Study on the Workability and Mechanical Properties of Pavement Concrete Modified with Graphite-tetradecane Phase Change Material

Yanzhao Feng[1], Chen Wang[1], Jianbin Sun[2,*]
[1]Shandong hi-speed Engineering Construction Group Co., LTD, Jinan, Shandong Province, China,
[2]Shandong Transportation Institute., Jinan, Shandong Province, China
**Corresponding Author.*

Abstract: In this paper, the effect of graphite-tetradecane phase change material (G-t PCM) on pavement concrete's mechanical properties and frost resistance was investigated. Different dosages of G-t PCM (0%, 4%, 8%, and 12%) were used to prepare modified concrete, and the effects of G-t PCM on the properties of concrete were systematically evaluated by compressive strength, flexural strength, and rapid freeze-thaw tests. The findings demonstrated that as the dosage of G-t PCM increased, concrete's compressive and flexural strengths tended to drop; the most significant loss was seen at a dosage of 12%. However, the introduction of G-t PCM significantly improved the frost resistance of concrete, especially the composite phase change material with 8% dosage (phase change temperatures of 5°C and -5°C, respectively), which showed the best frost resistance. The study showed that precise regulation of the dose of G-t PCM may significantly improve the frost resistance of concrete without considerably compromising its mechanical qualities, offering a novel approach to increase the longevity of pavement concrete.

Keywords: Phase Change Materials; G-t PCM Modified Concrete; Frost Resistance; Compressive Strength; Flexural Strength

1. Introduction

As a critical component of road infrastructure, pavement concrete's working and mechanical properties directly affect road service life and safety [1-3]. Researchers have recently focused on developing and applying modified pavement concrete to meet the increasing traffic flow and pavement performance requirements. Phase change materials are widely used in construction, energy, and other fields due to their unique energy storage and release properties [4-6]. In road engineering, graphite-tetradecane phase change material (G-t PCM) has been introduced as a novel modifier for concrete to improve its workability and mechanical properties [7]. G-t PCM can absorb or release heat, thus regulating the temperature of concrete, slowing down the development of thermal stress temperature strain, and improving the durability and stability of concrete.

This study involved the preparation of five different ratios of G-t PCM-modified pavement concrete by adding varying amounts of G-t PCM to the concrete. The objective was to investigate the impact of various quantities of G-t PCM on the compressive and flexural strength of the concrete, as well as its frost resistance. This was achieved through conducting tests on the concrete's compressive and flexural strength, as well as frost resistance.

2. G-t PCM Modified Pavement Concrete Preparation

2.1 Raw Materials

In this study, the G-t PCM was made of expandable graphite produced by Qingdao Hengrunda Graphite Products Company as the setting carrier material. The phase change setting carrier material has a pore size at the micron level, allowing it to absorb and stabilise the phase change material effectively. The selection of tetradecane as the phase transition material was made. The cement material is P.O 425 ordinary silicate cement from Qingdao Shanshui Innovation Cement Co.

2.2 Concrete Mixing Ratio

Five different admixtures of G-t PCM-modified pavement concrete were prepared by mixing a certain amount of fly ash on the baseline mix ratio, replacing fly ash with phase change material, and keeping the water-cement ratio constant. The one without phase change material was the control group, numbered as M-0. Three groups of G-t PCM with phase change temperature of 5°C were used to replace 4%, 8%, and 12% of fly ash by equal mass, numbered M-4, M-8, and M-12, respectively. The other group was mixed with 8% of G-t PCM with phase change temperatures of 5°C, -5°C, and a mass ratio of 1:1) to replace fly ash, numbered M-8. '. The concrete mixes are shown in Table 1.

Table 1. Mix Ratio of Cement Concrete for Pavement with PCM

Number	M-0	M-4	M-8	M-8'	M-12
Water (kg/m^3)	124.5	124.5	124.5	124.5	124.5
Cement (kg/m^3)	265	265	265	265	265
Flyash (kg/m^3)	65.0	62.4	59.8	59.8	57.2
Fine aggregate (kg/m^3)	705.6	705.6	705.6	705.6	705.6
Coarse aggregate (kg/m^3)	1254.4	1254.4	1254.4	1254.4	1254.4
Water reducer (kg/m^3)	15.18	15.18	15.18	15.18	15.18
Phase change material (kg/m^3)	0	2.6	5.2	5.2	7.8

3. Experiments

3.1 Compressive Strength Test of Concrete Cube

This research conducted mechanical property tests on G-t PCM-modified pavement concrete in accordance with the Test Regulations for Highway Engineering Cement and Cement Concrete (JTG 3420-2020). The size of the specimen was 100mm×100mm×100mm, and the specimen was taken out for test as soon as it reached its age, with the forming side of the specimen facing up. The press exerts a force at a rate of 0.5 megapascals per second and positions the center of the specimen in line with the center of the universal testing machine. It continues applying the stress until the specimen fractures. A 28-day compressive strength test was conducted on concrete specimens containing microencapsulated PCM with varying doses. Three specimens were examined for each composition ratio. The measured value was determined by calculating the average of the three specimens. The calculation of the compressive strength of concrete specimens is determined using formula (1):

$$f_{cu} = 0.95 \times \frac{F}{A} \quad (1)$$

The concrete cube compressive strength (f_{cu}) is measured in MPa. The size conversion factor is 0.95. The ultimate load (F) is measured in Newtons (N). The compression area (A) is measured in square millimetres (mm^2).

3.2 Bending Strength Test of Concrete Cube

This investigation used a 2000kN universal testing machine to conduct a three-point loading test. The specimen was positioned with its forming surface facing upwards, and the loading speed was set at 0.05Mpa/s. Flexural and tensile strength tests were conducted on microencapsulated phase change material concrete specimens with different dosages. Three specimens with similar characteristics were chosen from each group, and the average value of these three specimens was used as the test value. The flexural strength of the specimens was calculated according to formula (2):

$$f_f = 0.85 \times \frac{FL}{bh^2} \quad (2)$$

The flexural strength (f_f) of the specimen is measured in megapascals (MPa). The size conversion factor is 0.85. The height of the specimen is denoted as h in millimetres (mm), while the breadth is denoted as b in mm. The ultimate load (F) is measured in newtons (N), and the distance between supports is denoted as L in mm.After the freeze-thaw cycle test, the relative durability index is calculated as follows formula (3):

$$K_n = \frac{P \times N}{300} \quad (3)$$

K_n is the percentage of relative durability index of the specimen after n freeze-thaw cycles. N is the maximum number of freeze-thaw cycles that the specimen has undergone. P is the average value, expressed as a percentage, of the relative dynamic elastic modulus of the three specimens after n freeze-thaw cycles. The computation is precise to within a margin of error of 0.1%.

3.3 Rapid Freeze-thaw Test of Concrete

This research performed the fast freeze-thaw test in accordance with the specifications provided in the JTG3420-2020 Highway Engineering Cement and Cement Concrete Test Regulations. The concrete quick freeze-thaw testing equipment was configured with a specimen center temperature of -16℃, a maximum temperature of 4℃, and a total of 50 cycles. The test may be terminated when the relative dynamic elastic modulus of the specimen decreases to 60% or when the mass loss rate of the specimen exceeds 5%.

$$E_d = 13.224 \times 10^{-4} \times WL^3 f^2 / a^4 \quad (4)$$

Where: E_d is the dynamic elastic modulus (MPa) of the concrete specimen; Alpha is the side length of the specimen square section (mm); L is the length of the specimen (mm); W is the mass of the specimen (kg); The variable f_0 represents the transverse fundamental frequency of the specimen, measured in Hertz (Hz). The formula (5) is used to compute the relative dynamic elastic modulus of concrete:

$$P = \frac{{f_n}^2}{{f_0}^2} \times 100\% \quad (5)$$

Where: P represents the relative dynamic elastic modulus of the specimen expressed as a percentage after undergoing n freeze-thaw cycles, and fn is the transverse fundamental frequency of the specimen measured in Hz after undergoing n freeze-thaw cycles. F0 is the original transverse fundamental frequency (measured in Hz) of the material prior to conducting the test. The test result is derived by computing the mean value of the three specimens with a precision of 0.1%.

4. Results and Discussion

4.1 Influence of Different Dosages of G-t PCM on Bending and Compressive Strength of Concrete

Figure 1 and Figure 2 show the influence of different G-t PCM content on pavement concrete's bending and compressive strength. The figure clearly demonstrates that the flexographic strength and compressive strength of concrete decrease gradually as the amount of G-t PCM increases. This indicates that the addition of G-t PCM negatively impacts the mechanical characteristics of concrete. When the content reaches 12%, the flexographic strength of concrete has dropped to 5.04MPa. The compressive strength decreased to 40.5MPa, and the decline trend of concrete strength was more evident than before. The flexural strength loss rates of specimens M-4, M-8, M-8 ', and M-12 reached 6.13%, 13.72%, 14.74%, and 26.42%, respectively, and the compressive strength loss rates of specimens M-8' and M-12 reached 7.0%, 16.2%, 15.5%, and 24.7%, respectively.

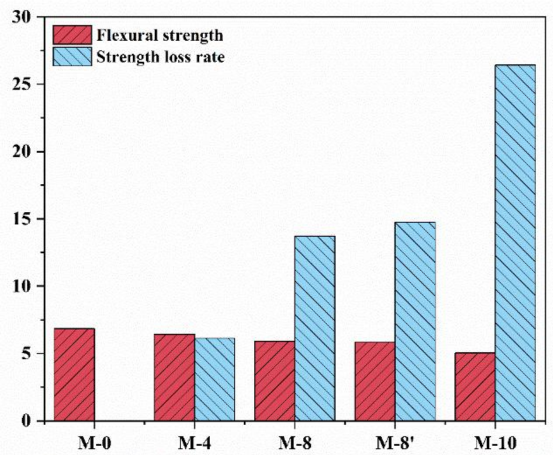

Figure 1. Influence of Different G-t PCM Content on Flexural Strength of Pavement Concrete

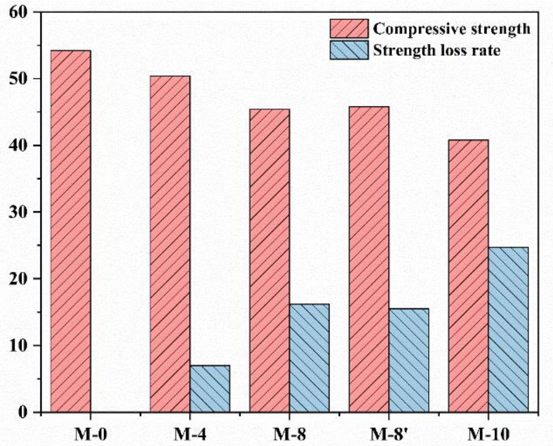

Figure 2. Influence of Different G-t PCM Content on Compressive Strength of Pavement Concrete

Studies have shown that the reasons for this may be: (1) Since G-t PCM phase change materials usually exist in the form of particles when added to concrete, a certain number of microscopic voids will be introduced to increase its porosity, and these voids will lead to the reduction of concrete compactness, thereby reducing the mechanical properties of concrete, so as the content of phase change materials increases, The decreasing trend of concrete strength is more apparent [8-10]. (2) Through SEM microscopic analysis of the internal microstructure of concrete, it is found that the interface between G-t PCM and concrete matrix has poor bonding or peeling phenomenon. During the loading process, due to the weakness of the interface, the G-t PCM is separated from the concrete, which weakens its bearing capacity and thus reduces the mechanical properties of the concrete. (3) G-t PCM's strength is comparatively feeble compared to cement hydration products, resulting in a decrease in the load-bearing capability of the concrete structure as a whole. There are cracks between the cement matrix and G-t PCM, which may result from thermal expansion and cold contraction [11,12]. The presence of voids and fractures in the concrete leads to a decrease in its strength. When comparing the strength of the modified concrete specimens with the addition of 8% mG-t PCM (phase change temperature is 5℃) and the compound addition of 8% mG-t PCM (phase change temperature is 5℃ and -5℃), it is evident that there is no substantial variation in strength when the phase change temperature does not match the precise dosage. The specimens saw a decrease in flexural strength of around 14% and a decrease in compressive strength of approximately 16%. The absence of a substantial influence of the phase change temperature of the phase change material on the strength of concrete is primarily due to the fact that the temperature of the external environment during the test is higher than the temperature at which phase change occurs, thereby impeding the occurrence of the phase change process.

4.2 Research on Frost Resistance of G-t PCM Modified Pavement Concrete

4.2.1 Relative Dynamic Elastic Modulus

The freeze-thaw damage to concrete may be assessed, and its durability can be evaluated by measuring the dynamic elastic modulus of concrete after undergoing the freeze-thaw cycle. The relative dynamic elastic modulus of the concrete test block after undergoing the freeze-thaw cycle may be calculated by measuring the transverse fundamental frequency of the specimen using formula (4). Figure 3 depicts the effect of the freeze-thaw cycle on the relative dynamic elastic modulus of G-t PCM-modified pavement concrete. Figure 3 illustrates that the relative dynamic elastic modulus of each test group declined with an increasing number of freeze-thaw cycles. Specimen M-0 experiences significant modifications throughout the freeze-thaw cycle, exhibiting a fast decline rate. At the point when the freeze-thaw cycle reaches a count of 200, the relative dynamic elastic modulus reduces to 59.8%, which signifies that the specimen has achieved its failure condition.

The change trend of specimens M-12 and M-8 'is similar. For specimen M-8', the relative dynamic elastic modulus decrease value is slightly smaller than specimen M-12. Once the freeze-thaw cycles reach a count of 275, the magnitude of the drop in relative dynamic elastic modulus becomes more significant, leading to an increased level of degradation in the specimen due to freeze-thaw. The relative dynamic elastic modulus is reduced to 59.1%, which achieves the failure condition. After subjecting the specimen M-8 to 325 cycles of freezing and thawing, the relative dynamic elastic modulus was reduced to 56.7%. Before freeze-thaw cycle 150, specimens M-4 and M-8 exhibited a comparable trend in modifying their relative dynamic elastic modulus. Following 150 freeze-thaw cycles, specimens M-4 and M-8 exhibited a notable disparity in their changing patterns, with specimen M-4 seeing a quick decline in its relative dynamic elastic modulus. After being subjected to 225 freeze-thaw cycles, the relative dynamic elastic modulus of specimens M-4 decreased rapidly. Specimen M-8 had a fall in its relative dynamic elastic modulus to 58.3% after undergoing 250 freeze-thaw cycles, indicating that it reached the point of freeze-thaw failure.

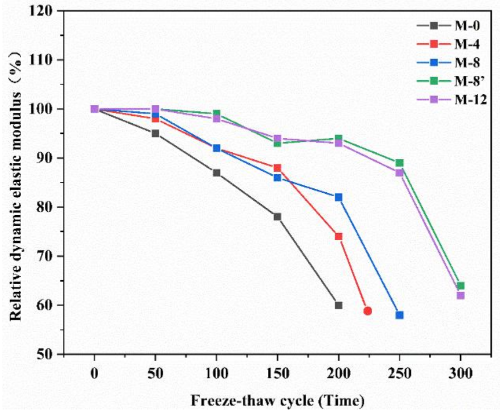

Figure 3. Influence of Freeze-Thaw Cycle on the Relative Dynamic Elastic Modulus of mPCMs Modified Pavement Concrete

4.2.2 Relative Durability Index

Figure 4 displays the relative durability index of G-t PCM-modified pavement concrete based on the maximum number of freeze-thaw cycles in each test group. The control test group, represented by specimen M-0, has a relative durability index of 39.867%. The relative durability index of M-4, M-8, M-8 ', and M-12 specimens containing phase change materials were 44.475%, 48.593%, 61452%, and 59.100%, respectively. The relative durability index of the specimens with PCM increased by 11.6%, 21.9%, 54.1% and 48.2%, respectively. The addition of 8%G-t PCM improved the freezing resistance of concrete better.

The freeze-thaw cycle test was conducted on pavement concrete modified with microencapsulated phase change materials (PCM). The mass loss rate, relative dynamic elastic modulus, and relative durability index of each sample group were compared and analyzed. It was found that the addition of G-t PCM had a better effect on the freezing resistance of concrete. With the increase of the content of phase change material, the freezing resistance of concrete is gradually improved. Still, when the content of phase change material is higher than a specific value, the improvement of its freezing resistance is slowly reduced, and even the freezing resistance is reduced. Therefore, it is necessary to control the phase change material's content reasonably. In this test, it can be seen that when the concrete is mixed with 8%G-t PCM (phase change temperature is 5°C and -5°C, respectively), the specimen shows better frost resistance than the other experimental groups, which is the optimal ratio in the test scheme.

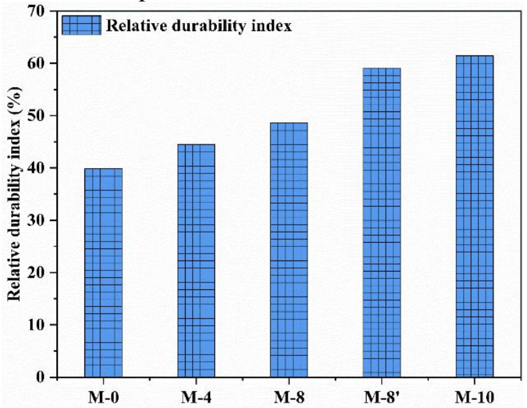

Figure 4. Relative Durability Index of mPCMs Modified Pavement Concrete

5. Conclusions

This study investigated the effects of graphite-tetradecane phase change material (G-t PCM) on pavement concrete's mechanical properties and frost resistance. The following conclusions were obtained:

(1) Influence on mechanical properties: With the increase of G-t PCM content, concrete's compressive and flexographic strength showed a decreasing trend. When the maximum dosage is 12%, the compressive strength decreases to 40.5MPa, and the bending strength decreases to 5.04MPa. This is mainly due to the introduction of micro-voidage in G-t PCM, which reduces concrete's compactness and interfacial bonding properties, resulting in a decline in overall mechanical properties.

(2) Improvement of frost resistance: incorporating G-t PCM significantly improves the frost resistance of concrete. Through the rapid freeze-thaw test, it was found that the G-t PCM composite specimens with the content of 8% (phase transformation temperature of 5°C and -5°C) showed the best freeze-resistance and its relative dynamic elastic modulus and relative durability index were significantly better than other specimen groups.

(3) Dosage optimization: The optimal dosage of G-t PCM in concrete is 8%. Excessive dosage (12%) can improve the freeze-resistance performance but hurts mechanical properties. Therefore, it is necessary to control the dosage of phase change materials reasonably and consider the comprehensive optimization of mechanical properties and freeze-resistance performance.

This study provides the theoretical basis and practical reference for applying G-t PCM in pavement concrete, points out the importance of reasonable dosage, and offers new methods and ideas for improving the durability and stability of pavement concrete.

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