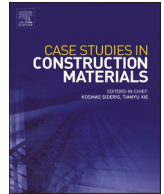




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Recycling of copper tailing as filler material in asphalt paving mastic: A sustainable solution for mining waste recovery

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ABSTRACT

Copper tailings are a category of solid waste discharged after the beneficiation process in mining plants. The significant concern raising stringent environmental issues give impetus to explore the multi-channel utilization of copper tailings in a sustainable manner. Concerning the fact that no study has systematically compared properties of copper tailings filled (CTP) asphalt mastic with conventional limestone filler mastic (LP) at different filler-to-asphalt ratios, multiscale and multi-dimensional comparisons between the characteristics of CTP-asphalt and LP-asphalt mastics were made in this study to thoroughly explore the feasibility and potential of recycling CTP as alternative filler in asphalt materials. Four ratios from 0.3 to 1.2 were used to manufacture asphalt mastics. The in-service pavement performance of asphalt mastics including resistances to rutting, low-temperature cracking and moisture damage was explored. Finally, the environmental and economic perspectives regarding the recycling of copper tailings are analyzed. Results indicate that CTP possesses a rougher surface, a larger specific surface area, and a more uniform pore size distribution than LP, particularly across the mesopores range. These characteristics could promote the adsorption of asphalt on its particle surface, potentially leading to enhanced filler-particle interaction. Regarding pavement performance, CTP-asphalt mastic outperforms LP-asphalt mastic in terms of high-temperature performance. Meanwhile, its low-temperature performance and moisture stability are only limitedly declined with the acceptable performance. Further, heavy metals leaching tests suggest that the risk for the substantial utilization of CTP in paving asphalt is absent. The related outcomes have verified the promising potential of CTP as an alternative candidate to substitute the conventional filler in paving asphalt from comprehensive consideration of in-service performance, and environmental and economic benefits.

1. Introduction

Whilst the exploitation and development of the mining industry deliver a great stimulus for social and economic progress, there are a large number of mine wastes at the same time [1–3]. From a global perspective, approximately 20–25 billion tons of mining waste are

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generated from the mining industry annually [4]. In mine plants, mine tailings are valueless materials after the extraction of those valuable ores [5]. Worldwide, huge amounts of tailings are generated through the mining industry and inevitably stacked in the tailings dams [6]. Copper tailings are a major category of mine tailings among various metallic and non-metallic tailings. It is reported the production of 1-ton copper is associated with approximately 196.5 tons of tailings [7]. According to relevant statistics, the total discharge of tailings from copper mills over 300 million tons each year in China, mainly in the provinces of Jiangxi, Hubei, and Yunnan [8]. These tailings often constitute certain concentrations of toxic quasi-metals or heavy metals, thus posing an adverse effect on humans and ecosystems via multi-channels [9]. The considerable amount of copper tailings accumulated not only results in a substantial financial and managerial burden to municipal authorities but also potentially causes serious ecological and social issues such as water pollution, soil contamination, and management of land resources [10]. Therefore, it is imperative to promote the recycling of copper tailings in the mining industry at present.

Nowadays, asphalt pavement has become the most prevalent type in pavement engineering due to its ease of construction and high riding quality [11]. In the majority of countries such as China, the European Union, the United States, and the United Kingdom, the proportion of asphalt pavement in highways exceeds 90 % [12–14]. However, asphalt pavement engineering is facing considerable challenges as the indispensable raw materials, especially mineral filler and aggregate are non-renewable materials [15]. Each year, numerous natural materials are consumed, and their rising demand and depletion will impede the progress of global highway construction in its efforts to pave new asphalt pavements. Consequently, recycling and reutilization of tailings to substitute natural fillers and aggregates as alternative construction materials is a promising choice in terms of resource preservation and sustainable development [16].

Within this context, researchers have begun to shift their focus towards the utilization of solid wastes in asphalt materials [17–21]. de Sousa et al. [22] replaced conventional gravel and lime fillers with 2 % oil well gravel residue to design the sustainable hot asphalt mixtures using the Superpave methodology, it was found that the incorporation of such residue does not significantly deteriorate the mechanical performance compared to the conventional mixture. In addition, the rheology evaluation substantiated there is a favourable enhancement in viscosity and stiffness for the residue-doped mixture, thus demonstrating less susceptibility to thermal change and improved deformation resistance. de Moraes et al. [23] explored various contents of iron tailings as an alternative to partially substitute fine natural aggregate, the results indicate the replacement rate of 12.5 % is the most viable option with the comprehensive concerns of the mechanical performance (including concerning tensile strength, resilient modulus, fatigue, and permanent deformation) and the economic efficiency. Likewise, Cao et al. [14] investigated the feasibility of applying iron tailings to substitute conventional mineral aggregate in AC-20 (gradation type) paving asphalt mixture, although it was proposed that the low density, hardness, and acidic compositions of iron tailings deteriorate its various performances, thus restricting its application in paving asphalt mixture [14]. However, these degraded properties could be potentially mitigated by applying high-viscosity, hydrated lime, and silane coupling agents [14]. Wang et al. [24] substituted conventional limestone aggregate with magnetite tailings, it was found that the rutting index of resistance to asphalt mixture is enhanced with the replacement of magnetite tailings. Wei et al. [10] evaluated the high-temperature performance of iron tailings-asphalt mastics, the results evidenced application of iron tailings can improve the viscosity, rutting factor, and elastic recovery.

There are limited studies having explored the potential of recycling copper tailings as alternative fillers in asphalt materials [25]. In the comparative and feasibility analysis between copper tailings and other six solid wastes as filler in asphalt mixes performed by Choudhary et al. [26]. The copper tailings-asphalt mix possessed a lower air void, which is deemed to be economic because of less requirement of asphalt. By substituting dolomite stone dust with copper tailings, Choudhary et al. [27] reported copper tailings filled asphalt mixtures demonstrated relatively inferior (yet satisfactory) performance than stone dust filled mixtures when concerning ravelling resistance, adhesion properties and moisture susceptibility, which was mainly ascribed to the silica-rich and absence of insoluble calcium-based minerals in the composition of tailings. Oluwasola et al. [16] pointed out that the hybrid utilization of copper tailings and electric arc furnace steel slag (EAF) to replace the conventional aggregates enhanced the performance of asphalt mix, including Marshall stability, Marshall quotient, flow properties, and resilient modulus. The results from dynamic creep indicated the mixes with EAF and copper tailings performed better in resistance to permanent deformation [28]. The existing results have demonstrated the possibility and promising potential of tailings as an alternative material to replace conventional fillers asphalt materials. However, these studies investigated the copper tailings-mixtures with fixed copper tailings content. In addition, the chemical composition of copper tailings varies independent on processing activity and extraction location. There is seems no study has systematically compared properties of copper tailings filled asphalt mastic with conventional limestone filler mastic prepared by different filler to asphalt ratios. In this study, multiscale and multi-dimensional investigations on the characteristics of CTP-asphalt and LP-asphalt mastics were conducted. Firstly, the physiochemical properties of fillers and the resultant asphalt mastics are characterized. Subsequently, the in-service performance of asphalt mastics including resistances to rutting, low-temperature cracking and moisture damage was explored. Finally, the environmental and economic evaluations in terms of the substantial utilization of copper tailings in paving asphalt were analyzed [29–33].

2. Experimental program

2.1. Materials and design

2.1.1. Raw materials

AH-70 base asphalt, which belongs to conventional petroleum asphalt and is classified as heavy-duty road asphalt, was selected as the base asphalt and its basic properties are listed in Table 1. Copper tailings were sourced from the tailings pond of Jiangxi province

shown in Fig. 1. Firstly, CT was air-dried and subsequently dried at 105 °C until constant weight. Then CT was artificially crushed and screened to 20 mesh. To obtain copper tailings powder (CTP), a laboratory planetary ball mill (GJ-3B, ball-to-mass ratio of 10:1) was utilized to grind CT at 120 r·min⁻¹ for 10 min. Both CTP and LP were passed through a 0.075 mm square sieve to fulfill the applicability requirement as filler. The basic properties of CTP and commercially available limestone powder (LP) are listed in Table 2.

2.1.2. Design of asphalt mastics

To investigate the suitability of using CT as an alternative mineral filler for asphalt mixture, a type of asphalt and two types of filler (LP and CTP) were used as raw materials, four filler-to-asphalt (F/A) ratio (0.3, 0.6, 0.9, 1.2) are shown in Table 3 were designed as the parameter to prepare the asphalt mastics. Since the density of CTP is comparable to LP causing similar volumetric proportioning, the required mass of CTP applicable to each F/A ratio is the same as the mass of LP. The preparation process of asphalt mastics was described as follows. Firstly, the filler was dried to a constant weight in the oven at 105 ± 5 °C. Subsequently, the asphalt was heated to 140 ± 5 °C. Finally, the asphalt was added into the container first and fillers were added into containers 3–5 times for a relatively uniform distribution. In the preparation of CTP asphalt mastic specimens, it was observed that the viscosity of asphalt mastic and the occurrence of CTP clumps tend to notably increase with increasing CTP content, especially for the CTP-AM-1.2. Therefore, the mixing of asphalt and filler adopted a relatively long regime, which was sustained for 30 mins at 1000 r/min and 10 mins at 300 r/min.

2.2. Experimental method

The overall experimental methodology is schematically presented in Fig. 2, which involves characteristics of fillers, conventional performance test, pavement performance test, and economical end environmental aspects.

2.2.1. Characterization of fillers

The X-ray Fluorescence (XRF) test was adopted to explore the chemical composition of CTP and LSP fillers and meanwhile to preliminarily evaluate the categories of toxic metal elements as a reference for the subsequent leaching tests. The Particle size distribution was assessed by a Laser Particle Size Analyzer (Malvern Mastersizer 2000). The micromorphologies of the fillers were explored by scanning electron microscopy (SEM) testing. Quanta Autosorb-IQ-MP automatic specific surface and porosity analyzer was employed to study the Brunauer-Emmett-Teller (BET) specific surface area and pore size distribution.

2.2.2. Conventional performance tests

The conventional properties of asphalt mastic including penetration, ductility, and softening point were tested in accordance with JTG E20–2011 (Standard Test Methods of Bitumen and Bituminous Mixture for Highway Engineering) [34,35]. The temperature sensitivity can be evaluated based on the penetration index (PI). The penetration test was conducted at different temperature conditions of 15, 25 and 30 °C. Firstly, the penetration temperature index (A_{lgPen}) was calculated based on tested data. Subsequently, the linear correlation between the logarithm of penetration (lgP) and temperature (T) was established based on Eq. (1) with the correlation coefficient (R^2) higher than 0.997, then PI can be derived from Eq. (2):

$$lgP = k + A_{lgPen} \times T \quad (1)$$

$$PI = \frac{(20 - 500A_{lgPen})}{(1 + 50A_{lgPen})} \quad (2)$$

where lgP denotes the logarithm of the penetration values acquired at various temperatures; T denotes the temperature in Celsius (°C); k represents the intercept; A_{lgPen} represents the slope.

2.2.3. Temperature sweep test

Dynamic shear rheological (DSR) was conducted to measure the rheological properties of asphalt mastic under high temperatures such as complex modulus ($|G^*|$), and phase angle (φ) parameters. Based on JTG E20–2011 [36], the DSR test was examined by temperature sweeping. In the temperature sweeping test, the temperature sweeping range was set to 46 °C to 70 °C with a 6 °C increment. The strain level and the shear rate were 12 % and 10 rad/s, respectively. The rutting resistance factor $G^*/\sin\varphi$ can be used

Table 1
Basic properties of AH-70 base asphalt.

Properties	Test results	Technical requirements JTG-E40-2011	Testing methods
Penetration (25 °C, 100 g, 5 s) (0.1 mm)	67	60–80	T 0604–2011
Penetration index I	-0.93	-1.5–1.0	T 0604–2011
Ductility (5 cm/min, 10 °C) (cm)	63.0	≥ 15	T 0605–2011
Ductility (5 cm/min, 15 °C) (cm)	> 100	≥ 100	T 0605–2011
Softening point (Ring ball) (°C)	48.0	≥ 46	T 0606–2011
Flash point (°C)	292	≥ 260	T 0611–2011
Solubility (%)	99.81	99.5	T 0607–1993

Note: JTG-E40–2011 stands for China's highway engineering asphalt and asphalt mixture test specification.



Fig. 1. Copper tailings stacking dam.

Table 2

Basic properties of fillers.

Properties	CTP	LP	Technical requirement JTJ 032–94	Testing methods
Density (g/cm^3)	2.87	3.04	> 2.5	T0352
Moisture content (%)	0.3	0.2	< 1	T0103
Hydrophilic coefficient	0.81	0.2	< 1	T0353

Note: JTJ 032–94 stands for Technical Specification for Construction of Highway Asphalt Pavements.

Table 3

Proportions of neat asphalt and asphalt mastics.

Groups	F/A ratio	Asphalt (g)	CTP (g)	LP (g)
Neat asphalt	0	400		
CTP-AM-0.3	0.3	400	120	
CTP-AM-0.6	0.6	400	240	
CTP-AM-0.9	0.9	400	360	
CTP-AM-1.2	1.2	400	480	
LP-AM-0.3	0.3	400		120
LP-AM-0.6	0.6	400		240
LP-AM-0.9	0.9	400		360
LP-AM-1.2	1.2	400		480

as an index of high-temperature performance for the asphalt mastic [37], where a higher $G^*/\sin\phi$ pertains to a more superior rutting resistance [38].

2.2.4. Fourier-transform infrared spectroscopy (FTIR)

FTIR Spectrometer (Thermo IN10) is performed to analyze the microscopic composition and potential interaction between asphalt binder and CTP. The scanning range, resolutions, and scan times were $4000\text{--}600\text{ cm}^{-1}$, 32, and 4 cm^{-1} , respectively.

2.2.5. Direct tension test

The crack susceptibility of paving asphalt materials is an important parameter in terms of pavement performance. Therefore, it is essential to study the fracture resistance of the CTP- asphalt mastic prepared by various F/A ratios and compared with reference mastic. In accordance with ASTM D6723–02 (Standard Test Method for Determining the Fracture Properties of Asphalt Binder in Direct Tension), the direct tension (DT) test was conducted to investigate the fracture properties of binders at low temperatures. The schematic of the asphalt mastic specimens and testing process are shown in Fig. 3. The preparation of the specimen is similar to the procedure for the ductility test of asphalt mastic; specimens were prepared by pouring hot bitumen into aluminium moulds. Before the tests, specimens were conditioned by the $-5\text{ }^\circ\text{C}$ cooling bath for 1 h to reach the temperature equilibrium. The DT test was performed at $-15\text{ }^\circ\text{C}$ temperature controlled by the temperature chamber equipped within the loading system. The tensile load was applied with a displacement-controlled mode and the loading rate was 1 mm/min until the fracture of the specimen.

2.2.6. Adhesion of aggregate-mastic interface

The moisture resistance of the aggregate-mastic interface is an important parameter closely related to the structural stability, serviceability, and durability performance of paving asphalt [39,40]. In this study, the bonding strength of aggregate-mastic interfaces was tested in accordance with ASTM D 4541 (Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers)

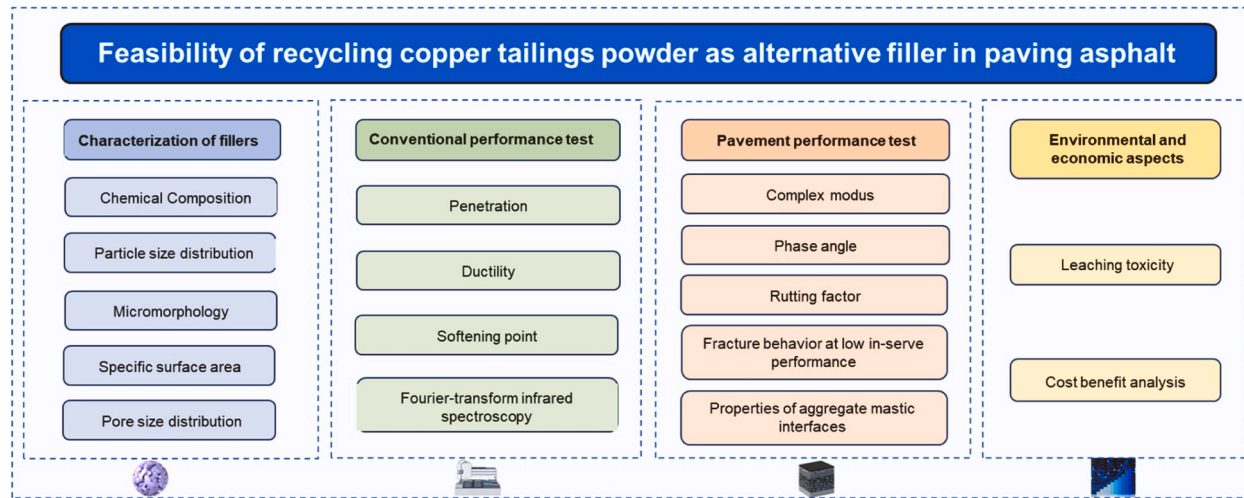


Fig. 2. Schematic diagram of experimental methodology.

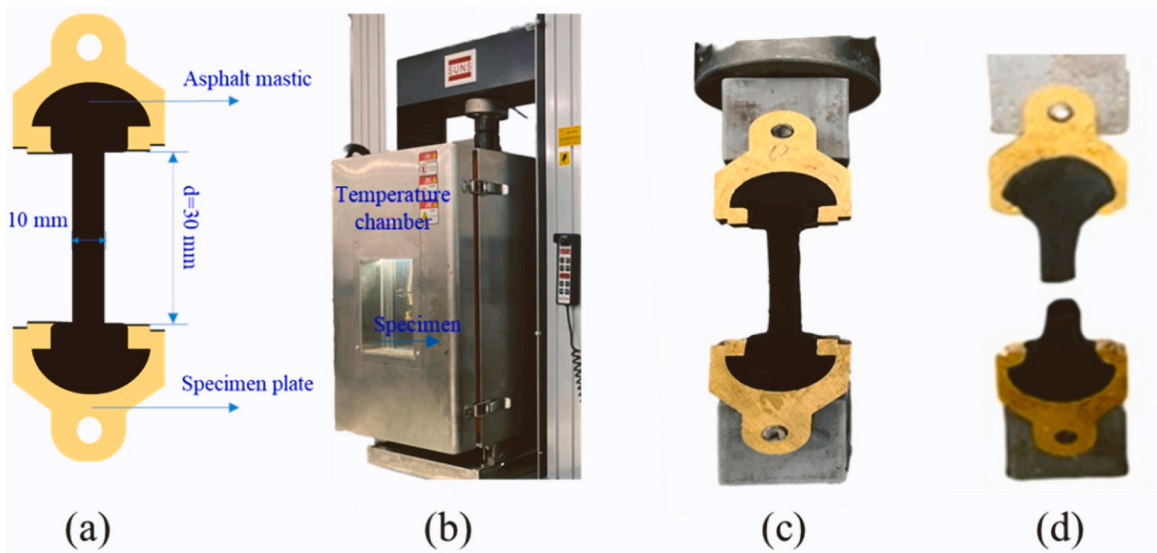


Fig. 3. Direct tension test: (a) Schematic of asphalt mastic specimen; (b) Testing equipment; (c) Specimen before testing; (d) Fractured specimen after testing.

[41]. The testing was performed through an automatic adhesion tester (Posi Test At-A apparatus, De Felsko, USA). As displayed in Fig. 4, the aggregate substrates were prepared by firstly segmenting large natural marble slabs into slices (1000 mm × 1000 mm × 15 mm) and subsequently cutting these slices into small aggregate substrates (80 mm × 80 mm × 15 mm). After cleaning and drying, hot bitumen was poured on the aggregate substrates and meanwhile, a pull-stub was promptly pressed to secure a good aggregate-mastic bond. After 24 h of cooling at room temperature, excess asphalt at the edge of the pull-stub was removed using a pallet knife. Different degrees of moisture damage were imitated by conditioning in a 26 °C water bath for various durations (3 days, 7 days, and 14 days). During the testing, a constant pulling rate of 0.4 MPa was executed to the pull-slab. Four parallel replicates were

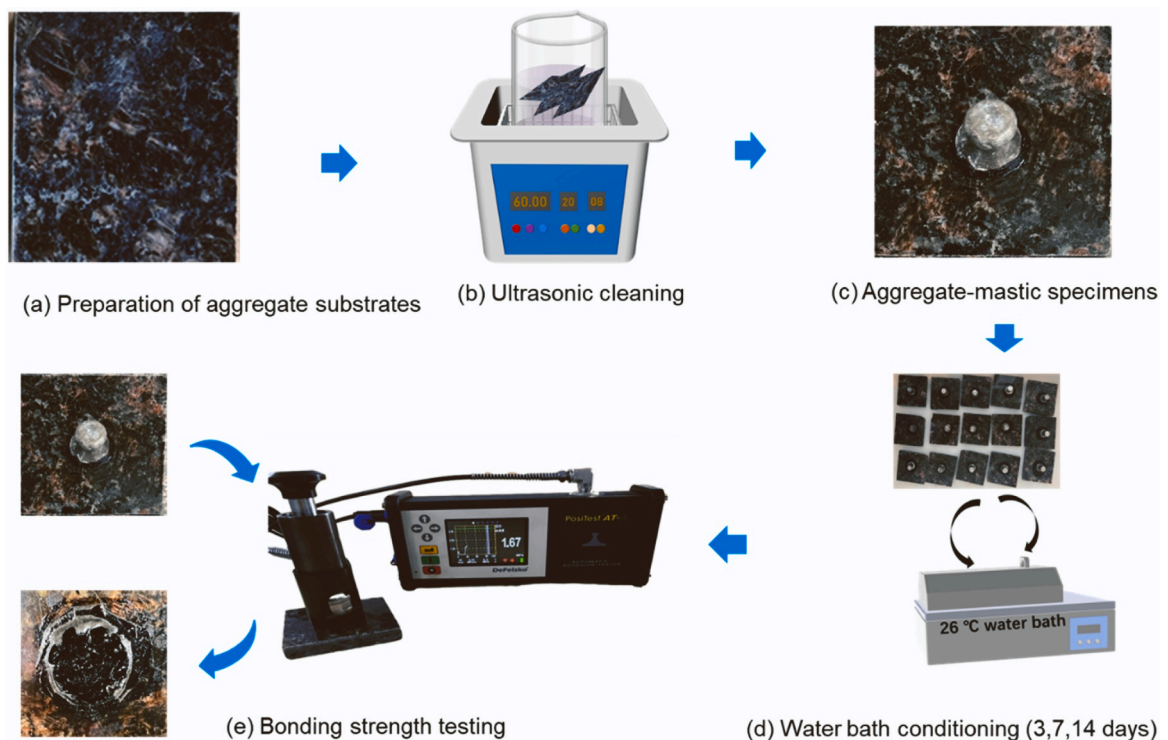


Fig. 4. Adhesion test of aggregate-mastic interface.

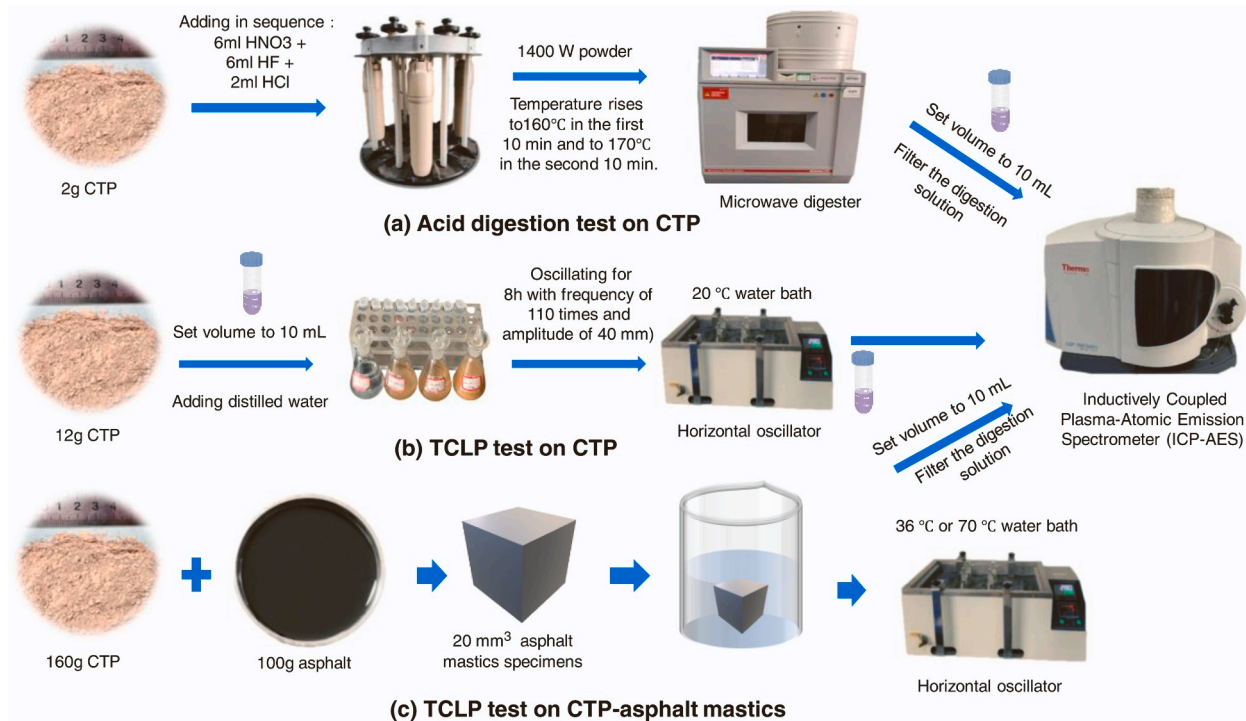


Fig. 5. Toxicity leaching test: (a) Acid digestion test on CTP; (b) TCLP test on CTP; (c) TCLP test on CTP-asphalt mastics.

tested for each group. The temperature for this experiment was controlled at 26 °C through air conditioning to eliminate the influence of temperature variation. Finally, the bond strength of the aggregate-mastic system before and after different degrees of moisture attack was compared to characterize the moisture resistance of tailings-asphalt mastics.

2.2.7. Acid digestion and TCLP tests

To investigate the potential risk of application of CTP into paving asphalt materials, the acid digestion test on CTP and the toxicity characteristic leaching procedure (TCLP) tests on CTP and asphalt mastics were performed according to GB 2019.7–2019 (leaching toxicity of inorganic elements and compounds) [42]. Three replicates were prepared for each test to ensure the validity of the results. The selective heavy metal elements were roughly determined by XRF results. The detailed testing procedure is illustrated in Fig. 5.

2.2.8. Economic analysis

Cost-benefit analysis (CBA) was performed to assess the economic benefits of the application of CTP in asphalt pavement [10]. The overall quantity assessment is estimated in monetary first. The function unit is 1 km of HMA-based asphalt pavement (two-lane). The relevant computational procedure is detailed as follows:

Step 1. The amount of demanded HMA (M_H):

$$M_H = 1000 \times W \times H \times \rho_H \quad (3)$$

where W denotes the width of pavement in m; H denotes the thickness of pavement in m; ρ_H denotes the bulk specific gravity of HMA in ton/m³. The bulk specific gravity of dense asphalt mixture is estimated to be 2.35 ton/m³ [43,44]. The width of each lane and the average thickness of highway asphalt pavement are 3.5 m and 8 cm, respectively [43].

Step 2. The amount of demanded asphalt (M_B):

$$\frac{M_B}{Q} + M_B = M_H \quad (4)$$

where Q denotes the optimum asphalt-aggregate ratio of HMA in %.

Step 3. The quantity of required LP (M_{LP}):

$$M_{LP} = M_B \times F \quad (5)$$

where F denotes the F/A ratio.

Step 4. The quantity of required CTP (M_{CTP}):

$$M_{CTP} = \frac{M_B \times F}{\rho_{LP}} \times \rho_{CTP} \quad (6)$$

where ρ_{LP} denotes the density of LP in ton/m³.

Subsequently, the present value (NPV) and benefit-cost ratio (BCR), defined as Eqs. (7) and (8) are adopted to evaluate the productivity of total economic profits [45,46]. To evaluate and compare the present worth of an investment regarding future cash flows, NPV and BCR calculate the present value of annual benefits (B_i) and costs (C_i) at time i over the period T by discounting them at the rate r . The project is considered as economically feasible if $NPV > 0$ and $BCR > 1$.

$$NPV = \sum_i B_i(1+r)^{-i} - \sum_i C_i(1+r)^{-i} = TB - TC_i = 0, 1, \dots, T \quad (7)$$

$$BCR = \frac{\sum_i B_i(1+r)^{-i}}{\sum_i C_i(1+r)^{-i}} = \frac{TB}{TC} \quad i = 0, 1, \dots, T \quad (8)$$

where $B_i = \sum_i b_i$, b_i denotes the segments of benefit at i years; $C_i = \sum_i c_i$, c_i denotes the segments of cost at i years; r is the discount rate and is anticipated to be 15% referring to previous studies [10,47]. T denotes period time and was set as nine to obtain the ten-year return; TB and TC is the total benefit and total cost in this period (10 years), respectively, with respect to dynamic investigation.

During the CBA process, only the material profits of CTP replacement are considered, and the following prerequisite anticipations are made:

- (1) The replacement of CTP is uninterrupted for years.
- (2) The acquisition rate of CTP is zero.
- (3) The inconsistent costs stemmed from the difference in workmanship (such as grinding of fillers), energy consumption and machinery are disregarded.
- (4) The transportation cost is calculated based on 20 km (local tailings producers).
- (5) The calculated costs and benefits are averaged for the next calculation period (10 years)

Referring to previous studies [10,44,48], the unit cost of individual components is listed in Table 4. The benefit for individual year B_i can be calculated as $P_L \times M_{LP} + P_D \times M_{CTP}$, and the cost for each year C_i can be calculated as $P_T \times M_{CTP}$.

3. Results and discussion

3.1. Physiochemical properties of fillers

3.1.1. Chemical composition

Table 5 lists the chemical compositions of CTP and LP. In LP, the dominating compound is CaO which accounts for approximately 92.1 %. In terms of CTP, the main components are CaO, SiO₂, and Al₂O₃, their mass proportions are in the order of SiO₂ > Al₂O₃ > Fe₂O₃. The cumulative mass proportion of SiO₂, Al₂O₃, and Fe₂O₃ is more than 77.05 %, which exceeds the required value (> 70 wt%) as mineral filler specified in Chinese standard JTGF20–2015 (Technical Guidelines for Construction of Highway Roadbases). The CTP has more acidic components (SiO₂) than LP although both of their main chemical compositions are dominated by alkaline oxides, indicating its inferior bonding potential with asphalt [10]. This is consistent with the relatively higher hydrophilic coefficient of CTP compared to LP. It is worth noting that the oxides composition of tailings varies depending on process activity, geological location, and extraction depth [23]. Pei et al. [49] obtained lower SiO₂ (28.6 %) and Al₂O₃ (26.1 %) but higher CaO (29.7 %) values. Kasap et al. [50] obtained 23.9 % SiO₂, 7.1% Al₂O₃, 4.3 % CaO and 41.6 % Fe₂O₃. Additionally, studies [14,23] have proposed a similar value of the hydrophobic coefficient for other types of mine tailings such as iron tailings, and they proposed that the high hydrophobic coefficient characteristic of the tailings may lead to higher asphalt binder consumption and unsatisfactory workability for the resultant mixture, which may limit the utilization rate of CTP in the asphalt mixture [14,23]. This aspect deserves further investigation and proper technical implications such as adopting pilot study to ascertain the maximum content CTP that could be possibly applied in asphalt mixtures.

3.1.2. Particle size distribution

The particle size distribution (PSD) and cumulative passing of CPT and LP are depicted in Fig. 6. In general, the PSD of CTP and LP are similar which is in the range of from 2 μm to 110 μm. There is a small proportion of particles larger than 75 μm, which is related to the phenomenon of CTP agglomeration under the atmospheric environment. The characteristic PSD values (D₁₀, D₅₀, and D₉₀) are listed in Table 6, indicating that the CTP filler is finer than the LP filler.

3.1.3. Surface characteristics

The representative microscopic characteristics of CTP and LP are displayed in Fig. 7(a) and (b), respectively. Although particles with various shapes and sizes in the range of 3 μm to 100 μm are captured for both fillers, different morphological structures can be differentiated from the typical large particles. From the surface characteristics, plenty of fine granular and floccular fines are attached on CTP while fewer fines are attached on LP. In addition, the surface texture of CTP is relatively rough compared to LP which has a smoother surface. The rough surface characteristic of CTP would be beneficial for its adhesion property to asphalt, balancing with the negative characteristic of being more acidic than LP. More open pores with increased tortuosity can be observed in CTP. The large specific surface area and rough surface texture of CTP particles favour its absorbance of free asphalt and the bonding to the asphalt binder, accordingly making the asphalt mastic system more stable [6,51].

3.1.4. Specific surface area

The specific surface areas of CTP and LP analysed by BET are 2.63 m²/g and 1.21 m²/g, respectively. The specific surface of CTP is similar to siliceous tailings (2.33 m²/g) reported in Ref [52]. As displayed in Fig. 8(a), both adsorption and desorption isothermal curves of CTP and LP present loop hysteresis characteristics at the mesopore range, indicating the relatively weak N₂ and solid interaction at the micropore and macropore ranges. The characteristic hysteresis loop implies that there are plenty of sheet-like particles and fracture holes in both CTP and LP. The slit-like holes formed by the interparticle accumulation, and the slender cracks of powder particles make it both fillers hard to reach adsorption saturation at high relative pressure. The pore size distributions of CTP and LP particles are shown in Fig. 8(b). CTP presents a more uniform pore size distribution across the pore size range of 3–120 nm while LP presents a relatively uneven pore size distribution across identical pore ranges. There is a high frequency of pores in LP particles distributed in the ranges of 3–6 nm and 80–120 nm, and fewer mesopores distributed in the range of 10–20 nm. The characteristics of a larger specific area, uniform pore size distribution, and rougher surface texture for CTP should promote the adsorption of asphalt on its particle surface, potentially leading to enhanced filler-particle interaction.

Table 4

The unit cost of individual components in CBA.

P_L [USD/ton]	P_D [USD/ton]			P_T [USD/ton]
	Tailing dam	Surface disposal method	Geotextile method	
43.00	2.25	2.29	7.39	6.20

Notes: P_L denotes the cost of LP; P_D denotes the disposal cost of CTP; P_T denotes the transportation cost. The cost of the tailing dam is the selective stream that counts for the disposal cost of CTP in the present study.

Table 5
Chemical compositions [wt%] of CTP and LP.

Fillers	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	K ₂ O	MgO	Na ₂ O	SO ₃	LOI
LP	92.1	1.5	0.8	4.1	—	0.8	—	—	0.7
CTP	6.75	49.24	21.19	6.63	9.02	1.47	0.47	3.43	1.8

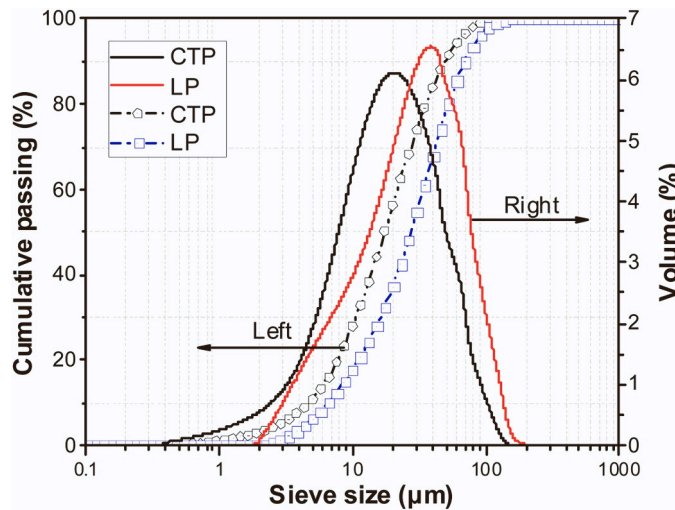


Fig. 6. The particle size distribution of CTP and LP.

Table 6
Critical index of particle size distribution (µm).

Filler type	D ₁₀	D ₅₀	D ₉₀
CTP	2.01	10.29	39.86
LP	6.60	27.30	69.30

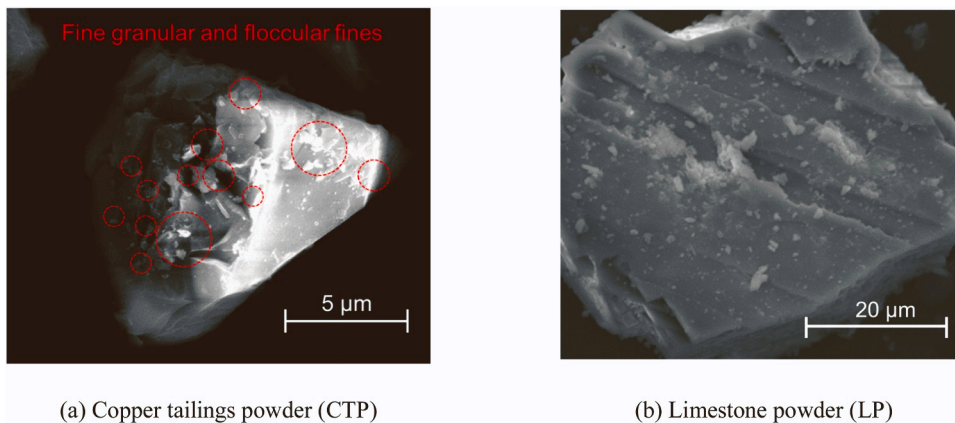


Fig. 7. Microscale morphology of fillers.

3.2. Physicochemical properties of asphalt mastics

3.2.1. Penetration, ductility, and softening point

The test results (softening point and ductility) of tailing-asphalt mastics are illustrated in Fig. 9(a) and (b). The asphalt softening point is an indicator of the viscosity of asphalt and is the temperature point at which the phase change starts to occur. Thus, high-temperature performance and temperature sensitivity can be reflected by the softening point. It is seen that the softening points of

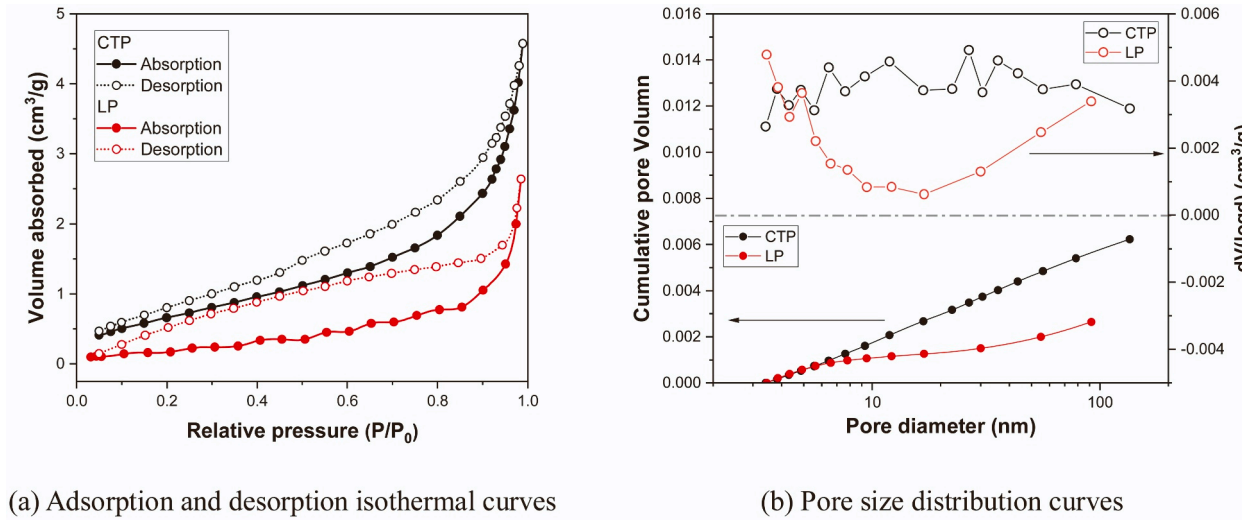
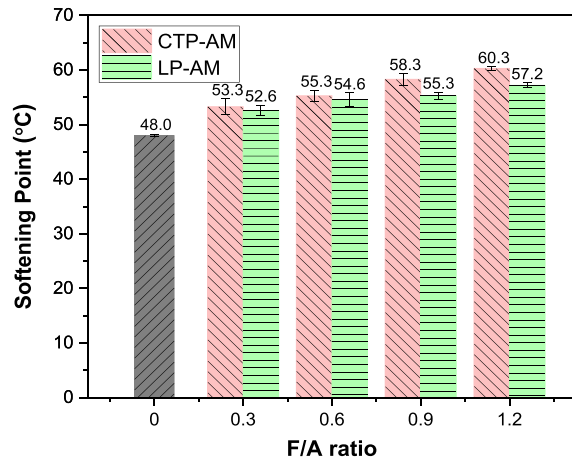
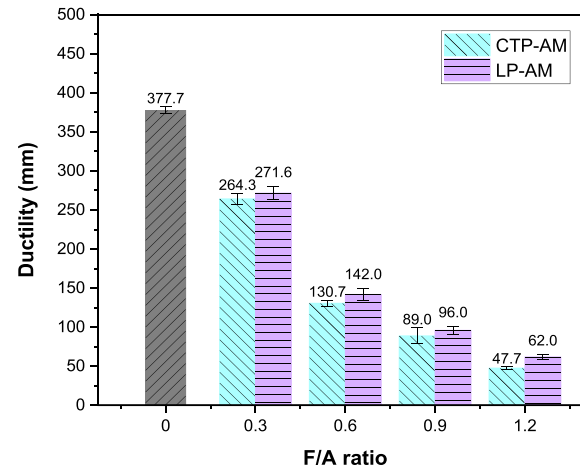


Fig. 8. Brunauer-Emmett-Teller results of fillers.



(a) Softening



(b) Ductility at 15 °C

Fig. 9. Penetration of tailing-asphalt mastics.

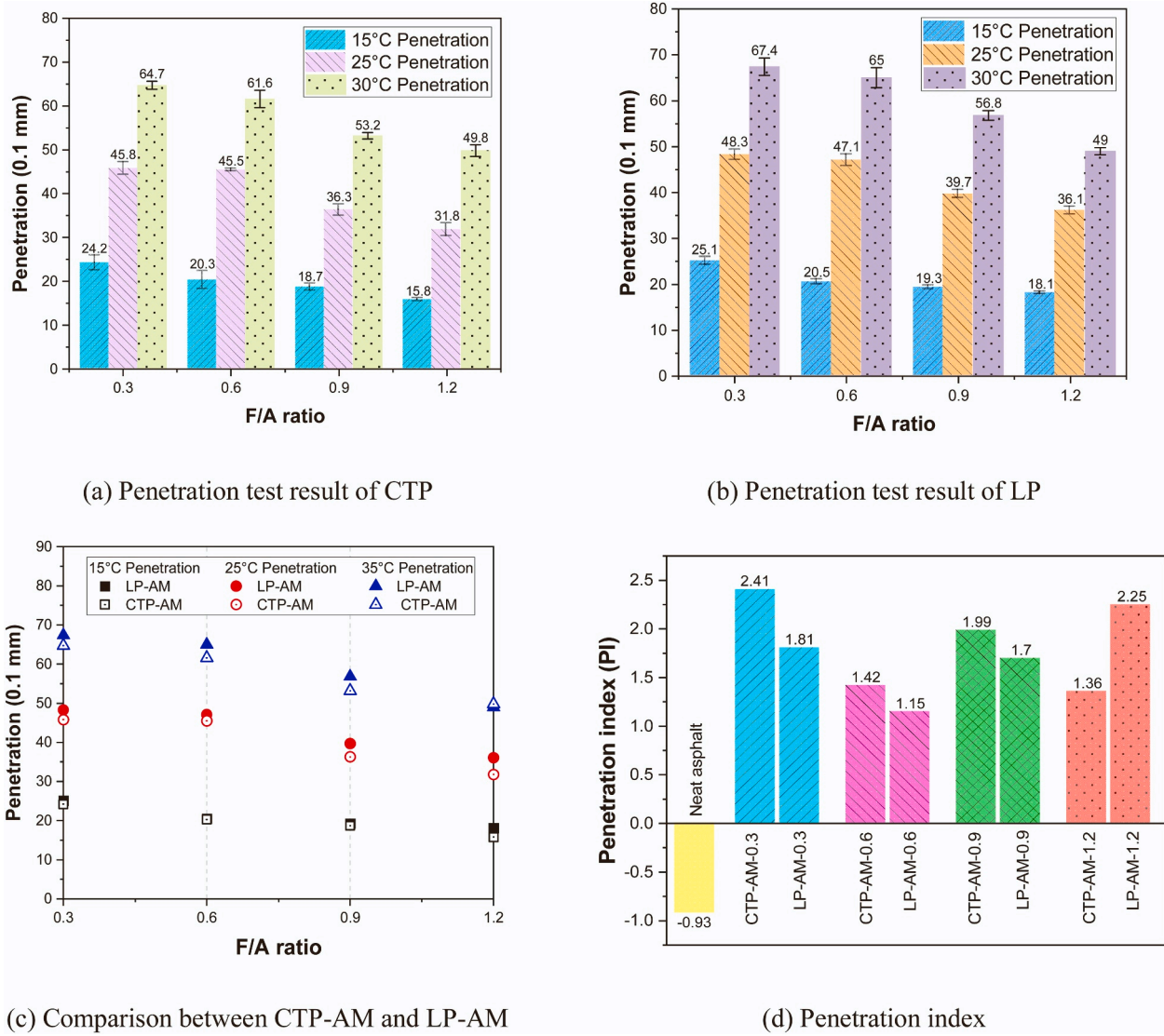


Fig. 10. Penetration of tailing-asphalt mastics.

both asphalt mastics are higher than neat asphalt and the softening point is incrementally improved with the increasing F/A ratio, which is aligned well with the previous study [53]. Contrarily, the ductility of asphalt mastics is incrementally decreased with increasing filler concentration, which is mainly ascribed to the reduced proportion of structural asphalt.

In terms of the difference between CTP and LP asphalt mastics, the CTP-asphalt mastics outperform LP-asphalt mastics at the same filler concentrations in terms of softening point while it underperforms LP-AM in terms of ductility. In particular, the improvement in softening point and the degradation in ductility for CTP-asphalt mastics compared to LP-asphalt mastics seems to be more pronounced at higher filler concentrations. In addition, once the F/A ratio exceeds 0.6, the failure mode of tailing-asphalt mastic transferred from viscous failure to brittle failure that presents a peculiar brittle cross-section at the tensile fracture. This phenomenon shows a good agreement with previous studies and is mainly attributed to the stress concentration as a result of excessive amounts of mineral fillers [54,55]. The ductility of 130.7 mm and 142.0 mm, respectively for CTP-AM-0.6 and LP-AM-0.6 implies the tailings-asphalt mastic still possesses good plasticity and ductility at a low F/A ratio of 0.6.

The consistency of asphalt mastic can be reflected by the penetration test. In general, a softer asphalt mastic is associated with a larger penetration, indicating a smaller consistency. A larger consistency of asphalt mastics at a higher temperature is desirable because it implies a higher temperature at the optimum construction consistency. The penetration results of CTP and LP asphalt mastics at different filler concentrations are displayed in Fig. 10 (a) and (b), respectively. The penetration of both asphalt mastics declined with increasing filler concentration at the same temperature. Although CTP asphalt mastics outperform LP asphalt mastics, the improvement in consistency is relatively limited and seems to be independent of the temperature at the selective range as depicted in Fig. 10 (c). Wei et al. [10] found the consistency of iron tailings-asphalt mastics with the F/A ratios 0.6–1.2 outperformed the LP asphalt mastics at the higher temperature range of 135–175 °C, and this increment is more pronounced with increasing filler concentrations. Similarly, Lei et al. [55] conducted penetration tests on asphalt mastic with recycled concrete powder (RCP) as an alternative filler to substitute LP. It was observed that the consistency is enhanced with increasing RCP replacement ratio from the F/A ratio of 0.6 ~ 1.2. They attributed the improvement to the better stiffening effect provided by a larger specific area of iron tailings particles than LP. Hence, it is predictable that CTP can improve the high-temperature properties as a consequence of an excellent stiffening effect.

CTP particles possessing a rough surface texture and high specific area are favourable for forming a high-viscosity ‘structural asphalt’ layer on its surface, which is beneficial for the stiffness and hardness development of the tailings-asphalt mastics [55,56]. In addition, the temperature sensitivity of asphalt can be described by a parameter PI shown. A lower temperature sensitivity of asphalt materials is represented by a higher PI value [57]. Temperature sensitivity refers to the susceptibility in viscosity and plasticity of asphalt materials in response to temperature variation.

The PI values for asphalt mastics with increasing filler concentrations are displayed in Fig. 10 (d). According to the relevant standard, the PI value for asphalt mastic as paving materials should be in a range of -1.5 to 1.0 to ensure the durability requirements. Nowadays, severe climatic conditions and increasing traffic volume set a higher performance requirement for newly constructed asphalt pavement. In such a background, the PI value is preferably higher than 2 to achieve low-temperature sensitivity and good rutting resistance [58]. Studies have proposed that the PI of asphalt mastics in the range of -2.0 to 2.0 pertains to solution-gel structure, while PI higher than 2.0 pertains to gel structure. Gel structure can provide improved temperature sensitivity to asphalt [59,60]. Asphalt mastics with gel-structure type will generate an elastic deformation when subjected to minimal or short-time loads and a viscoelastic deformation will occur when stress beyond the yield value [59]. In terms of the difference between CTP-AM and LP-AM, the PI of CTP-AM is always higher than LP-AM except for the case of F/A ratio of 1.2. The higher PI of CTP-AM implies its better low-temperature behaviour.

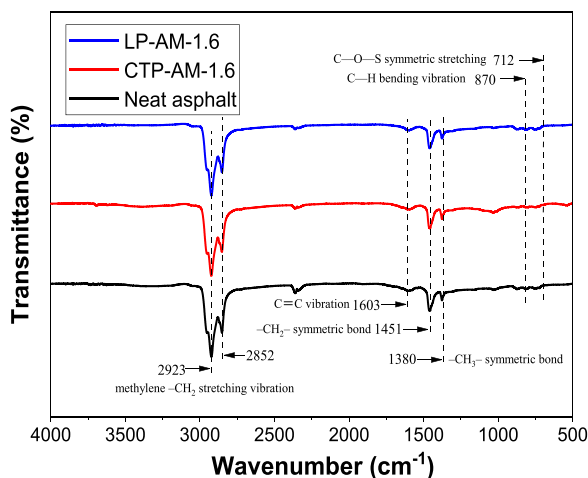


Fig. 11. Fourier-transform infrared spectroscopy test results.

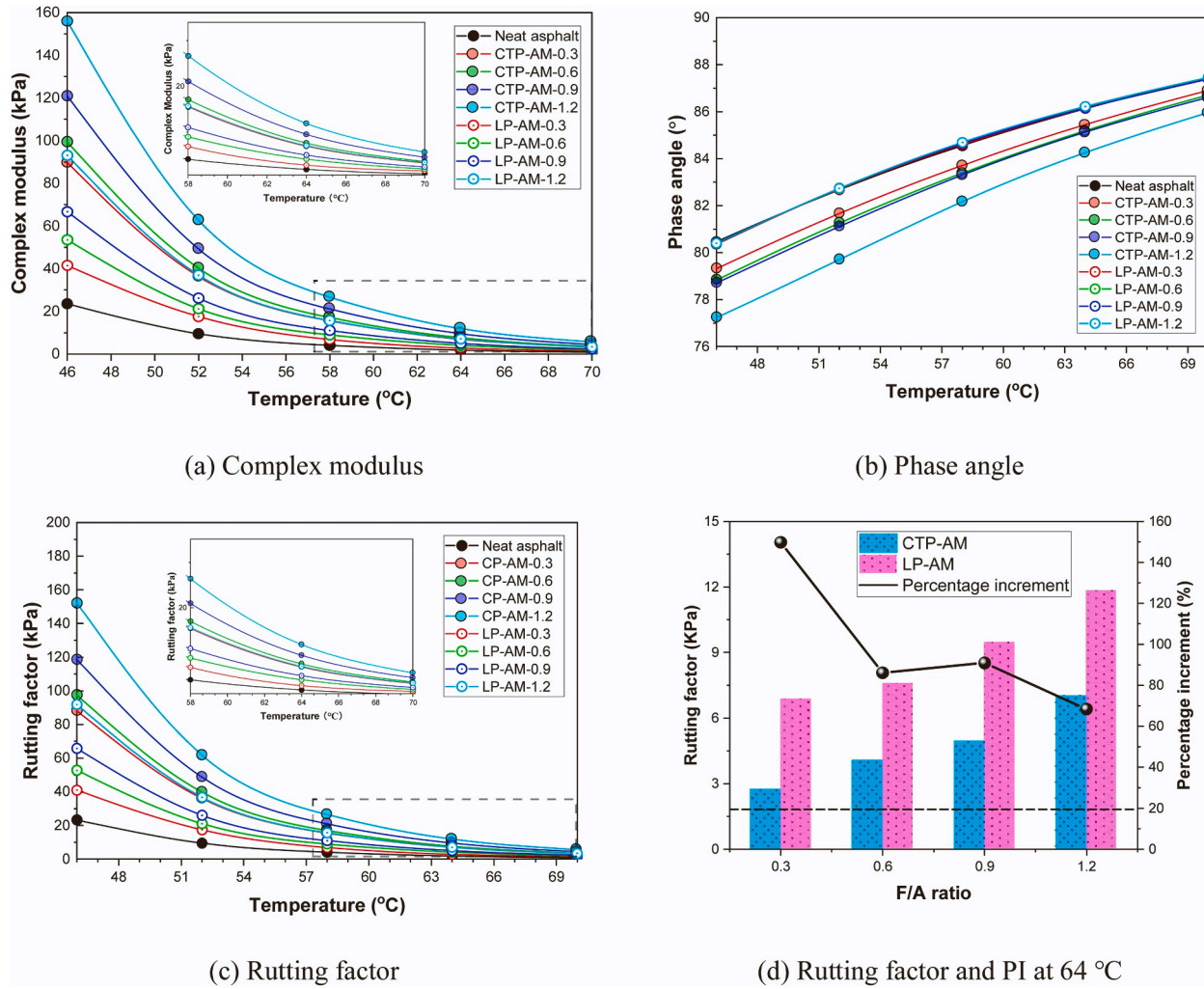


Fig. 12. Rheological properties and rutting factor for neat asphalt and asphalt mastics based on temperature sweeping test.

3.2.2. Fourier-transform infrared spectroscopy (FTIR)

Information about the chemical bond and functional group can be ascertained via the FTIR test. The infrared spectrogram of neat asphalt, CTP-AM-1.6, and LP-AM-1.6 are displayed in Fig. 11. It is seen that the characteristic absorption peaks for all groups are nearly unity. The result indicates that CTP is similar to LP, which mainly functions as an inert filler and there is no newly generated functional group.

3.3. In-service pavement performance of asphalt mastics

3.3.1. Rheological properties and rutting factor

To investigate the elastic and viscous behaviour at different temperatures, the variation regularity of complex modulus ($|G|^*$) and phase angle (φ) of neat asphalt, CTP asphalt mastics, and LP asphalt mastics are displayed in Fig. 12 (a) and (b), respectively. While the $|G|^*$ of asphalt mastics present an exponential decreasing tendency as the temperature rises, the relative ranking of individual groups is relatively stable. This phenomenon can be attributed to the fact wherein filler particles commence rotation and aggregation at elevated temperatures, thus leading to a significant increase in the viscosity of the asphalt binder [61]. The clear regularity that the increment of $|G|^*$ as the filler proportion increases (increasing F/A ratio) at all temperatures is aligned well with the results previously reported [55, 62,63]. In terms of the difference between CTP and LP asphalt mastics, it is seen that the replacement of CTP compared to LP evidently enhances the $|G|^*$ of asphalt mastics. At the identical filler proposition, the $|G|^*$ of CTP asphalt mastics is approximately 35~65 % higher than that of LP asphalt mastics, even the $|G|^*$ curves are nearly overlap for CTP-AM-0.3 and LP-AM-1.2. The result of $|G|^*$ indicates that the introduction of CTP can more effectively improve the stiffness of asphalt mastics compared to LP, inducing the hardening effect [64].

Contrasting with $|G|^*$, φ seems to be limitedly affected by filler type and concentration, especially for LP, but more significantly influenced by the temperature. For both CTP and LP asphalt mastics, the temperature sensitivity is very similar as reflected by the near comparable curve slope, which implies a similar transformative rate of asphalt mastic from elastic to viscous state [65]. Moreover, it is seen that the introduction of CTP and increasing filler proportion reduce the φ to certain level. CTP-AM-1.2 exhibits the lowest φ value among all groups. In general, a larger phase angle value is associated with more viscoelastic components [66], which is consistent with the increasing filler proportion. The above results can be interpreted by the finer particle size, higher specific area, and rough surface texture of CTP particles relative to LP, which absorbs more wrapped structural asphalt enclosing the CTP particles and thus limits the lower rheological capability of asphalt interspersed the CTP particles.

The calculated rutting factor ($|G|^*/\sin \varphi$) in Fig. 12 (c) reflects the viscous component of binder strength, which can characterize the rutting performance of asphalt mastic in its non-destructive state. This index manifests the vehicle-induced deformation resistance of asphalt pavement at high temperatures [67]. The higher the rutting index, the stronger the anti-rutting deformation of asphalt [68]. At the unity temperature, $|G|^*/\sin \varphi$ is progressively increased as the F/A ratio increases, implying a more stable filler-asphalt system. Despite the regularity that $|G|^*/\sin \varphi$ descends exponentially with the raised temperature, the relative ranks of each CTP and LP asphalt mastics generally coincide with those manifested in those of complex modulus. The results illustrate that $|G|^*/\sin \varphi$ is enhanced significantly by the substitution of CTP independent of the F/A ratio and temperature.

Fig. 12 (d) displays the $|G|^*/\sin \varphi$ of asphalt mastics at 64°C to extract more details wherein the $|G|^*/\sin \varphi$ of neat asphalt is presented as the baseline. The percentage increment (PI) of CTP-AM relative to LP-AM is calculated based on Eq. (9).

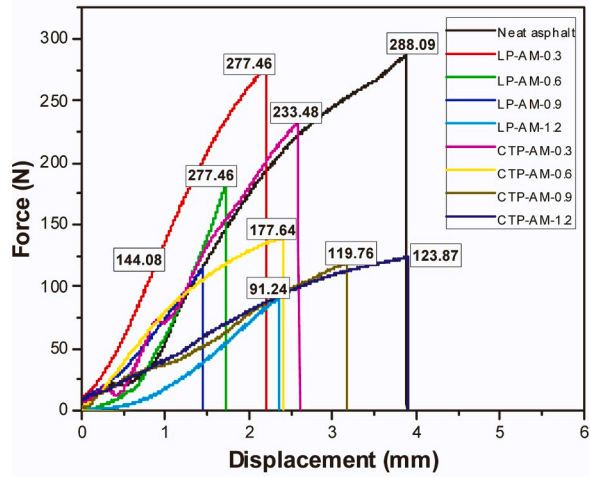
$$PI = \frac{(|G|^*/\sin \varphi)_{CTP} - (|G|^*/\sin \varphi)_{LP}}{(|G|^*/\sin \varphi)_{LP}} \quad (9)$$

where $(|G|^*/\sin \varphi)_{CTP}$ and $(|G|^*/\sin \varphi)_{LP}$ denote the rutting factor of CTP and LP at 64°C, respectively.

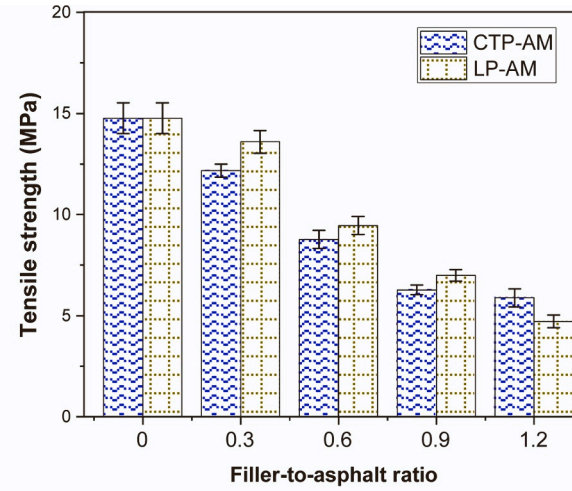
It is detected that the PI declines with increasing F/A ratio, demonstrating the descending of the improvement effect. Consequently, it shall be concluded that although the CTP as an alternative filler material to substitute the conventional LP can modify the stability of asphalt pavement at high temperature, the improvement efficiency of CTP-AM relative to LP-AM has gradually declined with the ascending filler concentration. In summary, the improvement of $|G|^*/\sin \varphi$ CTP-AM relative to LP-AM is a consequence of enhanced interaction between filler and asphalt. The pronounced stiffening effect of CTP is ascribed to its particle size, larger specific area, and rough surface texture, which facilitates the thicker asphalt film absorption by CTP particles. Consequently, there is a decreased quantity of free asphalt molecules and an increased quantity of structural asphalt molecules among the particles, thus leading to higher $|G|^*$ and enhanced rheological properties among filler particles. Hence, CTP asphalt mastic possesses better high-temperature performance, owing to its enhanced filler-particle interaction.

3.3.2. Fracture behaviour at a low in-service temperature

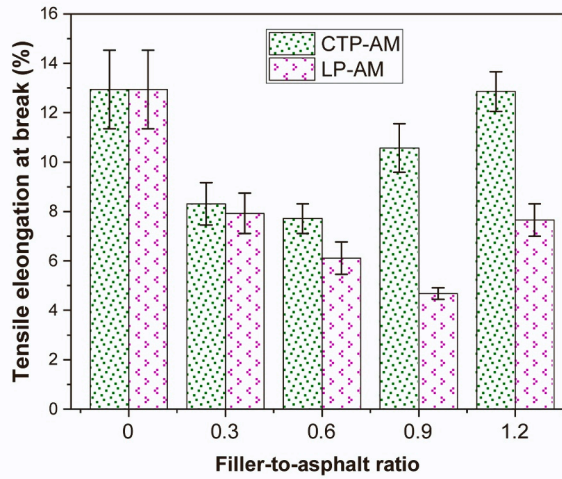
The fracture behaviour of asphalt mastics at low in-service temperatures is an essential parameter to assess the cracking resistance as paving material. The force-displacement curves of asphalt and asphalt mastics with various F/A are displayed in Fig. 13 (a). For all curves, it is seen that the loading force gradually grows with the displacement and then followed by an abrupt descent to zero with a clear fracture at the middle once reaching the peak load, suggesting a brittle failure pattern for all asphalt mastics at the low-temperature level if 15 °C. Compared to neat asphalt, the load force of tailings-asphalt mastic continuously declined with the increase of F/A ratio regardless of filler the type, which is ascribed to the weak adhesion between asphalt and powders in which low-temperature cracking is more prone to occur [69]. The fracture stress of LP-asphalt mastic outperforms that of CTP-asphalt when the F/A ratio does not exceed 0.9 in Fig. 13 (b). The drop in fracture stress is mainly ascribed to the reduced content of structural



(a) Representative force-displacement curves

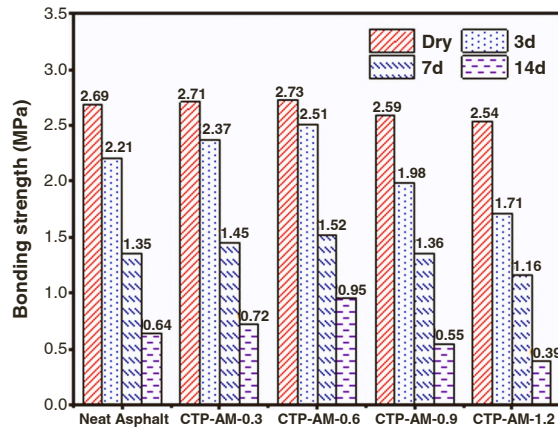


(b) Fracture stress

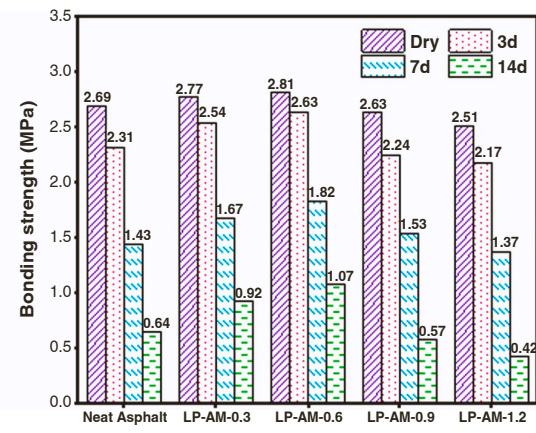


(c) Elongation at break

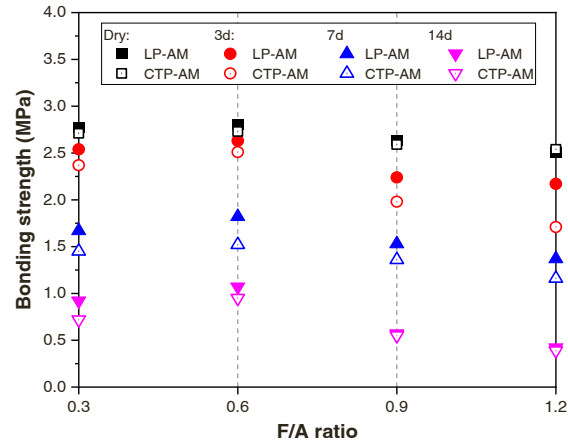
Fig. 13. DT test results of neat asphalt and asphalt mastics.



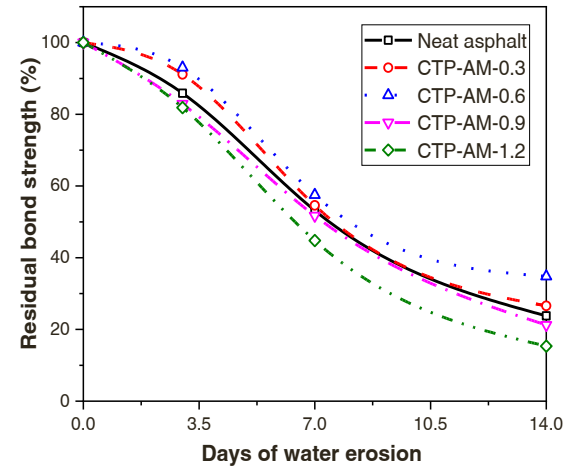
(a) Bond strength of CTP-AM



(c) Bond strength of LP-AM



(c) Comparison between CTP-AM and LP-AM



(d) Residual bond strength of CTP-AM

Fig. 14. Bond strength of aggregate-asphalt mastic interface after various periods of water immersion.

asphalt as a result of excess dosage of mineral fillers [70]. In addition, the stiffening effect of CTP on asphalt mastic due to its finer particle size distribution and more angular particle characteristics and through surface texture, these characteristics partially arise the occurrence of stress concentration at the interface, leading to the reduced fracture strength [71–74]. Moreover, CTP is wrapped by more structural asphalt because of its smaller particle size and larger specific area, leading to a less effective filling effect for CTP relative to LP [10].

Fig. 13 (c) shows tensile elongation at break as a performance indicator to further discriminate the fracturing resistance of asphalt mastics at low temperatures. For both asphalt mastics, the tensile elongation presents a firstly descending then ascending trend with an increasing F/A ratio. The lowest tensile elongation shows at the F/A ratio of 0.6 and 0.9, respectively for CTP and LP asphalt mastics. This phenomenon illustrates that the ductility is impeded until a certain F/A ratio, further increasing the F/A ratio to recover the durability, which discloses that increasing filler content above certain content is helpful to restore the low-temperature fracture behaviour in terms of tensile ductility. In terms of the difference between CTP and LP asphalt mastics, the elongation of CTP asphalt mastics outperforms that of LP asphalt mastics, especially at larger F/A ratios (F/A ratio ≥ 0.6). Chen and Peng [72] also observed that the tensile fracture energy of asphalt-mineral filler mastics at low temperature was also found to restore with the increasing F/A ratio. Indeed, it is widely accepted that fracture stress is not only dependent on the filler nature but also on the interaction between asphalt binder and filler [36]. It is deduced that the characteristics of rough surface texture and angular particle of CTP compared to LP can promote the bonding condition between tailings and asphalt binder, thus promoting the effective elongation recovery at a higher F/A ratio.

3.3.3. Bonding strength and moisture resistance of aggregate-mastic interfaces

The bonding strength of aggregate-mastics interfaces in dry conditions and after various periods of water bath immersions are illustrated in Fig. 14. (a) and (b). In general, the bonding strength initially ascends and then descends with increasing F/A ratio regardless of filler types and water immersion periods. With the prolonged water immersion time, all groups display a precipitous and continuous drop in bonding strength. In particular, the discrepancy among asphalt mastics at different F/A ratio obviously enlarged with prolonged water immersion time, implying that asphalt mastics with higher F/A ratio is more vulnerable to moisture damage. The limited discrepancy at the dry condition and the difference in terms of filler type (CTP or LP) seem to impart a negligible impact on the final value. This aligns well with previous studies and reveals that adhesion between aggregate and mastic is dominated by asphalt properties at dry conditions [69]. Differently, the LP asphalt mastic outperforms CTP mastics at all F/A ratios after being subject to moisture conditions in Fig. 14 (c). It is evident that all groups obtained in dry condition possess the most superior bonding strength and the bonding strength of asphalt mastics are comparable with that of neat asphalt. The limited difference among individual groups reveals that the adhesion between aggregate and mastics is mainly dominated by the property of asphalt binder. Contrastingly, a significant discrepancy is manifested in mastics with various F/A ratios after moisture conditioning. With the prolonged water immersion time, all groups display a precipitous and continuous drop in bonding strength. The residual bonding strength of CTP-AM-0.6 is approximately 93.0 %, 57.5 %, and 34.8 % after 3 days, 7 days, and 14 days of moisture conditioning, while these values of

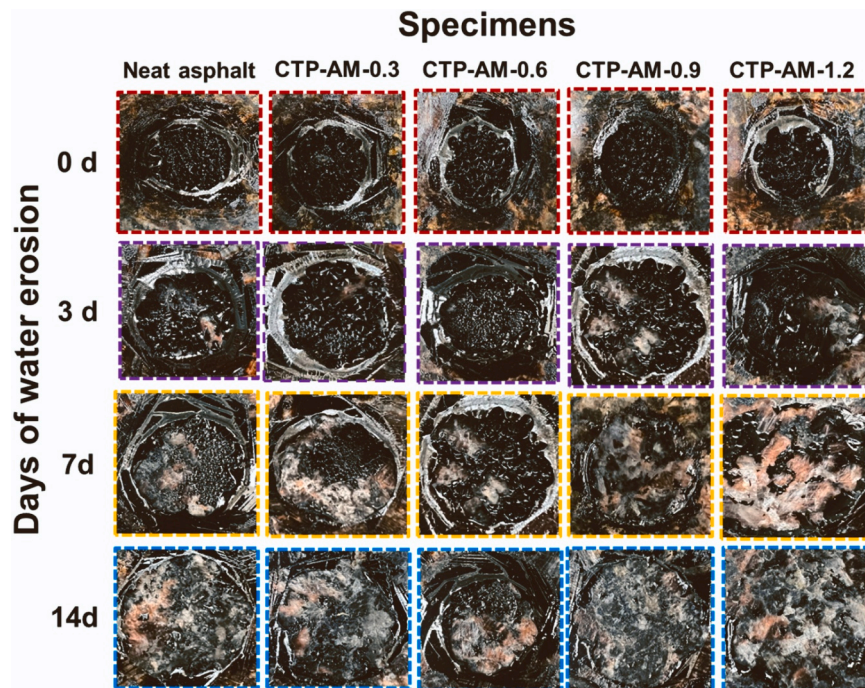


Fig. 15. Failure interfaces of neat asphalt and CTP-asphalt mastics in adhesion test.

CTP-AM-1.2 diminish to 81.9 %, 44.8 %, and 15.4 %. The service span of corresponding asphalt mixtures especially serviced in pluvial regions will be detrimentally impacted if the asphalt mastics is pronounced to moisture attack [69].

The failure interfaces of neat asphalt and CTP-asphalt mastics are displayed in Fig. 15. Previous studies proposed the failure interface of aggregate-mastic systems can be sorted into three types, including adhesive, cohesive and adhesive-cohesive mix [75]. Cohesive failure is manifested when the cohesive strength of asphalt mastic is surpassed by the adhesive strength between the asphalt mastics and the aggregate substrate [76]. Conversely, adhesive failure occurs when the cohesive strength of the asphalt mastic exceeds the mastic-aggregate adhesive strength [77]. It is witnessed that all groups in dry condition displayed cohesive failure type. After moisture conditioning, the cohesive failure gradually transforms into an adhesive-cohesive mix, and finally, the adhesive failure, which is mainly ascribed to the fact that moisture erodes and damages the aggregate-mastic bonding. Notably, more residual asphalt is left on the failure interfaces of CTP-AM-0.6, which is not contingent on the duration of moisture conditioning. The interface of CTP-AM-0.6 subjected to 14 days of immersion still manifests the adhesive-cohesive mix failure whereas the interfaces of the other four groups clearly show an adhesive failure. The retain of more cohesive failure demonstrates that CTP-AM-0.6 is less vulnerable to moisture damage. Overall, it is concluded that the moisture resistance of CTP-AM is only slightly inferior compared to LP-AM, demonstrating CPT is a suitable candidate as an alternative mineral filler.

3.4. Environmental impact and economic evaluation

3.4.1. Leaching toxicity

Copper tailings, like other mine tailings, probably contain various toxic substances and heavy metals. When it is applied to pavements, it is easily leached by surface water and groundwater [6]. Although CTP particles are wrapped by the asphalt molecules, heavy metal elements may still erode the soil with runoff especially over an extended period, hence irreversibly contaminating the natural circulation system of water, soil, and atmospheric environment. Consequently, leaching toxicity tests are vital to be performed to assess its potential leaching risk, and to identify the necessity of further processing prior to large-scale utilization. The toxicity test results including acid digestion test performed on CTP and TCLP tests performed on CTP and CTP-asphalt mastics. The threshold values of Class I groundwater (highest standard in groundwater hierarchy, complying with human health and safety) according to GB/T 14848-93 [78], and limitations specified in GB 2019.7–2019, 2019 (leaching toxicity of inorganic elements and compounds) [42] are displayed in Table 7. In conjunction with XRF results, the selective heavy metal elements are Co, Cr, Cu, Ni, Pb, and Zn. The acid digestion result reveals that exceed the regulatory limits for Class I groundwater environments. Among them, Cu shows the highest exceedance, surpassing the specified limit by 489 times. The acid digestion result indicates that there is a significant presence of heavy metal elements in copper tailings, directly depositing these tailings without proper treatment poses a high risk of groundwater contamination. The leaching behaviours of heavy metals are highly dependent on pH values, with all heavy metals exhibiting elevated leaching capacities in acidic environments. When the pH value exceeds 5, the leaching capacity of heavy metals significantly diminishes [79]. Therefore, the concentrations of heavy elements detected from the TCLP test are significantly lower compared to the acid digestion test; the concentrations of Cu, Pb, and Cr elements decreased by 98.3 %, 97.8 %, and 97.8 %, respectively.

In terms of the leaching results of CTP-asphalt mastics, in addition to the normal in-service temperature of 36 °C, the test was also performed at the additional elevated temperature of 70 °C, which is the maximum internal temperature of asphalt road reaches in the summer season for subtropical regions. Studies [80,81] have experimentally verified that the dissolubility and leaching rate of heavy metals in tailings were positively correlated to the temperature. The leaching results of CTP-asphalt mastic under 36 °C were much lower than the standard limits of GB/T 14848-93. Similarly, all toxic metal concentrations leaching from mastic under 70 °C below the limitations specified in GB/T 14848-93 except for Cu concentration. However, all metal concentrations are far below the toxic limits specified in GB 5085.7–2019 and such temperature may only be reached at a very limited period during the daytime of the summer season, implying that CTP contamination risks in temporary leaching and can be directly utilized in a large scale. Overall, the leaching results indicate that the asphalt mastic has an excellent toxic immobilization capacity in stabilizing heavy metals in CTP.

3.4.2. Cost-benefit analysis

The cost-benefit analysis (CBA) is performed in this section. The required quantity of M_H , M_B , M_{LP} , and M_{CTP} are presented in Table 8. The results indicate that 1 km of asphalt pavement construction consumes 18.42–73.69 tons of CTP while saving 19.51–78.06 tons LP. Benefiting from the advantages of high-riding quality and low capital cost, asphalt pavement has become the primary choice for the type of newly paved highways in the majority of countries nowadays [82]. As a matter of fact, the highway mileage is increasing by more than 100 thousand km annually in China wherein asphalt pavement dominates the type of newly constructed pavements [83]. Based on the estimation of the most conservative scenario with the exclusion of road maintenance and low-grade pavement renovation, it is anticipated that approximately 60 % of newly constructed highways is asphalt pavement, the large-scale utilization of CTP can at least save the consumption of limestone by approximately 7.8 million tons and approximately 7.4 million tons of copper tailings inventory could be recycled annually. Thus, the application of CTP as an alternative filler in asphalt pavement construction will alleviate the heavy burden of natural resource extraction but also is of significance for the field of sustainable construction materials and the built environment.

The results of TB , TC , NPV , and BCR based on defined function unit (1 km HMA asphalt pavement) are displayed in Fig. 16. It is observed that the total benefit TB and TC considering the return by the discount rate (10 years) are growing with the increase of the F/A ratio. The excellent economic feasibility with well-maintained profitability can be reflected by positive NPV and BCR greater than 1. Although NPV has considerably ascended and BCR has slightly descended increasing the F/A ratio, the relatively high BCR value greater than 7.4 confirms the excellent stability of the project in terms of profitability, which is negligibly affected by the variation of

Table 7
Toxic metal element traces in the leachates of CTP and the threshold value stated in the standards.

	Operating condition	Toxic metal elements	Co	Cr	Cu	Ni	Pb	Zn
CTP	Acid digestion	Contents [$\mu\text{g/L}$]	26	362	4890	51	324	1570
	TCLP		0	8	82	0	7	30
CTP-asphalt asphalt	36 °C		0	2	1	0	0	2
	70 °C		0	4	44	0	4	14
Threshold values according to GB/T 14848-93 [$\mu\text{g/L}$]			5	5	10	2	5	50
Toxicity threshold according to GB 5085.7-2019 [$\mu\text{g/L}$]			80000	5000	100000	100000	5000	100000

Table 8
Required quantity of M_H , M_B , M_{LP} , and M_{CTP} for two fillers at different F/A ratios.

F	M_H [ton/km]	M_B [ton/km]	M_{LP} [ton/km]	M_{CTP} [ton/km]
0.3	1316	65.05	19.51	18.42
0.6			39.03	36.85
0.9			58.54	55.27
1.2			78.06	73.69

the F/A ratio.

Overall, upon the analysis of environmental impact and economic evaluation, the CTP could be deemed to be a suitable alternative filler material to replace the conventional LP. It is also worth noting that the implicit cost benefit provided by beneficiation stages has not been counted in the analysis. Consequently, the application of CTP not only alleviates the heavy burden of natural resource extraction and built environment protection but also provides lucrative economic profits to relevant construction enterprises, which is a win-win for both sides.

4. Conclusions

The feasibility of recycling copper tailing as an alternative filler material to substitute the conventional limestone filler in paving asphalt mastic is comprehensively investigated in this study. The main findings and conclusions were summarized as follows:

- (1) The particle size distribution of CTP was relatively finer than LP. In terms of surface characteristics, microstructural characterization, and BET analysis indicate that CTP possesses a rougher surface, larger specific surface area, and uniform pore size distribution, particularly across the mesopores range than LP. These characteristics should promote the adsorption of asphalt on its particle surface, potentially leading to enhanced filler-particle interaction, which provides the groundwork for the utilization of CTP as a suitable alternative filler.
- (2) The CTP-asphalt mastic outperforms LP-asphalt mastic at the same filler concentration in terms of softening point while it underperforms LP-asphalt mastic in terms of ductility. In particular, the improvement in softening point and the degradation in ductility for CTP- asphalt mastic compared to LP- asphalt mastic seems to be more pronounced at higher filler concentrations.

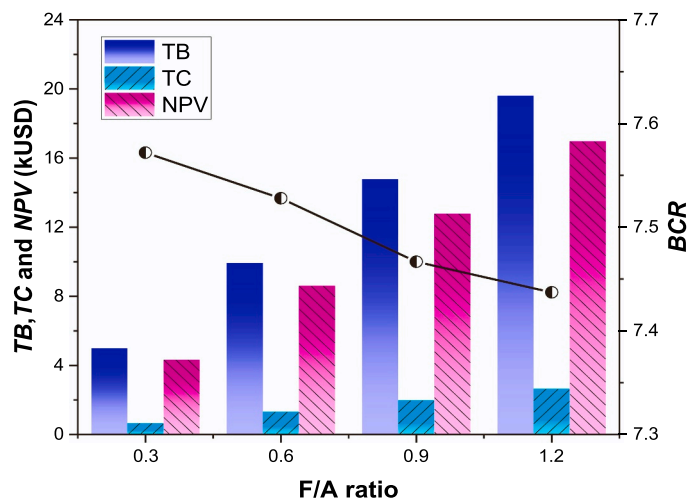


Fig. 16. The economic effectiveness of applying CTP to 1 km of asphalt pavement.

The penetration index of CTP-asphalt mastic is higher than LP asphalt mastic except for the case of F/A ratio of 1.2. The higher PI of CTP-asphalt mastic implies its better low-temperature behavior.

- (3) FTIR analysis reveals that CTP is similar to LP, which mainly functions as an inert filler and there is no newly generated functional group. There were no chemical changes that occurred at the filler-asphalt bond, and the asphalt-filler interaction for both CTP and LP is mainly the physical interaction.
- (4) The results of the temperature sweeping test indicate that although phase angle ϕ is limitedly affected by filler type, the complex modulus $|G|^*$ is significantly enhanced when CTP substitutes the LP, which promotes better high-temperature performance. This is aligned well with a considerable increase in rutting factor $|G|^*/\sin \phi$. Nevertheless, the efficiency of this improvement gradually declined as the F/A ratio rose.
- (5) The results of the direct test at the low temperature indicate that although the fracture stress of LP-asphalt mastic outperforms that of CTP-asphalt when the F/A ratio does not exceed 0.9, the elongation of CTP asphalt mastics outperforms that of LP asphalt mastics, especially at larger F/A ratios. In terms of adhesion between aggregate-mastic interface, it is found that the moisture resistance of CTP-asphalt mastics is only slightly inferior compared to LP-AM asphalt mastics.
- (6) From the environmental and economic aspects, the application of CTP not only alleviates the heavy burden of natural resource extraction and built environment protection but also provides lucrative economic profits to relevant construction enterprises.
- (7) In this study, multiscale and multi-dimensional assessments were made between the properties of CTP-asphalt mastics and conventional LP-asphalt mastics in terms of physicochemical properties of fillers, physicochemical of asphalt mastics, in-service pavement performance of asphalt mastics, and environmental impact and economic evaluation. The well-maintained and even superior properties and performances, as well as environmental and economic benefits of CTP-asphalt mastics, imply its promising potential to be a suitable candidate as an alternative filler material reutilized in asphalt pavement.
- (8) Although the feasibility of recycling copper tailings as an alternative filler has been primarily verified in asphalt mastic, further tests concerning various performances of the mixture specimens should be studied to promote its practical implementation. Future efforts could be placed on more in-depth investigations regarding adhesion properties of aggregate-tailings modified asphalt mastic interface such as the nano and microscopic characterization of adhesion interface. Moreover, creep, fatigue and deformation behaviors should be performed to verify its performance under the long-term deterioration environment. Additionally, more comprehensive life cycle assessment and economic analysis are worth conducted.

Declaration of Competing 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.

Data availability

Data will be made available on request.

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References

- [1] M.M.A. Aziz, M.T. Rahman, M.R. Hainin, W.A.W.A. Bakar, An overview on alternative binders for flexible pavement, *Constr. Build. Mater.* 84 (2015) 315–319.
- [2] Y.B. Attahiru, M.M.A. Aziz, K.A. Kassim, S. Shahid, W.A.W.A. Bakar, T.F. NSashruddin, F.A. Rahman, M.I. Ahamed, A review on green economy and development of green roads and highways using carbon neutral materials, *Renew. Sustain. Energy Rev.* 101 (2019) 600–613.
- [3] F.A. Rahman, M.M.A. Aziz, R. Saidur, W.A.W.A. Bakar, M. Hainin, R. Putrajaya, N.A. Hassan, Pollution to solution: Capture and sequestration of carbon dioxide (CO₂) and its utilization as a renewable energy source for a sustainable future, *Renew. Sustain. Energy Rev.* 71 (2017) 112–126.
- [4] A.M.T. Simonsen, S. Solismaa, H.K. Hansen, P.E. Jensen, Evaluation of mine tailings' potential as supplementary cementitious materials based on chemical, mineralogical and physical characteristics, *Waste Manag.* 102 (2020) 710–721.
- [5] F. Wang, H. Wang, A. Al-Tabbaa, Leachability and heavy metal speciation of 17-year old stabilised/solidified contaminated site soils, *J. Hazard. Mater.* 278 (2014) 144–151.
- [6] A.B. Ghazi, A. Jamshidi-Zanjani, H. Nejati, Utilization of copper mine tailings as a partial substitute for cement in concrete construction, *Constr. Build. Mater.* 317 (2022) 125921.
- [7] O. Onuaguluchi, Ö. Eren, Rheology, strength and durability properties of mortars containing copper tailings as a cement replacement material, *Eur. J. Environ. Civ. Eng.* 17 (1) (2013) 19–31.
- [8] S.-C. Chen, M.-Y. Gao, W.-T. Lin, J.-F. Liang, D.-W. Li, Effects of incorporating large quantities of copper tailings with various particle sizes on the strength and pore structure of cement-based materials, *Constr. Build. Mater.* 329 (2022) 127150.
- [9] O. Karaca, Environmental impact of mine wastes: an overview of problems with mining sites in Turkey, remediation possibilities, and an example from Turkey, *Environ. Geotechnol.: Proc. EGRWSE 2018* (2019) 63–72.
- [10] Z. Wei, Y. Jia, S. Wang, Z. Li, Y. Li, X. Wang, Y. Gao, Utilization of iron ore tailing as an alternative mineral filler in asphalt mastic: High-temperature performance and environmental aspects, *J. Clean. Prod.* 335 (2022) 130318.
- [11] A. Gedik, A review on the evaluation of the potential utilization of construction and demolition waste in hot mix asphalt pavements, *Resour., Conserv. Recycl.* 161 (2020) 104956.

- [12] D. Oldham, R. Mallick, E.H. Fini, Reducing susceptibility to moisture damage in asphalt pavements using polyethylene terephthalate and sodium montmorillonite clay, *Constr. Build. Mater.* 269 (2021) 121302.
- [13] AIA, Annual Local Authority Road Maintenance Survey 2022, Asphalt Industry Alliance, Wrrington, United Kingdom, 2022.
- [14] L. Cao, J. Zhou, T. Zhou, Z. Dong, Z. Tian, Utilization of iron tailings as aggregates in paving asphalt mixture: a sustainable and eco-friendly solution for mining waste, *J. Clean. Prod.* 375 (2022) 134126.
- [15] Y. Bi, F. Guo, J. Zhang, J. Pei, R. Li, Correlation analysis between asphalt binder/asphalt mastic properties and dynamic modulus of asphalt mixture, *Constr. Build. Mater.* 276 (2021) 122256.
- [16] E.A. Oluwasola, M.R. Hainin, M. Aziz, Evaluation of asphalt mixtures incorporating electric arc furnace steel slag and copper mine tailings for road construction, *Transp. Geotech.* 2 (2015) 47–55.
- [17] T.M. de Sousa, Od.M.M. Neto, A.Ed.F.L. Lucena, E.R. Nóbrega, Enhancing workability and sustainability of asphalt mixtures: Investigating the performance of beeswax as a novel additive for warm mix asphalt, *Constr. Build. Mater.* 405 (2023) 133306.
- [18] L.F. da Costa, Od.M.M. Neto, A.L.F. de Macêdo, L.Cd.F.L. Lucena, Ld.F.L. Lucena, Optimizing recycled asphalt mixtures with zeolite, cottonseed oil, and varied RAP content for enhanced performance and circular economy impact, *Case Stud. Constr. Mater.* 20 (2024) e02707.
- [19] L. Li, T.-C. Ling, S.-Y. Pan, Environmental benefit assessment of steel slag utilization and carbonation: a systematic review, *Sci. Total Environ.* 806 (2022) 150280.
- [20] L. Li, Y. Jiang, S.-Y. Pan, T.-C. Ling, Comparative life cycle assessment to maximize CO2 sequestration of steel slag products, *Constr. Build. Mater.* 298 (2021) 123876.
- [21] D.B. Costa, O. de Medeiros Melo Neto, P.M.S.G. Luz, L.C. de Figueiredo Lopes Lucena, A.E. de Figueiredo Lopes Lucena, Influence of aging, RAP content, and recycling agent on the performance of asphalt mixtures, *Environ. Sci. Pollut. Res.* 31 (1) (2024) 1419–1441.
- [22] Fd.SdS. Carvalho, A.Ed.F.L. Lucena, Od.M. Melo Neto, D.B. Costa, A.M.G.D. Mendonça, R.K.B. de Lima, Characterization of asphalt mixtures with addition of drill-well gravel, *J. Mater. Civ. Eng.* 35 (7) (2023) 04023180.
- [23] T.M.R.P. de Moraes, Od.M.M. Neto, A.Ed.F.L. Lucena, Ld.F.L. Lucena, M.S. Nascimento, Viability of asphalt mixtures with iron ore tailings as a partial substitute for fine aggregate, *Transp. Res. Rec.* 2678 (2) (2024) 770–794.
- [24] Z. Wang, C. Xu, S. Wang, J. Gao, T. Ai, Utilization of magnetite tailings as aggregates in asphalt mixtures, *Constr. Build. Mater.* 114 (2016) 392–399.
- [25] E.A. Oluwasola, M.R. Hainin, M.M.A. Aziz, S.S.A.L. Mahinder Singh, Effect of aging on the resilient modulus of stone mastic asphalt incorporating electric arc furnace steel slag and copper mine tailings, *InCIEC 2014: Proceedings of the International Civil and Infrastructure Engineering Conference 2014*, Springer, 2015, pp. 1199–1208.
- [26] J. Choudhary, B. Kumar, A. Gupta, Application of waste materials as fillers in bituminous mixes, *Waste Manag.* 78 (2018) 417–425.
- [27] J. Choudhary, B. Kumar, A. Gupta, Performance evaluation of asphalt concrete mixes having copper industry waste as filler, *Transp. Res. Procedia* 48 (2020) 3656–3667.
- [28] E.A. Oluwasola, M.R. Hainin, M.M.A. Aziz, Comparative evaluation of dense-graded and gap-graded asphalt mix incorporating electric arc furnace steel slag and copper mine tailings, *J. Clean. Prod.* 122 (2016) 315–325.
- [29] Y. Ke, S.S. Zhang, M.J. Jedrzejko, G. Lin, W.G. Li, X.F. Nie, Strength models of near-surface mounted (NSM) fibre-reinforced polymer (FRP) shear-strengthened RC beams based on machine learning approaches, *Compos. Struct.* 337 (2024) 118045.
- [30] F. Qu, Y. Su, D. Lu, N. Li, X. Zeng, W. Li, Anti-cracking and shrinkage performance of sustainable concrete incorporating high-volume natural pozzolans: A case design for high-speed railway concrete slab tracks, *Case Study, Constr. Mater.* 20 (2024) e03207.
- [31] Y. Wang, J. Xu, W. Li, W. Dong, Improved conductive and self-sensing properties of cement concrete by PDMS/NCB-impregnated recycled fine aggregate, *Constr. Build. Mater.* 426 (2024) 136229.
- [32] Y. Xu, Y. Lu, L. Meng, J. Cheng, F. Ouyang, P. Duan, W. Li, H. Zhang, Y. Zhu, Z. Zhang, Performance and heavy metal leaching of porous geopolymer based on solid wastes, *Constr. Build. Mater.* 427 (2024) 136186.
- [33] D. Lu, F. Qu, P. Punetha, X. Zeng, Z. Luo, W. Li, Graphene oxide nano-engineered recycled aggregate concrete for sustainable construction: A critical review, *Dev. Built Environ.* 18 (2024) 100444.
- [34] M. China, Standard test methods of bitumen and bituminous mixtures for highway engineering: JTG E20-2011, China Communications Press, Beijing, China, 2011.
- [35] C. Wang, M. Wang, Q. Chen, L. Zhang, Basic performance and asphalt smoke absorption effect of environment-friendly asphalt to improve pavement construction environment, *J. Clean. Prod.* 333 (2022) 130142.
- [36] A. Roberto, E. Romeo, A. Montepara, R. Roncella, Effect of fillers and their fractional voids on fundamental fracture properties of asphalt mixtures and mastics, *Road. Mater. Pavement Des.* 21 (1) (2020) 25–41.
- [37] L.F. Walubita, E. Mahmoud, L. Fuentes, A. Prakoso, S.I. Lee, M. Souliman, J.J. Komba, Correlating the asphalt-binder high-temperature properties (DSR) to HMA permanent deformation (RLPD) and field rutting: a laboratory-field study, *Constr. Build. Mater.* 262 (2020) 120761.
- [38] Z. Fu, Y. Tang, F. Ma, Y. Wang, K. Shi, J. Dai, Y. Hou, J. Li, Rheological properties of asphalt binder modified by nano-TiO₂/ZnO and basalt fiber, *Constr. Build. Mater.* 320 (2022) 126323.
- [39] R. Xiao, P. Polaczyk, Y. Wang, Y. Ma, H. Lu, B. Huang, Measuring moisture damage of hot-mix asphalt (HMA) by digital imaging-assisted modified boiling test (ASTM D3625): recent advancements and further investigation, *Constr. Build. Mater.* 350 (2022) 128855.
- [40] Md.V. do Nascimento, Od.M.M. Neto, A.Ed.F.L. Lucena, T.D. Guerra, A.M. da Silva Lopes, E.P. do Nascimento, Investigation of the adhesion conditions of the micro-surfacing applied on asphalt concrete, *Case Stud. Constr. Mater.* 18 (2023) e02155.
- [41] ASTM D4541-17: Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers.
- [42] GB 5085.7-2019, 2019. Identification Standards for Hazardous Waste General Rules. Ministry of Ecology and Environment of the People's Republic of China.
- [43] Y. Cheng, Y. Qin, Aggregates breakage introduction to optimize gradation of multi-supporting skeleton asphalt mixtures, *Constr. Build. Mater.* 200 (2019) 265–271.
- [44] H. Zhang, H. Li, A. Abdelhady, N. Xie, W. Li, J. Liu, X. Liang, B. Yang, Fine solid wastes as a resource-conserving filler and their influence on the performance of asphalt materials, *J. Clean. Prod.* 252 (2020) 119929.
- [45] E. Hsu, Cost-benefit analysis for recycling of agricultural wastes in Taiwan, *Waste Manag.* 120 (2021) 424–432.
- [46] J. Li, F. Xiao, L. Zhang, S.N. Amirhanian, Life cycle assessment and life cycle cost analysis of recycled solid waste materials in highway pavement: a review, *J. Clean. Prod.* 233 (2019) 1182–1206.
- [47] W. Long, S. Wang, C. Lu, R. Xue, T. Liang, N. Jiang, R. Zhang, Quantitative assessment of energy conservation potential and environmental benefits of an iron and steel plant in China, *J. Clean. Prod.* 273 (2020) 123163.
- [48] J. Gregor, R. Somplák, M. Pavlas, Transportation cost as an integral part of supply chain optimisation in the field of waste management, *Chem. Eng. Trans.* 56 (2017) 1927–1932.
- [49] C. Pei, P. Chen, W. Tan, T. Zhou, J. Li, Effect of wet copper tailings on the performance of high-performance concrete, *J. Build. Eng.* 74 (2023) 106931.
- [50] T. Kasap, E. Yilmaz, M. Sari, S. Karasu, Predicting long-term impact of cementitious mine fill considering sand as a copper-tailings substitution, *Powder Technol.* 428 (2023) 118887.
- [51] Z. Chen, Z. Leng, Y. Jiao, F. Xu, J. Lin, H. Wang, J. Cai, L. Zhu, Y. Zhang, N. Feng, Innovative use of industrially produced steel slag powders in asphalt mixture to replace mineral fillers, *J. Clean. Prod.* 344 (2022) 131124.
- [52] Z. Wang, H. Chu, J. Wang, E. Feng, Y. Zhang, X. Lyu, Mechanical activation of siliceous tailings and its application as cement admixtures, *Miner. Eng.* 177 (2022) 107366.
- [53] D. Singh, A. Habal, P.K. Ashish, A. Kataware, Evaluating suitability of energy efficient and anti-stripping additives for polymer and Polyphosphoric acid modified asphalt binder using surface free energy approach, *Constr. Build. Mater.* 158 (2018) 949–960.

- [54] J. Zhang, A. He, B. Xie, J. Wang, C. Yan, Characterization of various modified asphalts using force ductility test with “8” shaped mold and straight mold, *Constr. Build. Mater.* 356 (2022) 129251.
- [55] B. Lei, Q. Xiong, H. Zhao, W. Dong, V.W. Tam, Z. Sun, W. Li, Performance of asphalt mortar with recycled concrete powder under different filler-to-asphalt weight ratios, *Case Stud. Constr. Mater.* (2023) e01834.
- [56] Q. Gu, A. Kang, B. Li, P. Xiao, H. Ding, Effect of fiber characteristic parameters on the high and low temperature rheological properties of basalt fiber modified asphalt mortar, *Case Stud. Constr. Mater.* 17 (2022) e01247.
- [57] N. Yaro, M. Napiyah, M. Sutanto, A. Usman, S. Saeed, J. Kaura, Influence of modification mixing parameters on conventional properties of palm oil clinker fine (POCF)-modified bitumen, *Mater. Today.: Proc.* 48 (2022) 771–777.
- [58] A. Amini, H. Ziari, S.A. Saadatjoo, N.S. Hashemifar, A. Goli, Rutting resistance, fatigue properties and temperature susceptibility of nano clay modified asphalt rubber binder, *Constr. Build. Mater.* 267 (2021) 120946.
- [59] Z. Ju, D. Ge, Z. Wu, Y. Xue, S. Lv, Y. Li, X. Fan, The performance evaluation of high content bio-asphalt modified with polyphosphoric acid, *Constr. Build. Mater.* 361 (2022) 129593.
- [60] D. Ge, K. Yan, L. You, Z. Wang, Modification mechanism of asphalt modified with Sasobit and Polyphosphoric acid (PPA), *Constr. Build. Mater.* 143 (2017) 419–428.
- [61] R. Lackner, M. Spiegl, R. Blab, J. Eberhardsteiner, Is low-temperature creep of asphalt mastic independent of filler shape and mineralogy?—arguments from multiscale analysis, *J. Mater. Civ. Eng.* 17 (5) (2005) 485–491.
- [62] Z. Zhao, S. Wu, Q. Liu, J. Xie, C. Yang, P. Wan, S. Guo, W. Ma, Characteristics of calcareous sand filler and its influence on physical and rheological properties of asphalt mastic, *Constr. Build. Mater.* 301 (2021) 124112.
- [63] Q. Li, Y. Qiu, A. Rahman, H. Ding, Application of steel slag powder to enhance the low-temperature fracture properties of asphalt mastic and its corresponding mechanism, *J. Clean. Prod.* 184 (2018) 21–31.
- [64] H. Taherkhani, S.V. Kamsari, Evaluating the properties of zinc production wastes as filler and their effects on asphalt mastic, *Constr. Build. Mater.* 265 (2020) 120748.
- [65] S. Lv, C. Xia, Q. Yang, S. Guo, L. You, Y. Guo, J. Zheng, Improvements on high-temperature stability, rheology, and stiffness of asphalt binder modified with waste crayfish shell powder, *J. Clean. Prod.* 264 (2020) 121745.
- [66] A.M. Memon, M.H. Sutanto, M. Napiyah, N.I.M. Yusoff, R.A. Memon, A.M. Al-Sabaei, M. Ali, Physicochemical, rheological and morphological properties of bitumen incorporating petroleum sludge, *Constr. Build. Mater.* 297 (2021) 123738.
- [67] S. Lv, J. Yuan, X. Peng, M.B. Cabrera, S. Guo, X. Luo, J. Gao, Performance and optimization of bio-oil/Buton rock asphalt composite modified asphalt, *Constr. Build. Mater.* 264 (2020) 120235.
- [68] H. Yang, L. Pang, Y. Zou, Q. Liu, J. Xie, The effect of water solution erosion on rheological, cohesion and adhesion properties of asphalt, *Constr. Build. Mater.* 246 (2020) 118465.
- [69] J. Zhang, P. Li, M. Liang, H. Jiang, Z. Yao, X. Zhang, S. Yu, Utilization of red mud as an alternative mineral filler in asphalt mastics to replace natural limestone powder, *Constr. Build. Mater.* 237 (2020) 117821.
- [70] B. Lei, Q. Xiong, H. Zhao, W. Dong, V.W. Tam, Z. Sun, W. Li, Performance of asphalt mortar with recycled concrete powder under different filler-to-asphalt weight ratios, *Case Stud. Constr. Mater.* 18 (2023) e01834.
- [71] A.F. Faheem, C. Hintz, H.U. Bahia, I.L. Al-Qadi, S. Glidden, Influence of filler fractional voids on mastic and mixture performance, *Transp. Res. Rec.* 2294 (1) (2012) 74–80.
- [72] J.-S. Chen, C.-H. Peng, Analyses of tensile failure properties of asphalt-mineral filler mastics, *J. Mater. Civ. Eng.* 10 (4) (1998) 256–262.
- [73] Y. Chen, S. Xu, G. Tebaldi, E. Romeo, Role of mineral filler in asphalt mixture, *Road. Mater. Pavement Des.* 23 (2) (2022) 247–286.
- [74] A.E. Alvarez, E. Ovalles, S. Caro, Assessment of the effect of mineral filler on asphalt–aggregate interfaces based on thermodynamic properties, *Constr. Build. Mater.* 28 (1) (2012) 599–606.
- [75] J. Zhang, G.D. Airey, J. Grenfell, A.K. Apeageyi, Moisture damage evaluation of aggregate–bitumen bonds with the respect of moisture absorption, tensile strength and failure surface, *Road. Mater. Pavement Des.* 18 (4) (2017) 833–848.
- [76] Q. Chen, C. Wang, Z. Qiao, T. Guo, Graphene/tourmaline composites as a filler of hot mix asphalt mixture: preparation and properties, *Constr. Build. Mater.* 239 (2020) 117859.
- [77] S. Liu, S. Zhou, A. Peng, Analysis of moisture susceptibility of foamed warm mix asphalt based on cohesion, adhesion, bond strength, and morphology, *J. Clean. Prod.* 277 (2020) 123334.
- [78] G.A.o.Q.S. Inspection, Q.o.t.P.s.R.o. China, *Quality Standard for Ground Water*, Standards Press of China Beijing, 1993.
- [79] M.A. Azadgoleh, M.M. Mohammadi, A. Ghodrati, S.S. Sharifi, S.M.M. Palizban, A. Ahmadi, E. Vahidi, P. Ayar, Characterization of contaminant leaching from asphalt pavements: A critical review of measurement methods, reclaimed asphalt pavement, porous asphalt, and waste-modified asphalt mixtures, *Water Res.* 219 (2022) 118584.
- [80] M.-J. Luo, C.-L. Liu, J. Xue, P. Li, J.-G. Yu, Leaching kinetics and mechanism of alunite from alunite tailings in highly concentrated KOH solution, *Hydrometallurgy* 174 (2017) 10–20.
- [81] Y.-g Guo, P. Huang, W.-g Zhang, X.-w Yuan, F.-x Fan, H.-l Wang, J.-s Liu, Z.-h Wang, Leaching of heavy metals from Dexing copper mine tailings pond, *Trans. Nonferrous Met. Soc. China* 23 (10) (2013) 3068–3075.
- [82] S. Pranav, S. Aggarwal, E.-H. Yang, A.K. Sarkar, A.P. Singh, M. Lahoti, Alternative materials for wearing course of concrete pavements: a critical review, *Constr. Build. Mater.* 236 (2020) 117609.
- [83] Ministry of Transport of the People's Republic of China, *Statistical bulletin of transportation industry in 2022*, 2022.