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Grey relational evaluation on performance and mechanism of polyacrylonitrile fiber reinforced asphalt mixture

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Abstract. Aiming to improve pavement performance of polyacrylonitrile (PAN) fiber-asphalt mixture, five PAN fiber content was selected from 0% to 0.4% by 0.1% interval to evaluate the effect on the high temperature stability, crack resistance in low temperature and moisture stability of asphalt mixture. Then the enhancement mechanism of PAN fiber reinforcing asphalt mixture was revealed by SEM at the microscopic level. Based on the multi-index grey relational evaluation method, the optimum PAN fiber content is selected for the balance of both road performances and economic benefit. The results show that the PAN fiber significantly improves pavement performances of asphalt mixture, as it better infiltrates into the asphalt and forms higher interfacial strength. It also could be observed that the PAN fiber evenly distributed in the asphalt binder to form a spatial network structure, playing a significant role in bridging, reinforcement and toughening. When the amount of PAN fiber is 0.2%, the comprehensive performance of asphalt mixture is optimal on the basis of grey relational evaluation.

1. Introduction

The reduction of asphalt pavement diseases is a crucial issue in highway engineering area all the time. One of the main factors of pavement diseases is related to construction materials. Nowadays, fiber additives have been considered as the reinforcing materials for cracking resistance and toughness of asphalt pavement [1]. Among many types of fibers used today, PAN fiber is an ideal reinforcing material for asphalt mixture as a kind of organic synthetic fiber 100% made from petroleum. It has the unique surface performance in the process of special surface modification comparing to ordinary fiber, which has better compatibility with asphalt and excels in transferring load as well as deforming synergistically in the mixture, hence dramatically improve the pavement performance of asphalt mixture [2].

Currently, certain researches have been conducted on asphalt materials reinforced by PAN fiber [3-5]. It has been reported that PAN fiber can significantly improve the strength and toughness of asphalt mixture [6]. Cao QH studied the structure and properties of PAN fiber modified asphalt mixture, showing that the structure was transformed from the solvent gel type to the gel type modified by the PAN fiber, which could improve the fatigue cracking resistance of asphalt mortar [7]. The effect of various fibers on crack resistance of asphalt mixture in low temperature was investigated by Gao HT et al [8] and Shi HJ [9]. The results showed that PAN fiber performed better than other types of fibers on crack resistance in low temperature, following which the enhancement mechanism was also preliminary explored. Chen HX et al [10] and Xu QW et al [11] studied the volumetric,



mechanical properties, and the design method of fiber-reinforced asphalt mixtures, considering that proper content of PAN fiber can dramatically improve the high temperature performance of asphalt mixture, meanwhile, the optimum content of PAN fiber was recommended. Obviously, various studies mainly focused on the single pavement performance, while no substantive research has been found systematically looking into the comprehensive performance of PAN fiber-asphalt mixture. Besides, the mathematical analysis methods used in the existing studies have not yet reached the certain accuracy and reliability for comprehensive performance evaluation and materials optimization design. In addition, the microcosmic mechanism of PAN fiber reinforced asphalt mixture requires to be further discussed.

As a result, the main objective of this study is to investigate the effect of varying PAN fiber contents on high temperature performance, crack resistance in low temperature and moisture stability of asphalt mixture, which are essential for pavement performance. Rutting test, bending test, immersion Marshall test and freeze-thaw split test were carried out in this study. Then the crack resistance mechanism of PAN fiber acting on asphalt mixture was revealed by observing the microstructure with SEM. Furthermore, the multi-index weighted grey target method was proposed to evaluate the comprehensive performance of PAN fiber asphalt mixture. Finally, this research also recommended the optimum PAN fiber content according to pavement performance and economic benefit, which provides a reference for the utilization and popularization of PAN fiber-asphalt pavement.

2. Experiments design and grey relational method

2.1. Materials

The asphalt is made of A-70# matrix asphalt obtained from Guangdong province of China. The technical properties of asphalt are shown in Table 1. The fiber used in this study is PAN fiber with 6mm-cut bundles shape, which is presented in Table 2. The selected coarse aggregates are crushed basalt stone, the mineral powders are made from limestone and the fine aggregates are adopted from natural sands. All technical indexes of the materials meet the specification requirement.

Table 1. Basic technical properties of asphalt.

Asphalt type	Penetration (25°C)	Softening point	Ductility (15°C)	After TFOT		
	0.1mm	°C	cm	Quality changes	Residual penetration ratio (25°C)	Residue ductility (10°C)
				%	%	cm
70	71.6	51.4	>100	0.141	72.6	22

Table 2. Technical indexes of PAN fiber.

Index	Cutting length	Diameter	Proportion	Melting point	Tensile strength	Elastic modulus	Breaking elongation
	mm	μm	g/cm ³	□	MPa	GPa	%
Requirement	12 ± 1	10-15	-	≥240	≥500	≥7.0	≥20
Measured value	12	13	1.18	245	575	7.8	22

2.2. Experiments design

In order to improve the pavement performance of upper layer, PAN fiber asphalt made with AC-13 is designed using the Marshall method, within which the aggregate gradation is listed in Table 3. Based on the pavement construction experience and previous study [12], the range of PAN fiber content is

selected from 0% to 0.4% by 0.1% interval, in which each value means the mass percentage of the total amount of asphalt mixture. Specially, when the fiber content is 0%, 0.1%, 0.2%, 0.3%, 0.4%, the optimum asphalt proportion is tested to 4.9%, 5.1%, 5.2%, 5.2%, 5.3%, respectively. Owing to the adsorption effect of PAN fiber on asphalt, more fiber content means higher asphalt proportion. During the test procedure, three parallel specimens were carried out in each experiment, within which the average value of the three parallel specimens should be no more than 15% beyond the measured value of each specimen, or else the experiment is supposed to be conducted repeatedly [13]. As a result, it could be confirmed that the average value of the parallel specimens is relatively accurate that truly characterizes the pavement performance of the mixture.

Table 3. Aggregate gradation of AC-13 asphalt mixture.

Sieve size /mm	16	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Passing rate /%	100	94.1	78.6	53.7	32.5	24.7	18.6	13.1	9.5	5.2

2.3. Evaluation method of multi-index grey relation

The grey relational theory is generally used to evaluate and optimize the schemes with multi-index [14]. The steps are mainly to establish the index grey relational degree model, calculate the association degree between each indicator series and the ideal scheme series. By ranking the association degree with weighted (if necessary), the merits and demerits of each scheme is obtained, so as to optimize the best scheme. More detailed procedures are illustrated in the following:

Construct the sequence based on evaluation index: $X_{i(j)} = \{X_{i(1)}, X_{i(2)}, \dots, X_{i(m)}\}$; in which i represents the scheme number ($i=1, 2, \dots, n$) and j represents the number of evaluation index ($j=1, 2, \dots, m$). Then the same time, the optimal value of each evaluation index is selected as the ideal combination, which is determined as $(X_0)_{\max}$ or $(X_0)_{\min}$. When $X_{i(j)}$ means a positive index, the standard function is selected:

$$f_{ij} = \frac{x_{ij} - (x_j)_{\min}}{(x_j)_{\max} - (x_j)_{\min}}. \text{ On the contrary, when } X_{i(j)} \text{ means a negative index, the standard function is}$$

selected: $f_{ij} = \frac{(x_j)_{\max} - x_{ij}}{(x_j)_{\max} - (x_j)_{\min}}$. After the dimensionless transformation, the larger f_{ij} indicates the better

optimization. Subsequently, the correlation coefficient is calculated, as in equation (1):

$$\xi_i(j) = \frac{\min_i \min_j |X_0(j) - X_i(j)| + \rho \max_i \max_j |X_0(j) - X_i(j)|}{|X_0(j) - X_i(j)| + \rho \max_i \max_j |X_0(j) - X_i(j)|} \quad (1)$$

Where ρ the resolution coefficient, $\rho \in (0, 1)$, generally $\rho = 0.5$.

Combining with the maximal deviation method of objective analysis and the analytic hierarchy process (APH) of subjective analysis, the weight of each factor is designed. Then the relative dispersion of each index is determined by using the maximal deviation method, that is:

$$a_j = \frac{\sum_{i=1}^n \sum_{k=1}^n |x_{ij} - x_{kj}|}{\sum_{j=1}^m \sum_{i=1}^n \sum_{k=1}^n |x_{ij} - x_{kj}|} \quad (j=1, 2, \dots, 5) \quad (2)$$

In the above formula, the weight vector of each indicator is $A = (a_1, a_2, \dots, a_m)$, and $\sum_{j=1}^n a_j^2 = 1$.

Meanwhile, the relative importance weight is determined by APH method and its vector is $B = (b_1, b_2, \dots, b_m)$. Finally, the total weight is integrated of A and B, that is:

$$w_j = \frac{a_j \times b_j}{\sum_{j=1}^m a_j \times b_j} \quad (j=1, 2, \dots, 5) \quad (3)$$

According to the weighting design result W_j of each index, the comprehensive association degree is calculated: $\gamma_i = \sum_{j=1}^m W_j \times \xi_i(j)$, among which the optimum scheme is obtained.

3. Results and discussions

3.1. Effect on high temperature performance

Dynamic stability (DS) was considered as the evaluation index at the temperature of 60 °C during the rutting test. The effect of PAN fiber content on high temperature performance of asphalt mixture was shown in Figure 1.

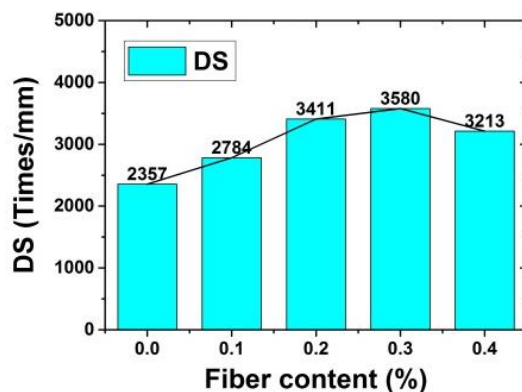


Figure 1. Rutting Test Results.

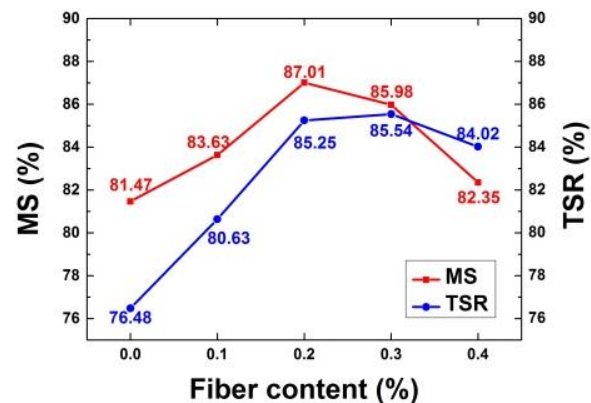


Figure 2. Testing results of moisture stability.

As we can see in Figure 1, the high temperature performance of asphalt mixture added with PAN fiber is superior to that without PAN fiber. As PAN fiber content increases from 0% to 0.2% and to 0.3%, DS enhances by 44.72% and 51.89%, respectively. However, as more PAN fibers added in the mixture, DS shows a degrading trend, indicating that excessive PAN fibers could result in themselves unevenly distributed and clumped, for which a sliding surface is formed between the asphalt mortars and thus the DS decreases.

Under the condition of high temperature, the lubricating effect of free asphalt in asphalt mixture is enhanced and the internal friction between aggregates is reduced, leading to the decrease of shear strength as well as the stability of the mixture at high temperature. Fortunately, PAN fiber can overcome the above handicap with its advantages in tow aspects: on the one hand, oil absorption of PAN fiber could increase asphalt membrane thickness and reduce free asphalt content, thus improving the shear strength of the mixture. On the other hand, PAN fiber improves the viscosity of asphalt and forms a spatial network structure in the mixture. Consequently, the cohesion of asphalt mortar is strengthen, thereby inhibiting the relative slip between the aggregates to guarantee the high temperature stability of the mixture.

Based on the mortar theory [15], asphalt mixture is regarded as the dispersed system of a three level space network. As the second level dispersed system, asphalt mortar contributes to the forming strength and structure of the mixture, which is vital for the pavement performance. In this regard, PAN fiber significantly improves the anti-rutting factor of asphalt mortar and upgrades the dynamic stability of the mixture.

3.2. Effect on low temperature crack resistance

Beam bending test was carried out to investigate the crack resistance at the low temperature of -10 °C, as shown in Table 4.

Table 4. Beam bending test results.

Fiber content /%	Loading /KN	Tensile strength /MPa	Failure strain / $\mu\epsilon$	Stiffness modulus /MPa
0	0.924	7.55	2035	3692
0.1	0.973	7.98	2456	3235
0.2	1.046	8.54	2661	3198
0.3	1.015	8.29	2702	3056
0.4	0.984	8.11	2590	3117

It is appreciable in Table 4 that PAN fiber improves low temperature crack resistance of asphalt mixture. When the fiber content increases from 0% to 0.2% and to 0.3%, the tensile strength increases by 11.6% and 9.8% and also the failure strain increased by 30.8% and 32.8%, respectively. From the statistics can be seen, PAN fiber slightly improved the low-temperature tensile strength of the mixture but remarkably advanced the low-temperature toughness, thus increasing the deformation capacity and postponing the cracking of the mixture at low temperature.

There exists micro grooves and pores on the coarse surface of PAN fiber. As long as PAN fiber is infiltrated by asphalt, both of them would intercalate with each other and produce synergetic mechanics deformation in the mixture. Besides, short-cut PAN fiber is evenly distributed in the mixture, which plays a role of bridging, reinforcing and transferring stress, resulting in blocking the crack propagation of the mixture. When asphalt mixture produces pores and cracks at low temperature, PAN fiber with co-deformation could dispersed the stress and make the mixture more uniformly stressed. Simultaneously, as the fiber stretches across the pores and cracks to form the bridge fiber, it could be protective for the weak interface, which allows to absorb the released energy of crack propagation, ie the crack propagation is constrained by short fiber.

Equipped with higher elastic modulus itself, PAN fiber can boost the modulus of asphalt mixture and increase its deformation capability. Additionally, PAN fiber processes a higher breaking elongation. When load and temperature stress are dissipated, PAN fiber enhance the self-healing ability and toughness of the mixture to alleviate its damage, which is characterized of improving the cracking resistance in a macroscopic aspect.

3.3. *Effect on moisture stability*

Remaining Marshall stability and freeze thaw split ratio are used to evaluate the moisture stability with varying PAN fiber content, which is displayed in Figure 2.

As can be seen from Figure 2, remaining Marshall stability and freeze thaw split ratio both rise first and then decline, following with the increase of the PAN fiber content. Specially, the MS increases by 6.8% and the TRS increases by 11.8% at the optimum fiber content, respectively. More PAN fiber results in more optimum content of asphalt, owing to the asphalt-absorption of PAN fiber. When the optimum content of asphalt increases, the amount of structural asphalt thereupon increases, that is, the asphalt membrane becomes thicker, and the interface adhesion of asphalt-aggregate gets stronger. Moreover, PAN fiber has no significant changes in its property after infiltrated by moisture due to the lower moisture absorption, which further prevents moisture from entering the internal structure. Consequently, it need more infiltrating energy for moisture to destroy the interface adhesion, which proves that the PAN fiber has great effect on the moisture stability of the mixture.

3.4. *Microstructure and anti-cracking reinforcement mechanism*

Figure 3 illustrates that PAN fiber is evenly distributed in all different directions in the asphalt mixture and forms a three-dimensional network structure. In each direction PAN fiber disperse and transfer stress uniformly without any weak force interface existed, which is remarkable in its bridging and reinforcing effect and thus improves the pavement performance of asphalt mixture dramatically.

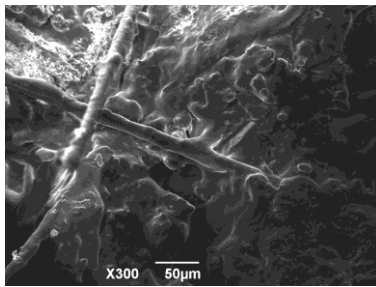


Figure 3 Microstructure of PAN fiber asphalt mixture.

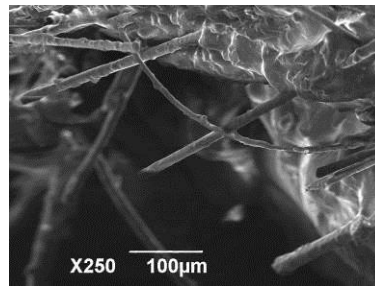


Figure 4 fiber tip.

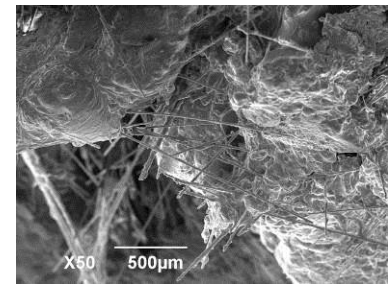


Figure 5. Microstructure of damaged surface.

The microstructure of damaged surface in PAN fiber-asphalt mixture could be observed in Figure 4 and Figure 5. On the damaged fracture surface, PAN fiber is pulled off rather than pulled out or degummed. Based on the Interface infiltration theory [16], the proper infiltration between two phases is the basic condition of forming interface strength. As a result, the better compatibility between PAN fiber and asphalt allows it to form a higher interfacial strength. When external force is applied, PAN fiber converts the load into its own breaking energy, which is manifested by coordination deformation with asphalt mixture until it is pulled off, thereby effectively increased the strength and delayed the cracking of asphalt mixture.

4. Multi-index weighted evaluation of PAN fiber-asphalt mixture

According to the economic analysis method [17] for PAN fiber-asphalt mixture, it could be calculated that the cost of PAN fiber-asphalt mixture is 272 yuan / ton, 295 yuan / ton, 314 yuan / ton, 329 yuan / ton and 348 yuan / ton when the PAN fiber content is 0%, 0.1%, 0.2%, 0.3%, 0.4%, respectively.

In the performance analysis of PAN fiber asphalt mixture, single pavement performance or economic index cannot fully reflect the merits and demerits of the overall performance, which is difficult to recommend the optimal PAN fiber content. Therefore, based on the multi-index weighted grey correlation method, six indexes are adopted for comprehensive evaluation under different proportion with five PAN fiber content from 0% to 0.4%. The grey relation coefficients of each evaluation index are shown in Table 5. According to the degree of seriousness of pavement disease, different evaluation index owns its different weight, which is shown in Table 6.

Table 5. Result of grey correlation coefficient.

Index Fiber content	Dynamic stability	Bending strength	Bending failure strain	Remaining Marshall stability	Freeze-thaw split ratio	Cost
0%	0.33	0.33	0.33	0.33	0.33	1.00
0.1%	0.43	0.47	0.58	0.45	0.48	0.62
0.2%	0.78	1.00	0.89	1.00	0.94	0.48
0.3%	1.00	0.66	1.00	0.73	1.00	0.40
0.4%	0.62	0.54	0.75	0.37	0.75	0.33

Table 6. Results of weight design.

Index	w1	w2	w3	w4	w5	w6	Total
Total weight	0.2667	0.1306	0.1142	0.1217	0.1233	0.2435	1

As a result, the grey relational degree of the comprehensive performance for each scheme is followed: $\gamma_1=0.496$; $\gamma_2=0.509$; $\gamma_3=0.794$; $\gamma_4=0.777$; $\gamma_5=0.541$, which is reflected that the

comprehensive performance of five PAN fiber content is ranked as: $0.2\% > 0.3\% > 0.4\% > 0.1\% > 0\%$. According to the results of multi-index weighted evaluation, it could be concluded that the pavement performance of asphalt mixture with is superior to that without PAN fiber. When the PAN fiber content is 0.2%, the comprehensive performance reach the best.

5. Conclusions

This paper presented the results of the physical and mechanical properties of polyacrylonitrile fiber-reinforced asphalt mixture under different environmental conditions. As a part of this study, PAN fiber content was recommended for comprehensive performance by means of multi-index grey relation method, following which the anti-cracking reinforcement mechanism was revealed basing on SEM analysis. According to the results and analysis, the following conclusions were made:

(1) PAN fiber helps to improve pavement performance and there exists an optimal fiber content for each performance.

(2) PAN fiber infiltrates well into the asphalt and distributes evenly in the mixture, forming a three-dimensional network structure that brings the bridging, reinforcing and toughening effects. Macroscopically, it could be characterized by the enhancement of strength and cracking resistance of mixture.

(3) Based on the grey relational theory and multi-index weighted method, pavement performances and cost of asphalt mixture are analysed under different PAN fiber content. When PAN fiber content is 0.2%, the comprehensive performance of asphalt mixture was optimal.

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