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Effect of carbon black on electrical curing of fresh concrete for cold regions

Emriye Çınar [a], Tayfun Uygunoğlu [b,*], Barış Şimşek [c], İlker Bekir Topçu [d]

[a] Osmaniye Korkut Ata University, Engineering Faculty, Civil Engineering Department, 03200 Osmaniye Turkey
[b] Afyon Kocatepe University, Engineering Faculty, Civil Engineering Department, 03200 Afyonkarahisar, Turkey
[c] Department of Chemical Engineering, Faculty of Engineering, Çankırı Karatekin University, 18120 Çankırı, Turkey
[d] Eskişehir Osmangazi University, Faculty of Engineering and Architecture, Civil Engineering Department, Eskişehir 26480, Turkey

HIGHLIGHTS

- Carbon black was used in the concrete for conductivity.
- Carbon black blended concrete exposed to cold weather conditions.
- Electrical curing was applied at different cold weather conditions to fresh concrete.
- The freezing of fresh concrete was prevented by electrical curing at low voltages.

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ABSTRACT

Nowadays, there are many accelerated curing methods which are an important issue for early strengthening of concrete. It was aimed to accelerate the hydration of carbon-black-blended concrete by shortening the molding time, and to achieve concrete casting under cold weather. For this purpose; 0, 1, 2 and 3 percent of carbon black added to the concrete instead of cement by weight and the concrete was produced by electrical curing method. During the curing, 0, 45, 60 and 90 V voltage values were applied on fresh concrete for 24 h. The voltage applications were carried out at different temperatures as under ambient temperature conditions (22 °C), and at 0 °C and −10 °C using an air-conditioning cabinet. After the electrical curing process, the concrete samples were demoulded and cured in the standard curing pool for 7 and 28 days, and then physical and mechanical properties were investigated. It was found that increased carbon black ratio and stress intensity resulted with increase in the internal temperature of the concrete. With an increase in voltage and carbon black ratio, it was found that the duration of the setting was accelerated and the molding time was shortened. With an increase in carbon black ratio, the setting times decreased. In the electrically cured concrete, 30% increase in strength was observed at early days.

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1. Introduction

The early strength and usability of concrete at the shortest time is a result of several improvements in curing methods that have been adopted by the industry [1]. The main curing methods include hot or boiling water preparation, autogenous curing, changing the hot water, microwaving, steam curing in prefabricated structures and electrical curing [2,3]. Hardening at high temperatures increases the kinetics of cement hydration, accelerating the hydration and providing early strength. However, as the curing temperature rises, faster precipitation of the hydration products occurs, leading to a denser hydration-product shell formed around un-hydrated clinker particles [4]. In relation to the hydration time, accelerated curing is important in terms of the timing of a project, and ready-mixed concrete is used because its compressive strength reaches the target level in the shortest time [5]. In addition, the prediction of early strength in concrete is very important, both in terms of performance and economy. A shortening of the concrete setting time is necessary for cold conditions, as well as for quick setting [6,7]. Where such concrete is cast under cold weather conditions, the water used in the concrete can freeze and, since the

* Corresponding author.
E-mail address: uygunoglu@aku.edu.tr (T. Uygunoğlu).

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concrete is fresh, an increase in volume will occur. Because some of the water that should be used in the hydration reactions with the cement freezes, the concrete will not have sufficient strength. Where the air or concrete temperature is increased by a curing method, the freeze water dissolves, allowing its continued reaction with the cement. However, the hydration product will not form enough bulk to fill the gap formed by the melting of the ice, and so the concrete strength will be low and its permeability high [8]. Increasing the setting time also extends the mold-taking time [9]. Therefore, negative economic consequences will occur. A 10 °C reduction in temperature doubles the setting time of concrete. Therefore, it is necessary to maintain concrete that is curing at a certain temperature, in order to get to the fresh concrete stage in a short time, and the freezing point of water can be reduced using antifreeze, preventing ice damage to the concrete.

There have also been many studies on improving the electrical and thermal properties of cement composites using different materials [10]. Their setting times can be shortened by heating the fresh cement paste using an electric current [11]. Electrically-conductive concrete is a category of concrete that contains electrically-conductive components to achieve stable and high electrical conductivity. Many factors can be effective on the electrical conductivity and performance of conductive concrete [12]. Conductive concrete, consisting of mainly concrete components and conductive materials, has attracted the attention of researchers and engineers due to its several applications. One of the conductive materials used in the production of conductive concrete is carbon black. Carbon black is obtained from waste car tires and is used in a diverse group of materials for enhancing their physical, electrical and optical properties. Its largest usage, by volume, is as a reinforcement and performance additive in rubber products. In rubber compounding, natural and synthetic elastomers are blended with carbon black, elemental sulphur, processing oils and various organic processing chemicals, which are then heated to produce a wide range of vulcanised-rubber products. In these applications, carbon black provides reinforcement and improves resilience, tear strength and conductivity, among other physical properties [13]. It is the most widely used and cost-effective rubber-reinforcing agent (typically called rubber carbon black) in tire components (such as treads, sidewalls and inner liners), mechanical rubber goods, including industrial rubber goods, roofing membrane, automotive rubber parts (such as sealing systems, hoses and anti-vibration parts) and in general rubber goods (such as hoses, belts, gaskets and seals) [14].

In the literature, the need for shortening the time of molding in concrete, and accelerating its curing methods under cold conditions, have been examined, and the effect of electrical curing on mold take-up times has been observed. Concrete curing methods under cold conditions are in continual development. The electrical curing method – a direct heating technique – has drawn attention, with its low energy requirement, compared to other curing methods.

The aim of this study was to increase the conductivity of concrete by adding carbon black to it, and to obtain higher internal temperatures at lower voltage values, in order to shorten both the mold-taking times and the setting of the concrete under cold conditions. For this purpose, 0, 1, 2 and 3% of carbon black was added to concrete mixture instead of binder. Electrical curing was applied on the fresh concrete at 0, 45, 60 and 90 V for 24 h in the mould. The curing process was carried out under ambient conditions (22 °C), and at temperatures of 0 °C and −10 °C using an air-conditioning cabinet. During the curing process, the internal temperatures of the fresh concrete were recorded, and the final curing times were determined. The early day properties of the concrete samples were determined and the microstructure was examined.

2. Experimental program

Crushed sand and aggregate were used in the concrete, their specific gravities being 2.67 and 2.70, and maximum grain sizes 4 mm and 11.2 mm, respectively. In the experiments, CEM I 42.5 R cement, which meets the TS EN 197-I standard, was used [15]. Carbon black, which is highly conductive, from waste tires was used as an additive [16]. The physical properties of the carbon black supplied from Marmore Green Engineering used here are given in Table 1.

2.1. Production of specimens

In order to be able to calculate the concrete mixture required; the properties of the aggregates, the percentage ratios of the aggregate mixture, and an ideal gradation curve were determined according to Turkish standards. After determining the material properties and aggregate mixing ratios for the concrete mixture, the concrete components per unit volume, based on the concrete calculations, were obtained (Table 2).

A 250-l-capacity mixer was used to mix the concrete. Initially, a dry mix was obtained by mixing sand, aggregate, carbon black and cement for 1 min. Then, about 2/3 of the mixing water was added. Finally, the remaining of 1/3 water was added, and mixing continued for 5 min. The molds were lubricated so that the samples could easily be removed. The prepared concrete was placed into electrically-isolated plastic molds, with dimensions of 10x10x10 cm and 10x10x30 cm.

For electrical curing, the freshly concrete was placed in 10x10x30 cm molds with copper conductive plates on the sides to apply tension to the concrete. Curing was applied to the fresh concrete, under ambient conditions, at 0 °C and −10 °C as 0, 45, 60 and 90 V. In order to apply the required voltage density to the samples, a data logger with a 10-channel capacity was used to record the alternating current (AC) power supply and temperature data. The positive pole of the AC power supply was connected to a board at a distance of 30 cm from the negative pole. A data logger

Table 1
Physical properties of carbon black.

ASTM	Name	Surface Area (m^2/g)	Grain Size (nm)
D 1765	ISAF	110–140	20–25

Table 2
Amount of material required for 1 cubic meter.

Carbon Black Ratio (%)	Cement, kg/m^3	Water, lt/m^3	Carbon Black kg/m^3	Crushed sand kg/m^3	Aggregate kg/m^3
0%	300	211	0	865	882
1%	297	211	3	865	882
2%	294	211	6	865	882
3%	291	211	9	865	882

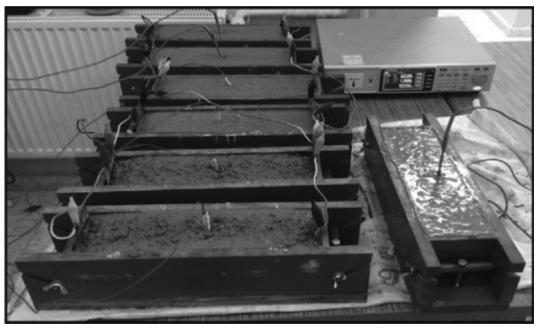


Fig. 1. Application of AC voltage to concretes.

was used to record the internal temperature of concrete every 10 min, and plots were plotted. The AC power supply was turned on for 24 h, in accordance with the ASTM C 1202 standard [17]. The curing process was repeated at 0 °C and −10 °C under ambient conditions in the climatic cabinet. The prepared test setup is shown in Fig. 1.

Fresh concrete samples, not destined to be electrically cured, were also placed in 10x10x10 cm molds for physical and mechanical testing. The samples placed in the molds were vibrated for 45 s to compact them. The concrete samples were removed from the molds after an average of 24 h. The extracted samples were placed in a curing pool. On the samples, compressive test at 1, 7 and 28 days as mechanical properties; apparent porosity and water absorption at 28 days as physical properties and microstructure properties were determined.

The setting time for concrete is generally determined using a Vicat needle test for the cement paste, or by measuring the penetration resistance of mortar and concrete. To establish a relationship between internal temperature and the final setting time, two cement pastes were prepared, the water/cement ratios of which were 0.40. One of them was used for measuring the internal temperature, with a thermocouple being placed in the centre of the cement paste to measure the temperature every 10 min for 1 day. The other paste was subjected to an automatic penetration device, which evaluated the penetration depth every 6.6 min. The setting time test was performed to ASTM C191 standards [18].

3. Results and discussion

3.1. Fresh concrete properties

Setting time and internal temperature of cement paste depending on time was compared in the same graphic (Fig. 2). It was found that the minute the maximum temperature occurred in was almost the minute of the final setting time of cement paste. The final setting time was measured at 160 min by the penetration device. The peak temperature of the cement paste was reached at 480 min, and this result was also interpreted as the final setting time. From Fig. 2, it can be seen that the socket expiration time measured by the Vicat tool and the temperature at the temperature measurement point occur the same time. The socket start time was measured as 160 min and the socket end time was 440 min. It was determined that the end time of the curing of the cement paste and the peak inner temperature of the cement paste occurred at 480 min. Setting times are generally determined using a Vicat needle test for cement paste, or by measuring the penetration resistance of hardened mortar and concrete. The relationship between setting time and internal temperature has been shown to fit Arrhenius equations around 10 and 45 °C, and can be used to predict penetration resistance using the maturity method according to ASTM C403 [19].

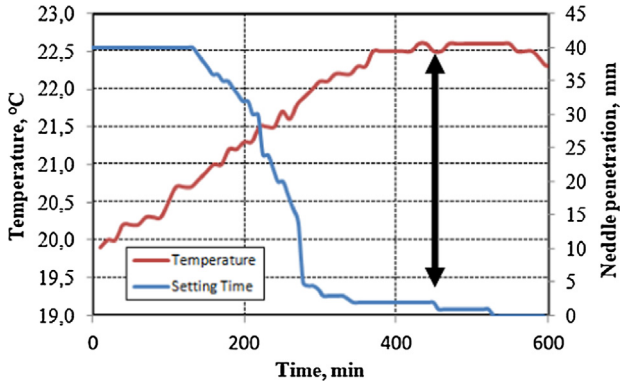


Fig. 2. Determination of the setting time of the cement paste with internal temperature.

A specially-designed AC power supply and 10-channel-capacity data logger were used to apply the requisite voltage density to the samples. This power supply was connected to the conductive plates in the molds, and the data logger measured the temperature of the samples every 10 min, the output being plotted. The internal temperatures of the concrete cured at laboratory conditions are given in Fig. 3. As can be seen from Fig. 3, the voltage value of the concrete (at 22 °C) increased for all carbon black ratios. The maximum temperature was 37.7 °C at 90 V in the reference concrete with no carbon black, while the maximum internal temperature at 90 V was 53 °C in the concrete with 3% of carbon black. Thus, the internal temperature of the concrete increases due to conductive structure of the carbon black.

The internal temperatures of the concrete cured at 0 °C, with respect to the carbon black ratio, are given in Fig. 4, whilst the internal temperatures of the concrete cured at −10 °C, with respect to the carbon black ratio, are given in Fig. 5. From Fig. 4, it is clear that the internal temperatures of the concretes cured at 0 °C were maintained above 0 °C, with the internal temperature increasing with increased voltage. No increase in temperature was observed with an increase in voltage in the reference concrete, which did not contain carbon black. In the concrete with 3% carbon black, an increase in voltage, especially to 90 V, increased the internal temperature by 21 °C when cured at 0 °C. During the curing, the internal temperature of the concrete was kept above 0 °C and the water in the concrete was prevented from freezing. A temperature of −10 °C is critical for concrete. The internal temperatures resulting from the curing showed a rapid temperature drop (Fig. 5). With increased voltage, the rate of decrease slowed. In the non-carbon-black reference concrete, the internal temperature of the concrete at 90 V was maintained above 0 °C for 1200 min, while the 3% carbon black sample was kept at 90 V for 1400 min at above 0 °C. The internal temperature of the reference concrete at 90 V was maintained above 0 °C for 1200 min, while the 3% carbon black sample was kept for 1400 min above 0 °C. Maintaining the internal temperature of the concrete above 0 °C prevents the freezing of the water in the concrete, thus ensuring the continuation of the hydration process.

3.2. Final setting of the concrete

The internal temperatures and setting times are shown in Fig. 6 for carbon black blended concretes. Under the ambient conditions (22 °C), 0 °C and −10 °C the final setting times were those where the highest temperature was reached based on the measured internal temperature. It was observed that, with an increase in voltage, under ambient conditions (22 °C), the final setting time decreased.

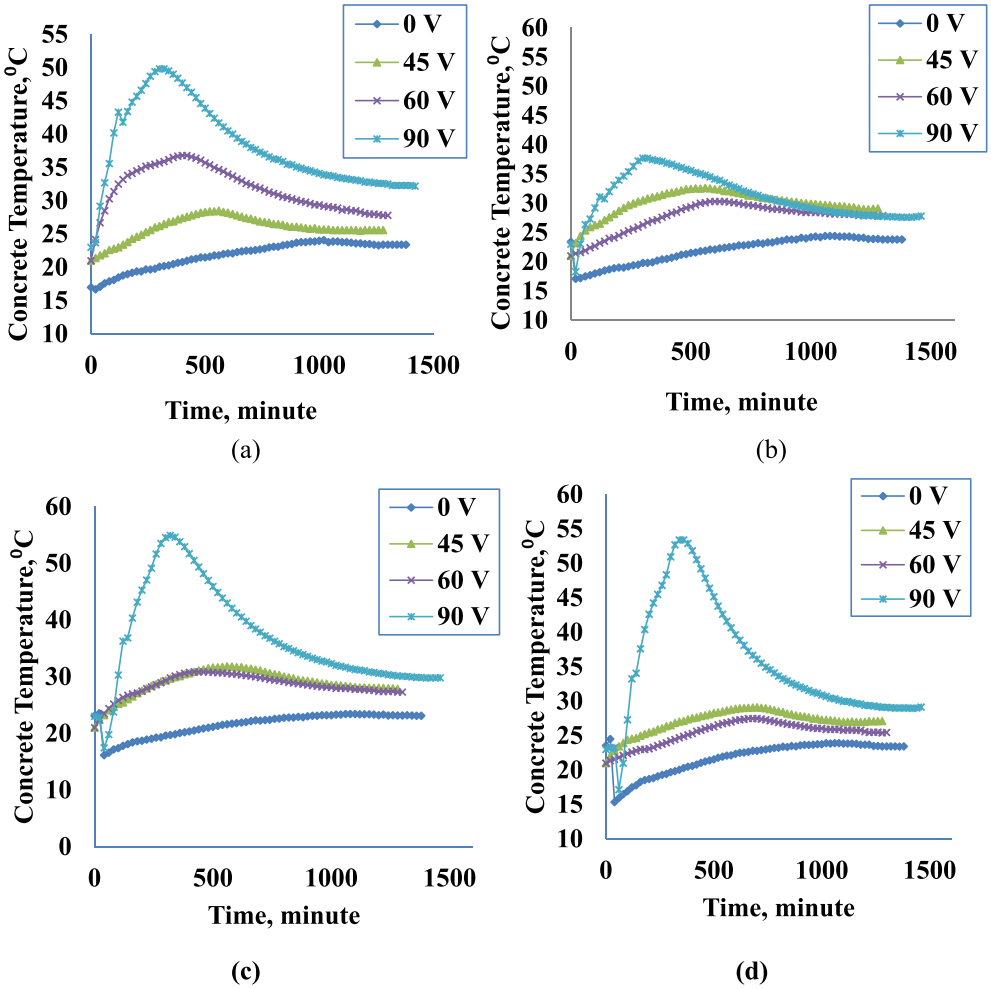


Fig. 3. The internal temperatures of the applied concrete in ambient conditions, (a): 0% CB, (b): 1% CB, (c): 2% CB, (d): 3% CB.

With an increase in carbon black ratio, the setting times of fresh concrete decreased. In the non-carbon-black and non-stressed concretes, when the setting time duration was 1200 min and 90 V were applied, the final setting time was 360 min. When the setting time was 1000 min in the non-stressed concretes containing 3% carbon black, the same carbon black content was found to be 300 min at 90 V. This, an increase in voltage decreases the final setting time, and the concrete becomes more conductive when it contains carbon black.

In the stress-free and 45 V applied concrete at 0 °C the concrete of final set was not seen. In the samples at 60 and 90 V, the outlet end was observed. In the samples containing carbon black, at 90 V, the setting time was 1060 min, being 1040 min for the 1% carbon black samples, 900 min for 2% carbon black, and 880 min for 3% carbon black. In cold ambient conditions, concrete can be removed from the mold in less than 24 h by applying 60 and 90 V. In the samples containing carbon black, there was a further decrease in the setting times due to the enhanced conductivity. In the concrete with no voltage applied at −10 °C, and the concretes applied at 45 and 60 V, 1440 min of final set was not seen. 90 V applied to the outlet was observed in concrete. In the samples with carbon black ratios of 0% and 1%, at 90 V, the end of the plug occurred at 1140 min. In the concretes at 90 V, final setting was observed. In the samples with carbon black ratios of 0% and 1%, the final setting occurred in 1140 min at 90 V. Under cold conditions, the setting did not occur, but under normal conditions, at 90 V, it can be molded in less than 24 h.

3.3. Porosity and water absorption of concrete

Water absorption (%) and porosity (%) tests were performed, according to TS EN 12390–7 (2010) [20]. The porosity and water absorption values of concrete poured under ambient conditions (22 °C) are given in Fig. 7. It was found that the porosity increased with increasing carbon black ratio. Carbon black does not dissolve in concrete, and so forms gaps. A reduction in the amount of cement also increases the porosity by reducing the amount of binder. The water absorption rate increased with increasing the percentage of porosity. With the application of tension, concrete hydration is accelerated due to an increase in the internal temperature and a reduction in the porosity, with hydration being more efficient. It was found that the water absorption and porosity increased when the voltage density was at 45 and 60 V. At 90 V, the porosity and water absorption decreased by 50% when compared to non-voltage applied series. The porosity and water absorption values were not affected by the application of 45 and 60 V to the poured concretes under ambient conditions.

The water absorption and porosity values of the concrete poured at 0 °C and −10 °C are given in Fig. 8. It was found that, in the concrete poured at 0 °C and −10 °C, the percentage of porosity and water absorption increased with increased carbon black ratio. The concrete poured at 0 °C and −10 °C decreased by about 15% with the increasing voltage density. Since a reduction in ambient temperature decreases the kinetics of hydration, the porosity and water absorption rates decreased.

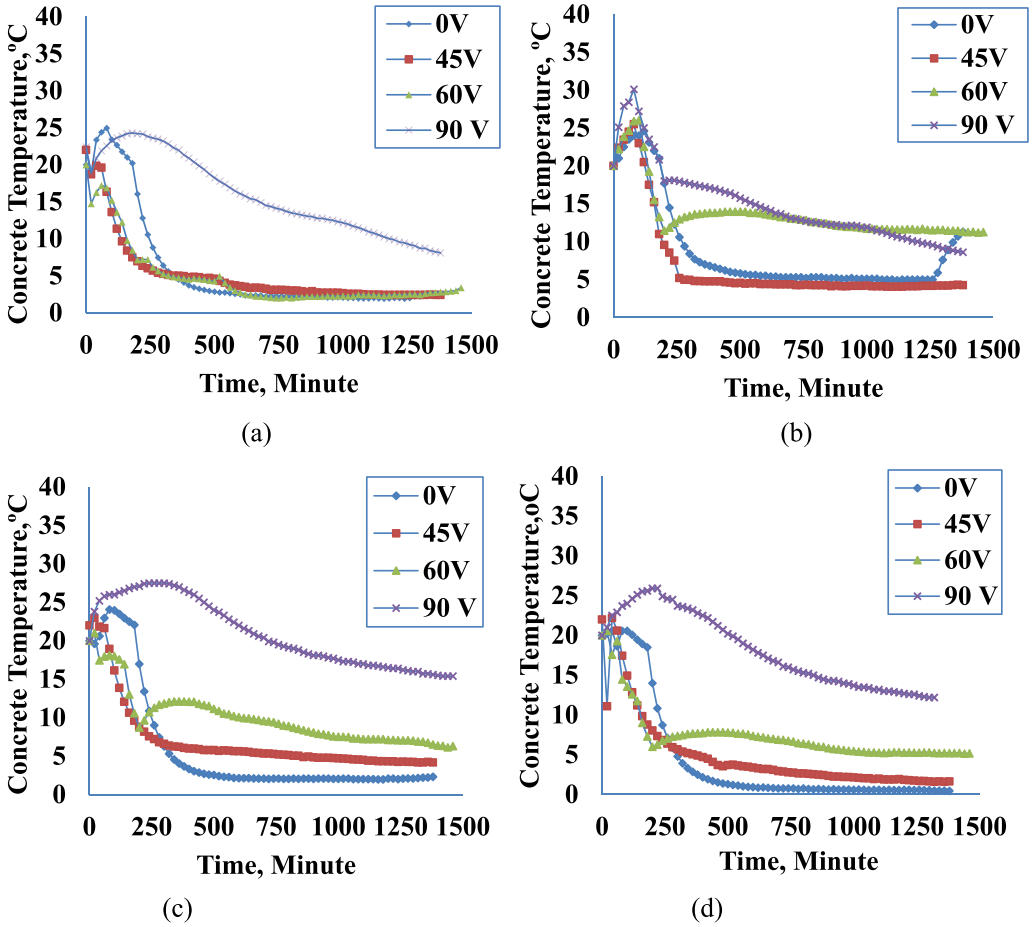


Fig. 4. Internal temperatures of concrete applied at 0 °C, (a):0% CB, (b): 1% CB, (c): 2% CB, (d):3% CB.

3.4. Compressive strength of concrete

The compressive strength of concrete specimens was determined according to TS EN 196-1 (2016) [21]. With an increase in carbon black ratio, there was a decrease in compressive strength. Carbon black is insoluble in water and, due to its fine-grained structure; it has a filling effect in concrete. It also increases the requirement for binder in the concrete due to this filler effect. Therefore, the compressive strength is reduced. It can be seen in Fig. 9, strength decreases with an increase in carbon black ratio in the concrete poured under ambient conditions (22 °C), when the 1-day strength of the poured concrete was examined, an increase was observed with the application of voltage. As a result of the acceleration of the hydration by electrical curing, the 1-day durability increased. With an increase in voltage, the 7-day strength decreased. For the 28-day strength, the concrete applied at 45 and 60 V were decreased but increased at 90 V.

It can be seen in Fig. 10, strength decreases with an increase in carbon black ratio in the concrete poured at 0 °C. For the 1-day strength, an increase in electrical stress increased the compressive strength because it accelerates hydration. For the 7- and 28-day strengths, the strengths of the concretes applied at 45 V increased compared to those to which no voltage was applied, whereas the strengths increased in the concretes at 60 and 90 V. In the cured concrete curing method, a 30% increase in strength was observed in the 1- and 7-day tests, but this was only 10% for the 28-day strength. Thus, the strength increased due to the acceleration of hydration in the first few days of curing with the application of voltage.

Fig. 11 shows that strength decreases with an increase in carbon black ratio in the concrete poured at −10 °C. The 1-day strength indicates that an increase in voltage increases strength as similar to other curing temperatures. For the concrete with no applied voltage, the 1-day strength was, on average, six times that observed in the concrete at 90 V. An average increase of 25% was observed when the compressive strength of the concrete was observed for 7 days. An average increase of 30% was observed when the compressive strength was examined at 28 days. Due to the acceleration of hydration in the first few days with the application of voltage, the strength values increased. In the following days, the effect of the voltage was less apparent.

3.5. Microstructure investigation

During the hydration of cement-based materials after mixing, calcium and hydroxyl ions go into solution within the first 10 min [22]. Then, while calcium and hydroxyl ion concentrations continue to rise slowly, little happens except for the slow precipitation of the semi-crystalline calcium silicate hydrate gel (C-S-H) [23–24]. The degree of hydration describes the process of hydration and is directly related to the fraction of hydration products or porous structures in a hydration system in cement-based materials [25]. Fig. 12 shows images of the concrete that was poured under ambient conditions (22 °C) and contained 3% carbon black. As can be seen from these images, a smooth structure was formed in the cement paste. Adherence to the aggregates and cement dough interface was largely achieved. Products resulting from hydration, such as C-S-H, portlandite and ettringite, occur more

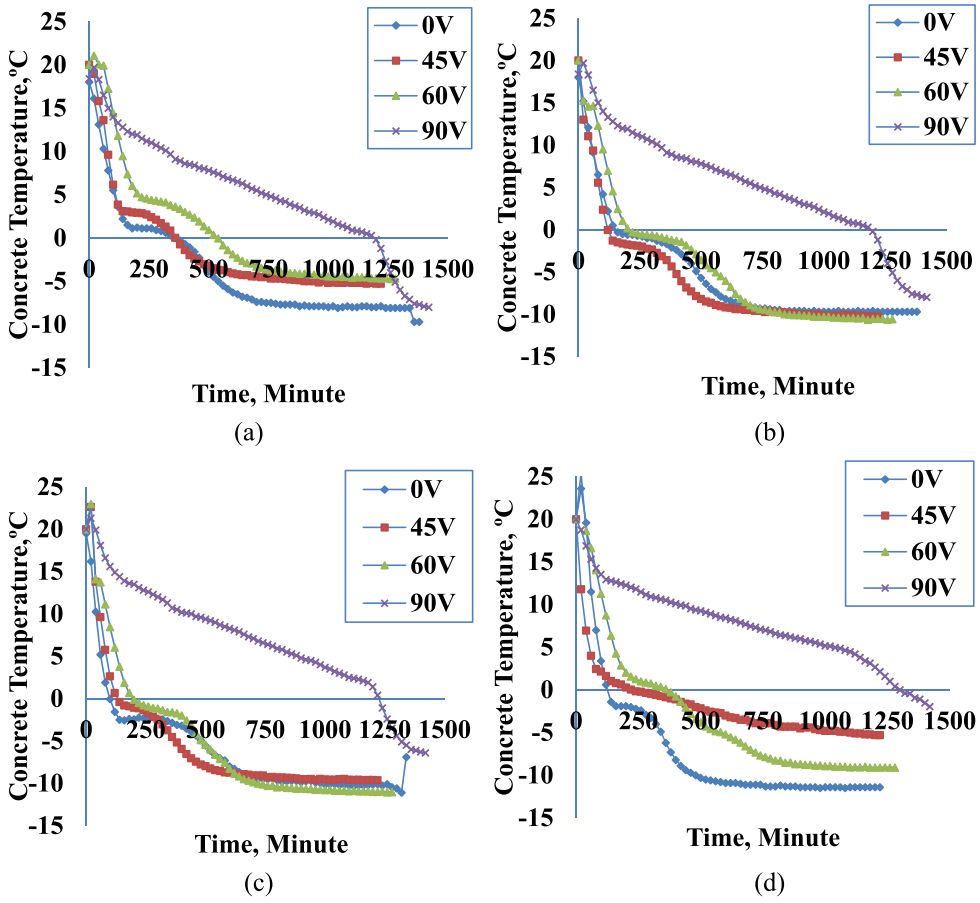


Fig. 5. Internal temperatures of concrete applied at −10 °C, (a):0% CB, (b):1% CB, (c):2% CB, (d):3% CB.

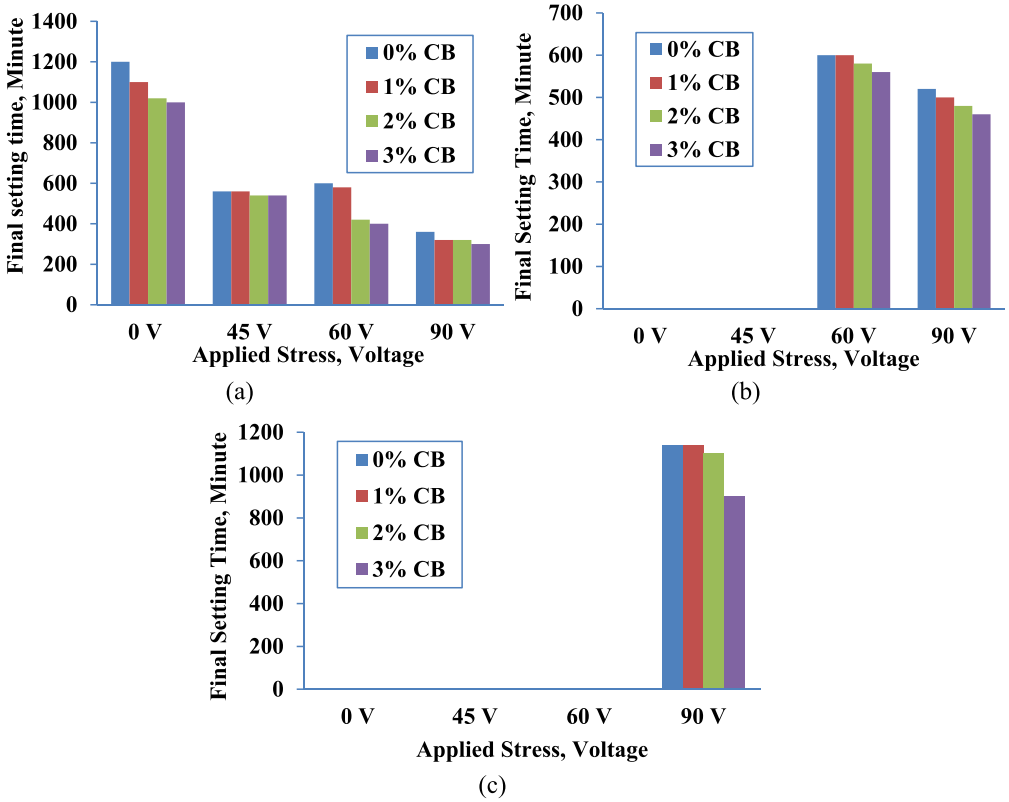


Fig. 6. Final setting times at different values of voltage (a): 22 °C, (b): 0 °C, (c): −10 °C.

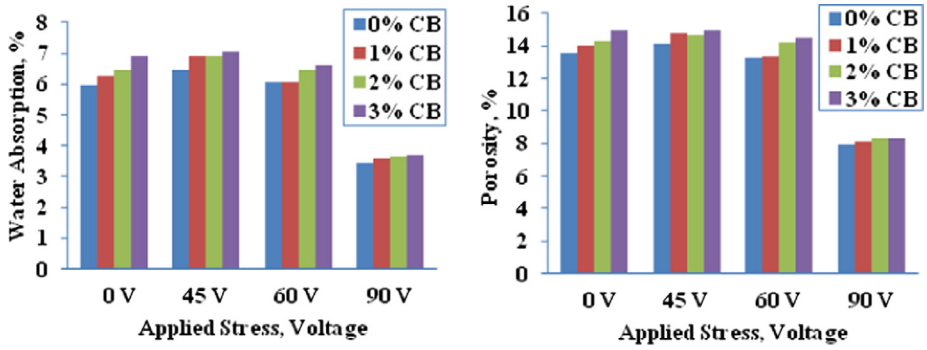


Fig. 7. Water absorption (%) and porosity (%) values of concrete poured under ambient conditions (22° C).

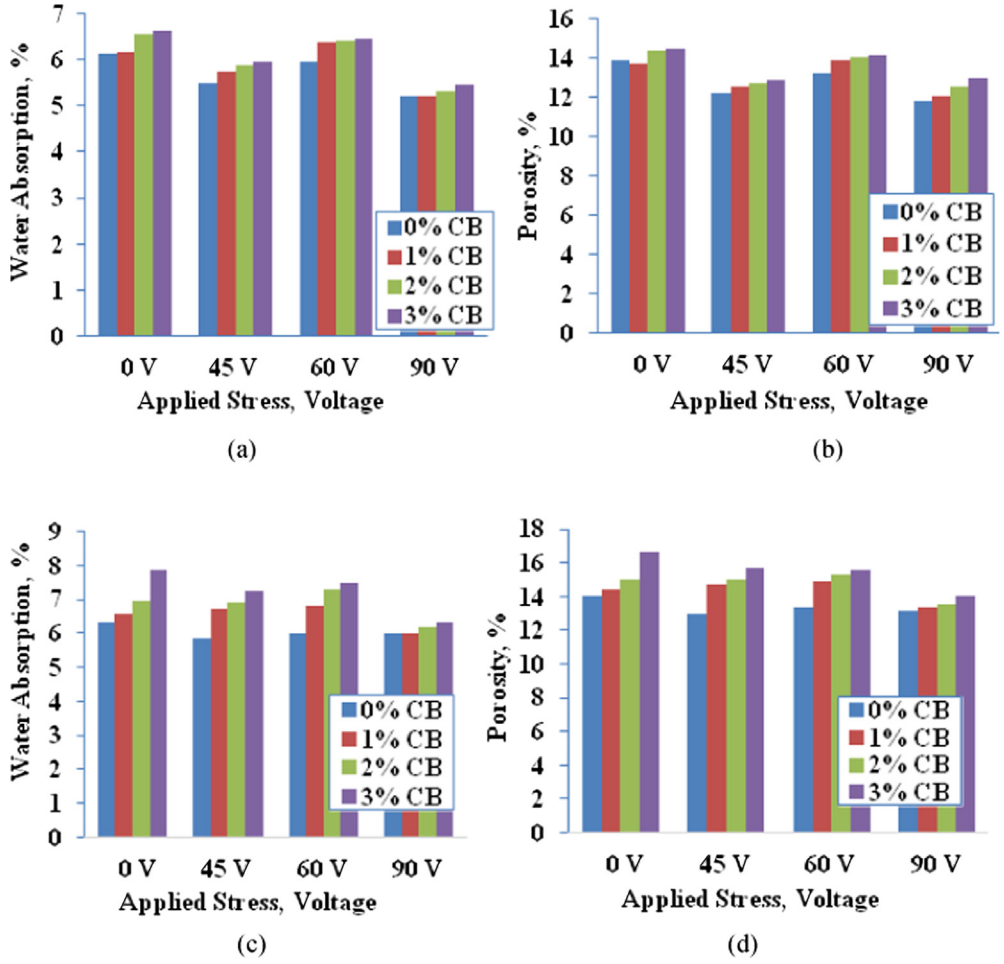


Fig. 8. Water absorption (%) and porosity (%) values of concrete poured in 0 °C and −10 °C.

rapidly with an increase in internal temperature. With an increase in stress, product formation by hydration was more intense.

4. Conclusions

With the cooling of the ambient conditions, the hydration slows down and the strength gain of the concrete get slower. By heating of the fresh concrete (max. 65 °C), hydration of concrete can be accelerated and it is possible to give early strength to concrete. In this study, it was aimed that prevent the freezing of fresh concrete at cold weather conditions by using electrically conductive concrete including carbon black. The following results can be output.

- Higher internal temperature temperatures were obtained with the increase of the applied voltage, and the setting times were shortened. It has been observed that with the increase of the voltage value and the carbon black ratio in the ambient conditions (22 °C), the end time of the setting has decreased.
- In the stress-free, 45 and 60 V applied concrete has not final setting time at 0 °C. In the samples with 90 V voltage applied, the outlet end is observed. Under cold conditions, the final setting time does not occur in normal conditions and 90 V voltage

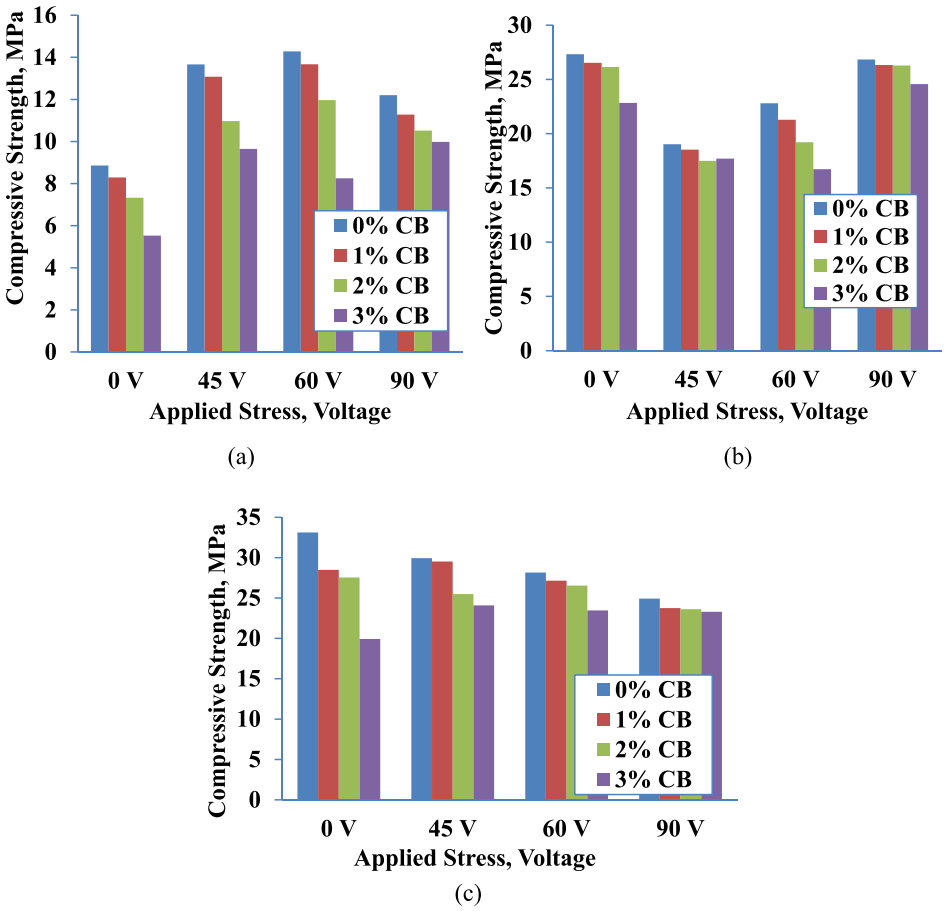


Fig. 9. Compressive strengths of concrete with different stress applied under ambient conditions (22 °C): (a):1, (b):7, (c):28 days.

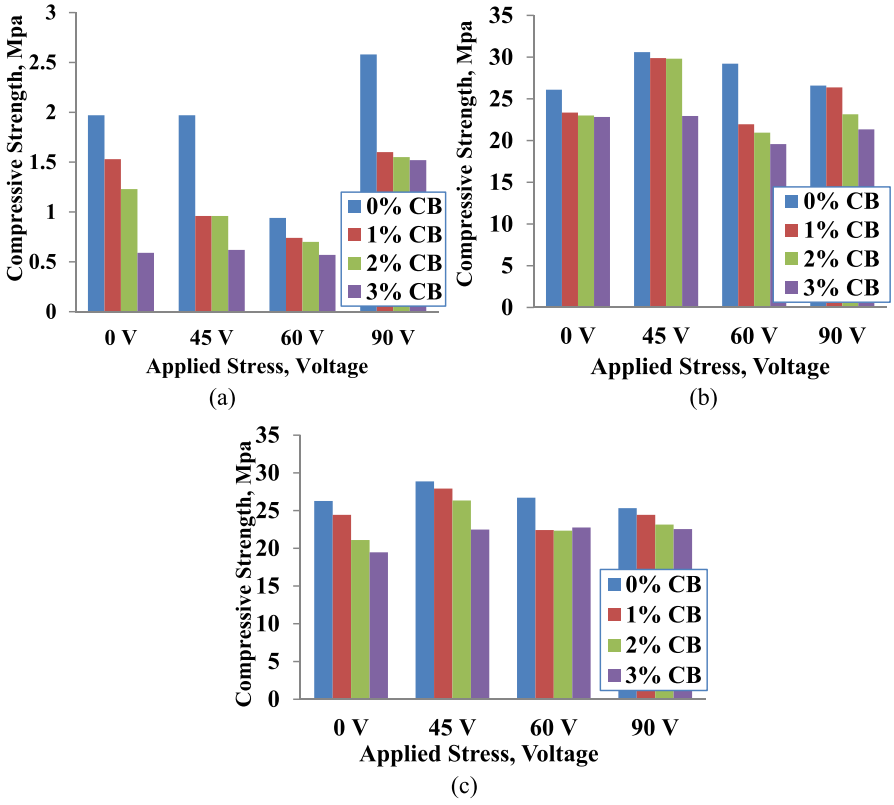


Fig. 10. Compressive strengths of concrete with different stress applied under 0 °C, (a): 1, (b): 7, (c):28 days.

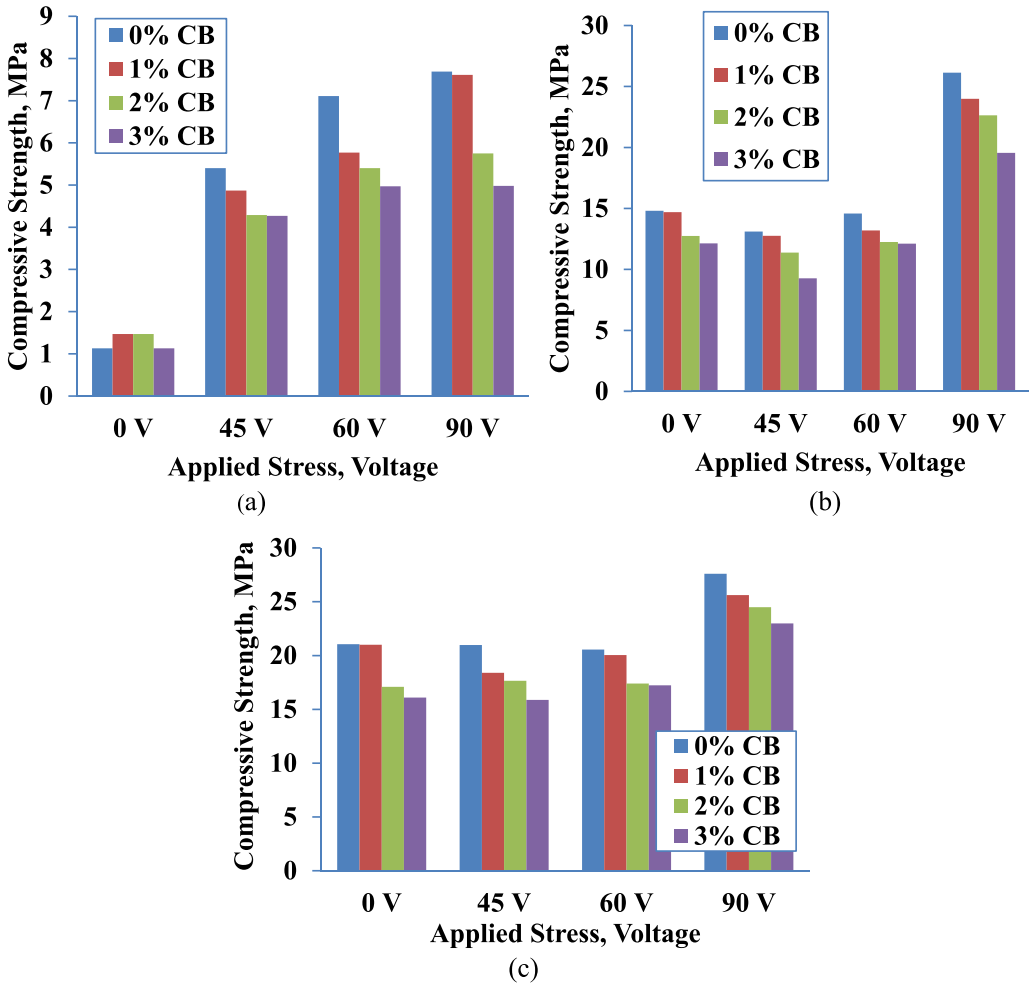


Fig. 11. Compressive strengths of concrete with different stress applied under −10 °C, (a): 1, (b): 7, (c):28 days.

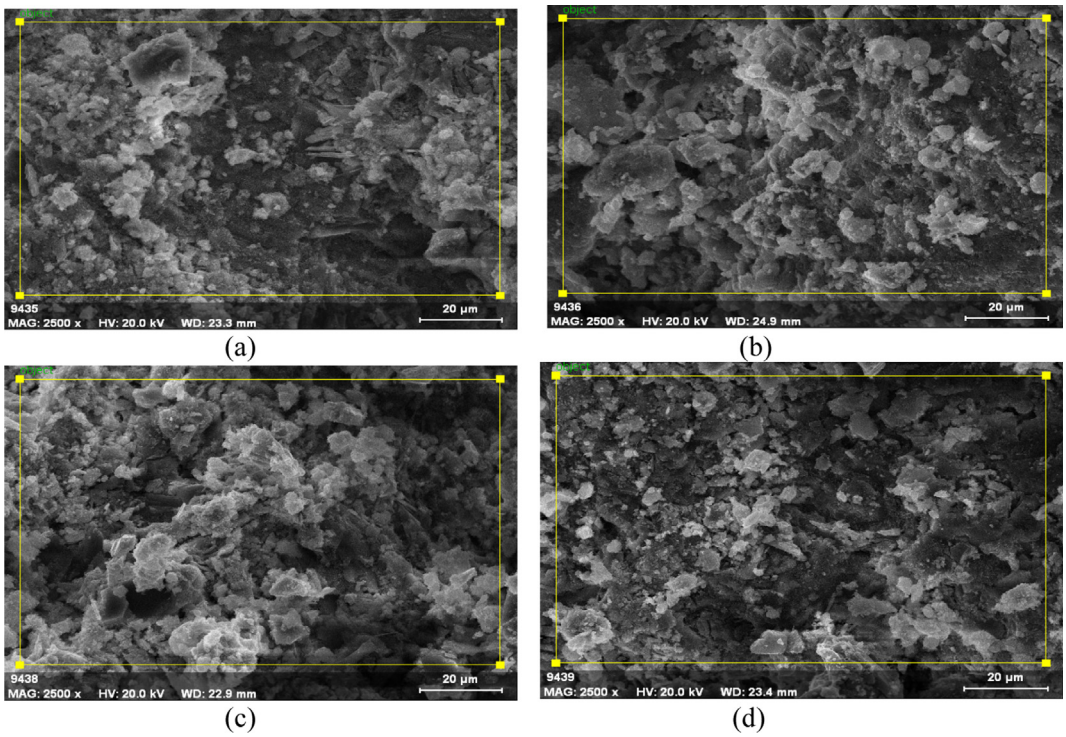


Fig. 12. Microstructure photos of concrete containing 3% Carbon Black under ambient conditions (a): 0 V, (b): 45 V, (c): 60 V, (d): 90 V.

can be applied in less than 24 h. In the concrete which is not applied voltage at −10 °C, in the concretes applied 45 Volts and 60 Volts, 1440 min at was not final set. 90 V voltage applied to the outlet was observed in concrete. In the samples used in carbon black, there was a further decrease in the setting times due to the conductivity.

- It was observed that the porosity in concrete increased with increasing carbon black ratio. Carbon black is insoluble in concrete, resulting in gaps in concrete. As a result of the addition of carbon black, substitution of carbon black with cement, the amount of cement decreases. Reduction of the amount of cement also increases the porosity by reducing the amount of binder. With the increase of the gap ratio, the water absorption rate increased. Because of the application of tension, the concrete accelerated the hydration by increasing the internal temperature and reduced the void ratio with more efficient hydration.
- With the increase in the ratio of carbon black, a decrease in compressive strength was observed. Carbon black is insoluble in water and due to its fine-grained structure; it forms a filling effect in the concrete. It also increases the requirement for binder in concrete due to the filler effect of carbon black. Therefore, the compressive strengths are reduced at all temperatures.

As a result of this study, it has been observed that the molding times can be shortened by using electrical curing method and this time can be shortened by replacing a conductive material in the concrete such as carbon black. Under cold conditions, electrical curing method was used to increase the internal temperature of the concrete. It has been observed that electrical curing method can final set to the concrete at a critical temperature such as −10 °C, which is considered to have stopped the outlet of concrete. By producing conductive concrete in cold conditions, it has been shown that the curing time can be shortened and fresh concrete prevented to freeze by applied at low cost by electric curing.

CRediT authorship contribution statement

Emriye Çinar: Resources, Data curation. **Tayfun Uygunoğlu:** Conceptualization, Writing - original draft. **Barış Şimşek:** Investigation, Writing - review & editing. **İlker Bekir Topçu:** Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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