





Many researchers have been identified that the electrical resistivity as an indicator of chloride penetration resistance, for quality assurance and acceptance of concrete. Presently in the USA, concrete resistivity is substituted for the Rapid Chloride Penetrability Test for use as a quality control parameter through construction, to evaluate for concrete permeability [7]. Table 2 shows the comparison of chloride penetrability levels established for standards based on electrical resistivity [8]. The purpose of this paper is to introduce measurement of the electrical resistivity of concrete, to study factors such as w/b ratio, fly ash content, and cement paste content affecting the concrete electrical resistivity and find a relationship with other concrete properties, such as compressive strength and rapid chloride penetration.

**Table 2. Comparison of Chloride Penetrability Levels Established for Standards Based on Electrical Resistivity (AASHTO TP95) and Charged Passed (ASTM C1202) [Whiting, 1981]**

ASTM C1202/ AASHTO T277		AASHTO TP95
Chloride Ion Penetrability	RCP Test Charged Passed (Coulombs)	Electrical Resistivity Test (kΩ-cm)
High	>4,000	<12
Moderate	2,000-4,000	12-21
Low	1,000-2,000	21-37
Very Low	100-1,000	37-254
Negligible	<100	>254

## Experimental Program

### Specimen Preparation

In this research, electrical resistivity was measured for 20 different concrete mix proportions, as shown in Table 3. Dimensions of the tested specimens were 100 x 100 x 100 mm for cubic specimens and  $\phi$  100 x 200 mm for cylindrical specimens. Three samples were cast for each mixture and shape. Ordinary Portland cement (type I) was used as a binder. Fly ash is also used to partially replace cement in concrete. Coal fly ash type 2b, according to TIS2135, from Mae-Moh power plant, was used as a cement replacement material at the levels of 0, 10, 30, and 40% by weight. Water to binder ratios were 0.35, 0.45, 0.55, and 0.65 respectively. Ratio of paste volume of concrete to void content between aggregate ( $Y$ ) was varied as 1.3 and 1.4. Void volume between aggregate can be determined based on ASTM C29 according to amount of fine and coarse aggregate used as shown in mix proportion. Natural river sand was used as a fine aggregate. Coarse aggregate, crushed limestone was used with a maximum size of 20 mm. To obtain good workability of concrete at low w/b ratio, a superplasticizer (Mighty-X) was used. Two types of curing regimes used in this study were air curing and water curing.

**Table 3. Mix Proportions of the Tested Concrete**

No	Designation	w/b	Y	Unit Content (kg/m <sup>3</sup> )					
				OPC	FA	Water	Sand	Gravel	SP
1	0.35 OPC	0.35	1.3	433	0	149	771	1138	2.16
2	0.35 FA 10	0.35	1.3	385	43	148	771	1138	2.14
3	0.35 FA 30	0.35	1.3	293	126	144	771	1138	2.93
4	0.35 FA 40	0.35	1.3	248	166	143	771	1138	2.07
5	0.45 OPC	0.45	1.3	377	0	168	771	1138	1.88
6	0.55 OPC	0.55	1.3	333	0	183	771	1138	0
7	0.55 FA 10	0.55	1.3	297	33	182	771	1138	0
8	0.55 FA 30	0.55	1.3	227	97	179	771	1138	0
9	0.55 FA 40	0.55	1.3	193	129	177	771	1138	0
10	0.65 OPC	0.65	1.3	299	0	194	771	1138	0
11	0.35 OPC	0.35	1.4	467	0	159	746	1101	4.67
12	0.35 FA 10	0.35	1.4	416	46	159	746	1101	2.31
13	0.35 FA 30	0.35	1.4	316	136	155	746	1101	3.16
14	0.35 FA 40	0.35	1.4	268	179	154	746	1101	2.24
15	0.45 OPC	0.45	1.4	407	0	181	746	1101	2.03
16	0.55 OPC	0.55	1.4	360	0	198	746	1101	0
17	0.55 FA 10	0.55	1.4	321	36	196	746	1101	0
18	0.55 FA 30	0.55	1.4	245	105	193	746	1101	0
19	0.55 FA 40	0.55	1.4	208	139	191	746	1101	0
20	0.65 OPC	0.65	1.4	322	0	210	746	1101	0

Remark: w/b is the water to binder ratio, Y is volume ratio of paste content to void content between aggregate in concrete, OPC is ordinary Portland cement, FA is fly ash, and SP is superplasticizer.

## Test Procedure

### Electrical Resistivity of Concrete

At 1 day after casting, specimen was demolded and cured in water. The four Wenner probe test, requiring wetting or saturating of the concrete before measurements, were undertaken in the laboratory. In addition, the tips or probes of the electrode were also moistened in water to improve the electrical connection. The size of the probe is 3.81 cm. Electrical resistivity was measured every four days from the age of 1 day to 28 days. After 28 days, measurements were taken every week until 91 days. After 91 days, specimens were kept in a room of which temperature and relative humidity is at  $28\pm 1^{\circ}\text{C}$  and  $70\pm 5\%$ , respectively. Three concrete specimens were removed from the water and extra surface moisture were wiped off. When measuring all the points, the probes were made in contact with the concrete and waited for three to five seconds until stable readings were obtained. Average resistivity for the set of sample was then derived from the three specimens.

#### *Cubic Specimen Measurement on Electrical Resistivity of Concrete*

For each cubic specimen, resistivity measurement was performed on two opposite surfaces, while on each surface, two diagonal measurements perpendicular to each other were conducted. To get a good indication of concrete resistivity, five measurements were taken for their average. The measurement using the Wenner probe is shown in Figure 2 and 3.

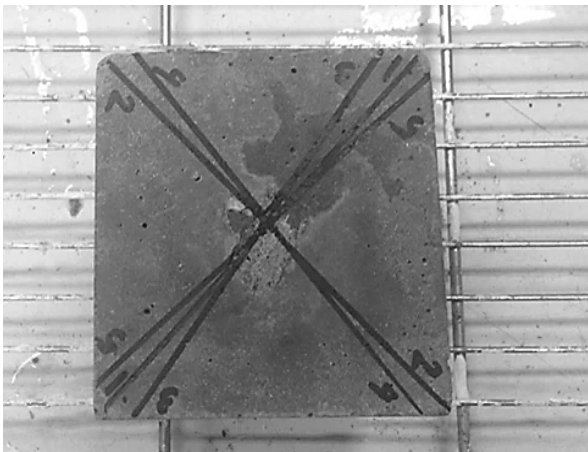


Figure 2. Cubic test specimen



Figure 3. Measurement technique for electrical resistivity of a cubic specimen using four Wenner probe

#### *Cylindrical Specimen Measurement on Electrical Resistivity of Concrete*

The test procedure was in accordance with AASHTO TP-95. Immediately after demolding, four permanent lines were drawn on the circumference face of the specimen marking 0, 90, 180, and 270 degree of the circular cross section. Then Wenner array probe was placed longitudinally on the specimen at the 0 degree line. The probe must be centered along the length of the concrete specimen [9]. Repetitions of the measurement were obtained at 90, 180 and 270 degree lines as shown in Figure 4 and 5.



Figure. 4 Cylindrical test specimen



Figure. 5 Measurement technique for electrical resistivity of a cylindrical specimen using four Wenner probe

### **Compressive Strength Test of Concrete**

The test procedure was in accordance with ASTM C39. Cubic specimens of (100 x 100 x 100) mm concrete specimens were cast and demolded at 24 hours after casting. Specimens were cured in water and air conditions. The compressive strength tests were conducted at 7, 14, 28, 56, and 91 days.

### **Rapid Chloride Penetration Test of Concrete**

For rapid chloride penetration of water- saturated concrete, 100 x 200 mm cylindrical specimens were tested after 91 days of curing in accordance with ASTM C1202. Three 50-mm disc samples were cut from a specimen and were placed in a vacuum for 3 hours. And, it was immersed in water and vacuum saturated for 1 hour and allowed to soak the water for 18 hours. Then each specimen was placed between two cells of 0.3N NaOH and 3% NaCl. The system was tested by applying potential difference of 60 V for 6 hours of direct current. After that sample was removed from the cells, the current passed through the sample was calculated.

## **Results and Discussion**

### **Effect of mix proportion on electrical resistivity of concrete**

#### *Effect of w/b Ratio*

As shown in Figure6, electrical resistivity increased with age of the concrete because of the densification due to cement hydration. According to the results, lower water to binder ratio concrete shows higher resistivity than those with higher water to binder ratios. This is because amount of interconnected pores decreases as the water/binder ratio decreases [10]. In long term, electrical resistivity still shows increasing trend even at the age of 270 days.

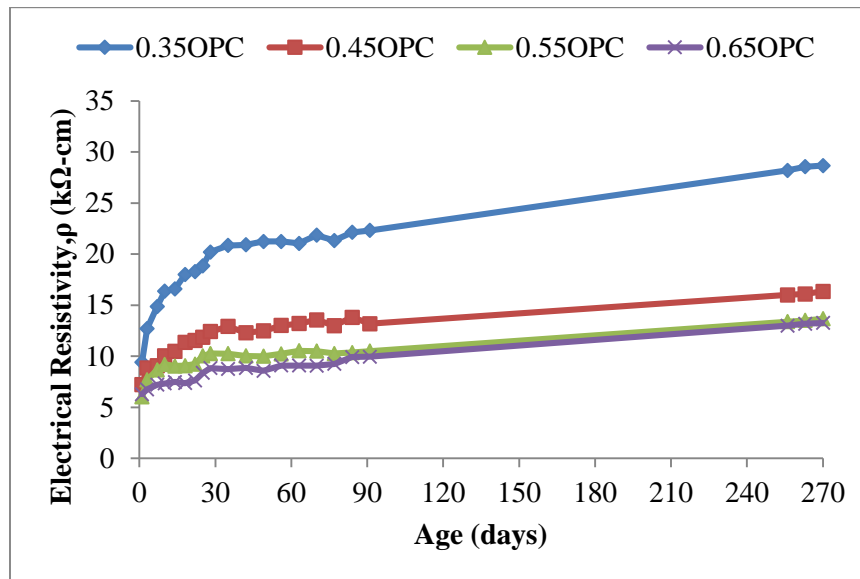


Figure 6. Effect of w/b ratio on electrical resistivity of concrete

#### *Effect of fly ash content*

Fly ash content has substantial influence on the concrete resistivity. Effect of fly ash on electrical resistivity is mainly related to the changes in the microstructure of concrete. The use of fly ash can reduce pore structure of concrete through its physical, and chemical effects both during the freshly mixed and subsequent hydrating states. The effects of changes in pore solution chemistry and refinement of pore structure on corrosion rate of 30% fly ash were also discussed [11]. Figure 7 and 8 illustrate the different fly ash replacement ratio with w/b ratio 0.35 and 0.55, respectively. As shown in Figures, after 14 days electrical resistivity sharply increased, especially in case of concrete with 30% and 40% fly ash replacements. The rate of electrical resistivity increase with time is higher for fly ash concrete. Concrete with 10% fly ash replacement is not significantly different in term of resistivity from OPC. When 30% of fly ash is replaced, the concentration of hydroxyl ions is reduced, and pore distribution is finer than OPC concrete and electrical resistivity rate was obviously increased. And when cement is replaced at 40% by fly ash, electrical resistivity increased four times when compared to Ordinary Portland cement concrete. Fly ash causes finer pores and lower ionic concentration in the pores, that leads to higher electrical resistivity than OPC concrete [12]. In long term, resistivities of fly ash concrete show trends of more significant increase when compared to the OPC concrete. This is because of the pozzolanic reactivity of fly ash which is still active in long term. Therefore, corrosion current flow, in fly ash concrete is expected to be retarded.

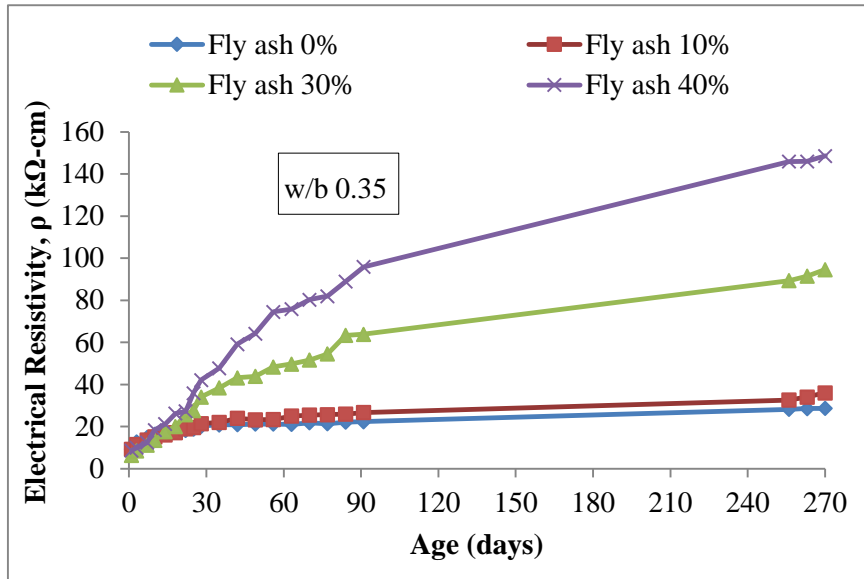


Figure 7. Effect of fly ash content with w/b 0.35 on the electrical resistivity of concrete

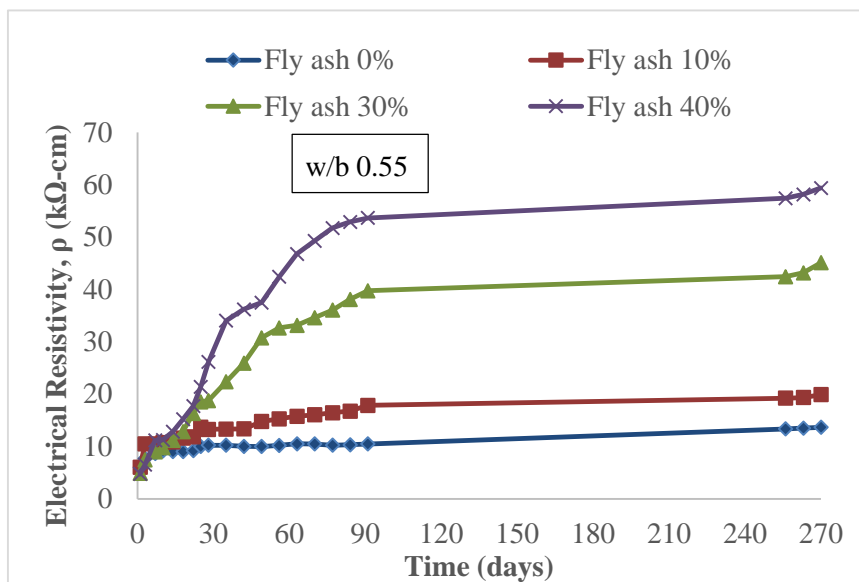


Figure. 8 Effect of fly ash content with w/b 0.55 on the electrical resistivity of concrete

*Effect of ratio of paste volume to volume between aggregate (Y)*

Low (Y) concrete has higher resistivity than high (Y) concrete because the larger amount of aggregate in lower content increases the electrical resistivity as shown in Figure 9. The aggregate electrical resistivity is higher than cement paste as shown in Table 4 [13]. At 91 days, the electrical resistivity of low paste content concrete was 15% higher than that of the high paste content concrete. Table 4 shows measured electrical resistivity of concrete materials.



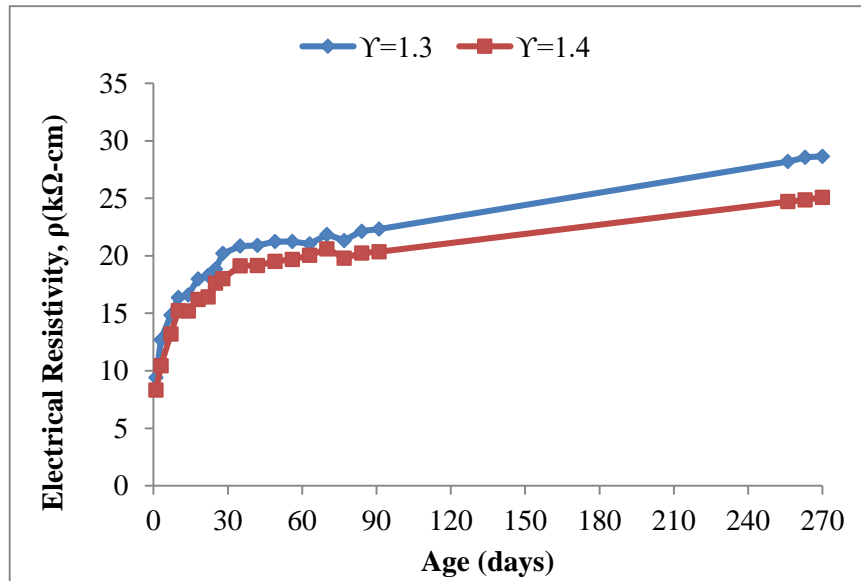


Figure 9. Effect of ratio of cement paste content of concrete to void between aggregate content on the electrical resistivity of concrete

**Table. 4 Electrical Resistivity of different materials**

Materials	Electrical Resistivity (kΩ-cm)
Cement	$1 \times 10^3 - 4 \times 10^3$ [14]
Cement paste	1 - 1.3 [15]
Limestone aggregate	$5 \times 10^3 - 10^8$ [16]
Sand	$5 \times 10^2 - 10^4$ [16]

## Relationship Between Concrete Properties and Electrical Resistivity

### Relationship between Electrical Resistivity and Compressive Strength of Concrete

The curing condition also plays an important role in the electrical resistivity, since the mobility of ions in the pores solution is largely affected. The electrical resistivity of concrete increased with age as a result of decreasing of pore space and increasing of hydration products. The concrete electrical resistivity highly depends on moisture content. Increasing of moisture content will result in decreasing in electrical resistivity. High compressive strength of concrete is due to increase of cement hydration that supports the growth of (C-S-H) gels. For hydration to proceed, (C-S-H) gels must be saturated with water. Therefore, compressive strength of water curing is higher than air-cured. Concrete with higher w/b ratio has lower strength and electrical resistivity due to larger amount of saturated capillary pores in the paste. The larger quantity of capillary pores results in lower density and lower strength of the paste. For fly ash concrete, strength at early ages is generally lower than that of the

cement only concrete but higher in long term. Therefore, the relation with age in fly ash concrete is different from that of the OPC concrete. Despite, there is a good correlation of electrical resistivity and compressive strength of concrete in water-cured as shown in Figure 10. Based on the results as shown in Figure 11, air cured specimen showed higher electrical resistivity than that of water-cured specimen, even strength was lower at the same testing age. This is because water curing resistivity will increase due to cement hydration and pores filling with hydration products, though electrical resistivity of air curing will increase by losing of moisture from the concrete. As shown in Figure 11, correlation between electrical resistivity and compressive strength is lower than that of water-cured. This may due to difficulties to measure electrical resistivity of dry specimen. Moisture need to provide before measuring the electrical resistivity.

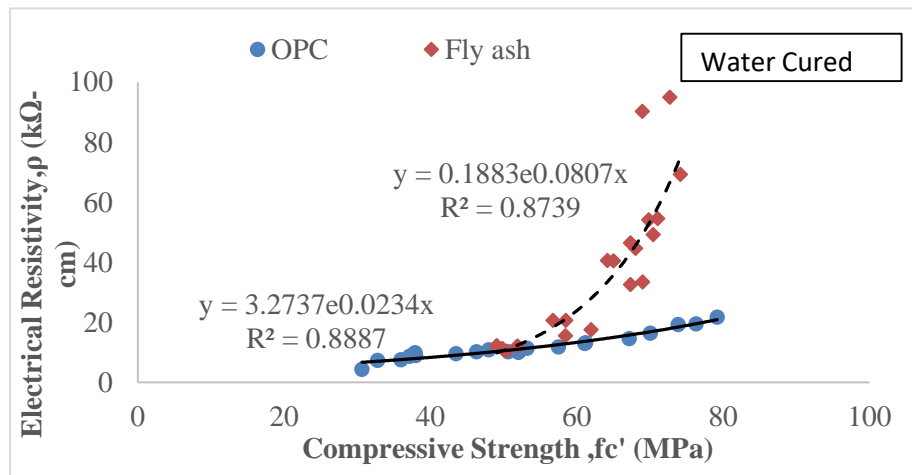


Figure 10. Relationship between compressive strength and electrical resistivity of concrete in water cured

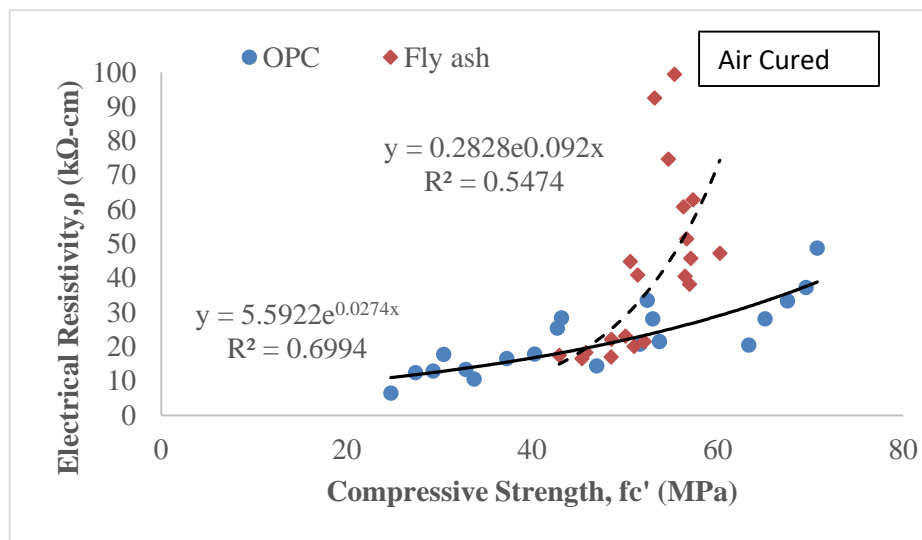


Figure 11. Relationship between Compressive Strength and Electrical Resistivity of Concrete in Air Cured

## Relationship Between Electrical Resistivity and Rapid Chloride Penetration (RCPT) of Concrete

Lower w/b ratio increases resistance to chloride penetration due to decrease in volume pores of concrete resulting in impermeable concrete and increased in electrical resistivity. Increasing w/b ratios lead to a decrease in electrical resistivity and amount of charge passed, indicating a more permeable concrete. As the percentage of fly ash replacement ratio is increased, the electrical resistivity also increased. This indicates that concrete became more impermeable, less porous, denser microstructure. A discontinuous pore system creates also reduced chloride ion permeability.. Lower cement paste content shows higher electrical resistivity and lower rapid chloride penetration because of increasing aggregate content. The relationship between electrical resistivity and rapid chloride penetration obtained from all concrete mixes in this study compared to Rupnow and Icenogle [17] is shown in Figure 12. The correlation between the two test results is  $R^2$  of 0.9851.

When electrical resistivity increased, charge passed significantly reduced. Charge passed is mainly controlled by pore structure, similar to electrical resistivity. Both of w/b ratio reduction and fly ash replacement can be considered a refinement of pore structure. Electrical resistivity test is easy to use, fast and repeatable to test, and a strong correlation with rapid chloride permeability can be obtained. Table.5 shows the relationship between electrical resistivity and rapid chloride penetration of concrete obtained by Rupnow and Icenogle and this study. Results showed that other results underestimate RCPT of concrete in Thailand. Therefore, the effect of local materials properties should be considered.

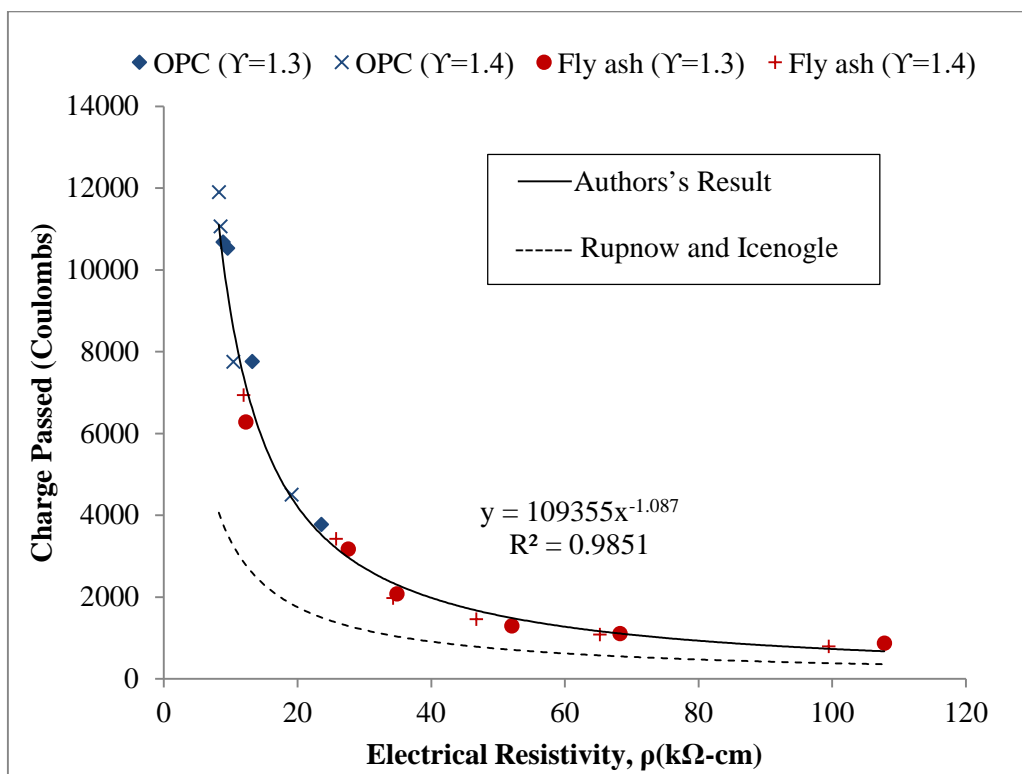


Figure 12. Relationship between rapid chloride penetration and electrical resistivity of all concrete mixes

**Table 5. Relationship between Electrical Resistivity and Rapid Chloride Penetration of Concrete**

ASTM C1202/ AASHTO T277	AASHTO TP95	Rupnow and Icenogle	Author's Result
	<b>RCP Test Charge Passed (coulombs)</b>	<b>Electrical Resistivity Test (kΩ-cm)</b>	<b>Electrical Resistivity Test (kΩ-cm)</b>
High	>4,000	<12	-
Moderate	2,000- 4,000	12-21	10-25
Low	1,000- 2,000	21 -37	25-40
Very Low	100- 1,000	37-254	40-80
Negligible	<100	>254	-

## Conclusions

Based on experimental results, good relationship was obtained between results of compressive strength and rapid chloride penetration with electrical resistivity of concrete. The results of this study can be applied further to predict electrical resistivity of concrete when mix proportions are provided. According to results, lower water/binder ratio had higher resistivity than those with higher water/binder ratio. When cement was replaced by fly ash higher than 30%, electrical resistivity was increased significantly. Moreover, lower paste volume increased electrical resistivity due to higher aggregate content.

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