Comparative Study on Microwave Absorbing Heating Characteristics and Microwave Deicing Performance of Airport Pavement Modified Concrete

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Abstract

In this paper, the airport pavement concrete has been taken as the main research object, three kinds of absorbing materials, namely silicon carbide (SiC), iron oxide (Fe_3O_4) and graphite, have been respectively mixed into the concrete, and an open microwave testing system has been established. Based on this system, the basic mechanical properties, microwave heating characteristics, microwave deicing effect and its influencing factors of modified concrete are systematically studied. In addition, a comparative analysis of the influence mechanism of different absorbing materials on the strength and absorbing performance of pavement concrete is carried out. The results showed that the addition of SiC, Fe_3O_4 , and graphite could effectively enhance the microwave effect of pavement concrete, and the more the addition, the more obvious the improvement. Furthermore, under the same mixing amount, the degree of improvement of microwave deicing performance of each absorbing material from large to small is graphite, Fe_3O_4 , SiC. However, the addition of graphite will form several weak links in concrete, thereby reducing its overall mechanical properties. SiC can slightly improve the mechanical properties of pavement concrete, but it has no significant effect on the microwave absorption properties. With the addition of Fe_3O_4 , the strength of concrete changes little, and the effect of microwave absorbing heating and microwave deicing is remarkable. In general, the comprehensive performance of microwave deicing of Fe_3O_4 modified concrete is optimal. This study has high scientific and practical significance, and can be widely applied to deicing projects on airports and high-grade highways.

1 Introduction

The cold areas in northern China are characterized by wide distribution, large precipitation in winter and long duration of low temperature. In some areas, severe snow and ice weather occurs frequently, which causes the airport pavement to be in a state of ice for a long time. The ice cover on the pavement surface will affect the friction coefficient and roughness to a great extent and significantly reduce the anti-skid performance, thus seriously endanger flight safety (Yang and Jin, 2002). Therefore, rapid and effective removal of pavement ice is a hot issue that needs to be solved urgently. Traditional deicing methods mainly include clearing method, melting method and restraining method (Zhou et al., 2014). Manual clearing method has high labor intensity and low working efficiency. Mechanical removal method has low ice removal rate and great damage to road surface (Yu, 2011). Chemical melting method has great harm to the pavement performance and ecological environment (Fu, 2010). Thermal melting method has high cost and low energy utilization (Wu, 2005). Although these methods can deice the road surface, they also expose the above defects at the same time. In order to make up for the problems existing in the traditional deicing method in practical operation, it is of economic value and practical significance to seek a deicing method with high energy utilization rate, less damage to the road surface and environmental protection.

Microwave heating technology, as rapid development of environmental protection technology, is widely used in the deicing of road surface in winter, and has achieved certain results. In recent years, many

studies have been carried out on microwave deicing. Hopstock (2003, 2005) tested the improvement of microwave deicing efficiency of asphalt pavement by preparing microwave absorbing concrete with iron tunnel rock as aggregate. Wang (2010) established magnetron heating model, and calculated the electric field distribution of heating material by HFSS simulation. Wang et al. (2016) put forward a standard evaluation method of deicing, and from the perspective of rapid deicing and optimal economy, presented the best matching scheme for the new deicing design. Gao et al. (2017) explored the feasibility of using steel slag as the aggregate of microwave deicing asphalt mixture through experiments, and determined the most effective volume and particle size to partially replace the traditional aggregate. Gallego et al. (2013) used steel fiber as microwave absorbing component in asphalt concrete to increase the surface temperature of asphalt concrete, thereby improving deicing efficiency. Liu et al. (2018) improved the efficiency of concrete deicing by adding iron black into concrete. In the previous research on microwave deicing, most scholars focused on asphalt concrete. However, there are great differences in appearance and performance between cement concrete and asphalt concrete. Therefore, the existing conclusions are not suitable for microwave deicing of cement concrete pavement. In addition, most of the current scholars focus on a single microwave absorbing admixture, and there is a lack of cross-sectional comparative studies on a variety of different absorbing admixtures. Therefore, it is of great significance to test and study the static mechanical properties and the effect of microwave deicing of concrete mixed with different absorbing materials, so as to seek the best absorbing materials, optimize the pavement mix design, and promote the microwave deicing technology.

In this paper, silicon carbide (SiC), ferric oxide (Fe_3O_4) and graphite have been respectively mixed into concrete to prepare three kinds of absorbing concrete. The microwave heating efficiency and deicing effect of concrete have been studied, and its compressive strength and flexural strength have been tested. Finally, the mechanism of different absorbing materials on concrete has been compared and analyzed. The research results provide a theoretical basis for further promotion of microwave deicing methods.

2 Raw Materials And Specimen Preparation

2.1 Raw materials

The cement used in this paper is 42.5 ordinary portland cement, and the water reducing agent is polycarboxylic acid water reducing agent with water reducing rate of 35%. The specific mix proportion design is shown in Table 1 below.

In this paper, silicon carbide (SiC), iron oxide (Fe_3O_4) and graphite are selected as the admixture of concrete (Fig. 1-Fig. 3).

Table 1
Concrete reference mix ratio

Material consumption per m ³ of concrete (kg)	cement	water	large stone	medium stone	small stone	sand	water- reducing agent
	330	135	575	575	287.5	562.5	3.63

2.2 Specimen preparation

The size of the specimens was 150 mm × 150 mm × 150 mm, and the amount of absorbing material was 0%, 5%, 10% and 15% respectively. In order to fully ensure the dispersion and uniformity of the distribution of the absorbing admixture in the concrete matrix and promote the formation of standardized specimen properties, this paper adopted PC mixing method. The specific steps were as follows: first, mixed coarse aggregate and fine aggregate for 60 s, then poured in absorbing material and cement and continue to mix for 60 s, and finally, added water and water reducing agent at the same time and mixed for 120 s.

After the concrete mixing process was completed, the concrete was poured into the mold of 150 mm×150 mm×150 mm, and cured for 28 days under the standard state ($T=20\pm2^{\circ}\text{C}$, relative humidity>95%). Subsequently, the concrete specimens were made.

After curing, we carried out the frozen ice layer treatment on the concrete surface. The specific methods were as follows: Rigid PVC board was used to surround and fix the specimen to ensure that the upper edge of the board was parallel to and 20 mm higher than the concrete edge, and the whole specimen was wrapped with plastic cloth. Subsequently, water was poured over the concrete surface, so that the water level just reached the upper edge of the PVC board. Finally, the specimen was placed in the low-temperature control cabinet for freezing. After the completion of freezing, the specimen could be prepared as shown in Fig. 4 below.

3 Test Equipment And Test Method

3.1 Test equipment

The test equipment used for microwave deicing is an open microwave transmitting system designed independently. The equipment was composed of magnetron, water cooling device, height adjusting device, infrared temperature tester and external microwave control box, as shown in Fig. 5.

The temperature sensor was tested by WZP-128 thermal resistance with a temperature range of $-30^{\circ}\text{C} \sim 250^{\circ}\text{C}$. Its performance was stable and the temperature measurement accuracy could reach 0.1°C . In the test, the MEACON multi-channel paperless recorder was used with a sampling accuracy of 0.1°C and a sampling period of 1s. It was able to collect and store the temperature data of 12 thermal resistances simultaneously.

3.2 Test method

- (1) The compressive strength and flexural strength of SiC, Fe_3O_4 and graphite concrete with different content are tested by electro-hydraulic servo test system, and the effects of three kinds of absorbing materials on the mechanical properties of specimens are compared and analyzed.
- (2) The microwave source port is controlled to be 20 mm above the specimen surface, and the real-time temperature of the surface center point of three modified concrete specimens with different dosages is monitored and recorded every 4 s.
- (3) Simultaneously, the microwave source height of the device is adjusted to 20, 30, 50, 70, and 100 mm. The real-time temperature at the center of the specimen is monitored and recorded every 4 s.
- (4) Subsequently, the height of the microwave source is fixed as 20 mm. The ice state of SiC15, Fe15 and C15 ice covered modified concrete specimens in the process of deicing is investigated, and the comparative analysis of the deicing efficiency and effect is conducted.

4 Test Results And Analysis

Through tests, the compressive strength and flexural strength of SiC, Fe_3O_4 and graphite modified concrete, as well as the real-time temperature during the microwave heating process are obtained. By comparing and analyzing the data and integrating the changing trends, the following quantitative results can be obtained.

4.1 Influence of absorbing admixture on mechanical properties of concrete

In this paper, with reference to the standard method for testing mechanical properties of ordinary concrete, an electro-hydraulic servo test system was used to conduct static compressive and flexural tests on ordinary concrete and wave-absorbing concrete specimens, with the loading rate of 0.5 MPa/s. The compressive strength and flexural strength of SiC, Fe_3O_4 and graphite concrete with different dosage were obtained respectively. Based on the test data, the effects of the three kinds of wave absorbing materials on the mechanical properties of concrete were compared and plotted as shown in Fig. 6.

It can be seen from the comparative analysis in Fig. 6 that the three kinds of absorbing admixtures have different effects on the basic mechanical properties of concrete. To some extent, SiC can improve the compressive strength and flexural strength of concrete, and the compressive strength and flexural strength increase with the increase of SiC content between 5% and 10%, and reach the peak value when the content is 10%. After the addition of SiC, the two performance indexes are reduced. The compressive strength and flexural strength of Fe_3O_4 concrete will decrease with the increase of Fe_3O_4 content. The rate of decrease in the early stage is small, and the rate in the later stage increases. Compared with Fe_3O_4 concrete, the compressive strength and flexural strength of graphite concrete decrease more. When the content of graphite is 15%, the compressive strength is only 58.1% of the PC compressive strength, and

the flexural strength is only 81.9% of the PC flexural strength. The reduced concrete strength can still meet the road standard.

4.2 Effect of SiC on microwave heating efficiency of concrete

The temperature rise curve of the surface central point of concrete with different SiC content is shown in Fig. 7. It can be seen that (1) The real-time temperature curves all show a linear upward trend, and the incorporation of SiC will increase the temperature rise rate of concrete, so that the final temperature rise range increase as well. (2) When the height of the microwave source is fixed at 20 mm and the content of SiC is 5%, 10% and 15%, the temperature rise range of the central point on the corresponding concrete surface is 58.3°C, 63.5°C and 70.8°C, which are 112%, 109% and 110% of that of ordinary concrete respectively. The greater the content of SiC, the greater the temperature rise of concrete. Each 5% increase in the amount of SiC increases the temperature rise by 6.2°C, 5.2°C, and 6.7°C, respectively. The increase in the same amount of SiC on the microwave effect of concrete is basically the same.

In order to further analyze the influence of the addition of SiC on the microwave effect of concrete, the temperature rise amplitude of SiC5, SiC10 and SiC15 at different microwave source heights is tested, as shown in Fig. 8. It can be seen that (1) After adding SiC with different content, the change trend of temperature rise amplitude is the same as that of PC, which decreases with the increase of microwave source height. (2) The higher the content of SiC, the higher the temperature rise of concrete. (3) When the microwave source height reaches 30, 50, 70, and 100 mm, the temperature rise amplitude of SiC15 relative to PC is 19.8°C, 15.2°C, 13.6°C, and 4.9°C, respectively. The incorporation of SiC increases the temperature rise to a lesser extent. As the height of the microwave source increases, the temperature rise gradually decreases.

4.3 Effect of Fe_3O_4 on microwave heating efficiency of concrete

The temperature rise curve of the central point on the surface of Fe5, Fe10 and Fe15 specimens is shown in Fig. 9. It can be seen that (1) The surface temperature rise of concrete increases with the addition of Fe_3O_4 . (2) At the same height of microwave source, the higher the content of Fe_3O_4 , the greater the microwave effect of concrete. (3) The real-time temperature curve of ordinary concrete shows a linear upward trend. After incorporation of Fe_3O_4 , the temperature rise rate gradually decreases with the increase of microwave action time, which is related to the temperature sensitivity of Fe_3O_4 microwave effect.

In order to further explore the influence of Fe_3O_4 on the microwave effect of concrete, the temperature rise amplitude at the central point of the specimen at different microwave source heights is measured, as shown in Fig. 10. It can be seen that (1) The temperature rise amplitude of concrete decreases with the increase of the microwave source height after adding different contents of Fe_3O_4 . (2) When the

microwave source height is fixed at 20 mm, the temperature rise of Fe15 can reach 99.9°C, while the temperature rise of PC is only 52.1°C. The addition of Fe_3O_4 increases the temperature by 47.8°C. The effect of the addition of Fe_3O_4 on the temperature of concrete gradually decreases with the height of the microwave source, and as the height increases, the decreasing amount gradually increases.

4.4 Effect of graphite on microwave heating efficiency of concrete

The temperature rise curve of the surface central point of concrete with different graphite content is shown in Fig. 11. It can be seen that (1) With the prolongation of microwave action time, the temperature rise curve of graphite concrete always shows a linear trend. (2) After graphite is added, the temperature rise of concrete in the microwave field increases significantly. When the graphite content is 5%, 10% and 15%, the temperature rise is 78.1°C, 101°C and 130.1°C, respectively, which is 149%, 193% and 249% of that of ordinary concrete.

In order to judge the improvement of the microwave effect of graphite on concrete more accurately, the temperature rise amplitude of C5, C10 and C15 at different microwave source heights is analyzed, as shown in Fig. 12. It can be seen that (1) When different amounts of graphite are added, the temperature rise amplitude of concrete decreases with the increase of the height of the microwave source, and the decrease rate is obvious. (2) When the microwave source height is 20 mm, the temperature rise amplitude increases by about 25°C for every 5% increase of graphite content. The microwave thermal effect of concrete is greatly improved by adding graphite.

4.5 Comparative analysis of deicing effect

In order to further explore the influence of SiC admixture on the microwave deicing efficiency of concrete, tests on the surface ice state of SiC15 specimen under different microwave action times is carried out. The results are shown in Fig. 13. It can be seen that when the microwave action time is within the range of 0~70 s, the ice layer above the SiC15 specimen always maintains the initial freezing state, and the thickness of ice does not change. When the microwave action time reaches 90 s, the melting phenomenon starts to appear below the ice layer at the central point of the concrete surface. When the microwave is applied for 120 s, the ice above the concrete central point has completely melted, and the surface melting area continues to increase. When the microwave action time reaches 160 s, the melting area of the ice layer above the SiC15 specimen expands further.

In order to explore the effect of Fe_3O_4 on the efficiency of microwave deicing of concrete, the ice state of Fe15 specimen surface under different microwave action time is given, as shown in Fig. 14. It can be seen that when the microwave action time is in the range of 0-50s, the ice layer above the concrete is always frozen and has not changed. When the microwave is applied for 70 s, the ice layer below the Fe15 central point melts, which is shortened by 20s compared with the time when the SiC15 specimen of sic begins to melt. When the microwave action time is 110 s, the ice layer above the Fe15 central point has completely melted, and the melting area on the surface of the specimen continues to increase. When the

microwave action reaches 160 s, the melting area on the concrete surface further expands, and at the same time, a considerable part of the ice layer has completely melted into water.

The ice state of C15 under different microwave time is given, as shown in Fig. 15. It can be seen that the ice layer above C15 is always frozen within 0-30 s of microwave action. When the microwave action is 50 s, the ice layer below the concrete central point has melted. Then the melting area at the center of the ice layer gradually becomes larger, while the thickness of the ice layer above the melting area becomes thinner. When the microwave is applied for 90 s, it can be seen that the central part of C15 specimen has completely melted, and the melting area of concrete surface continues to increase. When the microwave action reaches 130 s, the area where the ice layer on the concrete surface completely melts continues to increase. However, the increasing range is not obvious, and the water under ice layer has leaked out from the periphery of the concrete. To sum up, it can be analyzed that at the same 15% content, the microwave deicing efficiency of three microwave absorbing materials on concrete in order from high to low is graphite, Fe_3O_4 , SiC.

4.6 Mechanism analysis

Different wave absorbing admixtures have different effects on concrete strength. SiC is a hexagonal crystal with a specific gravity between 3.20 and 3.25, which has the advantages of stable chemical properties, high thermal conductivity and good wear resistance (Huang and Liu, 2009; Joshi et al., 2000). After mixing with concrete, due to its high hardness, it can improve the mechanical properties of weak links such as transition zone to some extent, so the mechanical properties of concrete have been improved. However, when the specimen is cured and formed in strength, the powdered Fe_3O_4 will not produce cohesive force, so the addition of Fe_3O_4 will not improve the mechanical properties of concrete. When a large amount of Fe_3O_4 is added, the cementation of cement will be weakened due to the dilution of Fe_3O_4 , so the compressive strength and flexural strength will show a downward trend with the increase of the content. For graphite, the density is small, the pores are well developed and the surface area is large. After the specimen is formed and cured, due to the small density of graphite itself, it basically has no strength and will form many weak links in concrete. When subjected to external forces, these weak links are destroyed rapidly, which makes the concrete specimen lose strength. Therefore, the compressive and flexural strength of graphite concrete show a decreasing trend, and the decreasing amplitude of the strength increases with the increase of the graphite content.

The mechanism of improving the microwave heating efficiency of concrete is also different with different absorbing admixtures. SiC material itself has low resistivity and strong electrical conductivity. Under the action of microwave, SiC will be polarized by particles inside the concrete (Shen et al., 2007). The direction of the polarization vector is shifted by an angle from the electric field, thus producing a current in phase with the microwave field, which generates vortices in the concrete and in turn generates heat. After adding Fe_3O_4 into concrete, the relative positions of Fe^{3+} and Fe^{2+} in Fe_3O_4 make it highly magnetic. The magnetic moment of Fe_3O_4 is determined by the direction of the low-frequency alternating magnetic field under the influence of microwaves. Therefore, the molecules will rearrange and rotate rapidly under

the influence of the magnetic field, thereby converting the microwave energy into heat. At the same time, due to the strong magnetism brought by Fe_3O_4 , the magnetic induction intensity of concrete lags behind its own magnetic field intensity in the process of repeated magnetization, which will also convert the microwave energy into heat (Liu et al., 2007; Zhang, 2010). Graphite has excellent conductive properties and can form a whole or partial conductive network in concrete. Under the action of microwave, graphite concrete will cause heat loss because of the conduction current. Graphite particle size is small and the specific surface area is large. When irradiated by microwave, it is easy to produce multiple scattering and reflection of microwave, which can make the microwave lose rapidly after entering concrete and emit a large amount of heat (Duan et al., 2008; Jahanbakhsh et al., 2018; Meng et al., 2009).

5 Conclusion

In this paper, pavement concrete with three kinds of absorbing materials doped with silicon carbide (SiC), ferric oxide (Fe_3O_4) and graphite has been taken as the research object. The basic mechanical properties, microwave heating characteristics and microwave deicing effect of pavement concrete after incorporating wave absorbing materials have been tested respectively, and the action mechanism of different wave absorbing materials on concrete have been compared and analyzed. The main conclusions are as follows.

(1) The addition of SiC, Fe_3O_4 , and graphite can effectively improve the microwave effect of concrete, and the more the amount is, the more obvious the microwave effect of concrete is. Under the same dosage, the improvement degree of the microwave deicing performance of each absorbing material on concrete is as follows: graphite, Fe_3O_4 , SiC.

(2) After adding SiC and graphite, the temperature rise curves of concrete show a linear upward trend, and the temperature rise rate is not affected by temperature. When Fe_3O_4 is added, the higher the temperature of concrete is, the lower the temperature rise rate is in the microwave field. When the temperature is greater than 40°C , the temperature rise rate of concrete decreases rapidly, and the microwave effect of Fe_3O_4 is temperature-sensitive.

(3) The addition of Fe_3O_4 and graphite will reduce the compressive and flexural strength of concrete, and the influence of graphite is greater than that of Fe_3O_4 . The addition of silicon carbide can increase the compressive and flexural strength of concrete by 5–10%, and improve the basic mechanical properties of concrete to a certain extent.

(4) Through a comparative analysis of concrete strength and temperature rise amplitude, among the three kinds of absorbing materials, SiC can slightly improve the mechanical properties of concrete, but the improvement of microwave effect is relatively low. Graphite can increase the efficiency of microwave heating of concrete by 9%, but the mechanical properties of concrete are greatly reduced. However, the addition of Fe_3O_4 has a small decrease in the strength of concrete, and the microwave effect on concrete

can be increased by 192%. The microwave heating effect and deicing effect are remarkable. Therefore, the Fe_3O_4 modified concrete has a better comprehensive performance.

Based on the above conclusions, this paper provides a certain theoretical basis and technical support for the microwave deicing technology of airport pavement, which is of high scientific significance and popularization value. In future studies, we will further study the interaction mechanism of various microwave absorbing materials and explore the optimal airport pavement modified concrete.

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Figures

Figure 1

SiC

Figure 2

Fe_3O_4

Figure 3

Graphite

Figure 4

Concrete specimens of frozen ice

(a) Deicing main equipment

(b) Magnetron

(c) Water cooling pipeline

(d) Height control handle

(e) Infrared thermometer

(f) Remote control box

Figure 5

Microwave deicing test equipment

Figure 6

Effects of SiC, Fe_3O_4 and graphite on the mechanical properties of concrete

Figure 7

Real time temperature of SiC concrete

Figure 8

Amplitude of rising temperature of SiC concrete

Figure 9

Real time temperature of Fe_3O_4 concrete

Figure 10

Amplitude of rising temperature of Fe_3O_4 concrete

Figure 11

Real time temperature of graphite concrete

Figure 12

Amplitude of rising temperature of graphite concrete

(a) 70s

(b) 90s

(c) 120s

(d) 160s

Figure 13

Microwave deicing effect of SiC15

Figure 14

Microwave deicing effect of Fe15

Figure 15

Microwave deicing effect of C15