THE FEASIBILITY OF CEMENT-CURING AGENT STABILIZED MATERIALS FOR INDUSTRIAL CONSTRUCTION SOLID WASTES IN TERMS OF MECHANICAL PROPERTIES AND MICROSTRUCTURE

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ABSTRACT

This article discusses the utilization of industrial construction waste for resource recycling and disposal. It focuses on researching a new water-resistant, self-healing soil curing technology called "road liquid," which is a fly ash-based soil curing agent. This technology is used for the curing of industrial construction waste disposal methods. For the first time, the soil curing agent is mixed into the construction waste along with cement stabilization. Different amounts of mixing are used as controls to evaluate the performance of the curing material after the construction waste is cured. The study focused on the material properties of cured construction waste, specifically examining strength, water resistance, and self-healing properties. The study showed that the curing agent "road liquid" enhanced the strength, water resistance, and self-healing properties of the cured construction waste at various cement dosages. The 7-day unconfined compressive strength of recycled aggregates with a 5% cement dosage, added with the curing agent "road liquid," was higher than that of recycled aggregates with a 6% cement dosage without the curing agent "road liquid." The experimental results show that using this type of granular solid waste as pavement base material is more practical for engineering purposes. The curing agent "road liquid" can enhance the curing effect of recycled aggregate, thereby reducing the need for cementitious materials and achieving cost savings for the project.

KEYWORDS

Construction waste; Soil stabilizer; Unconfined compressive strength; Road base

INTRODUCTION

As a result of accelerated urbanization and industrial restructuring, large-scale industrial site buildings are gradually becoming derelict, posing serious challenges to the environment and society. The disposal of these abandoned industrial buildings, which often contain complex structures and diverse materials, involves various aspects such as environmental protection,

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resource recovery, and urban regeneration. Disposal of the huge volume of solid waste from industrial buildings generated by redevelopment and demolition has become a major challenge to the government's "carbon emission reduction" efforts. In the past, solid wastes from industrial building sites were mostly disposed of in landfills using end-of-pipe methods, which not only caused a large amount of wasted space and increased secondary pollution of the urban environment but also affected the safe use of the surrounding buildings to a certain extent. Therefore, how to deal with these large amounts of solid waste has become the focus of the building community [1].

Currently, the low-carbon disposal of solid waste materials in the landscape creation for industrial building sites is considered a key method for balancing the relationship between urban construction and ecology in the economic development of industrial cities. The low-carbon development and recycling of solid waste have garnered significant attention from both government and industry. It has been reported that the recycling utilization rate of construction solid waste in some developed countries has exceeded 90%, while in China, it stands at a mere 5%, significantly lower than countries like Korea, Japan, and Germany. Numerous scholars have conducted feasibility studies on utilizing treated waste materials as road subgrade [2] [3]. However, the regeneration of industrial construction solid waste materials reveals that the main components are bricks and concrete, recycled brick slag, and concrete aggregates, which exhibit lower performance compared to natural aggregates [4]. These materials also suffer from structural damage, low early strength due to single use of cement curing stabilization, poor water stability, and limited self-repair ability. Moreover, a higher proportion of recycled concrete aggregate negatively impacts mechanical properties and fatigue characteristics, hindering their application in engineering practice [5]. These various factors contribute to the low utilization of industrial construction solid waste. The use of curing agents can alter the nature of recycled aggregate, enhancing the strength and compaction of solid waste materials [6]. For instance, the NS-SL type soil curing agent improves water stability performance when curing soil, thereby enhancing road performance [7]. Some scholars have discovered that by incorporating alkaline exciters and slag, the mechanical properties of cement-stabilized recycled aggregate mixes can surpass those of natural aggregate mixes [8].

Research and development of low-carbon geopolymer technology, which employs water-resistant self-healing materials, primarily focuses on roadbed and soil treatment [9] [10]. However, there is a significant lack of applications for this technology in the context of industrial construction solid waste. This study introduces a novel approach where a soil curing agent is blended into the construction solid waste and cement stabilization. Various dosages are used as controls to investigate the material properties of the cured construction waste, including strength, water resistance, and self-repairing capabilities. The aim is to analyze the impact of the curing agent on the construction waste and determine the most effective way to incorporate the curing agent for the regeneration of industrial construction solid waste applications, providing essential theoretical support.

1. EXPERIMENTAL PROGRAM AND METHODOLOGY, BASIC MATERIALS

1.1 Test material and maximum dry density and optimum moisture content test

The cement used is P-C 42.5 composite silicate cement produced by Huaxin Cement (Zhuzhou) Co. under the Huaxin Fortress brand. This cement meets the specification requirements for the construction of highway pavement at the grassroots level, as outlined in JTJ/T F20-2015 [11].

Recycled aggregates are granular construction solid wastes formed by demolition, sorting, crushing, and sieving of industrial building sites in the Qingshuitang area of Zhuzhou. The main component of concrete accounts for about 70% (by mass), while bricks account for about 30%. Gravel, metal, wood, and glass make up about 0.1%. After drying, the aggregates are sieved using standard sieves of 31.5, 19, 9.5, 4.75, 2.36, 0.6, and 0.075mm. They are then divided into 7 grades based on particle size and stored in sealed bags. According to the "Aggregate Testing Procedure for Highway Engineering" (JTG E42-2005), the basic performance of coarse aggregates larger than 4.75mm and fine aggregates smaller than 4.75mm were tested separately. The basic performance of the recycled aggregate met the requirements of the JTJ/T F20-2015 specification [11] [12]. Specific performance details are provided in Table 1 and Table 2.

The main property indexes of recycled coarse aggregate, such as needle flake content and water absorption, meet the standard road performance criteria. The crushing value of the sub-secondary and secondary road base is up to 35%. The crushing value of the recycled aggregate is 32.1%, exceeding the maximum crushing value of 26% for highways and primary roads, and the maximum crushing value of 30% for the sub-base level as specified in the of Highway Pavement Subgrade JTJ/T F20-2015. This complies with the requirement that the crushing value of subsecondary and lower-grade highways is less than 35%. The plasticity index of recycled fine aggregate meets the requirement of not exceeding 17 [11].

New water-resistant, self-repairing polymer is a strong base material with a water-resistant self-repairing strong base curing agent, also known as SRR-type curing agent. It is a brown liquid at room temperature, easy to dilute with water, non-flammable, non-volatile, non-toxic, non-corrosive, and structurally stable. Curing can be formed after the creation of a homogeneous molecular network structure. The use of this material involves the addition of polyol compounds and the role of strong charge ions. It utilizes rich hydrogen bonding to weaken water absorption within the particles, achieving water-resistant functionality. By incorporating the Diels-Alder diene addition reaction active groups with self-healing properties into the molecular chain structure of the aqueous polymer, and by introducing a large number of microcapsules rich in active substances into the material, a self-healing mechanism is realized. This mechanism involves the microcapsules breaking and responding to stress cracking in the hardened solid waste particles. This technology is crucial for achieving self-repair after microdamage of road subgrade. The basic physical properties of this material are outlined in Table 3.

TABLE 1. Basic properties of recycled coarse aggregate.

Apparent density/g·cm^{-3}	Crushing value/%	Needle-flake particle content/%	Water absorption rate/%
2.601	32.1	7.2	7.82

TABLE 2. Basic properties of recycled fine aggregate.

Apparent density/g·cm^{-3}	Water absorption rate/%	liquid limit	plastic limit	Plasticity index
2.335	11.13	27.8	20.6	7.2

TABLE 3. Basic Physical Property Indicators of Pipeline Fluid.

densities/ g·cm^{-3}	pH	Water-soluble /%	volatilization rate/%	boiling points/°C	condensation point/°C
1.05–1.10	7–8	100	<1	>100	<0

1.2 Gradation

The grading of recycled aggregate materials for construction and demolition waste should adhere to the recommended cement-stabilized grading of crushed stone or gravel as outlined in Table 6.1.6-2 of the "Highway Asphalt Pavement Design Specification" (JTG D50-2017) [13]. The recommended grading for the compacted skeleton dense grading range can be found in Table 4.

1.3 Optimum water content and maximum dry density

According to the grading of recycled aggregate materials for building solid waste, the compaction test method for inorganic stabilizing materials in highway engineering, as specified in the "Test Code for Stabilizing Materials of Inorganic Binders in Highway Engineering" (JTG E51—2009) T 0804—1994, should be followed. The third method is used to determine the optimal moisture content and maximum dry density of the stabilized recycled aggregate mixture with cement due to the particle size exceeding 19 mm [14].

In engineering practice, the cement dosage for stabilizing gravel at the grassroots level generally ranges from 3% to 7%. The dosage of the curing agent "road liquid" is typically 300 ml/m^3. In the design of this study, cement dosages of 3%, 4%, 5%, 6%, and 7% were considered, along with curing agent dosages of 0 ml/m^3 and 300 ml/m^3 for the control experiment. The study aimed to investigate the impact of different cement and curing agent dosages on the optimal moisture content and maximum dry density of recycled aggregates from industrial building solid waste. The relationship between these factors is presented in Table 5.

The experimental results show that: (1) the maximum dry density and optimum water content of recycled aggregate, with or without the addition of the curing agent "road liquid," increase with the increase of cement content. (2) Under the same cement content, the maximum dry density of recycled aggregate increases with the addition of curing agent "road liquid," and the optimum water content decreases with the addition of curing agent "road liquid." The curing agent "road liquid" utilizes a polymerization reaction to alter the loose physical structure of the regenerated aggregate, forming polymer molecules that adsorb and fill the fine aggregate, enhancing the mechanical properties and solidity of the regenerated aggregate. Based on the hydrogel connection and cementation connection characteristics of the regenerated aggregate,

TABLE 4. Grading of recycled aggregate materials for construction solid waste.

Percentage of mass (%) passing through the following square hole sieve (mm)							
Sieve hole size	31.5	19	9.5	4.75	2.36	0.6	0.075
basement layer	100	68~86	38~58	22~32	16~28	8~15	0~3
median grade	100	77	48	27	22	11.5	1.5

TABLE 5. Compaction test results.

Cement Admixture %	Dosage of curing agent "road liquid" ml/m^3	Optimum moisture content %	Maximum dry density g/cm^3	
3%	0ml/m^3	10.36	1.8931	Recycled Brick Mix Aggregate Grading: 4.75:9.5:31.5 = 27:21:52
4%	0ml/m^3	10.44	1.9146	
5%	0ml/m^3	10.53	1.9353	
6%	0ml/m^3	10.61	1.9517	
7%	0ml/m^3	10.69	1.9659	
3%	300ml/m^3	9.84	1.9531	
4%	300ml/m^3	9.9	1.9585	
5%	300ml/m^3	10.03	1.9662	
6%	300ml/m^3	10.18	1.9744	
7%	300ml/m^3	10.26	1.9807	

the connection extends to the point of crystal formation, obstructing the entry of free water to achieve the goal of preventing water entry. By blocking the entry of free water, the curing agent "road liquid" enhances water resistance, thereby optimizing water content reduction.

1.4 Specimen Preparation

The test specimen is prepared according to the test method T 0805-1994 in the "Test Regulations for Inorganic Binder Stabilized Materials in Highway Engineering" (JTG E51 2009) [14]. According to the results of the compaction test and regenerated aggregate grading to calculate the amount of water added to each part of the material and the mass of regenerated aggregate will be weighed regenerated aggregate and water together with the mix (reserved 1–2% of water), mixing and then put into an airtight container moistening standby. After 4 hours of infiltration, different dosages of cement are added for mixing. During the mixing process, the reserved water is added to adjust the recycled aggregate to the optimal water content. The mixture is thoroughly mixed within 1 hour [15]. Φ 150mm*150mm cylindrical standard specimens are made by vibration compaction, demolded after 2–6 hours, weighed, and the height of the specimen is measured.

1.5 Test Methods

1.5.1 Strength test

Strength tests include unconfined compressive strength tests and split strength tests. Thirteen specimens were prepared in each group. The cement dosages of 3%, 4%, 5%, 6%, 7%, and the dosage of the curing agent "road liquid" of 0 ml/m^3 and 300 ml/m^3 were used as control experiments. The specimens were placed in a standard curing room (Temperature 20 °C ± 2 °C, relative humidity > 95%). On the final day of the curing period, the specimens were removed, soaked in water for one day and one night, and then subjected to the strength test [15]. Outliers were eliminated using the 3-fold mean square deviation method during result analysis. If the number of outliers exceeded 2–3 tests, they were redone.

1.5.2 Water stability test

Twelve specimens were prepared for each group, with six specimens cured for 7 days under standard conditions (temperature of 20 ± 2 °C, relative humidity > 95%). On the final day of curing, these specimens were immersed in water at 20 ± 2 °C. The remaining six specimens were maintained under the same standard conditions until the same age, but without immersion in water on the last day. The unconfined compressive strength test was conducted on the cured specimens individually, and the water stability coefficient was calculated using Equation 1.1.

$$WSC = \frac{R_d^1}{R_d^0} * 100 \tag{1.1}$$

In the formula:

WSC—Water sability coefficient (%);

R_d^0—Unconfined compressive strength without water immersion (MPa);

R_d^1—Unconfined compressive strength with water immersion for 24h (MPa).

The material without the added curing agent is used as a reference specimen, while the material with the added curing agent is used as a test specimen. The water stability coefficient ratio is calculated by dividing the water stability coefficient of the test specimen by that of the reference specimen, as shown in Equation 1.2.

$$WSCR = \frac{wsc_1}{wsc_0} \tag{1.2}$$

In the formula:

$WSCR$—Water sability coefficient ratio;

WSC_0—Water stability coefficient of the reference specimen (%);

WSC_1—Water stability coefficient of test specimens (%).

1.5.3 Self-healing test

Twelve specimens were prepared in each group, and a standard age of 7 days was utilized. At the conclusion of the conditioning period, 6 specimens underwent a split strength test to determine the maximum load (Fd) and compressive strength (R_i^0). The remaining 6 specimens were loaded to 80% of the maximum load, unloaded, and then placed in the standard conditioning chamber for 15 days for the split strength test to calculate the split strength (R_i^1) and determine the self-repairing coefficient of stabilized materials using Equation 1.3.

$$SHC = \frac{R_i^1}{R_i^0} * 100 \tag{1.3}$$

In the formula:

SHC—Self-healing coefficient (%);
R_t^1—7-day splitting strength (MPa);
R_t^0—Splitting strength after 15 days of incubation (MPa).

The stabilized material without an added curing agent was used as the reference specimen, while the stabilized material with an added curing agent was used as the test specimen. The self-repair coefficient ratio was calculated by dividing the self-repair coefficient of the test specimen by the self-repair coefficient of the reference specimen, as shown in Equation 1.4.

$$SHCR = \frac{SHC_1}{SHC_0} \tag{1.4}$$

In the formula:

$SHCR$—Self-healing coefficient ratio;
SHC_0—Self-healing coefficient of reference specimens (%);
SHC_1—Self-healing coefficient of test specimens (%).

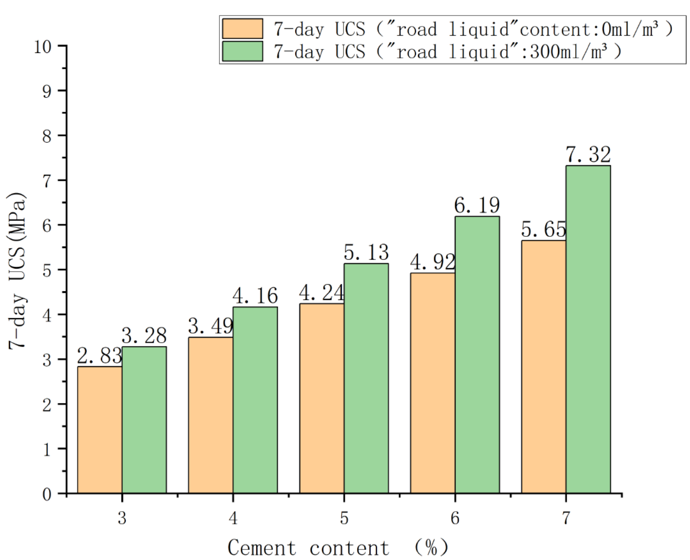
2. TEST RESULTS AND ANALYSIS

2.1 Strength properties

2.1.1 Unconfined compressive strength

A comparison of the 7-day unconfined compressive strength of recycled aggregates with varying cement dosages in the presence or absence of “road liquid” is illustrated in Figure 1.

FIGURE 1. 7-day unconfined compressive strength diagram of recycled aggregate with or without “road liquid.”

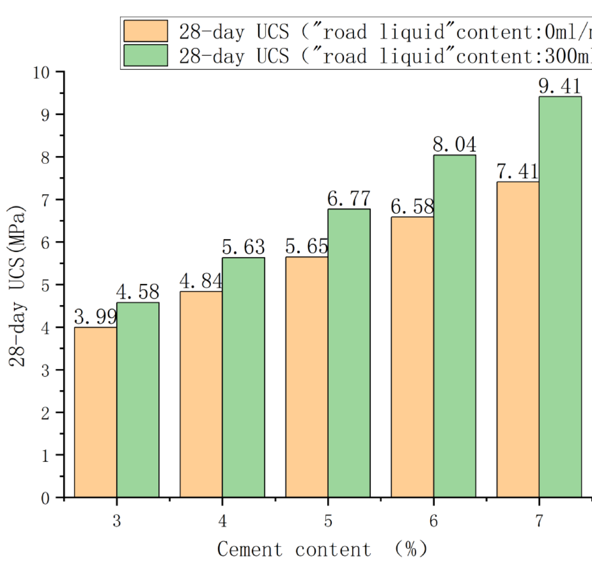


From Figure 1, it can be observed that the 7-day unconfined compressive strength of the recycled aggregate, without a curing agent, at cement dosages of 3%, 4%, 5%, 6%, and 7% were 2.83 MPa, 3.49 MPa, 4.16 MPa, 4.92 MPa, and 5.65 MPa, respectively. The compressive strength increased with the increase of cement dosage. The 7-day unconfined compressive strengths of "road liquid" recycled aggregate with cement dosage of 3%, 4%, 5%, 6%, and 7% were 3.28 MPa, 4.16 MPa, 5.13 MPa, 6.19 MPa, and 7.32 MPa, respectively, which were higher than those of "road liquid" recycled aggregates without curing agent. Compared with no curing agent, the compressive strength of "road liquid" recycled aggregate increased by 15.79%, 19.48%, 21.12%, 25.73%, and 29.62%. According to the Construction of Highway Pavement Grass-roots Level JTJ/T F20-2015 specification for heavy traffic in the second level and the grass-roots materials below the second level of the highway, 7-day unconfined compressive strength requirements are 3–5 MPa. A single cement-stabilized regenerated aggregate with a cement mixing amount of 3% without the addition of curing agent cannot meet the specifications but can meet the specification requirements after the addition of curing agent. It shows that the strength of recycled aggregate can be obviously increased by adding curing agent "road liquid" under the same cement dosage. The test results show that the 7-day unconfined compressive strength of recycled aggregate with 5% cement dosage and curing agent "road liquid" is slightly higher than the unconfined compressive strength of recycled aggregate with 6% cement dosage and no curing agent, indicating that the strength of recycled aggregate can be significantly increased by adding curing agent "road liquid" in engineering practice. This shows that in engineering practice, it is possible to reduce the dosage of cement by adding curing agent "road liquid, reducing the project cost.

At the same time, with the increase of cement dosage, the compressive strength of recycled aggregates with the addition of curing agent "road liquid" gradually increased, indicating that the curing agent "road liquid" can promote the curing effect of cement and recycled aggregates.

Figure 2 illustrates the 28-day unconfined compressive strength of recycled aggregates treated with various cement dosages, both with and without the curing agent the 28-day

FIGURE 2. 28-day unconfined compressive strength diagram of recycled aggregate with or without "road liquid."



unconfined compressive strength of recycled aggregates without the curing agent increased by 41.10%, 38.78%, 33.26%, 33.83%, and 31.21% compared to the 7-day unconfined compressive strength of recycled aggregates with the same cement dosage. On the other hand, the 28-day unconfined compressive strength of recycled aggregates with the addition of the curing agent “road liquid” increased by 39.73%, 35.19%, 31.90%, 29.97%, and 28.61%, respectively, in comparison to the 7-day unconfined compressive strength of recycled aggregates with the same cement dosage.

Experimental results show that during the maintenance period from 7 to 28 days, the addition of the curing agent “road liquid” recycled aggregate resulted in a lower increase in unconfined compressive strength compared to recycled aggregate without the curing agent. This indicates that the growth rate of unconfined compressive strength of recycled aggregate with the hardener “road liquid” initially increases rapidly, then slows down, with strength development primarily occurring in the early stages. This characteristic can fulfill the project requirements more promptly.

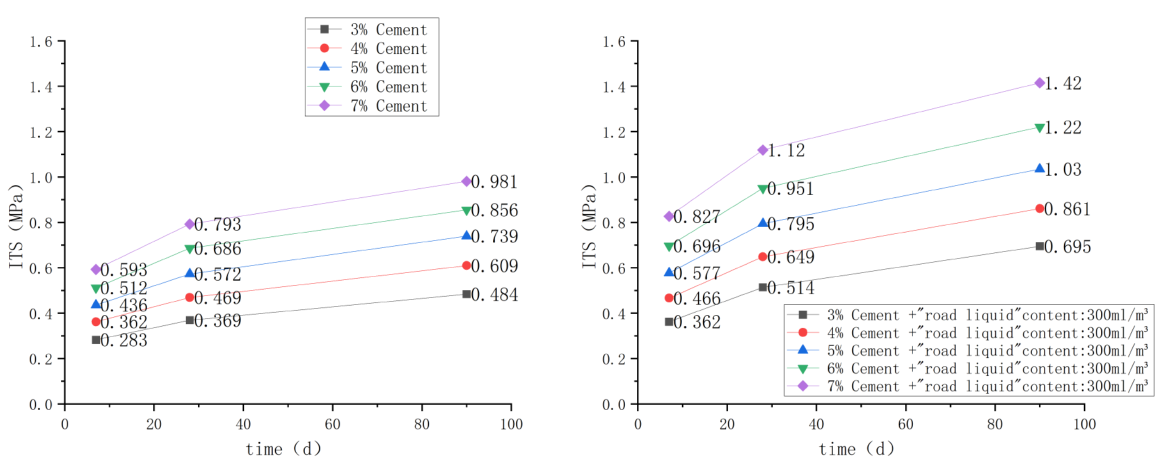
2.1.2 Splitting strength

The splitting strength of recycled aggregates with and without curing agent “road liquid” at different ages is shown in Figure 3

From Figure 3, it can be seen that the addition of the curing agent “road liquid” can improve the splitting strength of cement-stabilized recycled aggregates at all cement dosages. With the addition of the curing agent “road liquid, “ recycled aggregate in each cement dosage increased by 28.27%, 28.74%, 32.25%, 35.89%, and 39.49% compared to recycled aggregate without the curing agent the development trend aligns with that of unconfined compressive strength. As the cement dosage increases, the splitting strength of recycled aggregates with the curing agent, the increase in split strength surpasses the increase in the 7-day unconfined compressive strength of recycled aggregate, indicating that the curing agent “road liquid” can enhance the tensile properties of recycled aggregate.

The 90-day splitting strength of recycled aggregate without hardener “road liquid” and the 28-day splitting strength of recycled aggregate corresponding to the same cement dosage increased by 31.10%, 29.83%, 29.18%, 24.673%, and 23.75%, respectively. The 90-day

FIGURE 3. Comparison of splitting strength of recycled aggregates with and without “road fluid” at different ages



splitting strength of the recycled aggregate with the addition of the curing agent "road liquid" increased by 35.20%, 32.75%, 30.18%, 28.36%, and 26.43%, respectively, compared with the strength of the recycled aggregate with the same cement dosage corresponding to the same splitting strength at 28 days. It shows that the curing agent "road liquid" has a long-term enhancement effect on the curing of recycled aggregates. The addition of the curing agent "road liquid" can not only quickly meet the strength requirements but also maintain the strength needed later on.

2.2 Water stability

The table below shows the water absorption of recycled aggregates with and without "road liquid" for different cement dosages.

From Table 6, it can be observed that the water absorption rate of recycled aggregate gradually decreases with the increase in cement dosage. This trend suggests that a higher cement dosage can reduce the porosity of recycled aggregate, resulting in a decrease in the water absorption rate. Furthermore, the water absorption of recycled aggregate is further reduced after the addition of the curing agent "road liquid."

Separately, tests were conducted for different cement dosages of recycled aggregates, both with and without the addition of the curing agent as a control for the water stability test. The results of these tests are presented in Table 7.

The table illustrates that the water stability coefficient of the recycled aggregate increases with the addition of the curing agent "road liquid" compared to the recycled aggregate without this agent, for each cement dosage. The water stability coefficient ratio for each cement dosage is consistently above 1, indicating that the inclusion of the curing agent "road liquid" enhances the water resistance of recycled aggregates. Moreover, as the cement dosage increases, the water

TABLE 6. Water Absorption of Recycled Aggregate with and without "road liquid" with different dosages of cement.

Cement Admixture %	Dosage of curing agent "road liquid" ml/m^3	Quality before immersion g	Quality after immersion g	water absorption %
3%	0 ml/m^3	5648	5884	4.18%
4%	0 ml/m^3	5475	5689	3.91%
5%	0 ml/m^3	5637	5845	3.69%
6%	0 ml/m^3	5506	5689	3.32%
7%	0 ml/m^3	5499	5666	3.04%
3%	300 ml/m^3	5537	5667	2.35%
4%	300 ml/m^3	5382	5489	1.99%
5%	300 ml/m^3	5350	5437	1.63%
6%	300 ml/m^3	5548	5622	1.33%
7%	300 ml/m^3	5615	5670	0.98%

TABLE 7. Water stability test results of recycled aggregates with different cement dosage.

Cement Admixture %	Compressive strength of reference specimen /MPa		WSC0/%	Test specimen compressive strength /MPa		WSC1/%	WSCR
	R_d^0	R_d^1		R_d^0	R_d^1		
3	3.29	2.83	85.93%	3.66	3.28	89.62%	1.04
4	4.05	3.49	86.07%	4.53	4.16	91.83%	1.07
5	4.86	4.24	87.25%	5.43	5.13	94.48%	1.08
6	5.60	4.92	87.86%	6.46	6.19	95.82%	1.09
7	6.38	5.65	88.44%	7.49	7.32	97.73%	1.10

stability coefficient ratio also increases, leading to improved water stability. This improvement is attributed to the curing agent "road liquid" containing polyol compounds, which utilize strongly charged ions to weaken the internal water absorption of recycled aggregates, thereby enhancing their water resistance.

2.3 Self-healing properties

Nowadays, the research on concrete damage self-repair has garnered increasing attention from scholars. Currently, concrete self-repair technologies, both domestically and internationally, are primarily categorized into self-repair based on chemical principles, self-repair based on physical principles, and self-repair based on biological principles [16]. This study focuses on self-repair based on chemical principles. It examines the integration of natural self-healing with the addition of cement and capsule-based self-repair with the inclusion of the curing agent "road liquid" to identify a more effective self-repair approach. Through conducting split strength tests, we evaluate the self-healing capabilities of stabilizing recycled aggregates by solely adding cement, as well as the self-healing performance of stabilizing recycled aggregates by adding both the curing agent "road liquid" and cement simultaneously.

TABLE 8. Self-healing test results of recycled aggregates with different cement dosages.

Cement Admixture %	Splitting strength of base specimen/KPa		SHC_0/%	Splitting strength of Test specimen /KPa		SHC_1/%	SHCR
	R_i^1	R_i^0		R_i^1	R_i^0		
3	221.12	282.59	78.25%	304.53	362.48	84.01%	1.07
4	308.98	356.24	86.73%	439.89	466.33	94.33%	1.09
5	411.16	436.83	94.12%	596.76	576.92	103.44%	1.10
6	533.59	517.86	103.04%	813.12	696.17	116.80%	1.13
7	665.69	606.88	109.69%	1081.89	827.13	130.80%	1.19

The table demonstrates that the self-repair coefficient of recycled aggregate increases with the rise in cement dosage. This is attributed to the fact that as the cement dosage increases, unhydrated or incompletely hydrated cement remains after the initial seven days of curing. During the subsequent curing period, these cement particles continue to react, producing hydration products that accumulate around the cracks, leading to expansion and achieving the healing effect.

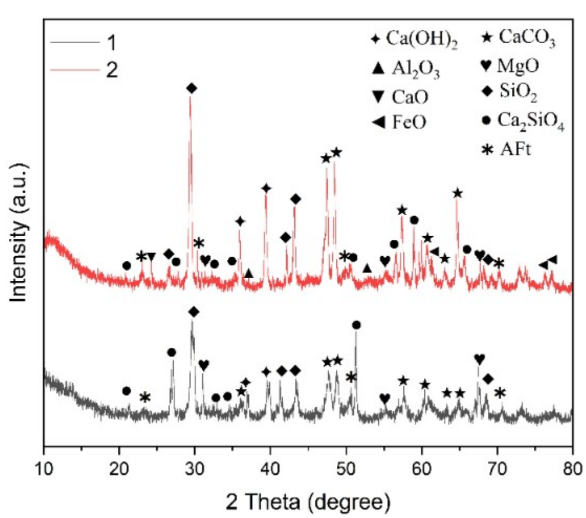
The ratio of the self-healing coefficient under each cement dosage is greater than 1, indicating that the self-healing performance of adding the curing agent "road liquid" and cement to stabilize recycled aggregate together is higher than that of adding cement to stabilize recycled aggregate alone. This suggests that the addition of the curing agent "road liquid" has a significant effect on the self-healing performance of recycled aggregates. This effect is attributed to the curing agent "road liquid" mixed with a large number of microcapsules rich in active substances. When the hardened earth experiences stress cracking, the microcapsules rupture, releasing the internal restorative agent which diffuses to the damage. Upon contact with the pre-mixed catalyst, it fills the cracks and simultaneously facilitates the self-repair of cracks. The self-repair coefficient ratio increases with the increase of cement dosage, indicating that the natural self-healing self-repair method with the addition of cement and the capsule-based self-repair method with the addition of curing agent "road liquid" can synergistically enhance the self-repair ability of recycled aggregates.

3. MICROSCOPIC PROPERTIES

3.1 XR/2 test

Figure 4 shows the XRD spectra of cement cured (1) and recycled aggregates cured with the addition of the curing agent "road liquid" (2). The analysis of the spectra of the two samples indicates that the main components are SiO_2, $Ca(OH)_2$, $CaCO_3$, Ca_2SiO_4, etc. The addition of the curing agent "road liquid" leads to an increase in the intensity of the XRD peaks. This is because the curing agent "road liquid" facilitates the crystallization process in the curing body,

FIGURE 4. XRD spectrum of recycled aggregate with or without curing agent "road liquid" (with or without curing agent).

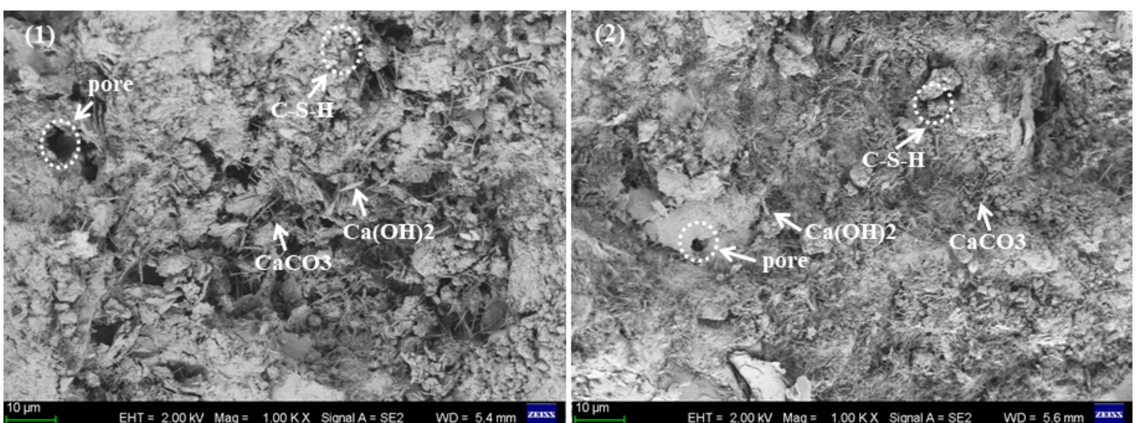


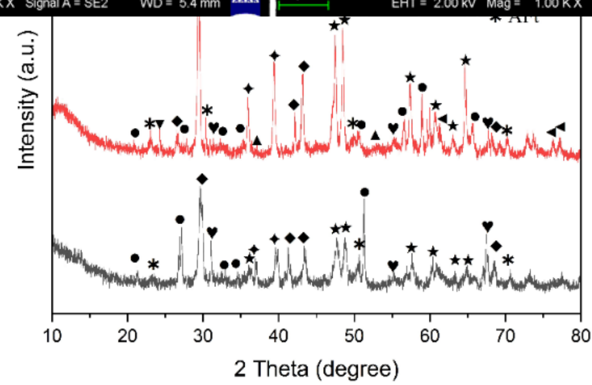
reduces lattice distortions, and increases the volume of the crystals. Since there are some fly ash and metal ions present in the curing agent "road liquid," certain characteristic diffraction peaks of the curing agent, such as Al_2O_3, CaO, and FeO, are observed in sample 2. Since there is some SiO_2 in the fly ash, the peak intensity of SiO_2 in sample 2 increases significantly. Chemical reactions take place within the specimen during the conditioning period, resulting in hydration and carbonation reactions that produce hydroxides and carbonates, including $Ca(OH)_2$, $CaCO_3$, and C-S-H gels. The primary factor contributing to the notable enhancement in the compressive strength of the specimen is the formation of carbonate crystals. These crystals play a crucial role in bonding the particles together, filling the inter-particle pores, and creating a stronger overall structure by forming bonds with the particle surfaces. As a result, the strength of the specimen is significantly increased. C-S-H gels are amorphous substances that exhibit diffuse peaks on XRD patterns. These gel substances play an important role in cementing materials, resulting in a more compact system. In summary, the presence of the curing agent known as "road liquid" helps enhance the structural stability of the curing body and improve the strength of the recycled aggregate.

3.2 SEM test

Figure 5 shows the SEM plots of cement-cured (1) and recycled aggregates cured with an added curing agent (2). Analysis of the plots of the two samples reveals differences in the size of the specimen particles, with a relatively uniform overall distribution. The contact between particles is based on surface-to-surface interaction, which promotes the formation of a denser structure.

FIGURE 5. Microscopic morphology of recycled aggregate with or without curing agent "road liquid" (left without curing agent and right with curing agent).





There are pores between the particles, and the sizes of the pores vary. There are relatively few open pores. Compared to sample 1, the pores in the image of sample 2 have significantly decreased. This suggests that the addition of the curing agent "road liquid" enhances the overall compactness of the sample, leading to increased strength. These findings align with the results of the XRD spectral analysis. The particles are adorned with crystals, primarily in the shape of columns and needles. Filamentous flocs are also scattered on the particle surface. The C-S-H gels exhibit an irregular spherical morphology, forming a compact structure as they stack on top of each other. The shape and size of $Ca(OH)_2$ typically resemble flakes. Inside the specimen, there is more $CaCO_3$ and C-S-H gel intergrowth, which are intertwined with each other. This tightens the bond between the two and serves to bond the soil particles and fill the pore space. This intergrowth and combination can increase the strength and durability of cementitious recycled aggregates.

4. CONCLUSION

The experimental results show that:

1. The addition of the curing agent "road liquid" in varying cement dosages has improved the unconfined compressive strength of recycled aggregates. A cement dosage of 5% of recycled aggregates with the curing agent "road liquid" shows slightly higher 7-day unconfined compressive strength compared to a cement dosage of 6% of recycled aggregates without the curing agent. Moreover, the 7-day unconfined compressive strength of recycled aggregates without a 6% cement dosage is slightly higher than that of recycled aggregates with a 6% cement dosage after the addition of the curing agent "road liquid"; consequently, the cement dosage can be reduced by incorporating the curing agent "road liquid" in engineering applications to lower project costs.
2. With the increase in cement dosage, the strength of recycled aggregates treated with the curing agent "road liquid" gradually increased. The rise in splitting strength exceeded that of unconfined compressive strength, suggesting that the curing agent "road liquid" could enhance the tensile properties of recycled aggregates more effectively.
3. From the growth rate of unconfined compressive strength, it can be observed that the strength of "road liquid" with a curing agent initially increases rapidly and then slows down, with strength formation primarily occurring in the early stages. Analyzing the change in splitting strength over time reveals that the strength of curing agent continues to exhibit growth potential in the later stages. This indicates that incorporating a curing agent in "road liquid" not only enables rapid attainment of strength requirements but also sustains strength for future needs.
4. The ratio of water stability coefficient to self-healing coefficient under each cement dosage after adding the curing agent "road liquid" is greater than 1. This suggests that adding the curing agent "road liquid" can enhance the water resistance of recycled aggregate and bolster the self-healing performance of recycled aggregate. The natural self-healing repair method with cement and the capsule-based repair method with the curing agent "road liquid" can synergize to effectively enhance the self-repairing capability of recycled aggregates.
5. The micro-mechanism analysis shows that the curing agent promotes the crystallization process in the curing body, reduces lattice distortion, and increases the size of the crystals. These crystals undergo internal hydration and carbonation reactions to produce

hydroxides and carbonates, including $Ca(OH)_2$, $CaCO_3$, and C-S-H gels. They effectively bind the particles, fill the inter-particle pores, and form bonds with the particle surfaces, resulting in a tighter overall structure and improved specimen strength.

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