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Laboratory Evaluation of Electrical Resistance of Concrete

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ABSTRACT

Common methods of controlling setting, hardness, process of strength concrete are tests for determining the setting time of mortar and concrete and determining the compressive strength of concrete It seems that these physical methods, do not fully reflect the behavior of concrete and the process of changing phase states during the hydration process; however, with the method of the electrical resistance of concrete, this observation is possible. Therefore, in this study, at the first stage, 11 samples of cement were prepared, the phases of which varied, but due to laboratory cementation, their fineness and grading conditions were almost the same. Physical and chemical analysis of cement samples was performed. In the next step, 22 concrete mixtures with 11 cement samples were prepared, so that 11 mixtures without additives and 11 mixtures with constant dosage of commercial super plasticizer. Also in the all concrete mixtures, the slump kept constant about 8 cm. Compressive strength tests of 7, 28 and 90 days hardened concrete were performed on concrete mixtures. Also, an electrical resistance test was performed, which was performed regularly from the time of cement contact with water until 31 days later. The results showed that at least three peaks of 8, 16 and 23 days in the electrical resistance curve are seen along the test time. In almost all samples, the electrical resistance is reduced to about 3 hours, which indicates the setting time of the concrete. Based on the results of this study, formula was presented.

Keywords: **Electrical resistance, cement, concrete, additives**

1. INTRODUCTION

Concrete electrical resistance monitors have been developed to provide faster and easier information. Some of these methods are standardized, and the maximum values of the test results are listed in the performance specifications. Electrochemical methods, including conductivity and strength measurements, have been proposed as methods for evaluating the transfer properties as well as changes in pore solutions and microstructures in cementitious base materials [1,2]. In addition to their high speed, these methods allow us to continue testing the same test while working without disturbing it. The use of the electrical resistance method was started by the Japanese researcher Shimizu (1928), who studied Portland cement by measuring its electrical conductivity [3]. This method in modern concrete science to determine the amount of water in concrete [4], water to cement ratio [5], research in the early stages of cement paste setting and mortar hardening [6-9], to determine the setting time of cement paste and concrete [10-14]. Research and evaluation of different structural properties of concrete, including their permeability properties [15-19] and study of reinforcement patterns [20-23] have been developed Monfore (1970) studies on the electrical properties of concrete, both DC and AC to investigate the effect of concrete performance on the electrical resistance of concrete [24]. Michelle et al. (2006) prepared various high-performance concrete mixtures (HPC) containing 0.4 w/c, silica fume, fly ash, slag, and ordinary concrete mix at w/c: 0.69 with Portland cement. They packed the samples in saturated, dry, and dry-saturated (SSD) modes with vinyl tape. The specimens were stored for the first 7 days in a standard test apparatus for determining the electrical resistance of concrete against chloride ion penetration (ASTM C1202) [25] and then processed in subsequent measurements in lime-saturated water. The experiment continued with two similar experiments at different ages. Electrical conductivity was measured using the test equipment, but there were several deviations from the standard test method. Due to the high conductivity in the early ages and the maximum allowable current of 500 mA for the equipment used, 30 volts were used instead of the usual 60 volts. 0.3 N sodium hydroxide solution was used in both test chambers. The researchers used an automated method to collect data at 3-hour intervals during the first week and then at weekly intervals until the subjects reached 28 days of age. At each test interval, 30 volts were applied to the testers for 15 minutes before recording the measurement used to calculate conductivity. The automated method allows the user to apply the time interval between cycles, the number of cycles, and the number of tests during the duration of using the desired voltage for each test. In this study, there was no significant difference between the measurements performed at 5 and 15 minutes.

The effects of the w/c ratio and cementitious additives are clearly seen in the results of this study. The greatest reduction in conductivity occurred in the first week after processing. They presented a relation according to the results [26]. Li et al. (2007) compared the results of two experiments on the initial and final setting time of fresh concrete [27] and the determination of electrical resistance of concrete, which showed a direct and clear relationship [28,29]. Sengul and Jarro (2007) studied the electrical resistance to control the quality of concrete during construction and its durability. The researchers' laboratory program was mainly based on the Wenner test of electrical resistance with different probe distances and different geometry. Their results showed that for the experimental conditions, the electrical resistance obtained from the Wener method is different from the resistance obtained in the two-electrode method. Therefore, they concluded that for a specific type of concrete test with humidity and temperature conditions, the Wener method is a suitable and reliable test method to control the quality of electrical resistance based on performance and, therefore, concrete durability [30]. Spragg et al. (2012) investigated the factors affecting the measurement of electrical resistance in cement systems. According to them, there are several key factors that can affect the results of concrete electrical resistance: geometry, temperature, and test performance. Therefore, they first studied the role of test geometry on electrical resistance using three common geometries: surface electrodes, uniaxial, and embedded. Then, the role of test temperature and the importance of processing (hydration rate and saturation rate) were investigated. Their results showed that both pore solution resistance and test resistance measurement follow the Arrhenius relationship with different conduction activation energy (EA-Cond). They also observed that when hardened specimens were processed in different solutions of different volumes, inconsistent results were obtained, which, in their view, were due to the dilution of the pore solution and appeared to alter the measured frequency spectrum. Thus, experiments at variable frequencies have the ability to reduce these effects, but for constant frequency experiments, the volume of solution around the specimen must be strictly controlled [31].

Layssi et al. (2015) evaluated the measurement of electrical resistance by uniaxial and Wenner methods. Accordingly, while the uniaxial method is suitable for concrete tests or drilled cores, the Wenner method is a better choice for an on-site evaluation. The nonlinear relationship between electrical resistance and RCP values is largely the result of changes in temperature and pore solution properties during the RCP test. The relationship between electrical resistance and penetration coefficient is more appropriate to determine the criteria required to control the quality of concrete based on durability, especially the criteria required to classify the permeability of concrete chloride [32]. Hughes et al. (2015) introduced an improved method for measuring the electrical resistance of concrete that solves the problems caused by the effects of polarization and capacitive reaction. The results of fresh and hardened concrete obtained by the proposed method were also presented and compared with the results using more conventional methods, which was desirable [33]. Azarsara and Gupta (2017) studied the electrical resistance of concrete in detail to evaluate its durability. According to the different results and analyzed articles, these researchers emphasized the following: a- The effect of the presence of rebar in concrete for this evaluation; B- Existence of cracks and its evidence; C- Humidity and temperature status of concrete [22, 34] (SSD mode is recommended); D- How to properly connect the electrodes to concrete; E- Effect of aggregate type on results; And- the effect of carbonation process; G. The effect of chlorine ion (which is inversely related to the strength and correlation and direct relationship between the results of electrical resistance of concrete and the amount of corrosion); H- Direct relationship between concrete compressive strength, electrical resistance, and porosity of concrete [35]; I- Geometric arrangement of electrodes for measurement [36,37]; Environmental conditions [38]. Minagawa et al. (2017) studied the electrical strength of concrete to design electrochemical corrosion methods or the durability index of reinforced concrete structures. In this study, the mechanism of the dependence of the distance between the probes on the apparent electrical resistance of the concrete with the ambient temperature in the direction of depth was investigated. They observed that the appearance of concrete was directly related to the amount of water, measuring the depth and distances of the probes [39]. Obla et al. (2017) evaluated the connection of electrical resistance of fresh concrete with concrete mix ratios. They were inspected with fresh cylindrical concrete formwork. What is the effect of different concrete mixtures (different amounts of cement and water) on the electrical resistance of concrete? Cement produces ions (mainly K+, Na+, and OH-) which are the main source of electrical conductivity, and water has this effect by creating conductive ducts. In eleven similar concrete mixtures with w/c, the amount of paste, the amount of air, the amount of fly ash, the amount of water-reducing consumer, and the alkaline amount of cement were different. According to them, only measuring the electrical resistance of concrete can predict the amount of dough or product [40].

Stackelberg et al. (2018) investigated the properties of Cement-concrete Compositions (CCC) using the electrical resistance method. These compounds are constantly changing during the hardening process; in the early stages of hardening, they had viscous plastic properties, while in the final structure, artificial stone often had elastic properties. The technical parameters (W / C ratio, slump, setting time, resistance, etc.) are also mostly incompatible with each other. This complicates the practical implementation and oversight of the CCC. In this study, various measurement sensors (dual-electrode sensors, tester type [9, 12], complex contactless systems [6, 22], and multi-electrode [41] have been used [42]. Obla et al. (2020), in a detailed study on the electrical resistance of concrete, announced the following results: 1. The classification of concrete mixtures for chloride permeability is valid as long as a single processing method is used; 2. Depending on the processing method used and the measured strength, the same mixture can be classified into two different groups for chloride permeability according to the relevant criteria; 3. The results of surface strength were about 10-20% less than the measured volumetric strength in concrete tests in this study. As a result, there were several cases where the chloride permeability classification based on SR reduced a level of classification based on BR measured; 4. Conductivity results are well correlated with RCP results; 5. The measured degree of saturation of aerobic concrete mixtures is on average 20% lower than that of equivalent non-aerobic concrete mixtures. The measured compressive strength was 25% higher for aerated concrete mixes, and the RCP results were 20% lower compared to equivalent non-aerated concrete mixes. For an aerated concrete mix, a 2-3% increase in air volume slightly reduces the degree of saturation and does not affect the strength; 6. For all concrete mixes evaluated, drying of the saturation test increases the strength; 7. For different mixtures evaluated, samples treated under the same conditions had different saturation values at the end of the processing period; 8. The BR test is significantly better than the RCPT and somewhat better than the SR test [43].

Cosoli et al. (2020) analyzed advanced methods for measuring the electrical impedance (and consequently electrical resistance) of mortar and concrete. The researchers reviewed more than twenty other studies and described a variety of methods, the advantages and disadvantages of which are determined by their performance, reliability, and maturity. Both monitoring and inspection methods are possible by measuring electrical resistance. Electrical resistance is an important indicator of the health status of mortar with concrete because whenever phenomena change the conductivity of mortar with concrete, this method acts as a guide. These researchers made recommendations for using the electrical resistance method of concrete (such as considering the humidity of the measuring surface, air and concrete temperature, the placement of rebar, the maximum size of concrete aggregates, the amount of frequency used, etc.) [44]. Nili (2011) made it possible to measure concrete's setting time by the concrete's electrical resistance. With the aim of providing a simple, accurate, and comprehensive method for determining the setting time of concrete, he evaluated the trend of changes in the electrical resistance of fresh concrete over time. For this purpose, he designed 14 concrete mix designs with three water-to-cement ratios of 0.35, 0.45, and 0.55. In addition, a zero-slump concrete design and a self-compacting concrete design were developed to evaluate a wide range of concretes. In this research, a system was designed that was able to record the electrical resistance of fresh concrete (sifted and unsifted) with an accuracy of 0.1 ohms at a time interval of 1 minute and automatically. The standard setting time for the concrete setting was also performed for all concrete mixtures. The properties of hardened concrete, such as compressive strength, electrical resistance, and volumetric water absorption of concrete, were also evaluated. The results of the electrical resistance test of fresh concrete over time show that the electrical resistance curves in all mixtures follow a similar and specific trend in which there are critical points that indicate important properties such as the setting of concrete. In this curve, the stages of the concrete hydration process were divided into 5 stages by evaluating the development of electrical resistance of fresh concrete, which includes the stages of dissolution, competitive equilibrium or prevention, setting, and hardening. Also, the identified critical points are zero stopping point, initial stopping point, final stopping point, and final stopping point or transition point to the hardening stage [45].

Parsan et al. (2016) conducted studies to predict the results of electrical resistance measurement using the standard method ASTM C1760. For this purpose, 49 concrete mix designs with low to very high electrical resistances were considered. Their study showed that there is a significant difference between the results of the apparent strength spectroscopy methods and ASTM C1760, but significantly, the electrical resistances measured by the ASTM C1760 method are slightly higher than the results of the apparent strength spectroscopy method in the same concrete. In the four-electrode method, several factors, including non-compliance with the proportion between the distance between the electrodes and the dimensions of the structure, can cause systematic errors in the results, which is why the measurement results with this method are about 140% larger than the standard method. In the one-electrode method, due to the lack of a comprehensive relationship to calculate the cell constant, first, the value of this constant is obtained in comparison with the results of the standard method, and then the values of electrical resistance are calculated. The results of measuring electrical resistance with this method are slightly different from the standard method [46].

Tadayon (2001) also investigated the relationship between the electrical resistance of lightweight and ordinary concrete with other parameters [47]. The purpose of this study is to investigate the local method of monitoring the electrical resistance of concrete using a variety of cement that have chemical analysis. Therefore, the method of measuring the electrical resistance of hardened concrete [48] was not considered. Lim & Lee (2022) study the electrical Conductivity and Compressive Strength of Cement Paste with Multiwalled Carbon Nanotubes and Graphene Nanoplatelets. Following the experiments, it was shown that the electrical conductivity was improved via the noncovalent functionalization of MWCNT and GNP, and The compressive strength increased up to approximately 0.30–0.60% of the CBNs content [49].

Horsakultha (2021) studied the effect of recycled concrete powder on the strength, electrical resistivity, and water absorption of self-compacting mortars. The chemical composition of recycled concrete powder (RCP) and the physical properties of self-compacting mortar with RCP as supplementary cementitious materials (SCMs) was investigated in detail. RCP was obtained by crushing and sieving recycled concrete from demolished buildings; particles that passed the No. 4 sieve were then ground to a fineness such that 80% of particles could pass through the No. 325 sieve. The RCP partially replaced OPC in varying ratios of 20%, 40%, and 60% by weight of powder in self-compacting mortars in which the water to powder ratio was maintained at 0.35. The compressive strength, electrical resistivity, porosity, and water absorption of the RCP self-compacting mortars were investigated. The results indicated that the RCP was reactive, having a strength activity index of 89.4% and 87.2% at 7 and 28 days, respectively. The porosity and water absorption coefficient increased, and electrical resistivity decreased with an increase in the RCP content. Based on the results of this study, the optimum RCP replacement ratio with the minimal negative effect on the compressive strength is up to 20% [50].

Pan et al. (2021) studied theoretical and experimental studies on the electrical resistivity method for evaluating fresh concrete segregation. This study aims to provide a theoretical foundation to support the application of the electrical resistivity method to in-situ monitoring segregation of fresh concrete. They proposed a new non-conducting sphere model and an electrical resistivity algorithm to study the correlation between the electrical resistivity and the volume fraction of coarse aggregates. Glass spheres with different sizes were used to replace coarse aggregates in validation experiments for neglecting the irregular surface of coarse aggregate particles. A modified rectangular column mold containing three pairs of electrodes at different heights was developed to evaluate the segregation of fresh concrete. The experimental results were also compared with those obtained by the conventional washing-sieving method. The applicability of the correlations between electrical resistivity values and volume fractions of coarse aggregates was confirmed. The segregation index obtained by the electrical resistivity method has a good linear correlation with the segregation coefficient obtained by the washing-sieving method. Therefore, the electrical resistivity method has a great potential for in-situ monitoring the stability of fresh concrete during placement and compaction processes [51].

Araújo et al. (2022) studied Concrete surface electrical resistivity: Effects of sample size, geometry, probe spacing, and SCMs. They used the surface electrical resistivity (SER) of concrete was studied according to UNE 83988–2 by Wenner probe on concrete samples with finite dimensions (Ø100·200 mm and Ø150·300 mm cylinders) and semi-infinite dimensions (250·250·250 mm cubes). This study evaluated the effect of several parameters on concrete SER, such as sample geometry and size, probe spacing, and the presence of supplementary cementitious materials (SCMs), namely, rice husk ash (RHA) and fly ash (FA). Additionally, UNE 83988–2 adjustment factors were evaluated. The results of them showed that SCMs increase concrete SER and have a direct effect on corrosion risk. Furthermore, the size, geometry, and probe spacing show an influence on SER; hence, new adjustment factors based on the experimental data were proposed and validated using a wide range of concrete mix designs containing SCMs. [52].

2. MATERIALS AND METHODS

In the first stage, 11 clinker samples were sampled from Tehran Cement Factory, whose phase values were varied. A sample of gypsum was prepared, and a chemical analysis was performed. Using these clinkers and a laboratory mill, laboratory cementation was performed, which was a combination of 96% clinker and 4% gypsum with the criterion of achieving a Blaine index of 50±3000 cm2/gr. The fineness and granulation of the cement samples were almost the same. Physical and chemical analysis of cement samples was performed (table 1). A sample of super-plasticizer additive was also prepared. The above lubricant was based on polycarboxylate ether. In the next step, 22 concrete mixtures with 11 cement samples were prepared. 11 mixtures with the title of control (without additives) were made with the aim of achieving 8 ± 0.5 cm slump, and 11 mixtures with the addition of additives were initially prepared with the aim of achieving slump of 8 ± 0.5 cm; Then 0.3% by weight of cement from super plasticizer additive (water reducing) was added to the concrete mix to make the slump of concrete in the range of S3, i.e. slump 100-150 mm (BS8500-2003) [53]. Compressive strength tests of 7, 28, and 90 days of hardened concrete were performed on concrete mixtures. Also, an electrical resistance test was performed, which was performed regularly from the time of cement contact with water until 31 days later.

Figure 1. Laboratory cementation and determination of their physical and mechanical characteristics

Figure 2 and Table 1 show the characteristics of aggregates used in this study. It is a place for preparing aggregates from the west of Tehran (Shahriar region).

Table 1. Technical specifications of materials used in concrete mix designs

Passing percent of sieve 200	Fracture (%)	ρ (SSD)	Water absorption (%)	fineness modulus (FM)	MSA	Type
0.1	79	2.53	2.64	*	19	gravel
0.2	*	2.54	3.88	3.5	*	sand

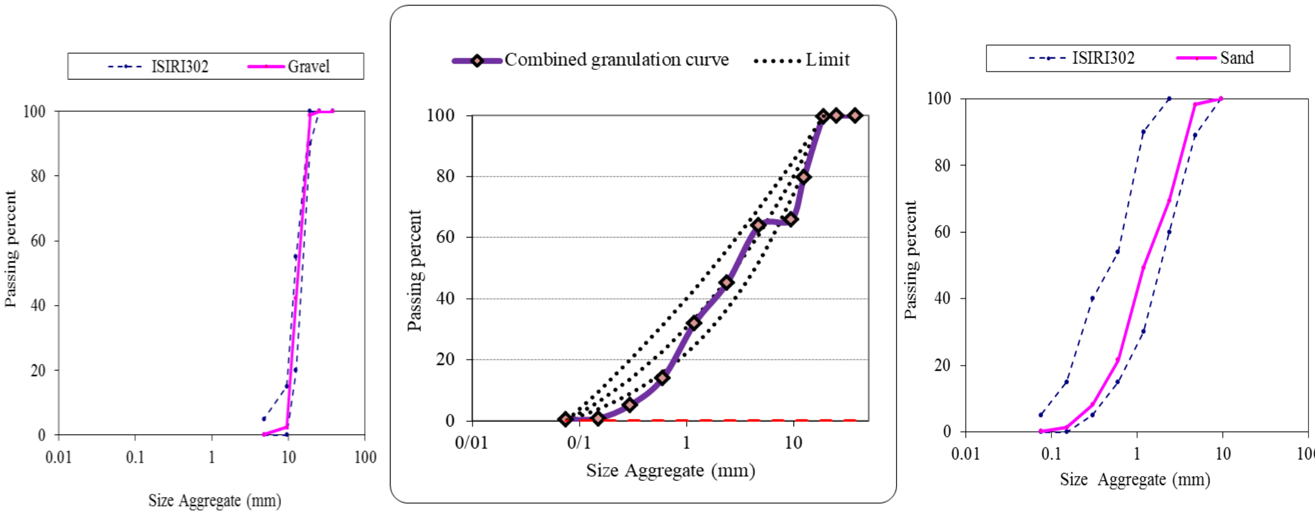


Figure 2. Graphs of sand (right), sand (middle) and composition of materials (left) used in concrete mixes

In all mixtures, the quality of aggregate and water materials, weight values of materials, physical conditions such as temperature, tools used, testers, and processing conditions have been as constant as possible to create the same conditions as the only variable of clinker phases used in cement (Figure 2). The grade of cement used in all designs was 350 kg/m3. The mixtures were designed according to the Iranian method, and the corresponding power in the modified Fuller-Thomson relationship was considered to be about 0.35 using the relevant proposed table, which has a wide range of applications [54]. To prepare this mixture, 65% sand with 35% coarse sand was used (Figure 3 and Table 2).

Table 2. General specifications of concrete mix designs

Additive amount Relative to cement(٪)	w/c	Weight in one cubic meter of concrete (kg)				
		Additive	water	cement	gravel	sand
0.3	0.54	1.027	188	350	602	1129

The compressive strength of hardened concrete was measured at 7, 28 and 90 days of all concrete mixes (Figure 3). Measuring electrical resistance with the settings introduced in the NIST paper by K. Obla [8] is a new method for fresh concrete. From each concrete mix, 2 cylindrical molds with a length of 20 cm and a diameter of 10 cm (8.4 inches) were prepared. The molds were designed and made for single use and special for this project so that two metal pins (steel) with a distance of 10 cm and a height of 15 cm were buried in the concrete. The current was applied between the two electrodes inserted in the test, and the voltage was measured simultaneously. The electrical resistance is calculated from the ratio of the measured voltage to the applied current and is reported directly by the device. A total of 44 templates and 88 pins were prepared, and readings were performed at the ages of 0, 1, 2, 3, 6, 24, 30, 48, 54, 54, and 774 hours (32 days). An electrical resistance measuring device was also designed and developed in accordance with the work.

Figure 3. Preparation of concrete mixes and related tests

Important points in how to measure the electrical resistance of concrete were as follows:

- ✓ The location of the device should be such that there is no need to move the device during the whole laboratory process and to read the tests;
- ✓ The value of K (which is a constant coefficient in resistance calculations) was considered a fixed number of 10 in all readings;
- ✓ At each reading, the value of Z (electrical resistance of the device display) was checked with previous numbers and similar tests;

- ✓ If the device shows an unrelated number, the values K and φ (the angle between the two electrodes of the device when measuring electrical resistance) are controlled. Given that the probes and cables of the device were mounted on two pins buried in concrete and were parallel to each other, the value of φ must be zero for the value of Z to be true;
- ✓ At each stage of the readings, the reproducibility of at least one reading is checked.
- ✓ The read value coefficient of 0.145 was applied as electrical resistance.

3. RESULTS AND DISCUSSION

Table 3 shows the chemical analysis of the clinker samples used in this study. Based on the results, C3S values are about 49.6-6.4%, and C3A values are about 3.7-4.4%. Therefore, there are various clinkers for cementing.

Table 3. Chemical analysis of clinker samples used in laboratory cementation (wet method)

Free CaO	C4AF	C3A	C2S	C3S	AlM	SiM	LSF	CaO	Fe2O3	Al2O3	SiO2	Sample Code
0.70	14.0	6.0	25.8	49.6	1.13	2.25	89.7	63.5	4.6	5.2	22.02	**5263**
1.01	12.8	5.0	26.5	50.0	1.09	2.56	89.1	63.12	4.2	4.56	22.4	**5159**
0.84	11.7	4.5	21.6	56.3	1.08	2.79	91.2	63.72	3.84	4.16	22.32	**5154**
0.39	12.1	3.7	16.5	61.4	0.99	2.77	93.2	63.88	3.96	3.94	21.9	**5155**
0.48	13.6	5.8	28.0	48.1	1.13	2.35	88.8	63.54	4.48	5.04	22.4	**5162**
0.70	12.5	6.1	35.7	41.5	1.19	2.58	85.8	63.34	4.12	4.92	23.34	**5156**
0.56	11.9	6.1	25.1	51.2	1.23	2.54	90.0	63.36	3.92	4.82	22.2	**5158**
0.39	11.9	6.0	25.8	51.3	1.22	2.60	89.8	63.86	3.9	4.76	22.5	**5157**
0.42	12.3	7.4	23.5	51.9	1.33	2.32	91.0	63.84	4.04	5.38	21.84	**5153**
0.45	11.8	5.6	19.4	57.8	1.19	2.59	92.4	64.16	3.88	4.6	21.96	**5160**
0.42	12.2	5.7	26.3	50.4	1.18	2.57	89.4	63.48	4	4.72	22.44	**5161**

Analysis of gypsum used for laboratory cementation was shownin Table 4. This chemical analysis shows that the gypsum used is of good quality.

Table 4. Chemical analysis of gypsum used in laboratory cementation (wet method)

Molecular water	CaSO4	SO3	MgO	CaO	Fe2O3	Al2O3	SiO2
18.42	70.6	41.54	0.78	31.8	0.22	0.78	1.84

Table 5 shows the results of physical and mechanical analysis of laboratory cement. The results of cement granulation showed similarities in their softness.

Table 5. Results of physical and mechanical analysis of laboratory cements

Code	Compressive Strength-Mortar (kg/cm2)			Setting Time (min)		Normal	Retained on sieve (%)		Blaine (cm2/gr)
	2 Days	7 Days	28 Days	Initial	Final	Consistency (%)	90μ	45μ	
5153	180	316	472	230	310	23.5	1.34	12.04	2951
5154	176	291	430	230	300	23.5	1.32	11.36	3052
5155	172	303	343	240	315	24.0	1.30	11.46	3052
5156	132	286	466	230	310	23.5	1.18	12.26	2951
5157	206	335	492	215	290	24.0	1.78	13.64	2985
5158	163	321	493	240	315	23.5	1.24	12.84	2951
5159	146	286	466	215	295	23.5	1.34	15.42	2985

5160	222	307	514	190	265	23.5	0.88	10.22	2985
5161	167	308	494	240	315	23.5	1.24	12.34	3019
5162	150	311	534	240	320	24.0	1.20	12.22	2951
5163	169	296	446	250	325	23.5	2.08	14.20	3019

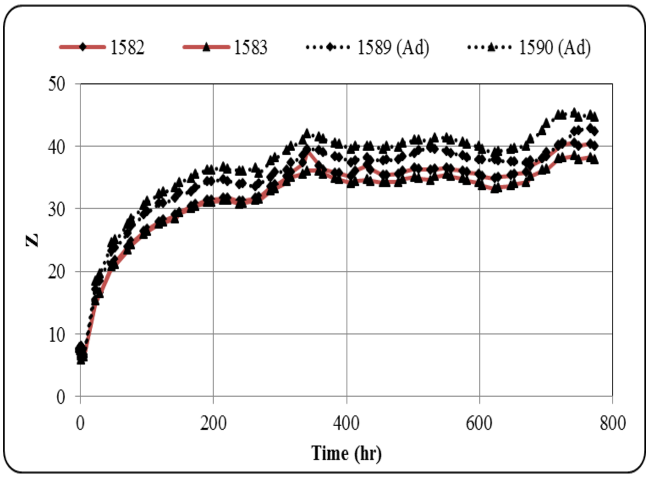
Table 6 summarizes the results of fresh and hardened concrete.

Table 6. Test results of concrete mixtures made with laboratory cements

	Without Admixture (Normal)					With Admixture				
Code	**Fresh Concrete**		**Compressive Strength-Concrete (kg/cm2)**			**Fresh Concrete**		**Compressive Strength Concrete (kg/cm2)**		
	Slump (mm)	**w/c**	**7 Days**	**28 Days**	**90 Days**	**Slump (mm)**	**w/c**	**7 Days**	**28 Days**	**90 Days**
5153	80	0.55	247	397	488	80	0.47	250	411	479
5154	90	0.54	248	392	427	85	0.48	286	458	438
5155	80	0.59	219	377	433	80	0.54	236	373	468
5156	80	0.56	209	392	499	80	0.51	225	389	479
5157	80	0.53	246	440	545	80	0.48	272	429	438
5158	80	0.57	239	382	490	80	0.52	254	401	425
5159	80	0.54	278	439	582	80	0.50	272	336	564
5160	80	0.54	284	428	451	80	0.48	328	443	505
5161	80	0.51	274	453	496	80	0.46	299	462	463
5162	85	0.56	251	366	500	85	0.51	277	399	464
5163	80	0.54	271	390	470	80	0.50	272	363	463

The graph of the electrical resistance results of the tests can be seen in Figure 4. - Almost three peaks were observed in all tests:

- ✓ The first peak is about 200 hours (8 days)….. ρ ≈ 30 Ωm;
- ✓ The second peak is about 400 hours (16 days)….. ρ ≈ 36 Ωm;
- ✓ Third peak about 560 hours (23 days)….. ρ ≈ 39 Ωm.



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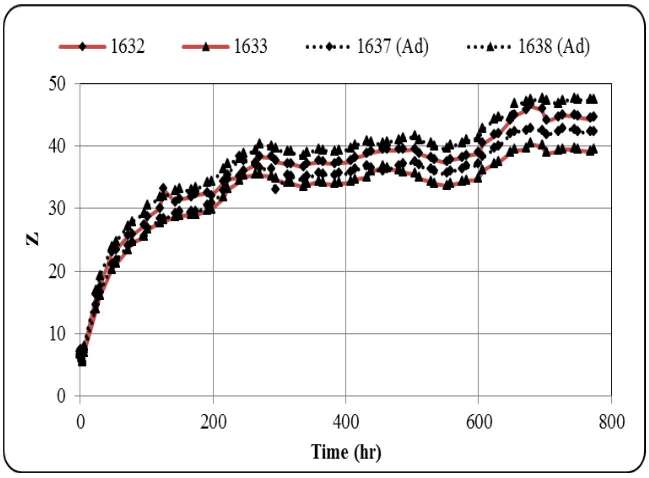

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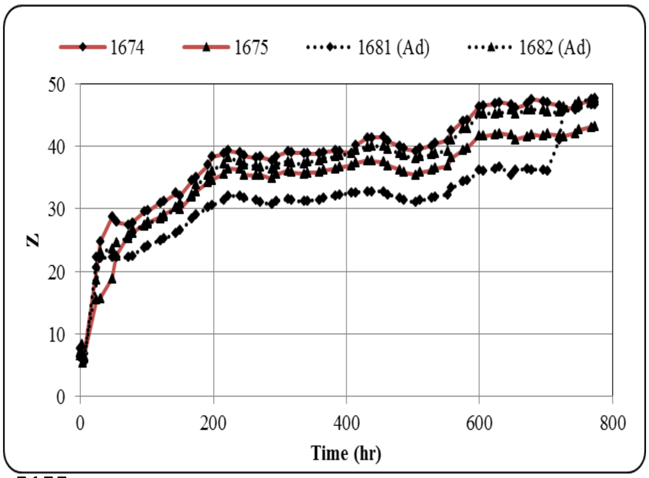

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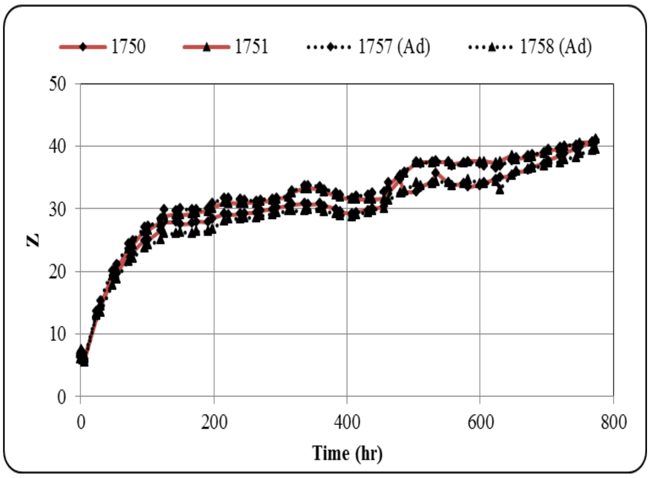

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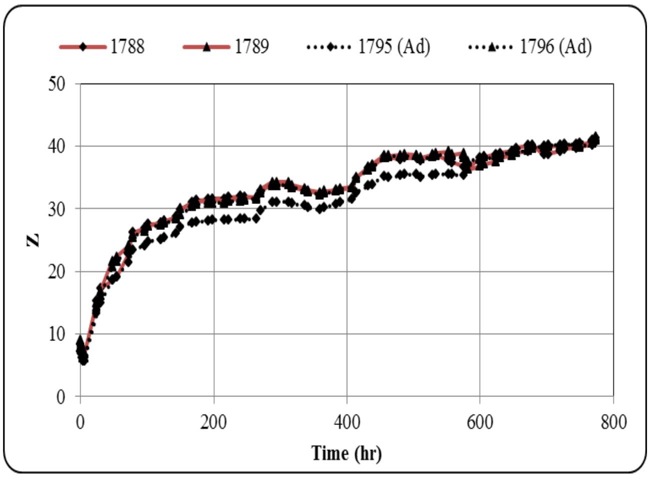

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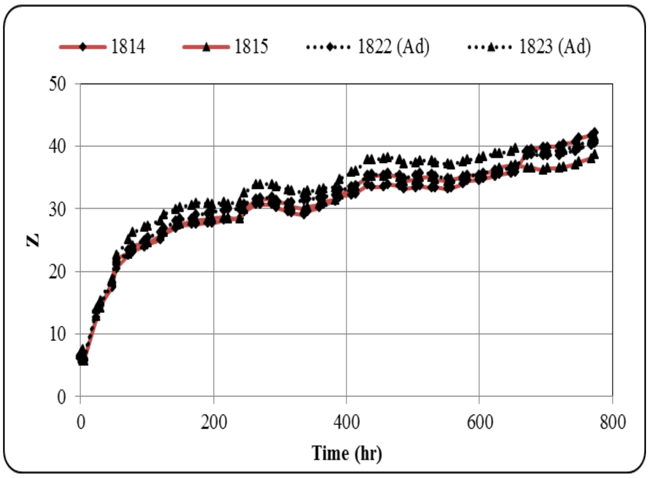

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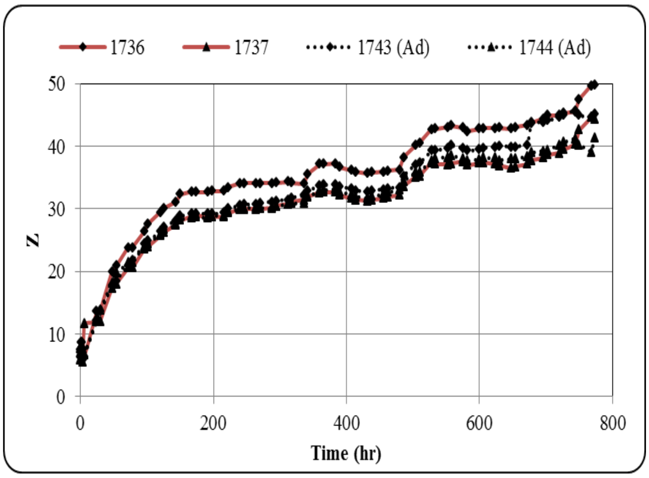

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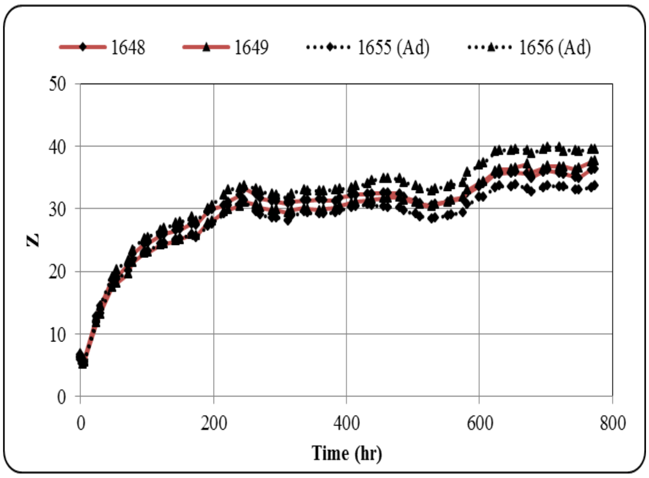
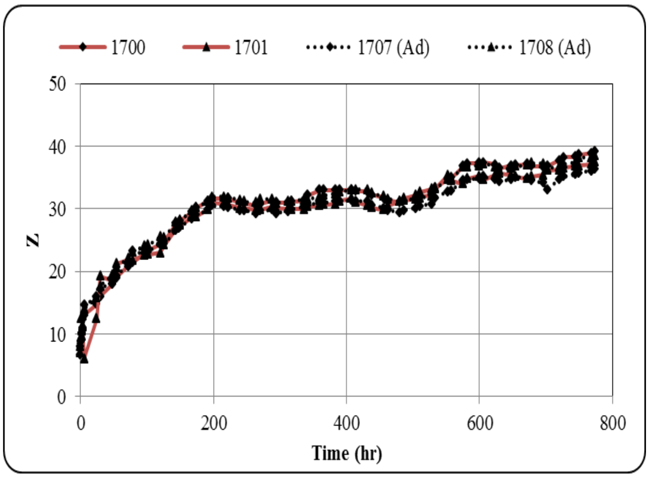
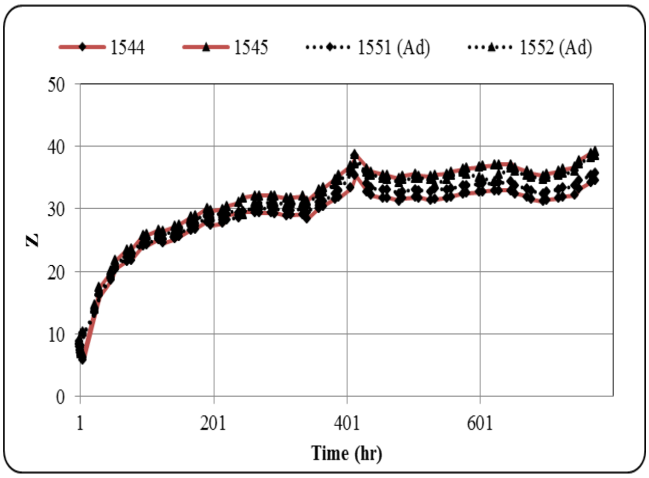


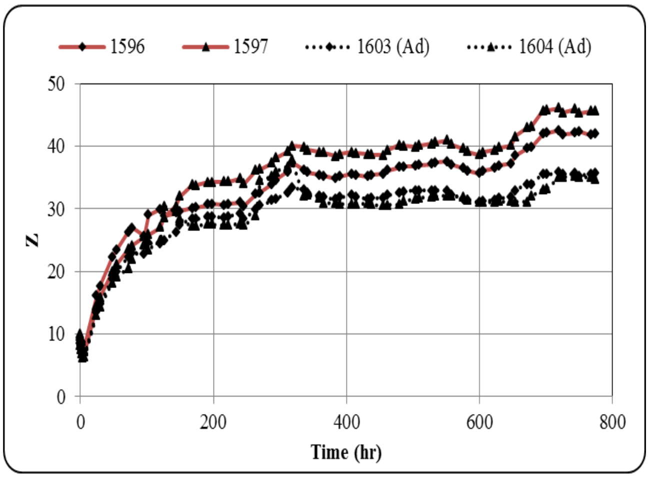
5160



5161



5162



5163

Figure 4. Electrical resistance curves over time for 22 concrete mixes (44 specimens)

To investigate the relationship between compressive strength, electrical resistance and cement phases, diagrams in Figure 5 were drawn.

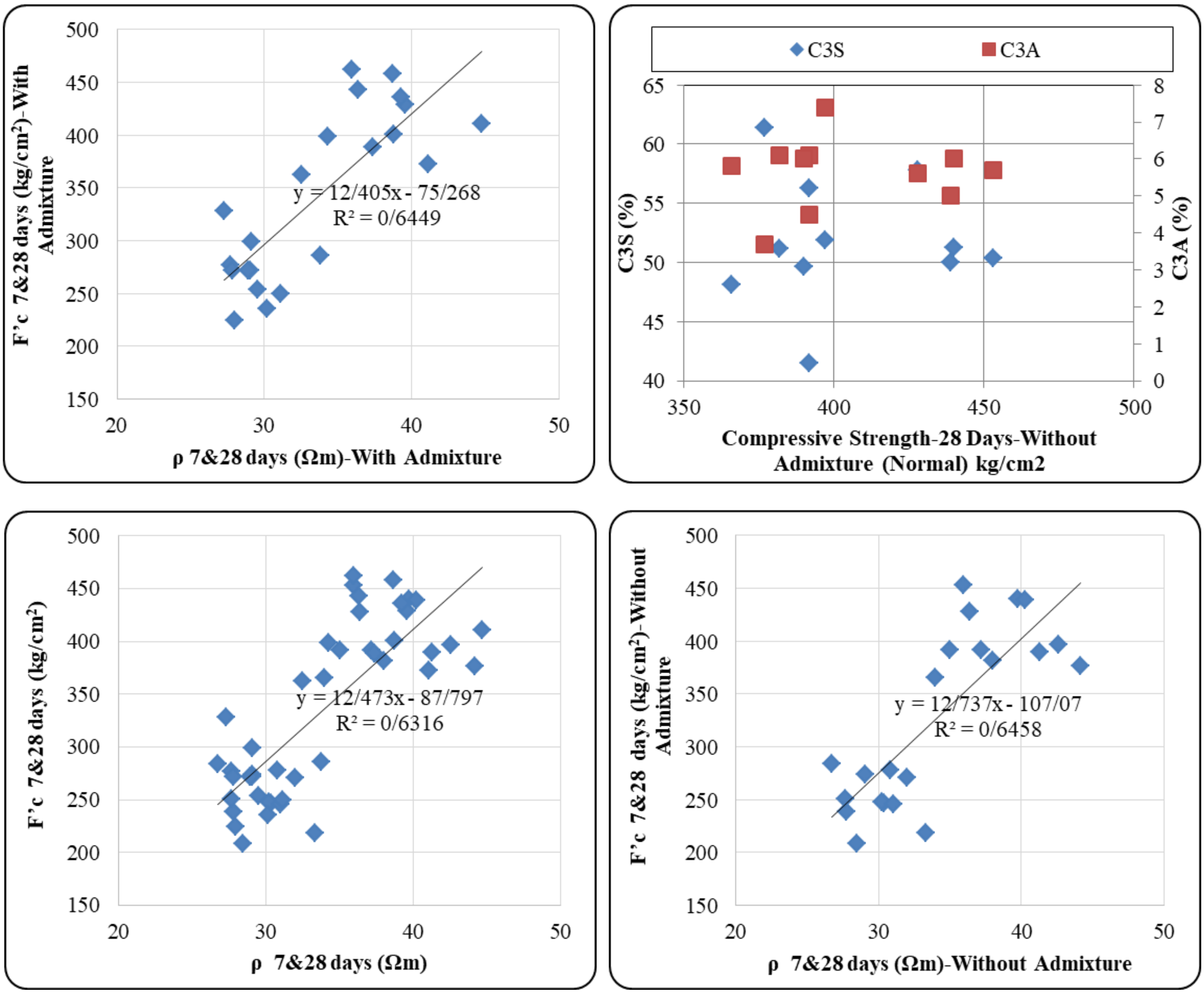


Figure 5. Relationships of compressive strength with cement phases and electrical resistance and compressive strength in laboratory concrete mixtures (7 & 28 days)

From the results and diagrams of Figures 5, it can be concluded that:

- ✓ In almost all tests, the electrical resistance is reduced to 3 hours, which indicates the setting time of the concrete;
- ✓ There is no relationship between W / C and ρ;
- ✓ There is no clear relationship between C3S and C3A with the compressive strength of concrete;
- ✓ The relationship between electrical resistance and compressive strength of concrete is as follows (with correlation: R2 = 0.63):

$$F'c\ (kg/cm^2) = 12.5\ \rho\ (\Omega m) - 88 \quad (1)$$

It should be noted that the purpose of this evaluation and presentation of the relationship is to ensure the achievement of compressive strength with the help of the electrical resistance method and not to estimate the compressive strength at different ages. An example is provided for a better explanation. In some projects, the condition for the next step is to obtain minimum concrete strength. For example, for molding in a project, achieving a resistance of at least 10 MPa, and for applying tensile stress on pre-tensioned cables enclosed with grout, minimum resistance of 40 MPa is considered. For this monitoring, it is necessary to prepare samples and determine the resistance at different time intervals. But with the electrical resistance method and the above relationship, it is easy to ensure that the desired resistance is obtained. Considering that in this particular study, the electrical resistance monitoring method was slightly different from most studies and was only similar to the research of Obla et al. (2018), therefore, it is not possible to make an exact comparison. Of course, the trend of electrical resistance changes over time in this study was similar to the studies of Nili and Tadayon (2010) and Lee et al. (2007). These researchers monitored the setting process of concrete with the help of an electrical resistance test, and in this research, the process of hardening and gaining compressive strength was evaluated with the help of electrical resistance test. In this study, similar to the researches of Sengul and Gjørv (2007) and Hughes et al. (2015), it is concluded that the method of measuring electrical resistance is a suitable and reliable monitoring method for quality control based on performance and, as a result, the durability of concrete.

4. CONCLUSION

In this study, significant relationships were observed between the results of electrical resistance tests and some concrete parameters, which were confirmed in some similar studies. Based on the results of this project:: 1-In almost all tests, the electrical resistance is reduced to 3 hours, which indicates the setting time; 2- It can be said that three peaks are observed in all electrical resistance tests: 200 hours (8 days) with an electrical resistance of about ρ ≈ 30 Ωm; About 400 hours (16 days) with an electrical resistance of about ρ ≈ 36 Ωm; About 560 hours (23 days) with an electrical resistance of about ρ ≈ 39 Ωm; 3- No relationship was found between W / C and ρ; 4- There is no clear relationship between C3S and C3A with the compressive strength of concrete; 5- Based on the results of this study, the relationship between electrical resistance and compressive strength is as follows:

$$(F'c\ (kg / cm2) = 12.5\ \rho\ (\Omega m) - 88)$$

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AUTHORS CONTRIBUTION

This work was carried out in collaboration among all authors.

CONFLICT OF INTEREST

The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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