WCO2%, indicating that the elastic properties of the MF5% + WCO3% are better than those of the MF3% + WCO2%.

4) Repeated creep and recovery properties: The MSCR test results of
base asphalt, MF3% + WCO2%, and MF5% + WCO3% are depicted in Fig. 15. Apparently, with the increase in stress level (0.1–3.2 kPa), the accumulated strains of three asphalt binders increase rapidly. Among, MF5% + WCO3% presents the lowest total accumulated strains. According to the report of Yalcin et al., the introduction of elasticity components (MF in this study) is conducive to enhancing the stiffness of the asphalt binder (Yalcin et al., 2022), which implies that MF can significantly improve the high-temperature permanent deformation resistance of asphalt binder. In addition, it can be seen from Table 4 that the percent recovery R of the MF5% + WCO3% is the highest, while the non-recoverable compliance Jnr is the lowest, which also indicates that the MF5% + WCO3% modified asphalt has the best creep and recovery performance.

5) Low-temperature performance: The m-value and creep stiffness of base asphalt, MF3% + WCO2%, and MF5% + WCO3% at the temperature of −6°C to −24°C are exhibited in Fig. 16. Referring to Ma et al., 2020, the creep stiffness S describes the anti-cracking capacity of asphalt binder at low temperatures as the low temperature causes the strain capacity of asphalt binder to drop sharply. The m-value reflects the creep rate of the asphalt binder, and a higher m-value means better relaxation capability. In Fig. 16, all three types of asphalt binder meet the requirements specified in AASHTO M320 (m-values ≥ 0.3; S ≤ 300 MPa) when the test temperature ranges from −6°C to −24°C. Notably, MF3% + WCO2% presents the largest m-values and lowest S, illustrating the MF3% + WCO2% modified asphalt binder has the best low-temperature cracking resistance performance among the three asphalt binders. This is attributed to that the content of WCO in MF3%
+ \text{WCO2}\% is higher than that in \text{MF5}\% + \text{WCO3}\%, which makes the asphalt binder softer. As reported by Ma et al., \text{WCO} can compensate for the light fraction in the asphalt binder and increase the relaxation capability of \text{MF} modified asphalt at low temperatures (Ma et al., 2020). Further support to this phenomenon could be found in the master curves of complex modulus and phase angle at high frequency, i.e., \text{WCO} contributes to a decrease of stiffness and an increase of viscous components of \text{MF} modified asphalt (as shown in Fig. 14).

6) Fatigue life: The LAS test results of base asphalt, \text{MF3}\% + \text{WCO2}\%, and \text{MF5}\% + \text{WCO3}\% at 25 °C are presented in Fig. 17 and Table 5. Fig. 17 depicts the relationship between the shear stress and shear strain during the LAS testing phase, and Table 5 lists the fatigue life (N_i) calculation results of the three types of asphalt binder. In Fig. 17, the curve of \text{MF5}\% + \text{WCO3}\% has the largest peak and width (brown curve), while the curves of base asphalt (green curve) and \text{MF3}\% + 

\begin{table}[h]
\centering
\caption{Percent recovery results of the three asphalt binders.}
\begin{tabular}{|c|c|c|c|c|}
\hline
Type & 0.1 kPa & 3.2 kPa & Jnr-diff \\
\hline
\hline
Base asphalt & 0.64 \% & 0.886 & 0.04 \% & 0.958 & 8.09 \% \\
MF3\% + WCO2\% & 12.58 \% & 0.617 & 0.13 \% & 0.989 & 60.10 \% \\
MF5\% + WCO3\% & 37.72 \% & 0.274 & 0.20 \% & 0.864 & 215.45 \% \\
\hline
\end{tabular}
\end{table}

Fig. 15. Repeated creep and recovery property of the three asphalt binders: (a) 0.1 kPa; (b) 3.2 kPa.

Fig. 16. BBR test results of the three asphalt binders: (a) m-value; (b) creep stiffness.

Fig. 17. Stress-strain curves of the three asphalt binders.
WCO2% (purple curve) almost overlap with each other. These patterns indicate that MF5% + WCO3% modified asphalt binder has the highest elastic capacity deformation (Micaelo et al., 2015), which leads to the largest Nf value, as exhibited in Table 5.

In conclusion, the above-presented rheological test results indicate that the high-temperature performance and fatigue cracking resistance of MF5% + WCO3% modified asphalt are enhanced, while its low-temperature performance is almost unchanged as compared with those of the #70 base asphalt. Thus, the MF5% + WCO3% is finally screened out as the best combination for asphalt modification.

4.3. Fourier transform infrared (FTIR) spectroscopy test results

It is well recognized that the chemical functional group analysis of asphalt binders is the key to unveiling the modification mechanism. Thus, to identify the modification mechanism of the MF + WCO, the FTIR spectroscopy test was performed to identify the change of chemical functional groups during the asphalt modification process. The infrared spectra of base asphalt, MF5%, and MF5% + WCO3% are exhibited in Fig. 18. Apparently, the transmittance peaks of MF5% modified asphalt are similar to those of the base asphalt. This is because polypropylene (PP), which is the major component of the waste mask, is a type of petroleum derivative. In other words, PP and asphalt binder originate from the same resources of petroleum (Yalcin et al., 2022). In this sense, the base asphalt and MF5% + WCO3% should have the same chemical functional groups. However, two clear peaks can be observed at 1198 and 1744 cm\(^{-1}\) in the MF5% + WCO3% modified asphalt when compared with the base asphalt and MF5% modified asphalt. These two new peaks correspond to the C=O and C-O-C (two bands) stretch of saturated fatty acid ester, which is the major component of WCO (Guduru et al., 2021). Thus, there is no new chemical functional group formed when incorporating the MF and WCO into the asphalt binder, which indicates that the addition of MF and WCO into the base asphalt involves only a physical modification rather than a chemical modification.

4.4. Hot mix asphalt (HMA) performance test results

1) Analysis of flow number test results: The flow number test results of the #70 base HMA and MF5% + WCO3% modified HMA at the temperature of 60 °C are listed in Fig. 19. Obviously, it can be seen that the flow number of MF5% + WCO3% modified HMA is 3496, which is increased by 23.5 % in comparison with 2675 of the #70 base HMA. The significant increase of flow number demonstrates that the high-temperature permanent deformation resistance of MF5% + WCO3% modified HMA is remarkably higher than that of the #70 base HMA. This finding agrees with those reported in a previous study by Wang et al., that is, the hardened MF provide stability and stiffness to HMA, and thus enhancing the high-temperature permanent deformation resistance (Wang et al., 2022).

2) Analysis of three-point bending test results: The three-point bending test results of #70 base HMA and MF5% + WCO3% modified HMA at
the temperature of −10 °C are illustrated in Fig. 20. Evidently, the MF5% + WCO3% modified HMA has the larger values of flexural-tensile strength (R_{f}) & flexural stiffness modulus (S_{f}), and the lower value of maximum flexural-tensile strain (Ɛ_{f}) in comparison with the #70 base HMA, which demonstrates the MF5% + WCO3% modified HMA has the better low-temperature cracking resistance. The reason accounting for this phenomenon may be that the addition of MF enhances the overall strength of the HMA by referring to the report of Wang et al. (Wang et al., 2020), and thus the low-temperature cracking resistance was improved to some extent.

3) Analysis of freeze-thaw splitting test results: The freeze-thaw splitting test results of #70 base HMA and MF5% + WCO3% modified HMA are presented in Fig. 21. It can be seen that the tensile strength ratio (TSR) of #70 base HMA (89.61 %) is higher than MF5% + WCO3% modified HMA (82.92 %), demonstrating the moisture stability of the #70 base asphalt HMA is better. However, referring to the Chinese standard, both types of HMA satisfy the requirement of TSR ≥ 80 % specified in JTG F40-2004, which means that the addition of MF5% + WCO3% for the asphalt modification can still ensure satisfactory moisture stability performance for the HMA.

5. Environmental benefit assessments

Referring to a previous study (Topal and Topal, 2021), the most common ways of dealing with disposable masks are incineration and landfill. Apparently, the high-temperature incineration of waste masks will produce a significant amount of CO₂ further aggravating global warming. It is estimated that every 1 kg of waste masks incinerated can yield 2.3 kg of CO₂. In addition, the landfill of the waste masks can not only cause secondary environmental pollution but also lead to the encroachment of land resources. Assuming that a disposable 3-layer breathable mask has a weight of 4 g and a compressed volume of 8.15 cm³ (Silva et al., 2021), the waste masks monthly generated from COVID-19 have a total weight of 490,201 tons, which can result in the emission of 1,127,462 tons CO₂ and the encroachment of 998,785 m³ land resource (Nam et al., 2022).

To alleviate the environmental crisis raised by the COVID-19 pandemic, this study innovatively uses the waste mask for asphalt modification and HMA performance improvement. The different approaches used for dealing with the waste masks are illustratively depicted in Fig. 22. To gain a quantitative comparison, a typical three-layer asphalt pavement with 1 km in length, 15 m in width, and 18 cm in thickness was assumed to be paved by MF5% + WCO3% modified HMA. The layer information of the asphalt pavement is given in Table 6. Evidently, the total amounts of asphalt required for pavement paving are 75.31 tons, which implies that a total of 3.77 tons of waste masks (approximately 941,397 masks) can be recycled and consumed for paving such a typical asphalt pavement with a length of 1 km. The recycling of these huge waste masks will be beneficial for reducing CO₂ emissions by 8.66 tons and decreasing land encroachment by 0.77 m³. To this end, the application of the COVID-19 disposable mask in HMA provides an enormous added value to pavement engineering in terms of carbon emission reduction and land resource saving.

6. Conclusions

This paper explored the feasibility of recycling mask fiber (MF) in combination with waste cooking oil (WCO) to develop a modified asphalt binder. The aim was to reduce the pollution that waste masks may pose to the environment as well as to promote the sustainable development of pavement engineering. The physical-rheological property tests were conducted to screen out the best combination of MF + WCO for the asphalt modification. The FTIR spectroscopy test was done to investigate the modification mechanism of MF and WCO. The hot mix asphalt performance evaluation tests were performed to validate the modification efficiency.
The environmental benefit assessments were carried out to quantify the added value of the application of MF into asphalt pavement. The following conclusions can be drawn:

1) The physical property test results of the MF-modified asphalt indicate that the softening point can be increased to some extent, while the ductility was decreased dramatically to fail to meet the specification requirement. This fact indicates that the MF can enhance the high-temperature performance of asphalt binder but at the same time has the tendency to lower its low-temperature performance.

2) To reduce the adverse effect of MF on the low-temperature performance of asphalt binder, WOC was incorporated into MF modified asphalt. The physical property test results demonstrate that WCO can compensate for the light component loss of the MF modified asphalt, thus enhancing the flowability of the asphalt binder as well as improving the low-temperature performance of the MF modified asphalt.

3) A series of physical-rheological performance assessments indicate that the high-temperature performance and fatigue cracking resistance of MF5% + WCO3% modified asphalt was enhanced, while its low-temperature performance was almost identical to that of the #70 base asphalt. The modified asphalt of MF5% + WCO3% was finally screened out to fabricate the HMA.

4) The FTIR spectroscopy test results reveal that the addition of MF and WCO into the base asphalt involved only a physical modification rather than a chemical modification.

5) The HMA performance test results show that the high-temperature permanent deformation resistance and low-temperature anti-cracking performance of MF5% + WCO3% modified HMA are greatly improved as compared to those of the #70 base HMA. Its moisture stability is slightly decreased but still meets the specification requirement.

6) The environmental benefit assessments prove that, in comparison to the traditional treatments, recycling waste masks for asphalt pavement construction provides an enormous added value to pavement engineering in terms of carbon emission reduction and land resource saving.

This paper presents a preliminary laboratory investigation on the added-value application of the COVID-19 disposable mask in hot mix asphalt (HMA). Some more efforts are still needed for the practical application of the disposable mask in asphalt pavement construction. For instance, the key processing steps for obtaining the uniform fine mask fibers from the waste masks are needed to consider and optimized. In addition, the long-term pavement performance of the MF modified asphalt roads, especially the low-temperature anti-cracking performance, needs to be monitored and evaluated before the large-scale application of the MF modified asphalt into pavement engineering.

CRediT authorship contribution statement

**Derun Zhang:** Conceptualization, Methodology, Investigation, Project administration, Funding acquisition, Writing – review & editing. **Yichen Guo:** Data curation, Investigation, Validation, Supervision. **Ziyang Liu:** Methodology, Investigation, Validation, Data curation. **Peixin Xu:** Conceptualization, Methodology, Data curation, Investigation, Validation, Writing – original draft, Writing – review & editing. **Zirong Ma:** Methodology, Investigation, Funding acquisition. **Jun Zhan:** Writing – review & editing, Funding acquisition.

Data availability

Data will be made available on request.

Declaration of competing interest

No.

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