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Mechanical Properties of Sandstone Cement-Stabilized Macadam

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Abstract: Application of sandstone in cement-stabilized macadam (CSM) is an effective way to utilize sandstone. To determine the feasibility of using sandstone as a CSM aggregate, a series of experimental investigations, such as unconfined compressive strength (UCS) tests, Brazilian splitting tests and freeze-thaw cycle tests, were conducted on sandstone cement-stabilized macadam (SCSM). Three mixed variables, covering the cement content, aggregate type and curing period, were set as influence factors. The testing results indicated that the UCS, indirect tensile strength (ITS) and frost resistance property of the test-pieces increased with cement content and curing age. Considering the asphalt pavement design specifications for China, the UCS and ITS values of the SCSM complied with the requirements of light traffic road construction before freeze-thaw cycles. However, the SCSM subjected to freezing and thawing meets the requirements only when the cement content is 4.5%. Therefore, it is noteworthy that CSM containing sandstone aggregates should be applied with caution in cold region because of insufficient freeze resistance.

Keywords: cement stabilized macadam; sandstone; limestone; road performance; freeze-thaw cycles

1. Introduction

Cement-stabilized macadam (CSM) is a family of compacted blends containing aggregates with appropriate grading, cement of 3–8% by weight of aggregates and water at optimum moisture content levels [1,2]. CSM has been widely used in highway bases and sub-bases because of better bearing capacity and lower tensile stress or strain at the bottom of the bituminous layer [3]. With the rapid development of road construction, natural stone materials as aggregates of CSM are becoming depleted at an increasing rate, making them insufficient to meet the increasing construction demands [4]. The task of road construction in remote areas, in particular, is a challenge due to its very high demand for aggregate resources. However, the use of high-quality stone may cost more manpower and financial capital in most of these economically underdeveloped areas as a result of stone resource shortages. Hence, it is very significant to hunt for materials as aggregate replacements within a close range along highways to solve the problem of stone resource shortage.

Soft rock is widely distributed along the highways in the southwestern region, South Central China, central China, and Shaanxi-Gansu-Ningxia regions [5], including a sequence of sedimentary rocks, such as mudstone, sandstone, argillaceous sandstone, sandy mudstone, and siltstone [6]. If these soft rocks are abandoned and high-quality rock is purchased from a long distance away, large increases in the construction costs will result, together with extended construction periods and environmental pollution problems caused by the disposal impacts of the abandoned rock. For example, 14×10^6 m^3 of red sandstone was converted into eligible roadbed materials in the construction of the Heng-Zao

Expressway in Hunan Province of China, which not only saved 842.5 hectares of farmland and 167.9 hectares of forest land, but also reduced millions related to the construction cost [7]. The use of widely distributed and not widely developed sedimentary rocks for CSM aggregates may be an effective means of addressing the shortages of high-quality stone, thereby simultaneously providing economic and environmental benefits.

Compared with natural aggregates, sedimentary rocks are considered undesirable road materials because of their high-water absorption and large crushing value [8]. Construction and demolition waste (CDW) with the same characteristics has been used as aggregates in existing studies, such as crushed clay brick and recycled concrete [9]. The successful research on the use of CDW for concrete gravel is mostly concentrated in the United States and European countries [10]. Poon and Chan [11] studied the properties of concrete blends with CDW used as an aggregate. Although the mixtures have a lower dry density and higher moisture content as a mixture of aggregates than natural materials, they can still be used in road sub-bases. Disfani et al. [12] studied the properties of CSM mixtures with crushed brick as aggregate through laboratory tests and found that the physical and strength properties of the mixture meet the road requirements. In addition, the researchers [13] conducted unconfined compression tests, split tensile tests and flexural strength tests; it was concluded that road base materials containing recycled concrete aggregates could be used for high-grade road construction. With the shortage of resources and worsening of the environment, recycling has gradually become a concern of academic experts in China. The feasibility of using recycled concrete aggregates as substitutes for natural aggregates was evaluated in lime-fly ash crushed stone bases [14]. The UCS values are better than those of natural aggregates and meet the requirements of road engineering. Based on the above facts, sedimentary rock may be feasible as a substitute for traditional aggregates in road construction.

At present, the research on sedimentary rocks used in highway engineering mainly focuses on the performance of red sandstone, and its uniaxial compressive strength and indirect tensile strength are superior to white sandstone and yellow sandstone [15]. Yao et al. [16] evaluated the physical and mechanical properties of red sandstone distributed in southern Anhui, with the aim of using this soft rock as a road construction material. The results demonstrated that the mixture consisting of sandstone can be directly applied into highway construction after particular preliminary steps are performed. The authors of [17,18] studied the improvement of red sandstone construction technology and applied it to the construction of some roadbeds in Hunan, a province in South Central China, and sufficient engineering results were achieved. In addition, Zhou [19] and Yang et al. [5] studied the performance of improved sandstones in the Yungui area and Gansu Province, respectively, and showed that the improved sandstones could fully meet the technical requirements. The mechanical properties of sandstones in different regions vary widely because of differences in their mineral composition. In addition to the above areas, there is also a large amount of sandstone in northern Shaanxi. However, there are few studies on whether the Cretaceous sandstone with weaker rock quality in the northern Shaanxi area can be used as a road base aggregate.

Therefore, the target of this paper is to assess the physical and mechanical properties of CSM consisting of sandstone through laboratory tests including UCS tests, splitting tensile strength tests and freeze-thaw stability tests. The research also assesses the feasibility of applying sandstone as a raw material of CSM by comparing the test results with the requirements of specifications. This research thus provides possible solutions for the lack of natural stone materials for infrastructure construction and more possibilities for material selection.

2. Materials and Testing Methods

2.1. Materials

2.1.1. Cement

Ordinary Portland cement is used in this study and its main mineral composition includes $3CaO{\cdot}SiO_2$, $2CaO{\cdot}SiO_2$, $3CaO{\cdot}Al_2O_3$ and $3CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$. Ordinary Portland cement can better hydrate and harden when in contact with water as well as maintaining and developing its strength [20]. The chemical composition of the ordinary Portland cement employed in this research is summarized in Table 1, and its physical properties include a specific gravity of 3.14 and a fineness value of 329 m^2/kg.

Table 1. The chemical composition of the ordinary Portland cement used in this study.

Label	**SiO_2**	**Al_2O_3**	**CaO**	**Fe_2O_3**	**MgO**	**SO_3**
Cement	20.36	5.67	62.81	3.84	2.68	2.51

2.1.2. Aggregate

Four different coarse aggregates, including three types of sandstone marked A, B, C and one type of limestone marked D, were selected for the experiment. These sandstones were randomly obtained from three different production areas in northern Shaanxi, China. The main physical characteristics of the coarse aggregates are recapitulated in Table 2. The bulk density, porosity, water absorption and compressive strength values before and after the ruggedness testing were measured according to JTG E41-2005 [21]. The crushing value was determined following JTG E42-2005 [22].

Table 2. The properties of the coarse aggregates.

Label	**A**	**B**	**C**	**D**
Bulk density (g/cm^3)	2.6	2.6	2.7	2.7
Porosity (%)	10.1	10.3	9.8	1.2
Water absorption (%)	3.54	3.61	3.18	0.32
Compressive strength (MPa)	48	44.7	59.7	118.6
Compressive strength after ruggedness test (MPa)	26.3	22.4	30.8	107.7
Crushed value (%)	26.7	27.4	23.1	14.3

As shown in Table 2, the porosity, water absorption and crushing values of the sandstones (A, B, and C) are significantly higher than those of the limestone. Among them, the porosity and water absorption values of the sandstones are approximately 10 times those of the limestone, while the crushing values are approximately 2 times the limestone value. In contrast, the sandstones have lower compressive strength values compared with that of limestone. Moreover, after the robustness tests, the compressive strengths of the sandstones were significantly reduced to approximately half of the values before the tests, while the limestone showed little change.

2.2. Experimental Programme

2.2.1. Gradation Design

Under the premise of fully considering the residual porosity and other factors, the coarse and fine aggregates should be sandstone/limestone with a continuous grading, and the grading was artificially compounded through experiment. The accumulated screening rates are demonstrated in Figure 1, where the upper and lower limits refer to the technical specifications of JTG F30-2003 [23].

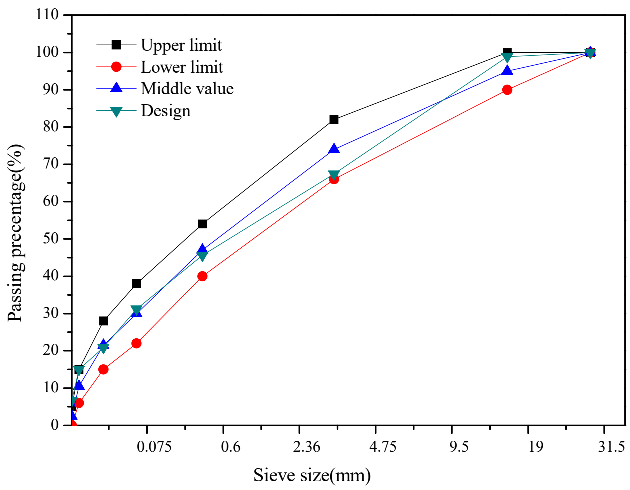


Figure 1. The gradation curve of the mixture.

2.2.2. Mixing Proportion Design

As demonstrated in Table 3, the specimens were assigned to four sets: three types of sandstone and one type of limestone. In China, the cement content of CSM may not exceed 6%, so ordinary Portland cement contents of 3.5%, 4.0%, and 4.5% were selected for the CSM of sandstone. Limestone with 4.0% cement content was chosen to analyse the difference between the sandstones and traditional aggregate materials.

Table 3. The cement content.

Aggregate Type	Code Number	Cement Content
Sandstone A	A1	3.5%
	A2	4.0%
	A3	4.5%
Sandstone B	B1	3.5%
	B2	4.0%
	B3	4.5%
Sandstone C	C1	3.5%
	C2	4.0%
	C3	4.5%
Limestone	D	4.0%

2.2.3. Unconfined Compressive Strength

According to the JTG E51-2009 [24], the SCSM and CSM mixtures were processed into standard test specimens of Φ150 mm × 150 mm by a compressor with a 98% degree of compaction and cured for 7 days, 28 days, 60 days, 90 days and 180 days under standard conditions (20 ± 2 °C and 90 ± 5% relative humidity (RH)). First, the specimens were placed on the pressure machine, and a flat ball base was placed on the lift platform. Then, the specimens were tested at an invariable loading velocity of 1 mm/min. The results are the average values of the three repetitive specimens from each specific combination.

2.2.4. Indirect Tensile Strength

Brazilian splitting tests were conducted in accordance with ASTM C496/C496 M-11 [25]. Concrete specimens were cast into Φ100 mm × 100 mm cylindrical mould for the Brazilian splitting tests and cured for 7 days, 28 days, 60 days, 90 days and 180 days under standard conditions. The concrete specimens were tested by applying force along the longitudinal axis of the cylinder utilizing an alignment fixture at a constant rate of loading of 0.5 k N/s, as shown in Figure 2. The maximum tensile force at the time of failure of the test piece is obtained, and the ITS can be calculated as follows:

$$R_i = \frac{2P}{\pi dh}\left(\sin 2\alpha - \frac{a}{d}\right) \tag{1}$$

where P is the maximum tensile force, d refers to the specimen diameter, h is the height of the test piece, a denotes the width of the batten, and α is the corresponding centre angle on the half width of the lath.

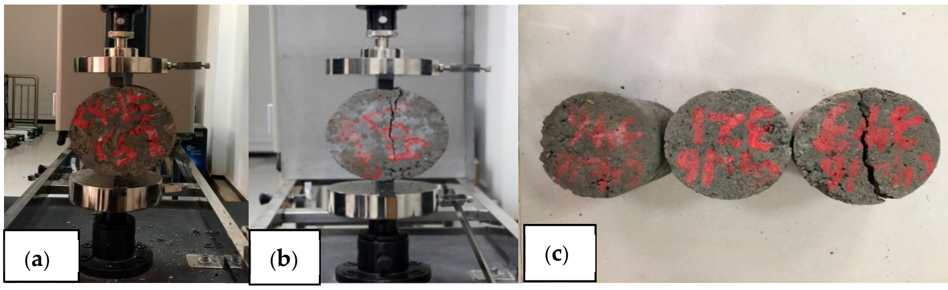


Figure 2. Indirect tensile strength test: (**a**). installation; (**b**). continuous loading; (**c**). damage.

The water stability is one of the factors considered in the study of the pavement material properties. The softening coefficient is an important indicator for characterizing a CSM. This coefficient reflects the ability of a mixture to resist water damage and has distinct influence on materials with high water absorption and porosity levels. Considering the high water absorption and porosity of the sandstone, the test pieces of each curing age were subjected to water immersion treatments, and the test pieces in the saturated and dry states were tested according to the above experimental methods. Then, the softening coefficient was calculated according to Formula (2):

$$K_p = \frac{R_w}{R_d} \tag{2}$$

where R_w refers to the ITS of a water-saturated specimen and R_d denotes the ITS of a dry specimen.

2.2.5. Freezing and Thawing

Freeze-thaw stability testing was based on JTG E51-2009 and the weight loss of the test specimens was conducted by an automatic freeze-thaw machinery. The freezing and thawing cycle experiments were carried out after the cylindrical specimens were cured for 7, 28, 60, 90, and 180 days under the specific curing conditions (20 ± 2 °C and 90 ± 5% RH). The cylindrical test-pieces were frozen at minus 20 degrees Celsius and thawed in water at 20 degrees Celsius. The freeze-thaw cycle experiments were set to 5 cycles. Usually, the ratio of the compressive strengths before and after freezing and thawing cycles is used to assessed the anti-frost property of blends, namely,

$$BDR_1 = \frac{R_{DC1}}{R_{C1}} \times 100\% \tag{3}$$

where BDR_1 represents the compressive strength loss of the specimen after freeze-thaw cycles, R_{DC1} refers to the compressive strength after freeze-thaw cycles, and R_{C1} denotes the compressive strength before freeze-thaw cycles.

In addition, the residual tensile strength ratio after a freeze-thaw cycle is used as a supplementary index. The supplementary anti-freeze index (BDR_2) can be calculated as follows:

$$BDR_2 = \frac{R_{DC2}}{R_{C2}} \times 100\% \tag{4}$$

where BDR_2 represents the ITS loss of the specimen after a freeze-thaw cycles, R_{DC2} refers to the ITS after freeze-thaw cycles, and R_{C2} denotes the ITS before freeze-thaw cycles.

3. Test Results

The following shows a series of tests results on the UCS and ITS under water-saturated and dry conditions and after freeze-thaw cycles. The results are summarized and presented in Table 4.

3.1. Unconfined Compressive Strength

The UCS is normally considered to be a major indicator for evaluating the quality of the CSM mixture. Many mixed variables affect the UCS, such as the type of aggregate, the cement content, and the curing time. The UCSs of the various mixtures are shown in Table 4 for the ages of 7, 28, 60, 90 and 180 days, and the experimental data presented are the averages of three specimens for each set of mixtures. It may be observed by comparing the experimental values of the three types of sandstone mixtures that the sandstone type has little effect on the strength. As mentioned earlier, there are few differences between the chemical compositions of the sandstones from the three producing areas. Therefore, only the data of sandstone A are used in the following analysis and comparison.

3.1.1. Influence of Cement Content

It is widely known that the cement used in CSM can effectively improve the adhesion level and mechanical properties of the mixtures. The effect of cement content on the UCS is displayed in Figure 3. The overall trend is a rise in the UCS value of the SCSM as the cement content increases, which is because the enhanced effect of cement on the strength of the material and the bonding force between the particles is enhanced by the increase in hydrated products as expected [26]. In addition, based on the slope of the curve, it can be seen that at the same age, the increase rate of the UCS is very low when the cement content adds from 3.5 to 4.0%, but the growth rate becomes significantly higher as the cement content increases from 4.0 to 4.5%. For instance, when the cement content increases from 3.5 to 4.0% at 60 days of curing, the strength of the SCSM rises by approximately 0.07 MPa, and the increase from 4.0 to 4.5% results in an approximate 0.6 MPa rise. However, the experimental results of Farhan et al. [26] show that the development rate of the UCS of a traditional CSM is almost proportional to the cement content. The reason for the above difference may be the large porosity of the sandstone. On the other hand, the strength of the SCSM with the highest cement content in the research range is still lower than those of the source rocks, which indicates that the main reason for the failure of the test piece may not the devastation of the aggregate. Usually, the initial micro-cracks of an aggregate concrete appear in the interfacial transition zone [27]. Therefore, the failure of the CSM may be caused by the low degree of bonding between the aggregate and mortar.

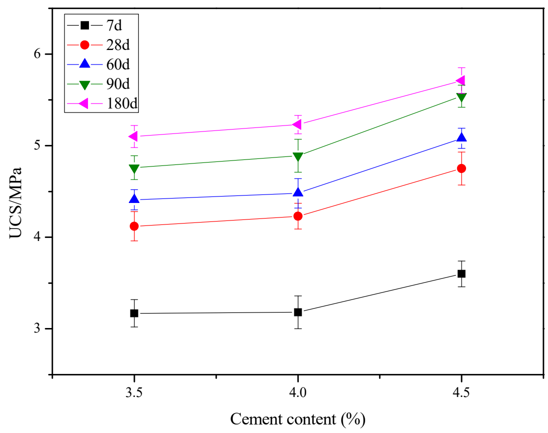


Figure 3. Relationship between the UCS and cement content.

Table 4. The experimental results of the unconfined compressive strength, indirect tensile strength.

Serial Number	UCS (MPa)										ITS (MPa)														
	Free From F-T					After 5 F-T Cycles					Dry State					Water-Saturated State					After 5 F-T Cycles				
	7 d	**28 d**	**60 d**	**90 d**	**180 d**	**7 d**	**28 d**	**60 d**	**90 d**	**180 d**	**7 d**	**28 d**	**60 d**	**90 d**	**180 d**	**7 d**	**28 d**	**60 d**	**90 d**	**180 d**	**7 d**	**28 d**	**60 d**	**90 d**	**180 d**
A1	3.17	4.12	4.41	4.76	5.10	2.79	3.63	4.03	4.34	4.59	0.32	0.42	0.43	0.46	0.48	0.26	0.35	0.37	0.40	0.42	0.25	0.31	0.34	0.37	0.39
A2	3.18	4.23	4.48	4.89	5.23	2.89	3.81	4.12	4.54	4.76	0.35	0.43	0.49	0.53	0.55	0.29	0.37	0.44	0.47	0.49	0.28	0.35	0.40	0.44	0.47
A3	3.60	4.75	5.08	5.54	5.71	3.35	4.42	4.78	5.26	5.31	0.39	0.47	0.54	0.57	0.60	0.34	0.41	0.49	0.52	0.55	0.32	0.39	0.45	0.47	0.51
B1	3.52	4.58	4.90	5.29	5.66	3.38	4.09	4.48	4.87	5.01	0.37	0.47	0.51	0.55	0.56	0.26	0.35	0.37	0.40	0.42	0.24	0.33	0.36	0.37	0.40
B2	3.61	4.80	5.09	5.55	5.94	3.47	4.09	4.47	5.19	5.40	0.39	0.49	0.57	0.60	0.63	0.29	0.37	0.44	0.47	0.49	0.27	0.35	0.40	0.44	0.46
B3	3.91	5.16	5.52	6.02	6.20	3.44	4.39	4.76	5.10	5.25	0.44	0.52	0.59	0.63	0.65	0.34	0.41	0.49	0.52	0.55	0.32	0.38	0.45	0.47	0.53
C1	3.44	4.47	4.79	5.17	5.53	3.28	4.01	4.39	4.78	4.90	0.36	0.47	0.50	0.54	0.56	0.29	0.38	0.43	0.47	0.49	0.27	0.37	0.42	0.44	0.47
C2	3.50	4.66	4.93	5.38	5.75	3.09	3.95	4.38	5.04	5.33	0.35	0.48	0.56	0.59	0.61	0.29	0.42	0.51	0.53	0.55	0.27	0.39	0.46	0.50	0.52
C3	3.88	5.12	5.48	5.97	6.15	3.44	4.36	4.77	5.08	5.32	0.45	0.52	0.59	0.63	0.64	0.38	0.45	0.54	0.57	0.59	0.36	0.41	0.51	0.53	0.57
D	5.18	7.25	8.12	8.53	9.13	4.92	6.82	7.72	8.10	8.58	0.63	0.85	0.99	1.07	1.12	0.55	0.77	0.93	1.01	1.05	0.53	0.72	0.89	0.97	1.01

3.1.2. Influence of the Aggregate Type

It is well known that the UCS of CSM is closely related to the aggregate strength in the mixture. Mixtures of sandstone A and limestone with a cement content of 4.0% were tested. It can be observed from Figure 4 that the compressive strength of the SCSM mixture is lower than the compressive strength of the CSM mixture for the same curing period. The UCS of the limestone sample is approximately twice that of the sandstone sample; correspondingly, the compressive strength of the limestone parent rock is 2.0 times that of the sandstone A parent rock. This finding means that the characteristics of the parent rock, including its chemical composition and physical mechanics, are significant factors influencing the UCS of the CSM with this rock as the aggregate. Meanwhile, the strength of the SCSM is lower than that of the CSM, which may be because the dust attached to the surface of the sandstone weakens its bond with the cement slurry.

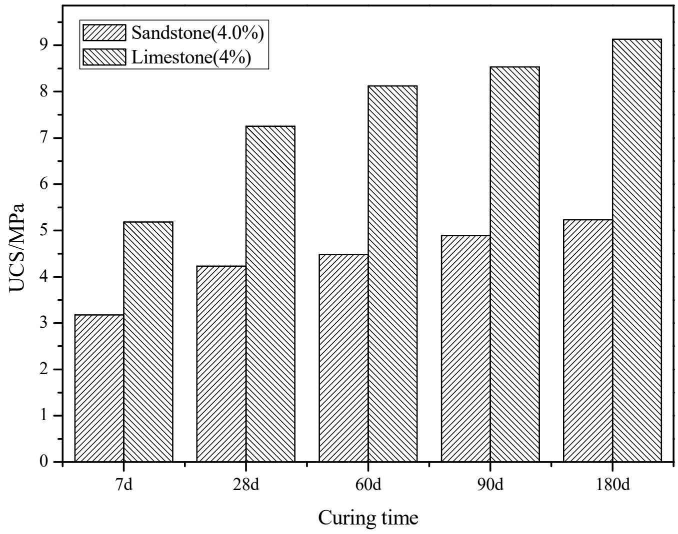


Figure 4. Relationship between the UCS and aggregate type.

3.1.3. Influence of Curing Time

In addition, a significant factor influencing the UCS of CSM is the curing period of specimens. Numerous studies have reported the curing time's influence on the UCS. The UCS development with the curing time is shown in Figure 5. It is observed from this figure that the effects of the curing period on the strengths of the SCSM blend and the CSM blend are similar in the case of the identical cement content. The longer the curing time, the greater the strength. Du carried out the same performance test on CSM with asphalt emulsion, and the growth trend of strength was similar to the test results in this paper with the increase of curing age [28]. The reason for this phenomenon is that the hydration reaction is the time-dependent action. The developing velocity of the UCS is usually proportional to the cement content, which is since the more cement is added in the blends, the more products of hydration reaction [29] and the better the strength enhancement and bonding effects. As shown in Table 5, the compressive strength increases rapidly in the first 28 days, but the increase slows down at 60 days and 180 days. In particular, from 7 to 28 days, the strength of the SCSM increased by 30%, while from 28 to 60 days, the SCSM strength only increased by 7%. This result is because the cement granules without hydration reaction are surrounded by formed cement slurry, making it difficult for water to enter the surface of the un-hydrated cement particles. This phenomenon impedes the hydration of the cement granules, thus leading to a slower increase in the UCS at late period. According to JTG D50-2017 [30], the UCS of CSM mixture bases used in medium or light traffic roads at an age of 7 days should be between 3.0 and 5.0 MPa. From the experimental results, the UCS of the 7-day SCSM successfully met the requirements.

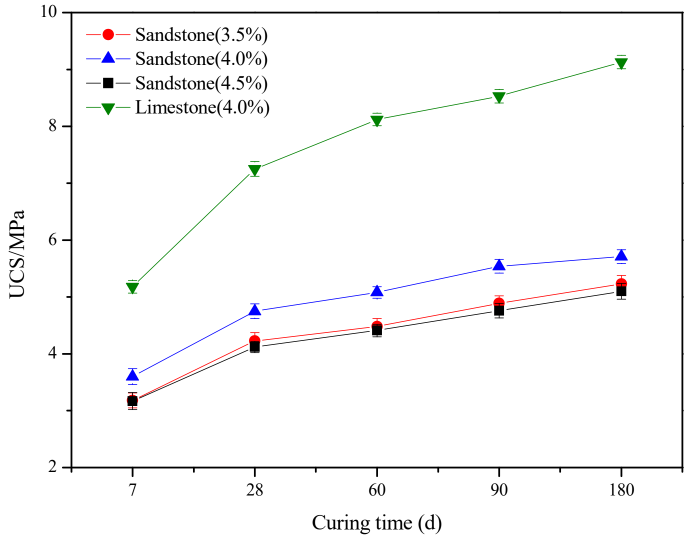


Figure 5. Relationship between the UCS and curing time.

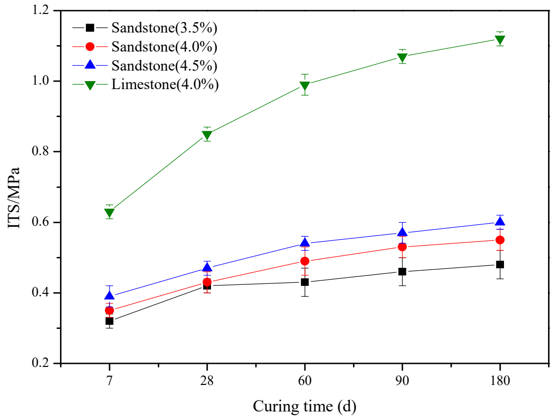
Table 5. The growth rate (%) of UCS at different ages.

Code	7 d	28 d (Based on 7 d)	60 d (Based on 28 d)	90 d (Based on 60 d)	180 d (Based on 90 d)
A1	-	30%	7%	8%	7%
A2	-	33%	6%	9%	7%
A3	-	32%	7%	9%	3%
D	-	40%	12%	5%	7%

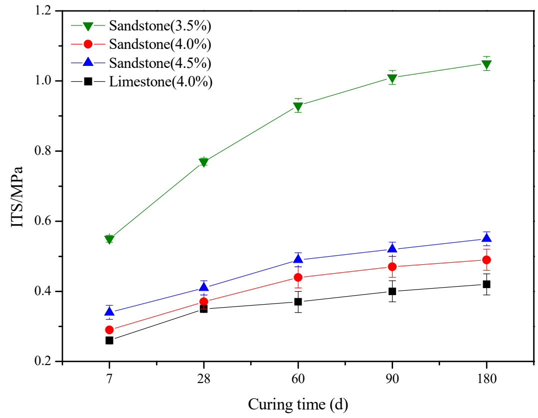
3.2. Indirect Tensile Strength

3.2.1. Crack Resistance

The tensile strength of the mixture was determined by the ITS test at the time of failure to evaluate the ability of the CSM to resist cracking [31]. Table 4 shows the ITS values of the SCSM with different cement contents and CSM with cement content of 4% at ages of 7, 28, 60, 90 and 180 days in water-saturated and dry situations. It was observed from Figure 6 that the values of ITS increased proportionately with the increase in the amount of cement and the curing time, whether under dry or water-saturated conditions. In fact, the mechanisms of the effects of cement content and curing age on the ITS are similar to those of the UCS. In addition, it can be observed in Figure 7 that the CSM exhibited much higher ITS than the SCSM for the same cement content at 7, 28, 60, 90 and 180 days. The reason for this phenomenon is most likely because the crushing value of the sandstone parent rock is significantly higher than that of the limestone, which can be seen in Section 2.1.2. Different from the UCS, the ITS is mainly affected by the interfacial bonding in the CSM between the cement mixture and lightweight aggregate particles [32]. This phenomenon may also be due to the high clay content of the sandstone, which is present in the form of fine aggregates or encased on the surface of the mixture, thereby significantly delaying the hydration of the Portland cement. This not only weakens the cohesion between the aggregate and the cement but also affects the ITS of the CSM. According to JTG D50-2017, the ITS of the CSM mixture base should be between 0.4 and 0.6 MPa at 90 days of age. It can be observed from the test results that if sandstone is used instead of a natural aggregate, the ITS values are higher than the criterion for cement stabilized base materials of the standard.



(**a**)



(**b**)

Figure 6. Relationship between the ITS and curing time. (**a**) Dry state (**b**) Water-saturated stat.

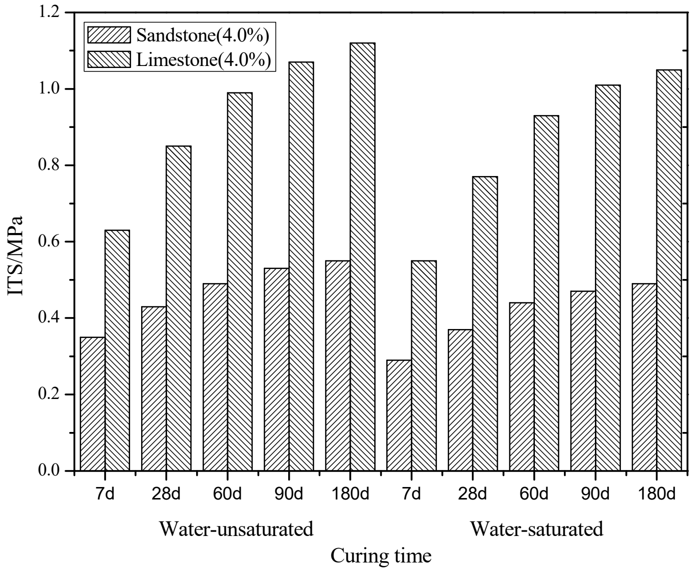


Figure 7. Relationship between the ITS and aggregate type.

3.2.2. Water Stability

Sandstone, a type of sedimentary rock, is usually affected by water action, so ITS tests were conducted in both dry and saturated states. The calculated softening coefficients are summarized in Table 6. It can be seen from the table that the softening coefficient is less than 1, which means that the water saturation has a weakening effect on the splitting tensile strengths of the SCSM and CSM. Apparently, for the same cement content, the softening coefficient of the CSM is higher than that of the SCSM. For example, the CSM value is 5% higher than the SCSM value at a curing age of 7 days. This result may be related to their different water absorption rates and porosities, as mentioned above. Meanwhile, as the curing age increased, the softening coefficient is gradually increased at a decreasing rate. With the curing age ranging from 7 to 60 days, the softening coefficients of the SCSM and CSM increased by 5% and 6%, respectively, while the coefficients were almost unchanged from 60 to 180 days. This finding might be mainly due to the increase in the curing age, which caused the transformation of the hydration products into a hydrophobic gel [33]. In addition, it is clear that the softening coefficient of the SCSM increases with the increase in the amount of cement. It is well known that the water resistance of a material is tightly related to the pore structure of the material and the method of adhesion between the particles. Therefore, effectively reducing the porosity of the sandstone is an important means to improve the performance of CSM with sandstone as the aggregate.

Table 6. The softening coefficient at different ages.

Code	7 d	28 d	60 d	90 d	180 d
A1	0.80	0.82	0.85	0.87	0.87
A2	0.83	0.86	0.90	0.89	0.90
A3	0.85	0.88	0.91	0.91	0.92
D	0.88	0.90	0.94	0.94	0.94

3.2.3. Relationship between the UCS and ITS

The fitting curve of the UCS and ITS values for SCSM and CSM blends in different curing periods is shown in Figure 8, from which it can be inferred that the ITS value is about 10% of the UCS value, which is suitable for total examined blends at different ages. The phenomenon represents there is a unique connection between the UCS and ITS, regardless of the composition of the mixture (aggregate type, cement content and curing age). In general, the tensile strength of ordinary concrete is 1/10 to 1/20 of its compressive strength. In the study of [34], for different natural aggregate mixtures with the disparate amount of cement, the results indicated that there was a linear relation, namely, UCS $=9.8 \times$ ITS. Thus, the current test results have been proven to be reasonable.

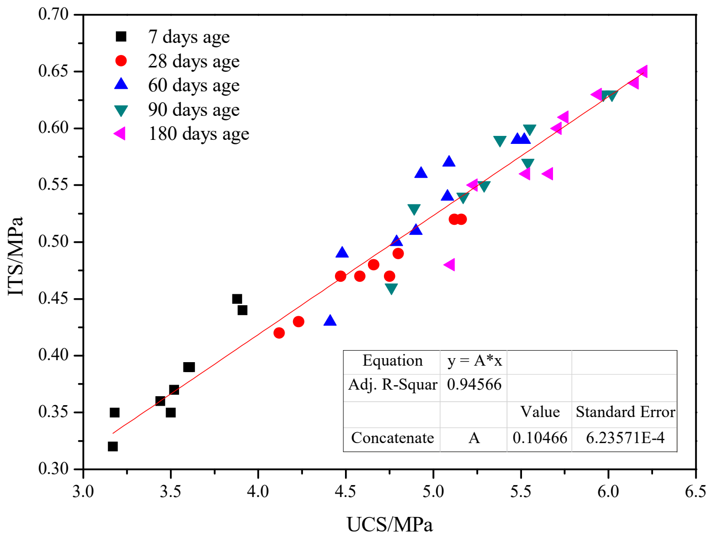


Figure 8. Relationship between the UCS and ITS.

3.3. Frost Resistance

In northern Shaanxi, the climate is characterized by cold and long winters. After repeated freeze-thaw cycles during the winter and early spring thawing, the semi-rigid base layer is susceptible to freeze-thaw failure, resulting in melt settling and frost heave. The frost heaving action of the pore water in the semi-rigid base material damages the cementing action between the particles, which is the cause of the instability of the mixture caused by freeze-thaw action. As a type of sedimentary rock, sandstone has lower mechanical properties and higher water absorption and porosity levels than those of limestone. Therefore, the frosting process (freeze-thaw cycles) that can destroy CSM is a significant problem. The anti-frost property of the material is characterized by BDR_1 and BDR_2 to determine the amplitude range of the mechanical properties of the cement stabilized substrate in cold weather conditions. The results of the different frost resistance indexes before and after freezing and thawing cycles are summarized in Figures 9 and 10. All frost resistance indexes are lower than 100%, which indicates that the freezing and thawing effect can cause the attenuation of strength. During the frosting process, the pore water of the mixture gradually freezes in the capillary chamber, creating a water pressure as frozen water bulk increases. As shown in Figure 9, the lower the cement incorporation is, the greater the intensity attenuation of the SCSM. For instance, when the cement content is 4.5%, both the UCS and ITS are attenuated by approximately 5%. However, the attenuation amplitude approaches 11% with a cement content of 3.5%. The reason for the faster deterioration of the mechanical properties of the mixture at a lower cement dosage is the cementation is the main factor of the adhesive property of the mixture. In the study of the antifreeze properties of other types of CSM bases, the experimental results showed that the cement content is an important factor affecting the antifreeze performance similarly [35,36]. Therefore, to increase the frost resistance of the SCSM mixture, increasing the cement content appropriately is an effective method. In addition, Figure 10 shows that the attenuation of the SCSM is significantly higher than that of the CSM. Compared with porous cement stabilized macadam, the strength loss of SCSM after freeze-thaw cycles is relatively smaller, which confirms the frost resistance is affected by the porosity of the material, its internal moisture and the environmental conditions. Therefore, the poor freezing resistance of the SCSM mixture is due to its high porosity and water absorption level.

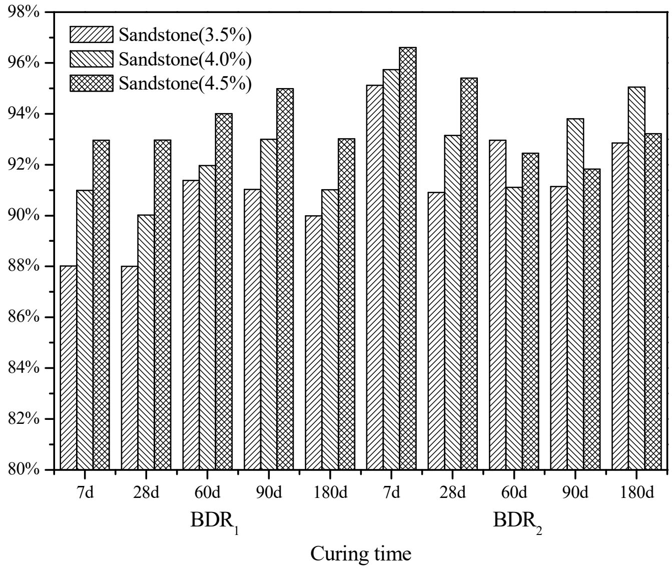


Figure 9. Relationship between the BDR and cement content.

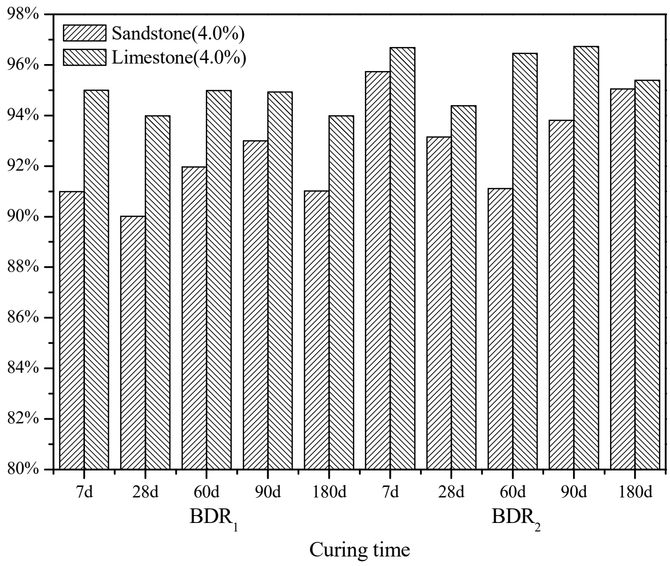


Figure 10. Relationship between the BDR and aggregate type.

4. Conclusions

In this paper, sandstone is utilized as a coarse aggregate for CSM, and the mechanical properties and influential elements of the SCSM and CSM are evaluated by laboratory tests. The results lead to the following conclusions:

1. The results show that the cement content and curing age are factors affecting the ITS and UCS. The mechanical properties of the SCSM blend increase with the cement dosage and curing period, similar to the CSM mixture.
2. The strength of the SCSM blend is significantly lower than the strength of the CSM blend. The cause of this phenomenon may be the differences in the properties of the parent rock, including the porosity, crushing value and compressive strength. It may also be due to the weak bonding at the interface between the sandstone and cement.
3. Both the UCS and ITS of the SCSM and CSM blends are affected by frost action. However, the strength degradation amplitude of the SCSM blend caused by freeze-thaw effect is larger than that of the CSM blend. The degradation amplitude increased with increasing cement content, and the curing age has little effect on the amplitude.
4. The properties of the SCSM, including the UCS, ITS, softening coefficient and frost resistance coefficient, meet the requirements of low-grade roads.

In view of the above conclusions, sandstone can be used for road base construction. Furthermore, applying sandstone to the actual construction of on-site resource utilization will bring suitable economic and environmental benefits.

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