



AKADÉMIAI KIADÓ

Pollack Periodica •
An International Journal
for Engineering and
Information Sciences

16 (2021) 3, 76–82

DOI:

[10.1556/606.2021.00314](https://doi.org/10.1556/606.2021.00314)

© 2021 Akadémiai Kiadó, Budapest


ORIGINAL RESEARCH
PAPER



*Corresponding author.
E-mail: zandi@iaut.ac.ir

 AKJournals

Durability evaluation of concrete made of fly ash and copper slag

Yousef Zandi* 

Department of Civil Engineering, Tabriz Branch, Islamic Azad University, 009841, Tabriz, Iran

Received: December 8, 2020 • Revised manuscript received: January 6, 2021 • Accepted: January 9, 2021

Published online: April 24, 2021

ABSTRACT

In this paper, to improve the durability of concrete, fly ash has been used as a percentage of cement and copper slag rather than a percentage of sand. Using a resistance test and water permeability test, four series of concrete specimens containing fly ash and copper slag, each containing 49 concrete mixing designs, were evaluated. After obtaining the results, eight samples with the highest electrical resistance were selected and the specimens were again tested in different environmental conditions. The results show that the environmental conditions of sulfate and carbonate have the least and most impact on reducing durability and there is a power relationship, with good precision, between the water penetration of the test specimens and the electrical resistance of the test specimens.

KEYWORDS

electrical resistance, fly ash, copper slag, electrolytes, concrete permeability, corrosion of steel

1. INTRODUCTION

The combination of one of the most common building materials in the world is reinforced concrete, which is used in a variety of ambient conditions. However, one of the early causes of Reinforcement Concrete (RC) damage is the corrosion of its steel and this is one of the major problems that the construction industry has faced in terms of durability [1], which lead to costly repairs and sometimes the rebuilding of damaged structures. The main reason for this is the pH reduction of the aqueous solution in the concrete pores and accelerating reaction of iron oxidation in the presence of chlorine ion [2], which corrosion damages the concrete in two ways: first, it reduces the cross section of the rebar; second, it creates corrosion products, which are larger in volume than the steel itself [2]. This increase in volume leads to cracking and eventually structural failure by creating tensile stresses in concrete [3]. Concrete permeability is another major factor contributing to concrete durability. Concrete with low permeability, show better resistance against chemical attack, in such a way that impermeable concrete can be considered as durable concrete [4]. When water penetrates into concrete, it carries some soluble salts along with itself into the concrete and these salts cause corrosion of steel inside the concrete. In general, high permeability results in less durability of concrete. Several investigations and methods have been conducted on the permeability of concrete. One of these methods is a water penetration test; the validity of these methods has been confirmed [5–7].

Hence, it is important to understand the properties of concrete and predict its performance in corrosive environments. Several factors affect concrete performance, for example, concrete permeability, environmental conditions, water to cement ratio, cement contents, ions in the area, etc., each of them is very effective in the manufacture of good concrete. If the cement in the mixture is insufficient, the concrete will not be properly condensed, and the honeycomb tissue will be created with other disadvantages on the surface, which will facilitate the access of harmful agents inside it [8]. On the other hand, the lots of cement increases the porosity of the mixture with increasing volume of cement paste, which is the most important porosity factor in concrete [9, 10]. The use of chemical and mineral admixtures will modify

some of the properties of concrete. The presence of mineral and cement admixtures in concrete improves the properties of concrete, including mechanical properties, rheological properties and conduction [11, 12]. Copper slag is a high-density metallurgical waste generated in the copper production process [13]. Copper slag has a high potential for replacing natural gravel and sand in the construction sector [14]. It reduces the consumption of natural gravel and sand [15]. The permeability and porosity of concrete in which slag was used is lower than of ordinary cement made concrete [16]. Copper slag increases the strength of concrete, but if not controlled, it may affect its stability [17]. The main substance of the copper slag is iron oxide and silica. To produce one ton of copper, about 2.2–3 tons of copper slag is produced as a waste material [18]. In terms of metallurgy, this material is no longer usable and as a waste material, it comes out of the production cycle. According to the United Nations report, the term “sustainable development” is a development that can meet the needs of the present so that the ability of future generations to meet their needs cannot be compromised [19]. Spherical particles of fly ash, due to the ball bearing effect, increase the efficiency and improve the cement accumulation and thus reduce the need for water [20, 21]. In the case of chloride ion penetration, in concrete containing fly, indicates an increase in electrical resistance in the concrete [22]. Corrosion damage in concrete containing fly ash is lower compared to ordinary Portland cement [23]. In fact, electrical resistance describes the possibility of the movement of charged particles under the influence of an external electric field. A special electrical resistance can be defined as the electrical resistance of a conductor with unit volume and a constant cross-section in which the flow is continuously distributed uniformly [24]. Due to the fact that the electrical resistance is affected by the cement paste microstructure, conductivity and ionic concentration of the pore solution and as a result, the amount of cement, water to cement ratio, chemical composition of the cement, and admixtures, also affect the electrical resistance [25–27]. Of course, the results of this test depend on the temperature, increasing temperature leads to reduced resistance [28]. In some references, including ACI 222, the relationship between the amount of concrete electrical resistance and the possibility of corrosion of the reinforcement is expressed. The relationship expressed in ACI 222 [29] is given in Table 1.

The purpose of this research is to investigate the electrical resistance in the presence of destructive ions for concrete structures, and then compare them with the results obtained from the standard conditions. For this purpose,

Table 1. Relationship between concrete electrical resistivity and corrosion rate

Resivity kΩ/cm	Corrosion
>20	Low
10 to 20	Low to moderate
5 to 10	High
<5	Very high

solutions of NaCl, Na₂SO₄, NaOH, Na₂CO₃ at 1 M concentration and normal water were selected as standard conditions and also an experiment was conducted to determine the relationship between the special electrical resistance with water penetration.

2. LABORATORY PROCESS

2.1. Material

Consumed cement is Portland cement, type 2, Sufian Cement Factory, according to the ASTM C150 standard [30]. According to ASTM C33 standard [31], crushed aggregates with a maximum size of 25 mm and natural fines were used as aggregates. In order to achieve optimum performance in concrete mixtures, the poly-carboxylate super-lubricant, which is manufactured by Chryso Co, was used according to ASTM C494 standard [32]. The fly ash is used in class F as standard ASTM C618 [33]. Also, the copper slag used in this research is manufactured by the Pishro Ravesh Pars Co.

2.2. Mix design

In this study, concrete mixtures have been tested in accordance with ACI 211.1 [34] at 25, 30, 35, and 40 MPa resistance. In this plan, 10–70% of the fly ash is already replaced instead of cement and 10–70% of the copper slag instead of 0–3 mm sand. This research was conducted under laboratory conditions at 23 °C in accordance with ASTM C192 [35]. The design of the mixing is as follows: P30-20-50 means the design in which f_c , the compressive strength of concrete, is considered to be 30 MPa (P30), as well as the second and third parts respectively, the percentage of fly ash 20% is replaced instead of cement and 50% copper slag instead of sand of 0–3 mm.

2.3. Details and testing procedures

2.3.1. Compressive strength. A compressive strength test was carried out according to ASTM C39 standard [36] on cube-shaped specimens with dimensions of 200 mm × 100 mm × 100 mm at each age of 7, 28, 42 days. A tensile strength test was performed according to ASTM C496 standard [37] on a 200 × 100 mm specimen at age of 28 days.

2.3.2. Specific electrical resistance. The electrical resistance test was performed according to the ACI 222 standard [29] on a 100 mm cubic test specimen at each of the ages of 7, 28, and 91 days. After obtaining the results, eight specimens (from each compressive strength of 28 days, two samples) with the highest electrical resistance were selected and other samples were made with the same mixing design of the selected specimens and placed in NaCl, Na₂SO₄, NaOH, Na₂CO₃, and saturated water solutions of lime and the results of these test specimens were compared with the results

of the control samples. Table 2 shows the concentration of dominant ions in the solution.

The code F is normal water, respectively. An electrical resistance measuring device was used to perform this test. For this purpose, two sheets of copper with a thin layer of low-slump cement paste were placed on both sides of the wet-saturated specimen, and the electrical resistance between the two was measured (Fig. 1). To determine the specific electrical resistance, the electrical resistance measured was multiplied by the cross section of the test piece and divided into its height, which is obtained from Eq. (1) [38],

$$\rho = R \frac{A}{H}, \quad (1)$$

where ρ is the electrical resistivity (ohms m); R is the readable electrical resistance of the device (ohm); $A = (B \times L)$ is the surface area of the specimen (m^2); H is the specimen height (m).

2.3.3. Water penetration depth test. Pressure water penetration depth test according to BS EN-12390-8 standard [39] was used to evaluate the permeability of concrete. In this method, one face of the cube sample of 150 mm is placed under water at a pressure of 0.5 MPa (Fig. 2). This pressure is applied for 72 hours. After this period of time, the samples are removed from the machine and divided into two halves. Then, according to the water penetration profile of the concrete, the maximum water penetration rate is recorded and is considered as an indicator for the permeability of the concrete. It should be noted that in this research, this test was performed on selected specimens. Also, according to DIN 1048 [40], if the water penetration rate in concrete is



Fig. 2. Water penetration depth device

less than 3 cm, the concrete is very good. If the water penetration rate in the concrete is between 3 and 5 cm, the concrete is of good quality and more than 5 cm, it is not suitable for sealing and impermeable purposes.

3. THE RESULTS OF THE TESTS AND THEIR ANALYSIS

According to the results (The results of tests of compressive strength tests of 7, 28, 42 days, the 28-day tensile strength and the electrical resistance of 7, 28, 91 days), an increase in the percentage of fly ash decreases the 28-day compressive strength of the concrete, because the fly ash reduces the heat content and thus reduces the hydration rate. It also causes a relative delay, which seems to be due to the release of SO_4^{2-} ions from the surface of fly ash particles. The fly ash continues its activity after 28 days, so that in 42 days the compressive strength of the test pieces reaches a reasonable level. This increases long-term compressive strength. Increasing the percentage of copper slag up to 50% will lead to an increase compressive strength with gentle slope. Because fine grained copper slag occupies small pores, like filler. According to the results it can be seen that if the percentage of copper slag is greater than 50, the compressive strength is falling and the downward trend continues. The reason for this slight decrease is due to the excessive growth of fine grains and changes in aggregate grading. Tensile indirect test results based on the Brazilian test, taking into account the conversion coefficient of the results to 100 mm cubic samples, shows that the tensile strength of the samples is about 11–15% of the 28-day compressive strength which is within acceptable ranges.

The results of the electrical resistivity test show that, the electrical resistance is increased with an increase in the percentage of fly ash to 50–60%. The reason for this increase is that the reduction in the concentration of hydroxide ions and the distribution of cavities relative to the ordinary concrete are finer and smaller. It is necessary to explain that by increasing the percentage of air ash by more than 60%, the electrical resistance is falling and the downward trend continues. The reason for reducing this decrease is due to the reduction of bonding materials in the sample. The

Table 2. Solutions used in the test

Code	Solution	Ion	ppm
B	NaOH	Na+	23,000
		OH−	17,000
C	NaCl	Na+	23,000
		Cl−	35,500
D	Na ₂ SO ₄	Na+	45,550
		SO ₄ ^{−2}	193,300
E	Na ₂ CO ₃	Na+	45,550
		CO ₃ ^{−2}	83,900
F	H ₂ O	Normal water	

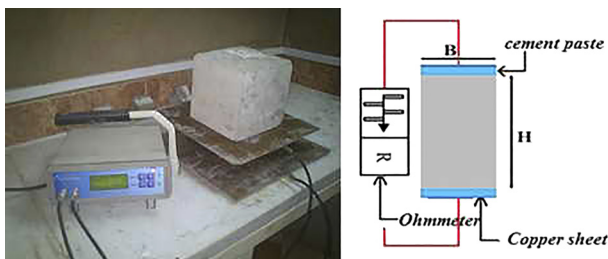


Fig. 1. Two-point electrical resistance device

specimens containing 30–40% of copper slag have a higher electrical resistance than other samples. The reason for this increase of up to 40% is that the copper slag resistance is more than ordinary sand, and fine grained copper slag can fill the pores in concrete. The electrical resistivity decreases by more than 40% in the presence of copper slag.

The reason for this reduction can be attributed to copper slag compounds. Since the main component of this material is iron oxide and some other metals, this leads to the conductivity of the samples. Based on the results, considering the conversion of the results to the cylindrical specimen, it can be concluded that the probability of corrosion in the test specimens is very low to moderate according to Table 1 and the ACI 222 standard [29]. The results of the electrical resistivity variations of the selected tests for the various environments are shown in Figs 3–6.

According to Table 2, water-saturated solutions of lime, NaOH, NaCl, Na₂SO₄, Na₂CO₃, and normal water pond are named codes A to F, respectively. At this stage, the code F is considered as a control sample only in the normal water pond. According to the results of Figs 3–6, it can be concluded that the least reduction of electrical resistance to the control specimen (F) belongs to the sulfate environment. Because the fly ash shows higher resistance to sulfate environments, it has been less effective than other solutions. The

electrical resistivity of the sulfate specimens is less than that of lime-saturated specimens at 7 days. Since the fly ash causes relative sluggishness and continues its activity after 28 days for long time, since the slope of the graph A is low, therefore, the fly ash for the saturated environment of lime does not have much effect. Figure 3 shows that the diagrams of the test specimens A, B, C are very close. However, with increasing f_c and decreasing the ratio of water to cement, as it can be seen in Fig. 6, the specimen, which is present in the NaCl solution, the reduction of electrical resistance is less than that of the control specimen and has more resistance than the specimens A, B has shown. This is due to the effect of fly ash and water to cement ratio, the fly ash causes less penetrability and resistance to spread of chloride. However, because of the presence of copper slag, which is a major component of it is iron oxide, it reduces the resistance of the test specimens in chloride environments. If copper slag is used more than 40%, it can be seen that the specimens will have a lower electrical resistance than the control sample. On the other hand, as it is seen in Figs 3–6, the electrical resistivity of the test specimens saturated in lime and NaOH and Na₂CO₃ environments is slightly different and the results are close to each other.

One of the main factors of concrete durability is its permeability. In this study, the pressure penetration depth

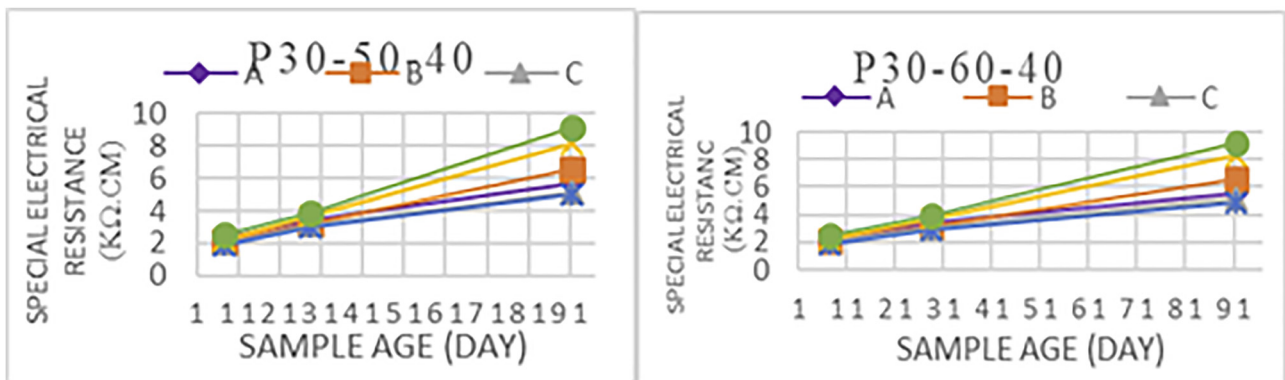


Fig. 3. Comparison of the electrical resistivity with a compressive strength of 25 MPa in the presence of various electrolytes

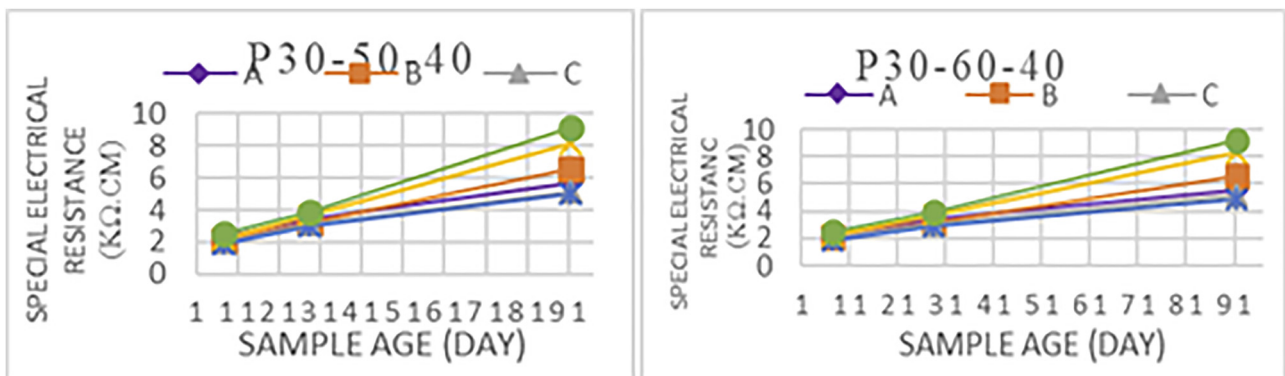


Fig. 4. Comparison of the electrical resistivity with a compressive strength of 30 MPa in the presence of various electrolytes

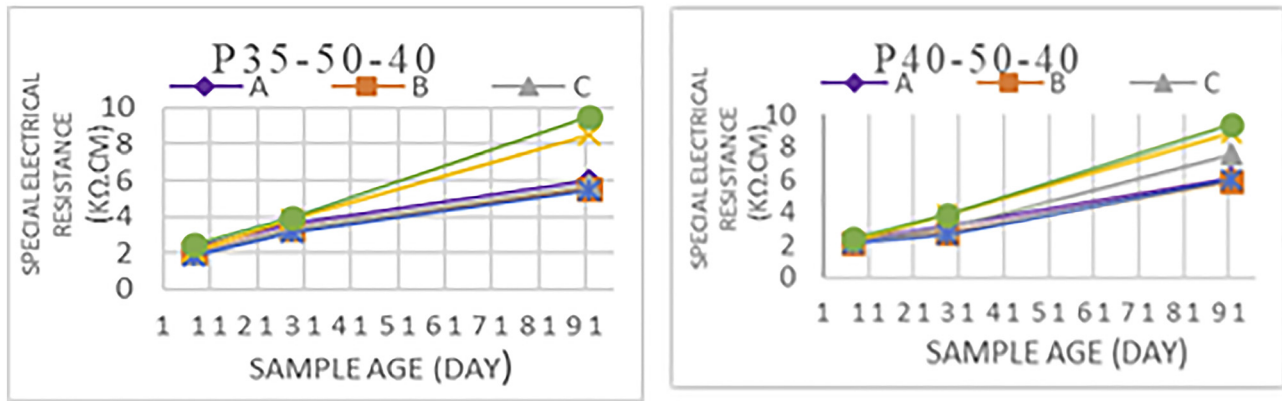


Fig. 5. Comparison of the electrical resistivity with a compressive strength of 35 MPa in the presence of various electrolytes

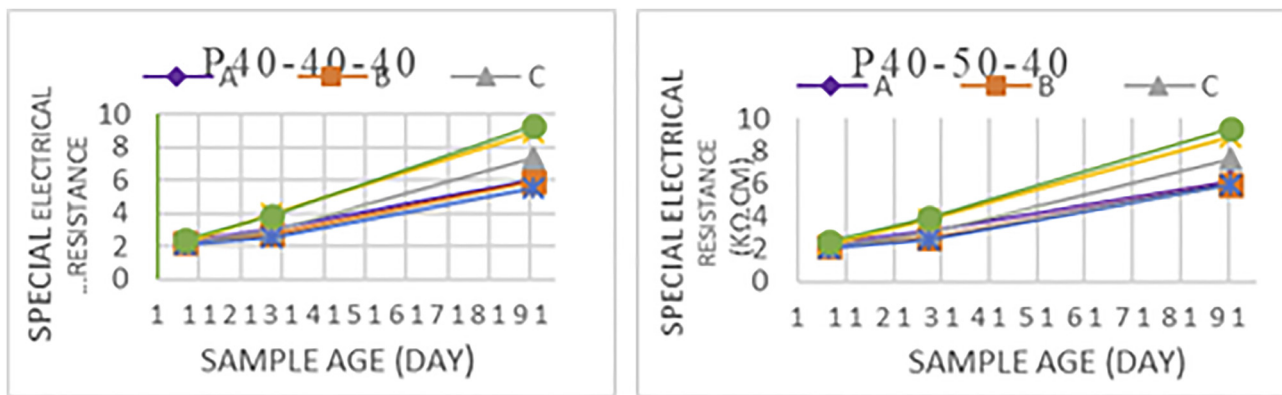


Fig. 6. Comparison of the electrical resistivity with a compressive strength of 40 MPa in the presence of various electrolytes

test was used according to BS EN-12390-8 [39] to evaluate the permeability of concrete. It needs to be explained that the electrical resistive test of 150 mm cubic has been performed to obtain a relationship between the electrical resistance and the depth of water penetration. According to Fig. 7, there is a general relationship between the specific electrical resistance of the concrete and the depth of water penetration. As the electrical resistance decreases, the penetration depth of the water increases since the specimens

are made of a single type of material, this is the reason why there is low dispersion in results. Therefore, the obtained relationship is more precise, and the more the substance used in each sample differs from the other, the more dispersion is seen in the results. The obtained relation will not be more accurate. According to Fig. 7, the range of variations in penetration depth is limited and low. This is due to the fact that the fly ash and copper slag reduce penetrability.

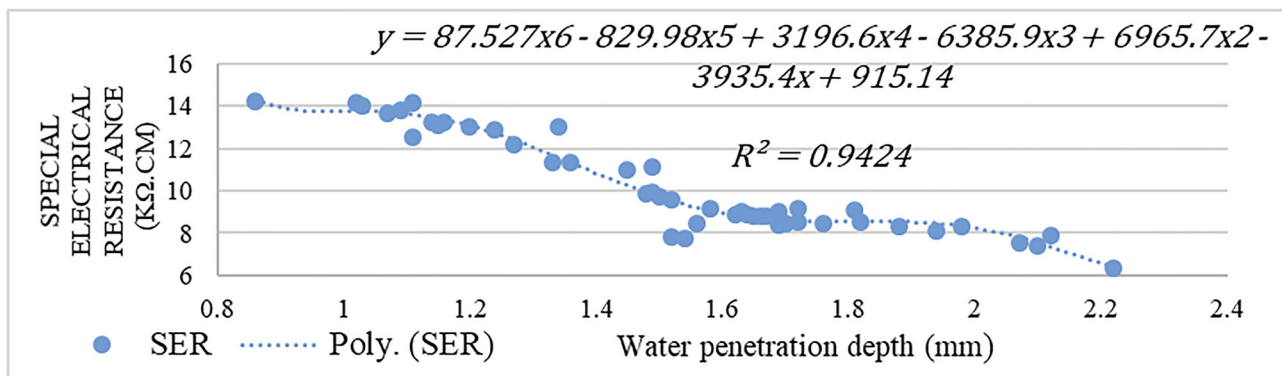


Fig. 7. The relationship between the results of water penetration experiments and special electrical resistance for selected samples

Because the specimens are made of a type of material, the scattering of results is low, therefore, the obtained relationship is more precise and as much as the substance used in each sample differs from the other, it causes more scattering of results; the resulting relationship will not be more accurate. According to Fig. 7, the range of variations in penetration depth is limited and low. This is due to the fact that the fly ash and copper slag reduce penetrability.

4. CONCLUSIONS

According to the performed experiments, the following results are evident:

- The compressive strength and tensile strength of the specimens located in the normal water pond are in an acceptable range;
- The possibility of corrosion in the samples located in the normal water pond is in good range;
- Specific electrical resistivity of the test specimens located in the ordinary water pond shows a downward trend with an increase in the percentage of copper slag of more than 40% copper slag instead of 0–3 mm sand and a fly ash above 60% replaced instead of cement;
- According to the plot of the test specimens located in the lime saturated water ponds, the NaOH and Na₂CO₃ environments get closer to each other by decreasing the ratio of water to cement and increasing the f_c ;
- Samples, which are in saturated solutions of lime, carbonation, alkaline have similar electrical resistivity and this similarity increase with increasing of f_c and reduction of water to cement ratio;
- The test specimens located in solutions saturated with lime, carbonate and alkali have special similar electrical resistances with each other, and this is similar to an increase in f_c and a decrease in water to cement ratio;
- The specimens saturated in Na₂SO₄ have less resistance than the control sample. As the f_c increases and the water to cement ratio decreases, the Na₂SO₄ graph is closer to the control diagram;
- The relationship between the electrical resistivity and the water penetration depth is obtained with a good accuracy of correlation coefficient $R_2 = 0.94$;
- The different material used in each sample differs from the sample, the dispersion results in the depth of water penetration and the accuracy of the relationship between the special electrical resistance and the depth of water penetration decreases;
- As much material as used in each sample differs from the other sample, the dispersion results in the depth of water penetration and the accuracy of the relationship between the special electrical resistance and the depth of water penetration decreases;
- Different environments have little effect on the distribution of water penetration depth.

REFERENCES

- [1] M. Shariati, S. Rafie, P. Mehrabi, Y. Zandi, R. Fooladvand, B. Gharehaghaj, A. Shariat, N. T. Trung, M. N. A. Salih and S. Poi-Ngian, "Experimental investigation on the effect of cementitious materials on fresh and mechanical properties of self-consolidating concrete," *Adv. Concr. Constr.*, vol. 8, no. 3, pp. 225–237, 2019.
- [2] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties and Materials*. New York: McGraw-Hill Education, 2014.
- [3] Y. S. Choi, J. G. Kim, and K. M. Lee, "Corrosion behavior of steel bar embedded in fly ash concrete," *Corrosion Sci.*, vol. 48, no. 7, pp. 1733–1745, 2006.
- [4] E. Guneyisi, M. Gesoslu, S. Karaoglu, and K. Mermerdaş, "Strength, permeability and shrinkage cracking of silica fume and metakaolin concretes," *Constr. Build. Mater.*, vol. 34, pp. 120–130, 2012.
- [5] J. Balogh, M. Fragiaco, R. Gutkowsky, R. Atadero, and P. Ivanyi, "Low-to-high cycle fatigue behavior of wood-concrete composite beams with notched interlayer connections," *Pollack Period.*, vol. 8, no. 1, pp. 3–14, 2013.
- [6] Y. Zanadi and M. V. Akpinar, "An experimental study on separately ground and together grinding Portland slag cement strength properties," *Res. J. Recent Sci.*, vol. 1, no. 4, pp. 27–40, 2012.
- [7] A. A. Ramezani-pour, M. M. Khani, and G. Ahmadibeni, "The effect of rice husk ash on mechanical properties and durability of sustainable concretes," *Int. J. Civil Eng.*, vol. 7, no. 2, pp. 83–91, 2009.
- [8] Y. Zandi and M. V. Akpinar, "Evaluation of internal resistance in asphalt concretes," *Int. J. Concrete Struct. Mater.*, vol. 6, pp. 247–250, 2012.
- [9] M. Shariati, A. Heiati, Y. Zandi, H. Laka, A. Togholi, P. Kianmehr, M. Safa, M. N. A. Salih and S. Poi-Ngian, "Application of waste tire rubber aggregate in porous concrete," *Smart Struct. Syst.*, vol. 24, no. 4, pp. 553–566, 2019.
- [10] S. Kolas and C. Georgiou, "The effect of paste volume and of water content on the strength and water absorption of concrete," *Cem. Concr. Compos.*, vol. 27, no. 2, pp. 211–216, 2005.
- [11] M. I. Khan and R. Siddique, "Utilization of silica fume in concrete: Review of durability properties," *Resour. Conserv. Recycl.*, vol. 57, pp. 30–35, 2011.
- [12] G. R. de Sensale, "Strength development of concrete with rice-husk ash," *Cem. Concr. Compos.*, vol. 28, no. 2, pp. 158–160, 2006.
- [13] K. Murari, R. Siddique, and K. K. Jain, "Use of waste copper slag, a sustainable material," *J. Mater. Cycles Waste Manag.*, vol. 13, pp. 13–26, 2015.
- [14] R. Sharma and R. A. Khan, "Influence of copper slag and meta-kaolin on the durability of self-compacting concrete," *J. Clean. Prod.*, vol. 171, pp. 1171–1186, 2018.
- [15] B. M. Mithun and M. C. Narasimhan, "Performance of alkali activated slag concrete mixes incorporating copper slag as fine aggregate," *J. Clean. Prod.*, vol. 112, Part 1, pp. 837–844, 2016.
- [16] A. Bouikni, R. N. Swamyb, and A. Bali, "Durability properties of concrete containing 50% and 65% slag," *Constr. Build. Mater.*, vol. 23, no. 8, pp. 2836–2845, 2009.

- [17] R. K. Dhir, J. de Brito, R. Mangabhai, and C. Q. Lye, "Use of copper slag as concrete sand," in *Sustainable Construction Materials*. Ch. 4, R. K. Dhir, J. de Brito, R. Mangabhai, C. Q. Lye, Eds. Woodhead Publishing, 2017.
- [18] K. S. Al-Jabri, M. Hisada, A. K. Al-Oraimi, and A. H. Al-Saidy, "Copper slag as sand replacement for high performance concrete," *Cem. Concr. Compos.*, vol. 31, no. 7, pp. 483–488, 2009.
- [19] J. de Brito and N. Saikia, *Recycle Aggregate in Concrete*. London: Springer, 2013.
- [20] A. Nosrati, Y. Zandi, M. Shariati, K. Khademi, M. D. Aliabad, A. Marto, M. A. Mu'azu, E. Ghanbari, M. B. Mahdizadeh, A. Shariati and M. Khorami, "Portland cement structure and its major oxides and fineness," *Smart Struct. Syst.*, vol. 22, no. 4, pp. 425–432, 2018.
- [21] D. M. Roy, "Hydration of blended cements containing slag, fly ash, or silica fume," in *Proc. of Meeting Institute of Concrete Technology*, Coventry, UK, April 29–May 1, 1987, 1987, pp. 22–31.
- [22] E. G. Moffatt, M. D. A. Thomas, and A. Fahim, "Performance of high-volume fly ash concrete in marine environment," *Cem. Concr. Res.*, vol. 102, pp. 127–135, 2017.
- [23] I. Zafar and T. Sugiyama, "The influence of bending crack on rebar corrosion in fly ash concrete subjected to different exposure conditions under static loading," *Constr. Build. Mater.*, vol. 160, pp. 293–307, 2018.
- [24] O. E. Esbach and M. Souders, *Handbook of Engineering Fundamentals*. New York: John Wiley & Sons, 1975.
- [25] C. Shi, "Effect of mixing proportions of concrete on its electrical conductivity and rapid chloride permeability test (ASTM C 1202 or ASSHTO T277) results," *Cem. Concr. Res.*, vol. 34, no. 2, pp. 537–545, 2004.
- [26] J. Balogh, "Laminated wood-concrete structural members," *Pollack Period.*, vol. 8, no. 3, pp. 79–86, 2013.
- [27] Y. Zandi, O. Burnaz, and A. Durmus, "Determining the temperature distributions of fire exposed reinforced concrete cross sections with different methods," *Res. J. Env. Earth Sci.*, vol. 4, no. 8, pp. 782–788, 2012.
- [28] F. Hunkeler, "The resistivity of pore water solution - a decisive parameter of rebar corrosion and repair methods," *Constr. Build. Mater.*, vol. 10, no. 5, pp. 381–389, 1996.
- [29] *ACI 222R-19*, Guide to protection of metals in concrete against corrosion, American Concrete Institute, 2019.
- [30] *ASTM C150-05*, Standard specification for portland cement, ASTM International, West Conshohocken, PA, 2005.
- [31] *ASTM C33/C33M-18*, Standard specification for concrete aggregates, ASTM International, West Conshohocken, PA, 2018.
- [32] *ASTM C494/C494M-19*, Standard specification for chemical admixtures for concrete, ASTM International, West Conshohocken, PA, 2019.
- [33] *ASTM C618-12a*, Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete, ASTM International, West Conshohocken, PA, 2012.
- [34] *ACI 211.1-91*, Standard practice for selecting proportions for normal, heavyweight, and mass concrete, American Concrete Institute, USA, reapproved 2002.
- [35] *ASTM C192/C192M-19*, Standard practice for making and curing concrete test specimens in the laboratory, ASTM International, West Conshohocken, PA, 2019.
- [36] *ASTM C39/C39M-20*, Standard test method for compressive strength of cylindrical concrete specimens, ASTM International, West Conshohocken, PA, 2020.
- [37] *ASTM C496/C496M-17*, Standard test method for splitting tensile strength of cylindrical concrete specimens, ASTM International, West Conshohocken, PA, 2017.
- [38] *COST 509*, Corrosion and Protection of Metals in Contact with Concrete. Final report, in European Commission, Directorate General Science, Research and Development R. N. Cox, R. Cigna, O. Vennesland, T. Valente Eds. EUR 17608 EN: Brussels, 1997.
- [39] *BS EN 12390-8:2019*, Testing hardened concrete, Depth of penetration of water under pressure, British Standards Institution, 2019.
- [40] *DIN 1048-1:1991-06*, Testing concrete; testing of fresh concrete, German Institute for Standardisation, 2006.