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The feasibility of waste nylon filament used as reinforcement in asphalt mixture

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Abstract

The recycle and reuse of waste nylon filament is a new problem. The aim of this paper is to discuss the feasibility of waste nylon filament used as reinforcement in asphalt mixture (AM). Before preparation, the physical and mechanical properties of waste nylon filament were investigated. Then the waste nylon filament was mixed with asphalt and aggregate to prepare waste nylon filament asphalt mixture (WNFAM) using Marshall design method. The properties of WNFAM were evaluated through Marshall stability test, rutting test, flexural test and freeze-thaw split test. The related results indicate as follows: waste nylon filament has an excellent physical and mechanical property, and can be used as reinforcement in asphalt mixture; the reasonable asphalt content is 5.0%-5.5%, and the waste nylon filament is 0.1%-0.2%. Besides, the addition of waste nylon filament can improve the high-temperature stability, low-temperature crack resistance and durability of asphalt mixture. It is the binding effect provided by the waste nylon filament on the aggregate and the fiber reinforced composite strength theory that are attributed to this improvement and reinforcement. The research result can offer technical support for waste nylon filament used in road construction materials.

Keywords: Waste nylon filament; Property; Asphalt mixture; Performance; Mechanism

1. Introduction

Fibers have been used as reinforcement in asphalt mixture for many years [1-3]. The addition of fibers in asphalt mixture not only significantly reduces the draining and leakage of asphalt by stabilizing the whole mixture [4-5], but also improves a variety of mechanical properties of asphalt mixture such as static and dynamic stabilities, ductility, moisture susceptibility, and general fatigue characteristics [6-8].

There are two main types of fibers utilized to reinforce asphalt mixture: inorganic fibers and organic fibers. The inorganic fibers include carbon fiber, basalt fiber and glasses fiber. The organic fibers include polyester fiber, polypropylene fiber, Polyethylene fiber and cellulose fiber [9-15]. Among these fibers, the price of carbon fiber and basalt fiber are very high. The glass fiber is easily broken during the mixing process. When fibers, such as Polyester fiber, polypropylene fiber, Polyethylene fiber and cellulose fiber, mixes with asphalt, problems with fiber clumping occur in the mixing process, which is likely to bring about little improvement [15].

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It is known that the fiber used as reinforcement in asphalt mixture should have the following properties: (1) heat resistance, (2) excellent mechanical property; (3) good distribution in asphalt mixture [16]. It is necessary to look for a new fiber that has low price, superior property and good distribution in asphalt mixture.

At the same time, there are nearly 5,400,000 tons of nylon filament produced in the world every year. These nylon filaments are used to manufacture brush filament products such as toothbrush, hairbrush, paintbrush, and so on. But in the process of manufacturing these filament products, about 10 percent of nylon filament is wasted. If these waste nylon filaments could not be recycled and reused properly, these will cause waste and environment pollution [17].

Therefore, the recycling and reuse of waste nylon filament (WNF) is on the agenda.At present, there two main ways of recycling waste nylon filaments, one is physical recycling, the other is chemical recycling. The physical recycling refers to the production of plastic particles by crushing, melting, extruding or injection molding waste nylon filament, and occupies 90%. The chemical recycling refers to the direct recovery of monomers after depolymerization through chemical reactions, and these monomers are reused in the production of nylon filament. However, both physical and chemical recycling poses a challenge in environment pollution and leads to the increase of cost, which will limit the recycling scale of waste nylon filament. It is a demanding issue of finding a non-polluting and low-cost way in

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reusing the recycled nylon filament. It is obvious that adding recycled nylon filament into composites without any pre-treating to improve the property is the most efficient and economical one. Some researchers added recycled nylon fibers directly into concrete to improve the mechanical and thermal performances of concrete [18-22]. It is confirmed that the addition of recycled nylon fiber in concrete can improve the splitting tensile strength, the flexural strength, toughness and ductility properties of plain concrete and it can reduce the shrinkage crack [23]. But there is little research on the utilization of recycled nylon filament in asphalt mixture, either the properties of waste nylon filament itself. What are the physical and mechanical properties of waste nylon filament? How about its heat resistance property? Can it be used as reinforcement in asphalt mixture? These questions need to be responded and resolved.

This paper gives the response. The paper firstly studies the physical and mechanical property of wasted nylon filament. Based on this, the waste nylon filament was mixed with asphalt and aggregates to prepare waste nylon filament asphalt mixture (WNFAM) using Marshall design method, at the same time the performance of WNFAM were evaluated through the following mechanical tests: Marshall stability test, rutting test and flexural test. Besides, the mechanisms of the improvement and reinforcement were discussed.

2. Materials and experiment

2.1. Asphalt and aggregate

70/100 penetration grade asphalt was used in this research. This asphalt was obtained from ZhongHai Refinery. The properties of the asphalt are shown in Table 1 [24].

The crushed limestone aggregates were used to mix with asphalt. The mix proportion of mineral aggregate test was presented in Table 2 and the aggregate gradation in Fig. 1.

2.2. Waste Nylon filament

The waste nylon filament (See Fig. 2) was the wastes of toothbrush and was collected from BangDa nylon factory, located in Yangzhou city, China. The length of waste nylon filament is 20-30 mm, and the diameter is 0.2 mm.

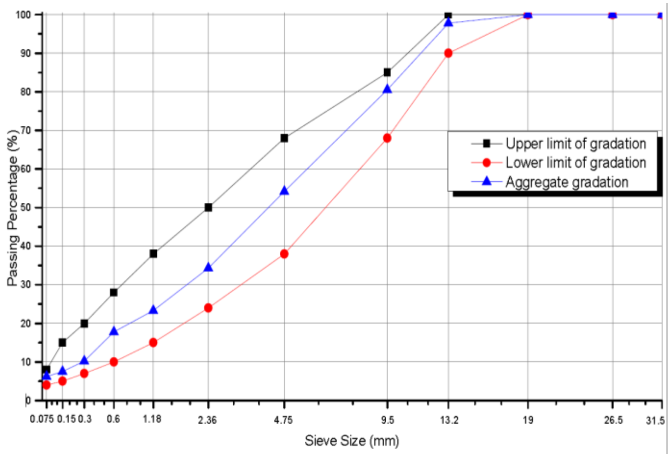

Fig. 1. Gradation curve of AC-13.

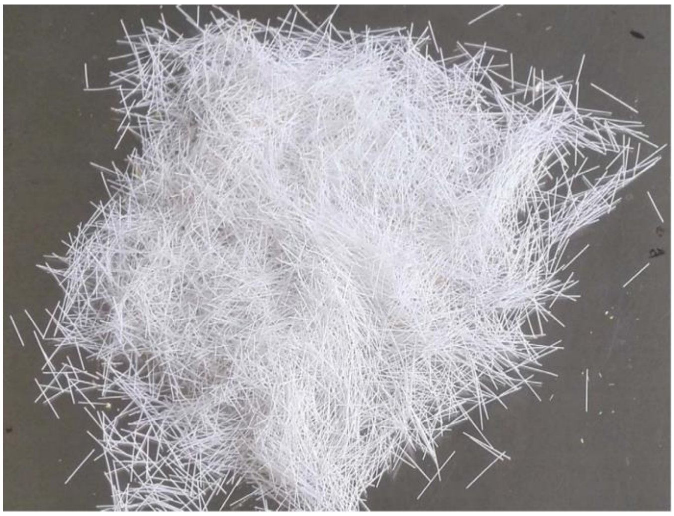

Fig. 2. Waste nylon filament.

Table 1
The properties of ZhongHai asphalt.

Parameter measured	Value	Standard limits	Standard method
Penetration (25°C, 5 s, 100 g)/0.1 mm	72	60-80	JTG E20 T0604-2011
Softening point(ring and ball)/°C	56.0	≥45	JTG E20 T0606-2011
Ductility (15°C, 50 mm/min)/mm	>1000	>1000	JTG E20 T0605-2011
Flash point (Cleveland open cup)/°C	≥230	≥230	JTG E20 T0611-2011
Wax content (distillation)/%	≤3	≤3	JTG E20 T0615-2011
Solubility (solvent: trichloroethylene)/%	≥99.5	≥99.5	JTG E20 T0607-2011

Table 2
The result of mineral aggregate component test.

Mineral aggregate	Mix proportion %	Passing percentage of the following sieve (mm)/%										
		19	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
2#	51	51.0	51.0	48.8	31.5	5.6	1.9	0.9	0.9	0.9	0.9	0.9
3#	12	12.0	12.0	12.0	12.0	11.7	0.4	0.1	0.1	0.1	0.1	0.1
4#	37	37.0	37.0	37.0	37.0	37.0	32.0	22.3	16.8	9.2	6.5	5.1
Mixture gradation		100	100	97.8	80.5	54.2	34.3	23.3	17.8	10.2	7.5	6.2

2.2.1. Heat-resisting property

Asphalt mixtures are produced and constructed at temperature range between 150 and 190°C [25]. It requires the additions in asphalt mixture should have a good heat-resisting property. The heat-resisting property test of waste nylon filament was carried out in an oven, where waste nylon filament was put on a steel plate . The oven temperature was set as 190°C, 200°C, 210°C and 220°C. At each temperature level, the waste nylon filament was kept drying for 20 min in the oven. After each drying, the colour of waste nylon filament was observed.

2.2.2. Oil absorption capacity

Oil absorption capacity refers to the ability of waste nylon filament to absorb or release oily liquids. The oil absorption capacity of waste nylon filament is represented by the oil absorption rate. The oil absorption rate refers to the percentage of the weight of the oil liquid absorbed by waste nylon filament to the dry weight of waste nylon filament, as the Eq. (1) is shown.

$$W = \frac{m - m_0}{m_0} \times 100\% \quad (1)$$

where, W is oil absorption rate of waste nylon filament (%); m_0 is the dry weight of waste nylon filament (g); m is the weight of waste nylon filament that fully absorbs oil liquid (g).

The test process of oil absorption rate of waste nylon filament was shown in Fig. 3.

2.2.3. The property of adhesion

The property of adhesion refers to the ability of waste nylon filament to resist the peeling of asphalt due to the erosion of water after the surface of waste nylon fiber is coated with asphalt. The property of adhesion of waste nylon filament can be characterized by the viscosity rate. The viscosity rate refers to the percentage of the weight of the residual asphalt attached to waste nylon filament after boiled by water to the weight of original asphalt, as the Eq. (2) is shown.

$$S_n = \frac{m' - m_0}{m - m_0} \times 100\% \quad (2)$$

where, S_n is the viscosity rate of waste nylon filament (%); m_0 is the dry weight of waste nylon filament (g); m is the weight of waste nylon filament coated by asphalt (g); m′ is the weight of waste nylon filament and asphalt after boiled by water (g).

The test process of viscosity rate of waste nylon filament was shown in Fig. 4. The test process of viscosity was based on the standard test method for adhesion of asphalt and coarse aggregates according to the Standard Test Methods of Bitumen and Bituminous Mixtures for High Way Engineering [26].

2.2.4. Mechanical property

For the mechanical property of waste nylon filament, the tensile strength is mainly investigated. The tensile strength is calculated as the Eq. (3) shown.

$$\sigma = \frac{F_m}{S_0} \quad (3)$$

where, σ is the tensile strength of waste nylon filament (MPa); F_m is the peak load at failure (N); S_0 is the cross-sectional area of waste nylon filament (mm^2).

The tensile test was carried on an Electronic Universal Testing Machine with capacity of 50 N by displacement control at a rate of 0.1 mm/min, as shown in Fig. 5.

2.3. Preparation of asphalt mixture containing waste nylon filament

In the experiment, the asphalt content accounted for from 4.5% to 5.5% of the mass of aggregates (by weight), and the waste nylon filament content accounted for from 0% to 0.4% of the mass of

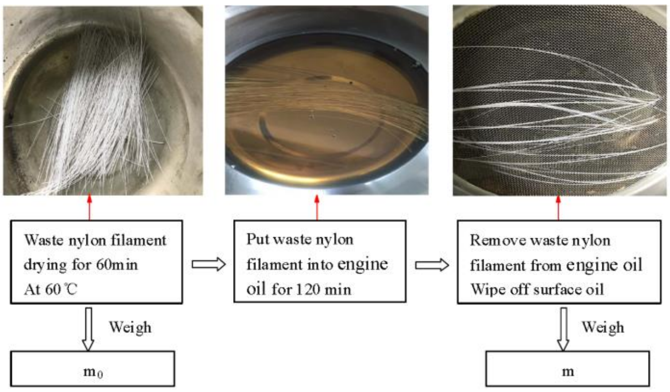

Fig. 3. The test process of oil absorption rate.

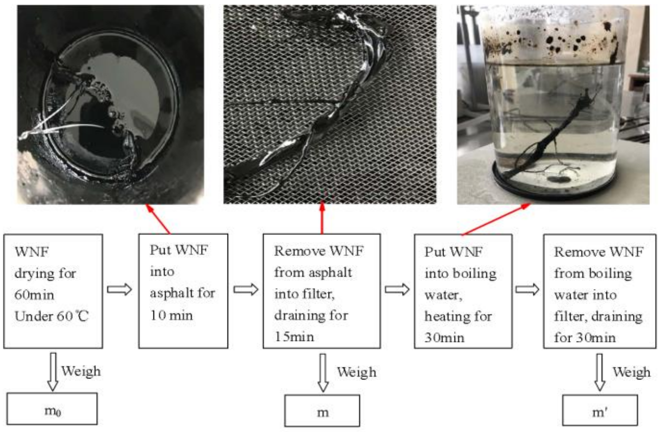

Fig. 4. The test process of viscosity rate.

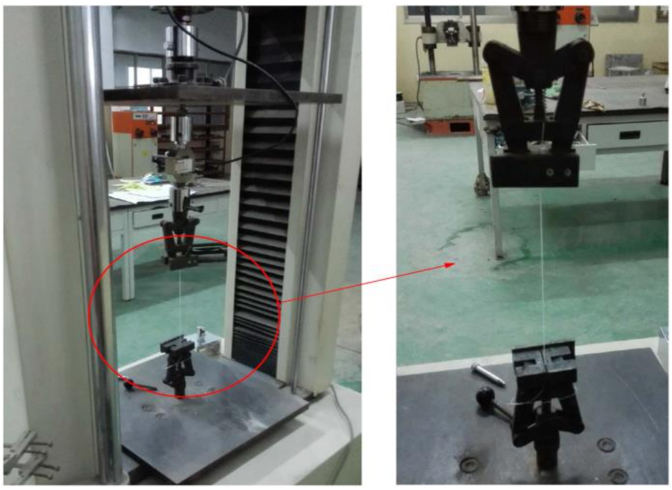

Fig. 5. The tensile test setup.

asphalt. The WNFAM was prepared in accordance with the Standard Test Methods of Bitumen and Bituminous Mixtures for High Way Engineering [26]. The process of preparation was the following: Firstly, the aggregates were drying at 163°C for 4 hours. Secondly, the aggregates were placed in a mixing cylinder where the temperature was kept at 163°C, then the waste nylon filament was directly added into the mixing cylinder and mixed with aggregates thoroughly. Thirdly, the asphalt added into the mixing cylinder kept mixing for 3 min. The final mixture was WNFAM.

2.4. Marshall stability test

The Marshall stability test was performed according to the Standard Test Methods of Bitumen and Bituminous Mixtures for High Way Engineering [27]. The test process was as follows: (1) The WNFAM sample weighing 1200 g was put into the Marshall mold (the inner diameter is 101.1±0.2 mm, the height is 87 mm). Then, the Marshall mold and its base were placed and fixed on a compaction table together. (2) A compacting hammer dropped from a height of 457 mm to compact the sample for 75 times. Then, the mold was turned over and the other side was compacted in the same way. (3) The sample was put out from the mold and placed in a sink in which the water temperature was kept at 60°C for 30 min. Then, the sample was removed from the sink and placed on the Marshall test machine. Finally, the sample was loaded at the speed of 50 mm/min.

2.5. Rutting test

The rutting test was performed according to the Standard Test Methods of Bitumen and Bituminous Mixtures for High Way Engineering [27]. The rutting test procedures were: (1) The sample was put into a mold (the length is 300 mm, the width is 300 mm, and the height is 50 mm) and compacted by a steel roller. (2) The sample was placed in a chamber where the temperature was kept at 60°C for 12 h. Then, the sample was removed to a rutting test machine where a single wheel was applied on the surface of the sample. (3) Once the rutting test machine was started, the wheel kept rolling on the sample back and forth for 1 h. The rolling distance was 230 mm and speed was 42 cycles/min.

The dynamic stability is used to evaluate the resistance to rutting of asphalt mixture. The dynamic stability is calculated according to Eq. (4).

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \tag{4}$$

where, DS is the dynamic stability of asphalt mixture, d_1 is the deformation of the sample at t_1 time (usually 45 min), d_2 is the deformation of the sample at t_2 time (usually 60 min) (mm), C_1 is the correction coefficient of instrument, C_2 is the coefficient of the sample, N is the rolling speed (42 times/min).

2.6. The flexural test

The flexural test was performed according to the Standard Test Methods of Bitumen and Bituminous Mixtures for High Way Engineering [27]. The flexural test process was as follows: (1) The sample was compacted by a steel wheel resulting in a solid slap, then, the slap was cut into beam specimens of size measuring 30 mm× 35 mm×250 mm. (2) The beam specimens were placed in a sink where the water temperature was -10°C for 45 min. Then, the beam specimen was removed into the universal testing machine. (3) A load with speed of 50 mm/min was loaded at the middle of the specimen till the specimen was broken.

The flexural strength is used to evaluate the crack resistance of asphalt mixture. The flexural strength (MPa) is calculated according to Eq. (5).

$$R_B = \frac{3LP_B}{2bh^2} \tag{5}$$

where, P_B is the ultimate load when the specimen is failure (N), b is the width of the specimen beam (30 mm), h is the height of the specimen beam (35 mm), and L is the span length (200 mm). The ultimate flexural strain ε_B is the calculated according to Eq. (6).

$$\varepsilon_B = \frac{6hd}{L^2} \tag{6}$$

where, d is the mid-span deflection of the specimen beam when it is failure (mm).

The ultimate flexural stiffness modulus S_B is calculated according to Eq. (7).

$$S_B = \frac{R_B}{\varepsilon_B} \tag{7}$$

2.7. Freeze-thaw split test

The resistance to moisture-induced damage is an important aspect of durability of asphalt mixture. The splitting strength ratio (TSR) is used to evaluate the resistance of asphalt mixture to moisture-induced damage. TSR is calculated according to the Eq. (8).

$$TSR = \frac{R_{T2}}{R_{T1}} \times 100\% \tag{8}$$

where, TSR is the splitting strength ratio of samples (%), R_{T2} is the splitting strength of the second group (MPa), and R_{T1} is the splitting strength of the first group (MPa).

R_{T1} and R_{T2} can be obtained through freeze-thaw split test. The test process was as follows: (1) The Marshall specimens were divided into two groups. The first group specimens were placed on the plat at room temperature. The second group specimens were immersed in a sink filled with water, then the sink with specimens was placed in a vacuum drying oven at the 730-740 mmHg vacuum degree for 15 min. (2) The second group specimens were removed from the sink and put into a plastic bag which was sealed after being added 10ml of water, later putting into a refrigerator at -18°C for 16 h. (3) The second group specimens were removed from the bag and put in water at 60°C for 24h. (4) the two groups specimens were both placed in water at 25°C for at least 2 h.Then, the specimens were loaded at the rate of 50 mm/min using an automatic splitting strength tester. The splitting strength R_{T1} and R_{T2} were calculated according to the Eqs. (9) and (10).

$$R_{T1} = 0.006287 P_{T1} / h_1 \tag{9}$$

$$R_{T2} = 0.006287 P_{T2} / h_2 \tag{10}$$

where, P_{T1} is the test load value of individual specimen in the first group (N); P_{T2} is the test load value of individual specimen in the second group (N); h_1 is the height of each specimen in the first group (mm); h_2 is the height of each specimen in the second group (mm).

3. Results and discussion

3.1. The properties of waste nylon filament

The change of surface of waste nylon filament was observed during the heating process, as shown in Fig. 6

Fig. 6 indicates that waste nylon filament has a good heat-resisting property, and at the temperature below 210°C, the waste nylon filament can be thoroughly mixed with asphalt mixture. It is pointed out in the Technical Specification for Warm Mix Asphalt Pavement that the heat resistance of fiber is not less than 165°C [27].

The test result of oil absorption rate of waste nylon filament as shown in Table 3. According to Eq. (1) and Table 3, the oil absorption rate is 10.4%. The oil absorption rate should be considered in the mix proportion design of waste nylon filament asphalt mixture.

The test result of viscosity rate of waste nylon filament was shown in Table 4. According to Eq. (2) and Table 4 , the viscosity rate of waste nylon filament is 93.4%. It is required that the viscosity rate of additives in asphalt mixture should not be less than 90% according to the Technical Specifications for Construction of Highway Asphalt Pavements [28]. For example, the viscosity rate of aggregate is 95%. The results indicate that the surface of waste nylon filament is easy to be adhered by asphalt, and waste nylon filament has a strong ability to resist the peeling of the asphalt. The property of adhesion provides the guarantee for the application of waste nylon filament as additive in asphalt mixture.

A complete non-linear tensile elongation curve for waste nylon filament is obtained from the tensile test, and the load-defection values plotted in Fig. 7. The result of tensile test was shown in Table 5.

Fig. 7 shows that there are three stages during the tensile elongation progress: elastic stage, plastic stage and ultimate strengthening stage. In the plastic stage, the load changes from 9.26 N to 11.17 N, while the deflection from 2.46 mm to 7.46 mm. The results indicate that waste nylon filament has a long stage of plastic deformation. As shown in Table 5, the tensile strength of waste nylon filament is 127.67 MPa, which means waste nylon filament has an excellent tensile property.

Table 3
The results of oil absorption rate test.

Sample No.	m_0 (g)	m (g)	W (%)
1	1.50	1.66	10.7
2	2.30	2.51	9.0
3	1.91	2.13	11.5
Average			10.4

Table 4
The results of viscosity rate test.

Sample No	m_0 (g)	m (g)	m' (g)	S_n (%)
1	3.05	4.57	4.49	94.7
2	4.28	5.82	5.69	91.6
3	5.56	7.21	7.11	93.9
Average				93.4

Table 5
The results of tensile test.

Sample No.	Diameter (mm)	F_m (N)	σ (MPa)
1	0.45	19.106	120.19
2	0.45	20.863	131.24
3	0.45	20.916	131.58
Average			127.67

Fig. 6. The change of surface of waste nylon filament.

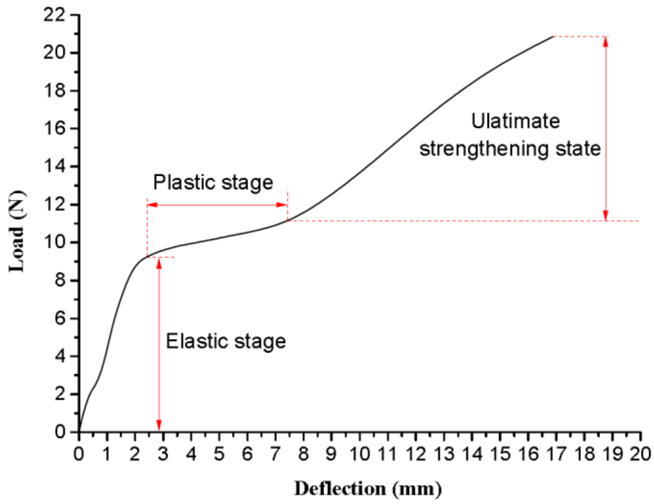

Fig. 7. The tensile elongation curve of waste nylon filament.

3.2. The performances of WNFAM

3.2.1. The high-temperature stability

Usually, the Marshall stability and dynamic stability are used to evaluate the high-temperature stability of asphalt mixture. The results of Marshall stability test and rutting test were shown in Table 6. The Variance analysis of test results was shown Table 7. Table 7 showed that both asphalt content and waste nylon filament content had a greatly significant impact on the Marshall stability and dynamic stability.

The effect of asphalt content and waste nylon filament content on the Marshall stability was reflected in Fig. 8. As shown in Fig. 8, the Marshall stability value first increased and then decreased with increases of the waste nylon filament and asphalt content. When the asphalt content was 5.0% and the content of waste nylon filament was 0.2%, the Marshall stability value of WNFAM

Table 6
The results of Marshall stability test and rutting test.

Asphalt content (%)	Waste nylon filament content (%)	Marshall stability (kN)	Flow value (0.1 mm)	Dynamic stability (times/mm)	Rut-depth (mm)
4.5	0	7.42	14.5	1038.24	5.433
	0.1	9.32	20.0	1214.37	4.297
	0.2	8.60	16.7	1637.70	3.826
	0.3	7.76	12.1	1570.75	4.275
	0.4	7.32	18.0	1046.48	5.176
5	0	8.65	19.8	1189.65	5.144
	0.1	9.81	21.6	1969.80	3.574
	0.2	10.04	17.3	2257.50	2.986
	0.3	9.10	19.6	2646.00	2.584
	0.4	8.59	23.4	1100.40	5.237
5.5	0	8.33	26.0	1523.60	4.460
	0.1	8.90	19.9	1675.44	4.066
	0.2	9.90	24.3	2092.48	3.175
	0.3	9.30	23.5	2673.84	2.515
	0.4	8.49	26.2	1512.16	4.670

Table 7
Variance analysis of rutting test.

Index	Source of variance	DF	Sum of squares	Mean square	F value	F critical value	Significance
Marshall stability	Asphalt content	2	3.68	1.84	12.13	$F_{0.01}(2,8)=8.65$	**
	Waste nylon filament content	4	5.08	1.27	8.38	$F_{0.01}(4,8)=7.01$	**
	Error	8	1.21	0.15	--	$F_{0.05}(2,8)=4.46$	
	Corrected Total	14	9.97	--	--	$F_{0.05}(4,8)=3.84$	
Dynamic stability	Asphalt content	2	1064850	532427	8.96	$F_{0.01}(2,8)=8.65$	**
	Waste nylon filament content	4	2640700	660175	11.11	$F_{0.01}(4,8)=7.01$	**
	Error	8	475544	59443	--	$F_{0.05}(2,8)=4.46$	
	Corrected Total	14	4181100	--	--	$F_{0.05}(4,8)=3.84$	

Note："**"refer to a factor has a greatly significant impact on the results；"*" refer to a factor has a significant impact on the results.

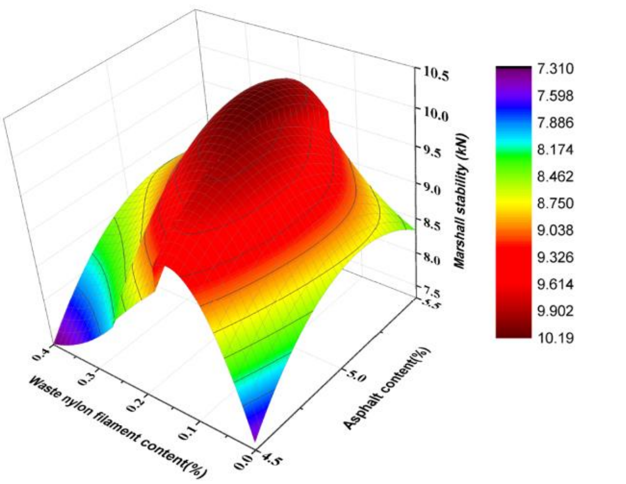

Fig. 8. The effect of asphalt content and waste nylon filament content on the Marshall stability.

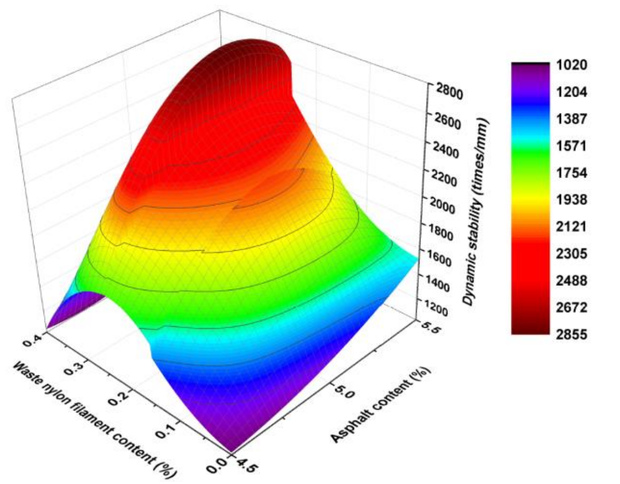

Fig. 9. The effect of asphalt content and waste nylon filament content on the dynamic stability.

reached the maximum (10.04 kN), which increased by 16% compared with the plain asphalt mixture (PAM).

The effect of asphalt content and waste nylon filament content on the dynamic stability was reflected in Fig. 9. As shown in Fig. 9, the dynamic stability value first rose and then decreased with increases of the waste nylon filament content. But with increase of asphalt content, there is no regular change in the dynamic stability value. When the asphalt content was 5.5% and the content of waste nylon filament was 0.3%, the dynamic stability value of WNFAM reached the maximum (2073.84 times/mm), which increased by 75% compared with the PAM.

The above mentioned indicate that the addition of waste nylon filament improves the high-temperature stability and the ability to resist flaking of PAM, which is due to the binding effect provided by the waste nylon filament on the aggregate. As shown in Fig. 10, waste nylon filament is uniformly dispersed in the PAM while some aggregates are bound by waste nylon filament, as shown in Fig. 11. The stress of the bound aggregate can be determined by Eq. (8) [29].

$$\sigma_c = \sigma_k + kp \tag{8}$$

where, σ_c is the stress of the bound aggregate, σ_k is the stress of aggregate without waste nylon filament binding, p is the lateral compressive stress presented by waste nylon filament binding aggregate, k is the coefficient that can be determined by Eq. (9).

$$k = 2 + \frac{3}{2\sqrt{p/\sigma_k}} \tag{9}$$

Eq. (8) shows that the ability of aggregate to resist stress is improved due to the binding effect of waste nylon filament. It is such aggregates inside the WNFAM that improve the high-temperature stability.

3.2.2. *The low-temperature crack resistance*

The ultimate flexural strength and the flexural stiffness modulus are used to evaluate the low-temperature crack resistance of asphalt mixture. The results of flexure test were shown in Table 8. The Variance analysis of test results was shown Table 9. Table 9 showed that the waste nylon filament content had a greatly significant impact on the ultimate flexural strength and a significant impact on the flexural stiffness modulus, while the asphalt content had little impact on the ultimate flexural strength and a greatly significant impact on the flexural stiffness modulus.

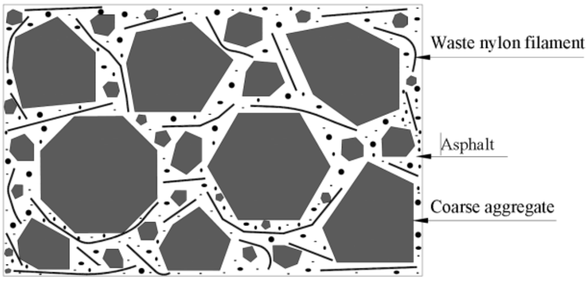

Fig. 10. Waste nylon filament disperse in asphalt mixture.

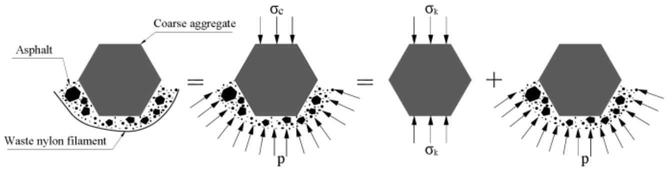

Fig. 11. Aggregate bound by waste nylon filament.

Table 8
The results of flexural test.

Asphalt content (%)	Waste nylon filament content (%)	Mid-span deflection (mm)	Ultimate load (kN)	Ultimate flexural strength (MPa)	Flexural stiffness modulus (MPa)
4.5	0	0.70088	0.785	6.41	1742
	0.1	0.72402	0.871	7.11	1871
	0.2	0.78275	0.833	6.80	1655
	0.3	0.69824	0.742	6.06	1652
	0.4	0.68180	0.668	5.45	1523
5	0	0.75165	0.856	6.99	1771
	0.1	0.70710	1.005	8.20	2210
	0.2	0.69160	0.869	7.09	1954
	0.3	0.61187	0.749	6.11	1903
	0.4	0.59057	0.703	5.74	1851
5.5	0	0.83112	0.783	6.39	1465
	0.1	0.80391	0.825	6.74	1596
	0.2	0.81208	0.878	7.17	1681
	0.3	0.82290	0.794	6.48	1500
	0.4	0.83640	0.751	6.13	1396

Table 9
Variance analysis of flexural test.

Index	Source of variance	DF	Sum of squares	Mean square	F value	F critical value	Significance
Ultimate flexural strength	Asphalt content	2	0.53	0.27	1.68	$F_{0.01}(2,8)=8.65$	
	Waste nylon filament content	4	4.70	1.17	7.37	$F_{0.01}(4,8)=7.01$ $F_{0.05}(2,8)=4.46$	**
	Error	8	1.27	0.16	--	$F_{0.05}(4,8)=3.84$	—
	Corrected total	14	6.51	--	--		—
Flexural stiffness modulus	Asphalt content	2	427143	213571	25.48	$F_{0.01}(2,8)=8.65$	**
	Waste nylon filament content	4	160086	40022	4.77	$F_{0.01}(4,8)=7.01$ $F_{0.05}(2,8)=4.46$	*
	Error	8	67059	8382		$F_{0.05}(4,8)=3.84$	
	Corrected total	14	654288				

Note："**"refer to a factor has a greatly significant impact on the results；"*" refer to a factor has a significant impact on the result.

The effect of asphalt content and waste nylon filament content on the ultimate flexural strength was reflected in Fig. 12. As shown in Fig. 12, the value of the ultimate flexural strength first grew and then dropped with increases of the waste nylon filament and asphalt content. When the asphalt content was 5.0% and the content of waste nylon filament was 0.1%, the ultimate flexural strength of WNFAM reached the maximum (8.20 MPa), which increased by 17% compared with the PAM.

The effect of asphalt content and waste nylon filament content on the flexural stiffness modulus was reflected in Fig. 13. As shown in Fig. 13, the value of the flexural stiffness modulus first rose and then dropped with increases of the waste nylon filament and asphalt content. When the asphalt content was 5.0% and the content of waste nylon filament was 0.1%, the flexural stiffness modulus of WNFAM reached the maximum (2210 MPa), which increased by 25% compared with the PAM.

With respect to the results, it is indicated that the addition of waste nylon filament improves the ability to resist the bending deformation of PAM, which can be explained by the fiber reinforced composite strength theory. As to a composite reinforced by a unidirectional aligned short fiber, the flexural strength of the composite is determined by Eq. (10).

$$\sigma_{cu} = \frac{\sigma_{fu}\Phi_f}{K} + \sigma_{mu}(1-\Phi_f) \tag{10}$$

where, σ_{cu} is the flexural strength of the composite, σ_{fu} is the flexural strength of the fiber, σ_{mu} is the flexural of the matrix, Φ_f is the volume percentage of fiber, K is the maximum stress concentration factor.

In fact, for WNFAM, the orientation of waste nylon filament inside WNFAM is random, so the flexural of WNFAM can be determined by Eq. (11).

$$\sigma_{cu} = \frac{\sigma_{fu}\Phi_f C_0}{K} + \sigma_{mu}(1-\Phi_f) \tag{11}$$

where, C_0 is the azimuth factor of waste nylon filament. Eq. (11) indicates that the flexural strength of WNFAM increases as the amount increases of waste nylon filament.

The load-deflection curves of WNFAM (the asphalt content is 5.0%) under the flexural test are shown in Fig. 14. As is presented from Fig. 14, the addition of waste nylon filament increases the peak load of WNFAM. In addition, for PAM, after peak load the curve drops to zero rapidly. As to WNFAM containing 0.2% waste nylon filament, after peak load the curve does not drop rapidly to zero. Instead, a holding load platform appears on the curve. It is because waste nylon filament with its binding effect that help waste nylon filament continue to withstand the load after WNFAM is broken. In view of this, it can be considered that the addition of waste nylon filament improves the toughness of WNFAM.

3.2.3. The durability

The results of freeze-thaw split test were shown in Table 10. The effect of asphalt content and waste nylon filament content on TSR was shown in Fig. 15. TSR first rose and then reduced with the increase of the waste nylon filament content, while TSR rose with the gradual increasing asphalt content. When the content of waste nylon filament was 0.1% and asphalt was 5.5%, TSR reached the maximum (85.6%), which increased by 5.5% compared with the PAM. These resulted in that the addition of waste nylon had tiny contribution to the improvement of TSR, which was due to the binding effect provided by the waste nylon filament on the aggregate. The binding effect strengthened the structure and prevented WNFAM from destroying by water.

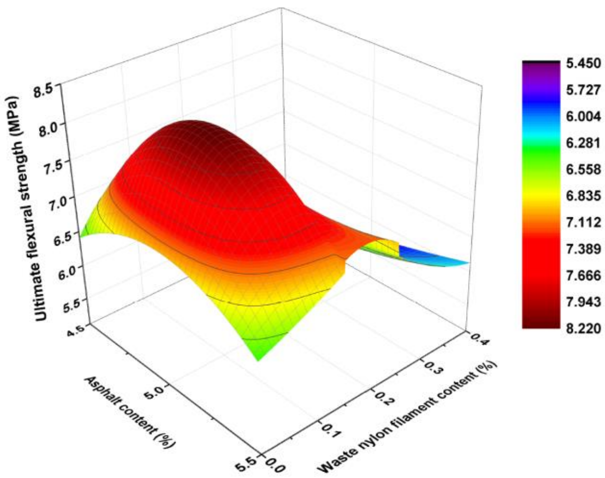

Fig. 12. The effect of asphalt content and waste nylon filament content on the ultimate flexural strength.

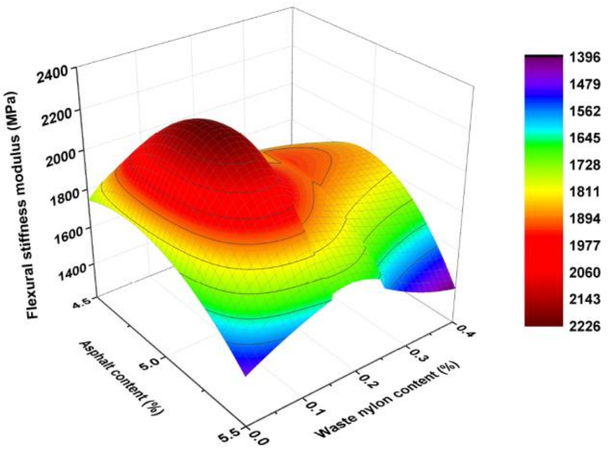

Fig. 13. The effect of asphalt content and waste nylon filament content on the flexural stiffness modulus.

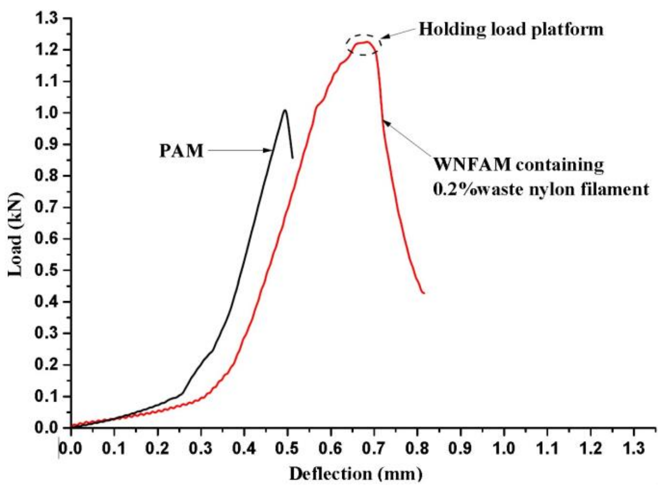

Fig. 14. The load-deflection curve of PAM and WNFAM.

Table 10
Freeze-thaw split test result.

Asphalt content (%)	Waste nylon filament content (%)	Group 1 Average Splitting Strength R_{T1} (MPa)	Group 2 Average Splitting Strength R_{T2} (MPa)	TSR (%)
4.5	0	1.37	1.03	75.3
	0.1	1.68	1.36	80.8
	0.2	1.13	0.79	70.1
	0.3	0.88	0.53	60.2
	0.4	0.65	0.37	56.5
5.0	0	2.00	1.54	77.0
	0.1	2.39	2.00	83.7
	0.2	1.78	1.38	77.7
	0.3	1.44	0.95	66.0
	0.4	1.26	0.77	61.2
5.5	0	1.99	1.61	80.9
	0.1	2.04	1.75	85.6
	0.2	1.82	1.46	80.2
	0.3	1.40	1.03	73.7
	0.4	1.21	0.84	69.4

Table 11
Cost of mixture.dd

Materials	Unit cost (CNY/ton)	AM		WNFAM	
		Content (kg/m^3)	Cost (CNY/m^3)	Content (kg/m^3)	Cost (CNY/m^3)
Asphalt	5000	117	585	115	575
Aggregate	260	2340	608.4	2300	598
Waste nylon filament	12000	--	--	0.115	1.4
Total (CNY/ m^3)		1193.4		1174.4	

Note: the asphalt content is 5.0%, and the waste nylon filament 0.1%. The density of AM is 2.45 g/cm^3, and the density of WNFAM 2.42 g/cm^3, 1 CNY= 0.1446 USD.

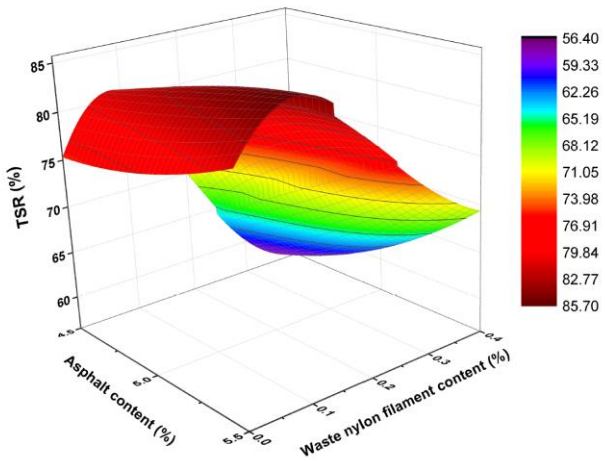

Fig. 15. The effect of asphalt content and waste nylon filament content on TSR.

4. Cost economic analysis

A cost analysis was conducted in order to assess the financial aspect of the investigated specimens, as shown in Table 11. Table 11 shows that the cost of WNFAM is 19 CNY/m^3 less than that of AM.

5. Conclusions

The paper investigated the physical and mechanical properties of waste nylon filament. Based on this,, the paper studied the feasibility of using waste nylon filament in asphalt mixture. The main conclusions were drawn as follows:

1. The waste nylon filament has excellent physical and mechanical properties which thus can be used as reinforcement in asphalt mixture, especially in warm mix asphalt. Once used in asphalt mixture, its content is 0.1%-0.2% of asphalt content for its very significant impact on the properties of asphalt mixture.
2. The high-temperature stability of asphalt mixture is improved, as well as the low-temperature crack resistance is reinforced by the addition of waste nylon filament. This improvement and reinforcement are attributed to both the binging effect provided by the waste nylon filament on the aggregates and the fiber reinforced composite strength theory. But the waste nylon does not perform well in improving the durability of asphalt mixture.
3. Adding brush filament wastes into asphalt mixture directly not only avoids the environment pollution caused by re-processing of brush filament wastes, but also improves the properties of asphalt mixture and reduces the cost. It is thus expected that brush filament wastes used as reinforcement in asphalt mixture have a bright future and broad application.

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