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Preparation and Performance Analysis of Magnesium Oxychloride Cement Stabilized Crushed Macadam Mixture

Sijie Li, Yi Sun

School of Civil Engineering, University of Science and Technology Liaoning, Anshan 114051, China

Abstract

An experimental study evaluated the effect of magnesium oxychloride cement- stabilized macadam as an alternative to conventional cement-stabilized macadam, which is commonly used in semi-rigid road bases due to its good integrity and moderate stiffness. Conventional cement stabilized macadam requires a curing period of 7 days and has slow strength development. Magnesium oxychloride cement was tested to address these issues. The optimum mix composition was determined through aggregate gradation design and orthog- onal tests, and the mechanical properties and durability were evaluated. The results of the study showed that a 5% magnesium oxychloride cement con- tent achieved rapid early strength development under natural curing condi- tions without the need for water curing. Strength values reached 4-8 MPa within the first 1 to 2 days and stabilized thereafter, making it suitable for further construction. To prevent strength loss due to contact with water, a waterproof seal coating was used, enhancing the practical application of magnesium oxychloride cement stabilized macadam in road construction.

Keywords

Cement stabilized macadam, magnesium oxychloride cement, water resistance, impermeability.

1. INTRODUCTION

Ordinarily, Portland cement is widely used in construction, but its pro- duction consumes large amounts of non-renewable resources and emits significant quantities of carbon dioxide. In contrast, magnesium oxychloride cement (MOC) has garnered attention due to its advantages over ordinary cement, such as rapid hardening, high early strength, and lower carbon emissions [1, 2, 3, 4]. MOC is an air-hardening binder, formed by mixing ap- propriate amounts of magnesium oxide with a magnesium chloride solution at a specific molar ratio [5, 6]. Similar to ordinary cement, MOC gains strength through chemical reactions and hydration products. The two primary hydration products in the system, $3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$ (Phase 3) and $5Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$ (Phase 5), combine to give MOC its exceptional mechanical strength [7].

Magnesium oxychloride cement (MOC) is characterized by early strength development, excellent corrosion resistance, and good frost resistance, with mechanical properties superior to those of ordinary cement. These advantages have led to increased research interest in applying MOC to fields such as construction, road, and bridge engineering [8, 9, 10, 11, 12]. Its versatility has driven many researchers to focus on characterizing its performance and developing applications, including improving water and corrosion resistance, as well as exploring its potential in road construction materials. Over 90% of China's high-grade highways use semi-rigid bases, valued for their high strength and stability, serving as a load-bearing layer in road structures. Cement-stabilized crushed macadam is currently the most commonly used semi-rigid base material. Like Portland cement, MOC has also shown promise as a road material. Chang [13]investigated the salt erosion resistance of magnesium oxychloride cement concrete (MOC) in concentrated brines of salt lakes, finding that MOC exhibits exceptional resilience against salt-induced crystallization damage, maintaining its mechanical integrity and material consistency. Further investigations using XRD, thermogravimetric analysis, and SEM revealed that MOC mortar, after exposure to saline solutions, demonstrated excellent salt resistance, making it suitable for road engineering in saline-alkali and salt lake regions, highlighting its potential in harsh environments [14]. Additionally, Zheng [9] conducted an experimental analysis of MOC concrete pavement, observing that its mechanical properties met the requirements for road base use, though its water resistance was found to be lacking.

Domestic and international researchers have advanced the application of magnesium oxychloride cement (MOC) in engineering, but its use in pavement engineering needs more study. Research gaps include optimal mix design, curing methods, and enhancing MOC's performance, especially its water resistance. There's a scarcity of research on using MOC in cement- stabilized crushed macadam. This study will investigate replacing Portland cement with MOC for crushed macadam stabilization. Through gradation design and orthogonal experiments, we'll find the best aggregate gradation and MOC mix ratio. Mechanical, freeze-thaw, permeability, and water resis-tance tests will assess the durability of MOC-stabilized crushed macadam. The study will also develop water resistance enhancement methods and validate MOC's applicability in pavement base layers, providing a theoretical and technical foundation for its use in road engineering.

2. MATERIALS AND METHODS

2.1. Materials

All materials used in this experiment were sourced from China. The light- burned magnesia was produced in Haicheng City, Liaoning Province. According to the Chinese standard hydration method outlined in WB/T1019-2002 [15], its active magnesia content was measured at 57.84%. Magnesium chloride hexahydrate ($MgCl_2·6H_2O$) is supplied by Dalian Salt Chemical Group Wudao Chemical Co., Ltd. The ordinary Portland cement (P.O. 42.5) was produced by Anshan Jidong Cement Co., Ltd. Fly ash, with a fineness of 300-400 mesh, is sourced from Gongyi City. Coarse aggregates included 5-10 mm and 10-25 mm limestone crushed stone, while fine aggregates were 0-3 mm and 3-5 mm crushed gravel. The physical and mechanical properties of these aggregates met the requirements specified in Chinese standard JTG/T F20-2015 [16]. Tap water was used as the mixing water. The main chemical components of the light-burned magnesia and fly ash are listed in Table 1.

Table 1. Chemical composition of Light burnt magnesium oxide and Fly ash

Material	MgO	SiO_2	Al_2O_3	CaO	Fe_2O_3	SO_3	LOSS
Light burnt magnesium oxide	85.13	8.34	0.38	2.98	0.45	0.14	0.26
Fly ash	0.78	54.94	34.86	2.63	2.52	0.31	2.41

2.2. Gradation and Mixture Proportions Design

2.2.1 Gradation design

The effective void ratio in the mixture has the greatest impact on the permeability of porous cement-stabilized crushed macadam bases. The effective void ratio of porous cement-stabilized aggregates depends on the gradation of the crushed macadam, cement content, particle shape, and compaction. In this experiment, aggregates were classified into three categories—coarse aggregate, fine aggregate, and mineral powder—based on the gap-graded de- sign theory. The optimal gradation for both coarse and fine aggregates was determined through testing. According to the stepwise filling theory, fine aggregates and mineral powder were added to the coarse aggregates to fill the voids created by the coarse aggregates' accumulation. To avoid issues such as segregation due to uneven mixing, which could affect the determination of the optimal mix ratio, the aggregate gradation was designed based on the C-B-3 dense-graded aggregate specification recommended in JTG/T F20-2015. Based on engineering experience, a cement content of 5% was selected. The optimal gradation of coarse and fine aggregates was calculated using the volume method [17]. The final gradation of the aggregates was determined through testing and calculations, as follows:

The calculated gradation ratio is as follows: coarse aggregate: fine aggregate: mineral powder = 70.14%: 22.88%: 6.98%. Based on the particle size distribution within each aggregate, the distribution of particle sizes in the 26.5–19 mm range is obtained, with the results shown in Table 2. This gra- dation conforms to the C-B-3 type dense skeleton gradation specified in the Technical Specifications for Construction of Highway Pavement Base (JTJ 034-2000) [18].

Table 2. Design gradation and specification gradation range

Size (mm)	26.5	19.0	9.5	4.75	2.36	0.6	0.075
Synthetic gradation (%)	100	73.5	43.8	26.4	20.1	10.5	1.5
C-B-3 grading range (%)	100	68~86	38~58	22~32	16~28	8~15	0~3

2.2.2 Orthogonal Experimental Design for Mixtures

The mechanical properties of magnesium oxychloride cement are closely related to the ratio of its reactants. Research has shown that the ratio of active MgO to $MgCl_2$ should ideally follow the chemical reaction equation, which suggests a molar ratio of 5:1 [19]. However, cement produced at this ratio often exhibits suboptimal performance. Subsequent studies on the material proportions for magnesium oxychloride cement have found that better performance is achieved when the molar ratio of active MgO to $MgCl_2$ is between 6 and 9, and the molar ratio of H_2O to $MgCl_2$ ranges from 14 to 18 [20].

Due to the poor water resistance of magnesium oxychloride cement, this study explores the use of fly ash as an additive to improve its properties. Research indicates that fly ash modifies magnesium oxychloride cement by reacting its active SiO_2 with Mg^{2+} to form $MgHPO_4 \cdot 3H_2O$, which has better water resistance and enhances the interlocking and adhesion between crystals. The addition of fly ash fills the spaces between needle-like crystals, significantly improving the product's structure. Moreover, the hydrophobic nature of carbon in fly ash further enhances the water resistance of magnesium oxychloride cement. The optimal fly ash content is between 20% and 30%, during which a significant improvement in water resistance is observed. However, when the fly ash content exceeds 30%, both the strength and water resistance of magnesium oxychloride cement decrease.

Building on existing research, an orthogonal test method is used to determine the optimal composition of magnesium oxychloride cement. The variables for the cement composition include three factors: the molar ratio of MgO to $MgCl_2$, the molar ratio of H_2O to $MgCl_2$, and the proportion of fly ash. Each factor is tested at three different levels. An $L_9(3^4)$ orthogonal array is used to combine these variables and perform the tests, with the de- sign combinations detailed in Table 3. Subsequent performance analysis is conducted based on these combinations.

Table 3. $L_9(3^4)$ Orthogonal level list

Test number	MgO: $MgCl_2$	H_2O: $MgC1_2$	Fly ash (%)
1	5 : 1	14 : 1	20
2	5 : 1	16 : 1	25
3	5 : 1	18 : 1	30
4	7 : 1	14 : 1	30
5	7 : 1	16 : 1	20
6	7 : 1	18 : 1	25
7	9 : 1	14 : 1	25
8	9 : 1	16 : 1	30
9	9 : 1	18 : 1	20

2.3. Testing Procedures

2.3.1 Mechanical Property Test

Magnesium oxychloride cement, being a non-hydraulic binder, requires different curing methods compared to ordinary cement. Therefore, the experiment followed two standards. One set of samples is prepared, cured, and tested for unconfined compressive strength and splitting tensile strength ac- cording to the Chiese standard JTGE51-2009 [21]. Another set of specimens is subjected to altered curing conditions. After demolding, these specimens are cured in indoor natural air without water immersion, while the remaining test methods and procedures adhere to JTGE51-2009.

2.3.2 Shrinkage Performance Test

To investigate the drying shrinkage behavior of cement-stabilized crushed macadam, this experiment follows the testing methods for inorganic stabilized materials' drying shrinkage properties as outlined in the Chinese standard T0854-2009 [22]. A total of 12 medium-sized beam specimens, each measuring 100 mm × 100 mm × 400 mm, were prepared. These included 6 specimens stabilized with magnesium oxychloride cement and 6 specimens stabilized with Portland cement. For each group, 3 specimens were used for drying shrinkage tests, while the other 3 served as standard control specimens. After demolding, the specimens were subjected to standard curing conditions as specified by the guidelines. Upon completion of the curing process, the specimens were transferred to a drying shrinkage chamber, where drying shrinkage tests were conducted according to the specified conditions. Use the following equations(Eq. 1, Eq. 2) to calculate the specimens' water loss rate and shrinkage strain based on the test data.

$$\omega_i = \frac{m_0 - m_i}{m_p} \tag{1}$$

$$\varepsilon_i = \frac{\delta_i}{l} \tag{2}$$

Where ω_i is the i-th time cumulative water loss rate (%); m_i is the mass of the standard specimen weighed for the i-th time (g); m_0 is the initial quality of specimen after curing (g); m_p is the average mass of the standard specimen after drying (g); ε_i is the cumulative drying shrinkage strain on the i-th day (%); δ_i is the cumulative drying shrinkage observed on the i-th day (mm); and l is the average length of the standard specimen (mm).

2.3.3 Freeze-thaw Cycle Test

This experiment involves two standard procedures. The first group of specimens is prepared according to the method outlined in T0858-2009 [23] of the regulations, with cylindrical specimens of 150 mm diameter and 150 mm height. These specimens are cured for 28 days under standard conditions and subjected to one freeze-thaw cycle: frozen at -20 °C for 16 hours and then placed in a 20 °C water bath for 8 hours. The second group of specimens is also prepared according to T0858-2009, with 28 days of indoor natural curing and no immersion treatment. During the freeze-thaw test, the specimens are frozen at -20 °C for 16 hours, then removed and allowed to naturally thaw indoors for 10 hours. Additionally, a non-freeze-thaw comparison test is conducted using specimens cured for 28 days under natural conditions.

After the specimens complete the specified number of freeze-thaw cycles, their compressive strength (RDC) is tested according to the method de- scribed in T0805-1994 [24], and the freeze-thaw resistance indicator (BDR) is calculated. The calculation method for the freeze-thaw resistance indicator of semi-rigid materials is given by Equation 3 (Eq. 3).

$$B_{DR} = \frac{R_{DC}}{R_C} \times 100 \tag{3}$$

Where B_{DR} is the compressive strength loss rate of the specimen after 5 freeze-thaw cycles (%); R_{DC} is the compressive strength of the specimen after 5 freeze-thaw cycles (MPa); R_C is the compressive strength of the comparison specimen.

2.3.4 Water Seepage Test

Specimens are prepared according to the method outlined in the regulation T 0843-2009 [25], with a diameter of 150 mm and a height of 150 mm, and cured for 28 days without immersion. The water permeability coefficient is calculated based on the amount of water permeated. Additionally, a modified permeability test is conducted where a 5 mm thick sealing layer is applied to the specimen’s surface. The sealing material consists of an organic asphalt diluent, which is mixed with coarse and fine aggregates and fly ash after being heated to form a slurry. The slurry is applied to the surface of the magnesium oxychloride cement-stabilized crushed macadam specimens before it solidifies. The performance of the sealing layer is evaluated by comparing specimens with and without the sealing material.

2.3.5 Water Resistance Test

According to method T 0843-2009, cylindrical specimens with a diameter of 100 mm and height of 100 mm are prepared. After demolding, the specimens are placed in natural indoor conditions for 7 days without immersion, after which the compressive strength of the first set of specimens is tested.

The remaining specimens are subjected to immersion, with the liquid in the tank maintained at a level that fully submerges the specimens, with the liquid level exceeding the specimens by 20 mm. After immersion, one set of specimens is removed every 24 hours, dried in a 60°C oven, and then tested for compressive strength. The softening coefficient is calculated based on the strength loss rate to evaluate the water resistance of the magnesia-cement stabilized crushed macadam. The specific calculation for the softening coefficient is as Equation: (Eq. 4).

$$K=\frac{f}{F} \tag{4}$$

Where K is the softening coefficient (dimensionless); f is the compressive strength of the specimen after i days of immersion (MPa); and F is the compressive strength of the specimen after i days of natural curing (MPa).

3. TEST RESULTS AND DISCUSSION

3.1. Orthogonal Test Results

According to the method specified in the standard T0843-2009, 9 groups of medium-sized cylindrical specimens with a diameter of 100 mm and a height of 100 mm were prepared and subjected to standard curing for 7 days. Testing was carried out in accordance with the method outlined in standard T0805-1994. After the tests were completed, the experimental data for each mix ratio were processed, and results are presented in Table 4.

Based on the data presented in the table, the analysis shows that the three factors influencing the strength of magnesium oxychloride cement-stabilized crushed macadam are ranked in the following order: MgO: $MgCl_2$ > H_2O:

$MgCl_2$ > fly ash content. The experimental data reveal that when the molar ratio of MgO to $MgCl_2$ is 5:1, the strength of the specimens exceeds 4 MPa, meeting the unconfined compressive strength requirements for base layers subjected to heavy and extra-heavy loads on secondary and lower-grade highways. This highlights the critical importance of the MgO to $MgCl_2$ molar ratio.

Although the molar ratio of H_2O to $MgCl_2$ has a weaker effect on the strength of magnesium oxychloride cement, it remains an important factor. The experimental results indicate that the optimal performance is achieved when the H_2O to $MgCl_2$ molar ratio is 18:1. However, due to limitations in the values tested, there is potential for further improvement in this ratio.

Table 4. Analysis of ranges of orthogonal results

Design	Factors			7d Compressive Strength (MPa)
	A	B	C	
1	5 : 1	14 : 1	20%	4.20
2	5 : 1	16 : 1	25%	4.28
3	5 : 1	18 : 1	30%	4.39
4	7 : 1	14 : 1	30%	2.08
5	7 : 1	16 : 1	20%	2.51
6	7 : 1	18 : 1	25%	2.56
7	9 : 1	14 : 1	25%	2.30
8	9 : 1	16 : 1	30%	2.67
9	9 : 1	18 : 1	20%	2.70
K_1	12.87	8.57	9.47	
K_2	7.15	9.46	9.06	
K_3	7.68	9.65	9.20	
k_1	4.29	2.86	3.14	
k_2	2.38	3.15	3.02	
k_3	2.56	3.22	3.07	
Range (R_j)	1.91	0.36	0.12	
Significance of factors		A>B>C		
Optimized results		$A_1B_3C_1$		

∗ R refers to the result of extreme analysis

Thus, the optimal formulation for magnesium oxychloride cement-stabilized crushed macadam is determined to be a molar ratio of MgO: $MgCl_2$: H_2O of 5:1:18, with a 20% fly ash content.

3.2. Test Results Analysis

3.2.1 Mechanical Properties Analysis

Figure 1 presents the test data of mechanical properties of magnesium oxychloride cement-stabilized crushed macadam. It is evident that under standard curing conditions, magnesium oxychloride cement behaves differently from ordinary Portland cement, with its compressive strength generally showing a decreasing trend over time. In contrast, under natural strength conditions, the compressive strength of magnesium oxychloride cement-stabilized crushed macadam specimens increases rapidly in the first 2 days, reaching 95.64% of the 7d strength, which is up to 9.87 MPa. This strength meets the requirements for the base layer of highways and first-class roads with special and extreme heavy traffic loads. Starting from the third day, the rate of strength increase in the specimens slows down and gradually levels off. Therefore, during construction, depending on the requirements of the construction section, the magnesium oxychloride cement-stabilized crushed macadam can proceed to the next construction stage after 1 to 2 days of curing, which significantly shortens the construction time compared to the curing time of ordinary cement-stabilized crushed macadam. The specimen strength under standard curing conditions after 7 days is only 49.4% of that under natural curing. The main reason is that in magnesium cement, the 3·1·8 phase and 5·1·8 phase, which provide strength and properties to the hardened cement macadam, have ionic crystal lattice components. Consequently, the 3·1·8 phase and 5·1·8 phase are unstable in polar solvents, especially water, and are prone to hydrolysis and dissolution. The invading moisture destroys the needle-like crystals formed, causing the mixture to lose a certain amount of mechanical strength. Additionally, the average splitting strength of magnesium oxychloride cement-stabilized crushed macadam after 90 days of curing is measured to be 0.85 MPa. According to the Chinese standard JTG D50-2017 [26], the splitting strength of cement crushed macadam and other base and sub-base materials should be between 0.4 to 0.6 MPa. The splitting strength of the specimens cured naturally in the test is greater than the standard specified by the regulation, indicating that the flexural strength of the magnesium oxychloride cement-stabilized crushed macadam designed in the test meets the road requirements.

3.2.2 Shrinkage Performance Analysis

Figure 2 shows the cumulative shrinkage and cumulative moisture loss rates for magnesium oxychloride cement and Portland cement specimens, respectively. Over the 7-day period, the shrinkage strain of the magnesium oxychloride cement specimens increases gradually with time, with a rapid increase in the first 4 days followed by a significant reduction in the rate of increase over the subsequent 3 days. In contrast, the shrinkage strain of the Portland cement specimens continues to increase throughout the 7 days. The shrinkage values for the two types of cement specimens show minimal differences.

Regarding moisture loss, the magnesium oxychloride cement specimens experience higher moisture loss in the first 2 days, followed by reduced moisture loss in the later period. In contrast, the moisture loss rate for Portland cement specimens shows a steady increase over 7 days. This is attributed to the fact that, upon immersion, the 5·1·8 phase crystals in magnesium oxychloride cement dissolve, and unreacted MgO reacts with water to form layered $Mg(OH)_2$. These factors increase the porosity of the magnesium oxy- chloride cement, thereby enlarging the surface area of moisture exposure to air and accelerating moisture loss. On the other hand, Portland cement hydration promotes strength development, resulting in a denser structure and reduced surface area for moisture exposure, which slows down the moisture loss.

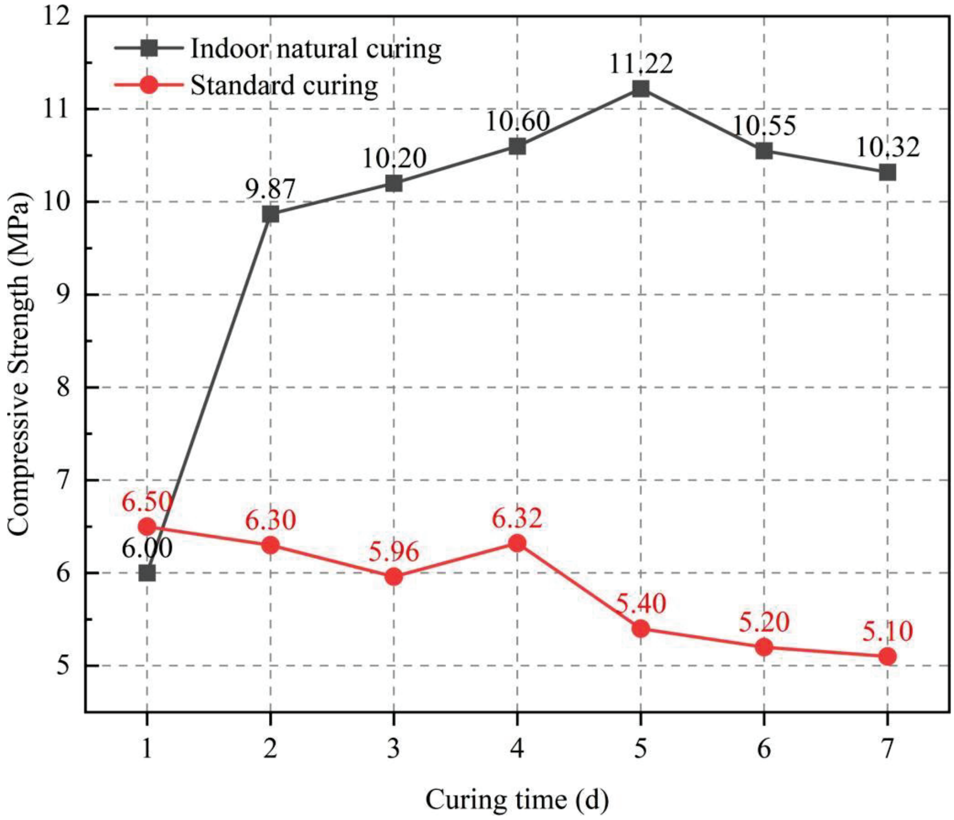

Figure 1. 7d compressive strength under under different curing conditions.

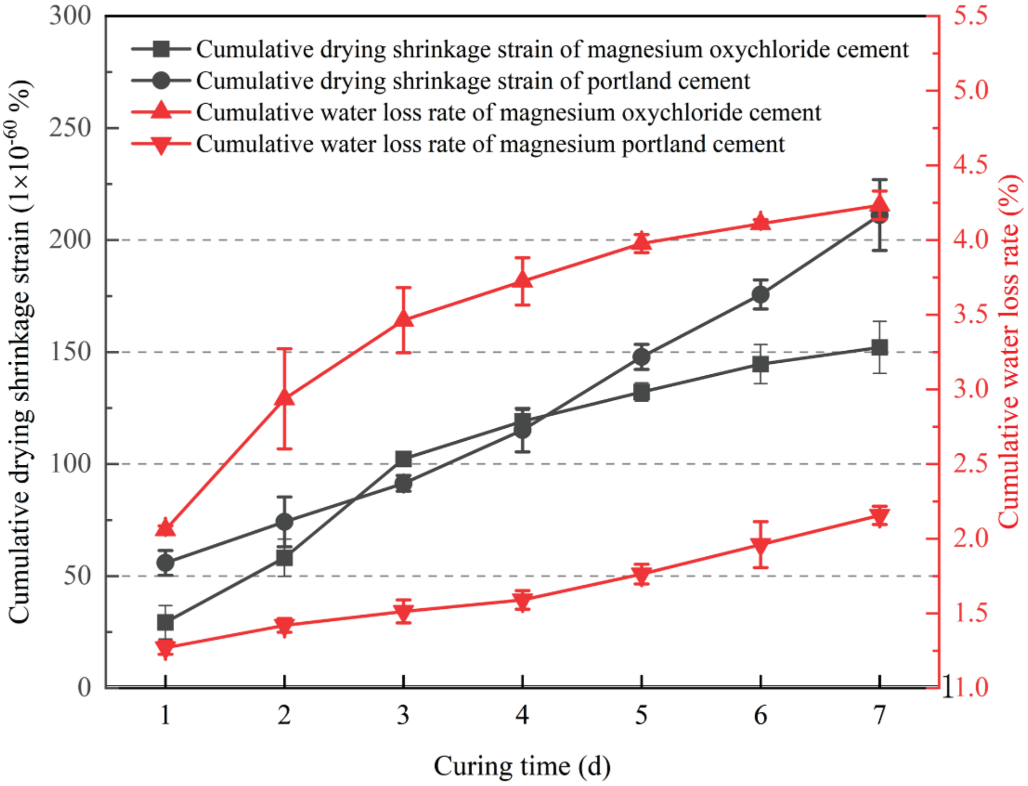

Figure 2. Shrinkage performance analysis

3.2.3 Freeze-thaw Cycle Test Analysis

Figure 3 presents the results of five freeze-thaw cycles under different conditions. The data indicate that, after 28 days of curing, the compressive strength of specimens subjected to the immersion freeze-thaw cycles significantly decreased after the fifth cycle, while the results for the wet freeze-thaw specimens were similar to those of the control group. The strength loss was greater under immersion conditions, highlighting the more severe impact of freeze-thaw cycles in the presence of water. To assess the frost resistance of semi-rigid base layers, we used the Freeze-Thaw Durability Ratio (D_{BR}), finding that the D_{BR} value for wet freeze-thaw specimens was lower than that for immersion freeze-thaw specimens with the same number of cycles.

Comparing with mechanical performance test results, specimens cured indoors for 7 days had lower strength than those cured for 28 days, indicating that the strength of magnesium oxychloride cement-stabilized crushed macadam increases gradually with curing time. The DBR value for the first group of freeze-thaw specimens shows a significant strength loss, approximately 50%, whereas the second group, subjected to wet freeze-thaw cycles, had strength comparable to that of non-freeze-thaw specimens, with only about 2% strength loss. This is attributed to the fact that water inside the specimens freezes at low temperatures, causing volumetric expansion and resulting in internal pressure that leads to cracking and strength reduction. Additionally, during the freeze-thaw cycles, external water seeps into the specimens through cracks, and the fine powdery particles in the specimens lose strength rapidly upon contact with water. Magnesium oxychloride cement has lower water resistance compared to Portland cement, and its main crystalline phases degrade in water, further reducing compressive strength. Therefore, freeze-thaw cycles under immersion conditions have a more significant impact on the structural stability of magnesium oxychloride cement samples. In contrast to conventional Portland cement-stabilized crushed macadam, magnesium oxychloride cement-stabilized crushed macadam exhibits minimal strength loss and better frost resistance under low-temperature dry conditions.

3.2.4 Water Resistance Performance Analysis

Figure 4 shows the strength variation of magnesium oxychloride cement- stabilized crushed macadam after 7 days of natural curing under immersion conditions. It is evident that after 1 day of immersion, the softening coefficient of the specimens is approximately 0.69. While the specimens with this softening coefficient can still support roadway loads, their strength will decrease further over time, eventually becoming insufficient to bear the loads and leading to potential damage to the road structure.

Under dry curing conditions, the strength of magnesium oxychloride cement- stabilized crushed macadam increases more rapidly. However, after 1 day of immersion, the strength decreases by 37.8%. Although there is a slight increase in compressive strength with extended immersion time, the com- pressive strength continuously declines between 3 to 7 days of immersion, dropping from 7.1 MPa to 4.8 MPa.

Therefore, the curing method specified in T0845-2009 is not suitable for magnesium oxychloride cement-stabilized crushed macadam. It is essential to cure magnesium oxychloride cement-stabilized crushed macadam in a natural air environment to achieve better performance. Additionally, effective waterproofing measures should be implemented during the curing and use of magnesium oxychloride cement-stabilized crushed macadam.

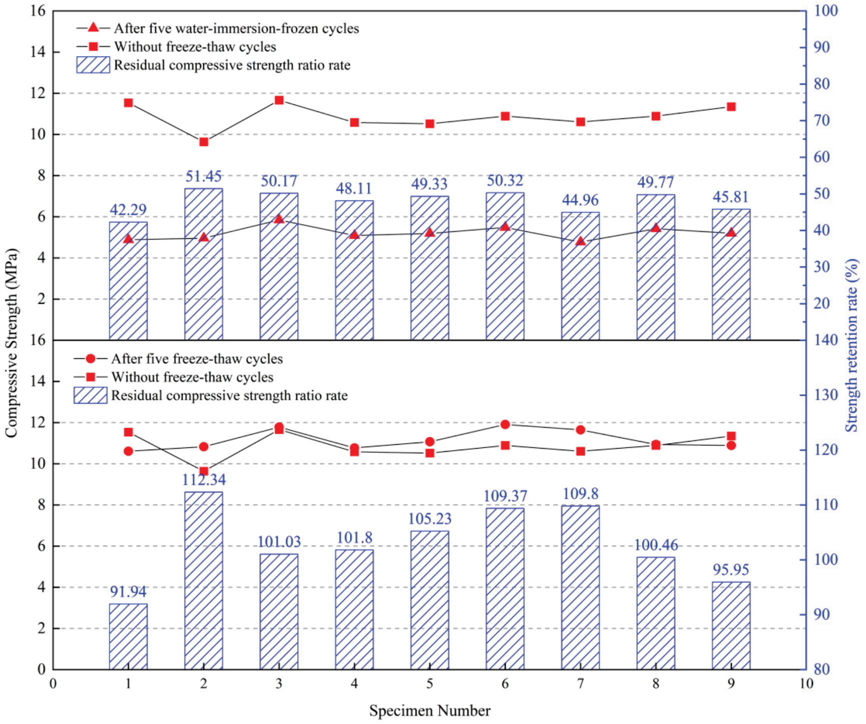

Figure 3. Results of freeze-thaw test

3.2.5 Water Seepage Performance Analysis and Anti-seepage Measures

Figure 5 presents the water permeability test data for three groups of magnesium oxychloride cement-stabilized crushed macadam specimens with- out a sealing layer. The results indicate that the water permeability of the specimens increases over time within the 5-minute period, but the rate of water permeability per minute shows a decreasing trend. This suggests that the structure of the specimens made with magnesium oxychloride cement as the inorganic binder is relatively dense, resulting in a decreasing water permeability rate over time.

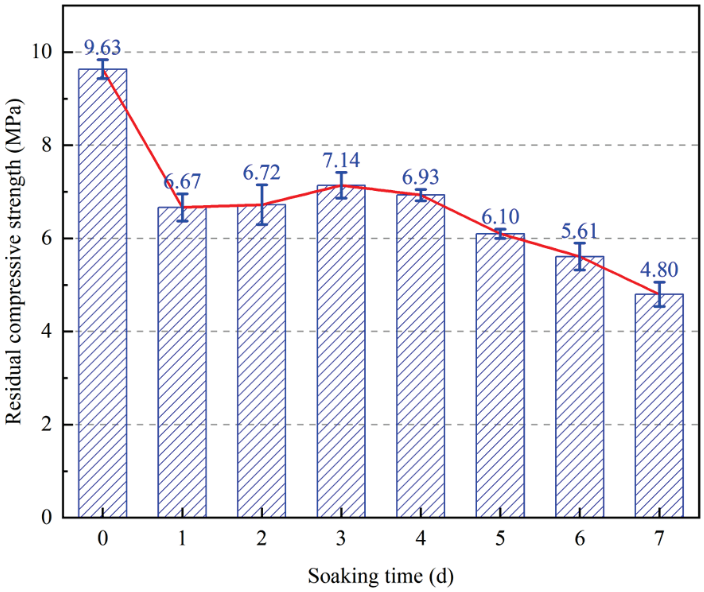

Figure 4. Strength changes of immersed specimens

After the conclusion of the experiment, an inspection of the underside of the specimens revealed that some areas had been wetted by the permeated water. At this juncture, although the permeability performance of the magnesium oxychloride cement-stabilized crushed macadam met the standard requirements, its strength was susceptible to a decline due to the influence of water. Therefore, the long-term water resistance of the material requires further enhancement. Therefore, this study designed a sealing layer structure to address the detrimental effects of water permeability on magnesium oxychloride cement-stabilized crushed macadam. Existing sealing materials are typically made by diluting asphalt and mixing it with fine aggregates and fillers to form a paste. In this experiment, the sealing material used was an organic asphalt diluent, which, when heated, was mixed with fine aggregates and fly ash to create a paste that was applied to the surface of the magnesium oxychloride cement-stabilized crushed macadam specimens (Figure 6).

The performance of the sealing layer was evaluated by comparing it with specimens without a sealing layer. For specimens with the sealing material, when the permeability device was placed on the specimen and the valve was opened, the liquid level in the device rapidly decreased and then remained at a low and stable value. This is because the good seal provided by the layer prevents water from penetrating into the specimen, causing the liquid in the permeability device to primarily fill the gap between the specimen and the instrument. This phenomenon demonstrates that the sealing layer structure has excellent anti-permeability performance, effectively isolating the mix from upper moisture intrusion.

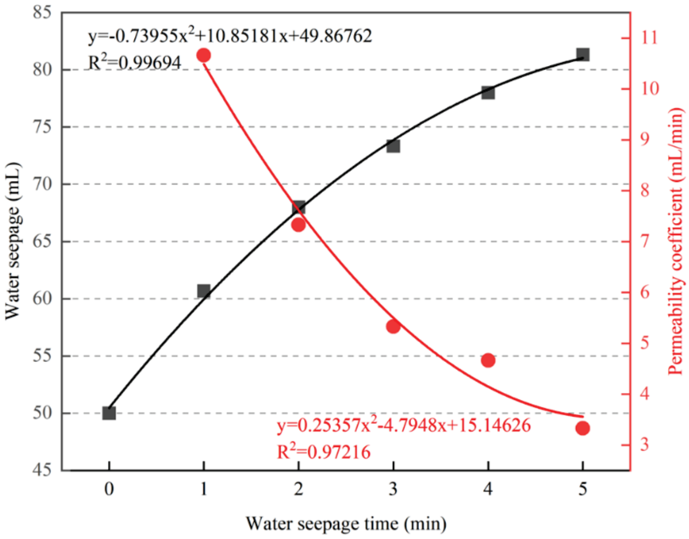

Figure 5. Water seepage test of non sealing specimen

Figure 6. Specimen with seal

4. CONCLUSION

From the laboratory results that used magnesium oxychloride cement stabilized crushed macadam mixture have been conducted including mechanical properties, shrinkage performance, freeze-thaw cycle, water resistance performance, and water seepage performance. These studies have indicated that:

1. The magnesium oxychloride cement-stabilized crushed macadam mixture develops early strength quickly, reaching 4-8 MPa in just 1-2 days versus the 7-day water curing needed for standard cement mixtures. This significantly reduces curing times and boosts construction efficiency.

2. With its high strength and low shrinkage properties, magnesium oxychloride cement stabilized crushed macadam mixture becomes a possible alternative to OPC concrete used for road pavements applications and large industrial floors.

3. To counteract the poor water resistance of magnesium oxychloride cement-stabilized crushed macadam, which can lead to damage and strength loss in damp environments, a sealing layer is advised for enhanced water- proofing. This layer has proven effective in preventing moisture penetration, thus reducing the material's vulnerability to water-related damage.

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APPENDIX A. NOTATION

The following symbols are used in this paper:

ωi = *i*-th time cumulative water loss rate (%);
m_i = Mass of the standard specimen weighed for the *i*-th time (g);
m_0 = Initial quality of specimen after curing (g);
m_p = Average mass of the standard specimen after drying (g);
ε_i = *i*-th day cumulative drying shrinkage strain (%);
δ_i = *i*-th day cumulative drying shrinkage observed (mm);
l = Average length of the standard specimen (mm);
B_{DR} = Compressive strength loss rate of the specimen after 5 freeze-thaw cycles (%);
R_{DC} = Compressive strength of the specimen after 5 freeze-thaw cycles (MPa);
R_C = Compressive strength of the comparison specimen (MPa);
K = The softening coefficient (dimensionless);
f = Compressive strength of the specimen after *i* days of immersion (MPa);
F = Compressive strength of the specimen after *i* days of natural curing (MPa).

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