International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 15, Issue 2 (February 2019), PP.70-77

Effect of blending proportion and mode of recycled aggregates on early strength of Cement-stabilized macadam

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ABSTRACT: *The old Cement-Stabilized Macadam(CSM) is reused after milling, it can solve the problem of disposal of waste materials, and reduce the consumption of natural materials. This paper studies the effect of blending dosages and methods of milling materials on the CSM strength. The dosages of recycled coarse and fine aggregates are 0%, 50% and 100%. The mixing mode of recycled coarse and fine aggregates are respectively replacing 100%, 50% and 0% natural coarse and fine aggregates. A series of mechanical tests were carried out to evaluate the impact of blending dosages and methods of waste milling materials. The results indicate that the increase of recycled aggregates dosage does not cause the decrease of early compressive and splitting strength of CSM. The usage of recycled aggregates even cause the increase of early strength, which affected by unhydrated cement particles. In terms of the blending methods, the strength of CSM that substituted with the fine aggregates decrease less than the coarse aggregates, in that the skeleton formed by the coarse aggregates is guaranteed.*
KEYWORDS: *Recycled aggregates; Cement-stabilized macadam; Early strength; Blending proportion*

Date of Submission: 28-07-2019 Date of acceptance: 10-08-2019

I. INTRODUCTION

Pavement structure built in the early years successively reached the stage of large-scale repair and reconstruction. There are about 12% of the roads need to be renovated every year in China [1]. For the waste generated by road renovation, the general method is to excavate and dispose of them, and to abandon the landfill, which will not only cause serious pollution to the environment, but also occupy a large amount of land. The reuse of cement stabilized macadam in old pavement base after milling can not only turn waste into treasure, but also reduce the exploitation of natural materials, which will bring enormous environmental and economic benefits to society.

Cement-Stabilized Macadam(CSM) are mainly composed of water, cement, fine and coarse aggregates, which have a certain strength, high load carrying capacity and fatigue resistance after compaction and curing. CSM are widely used in pavement base [2-4].

In 1998, the Florida department of transportation conducted a study on recycled concrete aggregate, and the results showed that recycled concrete aggregates had the same excellent performance as natural aggregate and could meet the performance requirements of most concrete aggregate specifications[5]. Torii, Kazuyuki et al. from kanazawa university, Japan studied the pavement structural performance of recycled aggregate. The test results showed that recycled concrete has good physical performance[6]. Ravindrarajah Sri, R et al. from the university of technology, Sydney, studied the influence of the amount of coarse and fine aggregate used in waste concrete on the strength and deformation of concrete. The results showed that the influence of recycled coarse aggregate on deformation performance was smaller than that of fine aggregate, and the use of recycled aggregate only had a slight impact on the performance of fresh concrete[7]. Qingguo Yang et al[8] from chongqing jiaotong university studied the physical and mechanical properties of recycled aggregate, as well as its application in pavement base layer and surface layer, and the results showed that recycled aggregate of road old cement concrete can be applied in road reconstruction and new construction. Wuxiang Wang[9] studied the performance of fly ash recycled aggregate concrete, and the results showed that the strength of recycled aggregate concrete mixed with some fly ash would be significantly improved. At this stage, the literature mainly focuses on the study of recycled aggregate of concrete, but the recycling utilization of CSM of pavement base is less. In today's advocating of circular economy, it is particularly urgent to study the recycling of pavement base materials.

This paper mainly studies the effects of different proportions of milling materials and different mixing methods on the performance of CSM. In the research, milling material was replaced by coarse aggregate and fine aggregate in different proportions, and the compaction characteristics, compressive strength and splitting strength of the mixture were tested. Comparing the test values with the strength values of base and subbase in (JTG D50-2017) Code for Design of Highway Asphalt Pavement [10].

II. RAW MATERIALS AND TECHNICSL SPECIFICATIONS

1.1 Cement

The cement adopts P•O42.5 ordinary Portland cement produced by Shandong Aluminum Group, According to the specification[11-12]], This text test the setting time and strength of cement. Comparing with the index of cement requirement in (GB 175-2007) General Portland Cement[13]. The comparison results are shown in Table 1. Its nature meets the requirements.

Table 1 Test results of cement technical indicators

Name	Normative value		Detected value
Specific surface area / (m^2•kg^{-1})	300		330
Stability	qualified		qualified
Initial setting time (min)	≥45		197
Final setting time (min)	≤600		263
Compressive strength (Mpa)	3d	≥17	29.8
	28d	≥42.5	52.5
Flexural strength (Mpa)	3d	≥3.5	6.2
	28d	≥6.5	8.5

1.2 Comparison of technical indicators of natural aggregates and recycled aggregates

The natural aggregates used in the test is limestone, which the specifications are 0-5mm stone debris, 5-10mm aggregates, 10-20mm aggregates and 20-30mm aggregates. The recycled aggregates used is waste CSM obtained by milling in a county road engineering (K3+300~K5+550) in Zibo City, Shandong Province.

2.2.1 Gradation of recycled aggregates

Gradation is the distribution of particle size at all levels, which is determined by screening test. This test is carried out according to the water sieving method provided in (JTG/E42-2005) Highway Engineering Aggregate Test Procedures [14]. The screening results are shown in Table 2.

Table 2 The screening test results of recycled aggregate

Particle size (mm)	Pass percentage (%)	Particle size (mm)	Pass percentage (%)
31.5	100	4.75	24.69
26.5	97.32	2.36	12.17
19	87.6	0.6	4.07
9.5	53.2	0.075	1.27

Comparing the pass rate in Table 2 with the grading requirements of the skeleton compact type and the suspension compact type in (JTP D50-2017) Code for Design of Highway Asphalt Pavement, It is found that the gradation of the recycled aggregates can not meet the requirements of the rigid compact grading, but can meet the grading requirements of the suspension compact type. In the milling process of recycled aggregates, the number of coarse aggregates decreases and the number of fine aggregates increases, which is caused by the rolling of vehicles and mechanical crushing of old pavement.

2.2.2 Comparison of physical and mechanical properties of recycled aggregates

(1) Apparent density

Apparent density refers to the dry mass of the material particles per unit volume. The maximum dry density of the recycled aggregates is affected by the apparent density. The apparent density of the coarse and fine aggregates is determined separately. The test results are shown in Table 3.

Table 3 The apparent density of recycled aggregate and natural aggregates

Aggregate name	Recycled aggregate （g/cm^3）	Natural aggregate （g/cm^3）	Specification requirement（g/cm^3）
Coarse aggregate	2.706	2.836	＞2.5
Fine aggregate	2.524	2.693	＞2.5

(2) Water absorption rate

The wled aater absorption rate of the aggregates is an important indicator to measure the nature of the aggregates. The water absorption rate of the recycled aggregates directly affects the optimum moisture content of the mixture, thus affecting the water consumption and the amount of each material. The water absorption rate of the coarse and fine aggregates was measured. The results are shown in Table 4.

Table 4 The water absorption of recycled aggregate and natural aggregates

Aggregate name	Recycled aggregate(%)	Natural aggregate(%)
Coarse aggregate	3.3	0.9
Fine aggregate	9.2	1.3

(3) Needle-like particle content

The needle-like particle content of the aggregate is an important index for evaluating the shape and crush resistance of the coarse aggregate, and the coarse aggregate of each specification is separately sampled and measured. The test results are shown in Table 5.

Table 5 The content of needle chip granules of recycled aggregate and natural aggregates

Particle size（mm）	Recycled aggregate（%）	Natural aggregate（%）
26.5~31.5	12.5	7.8
19~26.5	11.9	9.6
16~19	12.7	8.2
9.5~16	11.5	7.6
4.75~9.5	13.2	8.5

(4) Crush value

The aggregate crush value is used to measure the ability of aggregate to resist crushing under increasing load. It is an indicator to measure the mechanical properties of aggregate to assess the applicability in highway engineering. The crush values of the recycled aggregates and the natural aggregates were measured to obtain the values of Table 6 below.

Table 6 The cruishing value of recycled aggregate and natural aggregates

Aggregate name	Crushed value (%)	Specification requirement (%)
Recycled aggregate	28.2	≤35
Natural aggregate	16.7	≤35

The results of physical and mechanical properties determination of the natural aggregates of the recycled aggregates are based on the above. It can be seen that the apparent density of the recycled aggregates is smaller than that of the natural aggregates; the water absorption and crushing value of the recycled aggregates are larger than the natural aggregates; the content of the needle-shaped particles of the recycled coarse aggregates is larger than that of the natural coarse aggregates. However, the recycled aggregates can meet the requirements of (JTP TF20-2015) Technical Specifications for Road Surface Base Construction [15] for the strength of CSM base and base materials. It is indicated that the recycled aggregates has conditions as a material for the pavement base layer.

II. COMPOSITION OF THE MIXTURE

3.1 Grading and cement dosage

The purpose of this test is to discuss the effect of the substitution method and the dosage of recycled aggregates on the performance of the mixture. therefore, the influence of the performance of the graded mixture is minimized, and the suspended dense structure is uniformly adopted and a gradation composition is selected. First, the recycled aggregates and the natural aggregates are sieved, and the gradation of the aggregates is adjusted according to the upper and lower limits specified in the specification to make it close to the gradation median. The gradation composition of the aggregates is shown in Table 7 below.

Table 7 Gradation composition of aggregates

Classification	Percentage of mass by mesh with different pore sizes (mm) /%							
	31.5	26.5	19	9.5	4.75	2.36	0.6	0.075
Specification limit	100.0	90.0	72.0	47.0	29.0	17.0	8.0	0.0
Lower specification limit	100.0	100.0	89.0	67.0	49.0	35.0	22.0	7.0
Normative median	100.0	95.0	80.5	57.0	39.0	26.0	15.0	3.5
Mixing gradation composition	100.0	96.42	83.88	55.45	33.21	22.43	12.71	3.69

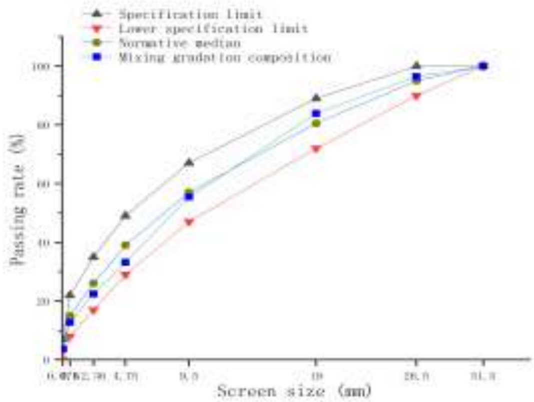

Fig.1 Grading curve

It can be seen from the curve of Fig. 1 that the synthetic gradation of the mixture meets the requirements of the specification.

According to the specification (JTP D50—2017) Code for Design of Highway Asphalt Pavement, the cement content of the cement-stabilized macadam in the base layer and the sub-base layer is not less than 3%, and it is not easy to exceed 6%. Therefore, the cement content of all the mixes in this test is uniformly 5%.

3.2 Mix ratio

In this experiment, we studied the influence of different substitution methods and recycled aggregates on the performance of the mixture. The dosage of recycled coarse and fine aggregates is 0%, 50% and 100%. The mixing mode of recycled coarse and fine aggregates are respectively replacing 100%, 50% and 0% natural coarse and fine aggregates. The mixtures were blended into five types: A0 (natural aggregates), A1 (natural coarse aggregates + recycled fine aggregate), A2 (recycled coarse aggregates + recycled fine aggregates), A3 (50% natural aggregates + 50% recycled aggregates), A4 (recycled aggregates). According to the gradation of the preceding section and the amount of cement admixture.

IV. TEST METTHOD

4.1 Preparation and maintenance of test samples

Since the test needs to measure the unconfined compressive strength and the splitting strength of the CSM recycled aggregates, Coarse-grained soils need to prepare cylindrical samples of φ150 mm×150 mm, which derived from (JTG E51-2009) Testing Procedure for Stabilized Materials for Inorganic Bonds of Highway Engineering [16].

Firstly, The Maximum dry density and optimum moisture content was determined based on the compaction test, Calculating the amount of water added to each material and the quality of inorganic binder and the quality of mixture according to the calculation method of cylindrical specimens in (JTG E51-2009) Test Rules for Stabilized Materials of Inorganic Binders in Highway Engineering T0843-2009. Then, the quality of each aggregates is determined according to its gradation. Then the aggregates and part of the water are put into the plastic bag and soaked for 2 hours. Finally, the cement and the remaining water are fully mixed with the soaked aggregate. Before loading, a small amount of hydraulic oil is applied to the inner wall of the test die and around the gasket to prevent the mixture from adhering to the test die. When loading, make sure that the pad at the lower part of the test sleeve is exposed about 2 cm. The mixed test material is loaded into the test mould three times and rammed layer by layer. Load into the test mold and insert it layer by layer. After the filling is completed, static pressure is applied at a loading rate of 1 mm/min with a universal hydraulic press until the gasket is completely pressed into the test sleeve, and is unloaded after being stabilized for 2 minutes. According to the specifications of the coarse-grained soil inorganic binder, it is best to leave the mold after 2~6h.

According to the experience of many indoor tests, the test piece is placed for more than 4h. The integrity of the demoulding block is good and it is not easy to break. After demolding, the test piece was weighed and the amount was high, and the mass was accurate to 0.1 g, and the height was accurate to 0.1 mm. In order to ensure the accuracy of the test, the test samples that do not meet the molding standards are treated as waste. Then, the test piece is wrapped tightly with a plastic bag and the air in the bag is discharged, and placed in a standard curing box under the constant temperature and humidity conditions. The temperature of the curing box is set to (20 ± 2) ° C, and the humidity is set to 98%. To maintain the age required for the test, immerse the test piece in (20 ± 2) °C water on the last day of the health period, and ensure that the water surface is about 2.5 cm higher than the test piece.

4.2 Test Methods

The test methods in this paper are mainly based on (JTG E51-2009) Testing Procedures for Stabilizing Materials for Inorganic Bonds in Highway Engineering. Among them, the compaction test was carried out according to the "T0804-1994 inorganic binder stabilized material compaction test method" C method for the test electric compaction test. First, preset six preset water contents for each group of materials are 5.5%, 6.0%, 6.5%, 7.0%, 7.5%, and 8.0%, sample preparation according to predetermined water content, Then, according to the required compaction work, the compaction and weighing in the test tube are carried out respectively, and the moisture content of the sample is measured, and different dry densities are obtained. The corresponding points are drawn on the water content-dry density coordinate system and connected into a smooth curve. The water content and dry density corresponding to the peak point of the curve are the optimal water content and the maximum dry density; The compressive strength test refers to (T0805- 1994) Inorganic binder stability material unconfined compressive strength test method, maintenance age is 7d; the split test is tested according to the split test method of inorganic binder stabilized material in (T0806-1994), maintenance age is 7d. The test samples were maintained in a standard environment with a temperature of (20 ± 2) ° C and a humidity of 98 %.

V. TEST RESULTS AND DISCUSSION

5.1 Maximum dry density and optimum moisture content

The compaction test is a very important test to determine the mix ratio of CSM. The purpose is to ensure that the optimum moisture content of the mixture is determined at the maximum dry density to determine the mixing ratio of the test. The compaction test is an important step in determining the amount of each material. The above-mentioned compaction tests were carried out on five different CSM mixtures, and the maximum dry density and the optimum moisture content of each group were obtained from the compaction curve. The test results of the respective batches are shown in Table 8.

Table 8 Mixture ratio

Mix type	Natural aggregates (A0)	Natural coarse + recycled fine (A1)	50% natural material + 50% recycled material (A2)	Recycled coarse + natural fine (A3)	Recycled aggregates (A4)
Optimum moisture content	6.1	6.8	7.0	7.2	7.8
Maximum dry density	2.246	2.202	2.172	2.155	2.089

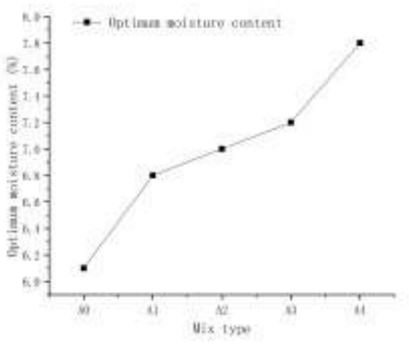

Fig.2 The optimum moisture content of mixtures

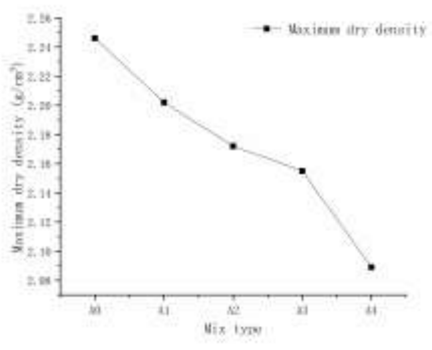

Fig.3 The Maximum dry density of mixtures

It can be seen from Fig. 2 and Fig. 3 that no matter whether the coarse aggregates or the fine aggregates of the natural aggregates is replaced by the recycled aggregates, the optimum moisture content of the mixture increases. With the increase of recycled aggregates content, the optimum moisture content of the mixture increases while the maximum dry density decreases. When the gradation of five mixtures is exactly the same as that of cement, the five mixtures exhibit different compacting properties. This is mainly because the hardened mortar contained in recycled aggregates increases the water absorption of the mixtures, thus increasing the amount of water needed for the maximum dry density of the mixtures. Since the apparent density of the recycled aggregates is smaller than that of the natural aggregates, the maximum dry density of the mixture decreases as the amount of recycled aggregates increases.

5.2 Unconfined compressive strength

The 7d unconfined compressive strength of the test piece was tested and the results are shown in Table 9.

Table 9 The unconfined compressive strength of mixed materials with different ratio for 7 days

Aggregate type	Poor label S	Average value $\overline{R_c}$ (Mpa)	Coefficient of variation C_v(%)	$R_{c0.95}$(Mpa)
A0(Natural aggregates)	0.458	5.39	8.51	4.63
A1(Natural coarse + recycled fine)	0.283	7.40	3.82	6.93
A2(50% natural material + 50% recycled material)	0.210	6.60	3.18	6.25
A3(Recycled coarse + natural fine)	0.484	5.56	8.71	4.76
A4(Recycled aggregates)	0.301	6.84	4.40	6.35

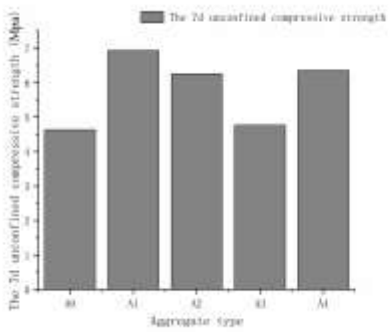

Fig.4 The unconfined compressive strength of mixed materials with different ratio for 7 days

It can be seen from Table 9 and Figure 4:

(1) When the cement dosage is 5%, the 7d compressive strength of the five kinds of mixed materials meets the requirements of (JTP D50—2017) Code for Design of Highway Asphalt Pavement, which is extremely heavy and heavy traffic in the secondary and secondary roads below the basement level. It is required for 2.5 to 4.5 MPa. Therefore, the alternative methods of the five kinds of recycled aggregates in this test have certain feasibility.

(2) In the five kinds of CSM mixture. With the increase of recycled aggregates content, the early compressive strength of the mixture not only did not decrease, but also increased. The main reason is that recycled fine aggregates contains a certain amount of unhydrated cement mortar and other active substances, which react with cement chemically [17]. In terms of the blending methods, the strength of CSM by substituting the fine aggregates decrease less than substituting the coarse aggregates because the skeleton formed by the coarse aggregates is guaranteed. The 7d unconfined compressive strength of the A1 group (natural coarse aggregates + recycled fine aggregates) was the highest, reaching 6.93Mpa, while the strength of the A3 group (regenerated coarse aggregates + natural fine aggregates) was 4.76Mpa. The main reason for this phenomenon is: First, the particle shape of the natural coarse aggregates is close to a spherical shape or a cubic shape (good particle size shape), and the natural coarse aggregates has a needle-like shape than the needle-like particle content of the recycled coarse aggregates. The particle content is high, the skeleton structure is more compact, and it is not easy to break after being stressed. Secondly, the incorporation of fine aggregates is chemically reacted with cement, which is superior to natural fine aggregates in early strength.

(3) With the increase of recycled aggregates content, the early compressive strength of the mixture increases. Through the mechanism analysis, it is explained that the first 7 days of cement-stabilized macadam mixtures, the cement undergoes intense hydration reaction with water, resulting in a large number of hydrated calcium silicate cementitious materials, which gradually become fibrous and plate crystalline, leading to the formation of the mixtures as a whole, so the strength of the CSM mixtures increases rapidly [18]. The active ingredients such as cement mortar in the regenerated fine aggregates are more than the natural fine aggregates, and the hydration reaction with water further increases the compressive strength of the mixture.

5.3 Splitting strength

The splitting strength is an important index to evaluate the crack resistance of cement-stabilized macadam aggregates. The splitting strength of the test samples was calculated by data processing. The results are shown in Table 10.

Table 10 7-day splitting strength of different proportions

Aggregate type	Poor label S	Average value $\overline{R_c}$ (Mpa)	Coefficient of variation C_v(%)	$R_{c0.95}$(Mpa)
A0(Natural aggregate)	0.022	0.34	6.44	0.30
A1(Natural coarse + recycled fine)	0.028	0.45	6.22	0.40
A2(50% natural material + 50% recycled material)	0.036	0.45	7.95	0.39
A3(Recycled coarse + natural fine)	0.024	0.43	5.57	0.39
A4(Recycled aggregate)	0.047	0.49	9.45	0.42

According to the test data of Table 10, When the cement dosage is 5% and the same grade, the splitting strength of different mixtures increases with the increase of recycled aggregates dosage, not only does it not cause the decrease of splitting strength, but also increases. The trend is basically the same as that of compressive strength. The main reason for this phenomenon is that there is a certain amount of mortar in the recycled aggregates, and the hydration reaction of these mortars with water and cement has a positive effect on the strength of the mixture. Secondly, the surface of regenerated aggregates particles is rougher and the fracture surface is more, which can form larger internal friction angle. The internal friction resistance and cohesion are increased to enhance the splitting strength [19].

VI. CONCLUSION

(1) The physical properties of recycled aggregates are analyzed and compared with natural aggregates. It is concluded that the recycled aggregates has smaller apparent density, higher water absorption, higher needle-like particle content and smaller crushing value, but it can meet the requirements of the specifications for the performance of raw materials of road base and subbase.
(2) With the increase of the amount of recycled aggregates, the optimum moisture content of the mixture showed an increasing trend, while the maximum dry density showed a decreasing trend.
(3) Through the measurement of 7d unconfined compressive strength and 7d splitting strength of CSM mixtures with five mixtures, it is concluded that the increase of recycled aggregates dosage does not cause the decrease of early compressive strength and splitting strength of CSM mixture. The mixing of recycled aggregates even cause the increase of early strength, which was affected by unhydrated cement particles. In terms of blending methods, the strength of CSM by substituting the fine aggregates decrease less than substituting the coarse aggregates because the skeleton formed by the coarse aggregates is guaranteed. The early splitting strength of the mixture is approximately the same as the compressive strength trend.
(4) The early strength characteristics of recycled aggregates CSM are studied, while the later strength and shrinkage properties are still to be further developed.

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Zhirong Jia." Effect of blending proportion and mode of recycled aggregates on early strength of Cement-stabilized macadam" International Journal Of Engineering Research And Development , vol. 15, no. 2, 2019, pp 70-77