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Experimental investigation on the application of the aggregate of gneiss-based migmatite in asphalt mixture of AC-13

Erhu Yan¹, Yan Gong^{1*}, Rong Chang¹, Zhijun Wang¹ and Jian Xu¹

Abstract: In this research, the aggregate of acid migmatite and its application in the asphalt mixture were evaluated experimentally. In order to study the performance of asphalt mixture with the aggregate of acid migmatite, four different compositions of mixtures were designed by Marshall method. Six test methods for aggregate were used, such as adhesion test, particle shape test, and so on. While four test methods for asphalt mixture were used, that is stability ratio test, indirect tensile strength ratio test, rutting test, scouring and pumping test after short-term aging. The Results indicated that the aggregate of acidic gneiss-based migmatite was of high strength. However, due to the high proportion of flat and elongated particles in the asphalt mixture and the poor affinity to asphalt binder, the untreated asphalt mixture was difficult to meet the current requirements. The four-stages crushing process was developed to reduce the percentage of flat and elongated particles. Besides, either adding hydrated lime or using limestone fine aggregate instead of acidic gneiss-based migmatite, might be attributed to improve the rutting resistance and reduce the water sensitivity of asphalt mixture.

Subjects: Environment & Agriculture; Environmental Studies & Management; Physical Sciences; Engineering & Technology

ABOUT THE AUTHOR

The authors are from the team of asphalt pavement materials and structure research. We are engaged in the development of the test method of asphalt and asphalt mixture and the investigation of new road materials, such as acidic tunnel slag, rubber asphalt, snow melting asphalt mixture, high modulus asphalt concrete, and so on. We are also interested in the nano/micro study on the asphalt materials and intelligent perception of the aggregate. Our main work is to research and develop test methods and technical standards for road materials.

PUBLIC INTEREST STATEMENT

The aggregates of acidic rocks, especially acidic migmatite, have been rarely used for the asphalt mixtures in last decades in China. The pavement industry is still in the construction climax and the shortage of high-quality rock resource has become increasingly prominent. This perspective article describes some disadvantages of the aggregate of gneiss-based migmatite and its adverse effects on the performance of asphalt mixture, based on the experimental application of 320,000 tons aggregate on the Yuewu expressway. It was found that the aggregate of acidic gneiss-based migmatite could be successfully applied to asphalt pavement after treated. The experimental investigation can not only improve the relevant specification of asphalt pavement but also help the pavement industry to utilize acidic rocks as new rock resources, which has good economic and environmental benefits.

Keywords: asphalt mixture; gneiss-based migmatite; mixture performance; rutting test; scouring & pumping test

1. Introduction

The aggregates of intermediate and basic rocks, such as basalt, diabase and limestone have been widely used in the asphalt mixtures in the past decades (Yang, Liang, & Lai, 2008). But the aggregates of acid rocks, especially gneiss, sandstone, are rarely used due to their poor adhesion and the water sensitivity of asphalt mixtures (Peng, Fu, & Huang, 2013; Zhang, 2010; Zhang & Li, 2013). Moreover, the aggregates of migmatites are not allowed in the asphalt mixture (Xu, 2010; Yan, 2013).

The pavement industry is still in the construction climax in China, which leads to a great deal of aggregates consumption every year. With the storages of basic and intermediate rocks declining dramatically, the exhaustion of these rock resources has become a serious problem. Therefore, it is necessary to develop and utilize new rock resources such as gneiss, granite and sandstone, which are widely distributed in China. Recently, researchers pay more and more attention to the application of the aggregates of acid rocks in the asphalt mixture (Zhou, Yang, & Yu, 2016). The application of the aggregate of acid migmatite in Yuewu expressway is a case.

Although researched in last decades (Figueroa Infante & Reyes Lizcano, 2015; LaCroix, Regimand, & James, 2016; Schram & Williams, 2012), moisture damage to asphalt pavements continues to be a major concern. Considering the annual rainfall in the vicinity is 1400 mm ~2200 mm, the water sensitivity of asphalt pavement needs special attention. The anticipated equivalent single-axle loads (100 kN) of Yuewu expressway over a 15-year period is estimated to be 23 million. According to the current Chinese standard (RIOH, 2017), the traffic level is "Very Heavy". There is almost no intermediate or basic rock along the project. The nearest source of limestone is 180 km away, while that of basalt is 320 km. At the same time, about one million tons of rock are produced during the tunnel excavation in the project, which will yield nearly 800,000 tons of aggregate. The produced rock is acidic migmatite composed mainly of gneiss. If the acidic migmatite can instead of the non-native rock used in asphalt mixture, long-distance transportation and additional mining will be prevented, thus reducing the cost of aggregates and the energy consumption. For the sake of economy and environmental protection, it is necessary to study the application of the aggregate of acid migmatite in asphalt mixture.

2. Materials

2.1. Aggregates

The coarse aggregate (Figure 1) used in this research was the rock produced during the tunnel excavation in the Yuewu expressway. By visual observation, the color and texture of aggregate

Figure 1. The aggregate of acid gneiss-based migmatite.



particles varied greatly. It was identified as an aggregate of migmatite by electron microscopy, which was composed mainly of gneiss and partly of amphibolite, leptyte and marble (Figure 2). The content of SiO_2 reached 70.5%, so the rock belonged to acidic gneiss-based migmatite. The sizes of the coarse aggregate were 3–5 mm, 5–10 mm and 10–20 mm, respectively.

There were two types of fine aggregates with the size of 0–3 mm in this research. One was the mentioned acidic gneiss-based migmatite. The other was the typical limestone, which was used to improve the anti-moisture performance of the asphalt mixture.

2.2. Filler

The mineral powder by grounding limestone is commonly used as filler in China. In this research, a certain amount of hydrated lime was used as an anti-stripping additive, replacing a part of mineral powder.

2.3. Asphalt binder

According to the traffic load and climatic conditions, SBS I-D polymer-modified asphalt binder was used in the Yuewu project. The properties of the asphalt binder met the relevant technical requirements in the specification of JTG F 40 (RIOH, 2004). The test result is shown in Table 1.

2.4. Formula of asphalt mixtures

The type of asphalt mixtures was AC-13C with SBS modified asphalt binder, which was a typical one used to the surface course in China. The compositions of mixtures were designed by Marshall method. The aggregate gradation and the asphalt content of asphalt mixtures are shown in Table 2.

Figure 2. The electron micro-graph of the aggregate of acid migmatite (Magnified 70 times).

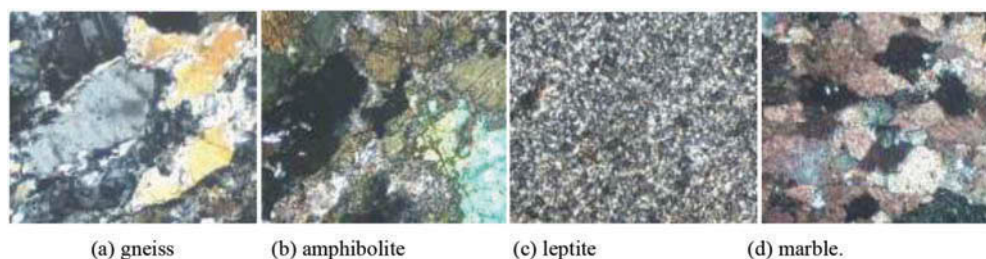


Figure 3. Particle shape change of aggregate by different crushing processes.



Table 1. The test result of SBS I-D modified asphalt binder

| Property | | Unit | Technical requirement (Figueroa Infante & Reyes Lizcano, 2015) | Test value |
|--|-------------------------------------|--------|---|------------|
| Penetration (100 g, 5 s, 25°C) | | 0.1 mm | 40 ~ 60 | 54 |
| Softening point ($T_{R\&B}$) | | °C | ≥75 | 84.5 |
| Dynamic viscosity (60°C) | | Pa·s | ≥10,000 | 11,064.1 |
| Kinematic viscosity (135°C) | | Pa·s | 2~3 | 2.275 |
| Ductility (5 cm/min, 5°C) | | cm | ≥25 | 34.0 |
| Flash point (COC) | | °C | ≥230 | 331 |
| Solubility (Trichloroethylene) | | % | ≥99 | 99.7 |
| Elastic recovery (25°C) | | % | ≥80 | 95 |
| Segregation (difference of softening point after 48 h) | | °C | ≤2.5 | 1.0 |
| After TFOT | Mass change | % | ≤1.0 | -0.062 |
| | Penetration ratio (100 g, 5s, 25°C) | % | ≥65 | 72.0 |
| | Ductility (5 cm/min, 5°C) | cm | ≥15 | 21.0 |
| PG | | - | 76-22 | 76-22 |

[i] The filler dosage values represent the mass percentage of the filler in asphalt mixtures.

[ii] The values presented under each sieve size represent percent passing values.

[iii] The asphalt content values represent the mass percentage of the asphalt binder in asphalt mixtures.

3. Test method

3.1. Test method of aggregate

3.1.1. Aggregate crushing value test (RIOH, 2005)

The specimen with a size fraction of 9.5 mm to 13.2 mm was compacted in a standardized manner into a steel cylinder with an internal diameter of 150 mm, which was fitted with a freely movable plunger. The specimen was then subjected to the standard load applied through the plunger. The loading rate should be as uniform as possible to make the required force reach 400 kN in 10 min ± 30 s. After the completion of loading, the quantity of materials passing through the 2.36 mm sieve was determined. The aggregate crushing value (ACV) was calculated, which was expressed as the percentage of the mass of the crushed materials passing through the 2.36 mm sieve to the initial mass of the specimen.

3.1.2. Los angeles coefficient test (RIOH, 2005)

The specimen with a mass of (5000 ± 5) g was rolled with steel balls of (5000 ± 20) g in a rotating drum at a speed of 30 to 33 r/min for 500 revolutions. After rolling, the quantity of materials retaining on the 1.7 mm sieve was determined. The Los Angeles coefficient was calculated, which was expressed as the percentage of the mass of the material retaining on the 1.7 mm sieve after rolling to the initial mass of the specimen.

Table 2. Aggregate gradation and asphalt content of asphalt mixtures with SBS modified asphalt binder

| Number of asphalt mixture | Coarse aggregate type | Fine aggregate type | Filler type and its dosage (%) ^a | Aggregate gradation (%) ^b | | | | | | | | Asphalt content (%) ^c | |
|---------------------------|-----------------------|---------------------|---|--------------------------------------|------|------|------|------|------|------|------|----------------------------------|-------|
| | | | | 16 | 13.2 | 9.5 | 4.75 | 2.36 | 1.18 | 0.6 | 0.3 | | 0.075 |
| 1# | Acid migmatite | Acid migmatite | 4% mineral powder | 100 | 93.9 | 72.8 | 43.1 | 29.4 | 20.5 | 14.2 | 10.1 | 5.6 | 5.2 |
| 3# | Acid migmatite | Acid migmatite | 2.5% mineral powder + 1.5% hydrated lime | 100 | 93.9 | 72.8 | 43.1 | 29.4 | 20.5 | 14.4 | 10.2 | 5.8 | 5.2 |
| 4# | Acid migmatite | Limestone | 4% mineral powder | 100 | 93.0 | 71.5 | 43.9 | 30.4 | 21.4 | 12.5 | 10.8 | 6.1 | 5.3 |
| 6# | Acid migmatite | Limestone | 2.5% mineral powder + 1.5% hydrated lime | 100 | 93.0 | 71.5 | 43.9 | 30.4 | 21.4 | 12.8 | 11.0 | 6.3 | 5.4 |

^aThe filler dosage values represent the mass percentage of the filler in asphalt mixtures.

^bThe values presented under each sieve size represent percent passing values.

^cThe asphalt content values represent the mass percentage of the asphalt binder in asphalt mixtures.

3.1.3. Bulk specific gravity and water absorption test (RIOH, 2005)

Bulk specific gravity and water absorption test was determined at a temperature of $23 \pm 2^\circ\text{C}$ after a soaking period of 24 h by adopting wire basket method. Water absorption was the mass of the absorbed water, which was expressed as the percentage of the mass of the oven-dried aggregate sample.

3.1.4. Magnesium sulfate soundness test (RIOH, 2005)

The specimen was subjected to five cycles of immersion in a saturated solution of magnesium sulfate, followed by oven drying at $(105 \pm 5)^\circ\text{C}$. The degradation arising from the disruptive effects was measured by the extent to which materials finer than 10 mm in particle size was produced. For the first cycle, the immersion time was 20 h, and the drying time was 4 h. For the second to fifth ones, the immersion time and drying time were both 4 h. The value of the magnesium sulfate was calculated, which was expressed as the percentage of the mass of the material passing the designated sieve after the test to the initial mass of the specimen.

3.1.5. Particle shape test (RIOH, 2005)

More than 100 particles of coarse aggregate were classified on the basis of the ratio of their length L to thickness E using a particle slide gauge or micrometer. The percentage of flat and elongated particles was calculated as the percentage of the mass of particles with a ratio of dimensions L/E more than three to the initial mass of particles tested.

3.1.6. Adhesion test (RIOH, 2017)

Firstly, five particles with the size fraction of 13.2 mm to 19 mm were selected. Secondly, the particles were immersed in hot asphalt binder at 150°C for 45 s. And thirdly they were taken out and cool down for 15 min at 20°C . Finally, they were immersed into boiling water for 3 min, and the area with remained binder was observed on each particle. Degree of asphalt was calculated as the average coverage proportion of the surface area of the aggregate particles covered with asphalt, which was expressed as the percentage.

*Note: When hydrated lime was added, the aggregate particles should be immersed into a 10% aqueous solution of hydrated lime for 5 s, and then test according to the above steps.

3.2. Test method of asphalt mixture

3.2.1. Stability ratio (RIOH, 2017)

Two sets of Marshall specimens were prepared, containing at least four specimens, respectively. The diameters and heights of the cylindrical specimens were 101.6 mm and 63.5 mm. The loose asphalt mixtures were artificially short-term aged at 135°C for 4 h before compaction. And then both sides were compacted for 50 times. The conditioning time of 48 h was applied for the first set of specimens at 60°C , and then the Marshall stability tests were carried out. For the second set of specimens, a conditioning time of 30 min combined with the temperature 60°C was used, and then the Marshall stability tests were performed. The stability value ratio between these two sets was defined as the stability ratio.

3.2.2. Indirect tensile strength ratio (RIOH, 2017)

Two sets of specimens were prepared by the same method as the stability ratio test. The first set of specimens was kept under vacuum conditions between 98.3 and 98.7 kPa for 15 min and then was immersed into water for 0.5 h after recovering to normal pressure. Next, the specimens were stored in a plastic bag at $-18 \pm 2^\circ\text{C}$ for 16 h. Then, the plastic bags were removed and the specimens were put into the water at 60°C for 24 h. At last, the indirect tensile strengths of the specimens after 2 h conditioning at 25°C were tested. The indirect tensile strength ratio (ITSR) was the ratio of the indirect tensile strengths between two sets of specimens.

3.2.3. Rutting test (RIOH, 2017)

Three asphalt mixture slabs were prepared by using a roller compactor. The sizes of the slabs were 300 mm *300 mm in both length and width, and 50 mm in the height, and the specimens were conditioned at room temperature (20°C) for 48 h. Then, the specimens were heated to 60°C, and the rutting tests were performed. A solid rubber tire with a diameter of 200 mm, the width of 50 mm was applied, and the constant contact pressure of 0.7 MPa was selected. The loading speed was 42 times/min. The testing duration time was 60 min. The corresponding deformation at 45 min and 60 min was recorded, then the dynamic stability (DS) was determined from the formula:

$$DS = \frac{(60 - 45) \times 42}{(d_{60} - d_{45})} \quad (1)$$

where:

DS—the number of loading per 1 mm deformation of asphalt mixture slab (times/mm);

60,45—the loading time (min);

42—the loading speed (times/min);

d_{60} —the corresponding deformation at 60 min (mm);

d_{45} —the corresponding deformation at 45 min (mm).

3.2.4. Scouring & pumping test after short-term aging in lab (ZHOU ET AL., 2016)

A specimen chamber was filled with 50°C hot water, which allowed the operation at higher temperatures and created pore pressure within a Marshall specimen. It could accelerate the effect that a mixture in a wet pavement would experience over time by a passing vehicle tire. The cyclic pressure peak which approximated to Lorentzian function had a peak within ± 30 kPa of the set point and a width at half maximum of 1 ± 0.5 s. After accelerated conditioning of 10,500 cyclic loadings, it would result in the stripping of asphalt and the loss of aggregate particle, so that the density and strength of the specimen would change.

Two sets of specimens were prepared in the same manner as the stability ratio test. The first set of specimens was accelerated conditioning. Then, the bulk density was measured for both sets of specimens. The difference of bulk density between the two sets was then calculated. The ratio of the difference with the bulk density of the second set of specimens was defined as the change rate of the bulk density.

4. Test results of the coarse aggregate of acidic gneiss-based migmatite

The results of Aggregate Crushing value, Los Angeles coefficient, water absorption, magnesium sulfate soundness value and bulk specific gravity (Table 3) met technical requirements in the specification of JTG F 40, which showed the aggregate had good performance of resistance to fragmentation and weathering. However, the results of the degree of asphalt coverage and the percentage of flat & elongated particles could not meet the technical requirements, which showed the coarse aggregate of the migmatite should not be directly used for asphalt mixture according to the current Chinese standard.

The low degree of asphalt coverage indicated the poor affinity between aggregate and bitumen. As we know, adding hydrated lime is a common measure to improve adhesion of aggregate. The degree of asphalt coverage of the aggregate treated with aqueous solution of hydrated lime can be improved obviously. The chemical reactions between hydrated lime and aggregate surface can improve the free energy of aggregate surface and increase the affinity between aggregate and asphalt (Xu, 2010) (Table 4). In our research, 1.5% the hydrated lime was determined to be added in asphalt mixture in the Yuewu expressway to increase the affinity.

Table 3. Test results of coarse aggregate of gneiss-based migmatite

| Property | Test value | | Technical requirement (Figueroa Infante & Reyes Lizcano, 2015) |
|---|---------------|---------------|---|
| | 9.5–19 mm | 4.75–9.5 mm | |
| Aggregate Crushing value, % | 17.6–20.6 | / | ≤26 |
| Los Angeles coefficient, % | 10.7–13.6 | 10.2–14.1 | ≤28 |
| Water absorption, % | 0.57 | 0.72 | ≤2.0 |
| Magnesium sulfate soundness value, % | 8.5–10.2 | 7.8–9.6 | ≤18 |
| Degree of asphalt coverage, % | 91 | 84 | ≥100 |
| Percentage of flat & elongated particles, % | 12.7–24.1 | 9.2–21.3. | ≤15 |
| Bulk specific gravity | 2.631 ~ 2.649 | 2.618 ~ 2.632 | ≥2.60 |

Table 4. Partial test results of coarse aggregate of gneiss-based migmatite after treatment

| Property | Testing value | | Technical requirement (Figueroa Infante & Reyes Lizcano, 2015) | Improvement measures |
|---|---------------|-------------|---|---|
| | 9.5–19 mm | 4.75–9.5 mm | | |
| Degree of asphalt coverage, % | 100 | 100 | 100 | Immersed into aqueous solution of hydrated lime |
| Percentage of flat & elongated particles, % | 8.1–10.5 | 8.6–11.6 | ≤15 | Four-stages crushing with double counterattack crushers |
| | 6.3–7.2 | 8.3–9.7 | | Four-stages crushing with impact crusher |

For the aggregate used in asphalt mixtures, the rock is usually rolled into aggregate by a typical three-stage crushing process. The first stage is jaw-crushing. The second stage is gyratory-crushing, and the third one is counterattack-crushing. Because of the high strength, the rock was easy to be worn out in the third stage, which led to an increase of the content of flat and elongated particles (Figure 3). Therefore, the percentage of flat and elongated particles often exceeded the engineering requirement, and its asphalt mixture was very difficult to be well compacted in the field. So, two new crushing processes of four-stage were researched to control the content of flat and elongated particles. Based on the typical three-stages crushing processes, one process added a new counterattack crusher, while the other added an impact crusher. The shape of aggregate was stable, and the percentage of flat and elongated particles was significantly reduced by four-stages crushing process. The asphalt mixture was easier to well compacted and its asphalt pavement had more uniform appearance. The percentage of flat and elongated particles of aggregate by four-stages crushing process with impact crusher is lower than that by four-stages crushing with double counterattack crushers. The former had better effect but cost higher.

5. Test results of asphalt mixtures of coarse aggregate of acidic gneiss-based migmatite

For #1 asphalt mixture, the results of dynamic stability could meet the technical requirement, while the other three results of stability ratio, indirect tensile strength ratio, and change rate of the bulk density could not. The test results of #1 asphalt mixture showed that the mixture with coarse and fine aggregate of acidic gneiss-based migmatite had good resistance to rutting and poor resistance to moisture damage. Therefore, three measures were used to improve the resistance to moisture damage, namely, adding hydrated lime, using limestone fine aggregate instead of facidic gneiss-based migmatite, and combining the above two measures. The corresponding asphalt mixtures were numbered by 2#, 3# and 4#, specified in Table 5.

According to the test results of # 2 and # 3 asphalt mixtures, the indicators of dynamic stability, stability ratio and indirect tensile strength ratio were significantly increased, while the change rate of the bulk density was significantly decreased, which indicated that the two measures were conducive to improve the rutting resistance of asphalt mixture and reduce the water sensitivity.

In terms of the resistance to moisture damage, the effect of adding hydrated lime was slightly better than that of using limestone fine aggregate. So it was very important to ensure sufficient dosage of hydrated lime in the plant.

It could be seen that the performance of 4# asphalt mixture was the best among all mixtures, which showed that the water sensitivity of asphalt mixture of acidic gneiss-based migmatite coarse aggregate could be significantly reduced by both adding hydrated lime and using limestone fine aggregate meantime. The AC-13 mixture was used for the surface layer, which was in the most severe service environment, so the 4# asphalt mixture was selected as the final solution.

6. Conclusions

It was the first large-scale application of the aggregate of acidic gneiss-based migmatite in asphalt pavements of an expressway in China. There were 320,000 tons of acid migmatite coarse aggregate used for asphalt mixture in the Yuewu project. The asphalt pavement was free from any disease since it was open to traffic in December 2015.

It is preliminarily believed that the application of the aggregate of acidic gneiss-based migmatite is successful. The conclusions are:

- (1) The aggregate of acidic gneiss-based migmatite had high strength. However, due to the high percentage of flat and elongated particles and the poor affinity to asphalt binder, the asphalt mixture without treatment was difficult to meet the requirements of current specification.

Table 5. Results of asphalt mixtures of coarse aggregate of acidic gneiss-based migmatite

| Number of asphalt mixture | Dynamic stability(mm/min) | Stability ratio (%) | Indirect tensile strength ratio (%) | Change rate of the bulk density after scouring & pumping test(%) |
|--|---------------------------|---------------------|-------------------------------------|--|
| 1# | 4841 | 76.1 | 73.4 | 1.3 |
| 3# | 5670 | 85.9 | 82.6 | 0.7 |
| 4# | 5328 | 85.7 | 80.9 | 0.9 |
| 6# | 6072 | 92.3 | 86.5 | 0.2 |
| Technical requirement (Figueroa Infante & Reyes Lizcano, 2015) | ≥2800 | ≥85 | ≥80 | ≤1.0 |

- (2) The particle shape of the aggregate was stable, and the percentage of flat and elongated particles would be significantly reduced by using the four-stages crushing processing. The effect of four-stages crushing with impact crusher was better than that with double counter-attack crusher, but the cost of the former was higher.
- (3) The measures by adding hydrated lime or using limestone fine aggregate instead of fine aggregate of acidic gneiss-based migmatite were both conducive to improve the rutting resistance of asphalt mixture and reduce the water sensitivity.
- (4) Because most of the aggregate of limestone or basalt in the asphalt mixture was replaced by gneiss-based migmatite, the total cost of the mixture could be reduced by 20%.
- (5) In this research, only the mixture with the two measures applied simultaneously was tested in the field, which was conservative. The mixture with the measures applied alone needed to be further tested.

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