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Feasibility Study of Using Quarry Waste for Pavement Application and its Optimization

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Abstract: Using the quarry waste (QW) obtained from the Rongxing quarry, located in Conghua City, Guangdong Province, China, the objective of this research was to evaluate the feasibility of using these waste materials for pavement applications. The study included both laboratory testing for material characterization and field test section construction and evaluation.

A large number of representative samples of QW were taken and laboratory tests were performed to analyze their particle size distribution, density, liquid limit, plastic limit, plasticity index, water absorption, etc. The laboratory tests showed that the QW materials did not meet the quality standards required for the bed course, with a high percentage of particles passing 0.6 millimeter and 0.075 millimeter sieves, and a significant fluctuation of the plasticity index. In Chinese pavement designs, the bed course is a functional layer in the pavement, located between the subgrade and the subbase. This layer is designed to provide drainage and other functions without contributing to the structural capacity of the pavement. Similarly, the QWs are not adequate for use as cement stabilized aggregate base course.

However, the QWs could be used for subgrade enhancement and for cement stabilized soil subbase. Analysis also showed that the thickness of the base layer in an asphalt pavement structure could be reduced by incorporating the QWs for subgrade enhancement. An economic analysis was conducted, which indicated a savings of nearly 16.25 million RMB (≈ 2.58 million US$) compared with the original design, with 100% consumption of the waste materials.

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***Key words:** Quarry waste; Recycling; Roadbed reinforcement; Structural optimization.*

Introduction

Highway and construction industries consume a large amount of aggregates each year, considering the fact that aggregates occupy 95% of the composition of an asphalt concrete mixture by weight. From their research, Zoorop and Suparma [1] stated that about 12,500 tons of natural aggregates were consumed for construction of one kilometer of road pavement. According to statistics in the United Kingdom in 2003, construction of major highways and expressways consumed 15 million tons of aggregates in one year, and high quality natural aggregate would be used up in 2020 [2]. Due to the rapid economic development in recent years, over 100,000 km of new highway pavements have been constructed each year in China. For asphalt pavement construction alone, China would need 250 million tons of high-quality aggregates each year. If we are to build a wall of 1-m height and 1-m depth with this amount of aggregates, the wall would encircle the Earth's equator 2.8 times. Natural aggregates required for the entire roadway construction would exceed several billion tons each year.

In addition to the consumption of the limited natural resources, the large amount of wastes generated from the aggregate production process has become an environmental concern [3, 4]. The rock crushing process produces 35 to 40% quarry wastes (QW) [5]. Across China, quarries generate approximately 400 million cubic meters of quarry wastes annually. Research in the United States (US) has shown that, after the development and adoption of the Superpave mix design system, asphalt mixtures are composed of more coarse aggregates and less fine aggregates; this has made the quarry waste an even more severe issue. Road construction has caused disruption to the environment and many countries have required or encouraged the use of recycled waste materials by legislation and other measures [6].

In China, The National Long-Term Development Plan of Science and Technology (2006-2020) proposed that, in key industries and cities, the mode of technological development focusing on renewed economic systems should be established to provide scientific and technological support for sustainable roadway construction, creating a resource-saving and environment-friendly society. Many researchers have begun to study how to utilize waste in roadway engineering [7-11], and have shown some promising results. However, the research on recycling and reuse of waste materials started relatively late in China.

Study Objective

Quarry wastes are mainly composed of chippings, top layer soils, clay, and some coarse particles. The large variation in composition and quality of the material is the biggest obstacle to its recycling. As a multi-layer structural system, the quality requirements for each layer can be different, depending on its function in asphalt pavement structure. This phenomenon provides an opportunity for a feasibility study of using QWs for various layers based on their quality

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a) Stone Chips Contained Various Clay Content

b) Gravel with Various Particles

Fig. 1. Quarry Waste Stock Piles.

Table 1. Properties of Quarry Waste Materials.

Sieve Size (mm)	Average Passing Percentage (%)	Variation Coefficient of the Gradation	Average Plasticity Index (IP)	Variation Coefficient of IP
4.75	78.92	6.8	6.3	35.1
2.36	57.29	11.6		
0.6	34.15	16.3		
0.075	14.01	20.0		

requirements to maximize its value for recycling. The goal of this research was to explore the feasibility of using QW for roadway construction.

Quarry Waste Materials Characterization

The QW area of Rongxing quarry is approximately 32,000 square meters, with about 600,000 cubic meters of QWs. The over 10-m high piles of QWs were accumulated over the last 10 to 15 years. The quality of the QW varied greatly. Finding additional sites for QW storage would require more land and increase pollution. Relocating the waste can cost a lot of money, as well as time, which will adversely affect the efficiency of pavement construction.

As mentioned in the previous section, the compositions and qualities of QW varied greatly, as shown in Fig. 1. Therefore, obtaining representative samples became very important, but difficult. To overcome this obstacle, the areas of the QW were divided into regions based on the time frame that QWs were stored in each region. Thirty samples were taken from different regions of the QW at three different times. The samples were subjected to laboratory testing, including density, water absorption, coarse aggregate crushing value, liquid and plastic limits, etc. Testing results are shown in Table 1.

The test results confirm that the variability of QW is large. With a crushing value of 20.9%, the coarse aggregate appeared hard enough. Ideally, the QWs can be separated by sieving and the various parts can be used as reinforced subgrade, subbase, base, or even the surface layer. However, separation of the QW materials can be difficult and costly, especially considering the high moisture content of the materials. Therefore, in order to maximize the benefits of using the QWs, mass production and utilization need to be considered.

From Table 1, the percent passing 0.6 mm and 0.075 mm sieves are very high and the variation coefficient of plasticity index is very large. These properties do not meet the requirements and, therefore, cannot be used as the bed course. From the particle size distribution and variability of QWs, considering the economical and quality requirements, the QWs should not be used in cement stabilized aggregate base and subbase, but may be used for roadbed enhancement and cement stabilized soil subbase. The following sections describe the feasibility evaluation of using QWs as roadbed reinforcement and soil cement subbase.

Evaluation of Using QWs for Roadbed Reinforcement

Effects of Coarse Aggregate Content and Clay Content on Optimum Moisture Content and Maximum Dry Density

Because of the large variations of QWs, maximum dry density and optimum moisture content could not be easily determined, which could cause difficulties for construction quality control and acceptance. Exploratory experiments indicated that the proportion of coarse aggregate retained on a 4.75 mm sieve and clay content greatly affected these two property indexes. Therefore, this paper focused on the evaluation of effects of these two factors on the maximum dry density and optimum moisture content. Firstly, the aggregate particles retained on a 4.75 mm sieve were removed. The QWs were then re-mixed to prepare samples containing 0%, 10%, 20%, 30%, 50%, 70%, and 90% coarse particles. The prepared QW samples were subjected to Modified Proctor Test (ASTM D1557), and the test results are shown in Figs. 2 and 3.

From Fig. 2, it can be seen that optimum moisture content of the mixed QW aggregate decreases with the increase of coarse particles percentage. It is also noted that the optimum moisture content decreases gradually, from 8% to 7%, when the coarse particle content increases from 0% to 50%; the rate of change becomes much greater once the coarse particle content goes above 50%. Fortunately, most QWs contained less than 50% coarse particles, making the quality control much easier during construction. Fig. 3 shows that the maximum dry density changes with the proportion of coarse particles. When the percentage is less than 50%, the maximum dry density increases with the increasing coarse particle content; the maximum dry density decreases rapidly when the percentage is greater than 50%.

To analyze the effects of clay content on the maximum dry density and water content of the QWs, three types of representative samples were obtained and subjected to sieve analysis and Modified

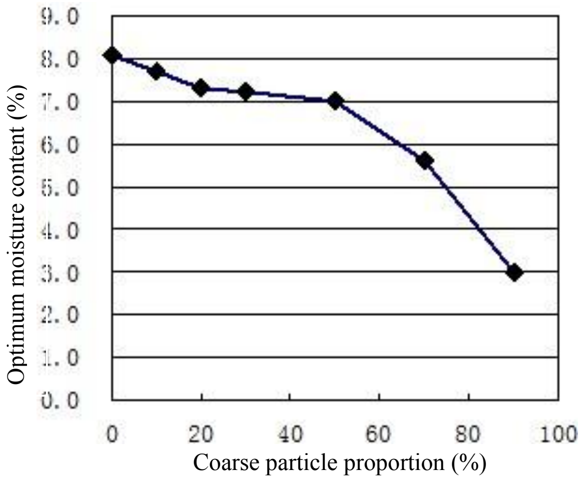

Fig. 2. Effect of Coarse Aggregate Proportion on Optimum Moisture Content.

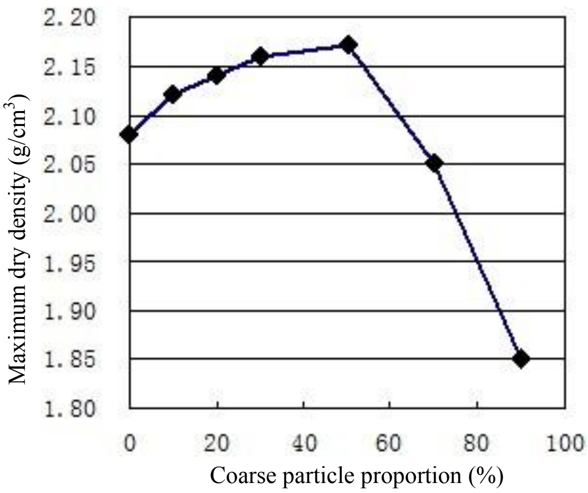

Fig. 3. Effect of Coarse Aggregate Proportion on Maximum Dry Density.

Proctor Test (ASTM D1557). Results of the sieve analysis are shown in Table 2, and the compaction test results are shown in Fig. 4. The test results show that the clay content affects the optimum moisture content and maximum dry density; however, the influence of the 4.75 mm coarse aggregate percentage is greater. The optimum moisture content is within the range of 7% ± 1% for the three QW samples.

Laboratory Resilient Modulus Test

The laboratory resilient modulus test was conducted on five representative samples of the QWs, with the bearing plate of 50 mm

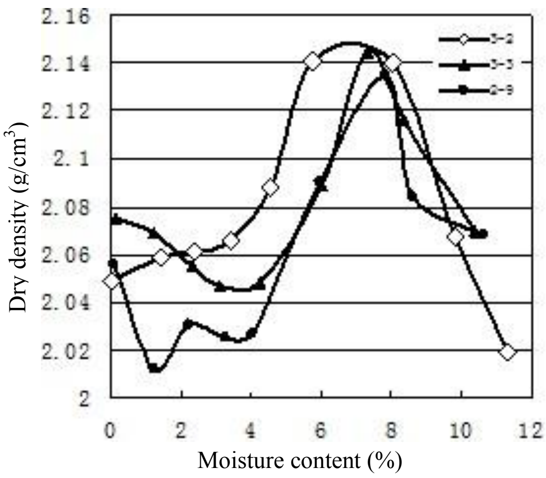

Fig. 4. Effect of Clay Content on the Optimum Moisture Content and Maximum Dry Density.

diameter (Chinese Testing Method T 0136-1993). The prepared 150-mm diameter subgrade soil samples were subjected to the following loading-unloading testing sequences:

1. Divide the expected the ultimate loading to 4 to 6 portions;
2. Load the sample to the first portion of the loading for 1 minute and record the deflection reading;
3. Release the loading completely and record the reading;
4. Compute the difference between the loaded reading and the unloaded reading, designated as d;
5. Repeat Steps 1 to 3 for the remaining magnitude of loading until reaching the ultimate loading.
6. Compute the resilient modulus using d and the applied pressure.

As shown in Table 3, the test results show that the average resilient modulus determined in laboratory is 103.5 MPa. According to Highway Asphalt Pavement Design Specification (JTG D50-2006), a modification factor for the bearing plate size needs to be applied (0.78 for the 50 mm diameter bearing plate). Furthermore, in accordance with Chinese specifications, when determining the design values of subgrade resilient modulus, other factors, such as the highway class (expressway, primary highway, etc.), seasonal effects, and roadway foundation types, etc., need to be considered. In this study, a factor of 0.66 was selected for expressway, and the design value of resilient modulus of QW was 51.9 MPa. This value is about 30% higher than the typical design value of 40 MPa.

The modification coefficient used in selecting the design values in the Chinese specifications was determined based on testing and statistical analyses on samples of common soils. However, the properties of QWs, such as gradations, water sensitivity, etc., could be much different compared to the natural soil. Therefore, the

Table 2. Sieve Analysis of Three Representative Quarry Wastes.

Sample ID	Sieve Size (mm)								
	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
	Percent Passing (%)								
3—2	100	95.4	76.2	63	55.4	45.5	26.6	21.3	17.3
3—3	100	100	75.2	52.3	42.4	33.9	20.9	15.7	11.2
2—9	100	100	83.5	60.5	49.1	33.8	23.7	10.5	6.5

Table 3. Test Results of Quarry Waste Subgrade Resilient Modulus.

Subgrade Resilient Modulus	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Test value (MPa)	98.2	103.1	117.8	85.9	99.4
Modified Value (MPa)			78.7		
Design Value (MPa)			51.9		

Table 4. Coarse Particles (4.75 5 mm) Content and Maximum Dry Density.

Coarse Particle Content (%)	0	10	20	30	50	70	90
Maximum Dry Density (g/cm3)	2.08	2.12	2.14	2.16	2.17	2.05	1.85

designed parameters obtained using the normal modification coefficients might be too conservative. Further research on this subject is recommended.

Field Evaluation of QWs for Subgrade Improvement

From March 30 to April 4, 2010, a 16 m-long experimental section was constructed on Zengcong expressway from Mile Post K15+220 to K15+380 using QWs for subgrade reinforcement. The experimental section had an 80-cm-thick improved subgrade layer constructed in three lifts of 30 cm, 25 cm and 25 cm (thickness after compaction). Because of the large variability of QWs, the dry density measured (using Sand Cone method, ASTM D1556) at each location along the test section was different, which made it difficult to accurately determine the degree of compaction. To overcome this difficulty, laboratory test results described in the previous section of the paper were applied to assist in determining the in situ density. QW samples were taken from each test location on the test section; the proportion of particles coarser than 4.75 mm was then measured. The maximum dry density of the samples was then calculated based on the results from earlier test results, as summarized in Table 4. The degree of compaction was then determined based on these calculated values.

Each lift of the test section was compacted using a roller. The rolling pattern consisted of one pass of compaction under static mode, followed by several passes under vibratory mode. Pavement and material characteristics, such as moisture content, degree of compaction and other indicators were measured at several compaction efforts. Three to four testing locations were randomly selected. The relationship between the degree of compaction and the compaction effort is depicted in Fig. 5, which shows that the degree of compaction increases rapidly as the compaction effort increases, reaching the maximum at about eight passes of compaction. Settlement at five cross sections, K15+280, K15+300, K15+320, K15+340, and K15+360, were monitored at different compaction levels. The incremental settlements at different compaction levels are presented in Fig. 6. As seen in this figure, the additional settlement after the passes of rolling decreases rapidly with increasing compaction, approaching zero after eight passes of rolling, indicating that the layers have become stable. Additional rolling might not be beneficial. This is consistent with the results of the degree of compaction (Fig. 5).

During construction of the test sections, it was observed that moisture content of the first lift was low and the desired compaction could not be achieved. Water was added to the layer to bring the moisture content close to optimal, and compaction resumed. The

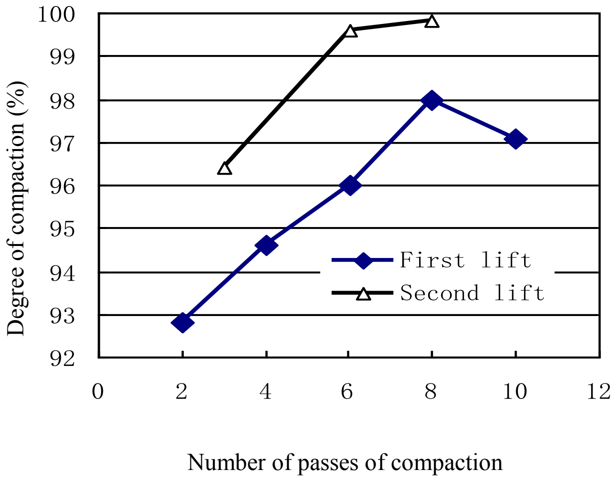

Fig. 5. Degree of Compaction vs. Compaction Levels.

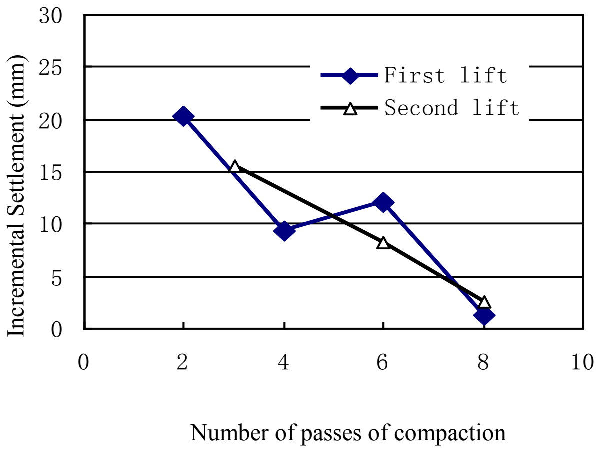

Fig. 6. Settlement Curves vs. Compaction Levels.

desired density was achieved. From field observation, it is recommended that the moisture content of the material be maintained at the optimum moisture content ±2% during compaction, preferably a little on the wet side. The optimum rolling pattern for each lift should consist of one pass under static mode and five to six passes of rolling under vibratory mode.

The loose paving coefficients, defined as the loose thickness of the lift divided by the thickness after compaction, were also measured while constructing the test sections. Since a grader was used for spreading and smoothing the QW materials, the coefficient was related to the looseness of the surface materials after grading. The coefficient would be lower if the materials were subjected to

Fig. 7. Resilient Modulus Test.

many passes of grading operations that would provide the initial compaction. In this study, the loose paving coefficient varied between 1.09 and 1.14.

Resilient Modulus of Roadbed Reinforced with QWs

On April 18, 2010, the resilient modulus of the top surface of the test section was measured in accordance with Chinese Specification JTG E60-2008 on six selected locations, as shown in Fig. 7. Deflection readings after repeated loading and unloading were measured and recorded. The applied loadings and the deflections were used to calculate the in situ subgrade resilient moduli. Since the tests were conducted after several days of raining, the QW layer surface was basically saturated, which was considered as the worst condition of the year. The resilient modulus test results are shown in Table 5.

The tests were performed under most unfavorable condition, so no adjustment was necessary for seasonal effects, taking the adverse season influence coefficient, K_l, as 1. At the 95% confidence level, with a coefficient Za = 1.645, the design resilient modulus is calculated to be 71.5 MPa. At the 98% confidence level, the coefficient Za would be 2 and the design resilient modulus is calculated to be 69.7 MPa. Under saturated condition, the design resilient modulus of soil in this region is generally taken around 40.0 MPa. The use of QWs can improve the subgrade stiffness by more than 70%.

Evaluation of Using Quarry Waste as Soil Cement Subbase

Feasibility Analysis

According to Technical Specifications for Construction of Highway Base/Subbase (Chinese Specification JTJ 034-2000), gradations for cement stabilized soil subbase are shown in Table 6. Also shown in Table 6 are the gradations of the QW aggregate. Other specification requirements include a soil uniformity coefficient greater than 5; the liquid limit less than 40% for fine-grained soil; and a plasticity index not more than 17. Data presented in Tables 6 and 7 indicate that the Rongxing QW materials meet the specification requirement and can be used as soil cement subbase for roadway construction.

Mix Design in Laboratory

Typical Rongxing QW and P.O.42.5 cement were used in the mix design. The standard compaction tests were carried out in accordance with the Testing Procedures for the Inorganic Stabilized Material of Highway Engineering (Chinese Specification JTG E51-2009). Cement contents of 3%, 5%, and 7% by weight were used to prepare the testing specimens. The maximum dry density and optimum moisture content were determined. The specimens were then subjected to unconfined compressive strength test, and the results are shown in Table 8.

From Table 8, it can be observed that, at a cement content of 5%

Table 5. Field Resilient Modulus Testing.

Technical Index	Stake					
	K15+260	K15+280	K15+300	K15+320	K15+340	K15+360
Resilient Modulus E_O (MPa)	85	74.5	77.4	74.6	80.7	85.9
Average Value, X (MPa)	79.7					
Standard Deviation, S (MPa)	5					
Coefficient of Variation, CV (%)	5.7					
Design Resilient Modulus, E_{OD} (MPa)	$E_{OD} = (X-ZaS)/K_l$					

Table 6. Typical Particle Gradation of Rongxing QW and Specification Requirements.

	Sieve Size (mm)							
Gradation Specification for Subbase	37.5	31.5	19	9.5	4.75	2.36	0.6	0.075
	Percent Passing (%)							
	100	—	—	—	50-100	—	17-100	0-30
Quarry Waste	100	—	—	—	58-85	—	26-45	10-20

Table 7. Properties of Quarry Waste.

Property	Apparent Specific Gravity	Crushing Value (%)	Characteristics of fine-Grained Soil		
			Liquid Limit (%)	Plastic Limit (%)	Plasticity Index
Range	2.541~2.668	20.9	20.4-24.8	10.9- 20.7	2.1- 9.5

Table 8. Results of Unconfined Compressive Strength.

Cement Content	Average Strength R (MPa)	Standard Deviation S (MPa)	Coefficient of Variation Cv (%)	$R_{design}/(1\text{-}ZaCv)$	Conclusion
3.00%	2.1	0.15	6.97	2.8	Unqualified
5.00%	3.2	0. 35	10.88	3	Qualified
7.00%	4.8	0.37	7.66	2.9	Qualified

Fig. 8. Construction of the QW Subbase and Coring.

Table 9. Unconfined Compressive Strength at 7 Days on Core Samples.

Core Location	Height of the Core Samples (cm)	Core Diameter (cm)	Ultimate Force (kN)	Compressive Strength (MPa)
K15+270	24.78	9.5	26.03	3.67
K15+280	23.03	9.59	20.53	2.84
K15+300	21.3	9.58	20.53	2.85
K15+310	23.03	9.56	20.35	2.84
K15+320	16.48	9.56	26.4	3.68
K15+340	21.1	9.55	21.27	2.97

Note: The average 7 days unconfined compressive strength for core samples was 3.14 MPa, with a coefficient of variation of 13.3%.

by weight, the average compressive strength of soil cement is 3.2 MPa, which is greater than the required strength $R \geq R_{design}/(1\text{-}Za*Cv)$. In practice, cement content was usually increased by 0.5%, which was 5.5% in this study.

Field Evaluation

The cement stabilized QW subbase was paved on top of the QW reinforced subgrade test section in late April 2010. Six cores were drilled from the test section after six days. The construction of the QW subbase and the cores are shown in Fig. 8, which shows solid cores were obtained. The core samples were tested for unconfined compressive strength at seven days, and the results are shown in Table 9. Original design called for cement stabilized aggregate subbase with design strength of 2.5 MPa. The results of the test section indicated that cement stabilized QW subbase met the design strength requirement and could be used as sub-base in the asphalt pavement structure, replacing the original design of cement stabilized aggregate subbase.

Pavement Structure Optimization Using QW Materials and Economic Analysis

Pavement Structure Optimization

As discussed in previous sections, QW materials could be used in improving the quality of the subgrade. Through proper pavement structural design, the required thickness of the pavement structures might be reduced. For example, an original pavement structure design consisted of the following layers:

- Asphalt concrete layer constructed in three layers of 4 cm, 6 cm, and 8 cm, from top to bottom;
- A 36 cm thick cement stabilized crushed stone base layer, with a 7-day unconfined compressive strength requirement of 4.0 MPa;
- A 20 cm thick cement stabilized crushed stone subbase, with a 7-day unconfined compressive strength requirement of 2.5 MPa;
- A 15 cm thick bed course (with gravel).

The pavement design parameters for the various layers are presented in Table 10. With the enhancement provided to the subgrade by QW materials (higher stiffness), the overall thickness of the pavement structure might be reduced.

Keeping properties and thickness of the asphalt concrete layers, the stabilized subbase, and graded gravel constant, Shell BISAR3.0 software was used to calculate the various pavement parameters with different base layer moduli. Parameters used in these calculations are shown in Table 11. Two levels of resilient modulus for the subgrade, 40 MPa and 60 MPa, were used in the calculation, and the results are presented in Tables 12 and 13, respectively.

Tables 12 and 13 show that, for an increase of 5 MPa in the

Table 10. Pavement Design Parameters.

Material Name	20°C Resilient Modulus (MPa)	15°C Resilient Modulus (MPa)	Splitting Tensile Strength (MPa)	Remarks
Fine-modified Asphalt Concrete Top Layer	1400	2000	1.4	AC-13C
Medium-grained Modified Asphalt Concrete Middle Layer	1200	1800	1	AC-20C
Coarse asphalt Concrete Bottom Layer	1000	1200	0.8	AC-25C
Cement Stabilized Aggregate Base (4.0MPa)	1300	1300	0.5	/
Cement Stabilized Aggregate Subbase (2.5MPa)	1100	1100	0.4	/
Graded Gravel	200	200		Bed Course

Table 11. Calculation Parameters.

Circle Equivalent Diameter, d (m)	0.213
Radius of the Equivalent Circle, r (m)	0.1065
Cumulative Equivalent Standard Axle Ne	2.42E+07
The Subgrade Soil Resilient Modulus E0	Variable
Designing Deflection (0.01 mm)	20
Tire Pressure (MPa)	0.7

subgrade resilient modulus, the thickness of the cement stabilized base layer could be reduced by 2 cm. When the resilient modulus of the subgrade increased from 40 MPa to 60 MPa, the thickness of the cement stabilized base layer could be reduced by 8 cm, theoretically. In practice, a reduction of 6 cm is recommended when the subgrade is improved with QW material, taking into account the variability during construction.

Economic Analysis

An economic analysis was conducted using the construction of the Jiekou Branch Expressway as an example. The basic pavement structure and other parameters listed below:

- Asphalt concrete layer constructed in three layers of 4 cm, 6 cm, and 8 cm, from top to bottom;
- A 36 cm thick cement stabilized crushed stone base layer, with a 7-day unconfined compressive strength requirement of 4.0 MPa;
- A 20 cm thick cement stabilized crushed stone subbase, with a 7-day unconfined compressive strength requirement of 2.5 MPa;
- A 15 cm thick bed course (with gravel);
- Length of embankment fill in mainline – 11.03 km;
- Length of embankment fill in branch – 1.78 km;
- Width of subgrade improved with QWs in mainline – 28.19 m;
- Width of subgrade improved with QWs in branch – 12.48 m;
- Volume of QWs required – 260,000 m^3;
- Average transportation distance – 10.0 km;

As presented in the previous section of the paper, the thickness of the cement stabilized crushed stone base layer could be reduced by 6 cm when the QWs were utilized in improving the subgrade quality. The original cement stabilized stone subbase was replaced with the cement stabilized QW subbase. Also considered in the analysis were the expenses required for relocation of the Rongxing quarry, since it is located on the construction site of the expressway. Typical cost

Table 12. Calculation Results with the Resilient Modulus of Subgrade Soils E0 of 40 MPa.

Pavement Structure Layer	Structural Thickness (cm)	Splitting Strength (MPa)	Tensile Strength Structure Coefficients Ks	Allowable Tensile Stress (MPa)	Layer Bottom Stress (MPa)	Design Deflection (0.01mm)	Calculated Deflection (0.01mm)
AC-13	4	1.4	3.79	0.37	-0.191	20	19.9
AC-20	6	1	3.79	0.26	-0.014		
AC-25	8	0.8	3.79	0.21	-0.02		
Cement Stabilized Crushed Stone (4.0 MPa)	30	0.5	2.27	0.22	0.052		
Cement Stabilized Crushed Stone (2.5 MPa)	20	0.4	2.27	0.18	0.101		

Note: Graded gravel was treated as a functional layer with no structural contribution

Table 13. Calculation Results with the Resilient Modulus of Subgrade Soils E0 of 60 MPa.

Pavement Structure Layer	Layer Thickness (cm)	Splitting Strength (MPa)	Tensile Strength Structure Coefficient Ks	Allowable Tensile Stress (MPa)	Layer Bottom Stress (MPa)	Designing Deflection (0.01 mm)	Calculated Deflection (0.01 mm)
AC-13	4	1.4	3.79	0.37	-0.196	20	19.9
AC-20	6	1	3.79	0.26	-0.012		
AC-25	8	0.8	3.79	0.21	-0.016		
Cement Stabilized Crushed Stone (4.0 MPa)	22	0.5	2.27	0.22	0.039		
Cement Stabilized Crushed Stone (2.5 MPa)	20	0.4	2.27	0.18	0.092		

Note: Graded gravel was treated as a functional layer with no structural contribution.

information was obtained from actual construction documents after the completion of the project, and the economic analyses are presented below:

- The 80-cm QW subgrade layer
  - Total quantity of 314,822 m^3
  - Total cost of 21,906,648 Yuan
  - Original subgrade cost of 3,848,782 Yuan
  - Additional cost of 18,058,258 Yuan
- The cement stabilized crushed stone base (6-in. thickness reduction)
  - Total quantity of 415,900 m^2
  - Unit cost of 59.33 Yuan for the 36-cm layer
  - Unit cost of 50.02 Yuan for the 30-cm layer
  - Saving of 3,872,029 Yuan
- The cement stabilized subbase layer
  - Total quantity of 484,873 m^2
  - Unit cost of 30.91 Yuan for the 20-cm cement stabilized crushed stone subbase
  - Unit cost of 24.83 Yuan for the 20-cm cement stabilized QW subbase
  - Saving of 2,948,028 Yuan
- The 15-cm thick bed course
  - Total quantity of 272,602 m^2
  - The bed course was eliminated when the 80-cm QW enhanced subgrade was installed
  - Unit cost of 18.31 Yuan
  - Saving of 4,991,342 Yuan
- Cost of relocation of the quarry of 22,500,000
- The total cost saving was about 16.25 million Yuan (= 3,872,029 + 2,948,028 + 4,991,342 - 18,058,258) or 2.58 million USD.

Conclusions

The objectives of the paper were to study the feasibility of utilizing QWs as various pavement structural layers and the benefits of using the recycled material, if any. From this research, the following conclusions can be drawn:

1. Large variations of the QW materials were observed. Therefore, careful and extensive sampling is very important for quality control during construction.
2. From test results, QWs did not meet the specification requirements and cannot be used as the bed course, the stabilized stone base, and stabilized stone subbase layers.
3. QW materials can be used for subgrade improvement. Field testing showed that the resilient modulus of the 80 cm QW improved subgrade was 70% higher than the original subgrade.
4. From the study, it is recommended that the moisture content of QW be within ±2% of the optimum moisture content during compaction. Optimum rolling pattern consisted of one pass of static rolling followed by 5 or 6 passes rolling under vibratory mode for construction of the QW subgrade. The loose paving coefficient fluctuated from 1.09 to 1.14.
5. QW materials can be used as cement stabilized soil subbase for pavement construction. Field evaluation showed that the 7-day compressive strength of cores taken from field met the required strength.
6. From the structural analysis, with the subgrade reinforced by the QWs, the thickness of the cement stabilized base layer could be reduced by 6 cm, as compared with the original pavement design.
7. Using the construction of an expressway (Zengcong highway) as an example, an economic analysis was conducted. The results showed that, by incorporating the QW materials for subgrade reinforcement and by using the cement stabilized QW subbase, a savings of nearly 8.26 million RMB (1.31 million US$) could be achieved.
8. QWs from different quarries might possess vastly different material characteristics. Therefore, testing and evaluation will need to be conducted before using the materials from individual quarries. This research provided an example on how to best utilize QW materials in pavement applications.

Future Research Needs

To further advance the use of QW materials for highway applications, more research will be required to:

1. Ensure adequate sampling to truly understand the variations of the materials before their use.
2. Confirm the engineering properties of the material in highway application.
3. Quantify environmental benefits of using QW materials.

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