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Thermal characteristics of a conductive cement-based composite for a snow-melting heated pavement system

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ABSTRACT

This study evaluated the thermal properties of an early-opening conductive heated pavement system with snow-melting functionality. The pavement system consisted of several layers: a base layer with copper plates, a conductive cement-based composite layer, and a protective layer of concrete. The conductive cement-based composite was placed over the copper-containing base concrete layer, followed by a concrete protective layer. The surface temperature of the protective concrete layer and the internal temperature of the conductive cement-based composite were measured to determine the thermal conductivity of the pavement system. Our results indicated that the thermal conductivity of the protective concrete was in the range of 1.8075–2.0534 kcal $(\mathrm{m\,h\,^\circ C})^{-1}$. Based on the thermal characteristics of the early-opening conductive heated pavement system and the experimental thermal conductivity results for the protective concrete, heat transfer analysis was performed on a full-scale sample; here, the separation distance between the copper plates in the base concrete layer (1000, 1250, and 1500 mm) was used as a variable. Our results indicated that separation distances of 1000 and 1250 mm provided a fairly uniform temperature distribution; however, with a separation distance of 1500 mm, the temperature between the copper plates in the central area was low.

1. Introduction

Losses and damage caused by abnormal climate are steadily increasing worldwide, and one contributing factor is heavy snow. Severe heavy snow paralyses national logistics systems, limiting snow removal efforts. To overcome this, many snow-melting systems have been developed; however, in practice, their application is restricted, due to economic reasons, environmental contamination, and problems and cost associated with construction technology. Currently, due to their effectiveness and convenience, spreadable de-icing materials are commonly used to pretreat the roads and melt existing snow accumulation [1]. Repeated cycles of freezing and melting from chloride de-icing spray causes concrete scaling, in which the concrete surface exfoliates in a misshapen manner, unlike conventional deterioration by frost damage [2,8]. In general, scaling is limited to small areas, but it expands gradually to a larger scale over time. Insignificant scaling does not expose coarse aggregates. If the scaling area expands, however, the aggregates become exposed, and the cement paste peels away from the concrete surface by ~3–10 mm.

Another approach for snow melting applications involves placing electrically heated cables inside the pavement to prevent the road from freezing during heavy snow [3]. This method is environmentally friendly because no chloride is used in the process. However, the heating cables are difficult to repair after their incorporation into the cement; thus, the entire cable must be exchanged and the entire pavement section reconstructed. The other drawback to this technique is the cost of supplying electricity to the heated cables.

One possible solution is to use conductive concrete [4]. The typical resistance of concrete is 106 Ω cm [1]; however, the addition of a conductive powder, such as carbon, to the concrete can lower the resistance to <10 Ω cm [4]. In low-resistance conductive concrete, electric current is generated via electron or electrolyte flow. A current supply is used to create a flow of electrons in the concrete. In contrast, electrolyte flow can occur by interior water flow, such as that associated with residual water, free water, bound water, and/or gravitational water, after concrete hardening [5]. Therefore, enhanced heating performance of the conductive concrete can be obtained through increasing the current flow by lowering the concrete's resistance or increasing the water content. Excessive water, however, may damage the concrete, in addition to presenting safety issues. Also, despite the concrete's resistance

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being lowered with water or conductive additives, concrete still maintains high resistance as a material property; thus, efficient heating is difficult to achieve. Therefore, conductive materials (e.g. carbon materials or metallic materials) must be added to optimise the heating capability of conductive concrete [5].

Conductive concrete can be produced by mixing conductive powder, cement, fine aggregates, and coarse aggregates and pouring the mixture into a uniform thickness to form the slab. Another approach is to divide the concrete into layers [6]. In the layered method, concrete is mixed with a conductive powder (e.g. carbon-based or metallic powder) to form the first layer. The second layer, a heating layer with low resistance, is placed over the first layer, followed by a protective concrete layer. In the former case (the mixed single concrete layer), the entire pavement behaves as a conductor that carries a low current over its surface. The second approach consisting of several layers is electrically safer because a protective concrete layer with relatively high resistance is placed over the current-carrying heated concrete [5].

Conductive concrete exhibits very different heat tendencies due to the materials it contains. Additionally, the thermal properties of conductive concrete depend on the ambient environment and the water content. The majority of previous studies used conductive powders (e.g. graphite, carbon materials, slag aggregates, and metallic materials) in normal concrete to lower the concrete's resistance [4,5,11]; however, snow melting proceeded at a slow pace with these earlier attempts.

In the present study, conductive cement-based composites with very low resistance were used to improve the thermal conductivity of the concrete. An early-opening, conductive, heated pavement system was used to further improve snow-melting performance. The thermal properties of the developed system were evaluated. Based on the experimental results, heat transfer analysis was performed on a full-scale specimen. The internal temperature of the conductive cement-based composite and the surface temperature of the protective concrete layer were measured. Heat generation in this pavement system was attributed mostly to Joule heating with current flow, generated by supplying current to the copper plates. Because it is difficult to express Joule heating analytically, the actual experimental temperature was used as the temperature of the conductive cement-based composite for the heat transfer analysis. The surface temperature of the protective concrete corresponded to the temperature transferred via thermal conductivity. Accurate heat transfer analysis requires determination of the thermal coefficients, including the thermal conductivity, specific heat, unit weight, and outside convection coefficient [7]. The thermal conductivity and outside convection coefficient of concrete affect the temperature difference between the interior and exterior of a structure, whereas specific heat and unit weight affect mostly the temperature increase. Therefore, in this study, the installation distance of copper plates was taken as a variable, and the thermal conductivity was measured experimentally and verified using heat transfer analysis.

2. Early-opening conductive heated pavement system

2.1. Composition of the early-opening conductive heated pavement system

Fig. 1 shows the composition of the early-opening conductive heated pavement system. The first layer consisted of copper plates set at specific separation distances within the concrete base. A conductive cement-based composite second layer was poured over the first. The copper plates served as a current supply to the conductive cement-based composite. Finally, a protective concrete layer was placed over the conductive composite layer to complete the pavement system.

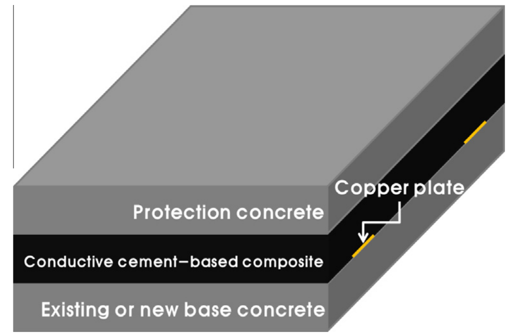

Fig. 1. Schematic diagram of the early-opening conductive heated pavement system.

2.2. Current supply and temperature measurement

The current supply for the pavement system supplied 220 VAC via connection wiring between the supply and fixed copper plates for quick heating of the pavement. Note that this configuration minimised substation costs for future application sites. The surface temperature and internal temperature of the conductive cement-based composite were measured using a digital thermometer over a period of 60 min in 10-min intervals. The internal temperature was measured over a total distance of 100 mm in the sample, as shown in Fig. 2, for application to heat transfer analysis.

Unlike the internal temperature, the surface temperature was not measured over the 100-mm distance, but instead was measured at specific points on the copper plates (points ML, MR, and C). The protective concrete outer layer was responsible not for generating heat but for protecting the heating layer to preserve proper operation in terms of the current supply and external load. Hence, the temperature was measured only at the points on the copper plates where heat was generated by contact resistance and at the centre region between the copper plates most affected by the separation distance.

3. Materials and mix proportion

3.1. Cement and aggregates

When the conductive, heated pavement system was constructed, early-strength cement (Union Co., Republic of Korea) was used for fast-opening pavement for traffic; the chemical properties of this cement are listed in Table 1. Crushed stones (specific gravity: 2.69; maximum size: 10 mm) were used as the coarse

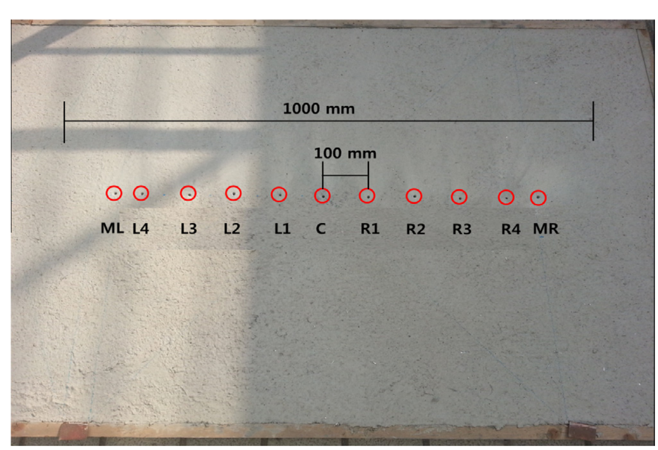

Fig. 2. Measuring points for a copper-plate separation distance of 1000 mm.