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Early Age Strength and Electrical Resistivity of Concrete as Durability Indicator through Maturity

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Abstract: *Fluid transport properties of concrete can be explained by measuring electrical resistivity in fresh state to hardened state. Electrical resistivity when compared with strength properties shows the quality of concrete. Bulk electrical resistivity measurements are compared with calculated maturity of concrete which is related to time and temperature of curing at early age. It is observed that electrical resistivity and strength are closely related with each other. This work addresses the effect of curing time, type of binder and effect of aggregate on strength and maturity of concrete using electrical resistivity measurements of saturated surface dry samples. Empirical results obtained are used as tools to derive maturity and strength both in non destructive manner. Resistivity is justified with ionic conductivity in pore structure.*

Keywords: *bulk electrical resistivity, maturity, compressive strength, ionic conductivity*

1. Introduction

1.1. Maturity of concrete

Publication in the American society of testing and materials (ASTM) and other literatures suggest strong relation between, maturity and strength of concrete. This is widely used to determine the early-age strength gain in concrete pavement [1-4]. The use of maturity method in paving projects help contractors to predict proper curing time and evade additional time required for concrete to gain sufficient strength. This helps to wait for any confirmation from the competent authority and saves time in further construction and finishing activities by the contractor.

Strength of concrete is dependent upon period of curing and temperature of the curing duration. The term 'maturity of concrete' can be seen as product of time and temperature. The temperature is reckoned from -10 °C, which is datum temperature. This is because at the temperature below this, concrete does not appear to gain strength with time. Moderate temperature 18 °C, is considered as base line to standardize the maturity value as [(18- -10) °C x (28 days x 24 hours) =] 19800 °Ch for full strength of concrete after 28 days of curing.

1.2. Nurse-Saul Method

Nurse-Saul method is the most commonly used method for computing maturity. The widespread use of this method is attributed to its ease of calculation. According to ASTM C1074 the equation for the maturity index or time-temperature factor is as follows:

$$M_t = \Sigma (T_a - T_0) \Delta t \qquad \text{(Eq.1)}$$

Where:

M_t = the maturity index, or time-temperature factor at age t, degree-days or degree hours, also known as the Time-Temperature Factor,

Δt = a time interval, days or hours,

T_a = average concrete temperature during time interval, Δt, °C, and

T_0 = datum temperature, °C.

One limitation to this equation is that the time-temperature factor is a linear approach to the maturity method. This is acceptable as long as the curing temperature does not vary widely during the period of concrete strength gain. The Nurse-Saul method is dependent upon the selection of an appropriate datum temperature.

The datum temperature is that corresponding to the start of significant strength gain within the concrete. Once the temperature of the mixture exceeds this datum temperature the strength gains that follow are considered significant and can be modeled using Nurse-Saul method.

Strength at any maturity as a percentage of strength at maturity of

$$19{,}8000\text{Ch} = A + B \log_{10}(\text{maturity})/10^3 \qquad \text{(Eq.2)}$$

Where, A and B are Plowman's coefficient given in the table 1, selected for the maturity equation 1, as shown above.

Rapid chloride permeability test which is based upon the measuring charge passed through a saturated sample over a period of time proved very tedious and time consuming , giving variable results and destructive in nature. [6-10] Various literature focusing on methodology, sample geometry, temperature and conditioning and shows electrical resistivity measurements proved cheaper, repeatable

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and rapid process. [11-13] It was observed that unlike the compressive strength-maturity relationship, samples cured at different temperatures develop resistivity at different rates with regard to maturity and shows a unique bulk resistivity-maturity relationship for a given concrete mixture [14].

Table1: *Plowman's coefficients for maturity equation [5]*

Strength after 28 days at 18°C Coefficient (Maturity of 19,800°Ch): MPa	Coefficient	
	A	B
Less than 17.5	10	68
17-35	21	61
35-52	32	54
52-69	42	46.5

1.3. Scope of research

The experimental work in this research aims to develop a correlation between concrete maturities and bulk electrical resistivity. Concrete maturity is a function of time and temperature (ASTM C1074, 2004). Therefore, concrete mixtures of varying cement (binder) and fine aggregate combination were cured in same environments like same relative humidity and temperature.

The aim of this work is to develop the standardization of a bulk electrical resistivity test that may be used with concrete maturity in performance specifications. The empirical relations can be best utilized as tool for conformity of strength and durability even after variation of mix proportions with replacement of ingredients. It is also an approach to verify the results obtained in the authors previous work on mechanical properties and shrinkage properties of the same mix [15, 16]

2. Experimental work

2.1. Raw Materials

2.1.1. Cement

In this experimental work, locally available cement of three varieties OPC, PPC and PSC were used. Tests were conducted as per respective IS codes and results are mentioned in table 2.

Table 2. *Physical and chemical characteristics of cements used as binder*

Chemical Characteristics	OPC	PPC	PSC
Loss on ignition(% by mass)	1.61	1.27	0.99
Insoluble Residue (% by mass)	2.42	26.3	1.98
Physical Characteristics			
Specific Gravity	3.15	2.5	2.7
Fineness Blaine(m²/kg)	296	345	335
Normal Consistency (%)	30.5	35.5	30
Initial Setting Time(minutes)	168	188	162
Final Setting Time(minutes)	235	244	230
Soundness			
1) Le- Chat Expansion(mm)	1	1	1
2) Auto clave Expansion (%)	0.15	0.05	0.06
Compressive Strength			
i) 3 days	28.5	20	22.5
ii) 7 days	38.6	35	34.4
iii) 28 days	49.2	50	52.5

2.1.2. Aggregates

Sand is obtained from Pairi river source (Gariyaband) GBFS were taken from, Granulation unit of Bhilai steel plant and pond ash was taken from NSPCL, Sirsa Bhilai 3 area. Coarse aggregate used were obtained from local crushers of Raipur region. Natural river sand, Pond Ash and Granulated blast furnace slag were used as fine aggregate and fine aggregate replacement with river sand as 50% replacement, respectively. The available coarse aggregate were used directly as required in the mix design. All the aggregates were tested as per the provisions of IS: 383 -1970, [17] and IS: 2386 (Part I-VII)-1963, [18].and satisfying its requirement as shown in table 3 and 4 respectively.

Table 3: *Sieve Analysis for Fine Aggregate*

Material	Sieve Size						Fineness Modulus
	4.75 mm	2.36 mm	1.18 mm	600 µ	300 µ	150 µ	
Sand	98.7	92.8	75.6	41.4	7.1	0.6	2.84
Pond Ash	93	87	79	58	13.1	2.1	2.7
GBFS	99.8	98.3	83.9	30.4	4.5	1.1	2.82

Table 4: *Sieve Analysis for Coarse Aggregate*

Sieve Size (% by wt passing)						Fineness Modulus
80 mm	40 mm	20 mm	10 mm	4.75 mm	2.36 mm	
100	100	100	78.8	3.40	0.00	7.17

2.2. Mix Proportion

The mix were prepared as per IS: 10262-2009,[19] as summarized in Table 5. Mix 1, was taken as control mix with OPC cement and natural river sand and compared with Mix 4, Mix 7 prepared changing the cement as PPC and PSC cements.

Table 5. *Mix Proportions (With 50% slag and pond ash replacements)*

Mix	Type of Cement	Cement (IN KG)	Water	Sand (IN KG)	GBFS (IN KG)	Pond Ash (IN KG)	Coarse Aggregate (IN KG)	W/C Ratio
M 1	OPC	379	208	757			1026	0.55
M 2	OPC	370	208	352	352		1026	0.55
M 3	OPC	425	233	287		287	1035	0.55

M 4	PPC	417	229	680			923	0.55
M 5	PPC	417	229	316	316		923	0.55
M 6	PPC	467	257	278		278	850	0.55
M 7	PSC	379	208	668			1068	0.55
M 8	PSC	379	208	312	312		1068	0.55
M 9	PSC	424	233	277		277	1000	0.55

2.3. Specimen Preparation

The materials in various proportions by weight are mixed with suitable water quantity in shaft type mixing unit in standard manner. Three cubes of nine mixes as per table 3, of size 100 mm x 100 mm x 100 mm, were casted, and cured for the compressive strength to observe strength at 1, 3, 7, 14, 21, 28 days as per IS 516-1959,[20] and accelerated curing test as per IS 9013-1978. [21]Temperature of the test environment was maintained by thermostat based water curing tank connected with heater. The test temperature was maintained 27+/- 2 °C, except for ACC (accelerated curing test (equivalent to Method B of ASTM C 684-89.) which was conducted on boiling water bath for temperature of 100+ °C maintained for 3 and ½ hrs.

Electrical resistivity test was conducted on saturated surface dry cube of size 100 mm x 100 mm x 100 mm, just before compressive strength test at 5 KHz frequency calibrated setup of the RCON by Giatec Inc. [22]Maturity is calculated as per (ASTM C1074, 2004) shown in Eq. 2 for temperature. Average of percentage maturity up to 28 days for each sample is mentioned in table 6.

Table 6. *Calculated maturity in % age and log scale*

No of Days	Average Maturity Value in %	Maturity (log scale)°Ch
1	14.82	792
3	43.94	2376
7	66.38	5544
14	84.74	11088
21	95.42	16632
28	100	22176

3. Discussion

Relation between maturity and compressive strength Maturity value as calculated by equation 2 is tabulated in table 6. This is equated as maturity indicator to each mixes of same duration for compressive strength value obtained as average of the three specimens. The log-linear fit presented in figure 1(a, b, c) and table 7 shows good correlation with acceptable value of R-square (ranging between, 0.9 to 1). This is indicating that even after changing the ingredient, target strength and maturity level is similar as standard mix i.e. M 1.

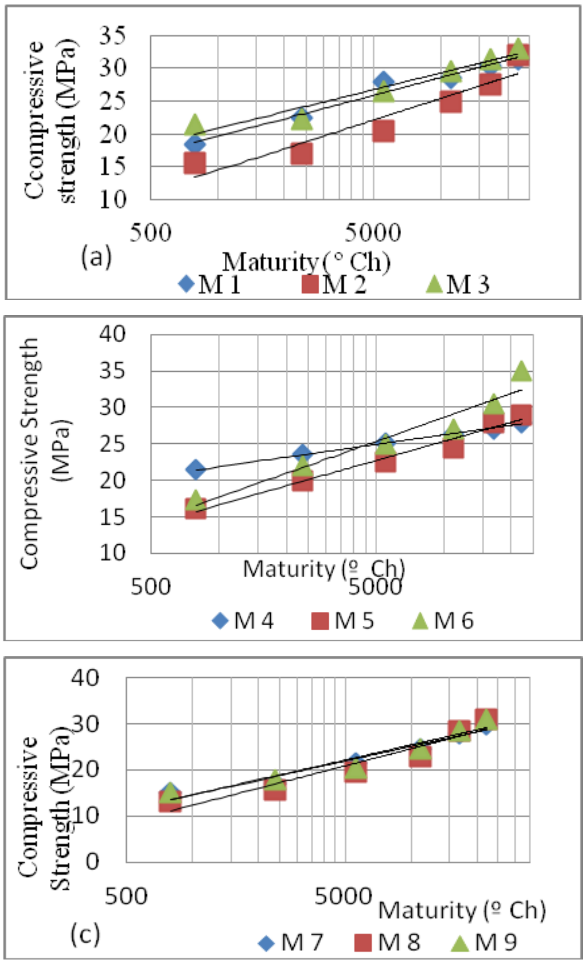


Figure 1. *Log-linear relation between maturity and compressive strength for (a) OPC cement, (b) PPC cement, (c) PSC cement and variable fine aggregate*

Table 7. *Correlation for various mixes and their compressive strength and maturity*

Mix	Trend line for logarithm fit	R Square
M 1	y = 3.869 ln (M) -7.222	0.97
M 2	y = 4.741 ln (M) -18.25	0.9
M 3	y = 3.65 ln (M) -4.322	0.94
M 4	y = 1.899 ln (M) -8.741	1
M 5	y =3.779 ln (M) -9.467	0.97
M 6	y = 4.757 ln (M) -15.19	0.93
M 7	y = 4.556 ln (M) -16.88	0.95
M 8	y = 5.33 ln (M) -24.52	0.92
M 9	y =4.712 ln (M) -17.99	0.93

3.1. Relation between compressive strength and bulk electrical resistivity

Relation between compressive strength and bulk resistivity can be seen from figure 2(a, b, c). The linear fit presented in figure 2 (a) and shows less R-square with more scattered value, but figure 2 (b and c) correlates the two properties with acceptable value of R-square (ranging between 0.9 to 1). Hence we can represent the maturity as indicator for proportionate bulk resistivity.

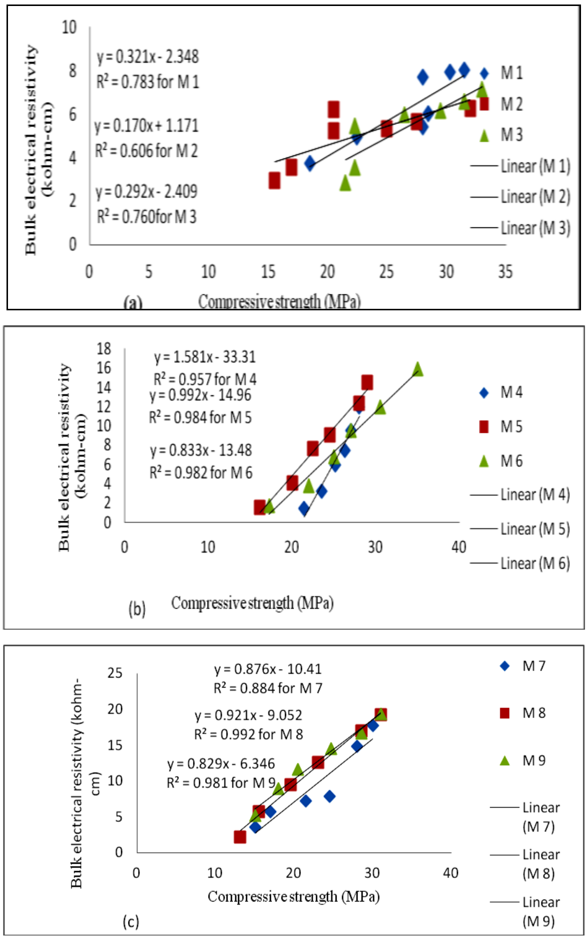
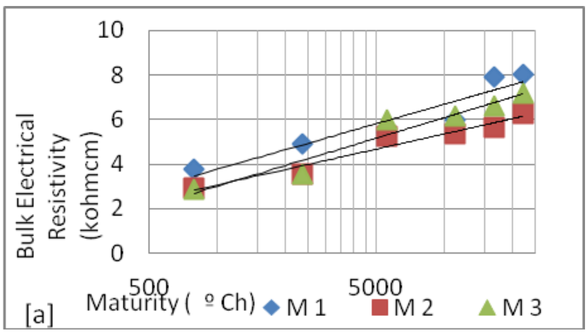


Figure 2. *Linear relation between maturity and bulk electrical resistivity for [a] OPC cement, [b] PPC cement, [c] PSC cement and variable fine aggregate*

3.2. Relation between maturity and bulk electrical resistivity

Maturity value as shown in table 6 is equated as maturity indicator for each mixes of same duration against their bulk electrical resistivity. The log-linear fit presented in figure 3(a, b, c) and table 8 shows good correlation with acceptable value of R-square (ranging between 0.9 to 1) except for the mixes M 6 to M 9 with more scattered results which can be neglected.



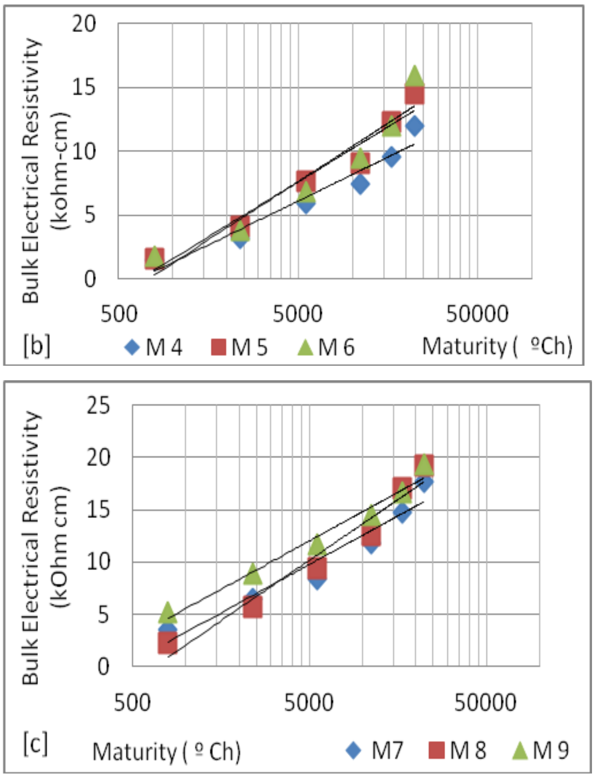


Figure 3. *Log linear relation between maturity and bulk electrical resistivity for [a] OPC cement, [b] PPC cement, [c] PSC cement and variable fine aggregate*

Table 8. *Correlation for various mixes and their bulk electrical resistivity and maturity*

Mix	Trend line for logarithm fit	R^2
M 1	y = 1.264 ln (M) - 4.967	0.9
M 2	y = 0.989 ln (M) - 3.764	0.94
M 3	y = 1335 ln (M) - 6.216	0.94
M 4	y = 2.999 ln (M) - 19.51	0.9
M 5	y =3.465 ln (M) - 22.75	0.9
M 6	y = 4.3 ln (M) - 28.87	0.78
M 7	y = 3.816 ln (M) - 23.68	0.77
M 8	y = 4.963 ln (M) - 31.05	0.77
M 9	y = 6.512 ln (M) - 42.8	0.62

The correlations between the compressive strength and electrical resistivity are very satisfactory as we see from figure 1-3 (all parts a, b, c) except for samples placed in a accelerated curing chamber (ACC) for boiling at 105º C in closed environment. With the increase of temperature humidity deceases, hence the amount of water present in pores also decreases that carries the current, thus increasing the resistivity. The temperature plays an important role in the electrical resistivity, since the mobility of ions in the pores solution is largely affected by this parameter. The result shows that, for the same age, as the temperature increased (for a constant relative humidity) decreases the electrical resistivity.

Table 7. *The following table gives values for the limiting molar conductivities for selected ions*

Anions	Conductivity UNIT at 25 º C
$(OH)^-$	19.8
SO_4^{2-}	15.96
Cl^-	7.634
NO_3^-	7.144
CO_3^{2-}	7.2
SO_3^{2-}	7.2

4. Conclusions

Nurse saul method is used widely in non destructive operation for the maturity, strength gain, form work removal with record of temperature and time of curing. The maturity index can be used as equivalent age at the reference temperature.

The electrical resistivity may be an additional element, as indicator of performance and durability of concrete structures, as defined in the project. This parameter can be measured during the construction and operation phase, as a record we maintain for the strength parameters. These values can be used later on for non destructive indicator of structure, thus, contributing to sustainable development of structures, minimizing repairs and maximizing the service life of concrete structures. Two concrete with equal compressive strength can be of varying resistivity value may be due to the differences in their permeability. The results of ACC samples are not matching in context of maturity calculation due to difference in their exposure condition. But from concern maturity - resistivity relation we can justify the strength obtained. Resistivity and porosity is related with the transport property of ions as we can observe with the help of table 7. Higher the conductivity lower will be the resistivity or vice-versa.[23] This can also be seen from recommendation of various codes/literatures.[6,13, 22]

5. Limitation s

1. High early age temperature results in incorrect prediction of long term strength as we see from obtained results of ACC.
2. Single source materials were used in this work, which can be of multiple sources for more generalization of results.

5.1. Recommendations

Maturity and bulk electrical resistivity measurement can be used as confirmatory data while using the non destructive testing as performance indicator. It can be good tool for quality control as it is quick, safe and economical.

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