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Pavement Performance Research Progress and Evaluation of Asphalt Mixture Incorporating Iron Ore Tailings

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Abstract

In order to solve the problems caused by the storage of iron ore tailings (IOTs), many researchers conducted a series of experimental studies on the reuse of IOTs. The results of many studies showed that it was feasible to use IOTs for road engineering. This paper summarized the composition, gradation and particle characteristics of IOTs from chemical and physical aspects, and proved the feasibility of IOTs replacing traditional aggregate for asphalt concrete. Then, the research on the road performance of asphalt concrete incorporating IOTs were summarized and reviewed, including the evaluation of high-temperature stability, low-temperature crack resistance, fatigue resistance and water stability. The water stability and the improvement of adhesion between asphalt and IOTs aggregate were discussed in detail. Finally, the performance of IOTs as asphalt concrete aggregate and the existing defects were evaluated, and future research directions were proposed.

Keywords

Iron Ore Tailings, Concrete, Asphalt Mixture, Adhesivity

1. Introduction

Tailings are the main component in the industrial solid waste, which are often regarded as low-value products that cannot be used after beneficiation processing [1]. The total tailings account for more than 80% of total industrial solid waste, including iron tailings, copper tailings, gold tailings, metal tailings or non-metallic tailings. As of 2018, the volume of total tailings has reached 60 billion tons [2]. Iron ore tailings (IOTs) account for the largest proportion of all tailings. IOTs are industrial solid waste discharged after iron ore refining, it contains few iron element, and a great number of valueless components. According to the Annual Report on Comprehensive Utilization of Resources in China (2021), the amount of IOTs produced in 2021 has reached 0.839 billion tons, accounting for 50.88% of the total tailings that produced 1.649 billion tons this year, the statistics of tailings production in 2021 is shown in **Figure 1**. As the steel and iron industries in China development rapidly, the IOTs reserve exceeds 60 billion tons, and grows rapidly to 500 million tons per year [3] [4] [5] [6]. The utilization ratio of tailings in China is lower compared with other developed countries, the rate in Western countries up to more than 60% [7], with only 14% in China [8] [9].

If waste IOTs could be used as road engineering materials that can replace or substitute some natural river sand in concrete, it will not only solve the pressure of natural resources shortage and storage of IOTs but also reduce the road materials outlay [10]. The goal of this article is to present a detailed overview of the utilization of IOTs, to analyze the physical and chemical characteristics of IOTs, and the impact of these characteristics on the IOT asphalt concrete as well as its pavement performance. The water stability of asphalt concrete with IOTs and the adhesion between asphalt and IOTs aggregate were emphatically discussed. The advantages and disadvantages of IOTs used in asphalt concrete are also discussed, so as to provide a reference for the research and development of concrete.

2. General Characteristics of IOTs

Owing to differences of source mining sites and beneficiation processes as well as complexity of symbiotic or associated minerals, the particle morphology and mineral composition of IOTs are different, the composition of IOTs is directly dependent on the composition of the ore and the process of mineral extraction used on the ore [11]. The asphalt concrete mixed with IOTs will be vitally affected. Hence, the research on the material composition, particle size and gradation,

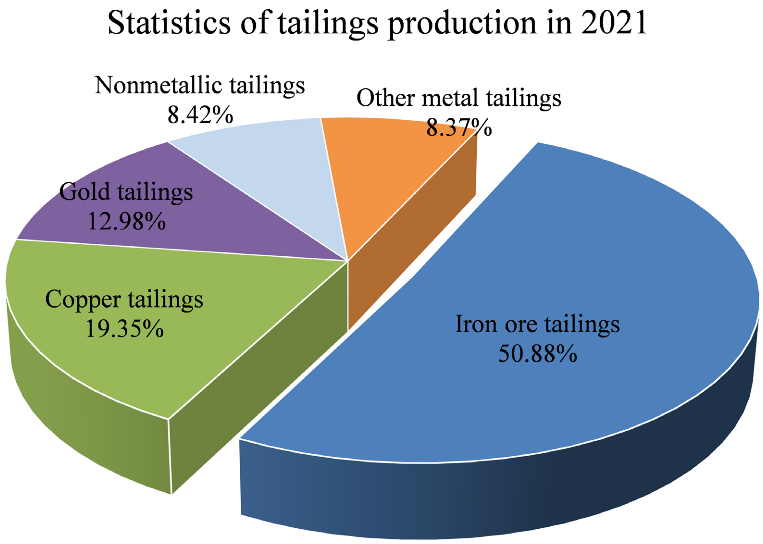


Figure 1. Statistics of tailings production in 2021.

particle morphology of IOT has a basic reference for fully understanding the preparation of concrete prepared by IOT.

2.1. Chemical and Mineralogical Composition of IOTs

The X-Ray diffraction (XRD) patterns of IOT analyzed by Dong Lu [6] indicated that the main mineral constituent contains quartz, mica, calcite, and other minerals. The chemical composition of IOTs generally contains seven major constituents, namely SiO_2, Fe_2O_3, Al_2O_3, CaO, MgO, K_2O and Na_2O. IOTs with different types and origins have a similar chemical and mineralogical composition, silicon dioxide always has the most content in different IOTs. Besides some metal components exist or not, other mineral compositions in IOTs only have the difference in content [1] [12] [13] [14].

Natural sand (NS) is the normal sand used in construction materials as fine aggregates, for instance, cement, concrete, cementitious materials, pavement materials etc. It could be identified that the composition and its proportion of IOTs and NS are largely consistent. Silica, as an acidic oxide, accounts for a large proportion in IOTs, so IOTs could be regarded as a kind of acid aggregates when IOTs are used as aggregates or mineral fines in asphalt concrete.

2.2. Particle Size and Gradation of IOTs

In China, many iron ores are lean ores with complex compositions, in order to improve the metal recovery rate, IOTs are always made much finer (less than 1 mm), via a more precise grinding process [15]. Fineness modulus (μf) is always used to characterize the roughness and fineness of aggregates. When $0.7< \mu f \leq 1.5$, $1.6 < \mu f \leq 2.2$, $2.3 < \mu f \leq 3.0$, $3.0 < \mu f \leq 3.7$, the aggregate is super fine sand, fine sand, medium sand, coarse sand, respectively. The fineness modulus range of IOTs is basically between 1.3 and 3.0, some scholars have calculated that the fineness modulus values of IOTs from different origins are 1.3 [16], 2.1 [17], 2.5 [18], 2.9 [19], with maximum particle size less than 4.75 mm, respectively, which indicates that most IOTs belong to fine sand and medium sand.

IOTs are mostly poorly graded soil. Uniformity coefficient (Cu) reflects the range of particle size distribution, which is generally greater than 1, and the value of Cu closer to 1, the more uniform the particles are, curvature coefficient (Cc) is used to reflect whether the particle gradation is continuous. When $Cu > 5$, $1 \leq Cc \leq 3$ indicates that the particle gradation is good, otherwise is bad. By analyzing the uniformity coefficient and curvature coefficient of IOTs, it is noted that IOTs can not meet the two conditions of $Cu > 5$ and $Cc = 1 - 3$ at the same time, it is identified as bad graded soil.

2.3. Article Shape Characteristic of IOTs

IOTs indeed exhibit many differences compared with NS in surface and shape morphology. Scanning electron microscopic (SEM) was used by Yunqi Zhao [15] to analyze the differences between IOT sand and NS, the SEM images are shown in **Figure 2**, NS exhibits a smoother surface, approximately elliptical particle shape, while IOT sand has a much more angular and irregular shape.

3. The Pavement Performances of Asphalt Mixture Incorporating IOTs

Pavement performance of asphalt mixture usually refers to high temperature stability, low temperature crack resistance, water stability, fatigue resistance, aging resistance, and construction performance, among which water stability, fatigue resistance, and aging resistance are collectively referred to as durability. In order to make asphalt pavement provide safety, high speed, comfort, and other service functions for vehicles, the asphalt mixture used in pavement must consider the above pavement performance.

3.1. High Temperature Stability

The formation mechanism of high temperature stability is derived from the high temperature adhesion of asphalt and the interlocking effect of mineral gradation. The permanent deformation of asphalt pavement mainly occurs in summer, the surface temperature of asphalt pavement is above 40˚C - 50˚C, which is easy to occur when it has reached or exceeded the softening point temperature of road asphalt, with the increase of temperature and load, the deformation is larger [20].

From the perspective of internal factors, the gradation form, asphalt type, and aggregates will affect the high temperature stability of the asphalt mixture. The effect of aggregate on high temperature stability of asphalt mixture is especially obvious, aggregate texture rough, hard, and multi-angle properties of high temperature stability is more favorable [20], IOTs have the above characteristics and could improve high temperature stability to some extent. Wu *et al.* [21] [22] used IOTs as fine aggregate mixed in 90# road asphalt and SBS modified asphalt mixture respectively. Marshall stability test was used to evaluate the high temperature

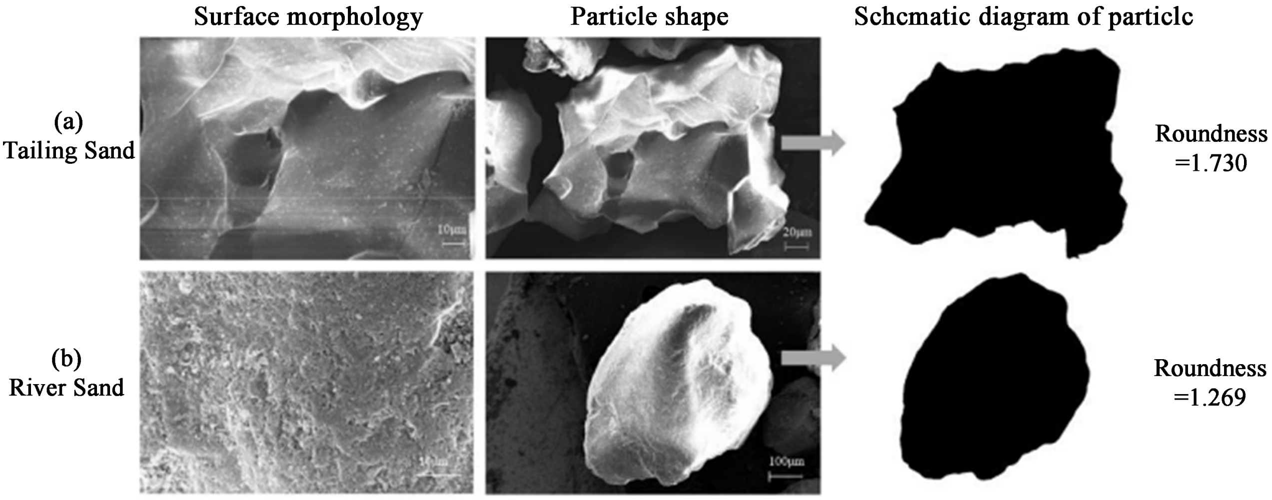


Figure 2. SEM images of iron tailings (a) and natural river sand (b) [15].

stability of asphalt mixture mixed with IOTs, stability and flow value were used as the evaluation index, the results showed that the stability reached 1.5 - 1.8 times of the minimum value required by the specification, far exceeding the performance of ordinary asphalt mixture. Zhang [23] replaced all the coarse aggregate in concrete with IOTs, and 20% IOT sand partially replaced fine aggregate, the total content of IOTs is as high as 75%, Hamburg rutting test results show that asphalt mixture incorporating 75% IOTs has higher ability to resist rutting deformation than ordinary asphalt concrete.

The influence of IOTs on the high temperature stability of asphalt mixture from the chemical composition and physical properties of aggregates is comprehensively analyzed by Zou [24] *et al.* They used IOTs instead of limestone and basalt as fine aggregate of asphalt mixture, the results of rutting test (**Figure 3**) showed that: The dynamic stability of micro-surfacing asphalt mixture prepared by IOTs in place of limestone increases gradually with the addition of IOTs content. The content of SiO_2 in IOTs is higher than that of limestone aggregate, and the content of CaO is lower than that of limestone aggregate, the compressive strength of SiO_2 is significantly greater than that of CaO, which makes the IOT aggregate have fewer flake particles and higher particle size than that of limestone fine aggregate, the internal skeleton of the mixture is easier to form, and the particles are not easy to move under the load.

3.2. Fatigue Resistance

Under the action of moving wheel load, asphalt pavement appears under the stress cycle of tensile-compressive-tensile, when the load repeatedly acts more than a certain number of times, the pavement will lose the effectiveness of resistance to stress, thus creating cracks, resulting in fatigue fracture damage, affecting the movement of vehicles. Fatigue resistance refers to the ability of asphalt

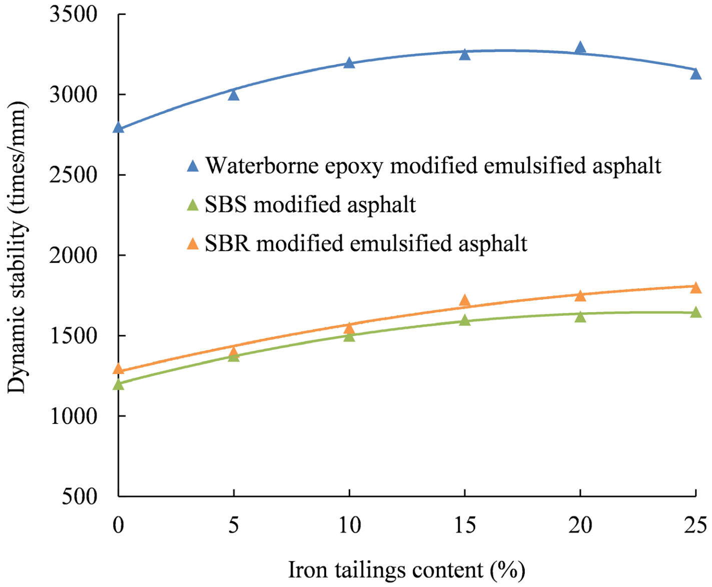


Figure 3. Rutting test result [24].

pavements to resist damage under repeated loading.

Hao [25] mentioned that rough and angular but well-graded aggregates can produce asphalt mixtures with relatively high strength values. Compared to mixes containing coarse textured aggregates and those containing smooth aggregates, the former can accommodate more asphalt content and thus can show longer fatigue life. IOTs have a rougher texture than NS, IOT asphalt mixture may exhibit better fatigue resistance.

Fatigue resistance tests of asphalt mixture mixed with 1% IOTs under controlled stress loading were carried out using a UTM testing machine by Juan [26], stress applied using a half-sine waveform with a loading frequency of 1 Hz, the number of load actions leading to complete fracture (Nf) was used to evaluate the fatigue resistance. It could be seen from the **Figure 4** that a noticeable increase in fatigue resistance of an order of magnitude (10×) is observed when using IOTs, compared to the control mixture, the stiffness and mechanical behavior of the IOT asphalt mixture improved, so that the fatigue resistance is better.

3.3. Low Temperature Crack Resistance

Low temperature crack resistance refers to the ability of asphalt pavement to resist low temperature shrinkage cracks. When the temperature drops, the asphalt surface will produce shrinkage deformation. In the general temperature range, asphalt concrete has the ability of stress relaxation. When the temperature drops sharply, the increase of stress caused by temperature drop exceeds the speed of stress relaxation, and residual stress is produced in asphalt concrete. When the residual stress exceeds the ultimate tensile strength of asphalt mixture, cracking occurs.

Through low-temperature bending test and splitting test, Xiao [27] systematically analyzed the influence of the dosage of IOT gravel instead of limestone as coarse aggregate on the flexural strength, splitting strength, and maximum flexural

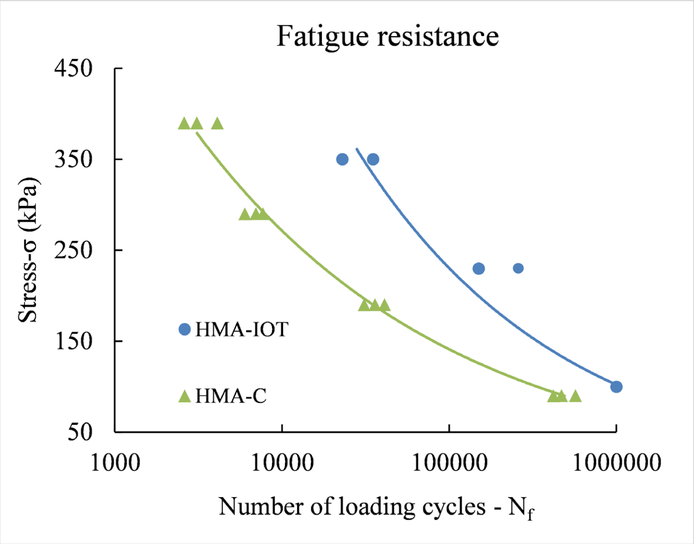


Figure 4. Fatigue resistance [26].

strain of asphalt concrete. The results of low temperature bending test show that the maximum bending strain of asphalt concrete decreases with the increase of IOTs content, the variation of maximum flexural tensile strain of asphalt concrete with IOTs content is shown in **Figure 5**. The results of the splitting strength test also show that the splitting strength decreases obviously with the increase of the amount of IOTs. The decrease of low temperature crack resistance is mainly due to the acidity of IOT gravel, and the adhesion between IOT gravel and asphalt is not as good as that between asphalt and limestone. Zhang [23] carried out low temperature bending test to evaluate the low temperature performance of asphalt concrete with different IOTs content, the results showed that the low temperature performance of asphalt mixture incorporating 75% IOTs decreased, slightly lower than that of ordinary asphalt mixture. Shao [28] carried out low temperature bending creep test, the results show that compared with limestone asphalt mixture, the bending tensile strain and bending stiffness modulus of iron tailing asphalt mixture are reduced by 7.5% and 9.6%, respectively.

It can be seen from the above research that the incorporation of IOTs has a negative impact on the low temperature crack resistance of asphalt concrete. In order to maintain the low temperature crack resistance of asphalt concrete, the amount of IOTs should not be too large.

3.4. Water Stability

Water damage of asphalt pavement refers to the asphalt pavement under the condition of the existence of water, through the repeated action of traffic load and temperature expansion and contraction, water gradually immersed in the interface between asphalt and aggregate, at the same time, due to the dynamic effect of water, asphalt film gradually peeled off from the surface of aggregate, and lead to the loss of cohesive force between aggregates and pavement failure process. The ability of asphalt mixture to resist this damage is the water stability

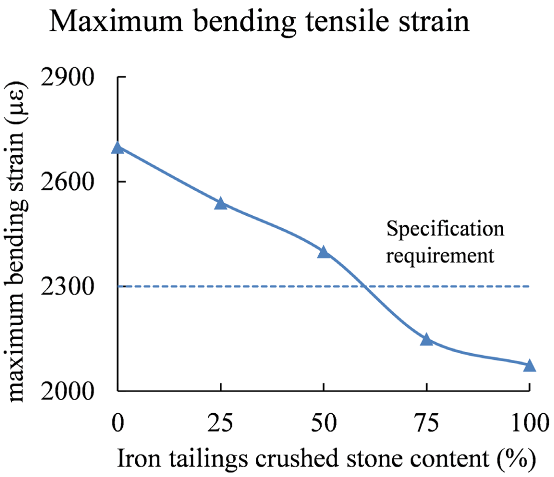


Figure 5. Change of maximum bending tensile strain of asphalt mixture with IOTs gravel content [27].

of asphalt mixture [29]. Water damage of asphalt pavement is sometimes more demanding than high temperature stability, fatigue, and low temperature crack resistance, especially in humid and rainy regions. Usually, the initial water damage of asphalt pavement is caused by the poor water stability of asphalt mixture itself [30].

Asphalt pavement water damage occurs in addition to external factors (water and load), mainly depending on the intrinsic properties of the asphalt mixture, the main factors affecting water stability are the nature of the aggregate, the nature of asphalt, the interaction between asphalt and aggregate, the porosity of the asphalt mixture and the thickness of the asphalt film. IOTs are acidic aggregates, with relatively poor adhesion to asphalt, and IOTs are irregular in shape, the thickness of the asphalt film formed on its surface is not uniform, which will affect the water stability of the asphalt mixture.

Han *et al.* [23] [31] used immersion Marshall test and freeze-thaw splitting test on asphalt mixture with 75% IOTs and asphalt mixture with 2% IOTs, respectively. Both of these methods are static water stability test methods, the results showed that the water stability of asphalt mixture with high content of IOTs was lower than that of ordinary asphalt mixture, while the incorporation of 2% IOTs did not affect its water stability. Later, Han also conducted the Hamburg rutting test. The results show that when the temperature rises to high enough, the water stability of IOTs asphalt mixture will deteriorate sharply, and the water stability of IOTs asphalt mixture is more sensitive to temperature than that of ordinary asphalt mixture. Shao [28] used the immersion Marshall test to examine the spalling resistance of the asphalt mixture by water erosion, with the growth of the immersion time, the test results show that the residual stability of IOT asphalt mixture after 48 h immersion test compared to limestone asphalt mixture decreased by 7.0%, the water stability of asphalt mixture mixed IOT has decreased, and then the Hamburg rutting test also supports this result. Juan [26] accessed the moisture susceptibility potential of control hot mix asphalt type C (HMA-C) and hot mix asphalt incorporating 1% IOT (HMA-IOT) with modified Lottman tests, Tensile Strength Ratio (TSR) as an evaluation index. The result showed that both of the HMA mixtures meet the requirements, and the HMA-IOT has a better result than HMA-C, which may be attributed to the presence of some oxides [32], HMA-IOT has a high percentage of iron oxide (83.95% hematite in IOT), which could improve the water damage resistance of asphalt mixture and the adhesion of asphalt and aggregate.

4. Adhesion between Asphalt and IOTs

The adhesion characteristics between asphalt and aggregate determine the high temperature, fatigue, especially water stability performance of asphalt mixtures, and are related to the durability of asphalt pavements [33]. The prominent properties of IOTs are acidic aggregates, many angles and rough surface, which may have an impact on the adhesion of asphalt to IOTs aggregates.

4.1. Adhesion-Exfoliation Theory

In the asphalt mixture, asphalt is used as a binder to bond a certain gradation of coarse and fine aggregate bonding into a whole, the bonding force is the key to provide the strength of the mixture, which is determined by the cohesion of asphalt itself and the adhesion between asphalt and aggregate [34]. The current research is more inclined to the adhesion failure between asphalt and aggregate [35]. In terms of asphalt aggregate adhesion mechanism, the current theories mainly include mechanics, chemical bond, molecular orientation, electrostatic and surface free energy theory, etc. [36]. However, there are many factors affecting the adhesion of asphalt and aggregate, the formation mechanism of mixture adhesion spalling is very complex and diverse, a single theory often does not fully elucidate the adhesion of asphalt to aggregate, and a combination of theories is generally used to consider its adhesion [37].

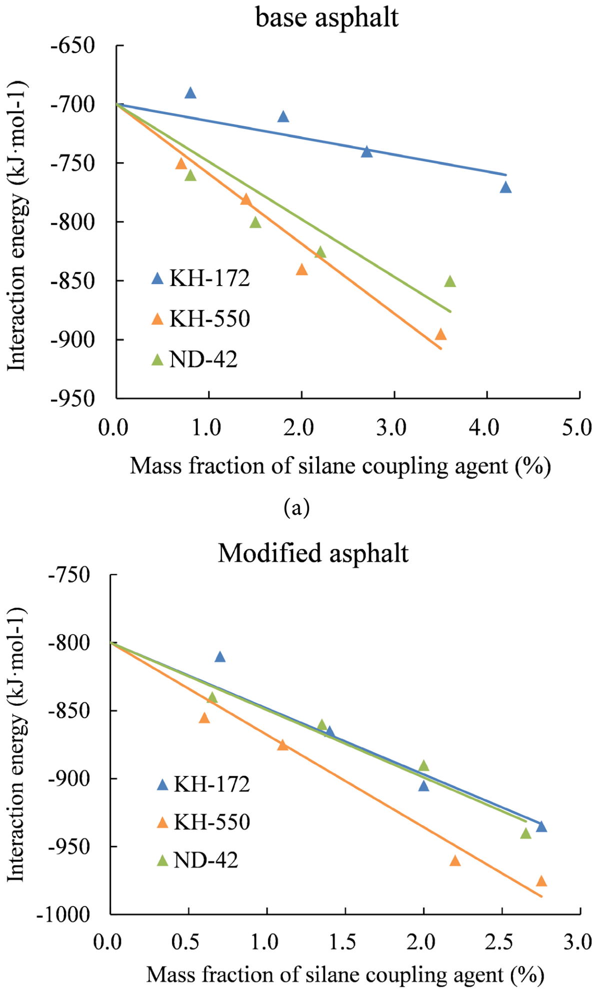
The chemical reaction theory states that asphalt and aggregate are bonded together by a chemical reaction between the acidic components in the asphalt and the alkaline components in the aggregate. Therefore, the higher the acid content (e.g. SiO_2) in the aggregate is, the worse the bond between asphalt and aggregate is. Yu [29] used acid-base titration method to determine the relationship between SiO_2 content and acid-base and adhesion strength respectively and found that the adhesion of acidic aggregates is not as good as alkaline aggregates, and the greater the acidity, the worse the adhesion with asphalt. Generally speaking, the acidity and alkalinity of the aggregate is determined by its SiO_2 content, and the higher the SiO_2 content, the more acidic the aggregate is. The more acidic the aggregate surface is, the poorer its adhesion to asphalt, and the more likely it is to peel off in the presence of water [38]. IOT is a kind of acidic aggregate, with relatively low adhesion to asphalt, in the presence of water is easy to occur with the asphalt binding material debonding, resulting in a certain degree of decline in the water stability of asphalt mixture [27].

4.2. Improvement Methods and Mechanism

Due to the poor adhesion of IOTs to asphalt when used as aggregates, the application in road projects will lead to a decline in the pavement performance of asphalt concrete, many researchers have studied the improvement measures for the adhesion of IOTs to asphalt, in order to improve the application value of IOTs, and break through the limit of IOTs in road projects, so that they can be more and more reasonable reuse.

Silane coupling agent is commonly used to improve the adhesion between acid aggregates and asphalt, and is also suitable for IOTs as aggregates [39]. SiO_2 is the main component of IOTs, and it is also the representative object of silane coupling agent. The interaction between silane coupling agent and inorganic minerals is mainly through the dehydration and condensation reaction between the hydrolysis products and the hydroxyl groups on the mineral surface to produce chemical bonds [40] [41] [42]. When the surface of IOTs is chemically modified, the surface of IOTs will be coated with hydrophilic organic functional groups. The hydrophilic organic functional groups will produce physical adsorption with asphalt, and improve the affinity of IOTs to asphalt [39]. The longer the length of the molecular chain at the hydrophilic organic end is, the easier it is to tangle with asphalt molecules [43].

Cao [39] used the molecular dynamics simulation method to study the improvement effect of silane coupling agent on the adhesion between asphalt and IOTs, and constructed the molecular models of hydrolysis products of matrix asphalt, rubber/SBS modified asphalt, IOTs and KH-550, KH-172 and ND-42 silane coupling agents. The results of molecular dynamics simulation show that the surface of IOTs and rubber/SBS composite modified asphalt has obvious adsorption, and the silane coupling agent grafted on the surface of IOTs is embedded in the asphalt system to form a stable mixing state. The molecular chains of hydrophilic organic groups of silane coupling agent are intertwined with molecules in modified asphalt, and have good compatibility. **Figure 6** shows that the



(a)

(b)

Figure 6. Trend of interaction energy changing with mass fraction of silane coupling agents [39]. (a) Base asphalt; (b) Modified asphalt.

interaction energy of matrix asphalt and rubber/SBS composite modified asphalt system changes with the mass fraction of different types of silane coupling agent. It can be seen that the modification effect of KH-550 is better, and the modification effect increases with the mass fraction of silane coupling agent. Sun [44] used silane coupling agent KH-550 as an additive to improve the adhesion ability of IOTs to asphalt, using the adhesion work of SiO_2 as an evaluation index. It was found that there exists an optimum value for the mass fraction of the adding silane coupling agent, which was 0.6% in this test. The contact angle between asphalt and aggregate was measured by the sessile drop method, and the measured contact angle value can reflect the size of the standard liquid's ability to wet asphalt and mineral, and then the surface energy and adhesion work between asphalt and aggregate were calculated. The results showed that when the mass fraction of silane coupling agent was 0.6%, the adhesion work increased by 16.5%, and the addition of silane coupling agent can effectively improve the adhesion of asphalt and IOTs.

The adhesion between modified asphalt and IOTs has been significantly improved. Because the water stability is the main macroscopic performance of adhesion strength, Cao [39] and Sun [44] have carried out the freeze-thaw splitting test on modified asphalt mixture, and evaluated the adhesion ability according to the test results. The test results show that the splitting strength and freeze-thaw splitting strength ratio of the modified asphalt mixture are increased by about 20% compared with those of the unmodified mixture, indicating that KH-550 can enhance the water stability of the asphalt mixture with IOTs and improve the adhesion between IOTs and asphalt. Tian [45] used slaked lime and silane coupling agent to improve the adhesion of IOTs, respectively. The results showed that the two modifiers had positive effects on the adhesion of IOTs to asphalt. The pavement performance of the modified asphalt mixture was evaluated, and it was found that the high temperature stability of the IOTs asphalt mixture with lime was better improved, and the low temperature crack resistance of the mixture with silane coupling agent was better improved. The reason for this result is that there is a certain difference in the improvement mechanism between the two modifiers: hydrated lime belongs to alkaline substances, and $CaOH_2$ reacts with acidic substances in asphalt to form insoluble calcium salts, which improves the strength of the mixture, and also has strong adsorption capacity and the ability to activate the surface of IOTs. On the other hand, one end of the hydrolysis product of silane coupling agent is adsorbed by hydrogen bonds with aggregates, and the other end is entangled with asphalt molecules to form a stable network structure, which enhances the overall bonding of the mixture, enhances the ability to resist deformation, increases the flexural tensile strength, and then improves the low temperature crack resistance of the mixture.

Yu [46] used anti-stripping agent to modify the surface of IOTs and asphalt, and evaluated the adhesion by boiling test. The results showed that the addition of anti-stripping agent could effectively improve the adhesion between IOTs and asphalt. From the results of adhesion grade improvement, the adhesion of mineral surface modification was better than that of asphalt modification. At the same time, the adhesion work between SBS modified asphalt and matrix asphalt is also compared. It could be found that the adhesion of SBS modified asphalt and IOTs is better than that of matrix asphalt.

5. Conclusions and Future Development Tendencies

5.1. Conclusions

IOTs are widely used as low grade road or pavement base materials. At present, the researches on IOTs as coarse and fine aggregates of asphalt concrete are increasing, and the experimental studies also prove that the various indicators and performance of IOTs asphalt concrete meet the requirements of the specification. IOTs have great potential in asphalt concrete.

1) The physical and chemical properties of IOTs in different regions are similar. Most of the IOTs belong to fine sand or ultra-fine sand, and excessive addition will have a negative impact on the pavement performance of asphalt concrete.

2) After adding IOTs into asphalt concrete, the high-temperature stability of its pavement performance is improved to a certain extent compared with that of ordinary asphalt concrete, but the low-temperature crack resistance and water stability have decreased to varying degrees, which is related to the nature of IOTs and the interaction between IOTs and asphalt.

3) Through the research on the adhesion between asphalt and IOTs and the water stability of IOTs asphalt mixture, it could be found that the adhesion between asphalt and IOTs aggregate can be improved by using silane coupling agent, slaked lime, anti-stripping agent and other chemical agents to modify asphalt or IOTs, which can improve the pavement performance of asphalt mixture, especially water stability.

5.2. Future Development Tendencies

Compared with foreign countries, the IOTs utilization rate is low and the utilization range is not wide enough in China. At present, there are still many deficiencies in the study of IOTs asphalt concrete. Research on various aspects of asphalt concrete with IOTs is still at the theoretical level.

1) Dynamic modulus is an important performance parameter of asphalt mixture, which is proposed based on the mechanical properties of materials. Therefore, researchers could measure the dynamic modulus and phase angle of asphalt mixture with IOTs to explore the mechanical properties of this new mixture in the future.

2) Most of the current research and conclusions on IOTs asphalt concrete are based on laboratory tests. In the future, researchers can set up test sections of IOTs asphalt mixture paving outdoors, and explore the influence of site construction conditions. Furthermore, the structural reliability, pavement damage characteristics, and repair technology of IOTs asphalt pavement could be studied

and compared with traditional asphalt pavement, so as to be able to apply IOTs asphalt pavement in practice.

3) In order to meet the needs of modern development, permeable asphalt pavement, modified asphalt pavement and other new pavements are widely used. Researchers could also explore the various properties of asphalt mixture required for paving new pavements mixed with IOTs.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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