# Electrical resistivity of fly ash blended cement paste at hardening stage

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**Abstract:** In this study, the effects of fly ash on the electrical resistivity of hardening (setting) cement paste were investigated. Different combinations of water/binder ratio and binder dosage levels were prepared for the mixtures. The fly ash were used in the mixtures by replacing the cement in ratio of 0%, 10%, 20% and 30% by weight. The measurements were done at room temperature. The relation between electrical resistivity and hydration time with and without electric current application was investigated. The results obtained indicate the influence of fly ash content and water to binder ratio on the electrical resistivity of all the pastes under investigation. As a result, electric current application can be used for obtaining to rapid setting time on the cement paste with high volume fly ash.

**Keywords:** Cement paste; Electrical resistivity; Fly ash; Hydration time.

## Introduction

The use of fly ash in the concrete production has gained prominence in global concrete construction. In general, the pozzolanic reaction is slow, so strength development and heat of hydration is low [1]. These cause some problems such as later de-moulding. On the other hand, pozzolanic reactions can be accelerated through increasing the temperature.

In monitoring of the whole hardening process of a cement paste, electrical resistivity can be used as a parameter [2,3]. Electrical conductivity process occurs primarily due to the ion transport through the pore solution in a cement-based system and it is a crucial parameter to study the hydration process of cement pastes at early stages [4,5]. During the hydration of cement paste after mixing, calcium (Ca) and

hydroxyl (OH) ions go into solution within the first ten minutes [6]. After that, little happens except for a slow precipitation of semi-crystalline calcium silicate hydrate gel (C-S-H) while the calcium and hydroxyl ion concentrations go on increasing slowly [7,8]. The degree of hydration describes the process of hydration, and directly relates to the fraction of the hydration products or porous structure in a hydration system in cement-based materials [9]. The variation of conductivity as function of time can indeed reflect internal changes of the pore solution of cement paste with time [10]. As it is well known, the hydration process in cement paste results in the formation of C–S–H, calcium CH, ettringite and other compounds. During hydration, the capillary pores in hardening cement paste are gradually filled up with hydration products and the solid phases form a rigid microstructure with increasing strength. Then, electrical resistivity of cement paste increases with time [11].

Xiao et al. used electrical resistivity for measurement and Marsh cone for provide a quick way to evaluate and select suitable superplasticizer in concrete. In another study, Xiao et al. [12] measured the electrical resistivity of the concrete mixes and the pore solution within the mixes by a non-contact electrical resistivity apparatus. They declared that electrical resistivity measurement reflects the hydration kinetics of fresh concrete. Chung [13] made research about the use of electrical resistance measurement to monitor damage in cement-based materials. Damage is demonstrated as through an increase in the resistivity. In order to identify the damage in the cement-based material, the volume resistivity can be used as a quantity. It is concluded that the volume resistivity can be enhanced due to the damage. Tamaás et al. [14] have shown that the time dependence of the electrical response of cement pastes is complex and

influenced by a number of variables such as water content, temperature, clinker fineness, gypsum and admixture content.

There are some articles have been published on various aspects of electrical measurement of setting and hardened cement paste. Therefore, this work aimed to study the electrical resistivity of blended cement pastes containing different types of fly ash (FA), from 0 to 30 mass % and different water/binder ratios (0.40, 0.45, 0.50, 0.55).

**Materials and Methods**

The cement paste mixes investigated in this study were prepared with Ordinary Portland cement (OPC) of CEM I/42.5 R, produced according to the European Standards EN 197-1 [15], Cement (OPC) and fly ash (FA) are demonstrated in Fig. 1. The physical and chemical properties of OPC and fly ash are presented in Table 1. The particle size distribution of OPC and fly ash were also given in Fig. 2. The main components of OPC are in the proportions of 60.11%, 11.02%, 6.97% and 9.95% for $C_3S$, $C_2S$, $C_3A$ and $C_4AF$, respectively. OPC has initial setting time of 182 min and final setting time of 310 min.

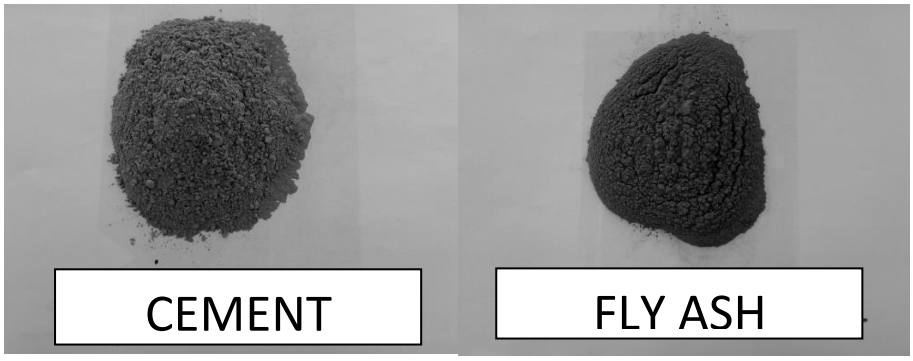



Figure 1. A view of OPC and fly ash admixtures

Table 1. Physical and chemical properties of OPC and fly ash admixtures

| **Component, %** | **OPC** | **FA** |
|---|---|---|
| CaO | 63.6 | 6.66 |
| $SiO_2$ | 19.6 | 47.4 |
| $Al_2O_3$ | 4.72 | 19.8 |
| $Fe_2O_3$ | 3.27 | 11.8 |
| MgO | 1.91 | 4.76 |
| $Na_2O$ | 0.34 | 0.57 |
| $K_2O$ | 1.06 | 2.62 |
| $SO_3$ | 4.72 | 1.86 |
| $Cr_2O_3$ | 0.04 | 0.13 |
| $TiO_2$ | 0.41 | 0.88 |
| LOI | 2.69 | 2.76 |
| Specific gravity | 3.07 | 1.99 |
| Fineness, $cm^2/g$ | 3312 | 3126 |

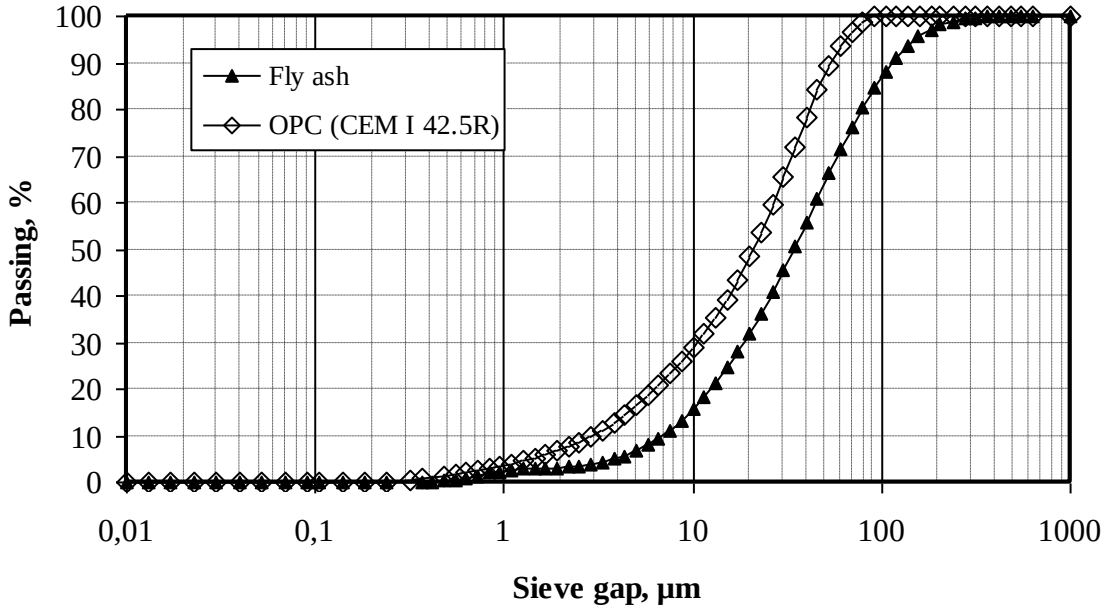



Figure 2. Particle size distribution of OPC and fly ash

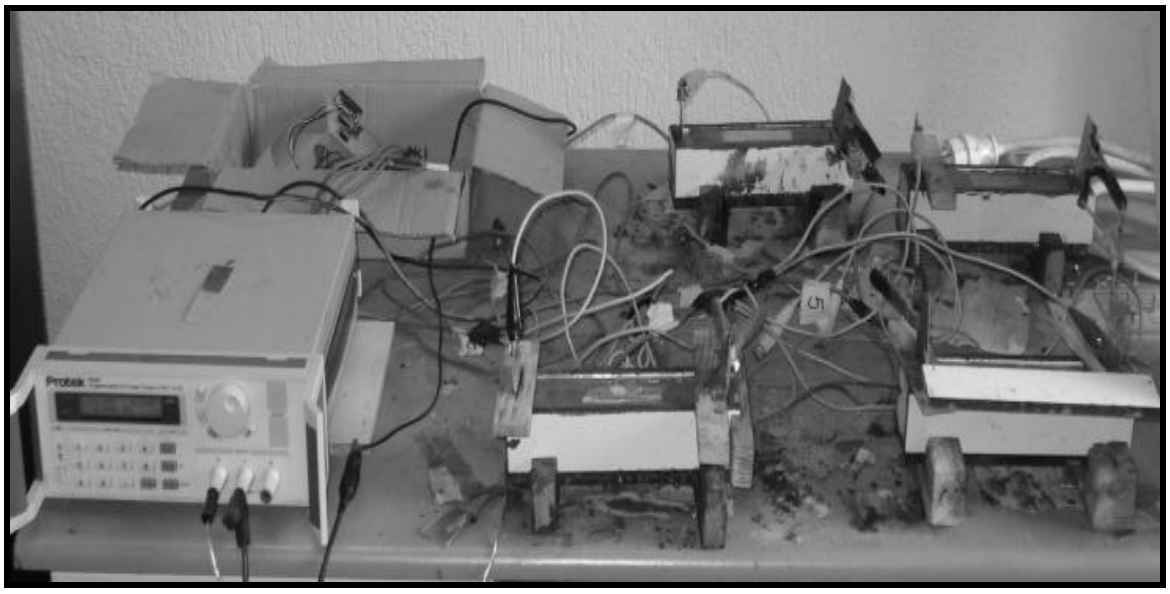


Fig. 3. A view of electrical conductivity test setup.

***Cement paste mixes for electrical resistivity***

The cement paste mixes were proportioned by replacing cement with fly ash in ratios of 0% (control), 10%, 20% and 30% (by weight of cement). The mixtures used in the study were also proportioned in water to binder (w/b) ratios of 0.40, 0.45, 0.50 and 0.55. The cement, water, and fly ash were mixed in the mixer for 5 min.

Apart from setting time measurements, following cement paste mixing, it was poured into moulds that in size of 40 x 40 x 160 mm. After pouring the mix into oiled wooden molds, an external vibrator was used to facilitate compaction and decrease the amount of air bubbles. Copper plates were embedded to both ends of the setting cement paste in the mold. The moulds used in the experiments were wooden because of prevention to the transmissions of electricity from molds. AC current was applied with a 15 V voltage to cupper plates during 24 h. In every 2 min, the current was measured and reported with an ampere meter (Fig. 3). The measurement began exactly 2 min after the first contact with water. The measurements were done at room temperature. In the experimental setup, 4 different molds were used, and the data collection was carried out by a data logger. The electrical resistivity (R) of each setting cement paste was calculated as follows.

$$R = \frac{A}{1} x \frac{U}{I} \quad (1)$$

Where; l: the distance between the voltage electrodes; A: the cross-sectional area of the sample; I: the current through the Sample; and U: voltage drop over the electrodes.

**Results**

The results being obtained by this research study are given below:

- The electrical resistivity value of the admixtures has also increased by being decreased of the water/binder ratio. Depending upon the hydration time, the electrical resistivity in higher water/binder ratio increases.
- When the fly ash added to the cement paste is being increased, the electrical resistivity has increased. The reason of this is the decrease of water content in the admixture. Therefore, it can be concluded that when the fly ash proportion is increased, the water in the cement paste reacts chemically faster with the fly ash and the admixture with the fly ash hardens faster than the admixture without the fly ash.
- For 10-30 min. of hydration span, the rate of the electrical resistivity of FA has risen in collaboration with enhancing the FA additive ratio from 0 % to 30 %, the rise of the electrical resistivity is an indicator for hardening of the cement paste.
- When the impact of the admixtures having different proportions (10 %, 20 %,30 %) of fly ash on the electrical resistivity has been examined, the most effective admixture on the rise of the electrical resistivity consists of 30 % of fly ash.
- The electrical resistivity has increased by the decreasing of the fly ash content (because of its pozzolanic feature) and this situation has occurred during the higher hydration time.
- The electrical resistivity value is an indication of hydration. With the help of being conducted electric current through mixtures with fly ash, hydration is occurred in less time. In other words, the curing period has become faster.

Consequently, electrical resistivity behaviour of blended cement paste composites can be greatly modified by the use of fly ash. Furthermore, the hydration duration of cement paste with FA additives can be accelerated as a result of conducting electric current.

## Discussion

### *Effect of fly ash and content on electrical current*

The conductor between two electrodes in cement paste mixture was initially the water in the mixture which is in the liquid phase. At the beginning, all the pores in the mixture have connections among themselves. Therefore, the electrolysis between the electrodes has arisen from the free water of these pores. However, hydrated products occur in the course of time because of the reaction of the main components in the cement paste with water, and the pores which were once connected to each other have been separated. Accordingly, electrical resistivity of cement paste increase in time and when the cement completes its hardening time, its electrical resistivity amount reaches the maximum value. Consequently, the electrical resistivity of cement is directly associated with the hydration of the cement.

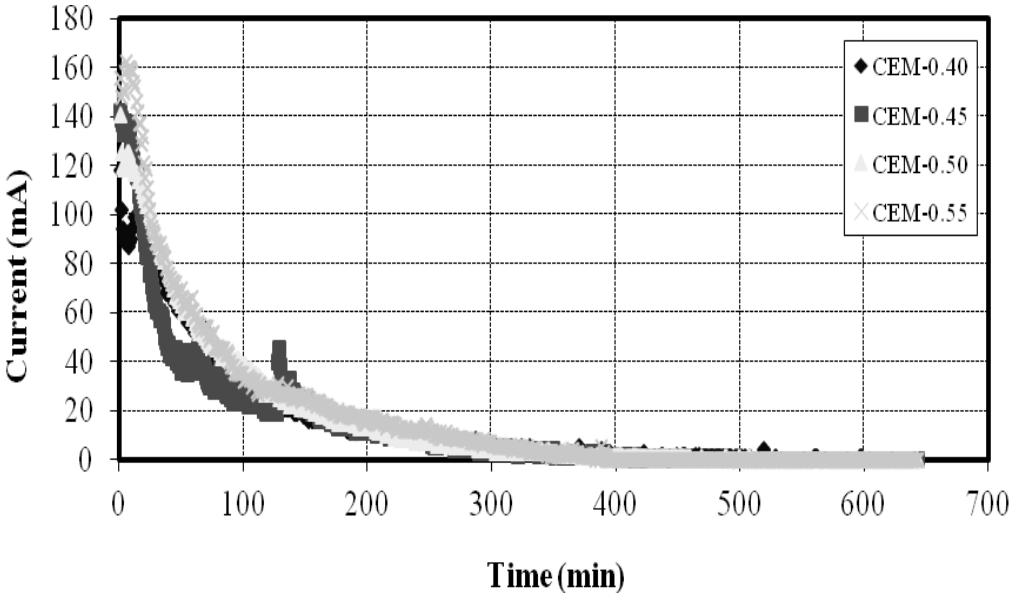
The cement paste having different water/binder proportions without any additives and the cement paste having different fly ash proportions have been investigated during the time until the setting time of the cement paste has taken (one day at the laboratory having suitable conditions).

The conduct of electrical current on the cement paste without any mineral additives is directly associated with water/binder proportion of the admixture. This experiment shows almost the same at the beginning. Due to the electrical conductivity

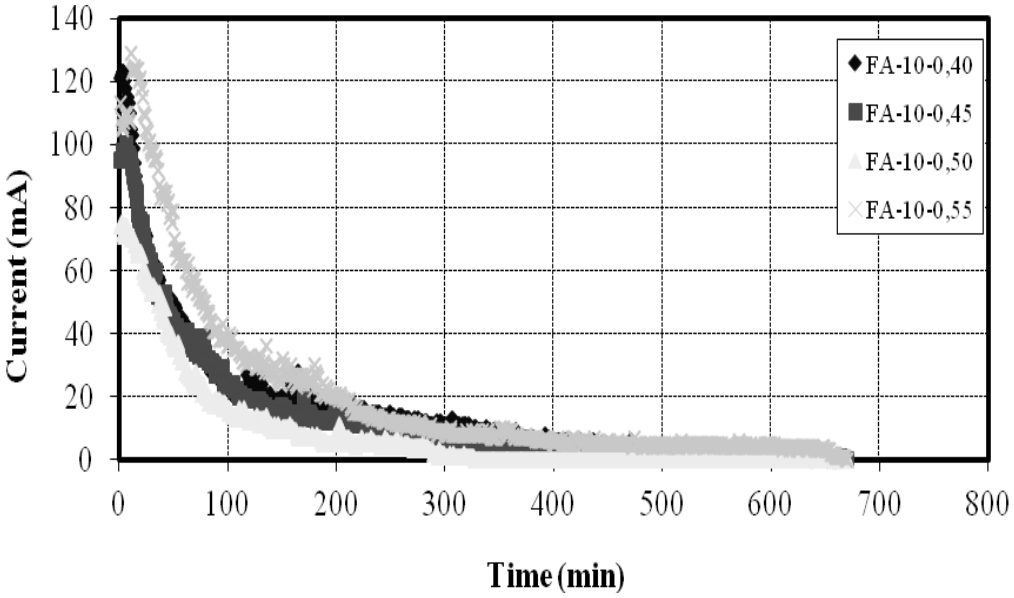
of water, it can be seen in Figure 4 (a) that the cement paste which has higher proportion of water/binder conducts much more electrical current. When the electrical conductivities of the cement pastes without any mineral additives whose water/binder proportions are 0.55 and 0.40, respectively, at the initial phase, are compared with each other, it has been concluded that the cement paste whose water/binder proportion is 0.55 is almost 17 % more conductive than the cement paste whose water/binder proportion is 0.40.

When the fly ash as a mineral additive is added to the cement paste, its electrical conductivity proportion is less than the cement paste without any mineral additive. (Figure 4) (b),(c),(d). Enhancing the fly ash proportion in the admixture, which has been added instead of cement, causes the cement paste's conducting less current and the increase of the electrical resistivity. It can be reached this conclusion from Figure 4 (b), Figure 4 (c) and Figure 4 (d). It has been measured that at the initial phase, the electrical conductivities of cement pastes, whose water/binder ratio is 0.55 and in which fly ash has been added in the proportions of 10 %, 20 % and 30 %, respectively instead of being added cement, are 124mA, 77mA and 26mA, respectively.

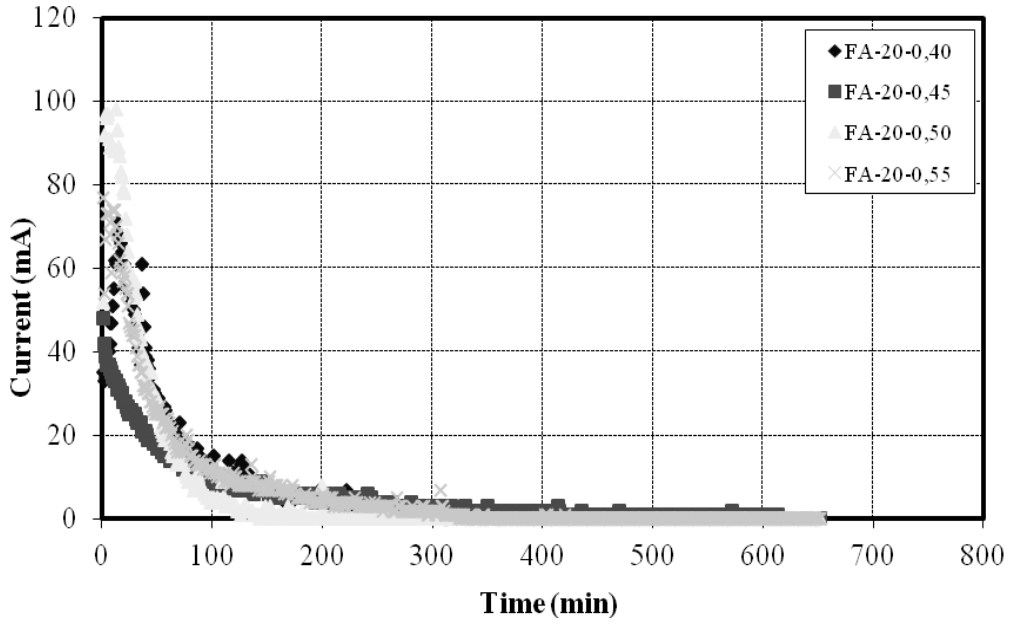
When the fly ash added to the cement paste is being increased, the electrical resistivity has increased. The reason of this is the decrease of water content in the admixture. Therefore, it can be concluded that when the fly ash proportion is increased, the water in the cement paste reacts chemically faster with the fly ash and the admixture with the fly ash hardens faster than the admixture without the fly ash.


Current (mA)
Time (min)
CEM-0.40
CEM-0.45
CEM-0.50
CEM-0.55

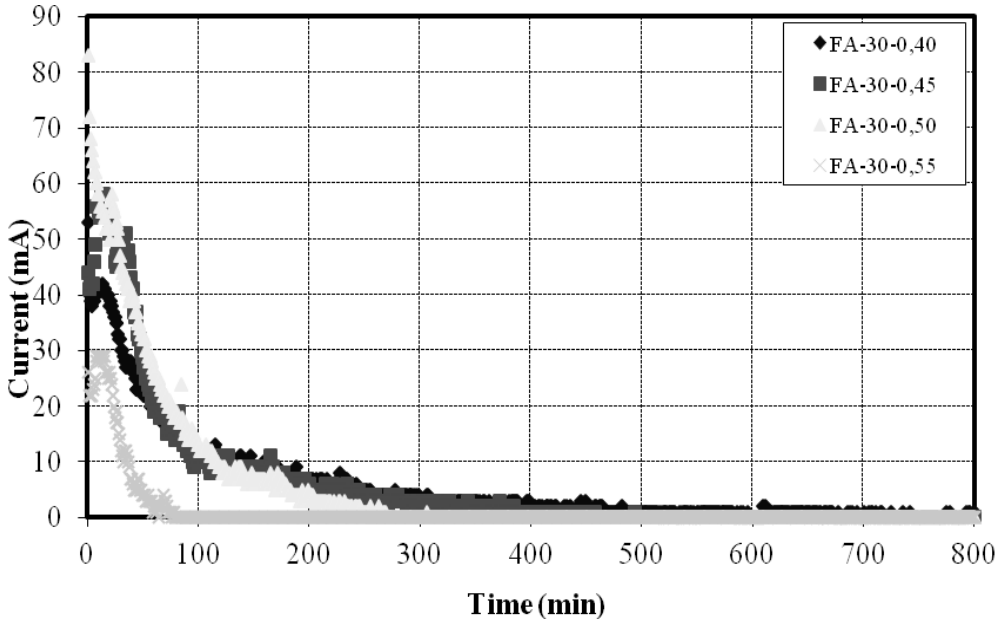
**(a)**


Current (mA)
Time (min)
FA-10-0,40
FA-10-0,45
FA-10-0,50
FA-10-0,55

**(b)**




**(c)**




**(d)**

Figure 4. Electrical current change in cement paste with both different ratio of w/b and fly ash (a: 0 %, b: 10 %, c: 20 %, d: 30 %).

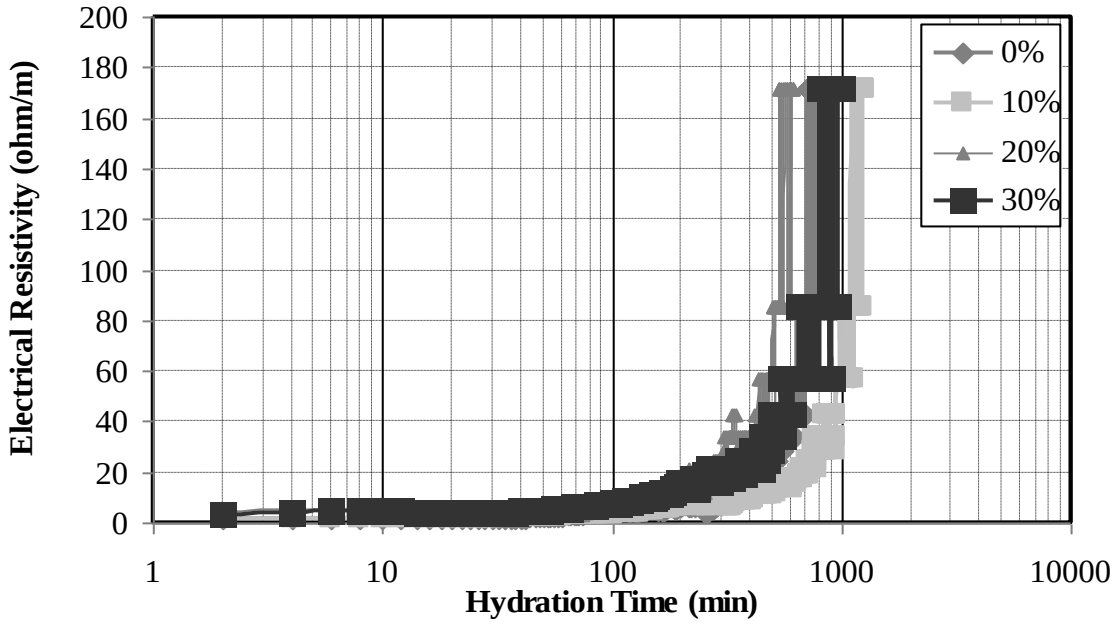
***Effect of fly ash and content on electrical resistivity***

In Fig. 5 (a, b, c, d), as a result of replacing FA with the cement in specific proportions by weight, the electrical resistivity of binder cement paste in fresh state, which depends on the hydration time, has been observed. Besides, different water-binder ratios have been used for fly ash. The lower resistivity values were obtained on the blends having higher OPC contents, during the initial stage of hydration for the each water to binder ratio. In general, the resistivity values increased sharply with a notable appearance located between 10 and 100 min for the pastes. During the initial stage of hydration time, the resistivity takes the lowest value as a result of the hydrolysis of the OPC components. In other words, the charge carrier are realized by $Ca^{+2}$, $OH^{-}$, $SO_4^{-2}$, and alkali ions [16]. Once the concentration of these ions in the cement paste becomes very high, ionic association starts. As a result of this ionic association, the electrical resistivity is increased.

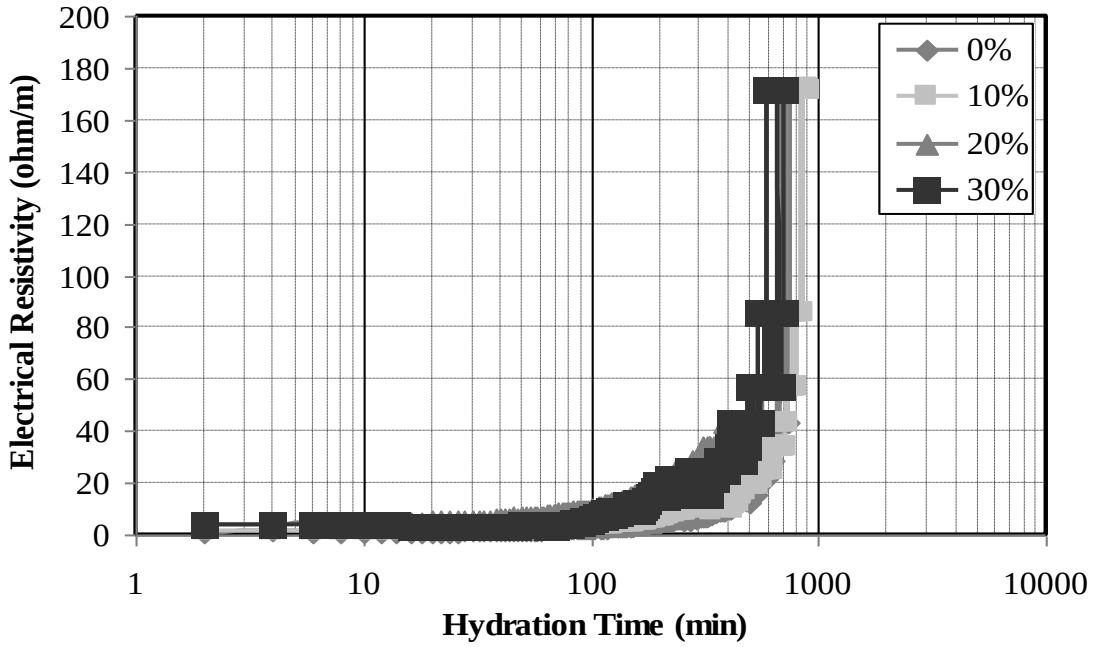
The results of Fig. 5 (a, b, c, d) show also the effect of different FA admixture content on the electrical resistivity values of the blended cement pastes. For 10-30 min. of hydration span, the rate of the electrical resistivity of FA has risen collaboration with enhancing the FA additive ratio from 0 % to 30 %. As it has been mentioned before, the rise of the electrical resistivity is an indicator for hardening of the cement paste. However, when the electric current is conducted through the admixtures, the cement starts to harden in less time in comparison with the control mixture. This situation can easily be recognized due to the increase of the electrical resistivity.

This result is mainly attributed to some factors, namely; the decrease in the number of leaching ions during the hydration of OPC as its proportion decreases in the

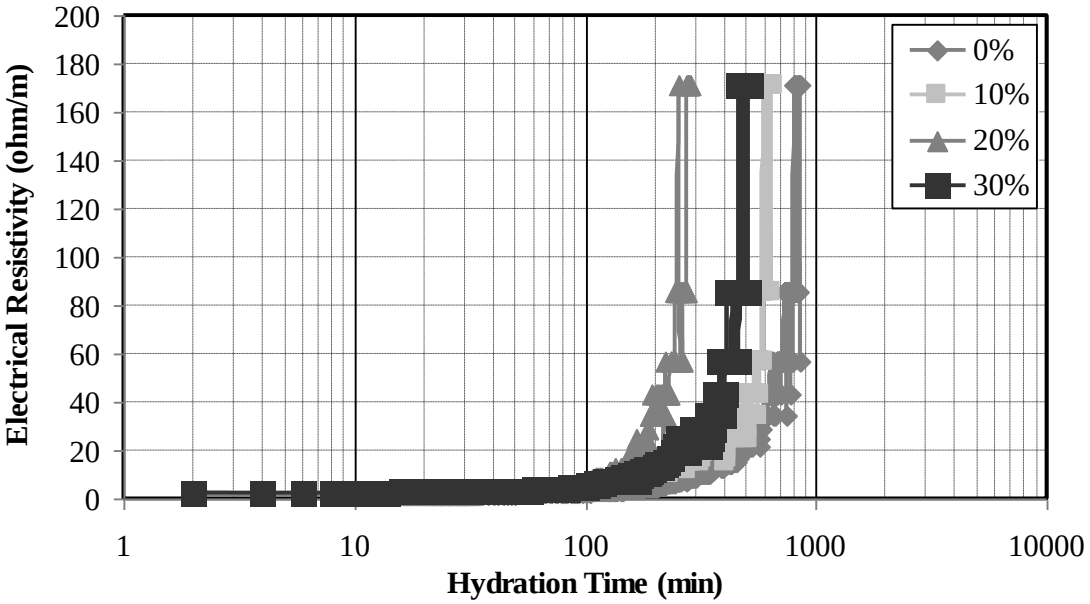
mixes. The degree of consumption of free $Ca(OH)_2$ released as a result of OPC hydration leading to the formation of poorly crystallized calcium silicate hydrates during the hydration of OPC increased as the pozzolanic mineral admixture FA content increases [16,17]. On the other hand the advance of time of hydration of all mixtures decreased electrical resistance. Due to the mixtures containing high amounts of fly ash additives, the electrical resistivity enhances. The hydration interaction between pozzolanic mineral admixtures (with high $SiO_2$+$Al_2O_3$+$Fe_2O_3$) and the free $Ca(OH)_2$ released to form C-S-H results in a decrease in the free water content of the paste leading to a sort of acceleration of the ettringite–monosulfate transformation [18,19]. For this reason adding the fly ash to the blend makes the electrical resistivity increased. An interaction between fly ash grains and the initially formed $Ca(OH)_2$ takes place that is leading to a further decrease in the $Ca(OH)_2$ content of the initially formed C-S-H with increasing duration of hydration time. The C-S-H is thus produced as a result of hydration interaction between the initially formed hydrates and the unhydrated parts of fly ash grains [19,20,21]. Sudden heigher of electrical resistivity related to hydration time is a clear proof of this case. So, an accelerated cure for cement paste can be made by using both fly ash and electric current.


Electrical Resistivity (ohm/m)
200
180
160
140
120
100
80
60
40
20
0
1
10
100
1000
10000
Hydration Time (min)
0%
10%
20%
30%

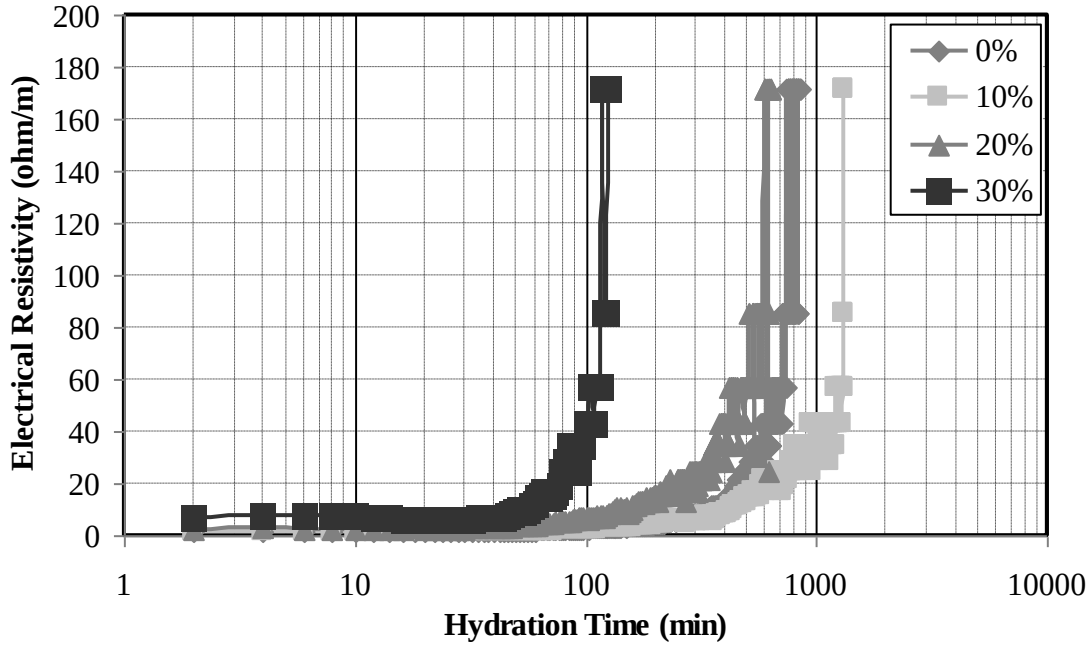
**(a)**


Electrical Resistivity (ohm/m)
200
180
160
140
120
100
80
60
40
20
0
1
10
100
1000
10000
Hydration Time (min)
0%
10%
20%
30%

**(b)**




**(c)**




**(d)**

Figure 5 Electrical resistivity of cement paste with fly ash in ratio of water/binder (a: 0.4, b: 0.45, c: 0.50, d: 0.55)

***Effect of water to binder ratio***

When the admixture which includes fly ash is considered, when cement paste is in liquid phase, in another words when it is on the hydration stage of which electric current is easily conducted, by increasing water and binder amounts, electrical resistivity is risen. Free space water which is in the gaps of the mixture is used in chemical reactions for producing hydration products and in hydrolysis for conducting electric current. Therefore, by increasing water and binder amount, hydrolysis reaction is accelerated. A high water to binder ratio lead to a greater ability to conduct electricity of blended cement paste [22].

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