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Research Article

Study on Material Properties of Magnesium Oxide Carbonized Prestressed Pipe Piles

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Traditional PHC pipe pile in foundation engineering consumes high energy and has insufficient durability. A magnesium oxide carbonization test block is a new type of environmental protection block which bases on activated magnesium oxide cementation technology. The use of CO_2 carbonation technology allows reactive magnesia to react to form basic magnesium carbonate to increase the compressive strength and durability of the block. Three kinds of different magnesium oxide powders were subjected to pressure test and determined the key technical parameters, such as optimal raw materials, sample preparation methods, carbonization environment and technology, and optimized design of pipe pile concrete material system.

1. Introduction

Prestressed high-strength concrete pipe piles (PHC pipe piles) are widely used in industrial and civil construction, roads and railway bridges, ports, and other engineering structures. With the continuous deepening of the theoretical research of high-strength concrete, its experimental research under the new preparation technology on various properties is more extensive. The large-scale use of traditional PHC pipe piles has seriously damaged farmland resources [1], and its main raw material Portland cement has huge environmental problems. Australian researcher Harrison (2001) [2, 3] developed a new type of cement mixed with activated magnesia and ordinary Portland cement, which is based on environmental protection to design. The hydration rate of active magnesium oxide is fast, and magnesium hydroxide can react with carbon dioxide (carbonization) to form magnesium carbonate compound which has strong cement strength, and this is an environmentally friendly, sustainable, and efficient new material. Magnesium carbonate can regenerate magnesium oxide after calcination [4], and it means that the process is reversible and active magnesium oxide products have recyclability and recycling characteristics.

More in-depth research on active magnesium oxide cement is led by Dr. Al-Tabbaa, Ph.D., University of Cambridge, UK. Al-Tabbaa has conducted extensive research on the carbonation technology of active magnesium oxide, including hydration characteristics, microstructure, carbonization properties, and industrial production; Liska and Al-Tabbaa [5] have found that active magnesia cement has superior capability to Portland cement in resisting hydrochloric acid and sulfuric acid. Cwirzen and Cwirzen [6] study the compressive strength of different magnesium oxide contents (0–20%); the experimental results show that, after 28 days of carbonization, the strength of the test piece with the magnesium oxide content of 0 is 32 MPa, the strength of the magnesium oxide is 10%, and the strength of the 20% test piece is 42 MPa and 40 MPa, respectively. Yi et al. [7, 8] used a modified three-axis device to carbonize and cure the sand; they found that blending 5% of active MgO can complete carbonization during 3~6 hours, and its strength can reach 2 to 3 times the strength of curing 28 d cement stabilized soil. However, this technology is still in the preliminary development stage; Formosaa et al. [9] indicated that MPC formulated with a low-cost MgO by-product could be an interesting alternative to other repair mortars; Zhang et al. [10] concluded that the carbonization blocks could have a higher strength; laboratory tests were performed to investigate the influence of the mixing amount of reactive MgO on compressive strength, microcharacteristics, and durability of the block, and they indicated that the carbonized products of reactive MgO are mainly hydromagnesite and nesquehonite/dypingite, with the higher amount of reactive MgO, the more carbonized products. Mo and Daman [11] concluded that active MgO produced a large amount of Mg-Ca carbonate, which made the microstructure of the cement paste denser. This is also the reason why MgO cement has stronger strength than ordinary Portland cement. Cai et al. [12] conducted comparative tests on different activated magnesia carbonized silt and found that, under the same conditions, the sample with high activity is stronger than the sample with lower activity and the sample with higher activity has higher density increase rate. Ye et al. [13] found that the strength of magnesium oxide cement decreased significantly with the increase of fly ash content in early stages. However, with the passage of time, the influence of fly ash content on strength becomes smaller and smaller. With the continuous progress of concrete technology, the preparation methods of high-strength concrete have been emerging. Some researchers have obtained ultrahigh-strength concrete materials through special ways. The carbonization technology based on active magnesium oxide is a new research direction which has attracted much attention in recent years; just a few scientific research institutions have conducted preliminary studies, and this technique is seriously lacking relevant experimental data. In order to reduce environmental pollution caused by Portland cement as a solidifying agent, mainly from the following three aspects to optimize the improvement (1) replacement of Portland cement as a curing agent for blocks with new materials, (2) research low emission, low energy, and recyclable recycling block preparation method, and (3) development of the best material mix ratio and preparation method were done in the previous research.

2. Materials and Methods

2.1. Experiment Materials. The cement used in this experiment is 32.5 grade ordinary Portland cement. Its various technical indicators meet the corresponding provisions of the *Ordinary Portland Cement* (GB175-2007); the chemical composition of the active magnesium oxide is shown in Table 1, and the identifier and quantity of different active magnesium oxide contents are shown in Table 2. Active magnesia content refers to the amount of MgO in active magnesia cement. According to the study by Mo and Panesar [14], after 56 days of carbonization, the strength of the 40% magnesium oxide test piece is close to that of the 20% magnesium oxide test piece so that three different proportions (mass ratio) are used; MgO in the curing agent doping are 15%, 25%, and 35%.

Table 1: Chemical composition of reactive MgO (%).

MgO	SO_3	CaO	Fe_2O_3	SiO_2	Al_2O_3	P_2O_5
95.50%	1.17%	1.05%	0.18%	1.02%	0.24%	0.28%

Table 2: Material usage.

Magnesium oxide activity	Number	Ratio (MgO/water)	Note
High	M_0	/	All is ordinary cement
High	M_1	1 : 2	The mass of magnesium
High	M_2	1 : 1	oxide and cement
High	M_3	2 : 1	mixture is 300 g

2.2. Sample Preparation

(1) *Optimum Carbonized Masonry Raw Material and Forming Method.* Unlike conventional blocks, the strength of carbonized blocks is based on the chemical interaction among magnesium oxide, water, and carbon dioxide (solid, liquid, and gas phases), so we should have specific requirements for the moisture content, porosity, saturation, and initial strength of the block.

(2) *Optimal Carbonization Environment and Carbonization Method.* Through indoor testing, based on (1), we choose the best raw materials and molding methods to make masonry in order to research carbon dioxide solubility, humidity, temperature, pressure, and other carbonization environmental parameters suitable for masonry carbonization and to research the most effective carbonization methods and processes.

(3) *Carbonized Masonry Strength and Durability.* Through laboratory tests based on (1) and (2), test the compressive strength, wet and dry cycles, and freeze-thaw cycle of typical carbonized masonry to determine the strength and durability of carbonized masonry.

2.3. Experiment Procedure. The static pressure method is adopted for sample preparation, and the specific process is as follows:

(1) Weigh a certain amount of raw materials, stir for five minutes in a small indoor blender, and add weighed water, and then stir for five minutes to ensure uniform mixing

(2) Weigh a sample of the required sample quality, pour the stirred sample into a cylindrical mold (diameter of 50 mm and height of 100 mm), with a vertical pressure on the jack to make cylindrical specimen height of about 80 mm

(3) Demold the cylindrical specimens after compaction and move them to the carbonation tank for curing

(4) When the specimens have been cured to the 3rd, 7th, 14th, 21st, and 28th days, they are, respectively, tested for compressive strength and shear strength, crack resistance, drying shrinkage and expansibility, and diameter, weight, and height of the final sample, and then other tests were carried out

3. Analysis of Test Results

3.1. Optimal Material Mix Ratio. Figure 1 shows the compressive strength values of different magnesium oxide contents in the case of using high-activity magnesia; Figure 2 is the compressive strength of different water-cement ratios in the carbon block. A total of 7 groups of trials were present, 15 test blocks per group.

As we can see from Figure 1, regardless of the amount of active magnesia tested, the strength of the blocks is significantly higher than the compressive strength of the active magnesia block. When the blending amount is M_1, the more the compressive strength of the block is, the more the carbonization time is; after 14 days of carbonization, the compressive strength of the block slightly decreased. When the blending amount is M_2, the compressive strength of the test block at 3rd day of carbonization is higher than that of other groups; after 14 days of carbonization, the compressive strength of the test piece decreased, and the final strength value was slightly closer to M_1. When the blending amount is M_3, the strength of the test block at 3rd day of carbonization is slightly higher than M_1, slightly lower than M_2. After 7 days of carbonization, the strength of the test block was significantly lower than M_1 and M_2 test blocks. And after 14 days of carbonization, the compressive strength of the test block decreased significantly.

From Figure 2, it can be seen that the compressive strengths of the water-cement ratios of the H_2 and H_3 cement blocks are increasing with time. The compressive strength of the H_1 block is reduced within 3–7 days, and the compressive strength of the block increased greatly after 7 days of carbonization.

3.2. Optimal Molding Method. A total of 7 groups of trials were present, 15 test blocks per group. Figure 3 shows the compressive strength of carbonized blocks with different forming methods; Figure 4 shows the effect of different pressure parameters on the compressive strength of carbonized blocks.

As we can see from Figure 3, the compressive strength of the test block produced by the pressure forming method is the highest, and it has the fastest growth rate and the highest compressive strength within 0–7 days. During 7–14 days, the growth rate of the test block made by the pressure forming

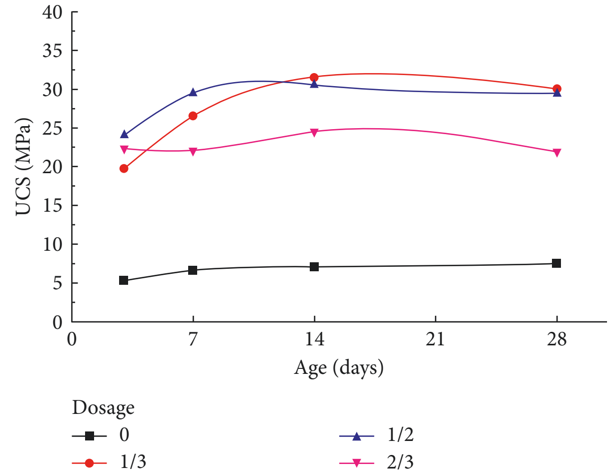

Figure 1: Compressive strength of different magnesium oxide contents.

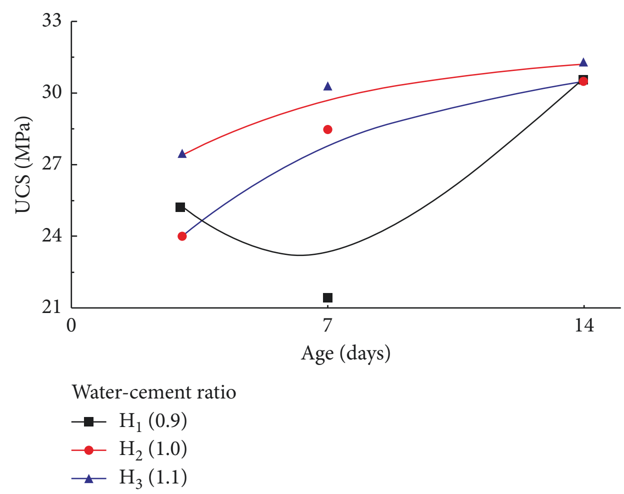

Figure 2: Compressive strength of different water-cement ratios.

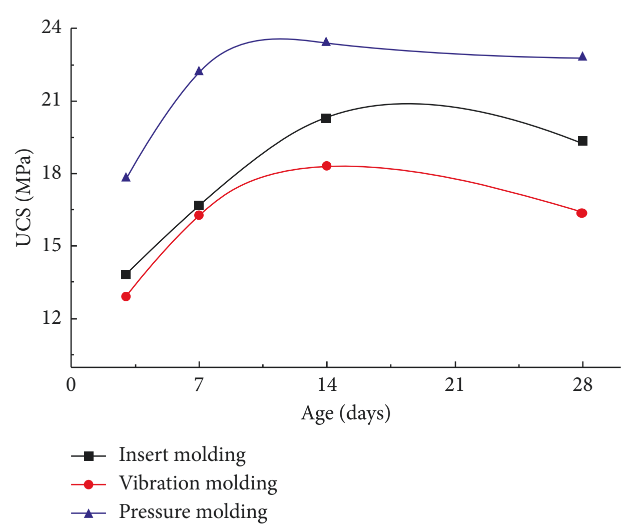

Figure 3: Compressive strength of different forming methods.

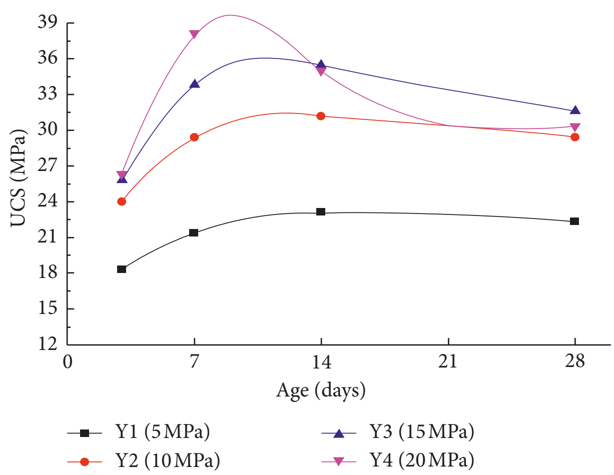

Figure 4: Compressive strength of different pressure parameters.

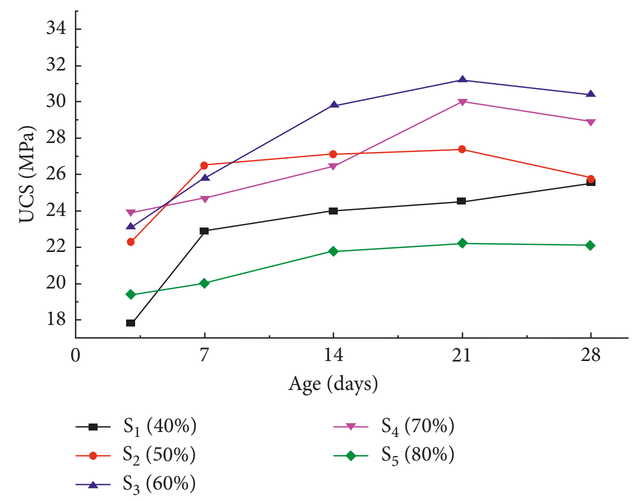

Figure 5: Compressive strength of different humidity.

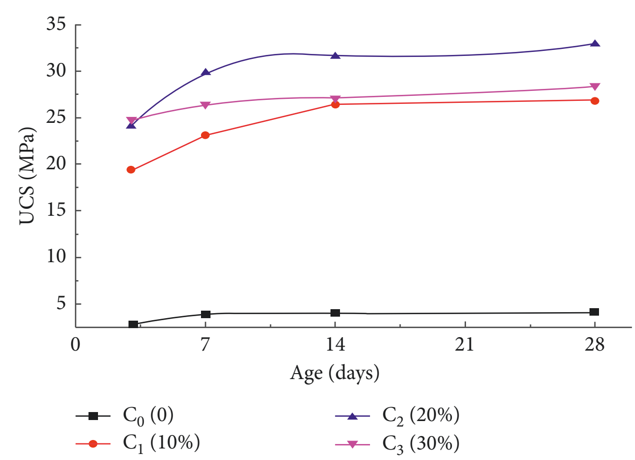

Figure 6: Compressive strength of different CO_2 concentrations.

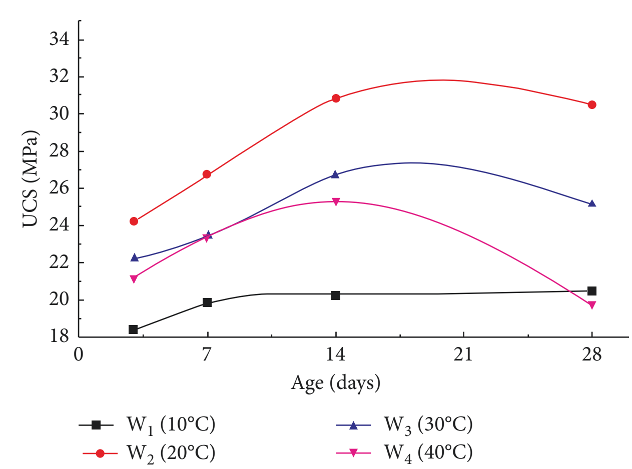

Figure 7: Compressive strength of different temperatures.

method is lower than that of the test block made by the transplant molding method and the vibration forming method.

From Figure 4, we can see that, in the early stage of carbonization (0–7 days), the Y_4 pressure parameter makes the highest increase in the strength of the test block. In the middle period of carbonization (7–14 days), the compressive strength of the Y_4 test block decreases greatly, and the compressive strengths of the Y_1, Y_2, and Y_3 test blocks slightly increase. In the later stage of carbonization (14–28 days), the decrease in compressive strength of the Y4 test block is slightly smaller than that in the medium term. The decreasing order from small to large is Y_1, Y_2, and Y_3.

3.3. Optimal Carbonization Environment. Liu et al. [15] and Collepardi [16] concluded that the performance of concrete is closely related to the humidity during curing, especially the control of temperature and humidity conditions in the early curing process, which has an important influence on the hydration hardening rate, microstructure characteristics, strength development, and durability of the concrete, especially on the concrete surface. The impact of the structure is more pronounced [14]. Figures 5–7 are the effects of different humidity, CO_2 concentrations, and temperatures on the compressive strength of the test block, respectively. A total of 13 groups of trials were present, 15 test blocks per group.

It can be seen from Figures 5–7 that the humidity, CO_2 concentration, and temperature during carbonization are closely related to the compressive strength of the block. Too low or too high will reduce the compressive strength of the carbonized block, which is very important for the practical application of the project. From the experimental results, it can be seen that the best optimal carbonization environment is S_3, C_2, and W_2.

3.4. Water Resistance Test. Whether the pipe piles produced under the current process conditions can meet the water resistance requirements of some severe service environments, especially in the sea, ports, and cold regions, and western regions with high concentration of corrosive media in the groundwater, coastal areas, and inland areas is tested. The index of water resistance is the softening coefficient; according to the softening coefficient, the water resistance of active magnesium oxide carbonized block can be evaluated. From the carbonization to the 28th day of the test block, five test pieces were selected for the test, and the test piece was a cylinder having a height of 80 mm and a diameter of 5 mm. The five pieces were numbered as S_1, S_2, S_3, S_4, and S_5. The selected five test pieces were immersed in water for 1–3 days; after that, the surface moisture was wiped out, and then the strength of the five test pieces was tested. According to the steps of the softening coefficient test in the test method for the performance of autoclaved aerated concrete, the specific steps of the test are carried out. Table 3 shows the water resistance test results of the carbonized blocks.

Putting the sample into the water, the shape of the sample does not change significantly from the previous. However, since the test piece was placed in water for a long time and chemically reacted with water, a small amount of magnesium carbonate trihydrate ($MgCO_3{\cdot}3H_2O$) and silicate crystals were precipitated on the surface of the test piece. When the sample is removed after 3 days, it will be found that the water will drop out of the sample, but soon drip dry, due to the presence of pores in the test piece. During the compression process of the test block, the failure mode of the test block is not significantly different from that of the test block without water immersion. However, due to the high compactness of the active magnesium oxide carbonized block, there will be a small amount of magnesium oxide not involved in the reaction (see the white part shown in Figure 8).

The test has determined that the softening coefficient of the block after putting in water is 0.9576. From the results, the compressive strength of the active magnesium oxide carbonized block is not significantly reduced. The increase in the strength of A_2 may be due to the presence of CO_2 in water. When the test block is placed in water, the strength of the test block is increased by the reaction of magnesium oxide without reaction with water and CO_2 in water. The active magnesium oxide carbon block has high water resistance.

3.5. *Freezing and Thawing Cycle Test.*

Through measuring the damage of the magnesia carbide block during freeze-thaw cycle and measuring the compressive strength loss rate and mass loss rate of the active magnesia carbide block after the specified freeze-thaw cycle test, the frost resistance of the block is evaluated. The test block is composed of 80 mm high and 50 mm diameter cylindrical blocks in one group with 5 pieces in each group. Respectively, they were numbered D_1, D_2, D_3, D_4, and D_5. The number of freeze-thaw cycles of freeze-thaw specimens is 25 cycles according to the specification for the number of freeze-resisting times in the hot summer freezing area. The temperature of the specimens was lowered to −15°C and began to count for 4 hours, and then water was released to dissolve, and they were heated up to 20°C and began to count for 2 hours as a cycle. The test procedure was carried out in accordance with the freeze resistance test procedure in the "Test Methods for the Small Concrete Hollow Block". The mass loss rate and compressive strength loss rate of the active magnesium oxide carbonized block after freeze-thaw are shown in Tables 4 and 5.

Table 3: Compressive strength after water immersion.

Numbering	Diameter (mm)	Destructive load (kN)	Compressive strength (MPa)
S_1	50	17.9	18.14
S_2	50	20.4	20.79
S_3	50	19.7	20.08
S_4	50	19.2	19.57
S_5	50	19.2	19.57
Arithmetic mean			19.63

According to the requirement of dry shrinkage value of blocks in "Test Methods for the Small Concrete Hollow Block" [17–19], the influence of the pressure-temperature coupling on the block displacement of the block is also tested in this experiment. The relevant test was carried out using the frost heaving-thawing universal testing machine. The specific parameters are as follows: displacement change rate—0.004 mm/s; displacement final change—2 mm; temperature settings—ambient temperature to −15°C; and data acquisition—2 times/s. The results are shown in Figure 9.

There was no obvious change in the appearance of the sample during freeze-thaw cycles. After freezing resistance of the sample, it was obvious that the temperature of the sample was low, and the block did not show freeze-thaw damage. After the sample was placed at 20°C for 2 hours, it was obvious that a few crystals appeared around the sample. It can be seen from Figure 9 that the large displacement in the AB stage is due to instrument error, the BC stage temperature has no effect on sample displacement changes due to the coupling of pressure and temperature, and the displacement of the specimen is greatly changed in the CD stage. In the DE stage, the temperature plays a dominant role, the pressure gradually decreases, and the displacement of the sample is 2 mm, and this means that the durability of the test block is well. The freeze-thaw loss rate of the sample mass is less than 5%, and the freeze-thaw loss rate of the compressive strength is less than 25%, which also shows that the sample has good frost resistance.

3.6. *Pipe Pile Preparation Application Analysis.*

The mixing, molding, and curing of PHC pipe pile determine the workability of concrete. The good workability of pipe pile concrete is the key to ensure the quality and production efficiency of pipe pile. Sand and stone aggregate have significant influence on the workability and compressive strength of pipe pile concrete. Sand and stone aggregate with low mud content, good gradation, and sufficient strength should be used for pipe pile preparation. However, under the process, current production conditions indicate that the quality is low and the price is high. Besides, the production cost of the pipe piles is difficult to control. For large building projects and underground projects, when ordinary concrete is used, the concrete structure has a large section, large self-weight, insufficient bearing capacity, high transportation and pouring capacity, and excessive consumption of materials and energy, which really cannot meet the design and construction requirements well. The technology of Portland

(a)

(b)

Figure 8: Picture inside the sample.

Table 4: Mass loss rate of active magnesium oxide carbonized block after freeze-thaw.

Numbering	Quality before freezing and thawing (g)	Quality after freezing and thawing (g)	Loss rate (%)
D_1	362.1	357.3	1.33
D_2	358.9	356.7	0.61
D_3	375.2	371.4	1.01
D_4	365.4	362.3	0.85
D_5	371.6	366.1	1.48
Arithmetic mean			1.06

Table 5: Compressive strength loss rate after freeze-thaw.

Numbering	Compressive strength before freezing and thawing (MPa)	Compressive strength after freezing and thawing (MPa)	Compressive strength loss rate (%)
D_1	24.5	22.1	9.80
D_2	24.0	22.3	7.08
D_3	26.5	23.2	12.45
D_4	24.2	22.4	7.43
D_5	25.5	19.4	23.92
Arithmetic mean			12.14

cement, active mineral admixture, and high-efficiency water reducer are more mature. Its main mechanism is to reduce the water-binder ratio of concrete while reducing the content of harmful pores and defects in the concrete structure, to reduce the alkalinity of hydration products, and to promote the conversion of low-strength hydration products to high-strength hydration products. The strength of concrete materials mainly depends on the ratio of water to cement. According to the classical water-cement ratio theory, the lower the ratio of water to cement ratio is, the higher the strength of concrete is. In the preparation of high-strength concrete, the water-cement ratio should be reduced as much as possible while maintaining the concrete's

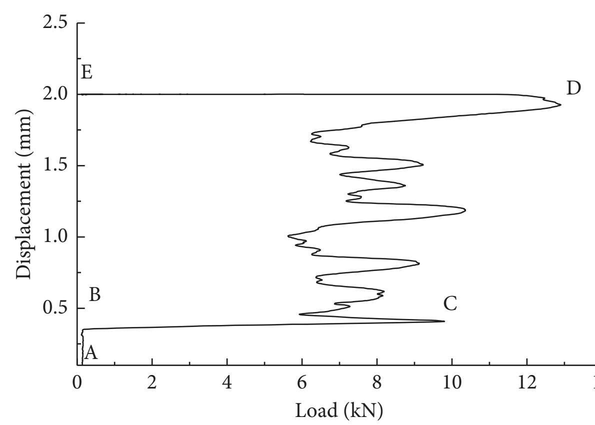

Figure 9: The influence of pressure-temperature coupling on block displacement.

working performance. In order to realize the bureaucratic and bureaucratic performance in coagulation, in addition to the control of the water-binder ratio, the selection of raw materials is also a key factor in the preparation of high-strength concrete. At the same time, it is also necessary to improve the compressive strength of concrete, significantly improve the durability of concrete structures, and improve the application of prefabricated concrete pipe piles in geotechnical engineering examples. The development of energy-saving preparation technology for high-strength and high-performance tubular pile concrete has achieved a new breakthrough in the concrete material system, which provides a better theoretical basis for the popularization and application of tubular pile in underground engineering and, at the same time, opens a new way to the high-performance and long-life of concrete structures in complex environments.

4. Conclusions

(1) The optimum content of active magnesium oxide carbonized block is 35%. The optimum carbonization environment is humidity 60%, temperature

20°C, and 20% CO_2. Best forming method is 10 MPa pressure. The best optimum water-cement ratio is 1.0.

(2) With the greater the compressive strength, the content of active magnesium oxide is the higher, and the compressive strength of the carbonized block reaches or even exceeds 80% on the 3rd day of carbonization, and the maximum compressive strength is 2–3 times of that of the ordinary cement block.

(3) Compared with ordinary cement block, active magnesium oxide as the curing agent for masonry can reduce energy consumption and CO_2 emission; the popularization and application of this energy-saving technology are of great significance to the energy saving and emission reduction and sustainable development of pipe pile industry and has a broad application prospect.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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