

Investigating the Relationship Between Compressive Strength and Electrical Resistivity of Concretes Containing Micro Silica and Fly Ash at Early Ages

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Abstract:

Non-destructive testing methods can be employed to determine the properties of concrete in its early ages, providing a means to assess concrete quality and safety during construction. The main objective of this research is to estimate the compressive strength of concrete containing micro silica (5% and 10%) and fly ash (15%, 25%, and 50%) in its early ages based on electrical resistivity. Establishing a correlation between these two crucial concrete parameters allows for the calculation of concrete compressive strength without the need for destructive tests, utilizing electrical resistivity. This approach ensures damage-free test samples, allowing for consecutive testing on a specific concrete specimen. Additionally, the study investigates the impact of pozzolanic materials, micro silica, and fly ash on the electrical resistivity of concrete. To achieve this, 18 concrete mixtures were prepared with water-to-cement ratios of 0.4, 0.45, and 0.5 and a cementitious material content of 350 kilograms per cubic meter. Planned tests were conducted at 1, 3, 7, 14, and 28 days. The results indicate that concrete compressive strength can be estimated as a function of electrical resistivity in the early ages.

Keywords: Concrete, micro silica, fly ash, electrical resistivity, compressive strength.

1. Introduction:

Concrete, one of the most widely used construction materials, holds significant importance in today's construction industry. Researchers continually seek an appropriate relationship among influential parameters to enhance compressive strength and improve concrete properties. Compressive strength is generally the most crucial criteria for evaluating concrete quality and safety. Destructive tests are commonly used to measure the concrete's compressive strength. The electrical resistivity of concrete, as a non-destructive testing method, plays a substantial role in determining concrete's physical and mechanical characteristics. The value of concrete electrical resistivity directly depends on concrete permeability and environmental conditions. Naturally, as concrete's permeability and moisture content increase, ions can move more easily and rapidly within the concrete. Concrete electrical resistivity serves as a parameter for assessing the potential corrosion rate of reinforced concrete specimens under chloride attack [1]. What is crucial in the electrical resistivity test is the ability to measure and assess the potential corrosion of reinforcements when concrete is exposed to chloride-rich environments. According to studies conducted by Vassie, if the electrical resistivity is greater than 12 kilohm-centimeters, corrosion is unlikely.

Conversely, if it is less than 5, corrosion is definite. Corrosion is considered probable within the range between these two values [2]. To measure the electrical resistivity of concrete, scientists initially utilized direct current (DC). However, through subsequent experiments, research has shown that when using alternating current (AC),

concrete exhibits both resistive and capacitive behavior [3]. The most common laboratory method for measuring the electrical resistivity of concrete is the volumetric method [4].

Additionally, three in-situ methods are employed for electrical resistivity measurement: the two-electrode method [5, 6], the Wenner four-electrode method [7], and the single-electrode or disc method [8, 9]. Rapin investigated the water-to-cement ratio's effect on concrete's electrical resistivity. According to his study's results, an increase in the water-to-cement ratio reduces electrical resistivity. When the behavior of concretes containing cementitious alternatives such as slag differs, the electrical resistivity has been observed to rise with an increase in the water-to-cement ratio from 0.35 to 0.65 [10]. Consequently, the impact of moisture content on the electrical resistivity of concrete was examined. The results of this research indicated that the difference in electrical resistivity for mixtures with water-to-cement ratios of 0.55 and 0.65 was not significant [11]. Results from a practical study conducted by Sengul demonstrate that an increasing in aggregate particle size leads to higher electrical resistivity in concrete. It was also shown that the electrical resistivity of mixtures with 60% of aggregate particle dimensions in the 16 to 32 millimeters range is approximately three times that of hardened cement mortar [12]. One of the most significant properties of pozzolans, as a substitute for cement, is their considerable capability to reduce large pores and concrete permeability. The reactions of siliceous pozzolans and lime resulting from cement hydration contribute to the filling property, leading to a reduction in large pores, decreased permeability, and increased durability of concrete. The use of various pozzolans as cement substitutes not only aids in reducing cement consumption, energy use, and greenhouse gas emissions but also improves mechanical properties at later ages and concrete durability, such as permeability [13, 14]. Some researchers have found that microsilica enhances the compressive strength of concrete, with its major impact observed in the compressive strength of concrete at ages ranging from 3 to 28 days [15, 16]. The use of microsilica significantly increases electrical resistivity. Microsilica's positive effect in enhancing concrete's electrical resistivity has been recognized since its inception in concrete. Due to its very fine particle size and pozzolanic characteristics, microsilica creates a structure with fine pores and a low ionic concentration in the pore solution. The formation of such a fine structure in the cement matrix leads to a significant increase in the electrical resistivity of concrete [17, 18]. Fly ash is a material with very fine spherical particles derived from the combustion of coal powder residue in thermal power plants [19-21].

Fly ash is widely used as a cement substitute in ordinary concrete, exhibiting high resistance. In ordinary concrete, the substitution rate can even reach 50%. However, the substitution level is limited to 15-25% in high-strength concrete. The reason for using this material in high-strength concrete is to reduce heat generation and achieve better durability characteristics [22, 23]. Under favorable processing conditions, concrete containing fly ash has a higher long-term compressive strength compared to Portland cement concrete [24]. The use of cement substitutes such as fly ash and microsilica improves the microstructure of the cement matrix, resulting in a significant reduction in concrete permeability [25]. Most studies on fly ash's effect on concrete's electrical resistivity have been accompanied by an investigation of its impact on the corrosion of reinforcing steel. Due to the significant relationship between electrical resistivity and corrosion, researchers have examined the performance of supplements based on electrical resistivity in more detail. The effect of fly ash on electrical resistivity is primarily related to changes in the fine structure of concrete. Ehtisham studied the alteration in pore chemistry, refinement of pore structure, and its effect on electrical resistivity. By replacing 30% of cement with fly ash, the concentration of hydroxide ions decreased, and pore distribution became finer than plain concrete. The average radius of the pores in the fly ash cement matrix is 30% smaller than that in the plain cement matrix. Therefore, the electrical resistivity of fly ash concrete is approximately 2.2 times that of ordinary concrete [21]. This study used the bulk resistivity method to calculate the electrical resistivity of concrete containing microsilica and fly ash. Furthermore, the relationship between compressive strength and electrical resistivity of pozzolan-containing concretes will be experimentally investigated. The effect of using different amounts of pozzolans on the correlation between these two parameters will also be examined.

2. Experimental programs

2.1. Materials and mix proportions:

The cement used was ASTM C150/C150M-11 Type II Portland cement [26]. The specific gravity is 3.15 g/cm³. The chemical analysis and physical properties of cement, fly ash, and silica fume are given in Table 1. The coarse

aggregate was angular crushed gravel with a 25-mm nominal maximum size, and the fine aggregate was river sand. The coarse and fine aggregates' specific gravity and water absorption were 2.61 and 2.04%, and 2.56 and 2.3%, respectively. The sieve analyses of fine, coarse, and final mixture of aggregates used in the concrete are listed in Table 2. Table 3 shows the mix proportions of the ten concretes used in the experiments. The concrete was proportioned using w/c ratios of 0.4 and 0.5 to obtain concrete with different strengths. Furthermore, a polycarboxylate-ether (PCE) superplasticizer was used to increase the concrete's fluidity and workability. It has an approximate density of 20 °C of 1.05 g/cm³, Ph equal to 5.0, and 37.0% dry residue. This superplasticizer content ranged from 0.1% to 0.8% of the cement weight for each mix studied, as recommended by the manufacturer. In SF5 and SF10 mixtures, 5% and 10% of cement were substituted by silica fume, respectively. Similarly, 15%, 25%, and 50% cement were substituted by fly ash in FA15, FA25, and E-FA50, respectively.

2.2. Test methods

The compressive strength test on concrete was conducted on standard cylindrical specimens with a diameter of 150 millimeters and a height of 300 millimeters at the ages of 1, 3, 7, 14, and 28 days, in accordance with ASTM C39 standards [27].

Table 1: Chemical analysis and physical properties of cement, fly ash and silica fume.

Parameters	Cement	Fly ash	Silica fume
SiO ₂	20.68	36	98.41
Al ₂ O ₃	4.51	9.5	0.20
Fe ₂ O ₃	4.13	0.5	0.89
CaO	63.66	35	0.28
MgO	1.35	9	---
Na ₂ O	0.26	---	0.03
K ₂ O	0.74	---	0.022
SO ₃	2.55	---	---
LOI	2.50	---	---
Fineness, m ² /kg	318	400	---

Table 2: Sieve analysis of the aggregates.

Sieve size(mm)	River sand (%)	Gravel (%)	Aggregate mixture (%)
19	100	100	100
12.5	100	68	89.6
9.5	100	34.4	83.7
6.35	92.8	1.1	66.4
4.75	63.6	0.8	49.4
2.38	41.5	0	32.7
1.18	24.2	0	23.7
0.6	14.3	0	16.4
0.3	12.2	0	13.1
0.15	4.3	0	7.2

Table 3: Mix proportions of concrete per cubic meter (kg/m³).

mixture	W/C	Cement	Fine Aggregate	Coarse Aggregate	SF	FA	SP (%)
A1	0.4	350	1167	778	0	0	0.6

A2	0.45	350	1139	759	0	0	0.4
A3	0.5	350	1111	741	0	0	0
A1-SF5	0.4	332.5	1163	775	17.5	0	0.7
A1-SF10	0.4	315	1159	773	35	0	0.8
A1-FA15	0.4	297.5	1160	773	0	52.5	0.5
A1-FA25	0.4	262.5	1155	770	17	87.5	0.3
A1-FA50	0.4	175	1144	763	0	175	0.3
A2-SF5	0.45	332.5	1135	757	17.5	0	0.6
A2-SF10	0.45	315	1131	754	35	0	0.7
A2-FA15	0.45	297.5	1132	755	0	52.5	0.4
A2-FA25	0.45	262.5	1128	752	0	87.5	0.2
A2-FA50	0.45	175	1116	744	0	175	0.1
A3-SF5	0.5	332.5	1107	738	17.5	0	0.2
A3-SF10	0.5	315	1104	736	34	0	0.4
A3-FA15	0.5	297.5	1104	736	0	52.5	0.1
A3-FA25	0.5	262.5	1100	733	0	87.5	0.1
A3-FA50	0.5	175	1088	726	0	175	0

In this study, the bulk resistivity method was used to measure the electrical resistance of concrete. This method is commonly used for measuring concrete's electrical resistance [28-33]. In the bulk resistivity method (or uniaxial method), two electrodes are placed on the concrete surface (usually two parallel metal plates) with the moist sponge in between (Figure 1). For the experiment to take place, a voltage difference is applied between the two sides of the specimen (Figure 2). The resistance value is obtained by applying Ohm's law to the amount of current measured by the multimeter. Equations 1–3 are used for the calculation of the electrical resistivity [30, 31].

$$V = R \cdot I \text{ (V)} \quad (1)$$

$$R = \frac{V}{I} \text{ (}\Omega\text{)} \quad (2)$$

$$\rho = R \cdot \frac{A}{L} \text{ (}\Omega \cdot \text{m)} \quad (3)$$

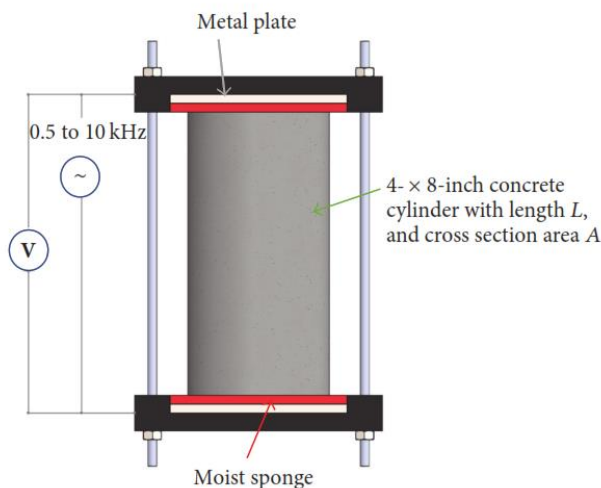


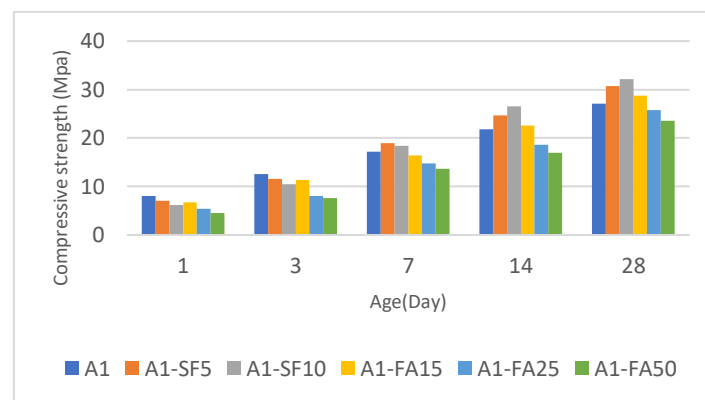
Figure 1: two-point uniaxial method

3. Results and discussion

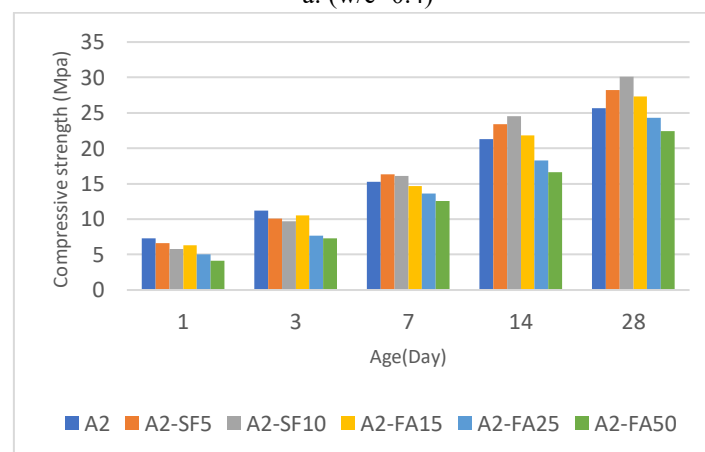
3.1. Compressive Strength Results

The compressive strength of concrete was determined in accordance to ASTM C.39 [27]. The evolution of the compressive strength for different water-cementitious materials ratios between 1 day and 28 days is represented in

Figure 2. The compressive strength increases due to the pozzolanic reaction of silica fume with calcium hydroxide in cement paste and calcium silicate hydroxide gel formation. Silica fume can improve the microstructure and increase the mechanical strength of concrete. By filling the holes in the cement paste and reacting with calcium hydroxide, very fine particles of silica fume improve the density, as well as the physical and chemical properties of concrete. The results show that the replacement of silica fume reduces the compressive strength of concrete at early ages. Over time and at older ages, concrete incorporating silica fume exhibits higher compressive strength compare to concrete without silica fume. According to the results, replacing 5% silica fume with 10% silica fume increased the compressive strength at early ages but decreased it at older ages. With the passage of time and the continuation of cement hydration and the pozzolanic reaction that leads to the formation of excess calcium silicate hydrates, the compressive strength gradually increases, and the distance between the strength of concrete containing 10% silica fume and concrete without silica fume is less at early ages and becomes more at older ages. According to Figure 2, the use of fly ash instead of cement reduces the compressive strength at early ages. By increasing the consumption of fly ash, the adhesion force between cement and other components of concrete decreases, which can lead to a decrease in the compressive strength of concrete at an early age. It can be concluded that increase in contents of silica fume increases the compressive strength development of concrete. For water-cement ration 0.4, 0.45 and 0.5, There are an increase of 15 %, 10 %, and 7 %, respectively in compressive strength development of concrete with 5% silica fume contents after 28 days when compared with the reference concrete and an increase of 20%, 17% and 10 % respectively when compared with concrete containing 10% silica fume.



a: (w/c=0.4)



b: (w/c=0.45)

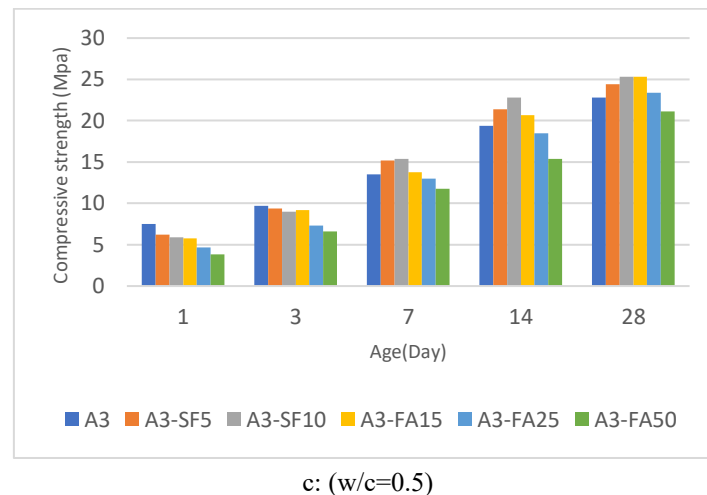


Figure 2: Strength development of concretes at different water-cementitious materials ratios.

It can be observed that the increase in the water-cement ratio decreases the overall strength of concrete. Consequently, 0.1 increments in water-cement ratio decreased the compressive strength of concrete containing 5 % silica content by 20 %, and for reference concrete and concrete containing 10% silica fume content, this strength reduced by 15% and 21% respectively after 28 days of casting the concrete. According to Figure 2, With the increase of water-cement ratio, the reduction in compressive strength of concrete containing silica fume is more than the concrete without silica fume. Also, it can be concluded that increase in contents of silica fume increase the compressive strength reduction. According to Figure 2, the compressive strength of concrete decreases with increase of fly ash contents. The results show that the replacement of 15 % fly ash compared to other mixtures results in higher compressive strength. For water-cement ration 0.4,0.45, and 0.5, There are an increase of 6%,7%, and 11%, respectively, in compressive strength development of concrete with 15% fly ash contents after 28 days when compared with the reference concrete.

3.2. Bulk resistivity

The electrical resistivity of all mixtures was measured according to the two-point uniaxial method. Figure. 3 to 5 show the bulk resistivity values containing microsilica.

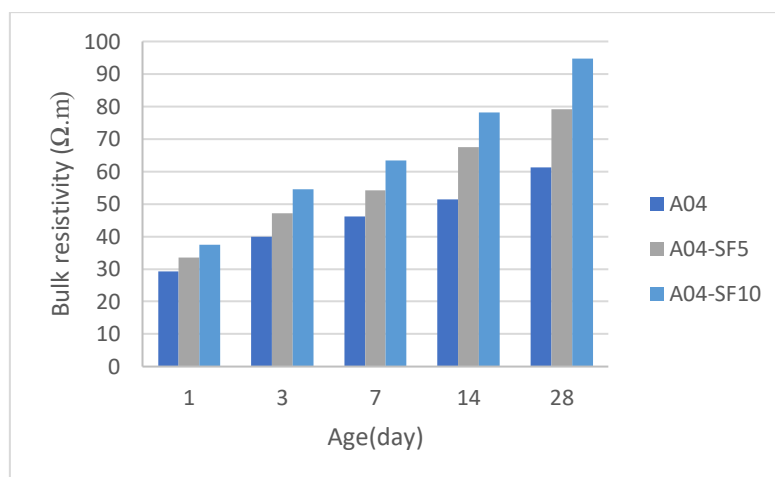


Figure 3: The effect of silica fume on bulk resistivity (W/C=0.4)

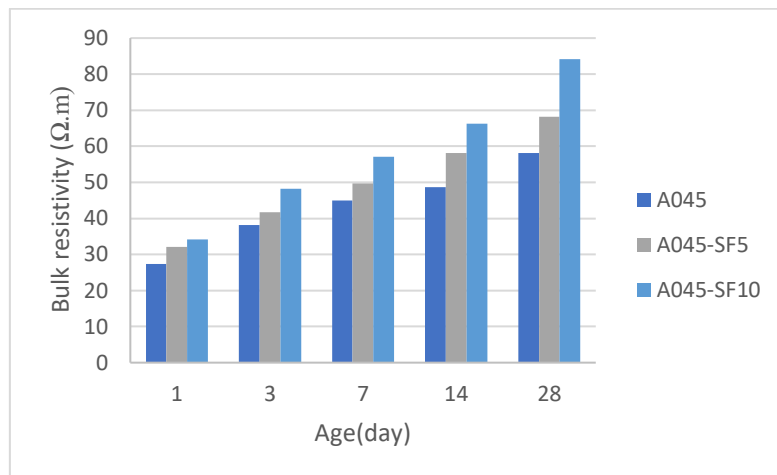


Figure 4: The effect of silica fume on bulk resistivity (W/C=0.45)

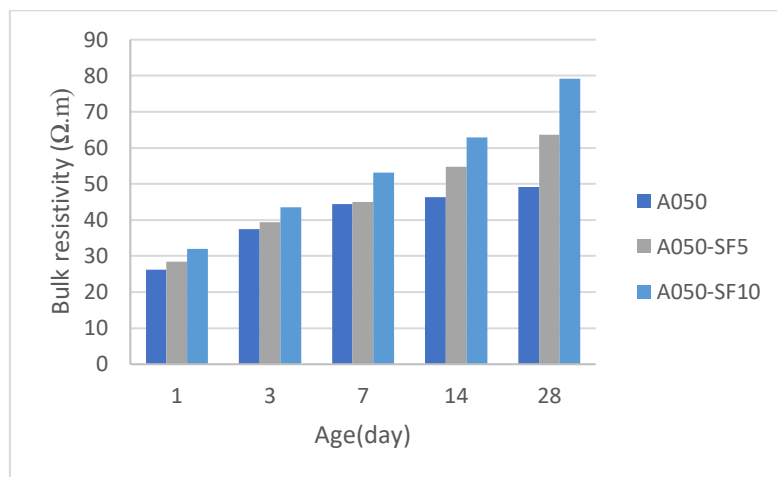


Figure 5: The effect of silica fume on bulk resistivity (W/C=0.5)

According to the results, the electrical resistivity of all designs containing microsilica is higher than the electrical resistivity of the control sample. The reason for this is that pozzolans, due to their pozzolanic effect and physical properties, affect the fine structure of cement paste, concentrate ion solution in pores, and ultimately influence the electrical resistivity of concrete. The most important characteristic of microsilica is the exceptionally fine particle size. Excessive fineness accelerates the pozzolanic activity significantly. During the cement hydration process, the pozzolanic activity of microsilica causes the free calcium hydroxide crystals to transform into hydrated calcium silicate.

Additionally, the filling property of microsilica ensures the uniform distribution of hydration products in the mixture. Ultimately, the combination of both filling and pozzolanic properties of microsilica leads to the formation of a dense and low-porosity structure. Furthermore, as the age of the sample increases, the rate of hydration reactions in concrete decreases, reducing the concentration of ions in the concrete and consequently increasing the electrical resistivity of the concrete.

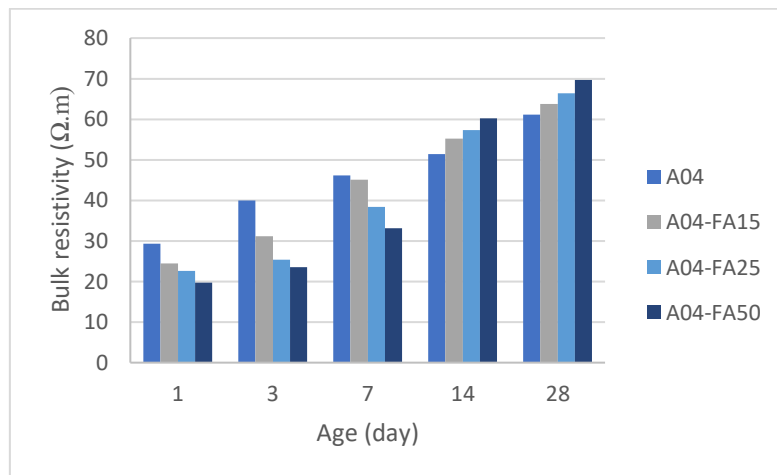


Figure 6: the effect of fly ash on bulk resistivity (W/C=0. 4)

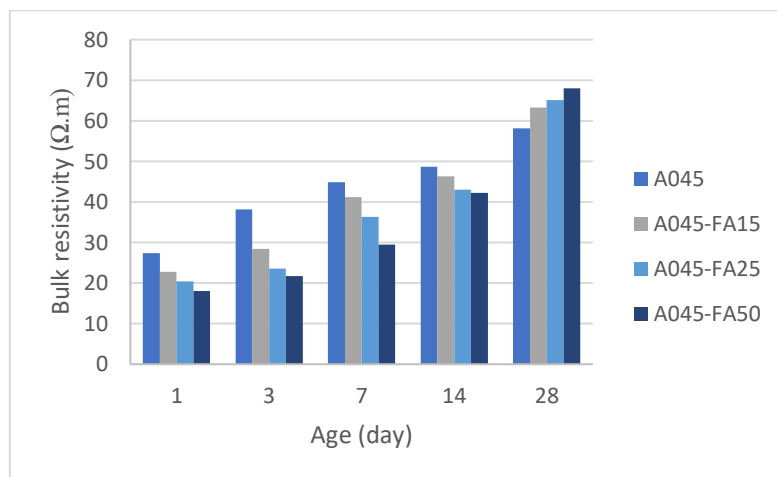


Figure 7: the effect of fly ash on bulk resistivity (W/C=0. 45)

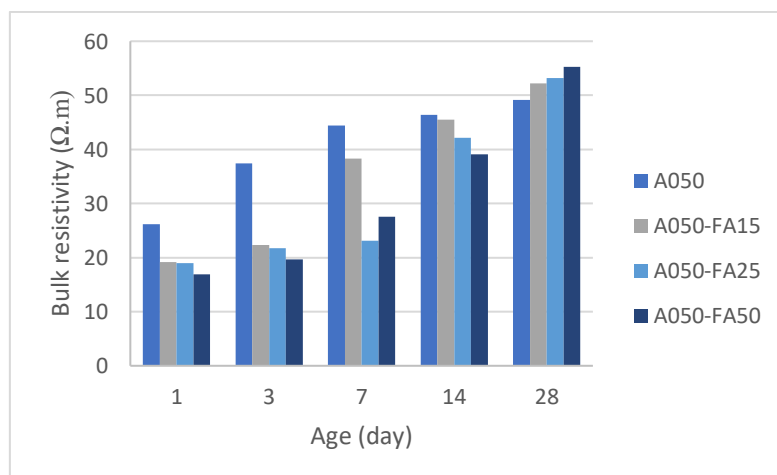


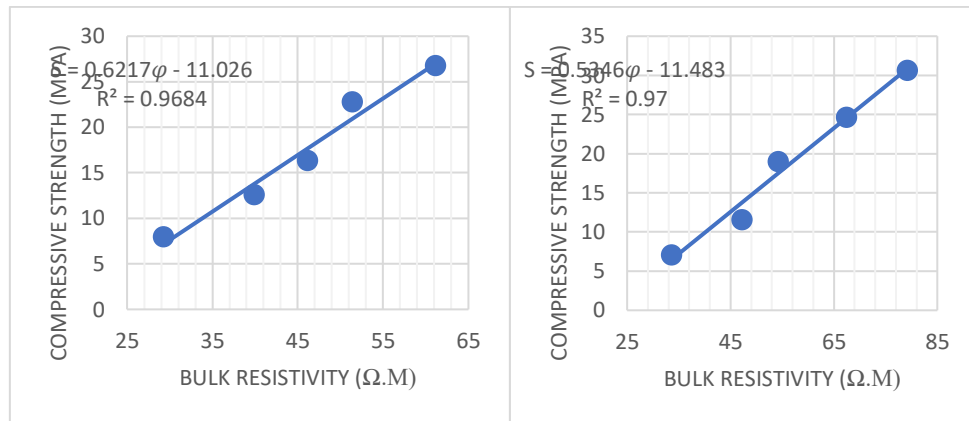
Figure 8: the effect of fly ash on bulk resistivity (W/C=0. 5)

The use of fly ash reduces the rate of cement hydration reactions, preventing the complete formation of cement crystals in the early ages and consequently increasing the permeability of the concrete. This phenomenon leads to a decrease in the electrical resistivity of concrete containing fly ash in the early ages (Figures 6 to 8). After

stabilizing the concrete structure and forming cement crystals, permeability gradually decreases, and electrical resistivity increases at later ages. Therefore, an increase in the amount of fly ash used in the early ages reduces electrical resistivity. The results of other studies indicate that the electrical resistivity of concrete containing fly ash is higher than that of ordinary concrete at later ages (90 days) [25, 34].

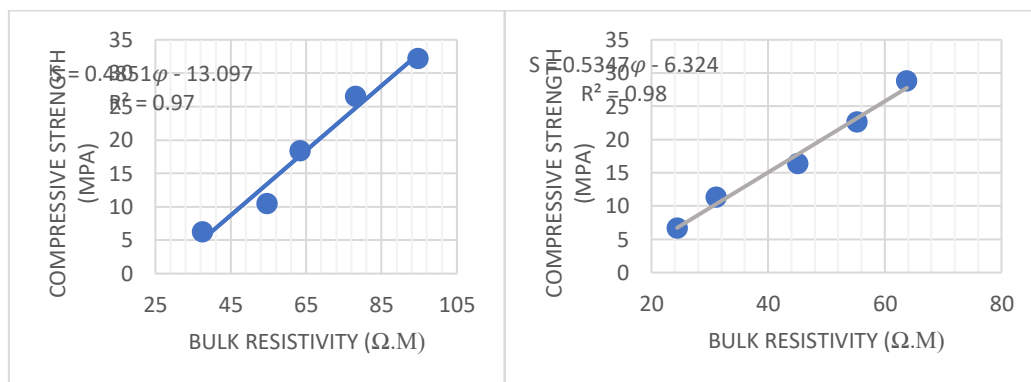
3.3. The Relationship Between Compressive Strength and Electrical Resistivity of Concrete

In this section, based on the obtained results, the curve fitting of the electrical resistivity and compressive strength of concrete has been performed for various functions. Considering the results obtained from the previous sections, the compressive strength-electrical resistivity diagram for concrete is illustrated in Figure 9.



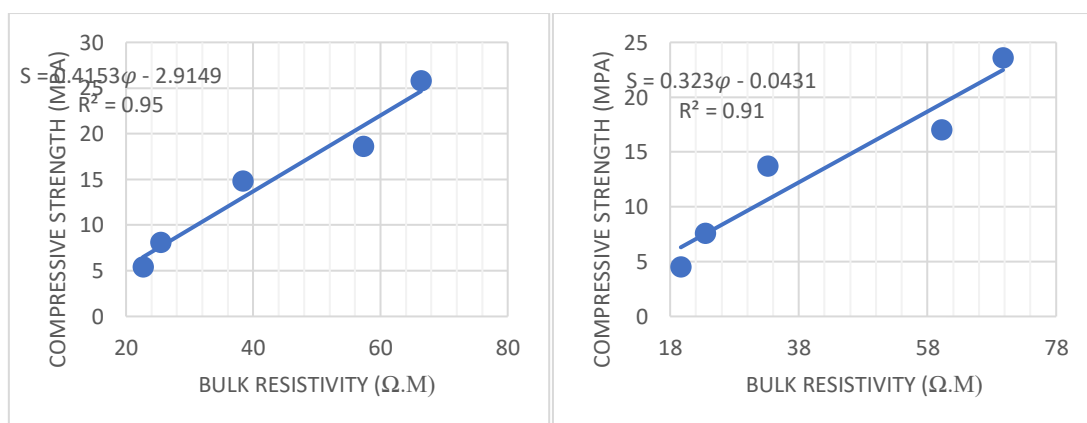
a) Mixture code:A04

b) Mixture code:A04-SF5



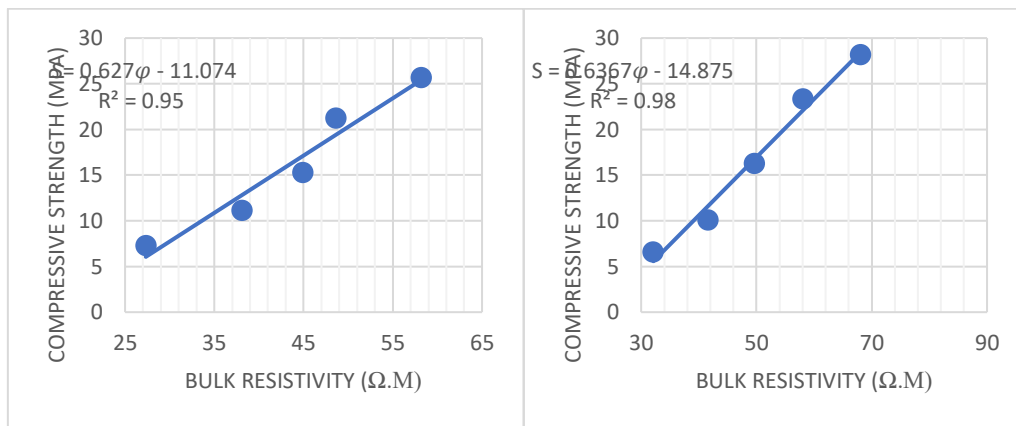
c) Mixture code:A04-SF10

d) Mixture code:A04-FA15



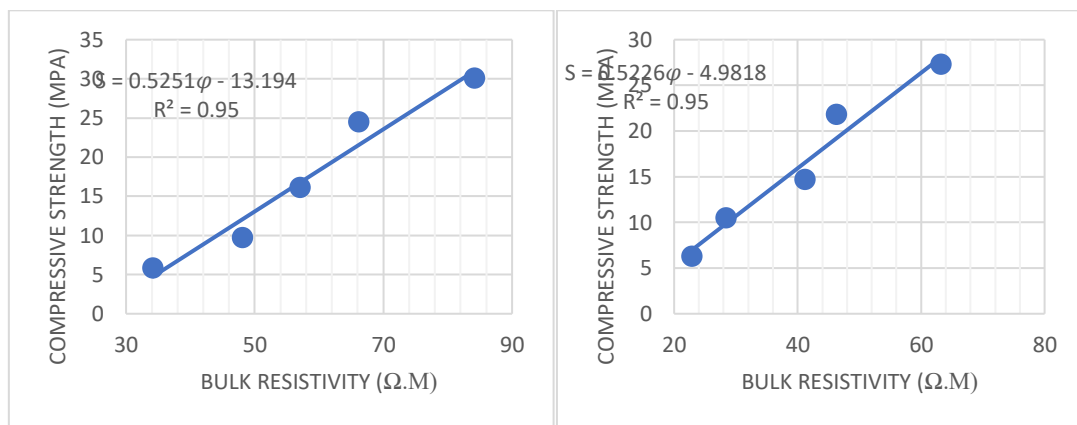
e) Mixture code:A04-FA25

f) Mixture code:A04-FA50



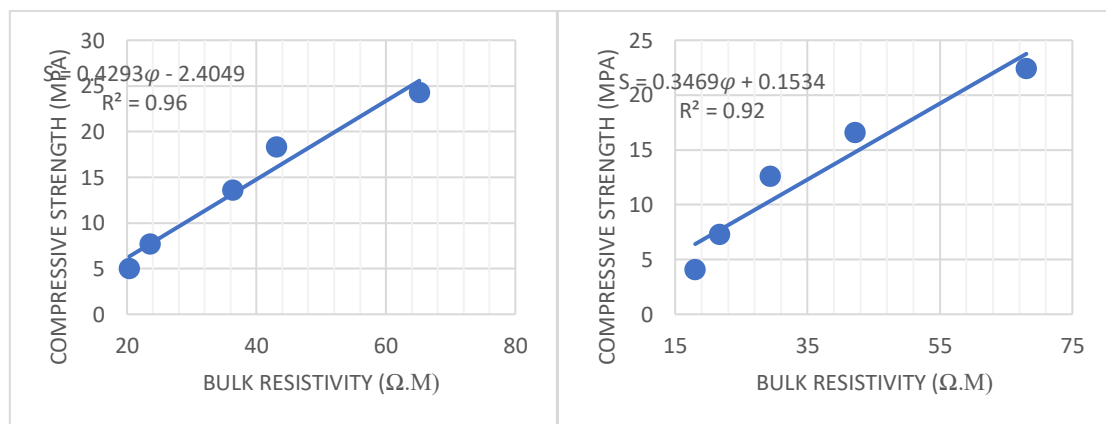
g) Mixture code:A045

h) Mixture code:A045-SF5



h) Mixture code:A045-SF10

i) Mixture code:A045-FA15



j) Mixture code:A045-FA25

k) Mixture code:A045-FA50

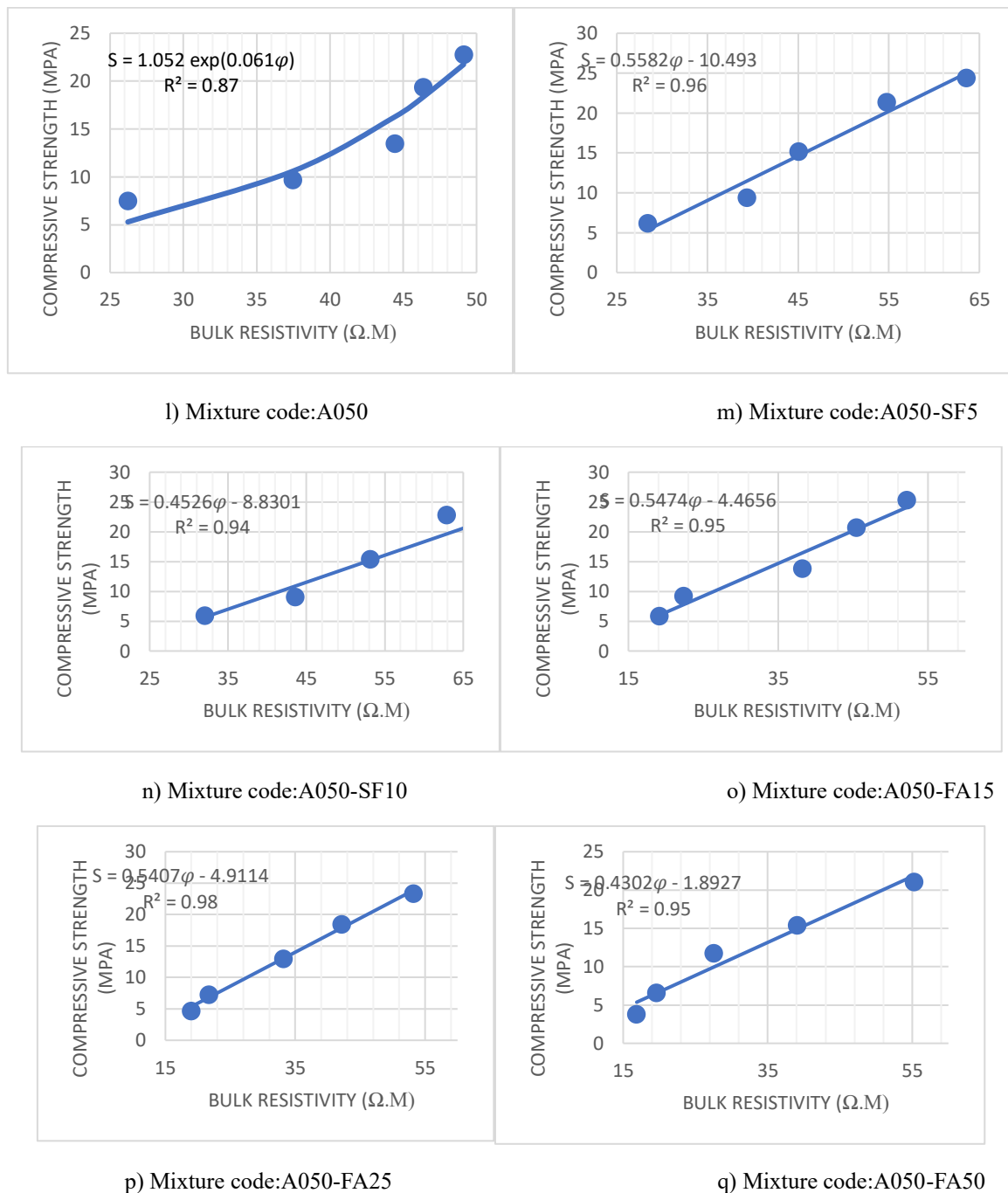


Figure 9. The relationship between compressive strength and electrical resistivity of concrete

The obtained results indicate that in all designs except for design A050, a linear relationship exists between compressive strength and electrical resistivity of concrete. Regarding concrete mixes containing microsilica, according to the results, using lower amounts of microsilica (5%) leads to the establishment of a linear relationship with a high correlation coefficient. However, the use of 10% microsilica as a partial replacement for cement has reduced the correlation coefficient. In designs incorporating fly ash, it is observed that increasing the water-to-cement ratio enhances the correlation coefficient.

4. Conclusions

This study investigated the effect of using various amounts of fly ash and microsilica as partial replacements for cement on the compressive strength and electrical resistivity of concrete at early ages. Additionally, the correlation

between compressive strength and electrical resistivity in concrete mixes containing fly ash and microsilica was examined.

The results obtained indicate that:

- 1) The use of pozzolanic materials improves the mechanical properties of concrete. The results show that concretes containing microsilica have achieved the highest compressive strength. The presence of silica fume, due to its pozzolanic reaction with the calcium hydroxide in the cement paste, leading to the formation of calcium silicate hydrate gel, contributes to an increase in compressive strength. Silica fume can enhance the microstructure and increase the mechanical strength of concrete. The very fine particles of silica fume fill the voids in the cement paste, and their reaction with the calcium hydroxide improves the density and physical and chemical properties of concrete. Increasing the use of fly ash reduces the bond between cement and other components in the early ages, resulting in a decrease in compressive strength. The optimal percentage of fly ash consumption, based on the obtained results, is 15% of the cement content.
- 2) The rate of compressive strength development in concrete mixes containing microsilica at water-to-cement ratios of 0.4 and 0.45 (7 days compared to 28 days) is higher than that in ordinary concrete. The use of a water-to-cement ratio of 0.50 results in a reduction in the rate of compressive strength development. Moreover, for concrete mixes containing fly ash, due to the increased reaction rates over time, the rate of compressive strength growth is higher compared to ordinary concrete. The rate of compressive strength development in designs with a 15% replacement of cement with fly ash, across all water-to-cement ratios, is greater than that in ordinary concrete samples.
- 3) The electrical resistivity of pozzolan-containing concrete increases at later ages. The results of this study demonstrate that the use of microsilica as a partial replacement for cement increases the electrical resistivity of concrete at early ages. Additionally, reducing the water-to-cement ratio leads to an increase in electrical resistivity. The findings indicate that a decrease in the water-to-cement ratio results in an increase in the rate of electrical resistivity growth from 7 days to 28 days. The use of fly ash as a partial replacement for cement decreases the electrical resistivity of concrete at early ages. With the increase in the age of the test, the stabilization of the concrete structure, and the formation of cement crystals, the electrical resistivity of concrete increases at later ages.
- 4) In this study, an analysis of linear regression was conducted to explore the correlation between compressive strength and electrical resistivity of concrete. The results demonstrate that substituting cement with pozzolanic materials enhances the relationship between compressive strength and electrical resistivity in concrete. As the water-to-cement ratio increases, the correlation coefficient decreases, reaching 0.87 in the A050 design, leading to a transformation in the curve fitting from a linear to an exponential relationship.

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