Computers and Concrete, *Vol. 12, No. 3 (2013) 337-349*
DOI: http://dx.doi.org/10.12989/cac.2013.12.3.337

A study on electrical and thermal properties of conductive concrete

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(Received November 29, 2012, Revised April 10, 2013, Accepted April 14, 2013)

Abstract. Traditional concrete is effectively an insulator in the dry state. However, conductive concrete can attain relatively high conductivity by adding a certain amount of electronically conductive components in the regular concrete matrix. The main purpose of this study is to investigate the electrical and thermal properties of conductive concrete with various graphite contents, specimen dimensions and applied voltages. For this purpose, six different mixtures (the control mixtures and five conductive mixtures with steel fibers of 2% by weight of coarse aggregate and graphite as fine aggregate replacement at the levels of 0%, 5%, 10%, 15% and 20% by weight) were prepared and concrete blocks with two types of dimensions were fabricated. Four test voltage levels, 48 V, 60 V, 110 V, and 220 V, were applied for the electrical and thermal tests. Test results show that the compressive strength of specimens decreases as the amount of graphite increases in concrete. The rising applied voltage decreases electrical resistivity and increases heat of concrete. Meanwhile, higher electrical current and temperature have been obtained in small size specimens than the comparable large size specimens. From the results, it can be concluded that the graphite contents, applied voltage levels, and the specimen dimensions play important roles in electrical and thermal properties of concrete. In addition, the superior electrical and thermal properties have been obtained in the mixture adding 2% steel fibers and 10% graphite.

Keywords: electrical properties; thermal properties; conductive concrete; steel fibers; graphite

1. Introduction

Traditional concrete is a poor electrical conductor, especially under dry conditions. The electric resistivity of normal weight concrete ranges from 6.54 to 11 KΩ·m (Whittington *et al*. 1981). However, conductive concrete can attain relatively high conductivity by adding a certain amount of electronically conductive components in the regular concrete matrix (Yehia and Tuan 2000). Conductive concrete is a relatively new material technology and belongs to a functional concrete

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http://www.techno-press.org/?journal=cac&subpage=8 ISSN: 1598-8198(Print), 1598-818X (Online)

that is synthesized by mixing a special blend of carbon powder and steel fibers in concrete to attain high and stable electrical conductivity (Cantin and Pigeon 1996, Liu and Shaopeng 2011, Xin and Hu 2012). The improvement mechanism can be taken into account two effects: conductive filler particles exhibit short-range contacts or connections in the form of clusters whereas fibers have a long-range conductive bridging effect and short-circuit effect between these clusters (Cheng *et al*. 2004, Shihai and Chung 2007, Wu *et al*. 2005a).

In 1995, Xie *et al*. (Xie and Beaudoin (1995), Xie *et al*. (1996)), of the Canadian National Research Council, developed an innovative concept of using an electrically conductive concrete mix, which mixed carbon, steel fibers, and coke breeze - a cheap by-product of steel production, in the cement to increase the electrical conductivity and maintain sufficient mechanical strength of concrete. The first-generation conductive concrete mixture was developed by Yehia and Tuan (Sherif *et al*. 2000, Tuan 2004, Yehia and Tuan 2002, Yehia *et al*. 2000, Yehia and Tuan 2000) in 1998. They made conductive concrete containing steel fibers and shavings for bridge deck deicing and proved effective as a bridge deicer (Tuan 2008, Yehia 2008). Conductive concrete has the potential to address a wide variety of applications because of its electric conductivity, thermoelectric effect and electromagnetic effect. The potential applications include anti-static flooring, electromagnetic shielding, cathodic protection of reinforcing steel in concrete structures, and roadway deicing (Jiang *et al*. 2000, Sherif *et al*. 2008, Tuan 2004, Tuan and Yehia 2004, Yehia 2008).

Conductive concrete particles and fibers are added to conventional aggregate and cement paste compositions to achieve the conductive concrete. The electrical and thermal properties of conductive concrete were affected by its components, other additives and conductive materials. In addition, the dimension of testing specimen significantly has an influence on the test data (Xin and Hu 2012). At present, there is no standard or specification formulated for testing the electric conductivity of the conductive concrete. Meanwhile, relatively few studies perform the electrical and thermal properties of conductive concrete. Based on the previous research, this study aims to investigate the effect of steel fibers and graphite contents on electrical and thermal properties of conductive concrete. For this purpose, six different mixtures were prepared and concrete blocks with two types of dimensions were fabricated. Four test voltage levels, 48 V, 60 V, 110 V, and 220 V, were applied for the electrical and thermal tests. In addition, the performances were discussed and compared with ordinary Portland cement concrete (OPC).

2. Theoretical background

Conduction of electricity through concrete may occur in two ways: electronic conduction and ionic conduction. Electronic conduction is through the motion of free electrons in fiber and ionic conduction is through the motion of ions in the pore solution (Sun *et al*. 1998, Whittington *et al*. 1981). The electrical conductivity is an uppermost index of conductive concrete and reflects its electric property. It is important to obtain the electrical conductivity (or electrical resistivity) data to the research on the property of conductive concrete. Therefore, the resistance of conductive concrete, the electrode conductive area and the internal electrode distance must be measured for testing the property of conductive concrete. From the first Ohm-law in Eq. (1).

$$R = \frac{V}{I} \tag{1}$$

where *V* is the voltage and *I* is the measured current.

The electrical resistivity was obtained from the second Ohm-law in Eq. (2).

$$\sigma = \frac{RA}{L} \tag{2}$$

where ρ is the electrical resistivity of conductive concrete, *R* is the resistance in omega mentioned above. *L* is the internal electrode distance in meter and *A* is the electrode conductive area in square meter.

The electrical conductivity is the reciprocal of the electrical resistivity of this material, as shown in Eq. (3).

$$\sigma = \frac{1}{\rho} \tag{3}$$

Thus

$$R = \frac{L}{\sigma A} \tag{4}$$

The unit of the electrical resistivity is Ω·m in the SI system.

Joule’s laws are a pair of laws concerning the heat produced by a current and the energy dependence of an ideal gas to that of pressure, volume, and temperature, respectively. Joule's law, also known as the Joule effect, is a physical law expressing the relationship between the heat generated by the current flowing through a conductor. It is expressed as Eq. (5)

$$H = I^2Rt \tag{5}$$

where *H* is heat generated by a constant current *I* flowing through the conductor of electrical resistance *R*, for a time *t*. *R* is the resistance in omega mentioned above, *t* is the time in second, and the unit of *H* is the joule.

3. Experimental program

3.1 Materials

The conductive concrete considered here is prepared by the following ingredients: cement; water; river sand; crushed gravel; steel fiber, and graphite. Type I ordinary Portland cement (OPC) conforming to CNS 61 R2001 (2011) was used in all mixes. The physical properties and chemical compositions of cement are listed in Table 1. Crushed gravel and river sand were used as coarse and fine aggregates in the manufacture of concrete. The coarse aggregate was of 19 mm maximum size, bulk density of 2650 kg/m^3 and absorption of 1.36%. The fineness modulus, bulk density and absorption of fine aggregate were 2.54, 2620 kg/m^3 and 2%, respectively. The steel fibers were wavy fibers made by cutting steel sheet and its specific gravity was 7.8. The fiber length (L), width (D) and aspect ratio (L/D) were 50 mm, 2 mm and 25.5, respectively. Graphite was dried and ground into fine powder of which 97% passing the no. 100 sieve before it was used as a fine aggregate replacement material. The average specific gravity of graphite is 2.20 and the particle size distribution is presented in Table 2.

Table 1 Physical properties and chemical compositions of raw materials

	CNS 61	Test values (%)
Chemical compositions (%)		
Calcium oxide, CaO		63.8
Silicon dioxide, SiO_2		20.6
Aluminium oxide, Al_2O_3		5.4
Ferric oxide, Fe_2O_3		3.2
Magnesium oxide, MgO	Max : 6.0	2.0
Sulfur trioxide, SO_3	Max : 3.5	2.2
Loss on Ignition, L.O.I.	Max : 0.3	1.0
Physical properties		
Specific gravity	3.15	3.05
Initial setting time (min)	Min : 45	150
Final setting time (min)	Max : 375	230
specific surface (cm^2/g)	Max : 2800	3310
Air content (%)	Max : 12.0	8.2
Soundness (%)	Max : 0.80	0.05
Compressive strength (MPa)		
3-days	Min : 12.35	20.6
7-days	Min : 19.31	27.66
28-days	Min : 27.54	37.67

Table 2 The particle size distribution of graphite

Sieve Size	#8	#16	#30	#50	#100	#200	#300	Sample wt.
Retained								
Weight (g)	0	0	0.3	0.2	6.1	213.4	47.8	300
Amount (%)	0	0	0.1	0.1	2.0	71.1	15.9	
Cumulative (%)	0	0	0.1	0.2	2.2	73.3	89.3	
Passing								
Cumulative (%)	100.0	100.0	99.9	99.8	97.8	26.7	10.7	

3.2 Mix design and specimens preparation

The control mixtures and five conductive mixtures adding 2% steel fibers by weight of coarse aggregate and using graphite as fine aggregates replacement at the level of 0%, 5%, 10%, 15% and 20% by weight were produced in the laboratory. The water to binder ratio was chosen as 0.5. Cement content was kept at a constant of 420 kg/m^3. Details of mixture proportions are given in Table 3. Cylinders of 100 mm in diameter and 200 mm in height were cast for the compressive strength test. Concrete blocks were fabricated for the electrical and thermal tests. Two types ofdimensions of 400 × 100 × 50 mm with symbol L and 200 × 100 × 50 mm with symbol S were cast in suitable steel moulds. (see Fig. 1). When the mix was fed into the mould, two carbon steel plates of 160 × 25 ×3 mm were embedded on both sides of the block as the electrodes. The intervals between the two electrodes are 320 mm for Type-L block, and 160 mm for Type-S block, respectively. Subsequently, four thermocouples were embedded into the blocks shown in Fig. 2. The thermocouples are located at the center of the block, at the top surface center of the block, at

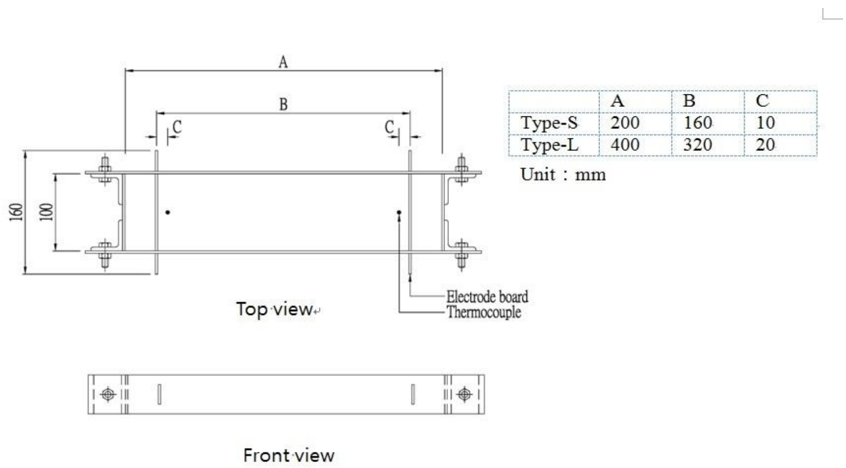

Fig. 1 Dimension of steel mould for block

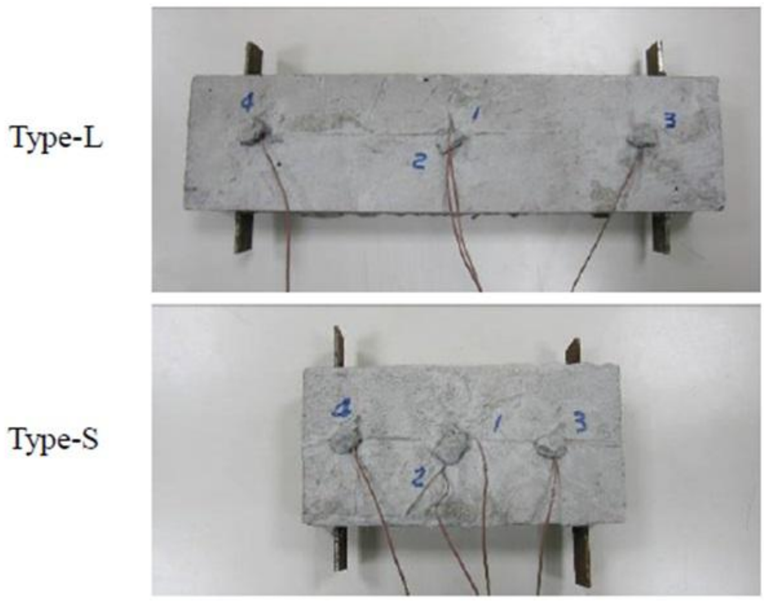

Fig. 2 Thermocouples located into the blocks

Table 3 Mix proportions of conductive concrete

Mix No.	w/c	Water (kg/m^3)	Cement (kg/m^3)	Steel fiber (kg/m^3)	Graphite (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
OPC	0.5	210	420	---	---	725	1000
SG0	0.5	210	420	19.6	---	725	980
SG5	0.5	210	420	19.6	36.3	690	980
SG0	0.5	210	420	19.6	72.5	653	980
SG15	0.5	210	420	19.6	108.8	616	980
SG20	0.5	210	420	19.6	145	580	980

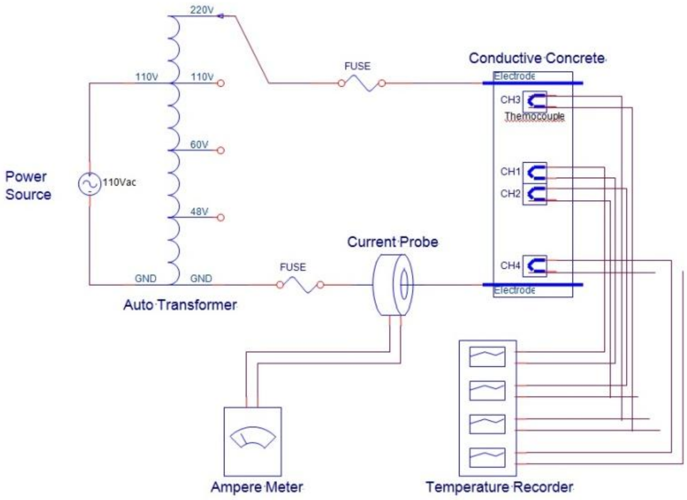

Fig. 3 The set-up circuit diagram of test

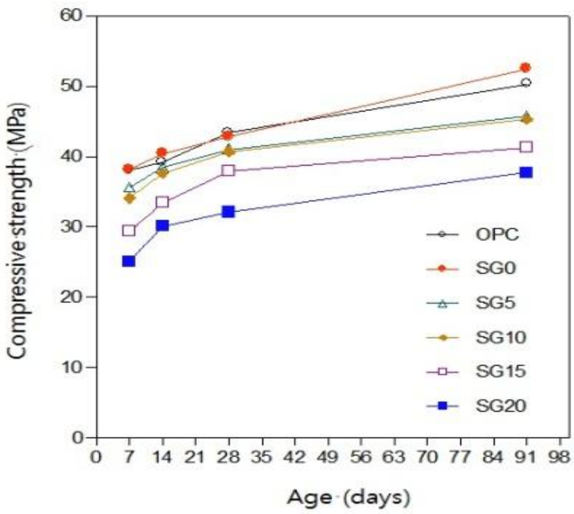

Fig. 4 Compressive strength vs. Age

20 mm for Type-L and 10 mm for Type-S of the electrode plate center, respectively. After 24 hours, the specimens were removed from the mould and moved into a curing room for 28 days in a humidity chamber at room temperature of 23℃ and relative humidity of 70~80% RH until the time of testing.

3.3 Methods

The compressive strength test was conducted according to ASTM C39 (2012). Three cylindrical specimens of 100 mm diameter and 200 mm height were prepared and tested for each mixture at the ages of 7, 14, 28, and 91 days, respectively. For the current measurement, account must be taken into the selection of power supply first. The power frequency alternative current was used in the test. An alternative current voltage regulator must be equipped with an isolation transformer for guarantee the operators' personal safety. The alternating current voltage regulator can be used to supply a wide voltage range. In this study, four test voltage levels, 48 V, 60 V, 110 V, and 220 V, were applied. An autotransformer was connected to the electrodes of the concrete block by cables. All test voltage levels were adjusted through the autotransformer. The current transformer arranged on the cables was used to measure the loop current. Two fuses were added into the circuit for safety reasons and each thermocouple embedded was connected to the temperature recorder. The set-up circuit diagram of test was shown in Fig. 3. The ampere recorder and the temperature recorder automatically record the current and temperature for every five minutes for 5 hours.

4. Results and discussion

4.1 Compressive strength

The compressive strength test results are given in Fig. 4. The compressive strength of concrete increases with an increasing age and decreases with an increase amount of graphite replacing fine aggregates. The control specimen (OPC) has a compressive strength of 38.1 MPa at the age of 7 days, 39.2 MPa at the age of 14 days, 43.4 MPa at the age of 28 days and 50.3 MPa at the age of 91 days, respectively. The specimen (SG0) without graphite has the highest compressive strength of 52.4 MPa at the age of 91 days due to the addition of 2% steel fibers. However, concretes with steel fibers and graphite show a lower compressive strength than the OPC at all ages. The compressive strengths of specimens SG5, SG10, SG15, and SG20 with addition of 2% steel fibers and using graphite at the level of 5%, 10%, 15% and 20% have a smooth decrease of 9.1~25% compared to OPC at the age of 91 days. The addition of steel fibers can increase the compressive strength because steel fibers randomly distributed in the matrix behave as crack arresters by bridging mechanism (Kurihara *et al*. 2000). In contrast, the addition of graphite does not enhance the compressive strength to conductive concrete because of its intrinsic feature (Wu *et al*. 2005). The bulk density of graphite is less than that of fine aggregate. Meanwhile, the graphite has a sheet like structure where the atoms all lie in a plane and are only inadequately bonded to the graphite sheets above and below, so reduces the compressive strengths (Liu and Shaopeng 2011). Therefore, the graphite content should be controlled to a certain content in order to prepare conductive concrete with both excellent conductive property and mechanical property.

4.2 Electrical conductivity

As shown in Fig. 5, the relationship between the applied voltage and the current going through the specimens adding steel fibers and with various contents of graphite was established. During the test, the applied voltage to the blocks was intentionally fixed by the autotransformer and electricity powered all the specimens for 5 hours. It can be seen that the higher the applied voltage, the higher the current in 5 hours, and the relationship between the applied voltage and the current shows linear. The current conducting in the conductive concrete has three paths: electrons conducting in the channels made by contacted graphite particles, made by graphite and steel fiber, and made by

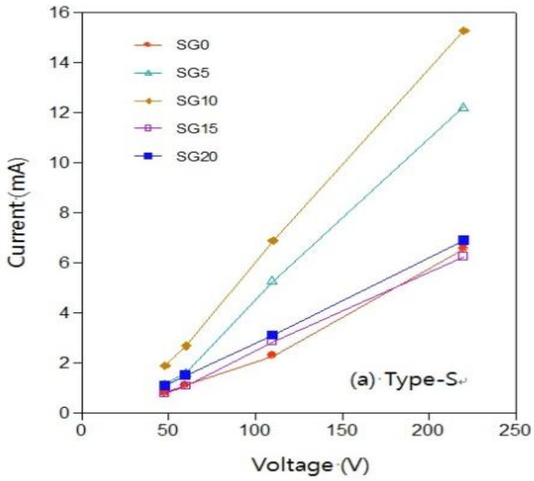

Fig. 5(a) Current vs. Voltage (Type-S)

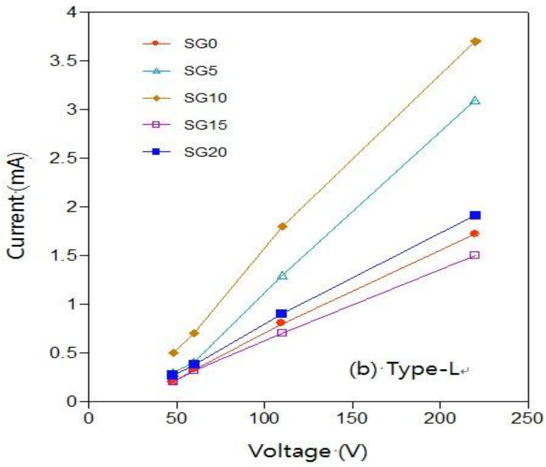

Fig. 5(b) Current vs. Voltage (Type-L)

bridged steel fiber. The three conductive paths may exist in the same time because steel fiber and graphite powders are randomly distributed in the concrete. Under the same conditions (the same specimen), the current of Type-S group is higher than that of Type-L group, about 4 times of the current of Type-L group. It is because the path of specimens in Type-S group is shorter than that in Type-L group. No matter whether in Type-S group or in Type-L group, specimen SG10 has the highest current than any other specimens in the same group, followed by the specimen SG5. Meanwhile, in comparison with the specimens SG10 and SG5, the specimens SG0, Sg15 and SG20 show lower current. The current of SG10 increased from 1.88 mA in the voltage of 48 V to 15.28 mA in the voltage of 220 V in Type-S group, and from 0.5 mA in the voltage of 48 V to 3.7 mA in the voltage of 220 V in Type-L group. It indicates that both the graphite contents and the specimen dimensions have a significant influence on the current.

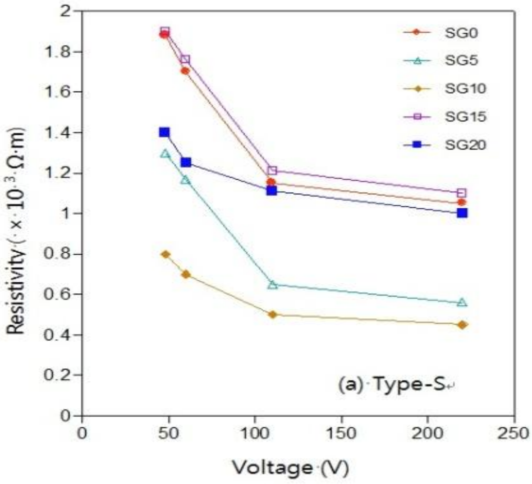

Fig. 6(a) Resistivity vs. Voltage (Type-S)

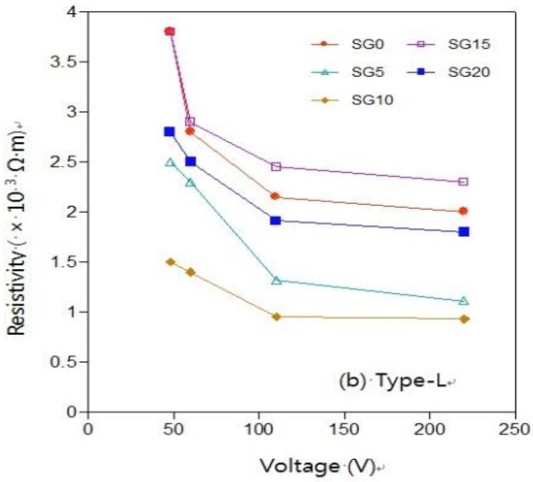

Fig. 6(b) Resistivity vs. Voltage (Type-L)

In general, as the voltage keeps constant on an object, the current passing through this object isinversely proportional to the electrical resistivity of this object. The relationship between the applied voltage and the electrical resistivity of specimens adding steel fibers and with various contents of graphite is shown in Fig. 6.

The electrical resistivity of all specimens decreased with an increasing applied voltage. The trend of the electrical resistivity is consistent with that of measured current. The higher the current measured, the lower the electrical resistivity obtained for all specimens with various applied voltage levels. In addition, the trends of the electrical resistivity in two different groups are similar. As can be seen from the Fig. 6, no matter whether in Type-S group or in Type-L group, specimen SG10 has the lowest electrical resistivity than any others. The electrical resistivity of SG10 decreased from 800 to 450 Ω·m as the applied voltage from 48 V to 220 V in Type-S group, and decreased from 1500 to 930 Ω·m as the applied voltage from 48 V to 220 V in Type-L group. It is followed by the specimen SG5, which decreased from 1300 to 560 Ω·m as the applied voltage from 48 V to 220 V in Type-S group, and decreased from 2500 to 1110 Ω·m as the applied voltage from 48 V to 220 V in Type-L group. The higher electrical resistivity has been obtained in specimen G15, which decreased from 1900 to 1100 Ω·m as the applied voltage from 48 V to 220 V in Type-S group, and decreased from 3800 to 2300 Ω·m as the applied voltage from 48 V to 220 V in Type-L group. It is worth mentioning that the electrical resistivity of specimens in Type-L group is about 2 times as much as that of specimens in Type-S group. As the applied voltage increased from 48 V to 110 V, the electrical resistivity decreased sharply, then the falling trend of electrical resistivity began to level off as the applied voltage from 110V to 220 V. García *et al*. (2009) investigated the electrical conductivity of asphalt mortar containing steel wool and graphite and discovered that the use of conductive fibers is more effective to reach the desired conductivity than the use of graphite. Based on the results mentioned above, there is not a significant difference on electrical resistivity of all the specimens. It is because all specimens were mixed with various contents of graphite, but adding the same content of steel fibers. In this study, the concrete with adding 2% steel fibers and 5% to 10% graphite contents in Type-S group seems to be the optimal limit based on the electrical conductivity test results.

4.3 Thermal property

The relationship between the applied voltage and the temperature of the specimens adding steel fibers and with various contents of graphite in 5 hours is given in Fig. 7. As shown in Fig. 7(a), the temperature of SG0 keeps around 24~25.5℃ with different applied voltage levels. In the group of Type-S specimens, the temperature increased with the increase of applied voltage except SG0. When applied voltage increased from 48 V to 110 V, the increase of temperature was slow but steady. As the applied voltage reached 220 V, the temperature began to pick up speed. At applied voltage of 220 V, SG5 has the highest temperature than the others in the group of Type-S specimens, followed by the SG10, SG15 and SG20. In the group of Type-L specimens, the temperatures of SG0, Sg15 and SG20 maintained 20.5~26℃ with different applied voltage levels. The temperatures of SG5 and SG10 was less than 25.5℃ as the applied voltage from 48 V to 110 V and began to increase, which were 32℃ and 36℃, at applied voltage of 220 V, respectively.

The heat depending on voltage, current, resistivity and time was calculated by Joule's law. The trend of the heat is principally correspondent with the results of these parameters. The relationship between the applied voltage and the heat of the specimens adding steel fibers and with various contents of graphite in 5 hours is given in Fig. 8. It can be seen that the heat increases with an increase of applied voltage and the higher heat has been obtained in Type-S specimens than the comparable Type-L specimens because of the short path in Type-S group. In addition, the trend of heat is similar to that of current. No matter whether in Type-S group or in Type-L group, specimen SG10 has the highest heat than any other specimens in the same group, with 0.09 Joule in the voltage of 48 V to 3.36 Joule in the voltage of 220 V in Type-S group, and with 0.024 Joule in the voltage of 48 V to 0.814 Joule in the voltage of 220 V in Type-L group. Specimen SG15 is on the other end of the scale, with 0.038 Joule in the voltage of 48 V to 1.375 Joule in the voltage of 220 V in Type-S group, and with 0.01 Joule in the voltage of 48 V to 0.33 Joule in the voltage of 220 V in Type-L group. Specimens SG5, SG0 and SG20 are in the middle. Basically, the higher the heat produced, the higher the temperature increased. However, the trend of heat is not similar to

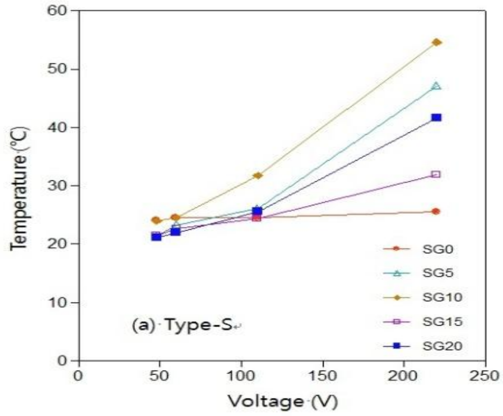

Fig. 7(a) Temperature vs. Voltage (Type-S)

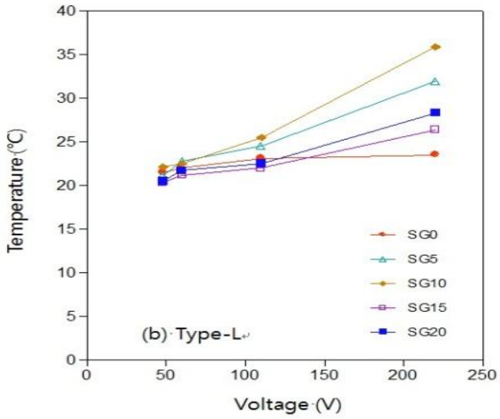

Fig. 7(b) Temperature vs. Voltage (Type-L)

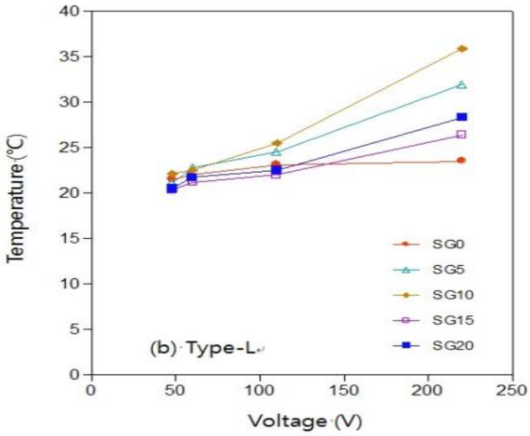

Fig. 8(a) Heat vs. Voltage (Type-S)

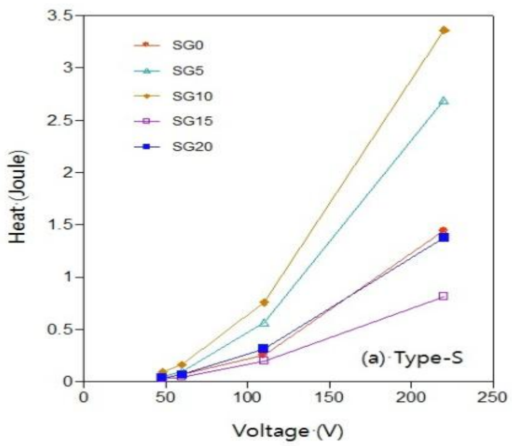

Fig. 8(b) Heat vs. Voltage (Type-L)

that of the temperature. In contrast, the trend of heat is similar to that of current. It may be inferred that the graphite contents, current, and the specimen dimensions have a significant influence on the heat, which play important roles in thermal property.

5. Conclusions

This study presents testing results of the electrical and thermal properties of conductive concrete. The conclusions are as follows

(1) Steel fiber concrete has about the same compressive strength as ordinary Portland cement concrete, however, concrete adding steel fiber and graphite have a lower compressive strength and compressive strength decrease with an increasing amount of graphite.

(2) The graphite content, applied voltage level, and the dimension of specimen have a significant influence on the electrical resistivity and heat generation and the graphite content play a major role on the electrical and thermal properties. Higher electrical current and temperature have been obtained in small specimens than in the relatively large specimens.

(3) For obtaining proper electrical and thermal properties, the testing results suggest that 2% steel fibers and 10% graphite would be applied in concrete.

References

ASTM C39/C39M (2012), Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, *American Society for Testing and Materials*.

Cantin, R. and Pigeon, M. (1996), “Deicer salt scaling resistance of steel-fiber-reinforced concrete”, *Cem. Concr. Res.*, **26**(11), 1639-1648.

Cheng, B., Keru, W. and Yao, W. (2004), “Piezoresitivity in carbon fiber reinforced cement based composites”, *J. Mater. Sci. Tech..*, **20**(6), 746-750.

CNS 61 R2001 (2011), Standard specification for portland cement, *Chinese National Standards.*
García, Á., Schlangen, E., Ven, M.V.D. and Liu, Q. (2009), "Electrical conductivity of asphalt mortar containing conductive fibers and fillers", *Constr. Build. Mater.*, **23**(10), 3175-3181.
Jiang, Z., Sun, Z. and Wang, X. (2000), "Conductive concrete technology", *Concrete*, **9**, 55-58.
Kurihara, N., Kunieda, M., Kamada, T., Uchida, Y. and Rokugo, K. (2000), "Tension softening diagrams and evaluation of properties of steel fibre reinforced concrete", *Eng. Fract. Mech.*, **65**, 235-245.
Liu, X. and Shaopeng, W. (2011), "Study on the graphite and carbon fiber modified asphalt concrete", *Constr. Build. Mater.*, **25**(4), 1807-1811.
Sherif, Y., Tuan, C.Y., Ferdon, D. and Chen, B. (2000), "Conductive concrete overlay for bridge deck deicing: mixture proportioning optimization and properties", *Mater. J.*, **97**(2), 172-181.
Shihai, W. and Chung, D. (2007), "Piezoresistivity-based strain sensing in carbon fiberreinforced cement", *ACI Mater. J.*, **104**(2), 171-179.
Sun, M., Li, Z., Mao, Q. and Shen, D. (1998), "Study on the hole conduction phenomenon in carbon fiber-reinforced concrete", *Cement Concr. Res.*, **28**(4), 549-554.
Tuan, C.Y. (2004), "Electrical resistance heating of conductive concrete containing steel fibers and shavings", *ACI Mater. J.*, **101**(1), 65-71.
Tuan, C.Y. (2008), "Roca spur bridge: the implementation of an innovative deicing technology", *J. Cold. Regions. Eng.*, **22**(1), 1-15.
Tuan, C.Y. and Yehia, S. (2004), "Evaluation of electrically conductive concrete containing carbon products for deicing", *ACI Mater. J.*, **101**(4), 287-293.
Whittington, H., McCarter, W. and Forde, M.C. (1981), "The conduction of electricity through concrete", *Mag. Concrete. Res.*, **33**(114), 48-60.
Wu, S., Mo, L., Shui, Z. and Chen, Z. (2005), "Investigation of the conductivity of asphalt concrete containing conductive fillers", *Carbon.*, **43**, 1358-1363.
Xie, P. and Beaudoin, J.J. (1995), "Electrically conductive concrete and its application in deicing: advances in concrete technology", *Proceedings of the second CANMET/ACI International Symposium on Advances in Concrete Technology*, Las Vegas, June.
Xie, P., Gu, P. and Beaudoin, J.J. (1996), "Electrical percolation phenomena in cement composites containing fibers", *J. Mater. Sci.*, **31**, 4093-4097.
Xin, T. and Hu, H. (2012), "Test and study on electrical property of conductive concrete", *P.E.P.S.*, **5**, 83-87.
Yehia, S. (2008), "Electrically conductive concrete proves effective as bridge deicer", *Road Bridge*, **46**, 32-35.
Yehia, S. and Tuan, C.Y. (2002), "Conductive concrete overlay-An innovative solution for bridge deck deicing", *Concr. Int.*, **24**, 56-60.
Yehia, S., Tuan, C.Y., Ferdon, D. and Chen, B. (2000), "Conductive concrete overlay for bridge deck deicing :mix design, optimization, and properties", *ACI Mater. J.*, **97**, 172-181.
Yehia, S.A. and Tuan, C.Y. (2000), "Thin conductive concrete overlay for bridge deck deicing and anti-icing", *Transport. Res. Rec.*, **1698**, 45-53.

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