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Laboratory evaluation of cement treated aggregate containing crushed clay brick

Liqun Hu[1,*], Jingxian Hao[2], Linbing Wang[3]

[1]*Key Laboratory of Special Area Highway Engineering of Ministry of Education, Chang'an University, Xi'an, Shaanxi, China*

[2]*CCCC Highway Consulants Co., Ltd., Beijing, China*

[3]*Department of Civil and Environmental Engineering, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA*

Abstract: The waste clay bricks from debris of buildings were evaluated through lab tests as environmental friendly materials for pavement sub-base in the research. Five sets of coarse aggregates which contained 0, 25%, 50%, 75% and 100% crushed bricks, respectively, were blended with sand and treated by 5% cement. The test results indicated that cement treated aggregate which contains crushed clay brick aggregate had a lower maximum dry density (MDD) and a higher optimum moisture content (OMC). Moreover, the unconfined compressive strength (UCS), resilience modulus, splitting strength, and frost resistance performance of the specimens decreased with increase of the amount of crushed clay brick aggregate. On the other hand, it can be observed that the use of crushed clay brick in the mixture decreased the dry shrinkage strain of the specimens. Compared with the asphalt pavement design specifications of China, the results imply that the substitution rate of natural aggregate with crushed clay brick aggregate in the cement treated aggregate sub-base material should be less than 50% (5% cement content in the mixture). Furthermore, it needs to be noted that the cement treated aggregate which contains crushed clay bricks should be cautiously used in the cold region due to its insufficient frost resistance performance.

Key words: cement treated aggregate; crushed clay brick aggregate; sub-base material; compaction property; frost resistance performance

1 Introduction

Civil engineering construction often consumes large quantities of natural resources, including aggregates, which become insufficient to meet ever increasing construction demands. At the same time, a lot of old

* **Corresponding author:** Liqun Hu, PhD, Professor.
E-mail: hlq123@126.com.

buildings have reached the end of their service life facing to be demolished, which bring mountainous wasted clay bricks in many countries. Some waste bricks were used as backfill material, and a great proportion of them were sent to landfills. Recycling waste clay bricks used as aggregates could considerably reduce the problem of waste disposal and simultaneously help the preservation of natural aggregate resources (Moriconi et al. 2003; Levy and Helene 2004; Poon and Chan 2007; Yang et al. 2011; Aliabdo et al. 2014).

Over the last two decades, with increasing environmental awareness, many researches have been undertaken to investigate the possibility of using waste brick in cement concrete. Kibriya and Speare (1996) used three different types of brick aggregates to assess their impacts on strength and long-term durability of concrete. The results indicated that the concrete containing crushed brick aggregate had compressive, tensile, and flexural strengths comparable to those of normal concrete, but the modulus of elasticity was drastically reduced. Test results which use crushed brick as 100% replacement of coarse natural aggregates in concrete indicated that the tensile strength of brick concrete was higher than that of normal concrete by about 11%. However, the modulus of elasticity was 30% less than that of normal concrete (Akhtaruzzaman and Hasnat 1983). Padmini et al. (2001) studied the relative influence of different parameters on strength of concrete using low-strength bricks as aggregates. It was found that the strength of brick concrete was most influenced by the cement content, the aggregate conditions, and the strength of brick from which the aggregates were derived. Since the strength of brick varies considerably, it is therefore very difficult to quantify the quality of the resulting brick concrete. Compared with the natural aggregate, crushed brick aggregate has lower strength and higher water absorption (Khaloo 1994; Cachim 2009; Bekta 2014). This leads to some potential problems when using crushed clay brick in concrete. And some international agencies restrict the amount of crushed brick that can be used in concrete, which hinders the recycling of this masonry waste.

Pavement is a multi-layered structure composed of a concrete or an asphalt slab resting on a foundation system comprising various layers such as the base, sub-base, and sub-grade. Conventionally, natural materials such as crushed rocks, selected gravels are widely used as road materials (Nataatmadja and Tan 2001; Kuo et al. 2002; Molenaar and van Niekerk 2002; Park 2003; Leite et al. 2011; Arulrajah et al. 2014). Road construction often needs large quantities of aggregate. Thus, incorporating construction and demolition debris in road materials can consume a greater amount of these waste materials, which can induce great environment protecting effects. Many researches have been undertaken to investigate the possibility of using recycled aggregates in road base or sub base courses (Bennert et al. 2000; Chini et al. 2001; Poon and Dixon 2006; Huang et al. 2007; Velasquez et al. 2009; Jankovic et al. 2012; Soutsos et al. 2012; Rahardjo et al. 2013). As for waste clay brick, Poon and Chan (2005) researched unbound road sub-base using crushed clay brick and recycled concrete. The results showed that recycled sub-base had a lower maximum dry density and a higher optimum moisture content when compared to the maximum dry density and optimum moisture content of the sub-base prepared with natural materials. Sub-base using crushed clay brick as fine aggregate had a lower California bearing ratio (CBR) value compared to the sub-base using recycled concrete aggregate as the fine aggregate. Disfani et al. (2014) studied the performances of cement-stabilized blends with recycled concrete aggregate and crushed brick as supplementary material. The laboratory evaluation comprised pH, plasticity index, foreign materials content, particle size distribution, linear shrinkage, CBR, modified proctor compaction, repeated load triaxial test, unconfined compressive strength (UCS) test, and flexural beam tests. Results indicated the cement stabilized blends with 50% crushed brick content and 3% cement could meet the local state road authority requirements.

Cement treated material which is a family of compacted mixtures with granular materials, Portland cement and water has been used for road sub-base for many years. In this paper, aggregates containing crushed waste clay bricks were treated by cement as road sub-base course material. The objective of the study is to evaluate the physical and mechanical properties of cement treated aggregate containing crushed clay bricks by lab tests and to assess the feasibility of using clay brick aggregate as raw material of cement treated aggregate through comparing the test results with the requirements of specifications. In the experiment, natural coarse aggregates were substituted by weight by crushed brick aggregates with various percentages of 0, 25% , 50% , 75% , and 100% . Compaction characteristics, UCS, resilience modulus, splitting strength, dry shrinkage strain, and frost resistance index were tested respectively.

2 Materials and experiments

2.1 Materials

2.1.1 Coarse aggregate

Two kinds of coarse aggregates were prepared to study. One is natural aggregate, and the other is crushed clay brick aggregate. In order to control gradation strictly, crushed limestone were manually sieved into the following sizes: 26.5-31.5 mm, 19.0-26.5 mm, 16.0-19.0 mm, 13.2-16.0 mm, 9.5-13.2 mm, and 4.75-9.5 mm. Then they were blended together according to the gradation of coarse aggregate (Fig. 1) .

The waste clay brick is from a demolition site in Xi′an (Fig. 2) . The impurities such as tile, wood, and dust were removed firstly and then the waste clay brick was crushed manually using a hammer and a crusher to produce coarse aggregates. The crushed clay brick particles were also sieved into the size of 26.5-31.5 mm, 19.0-26.5 mm, 16.0-19.0 mm, 13.2-16.0 mm, 9.5-13.2 mm, 4.75-9.5 mm and then blended together according to the gradation of coarse aggregate (Fig. 1) .

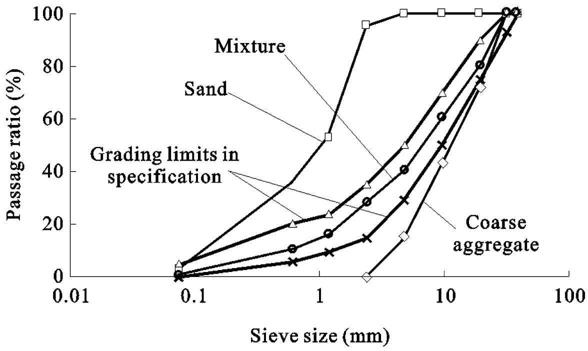

Fig. 1 Particle size distribution

The crushed stone values, densities, and water absorption rates of natural aggregate and clay brick aggregate are shown in Tab. 1.

Tab. 1 Properties of coarse and fine aggregates

Property	Clay brick aggregate	Natural aggregate	Sand
Crushed stone value (%)	36	25	—
Water absorption rate (%)	13.20	1.42	0.94
Density-oven-dry (kg/m^3)	1.854	2.632	—
Density-SSD (kg/m^3)	2.136	2.644	2.595

Fig. 2 Waste bricks

The crushed stone value, density, and water absorption rate of the coarse aggregate were conducted according to T0308, T0316 in Test Methods Aggregate for Highway Engineering (JTJ 058-2000) of Ministry of Communications of China, which are similar to ASTM C128(2007) . The test results show that the density of crushed stone is higher than that of crushed clay brick, and the crushed stone value and water absorption rate of crushed stone are lower than those of crushed clay brick. Test results on the physical properties of raw materials indicate that the crushed stone has better performance than waste clay brick.

2.1.2 Fine aggregate

The fine aggregate used in the study is sand from Bahe River near Xi´an. The maximum size is 4.75 mm and the fineness modulus is 3.11. The sand particle size distribution is shown in Fig. 1 and its properties are presented in Tab. 1.

2.1.3 Portland cement

The cement supplied by Shaanxi Qinling Cement Ltd. is grade 32.5 Ordinary Portland Cement with the density of 3140 kg/m^3, and the properties of the cement meet the requirements in the Portland Cement and Ordinary Portland Cement (GB 175-1999) of Ministry of Transport of China.

2.2 Mix proportion

In this study, 70% coarse aggregate and 30% fine aggregate were blended together to meet the gradation limits of cement treated sub-base material of Specifications for Design of Highway Asphalt Pavement (JTG D50-2006) of Ministry of Transport of China (Fig. 3). The grading curves of mixture and limits of specification are presented in Fig. 1.

In order to evaluate the properties of cement treated aggregate which contains different crushed waste brick aggregates, a portion of natural coarse aggregate (>4.75 mm) was replaced by crushed clay brick aggregate (>4.75 mm). The substitution rates were 0, 25%, 50%, 75%, and 100% by the weight of natural coarse aggregate.

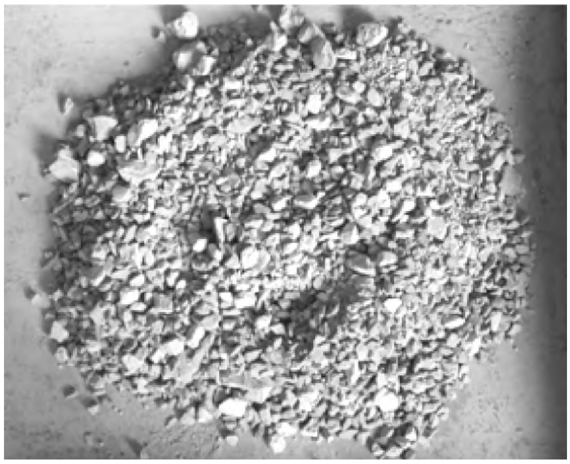

Fig. 3 Blended mixture

Many research results show that the strength of cement treated aggregate increases with the increase of cement content in the mixture, but the excessive cement content will make the material stiffer and easier to crack. In China, the cement content of cement treated aggregate is usually from 4% to 6%. In this study, five sets of aggregates which have different coarse clay brick aggregate contents were treated by cement. The cement content in mixtures was all set as 5%. The details of mixture proportions are listed in Tab. 2.

Tab. 2 Mixture proportions and descriptions

Mixture	Mix proportion (%)				Description
	Coarse aggregate		Sand	Cement	
	Crushed brick	Natural aggregate			
C-0	0.0	70.0	30	5	0 coarse aggregate replaced by clay brick aggregate
C-25%	17.5	52.5	30	5	25% coarse aggregate replaced by clay brick aggregate
C-50%	35.0	35.0	30	5	50% coarse aggregate replaced by clay brick aggregate
C-75%	52.5	17.5	30	5	75% coarse aggregate replaced by clay brick aggregate
C-100%	70.0	0.0	30	5	100% coarse aggregate replaced by clay brick aggregate

2.3 Preparation of specimens

Two kinds of steel moulds were used to prepare specimens in the study. One is cylinder mould, and the other is rectangular mould. The dimension of cylinder specimens is 150 mm in diameter and 150 mm in height. The dimension of rectangular beam specimen is 400 mm in length, 100 mm in width, 100 mm in depth. The testing mixtures were prepared by blending cement, natural aggregate, waste brick aggregate, and water together by hand. The weight of the mixture put into the mould was calculated according to the results of maximum dry density. The optimum moisture content determined from compaction test and relative compaction of test specimens was 98%. The materials were put into the mould by three layers with approximately equal depth and were inserted up and down using a steel bar. After the third layer was filled, the mixture was compacted to designed dimension using a hydraulic press with a maximum capacity of 2000 kN at a rate of 450 kN/min. Those mixtures with cement must be compacted into the mould within 1 h after the cement is added in. Cylinder specimens were used for test of UCS, resilience modulus, split strength, and freeze-thaw. Rectangular specimens were used for the test of drying shrinkage strain. During the curing period, all the specimens used for UCS, resilience modulus, split strength, and freeze-thaw test were sealed in plastic bags, and stored at a temperature of (20 ± 2) ℃ with a relative humidity above 95%. Before the test they were soaked in the water at room temperature for 24 h.

2.4 Test methods

Performance tests of specimens mainly complied with the Test Methods of Materials Stabilized with Inorganic Binders for Highway Engineering (JTG E51-2009) of Ministry of Transport of China.

2.4.1 Compaction test

The compaction test was performed in accordance with test method T0841-2009 in JTG E51-2009, which is very similar to ASTM D1557 (2001) and AASHTO T180 (2004). The mould dimension is 152 mm in diameter and 120 mm in height. The hammer weight is 4.5 kg, and it has a free-fall distance of 500 mm. The aggregates were air dried for 24 h to remove any moisture. All particle sizes greater than 31.5 mm were rejected from the mixture. Each mixture was compacted in three layers with 98 blows per layer.

2.4.2 UCS

The UCS test was measured following test method T0805-94 in JTJ 57-94, which is similar to ASTM D1633 (2000). Testing ages of the specimens were 7, 28, and 90 days, respectively, with 9 specimens in each group.

2.4.3 Resilience modulus

The resilience modulus was measured following test method T0808-94. 9 cylinder specimens were tested for each data point, testing ages of the specimens were 28 and 90 days.

2.4.4 Splitting strength

The splitting strength was tested according to T0806-94 in JTJ 57-94, which is similar to ASTM C496-96 (1996). The testing periods of the specimens were 28 and 90 days, respectively. 9 specimens were tested for each group.

2.4.5 Dry shrinkage

Dry shrinkage test was performed according to T0854-2009 in JTG E51-2009. The rectangular specimens were removed from the mould carefully after six hours of curing in an environmental chamber maintained with 100 percent relative humidity and 20 ℃. Afterwards, metal gauge studs were glued onto the ends of the samples with epoxy to facilitate shrinkage measurements over the following 14 days. The device used for shrinkage measurements was equipped with a dial gauge capable of measuring deflection to the nearest 0.0004 inches. 14 days was proposed to judge the performance of specimens. The drying shrinkage strain was calculated by Eq. (1)

$$E = \Delta L / L \tag{1}$$

where E is drying shrinkage strain; ΔL is change of specimen length in the test (mm); L is the length of specimen before test (mm).

2.4.6 Frost resistance

The frost resistance test was carried out in line with the following method: after 28 d curing, the test specimens were soaked in water at room temperature for 24 h; then they were taken out of the water, and put into a freezer for 8 h freezing at a temperature of (−18 ± 1) ℃, followed by 8 h thawing at the normal temperature of (20 ± 1) ℃. That is, 16 h were taken as a freezing-thawing cycle. After five cycles, UCS was tested. The frost resistance index F was calculated by Eq. (2)

$$F = U_1 / U_2 \tag{2}$$

where U_1 is average soaking UCS of test specimen after five freezing-thawing cycles (MPa); U_2 is soaking UCS of test specimen without going through freezing and thawing (MPa).

In the experiment, the loading rate of UCS, resilience modulus, and splitting strength tests is 1 mm/min.

3 Results and discussion

The test results of compaction property are summarized in Tab. 3. The UCS, resilience modulus, splitting strength test results of the specimens are shown in Tab. 4. Test results of dry shrinkage and frost resistance are listed in Tab. 5.

3.1 Compaction property

Maximum dry density (MDD) and optimum moisture content (OMC) test results of five sets of cement treated mixtures were shown in Figs. 4, 5 respectively. It can be observed that the MDD decreased with the increase of crushed brick aggregate content. The maximum dry density of mixture using 100% natural aggregate as coarse aggregate is the highest, up to 2.376 g/cm^3, while the value of the mixture using 100% crushed clay brick aggregate as coarse aggregate reaches the lowest, only 1.849 g/cm^3.

Tab. 3 Test results of compaction property

Mixture	Maximum dry density (g/cm^3)	Optimum moisture content (%)
C-0	2.376	5.72
C-25%	2.311	8.33
C-50%	2.132	9.54
C-75%	2.035	12.27
C-100%	1.849	14.05

Tab. 4 Test results of UCS, resilience modulus, and splitting strength

Mixture	UCS (MPa)			Resilience modulus (MPa)		Splitting strength (MPa)	
	7 d	28 d	90 d	28 d	90 d	28 d	90 d
C-0	3.34	5.20 (5.07*)	6.87	1450	2150	0.31	0.62
C-25%	2.46	4.36 (3.75*)	5.75	1160	1730	0.27	0.55
C-50%	1.80	3.16 (2.44*)	4.68	920	1430	0.23	0.50
C-75%	1.43	2.40 (1.52*)	3.52	760	1070	0.20	0.44
C-100%	1.14	1.88 (1.05*)	2.93	590	930	0.17	0.40

Note: * UCS after freeze-thaw cycle.

Tab. 5 Test results of dry shrinkage and frost resistance

Notation	Dry shrinkage (10^{-6})		Frost resistance index (%)
	1 d	14 d	
C-0	254	482	97.5
C-25%	246	449	86.1
C-50%	222	435	77.2
C-75%	200	415	63.3
C-100%	187	390	55.8

However, the results of OMC exhibit opposite tendency of the maximum dry density. The OMC of mixture increased with the increase of crushed brick aggregate content. The OMC of mixture using 100% natural aggregate as coarse aggregate is lowest, only 5.72%, and the value of the mixture using 100%

clay brick aggregate as coarse aggregate is highest, up to 14.05%.

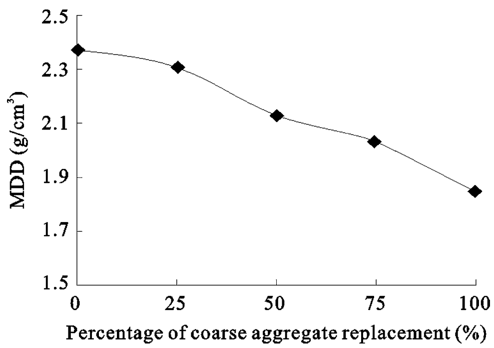

Fig. 4 MDD of different mixtures

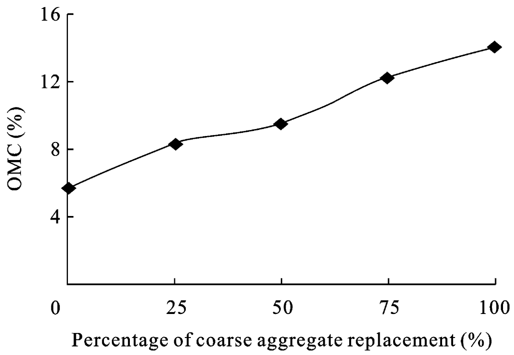

Fig. 5 OMC of different mixtures

According to Tab. 1, the strength of crushed clay brick aggregate is much weaker than natural aggregate while the water absorption rate is higher. Since the gradation and cement content of each mixture were the same, the compaction property difference between the maximum dry density and the optimum moisture content was mainly influenced by the density and the water absorption of aggregate used. Moreover, the irregular shape of the crushed clay brick particles due to manual crushing possibly increased the amount of voids within the material and led to a decrease in the maximum dry density as well.

32 UCS

The UCS is generally known as an important indicator of the mixture quality of cement treated aggregate in many countries. The 7, 28, and 90 days curing period UCS results of five sets of mixtures are shown in Fig. 6. It can be seen that the UCS of five mixtures all increase along with the curing period. Furthermore, when the coarse aggregate replacement level increased from 0 to 100%, the 7-day, 28-day and 90-day UCS of mixtures ranged from 3.34 MPa to 1.14 MPa, from 5.20 MPa to 1.88 MPa, and from 6.87 MPa to 2.93 MPa, respectively. The UCS of mixtures obviously decreased with the increase of crushed waste brick content. The decrease of 7-day UCS with the coarse aggregate replacement level of 25%, 50%, 75%, and 100% were 26.3%, 46.1%, 57.1%, and 65.9%, respectively as compared with the specimens using 100% natural aggregate as coarse aggregate.

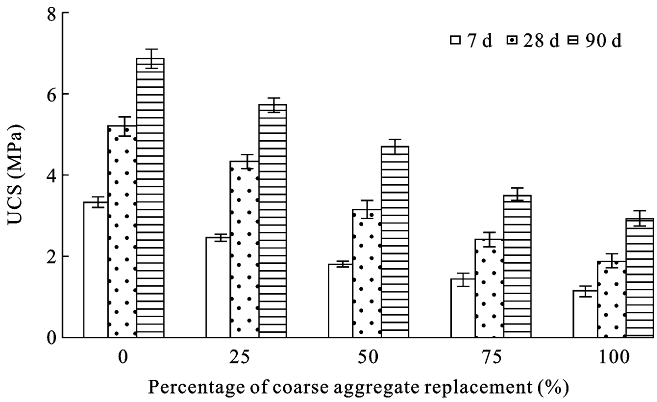

Fig. 6 Test results of UCS

It is known that there is a close relationship between UCS of cement treated material and the strength of aggregate used. According to Tab. 1, the crushed stone value of waste brick aggregate is 44% bigger than that of natural aggregate. During the experiment, there were many brick aggregate particles crushed. Therefore, it can be concluded that the use of clay brick aggregate as coarse aggregate would affect the UCS of mixtures.

According to the requirements of Specifications for Design of Highway Asphalt Pavement (JTG D50-2006) of the Ministry of Transport of China, the cement treated aggregates with 1.5 MPa, 2.0 MPa, and 2.5 MPa of 7-day UCS may be used for the sub-base courses of light traffic highway, middle traffic highway, and heavy traffic highway, respectively. Therefore, according to the test results, when the coarse aggregate replacement of natural aggregate with clay brick aggregate is lower than 50%, the UCS of the mixture can meet the requirements of light traffic road sub base at least.

3.3 Resilience modulus

The resilience modulus of cement treated aggregate is a key mechanical factor to pavement structure design. The 28-day and 90-day resilience modulus of the mixtures with different coarse clay brick aggregate contents are illustrated in Fig. 7. As shown in Fig. 7, with the increase of curing time, the resilience modulus of all mixtures increases. Also, it can be seen that the 28-day and 90-day resilience moduli decreased with the increase of the coarse aggregate replacement from 0 to 100% and the maximum values of 28-day and 90-day were 1450 MPa and 2150 MPa, respectively, and the minimum values of 28-day and 90-day were 590 MPa and 930 MPa, respectively. Furthermore, the decrease of 90-day resilience modulus in the coarse aggregate replacement levels of 25%, 50%, 75%, and 100% were 19.5%, 33.5%, 50.2%, and 56.7%, respectively as compared with the specimens using 100% natural aggregate as coarse aggregate.

The resilience modulus of the mixtures decreased with the increase of clay brick aggregate content. It was mainly due to the higher porosity of the clay brick particle compared to the natural aggregate. The material with higher porosity always has greater deformation potential under the load.

According to Specification of Asphalt Pavement Design for Highway (JTG 50-2006), the 90-day resilience modulus of cement treated aggregate should be 1300-1700 MPa. From the test results, it can be seen that if the coarse aggregate replacement of natural aggregate with clay brick aggregate is less than 50%, the resilience modulus can also meet the requirement of the resilience modulus design value.

Fig. 7 Test results of resilience modulus

3.4 Splitting strength

The tensile strength of cement treated material is considered as a significant material parameter for designing pavement structures. The reason is that the bottom of the cement treated material layer suffers the tensile stress. In general, flexural beam tests, direct tensile tests, and indirect tensile tests have been conducted to evaluate the tensile strength of cement treated material. In the study, splitting strength (indirect tensile strength) was tested. Fig. 8 presented 28-day and 90-day splitting strength test results of five mixtures used in the study.

From Fig. 8, it can be seen that 28-day splitting strength of different mixtures ranged from 0.31 MPa to 0.17 MPa, and 90-day splitting strength of different mixtures ranged from 0.62 MPa to 0.40 MPa. It also can be seen that splitting strength decreased with the increase of the crushed waste brick content in the mixture. The splitting strength value of specimen using 100% natural aggregate as coarse aggregate is the greatest and the values of specimen using 100% crushed clay brick as coarse aggregate is the lowest. Moreover, test results show that the decrease of 90-day splitting strength in the coarse aggregate replacement level of 25%, 50%, 75%, and 100% were 11.3%, 19.4%, 29.0%, and 35.5% as compared with the specimens using 100% natural aggregate as coarse aggregate, respectively. Compared to the test results of UCS, it can be seen that although using crushed clay brick as coarse aggregate affects both the splitting strength and the UCS of the mixture, the influence on the former is smaller than the latter. This is because the tensile strength mainly depends on the cohesion of the mixtures and has little relationship to the strength of aggregate particles. The surface of clay brick aggregate is rougher than that of natural aggregate and allows the mortar to permeate the particle surface, so the bond strength at the interface between the mortar and the brick aggregates seems to be higher.

According to Specification of Asphalt Pavement Design for Highway (JTG 50-2006), the 90-day splitting strength of cement treated aggregate is 0.4-0.6 MPa. From the test results, it can be seen that if the coarse aggregate replacement of natural aggregate with crushed clay brick is less than 75%, the splitting strength of mixture is higher than the criteria of cement treated road sub-base material in the specification.

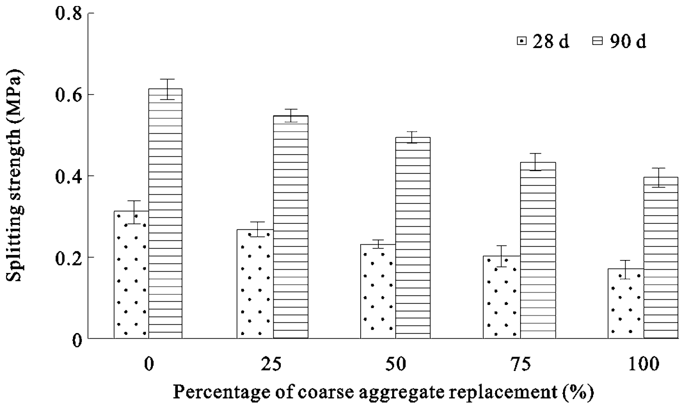

Fig. 8 Test results of splitting strength

3.5 Dry shrinkage

Cement treated material may induces cracking due to the dry shrinkage during the paving stage. These cracks not only cause pavement structural issues, but also accelerate deterioration of the pavement by allowing water to enter lower pavement layers. In the study, dry shrinkage strain was tested to evaluate the crack resistance performance of the specimens with different crushed clay brick replacement ratios.

The relationships between curing time and dry shrinkage strain of various mixtures are shown in Fig. 9. It can be seen that the dry shrinkage strain of all specimens increased along with the increase of curing time and the value slightly decreased with the increase of the crushed clay brick aggregate content no matter how long the curing time was. The 1-day and 14-day dry shrinkage strains of the specimens using 100% natural aggregate as coarse aggregate were 254×10^{-6} and 482×10^{-6}, respectively, and the 1-day and 14-day dry shrinkage strains of specimens using 100% crushed brick as coarse aggregate were 187×10^{-6} and 390×10^{-6}, respectively. So it is significantly notable that using crushed clay brick would be benefitial for reducing the dry shrinkage of mixture.

The shrinkage of cement treated materials mainly results from the loss of water by drying and self-desiccation during the hydration of cement. Usually, the cement treated material mixtures containing more water exhibit greater shrinkage potential which implies the mixture containing clay brick aggregates would have higher dry shrinkage strain value than that of mixtures compose of pure natural aggregates. This is because the OMC of mixtures adding clay brick aggregate is higher and it needs more water during the mixture blend process. But the experiment showed the opposite results. This might be primarily due to the self-curing action of the clay brick aggregates in the specimens. During the initial mixing, the crushed clay brick might have initially absorbed a relatively large amount of water, but the water was kept in the pores of brick aggregate before it released as the curing progressed (Corinaldesi and Moriconi 2009). Therefore, the overall drying shrinkage was reduced owing to the presence of this internal moisture. Although there is no clear criteria about dry shrinkage strain of cement treated material in the specification in the most countries, using mixtures which have smaller dry shrinkage strain is benefitial for preventing the road sub-base cracking.

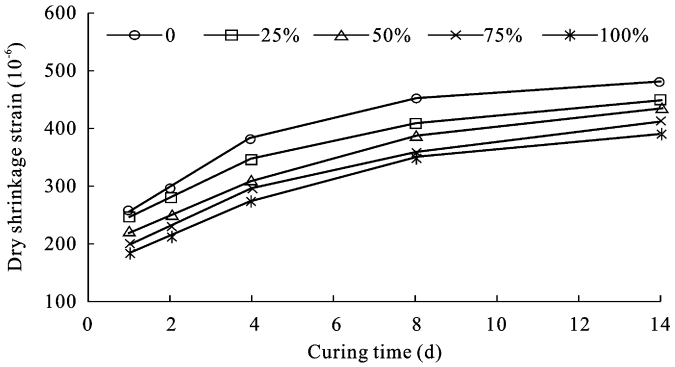

Fig. 9 Test results of dry shrinkage

3.6 Frost resistance

In cold climates, it is a notable issue that frost action (freezing and thawing cycles) can damage cement treated materials. The performance of frost resistance is used to judge the attenuation degree of mechanical property of material in the cold weather. Frost resistance performance was measured by frost resistance index which is the ratio of UCS before to that after freeze-thaw cycles in the study.

Test results show that the 28-day UCS of all mixes decreased after freeze-thaw cycle, but the extents of decrease were different. For instance, the 28-day UCS of mixture containing no clay brick aggregate and that containing 100% crushed brick aggregate were 4.4 MPa and 3.3 MPa, respectively before freeze-thaw cycles, and the values after freeze-thaw cycles were 4.2 MPa and 2.2 MPa, respectively. The 28-day UCS loss of mixture containing 100% crushed brick aggregate is obviously bigger than that of mixture with 100% natural aggregate.

Test results of frost resistance index of the materials are shown in Fig. 10. It can be seen that the frost resistance index decreased with the increase of crushed waste brick content in the mixture. The frost resistance index of mixture which using 100% crushed stone as coarse aggregate is almost 1.75 times as much as that of mixture using 100% crushed brick as coarse aggregate. The frost resistance index loss is about 10.35% when the replacement of crushed brick aggregate increases by every 25%.

During frost action, the water begins to freeze in a capillary cavity of the specimen, and the hydraulic pressure is generated due to the increase in volume of the water accompanying the freezing. The magnitude of the pressure is closely related to the water content of the specimen. Generally, the more water content the specimen has, the bigger hydraulic pressure in the specimen occurs during the freezing. The pressure often causes deterioration in the specimen and affects its strength. Because clay brick aggregate has higher water absorption than natural aggregate, the specimen containing clay brick aggregate often absorbs more water during the experiment. This leads to the fact that using crushed clay brick aggregate would exert negative influence on the frost resistance performance of cement treated aggregate.

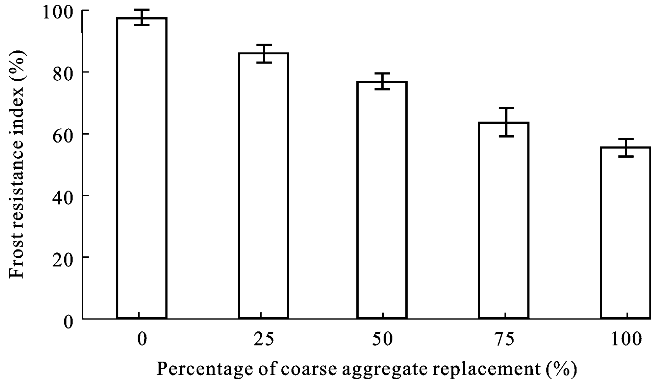

Fig. 10 Frost resistance indexes of different mixes

4 Conclusions

This paper presents the result of an investigation on the use of crushed clay brick as coarse aggregates in cement treated sub-bases materials (5% cement content). Based on the laboratory results and the comparisons with the Specifications for Design of Highway Asphalt Pavement (JTG D50-2006) of Ministry of Transport of China, the following conclusions can be obtained.

The test results of compaction property indicated that the cement treated aggregate which contains crushed clay brick had a lower maximum dry density and higher optimum moisture content.

The UCS decreased with the increase of crushed brick aggregate in the mixtures. 7-day UCS of mixture which contains less than 50% crushed brick can meet the sub-base strength requirements of light traffic road in specifications.

The resilience modulus decreased with the increase of crushed clay brick and if the coarse aggregate of natural aggregate replacement ratio with crushed clay brick aggregate is lower than 50%, the 90-day resilience modulus of the mixture can also meet the pavement design requirements of the specifications.

The splitting strength was also affected by using crushed clay brick as coarse aggregate in the mixture and coarse aggregate replacement. As substitution rate is lower than 75%, the splitting strength of mixture can meet the pavement design requirements of the specifications.

The cement treated aggregate using crushed brick as aggregate had a lower dry shrinkage strain compared to the cement treated aggregate using natural crushed stone.

The frost resistance performance test results indicated that due to the high water absorption rate of the crushed brick aggregates, the frost resistance performance decreased with the increase of crushed brick aggregate content in the mixture.

The overall results demonstrate that it is feasible to use the crushed clay brick derived from demolition sites as coarse aggregate of cement treated aggregate material. It is suggested that when the cement content of mixture is 5%, the coarse aggregate of natural aggregate replacement with crushed clay brick should be less than 50%, and the cement treated aggregate which contains crushed brick aggregate should be used cautiously in the cold region due to its lower frost resistance performance.

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