Factors Affecting the Relationship Between Total Porosity and Electrical Resistivity for Concrete Repair Materials

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Abstract

The paper examines the properties of five different types of repair and substrate materials, including conventional mortar, fly ash mortar, silica fume mortar, conventional concrete substrate, and high-performance concrete substrate materials. Assessment was carried out on the basis of some physical properties (total porosity, and electrical resistivity). These properties were measured at early age and later after 14 weeks of exposure conditions to 6 % (by weight) of sodium chloride solution to simulate typical marine environment.

The results show that the electrical resistivity and total porosity measurements appear to be related and the measurements obtained are affected by the pore structure of the materials. It is also expresses that if a material has grater proportion of coarse aggregates (e.g. the substrate concrete in this study) it will appear to have a lower porosity although the porosity of mortar surrounding the aggregates could be higher. This makes comparisons between materials containing different aggregates proportions and size difficult.

Keywords: Repair materials; Concrete; Total Porosity; Electrical Resistivity; Silica fume; Fly ash.

العوامل المؤثره على العلاقه بين المساميه الكليه والمقاومه الكهربائيه في مواد اصلاح الخرسانه.

الخلاصه:

تهتم هذه الدراسه باختبار صفات خمسة مواد مختلفه بعضها يستخدم كمونه في اصلاح الاضرار في المنشات الخرسانيه وبعضها يمثل الخرسانه المتضرره ذاتها. أشتملت المواد قيد الدراسه على مونه تقليديه, مونه باستعمال رماد وقود متطاير, مونة السليكا, خرسانه تقليديه, وخرسانه عاليه الاداء. أن الصفات الفيزيائيه التي تم اختبارها هي المساميه والمقاومه الكهربائيه. وقد تم حساب قيم هذه الصفات في عمر مبكر وكذلك بعد 14 اسبوع من التعرض الى السائل الملحي الذي يحتوي على 6% وزنا من كلوريد الصوديوم وذلك لمحاكاة الظروف البحريه.

بينت النتائج وجود علاقه واضحه بين المساميه والمقاومه الكهربائيه, وان هذه النتائج تتأثر بالهيكل المسامي للمواد. كما بينت النتائج ايضا ان المواد التي تحتوي على نسبة ركام خشن اكثر (حصى) كما هو الحال في الخرسانه تكون قيم المساميه فيها اقل على الرغم من ان المسافات البينيه المحيطه بحبيبات الركام الخشن تكون اكثر مساميه وهذا يجعل المقارنه بين المواد الخرسانيه التي تحتوي على تدرجات ونسب مختلفه من الركام الخشن صعبه.

1.0 Research Significance:

During the lifetime of any reinforced concrete structure it is likely to require maintenance and repair. The most usual scenario is to carry out repair to the structure as and when it is needed. Repairs are carried out with a number of factors that to be considered:

- Aesthetics - the look of the structure.
- To maintain the structural integrity.
- The durability of the structure. i.e. the prevention of further deterioration of the structure.

One of the main causes of deterioration of reinforced concrete structures is the corrosion of the reinforcement. Corrosion may be due to carbonation of the concrete or chloride diffusion into the structure, breaking down the passive film on the steel allowing corrosion to initiate [1,2]. Repair materials are used as a form of "corrosion prevention" on deteriorated areas of a structure. As a result repair materials are typically designed to keep the structure within the acceptable criteria from the durability view. In new structure, unlike old one, there is a wide range for solution to choose, while for existing structure which is suffer from deterioration due to corrosion it is not available to change neither the cover depth, since the steel location is fixed inside the concrete, nor the type of steel itself. So, solution is

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mostly limited to the selection of appropriate repairing materials. Other Problems can occur because the repair material provides a totally different chemical and physical environment to that of the existing concrete. A single reinforcement bar may have more than one repair along its length; therefore, the bar can be subjected to a complex chemical and physical environment [3].

Concrete and mortars consist of two principal components namely hydrated cement paste (hcp) and aggregate. However it is widely acknowledged that there exists a third morphologically district constituent at the hcp- aggregate boundary [4-7]. This region called the interfacial transition zone (ITZ). The size and connectivity of the pores in the hcp determine the availability of oxygen and moisture at the steel surface, both of which are necessary for the maintaining of a passive film. They also determine the resistivity of the concrete material, which has been recognized as a diagnostic technique for measuring the tendency of reinforcement in the concrete to corrode.

The present study aims to achieve a better understanding of the relationship between the porosity and the resistivity of the repair material and factors affected them. A number of different mortars and substrate concretes were examined, ranging from traditional to modern high-performance types. The mortars and concrete were exposed to of 6% (by weight) chloride ion solution along duration of 14 weeks of exposure.

2.0 Some Physical Properties of Substrate and Repair Materials.

2.1 Total Porosity.

Pores or voids in concrete consist of pores in the hardened cement paste, entrained or entrapped air voids and voids in the aggregate. These are created during mixing and initial hydration of the cement and are further refined by the setting and continued hydration of the cement paste with time. Other void spaces can be created as a result of effects such as bleeding, honeycombing and air pockets [8, 9].

Most of the important properties of hardened concrete can be related to the volume and size distribution characteristics of the various types of pores in it. The mechanical properties such as strength and elastic modulus are primarily affected by the total pore volume, not their size or continuity. The durability properties of concrete involve mass transport phenomenon of deleterious substances and are concerned with the permeability and ionic movement in the concrete. The volume, size and continuity of the pores have been found to influence these types of properties [10-12].

2.2 Electrical Resistivity.

Electrical resistivity measures the resistance of a material to the flow of an electric current. This is a measure of the ease of movement of ions through the cementitious material [13]. The movement of ions through the material is required in a corrosion reaction; therefore, electrical resistivity is an important parameter in assessing the viability of corrosion cells. Electrical resistivity as a technique is often used in conjunction with rest potentials to give an indication of the corrosion rate [14] of steel embedded in cementitious materials. A low electrical resistivity material indicates easy movement of ions and ,therefore, a possible high rate of corrosion. This depends on the environment within the concrete being suitable to support the corrosion reactions. Electrical resistivity is linked to the mass transport properties of the material such as porosity, permeability and diffusion. It is also likely that the electrical resistivity of the constituent materials used in the repair and substrate mixes will have an effect on the electrical resistivity of the material. The degree of saturation has a critical influence on electrical resistivity and is also governed by the mass transport properties.

3.0 Experimental Program.

The initial stage of the experimental program was the measurement of the corrosion related physical properties for the repair and substrate materials. The following properties were identified as important to

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corrosion processes: total porosity, and electrical resistivity. These properties are used to define the level of relationship between pore structure properties and electrical resistivity of the repair and substrate materials, which is influence the reinforcement corrosion. Test specimens considered both a repair material and a substrate concrete.

3.1 Specimen Design.

It was suggested to use the specimen of a cylindrical shape as shown in Figure 1 to be the repair and substrate structural element of this study. Each specimen was a cylindrical of 300 mm high, and 150 mm in diameter. All specimens had been exposed to 6% by weight, sodium chloride wetting solution.

Mortar mixes were used for all specimens with mix proportions of 1:2 (cement: sand by weight) with a flow of 120 – 130 mm. To improve the quality of the mortar mixes two types of admixture are used. A 1.5 % by weight of cement of a water reducing agent was used for some mixes. Also a 10% by wt. of mineral admixture as a partial replacement of cement was used to improve the durability of repairing material (mortar). Table 1 shows the details of the experimental program.

The cylinders were filled in three layers; each layer was compacted on a vibrating table. The moulded cylinders were covered with polythene and cured overnight in a mist curing room. The specimens were demoulded 24 hours after casting and then cured in a water tank for 28 days at 20^{o}C. Two cylinders were cast for each test material.

4.0 Evaluation Method:

4.1 Total Porosity.

After 28 days curing, one of the two cylinders of each test material was sectioned across the 150mm diameter cross-section using a masonry saw. Two discs 25mm thick and 150 mm diameter were cut from the top and bottom of each cylinder and discarded. The remaining 250 mm length of the cylinder was cut into five discs of 150mm diameter X 50mm (+/-5mm) thick (see Figure 2). Three of these disc specimens were used to measure the porosity. Following cutting and prior to testing all disc specimens were stored in a water tank at 20^{o}C for approximately 3 to 7 days. The second cylinder of each material was cured in a water tank at 20^{o}C for 14 weeks, following which it was also cut into discs as described above.

Total porosity was determined by measuring the evaporable water from the disc specimens. The experimental technique of BS3921 (1985) was used for the determination of total porosity. The disc specimens were dried at 105°C until a constant mass was achieved and were then cooled down to 20°C in a dessicator and weighed to give the dry mass (m_D). The samples were then vacuum saturated according to BS3921. The mass of the water-saturated sample (m_S) was taken, followed by the buoyed mass of the sample suspended in water (m_B). The buoyed and water saturated mass measurements were taken in water at a constant temperature of 20°C (+/- 2°C). This minimized errors in the calculations from changes in water density with temperature. A value of 998.21 kg/m^3 was taken as the density of water (ρ_W) for the calculations. Standard methods allow the calculation of total porosity, bulk density, percentage water absorbed and apparent solid mass from the experimental data as shown in the next section. Each calculation represents the average of the three disc specimens tested for each material at each age.

4.1.1 Calculations

Total Volume

Total volume of solids and voids, V_T, is equal to the buoyed mass of the test specimen suspended in water, m_B, after correction for the true density of water.

$$V_T = \frac{m_B}{\rho_W} \quad [cm^3]\ldots\ldots\ldots\ldots(1)$$

Volume of Voids

Total volume of voids in the specimen, V_V, is calculated by subtracting the dry mass of the sample, m_D, (solids plus voids filled with air) from the saturated mass, m_S, (solids plus voids filled with water).

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$m_V = m_S - m_D$ [kg]

Where m_V mass of water in the saturated voids.

$$V_V = \frac{m_V}{\rho_W} \quad ....(2)$$

$$V_V = \frac{m_S - m_D}{\rho_W} \quad [cm^3]$$

Volume of solids:

Volume of solids in the specimen, V_S, is calculated by subtracting the volume of voids, V_V, from the total volume, V_T.

$V_S = V_T - V_V$ [cm^3]……..…(3)

Bulk Density:

Bulk density, ρ_{Bulk} , is the mass of the whole material per unit volume, reflecting the density of the mineralogical content of the material and the amount of pore spaces. It is usually specified as mass per unit volume e.g. g/cm^3 or kg/m^3.

$$\rho_{Bulk} = \frac{m_D}{V_T}$$

Substituting for V_T from equation 1 gives:

$$\rho_{Bulk} = \frac{m_D}{m_B / \rho_W} \quad [g/cm^3] .....(4)$$

Apparent Solid Density

Apparent solid density, $\rho_{Apparent\ Solid}$, is the density of the solids in a material, which is due purely to the mineralogical components of the material. It is usually specified as mass per unit volume e.g. g/cm^3 or kg/m^3. However, using the vacuum saturation method, the measurement of the volume of the sealed pores is impossible. Picnometry is the only method which can calculate the true solid density of the material. Therefore, the solid density determined in this investigation is not the true solid density of the material but the apparent solid density.

$$\rho_{Apparent\ Solid} = \frac{m_D}{V_S}$$

Substituting for V_S from equation 3 gives:

$$\rho_{Apparent\ Solid} = \frac{m_D}{V_T - V_V} \quad [g/cm^3] ..(5)$$

Total Porosity

Total porosity, p [%], is the amount of voids expressed as a percentage of the total volume V_T and is given by the expression.

$$p\ [\%] = \frac{V_V}{V_T}.100 \quad .... (6)$$

Water Absorption

Water absorption (w_A) is the amount of water taken in by the material under normal temperature and pressure. Water absorption of each specimen was calculated as the increase in mass resulting from submersion, expressed as a percentage of the mass of the dry specimen.

$$w_A = \frac{(m_S - m_D)}{m_D} * 100 \quad [\%].....(7)$$

4.2 Electrical Resistivity.

After 28 days curing one cylinder for each test material was sectioned using a masonry saw into discs as described above.

A hand held electrical resistivity meter was used to measure the electrical resistivity of each test material. The meter had 2 probes with a spacing of 5 cm between them. Two holes of 5mm depth and 5cm apart were drilled into the cut face of each cylindrical disc specimen. This allowed the electrical resistivity to be taken across the diameter of each disc. This technique avoided any high resistance surface films that could have interfered with the results. The probe was then reversed in the holes and a second reading taken for each specimen. This allowed two readings for each specimen and two specimens for each material provided a

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total of four readings for each material. The electrical resistivity results were averaged over both specimens.

5.0 Results and Discussion

5.1 Total Porosity

Table 2 presents the values for bulk density, solid density, water absorption and total porosity of the test materials at early age, before chloride exposure and 14 weeks of chloride exposure. The results are consistent with fewer than 2% variation in calculated values for the three disc specimens of each material.

All the materials results showed a significant decrease in porosity between early and later age. The reason for this is the porosity of concrete and mortar depends on the water cement (w/c) ratio and degree of hydration (Figure 3). The w/c ratio will determine the original porosity and the degree of hydration how much the original pores are filled with new solid products. So the capillary pores of early age were fillet by new C-S-H gel with time. While the using of pozzolanic materials such as fly ash or silica fume hydrated later than ordinary Portland cement.

The technique was sensitive enough to detect differences in the mix proportions of the materials. The 0.38 w/c and 0.51 w/c substrates have different solid densities, reflecting the fact that they have different solid constituents, but similar bulk densities reflecting the different water content. Repair material (Mix 1-mortar) also has a similar bulk density to the substrate materials (Mix 4, and Mix 5). Repair materials (Mix 2 and Mix 3) are both containing mineral admixture as a cement replacement materials and this is reflected in different bulk and solid densities with both repair material (Mix 1) and substrate (mix 4 and Mix 5).

The 0.4 w/c substrate had the lowest porosity of 12.5%. The 0.5w/c substrate and repair materials mix 2 and mix 3 all had porosities in the range 13-16%. Repair material mix 1 had the highest porosity 24.19%. The higher porosities of the repair materials result from the different constituent materials used. The repair materials contain finer aggregates, so they have higher porosities than concrete mixes due to the absence of the low porosity coarse aggregate. The results are in accordance with previously published results [8,9,15,16]

5.2 Electrical Resistivity.

The electrical resistivity measurements are given in table 3; the total porosity values for each material have also been included for comparison. All the electrical resistivity measurements are below 5 kΩ.cm, this would indicate the potential for a high corrosion rate of steel embedded in these materials [14].

These measurements were much lower than expected from available literature on the materials [14]. The measurements were made on the cut surface of the specimen, this removed the influence of the fine, high resistance cast surface layer from the measurements. In addition, all the specimens were saturated with water, to ensure that all the measurements were conducted under the same conditions. As a consequence of this, the materials would be expected to have a lower electrical resistivity. A comparison of the electrical resistivity measurements with the total porosity measurements showed a close correlation between the electrical resistivity and the percentage porosity of the material (see table 3, Figure 4). This suggests that the water contained in the pores of the specimens was the main controlling factor of the material electrical resistivity.

It would be expected that the chloride contamination would have lowered the electrical resistivity of repair and substrate materials. However the trend between total porosity and electrical resistivity did not appear to be effected by the chloride exposure conditions (see Figure 4). This suggests that the degree of water saturation was the controlling factor for the values of electrical resistivity measured.

6.0 Conclusions

1- The repair and substrate materials selected for the investigation provided a wide range of total porosity values. The

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experimental technique proved to be sensitive enough to detect these differences. The 0.38 w/c concrete had the lowest porosity of 12.30%. The 0.51w/c substrate and repair materials mix 2 and mix 3 all had porosities in the range 13-16%. Repair material mix 1 had the highest porosity 24.19%. A likely cause for the higher porosity of the repair materials was their lack of coarse aggregate.

2- The electrical resistivity values were lower than expected at below 5 kΩ.cm. This was considered to be due to the water saturation of the specimens and the use of the cut face to take the readings, avoiding the high resistance cast surface layer. There was a close correlation between electrical resistivity and total porosity, indicating that the water content in the pores controlled the electrical resistivity reading (see Figure 4).

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5.2 Electrical Resistivity

Table 1: Details of Experimental Program.

Specimen designation	Mix proportion	Water cement ratio	Flow[mm] (or slump for concrete)	Type of admixture			Type and age of test	
				Water reducing agent % by wt. of cement	FA % by wt. of cement	SF % by wt. of cement	Total Porosity	Electrical Resistivity
Control	1: 2 (cement: sand) and Flow 100-110 mm	0.42	125	-	-	-	Early age before ponding, and at 14 weeks of ponding	Early age
Mortar - F.A		0.33	120	1.5	10	-		
Mortar - S.F		0.34	130	1.5	-	10		
Concrete 0.51	1: 2 :4 (cement: sand: gravel)	0.51	150	-	-	-		
Concrete 0.38		0.38	40	-	-	-		

Table 2: Total Porosity results for substrate concrete mix and repair materials.

Material	Compressive Strength (MPa) 28 Days	28 Days				14 Weeks			
		Bulk Density kg/m^3	*Solid Density kg/m^3*	*Water Absorption [%]*	*Total Porosity [%]*	*Bulk Density kg/m^3*	*Solid Density kg/m^3*	*Water Absorption [%]*	*Total Porosity [%]*
Mix 1 Mortar	44.3	2031.4	2679.6	11.88	24.19	2112.65	2512.67	7.522	15.92
Mix 2 Mortar F.A	88.7	2114.23	2484.405	7.03	14.899	2198.79	2419.7	4.144	9.13
Mix 3 Mortar S.F.	84.58	2122.06	2501.533	7.13	15.169	2206.94	2438.87	4.301	9.51
Mix 4 Concrete 0.51	51.96	1997.562	2322.012	6.98	13.97	2077.46	2248.65	3.658	7.613
Mix 5 Concrete 0.38	54.46	1991.878	2271.496	6.16	12.30	2091.55	2255.429	3.467	7.266

Table 3: Electrical Resistivity Measurements.

Material	**Electrical Resistivity (kΩ cm)**					**Total Porosity (%)**
	1	2	3	4	*Average*	

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Mortar-Control	0.8	0.8	0.8	0.8	0.8	24.19
Mortar -F.A	3.6	3.6	3.75	3.75	3.675	14.899
Mortar -S.F	3.3	3.3	3.5	3.5	3.4	15.169
Concrete 0.51	3.5	3.56	3.7	3.69	3.61	13.97
Concrete 0.38	4.0	4.0	4.2	4.2	4.1	12.30

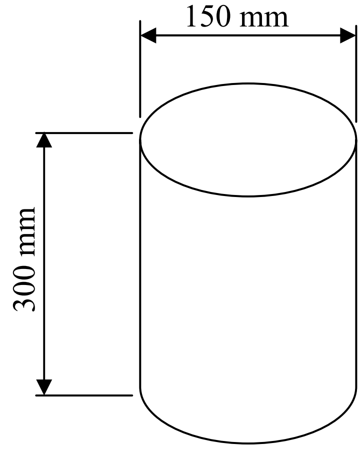

Figure 1: Typical specimen.

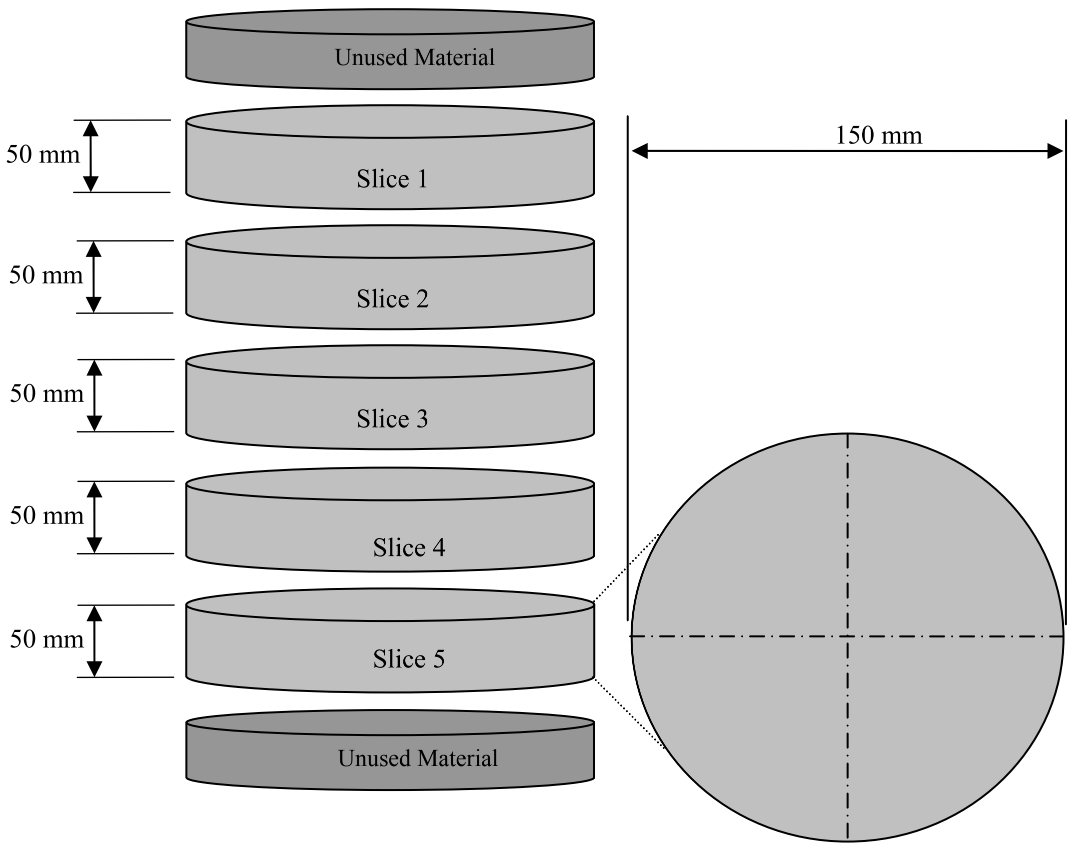

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Figure 2: Schematic diagram of the specimen used for total porosity and electrical resistivity analysis.

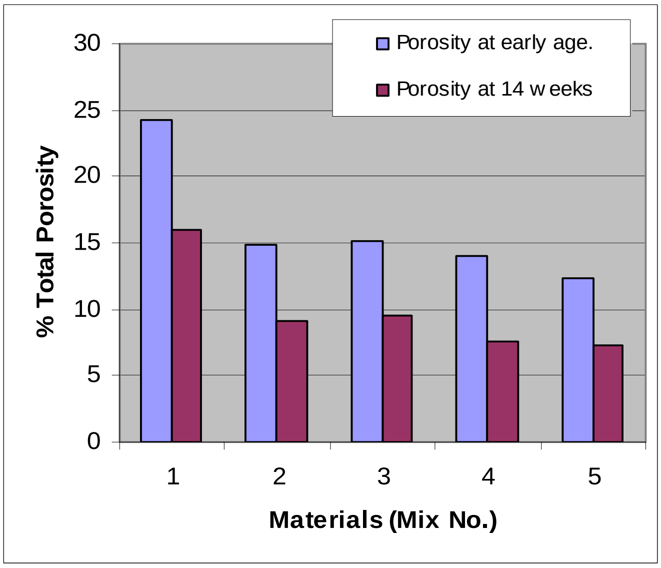

Figure 3: Change in Porosity between early age and 14 weeks.

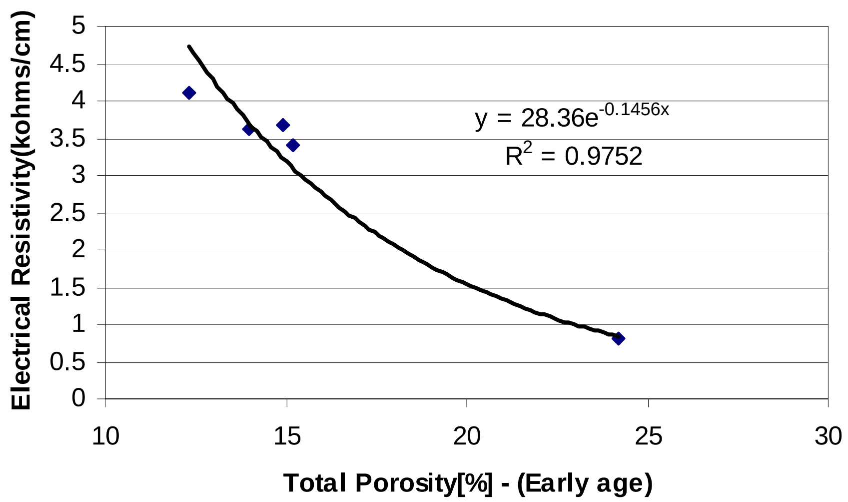

Figure 4: Relationship between total porosity and electrical resistivity measurements.

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