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Evaluation of Migration Characteristics of OPC Concrete from Non-Steady-State Experiments

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ABSTRACT- *Chloride ion diffusion is one of the main factors affecting the durability of reinforced concrete structures. The purpose of the present study is to evaluate the chloride migration coefficient under accelerated test conditions. Accelerated test methods permit migration rates to be evaluated for a specific mix design in a relatively short time. Ordinary Portland Cement concretes of three different water-cement ratios 0.55, 0.45, 0.35 are used in this study. Two accelerated non-steady state test methods (i) Rapid chloride migration test (RCMT) (NT BUILD 492) and (ii) Accelerated chloride migration test (ACMT) with 24V are used. Chloride penetration depth is obtained by Colourimetric method (0.1N $AgNO_3$) and comparison is made with two accelerated test methods. It has been observed that in RCMT, the chloride migration coefficient increases with increase in water-cement ratio and is about 2.5 times less for w/c ratio 0.35 when compared to that of w/c ratio 0.55 and in ACMT, the chloride migration coefficient is 1.7 times less. The rate of penetration between two accelerated test methods showed good correlation.*

Keywords*- Concrete; Chlorides; Durability; Migration Coefficient; OPC Concrete*

I. INTRODUCTION

Two methods i.e., RCMT and ACMT. Also, Colourimetric technique is used to obtain the chloride penetration depth Chloride-induced corrosion is one of the major causes affecting the reinforcement of steel bars in concrete structures exposed to marine environment or de-icing salts. The penetration rate of chlorides into the concrete depends upon many factors such as pore geometry, chloride diffusivity, chemical reactions, and environmental conditions in which chloride diffusivity is the major key factor affecting the durability of the concrete structures. The chloride diffusion coefficient can be determined by natural diffusion methods such as salt ponding test (AASHTO T259), Immersion test (NT BUILD 443) etc. However, such tests are time consuming and costly [1]. By considering those limitations, some researchers found rapid test methods such as Rapid chloride permeability test (RCPT), Rapid chloride migration test (RCMT), Acceleration chloride migration test (ACMT) etc.

A quick and easy method of predicting the durability of concrete structures is RCPT, adopted as an ASTM standard method, which is originally designed by Whiting [2]. There are so many criticisms towards RCPT because of poor test results due to total charge passed through the concrete specimen and this result does not give information about the diffusion of chloride ions [3]. One of the quick methods for predicting migration coefficient in concrete, which has shown good performance in test results and linearly correlated well with natural diffusion test method is Rapid chloride migration test [4] and later these rapid test method standardized as NT BUILD 492 [5] by Nordic Council Of Ministers. In order to avoid the heating of specimen as in RCPT, applied voltage and volume of salt solution may be increased to help with heat dissipation and temperature rise does not occur during the test [6],[7]. The chloride ion penetration depth can be determined using 0.1N silver nitrate solution ($AgNO_3$) on the freshly split concrete and this method is known as Colourimetric method [8], [9]. This method used the principle of which a white deposit is formed through the reaction between silver ion (AG^+) and chloride ion (Cl^-). If colourimetric method is applied to concrete structures exposed to chloride ion, additional precipitation reaction happens beside white precipitation i.e. brown precipitation, occurs due to calcium hydroxide [$Ca(OH)_2$] resulting from hydration of cement [10].Another effective method is to apply an electric field for accelerating chloride migration or penetration is Accelerated chloride migration test (24V) [11]. In this present study, chloride migration coefficient for concretes is evaluated by.

II. EXPERIMENTAL PROGRAM

2.1. Materials and Specimen Preparation

Table 1 presents the mix design for OPC concretes with three different water-cement ratios 0.55(S1), 0.45(S2), and 0.35(S3). The materials used are: commercially available 53-grade ordinary Portland cement (specific gravity 3.15), river sand (fineness modulus 3.0) conforming zone II as per IS 383-1970, coarse aggregate (specific gravity 2.6) and normal potable water.

For each w/c ratio, cylindrical specimens (ø100×200mm) were cast. In addition 150 mm cubes also cast for compressive strength. Table vibrator was used to ensure proper compaction. Surface of the specimen is smoothened with the trowel. All the specimens are demoulded after 24 h and cured in water for 28-days. The 28 day average cube compressive strength are 42 MPa, 57 MPa, 66 MPa respectively for S1, S2, S3 concretes.

TABLE 1 MIX DETAILS

Set	W/C ratio	Water (kg/m^3)	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)
S1	0.55	170	309	860	1056
S2	0.45	170	378	801	1056
S3	0.35	170	486	709	1056

2.2. Rapid Chloride Migration Test (RCMT)

In this study, chloride migration test described in NT BUILD 492 is used. At the age of 28 days, the (ø100×200mm) cylindrical specimens are sliced for 50mm thick using water-cooled concrete cutting machine denoted as top, middle and bottom. The 50 mm thick sliced specimens are used for RCMT test and the test arrangement is shown in Fig. 1.The slanting position was designed to expel small gas bubbles that appear on the cathode plate during testing [4]. DC Power packs with constant voltage out-puts (adjustable in the range of 0-60V) are used. The solution level of anolyte chamber (0.3 N NaOH solution) and Catholyte chamber (10% NaCl solution) are same. Cathode chamber (10% NaCl) is kept large to prevent build-up of the OH^- and depletion of Cl^- [6], [12]. Turn on the power, with the voltage preset at 30V, and record the initial current and initial temperature in anolyte chamber. During the test, temperature in anolyte chamber should be maintained between 20-25^0 C. The variable such as voltage to be applied and test duration depends on the initial current and is shown in Table 2. Table 3 shows the applied voltage and test duration adopted for different w/c ratio used in the present study. It may be noted that the test duration is 24 hrs for all three sets of concrete. Record the final current and temperature in anolyte chamber before terminating the test. Remove the specimen from the test setup, rinse it with tap water, wipe-off excess water and split them axially into two pieces. Spray 0.1N $AgNO_3$ on the freshly split specimen as represented in Fig 2. When the white silver chloride precipitation on the split surface is clearly visible (nearly about 15mins), measure the chloride penetration depth with the help of ruler or Vernier calliper, at an intervals of 10mm.

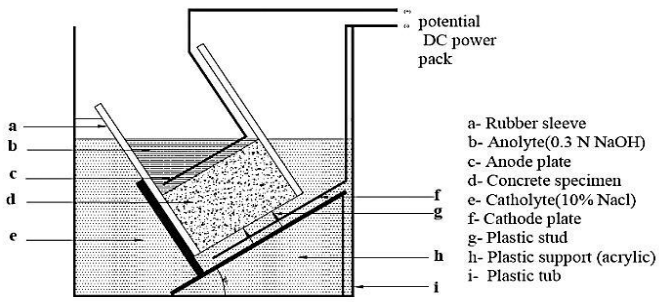

Fig 1 Arrangement of RCMT setup

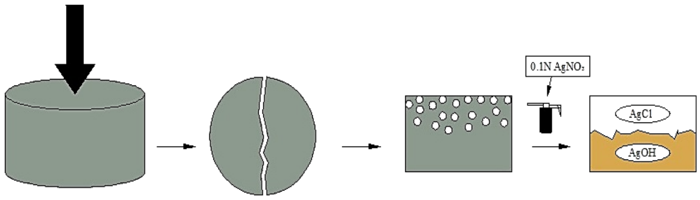

Fig 2 Schematic representation of colourimetric method

2.3. Accelerated Chloride Migration Test (ACMT)

Chiang et al [1] and Yang et al [12] used ACMT for evaluating the migration coefficient and the test procedure is described below. Ø100×50mm specimen was placed in between two acrylic cells as shown in Fig 3. Each cell with a solution volume of 250ml was used. The anode cell was filled with 0.3mol/l of NaOH solution and the cathode cell was filled with 0.52mol/l NaCl solution (3% NaCl). Two mesh electrodes (ø100mm) were placed on the ends of the specimen in such a way that the electrical field is applied across the 50mm thick concrete slice. The cells were connected to 24V DC power pack for a duration of 24-hr, in which cathode is connected to negative terminal and anode is connected to positive terminal of the power supply. After switching on the electric field, initial current and initial temperature in an anolyte solution is to be measured. Higher volumes of catholyte and anolyte solutions may minimize the temperature effect on the test results [11]. Before terminating the test final temperature in anolyte solution is measured as 24°C. Colourimetric method was then used on the freshly split specimen to measure the chloride penetration depth.

III. RESULTS AND DISCUSSIONS

The migration coefficient obtained from Non-steady–state RCMT and Non-steady-state ACMT is discussed below.

3.1. Chloride Migration Coefficient from RCMT

In the RCMT, chloride ions will be transport through concrete sample under an applied voltage.

The non-steady-state migration coefficient (M_{ns}) was calculated from modified Fick's second law which is given in Eq. (1)

$$\frac{dC}{dt} = M_{ns}\left(\frac{d^2C}{dx^2} - \frac{|z|FE}{RT}\frac{dC}{dx}\right)$$
(1)

TABLE 2 VOLTAGE AND TEST DURATION FOR CONCRETE SPECIMEN (NT BUILD 492)

Initial current I_{30v} (with 30 V) (mA)	**Applied voltage U (after adjustment) (V)**	**Possible new initial current I_o (mA)**	**Test duration t (hour)**
$I_o < 5$	60	$I_o < 10$	96
$5 \leq I_o < 10$	60	$10 \leq I_o < 20$	48
$10 \leq I_o < 15$	60	$20 \leq I_o < 30$	24
$15 \leq I_o < 20$	50	$25 \leq I_o < 35$	24
$20 \leq I_o < 30$	40	$25 \leq I_o < 40$	24
$30 \leq I_o < 40$	35	$35 \leq I_o < 50$	24
$40 \leq I_o < 60$	30	$40 \leq I_o < 60$	24
$60 \leq I_o < 90$	25	$50 \leq I_o < 75$	24
$90 \leq I_o < 120$	20	$60 \leq I_o < 80$	24
$120 \leq I_o < 180$	15	$60 \leq I_o < 90$	24
$180 \leq I_o < 360$	10	$60 \leq I_o < 120$	24
$I_o \geq 360$	10	$I_o \geq 120$	6

TABLE 3
VOLTAGE AND TEST DURATION ADOPTED FOR DIFFERENT CONCRETES

Concrete	**Initial current I30v (mA)**	**Applied Voltage (V)**	**New current (mA)**	**Test duration (hr)**
S1	57	30	57	24
S2	66	25	56	24
S3	48	30	48	24

where C is the concentration of chloride ions as a function of distance x, at any time t, z is the electrical charge of chloride (-1), F is the Faraday constant (9.648×10^4 J/ (V·mol)), E is the strength of electric between anode and cathode (V/m), R is the universal gas constant (8.314 J/K·mol), T is the average value of initial and final temperature in anolyte solution (K).

As shown in equation (1), M_{ns} is relatively constant and has the dimension as m^2/sec. In this case analytical solution to Eq. 1 can be derived, as reported by (Tang et al., 2012; Crank., 1975)

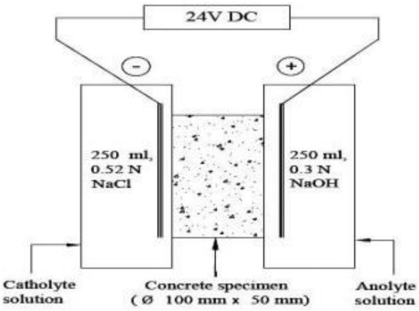

Fig 3 Arrangement of ACMT setup

$$C = \frac{c_0}{2}\left(e^{ax}.\mathrm{erfc}\left(\frac{x+aM_{ns}.t}{2\sqrt{M_{ns}.t}}\right) + \mathrm{erfc}\left(\frac{x-aM_{ns}.t}{2\sqrt{M_{ns}.t}}\right)\right) \tag{2}$$

where a is the factor of the electrical potential (a=zFE/RT) and erfc is complement to the error function erf. When the electrical field is large enough and the chloride penetration depth x_d is sufficient then M_{ns} can be calculated as:

$$M_{ns} = \frac{RT}{zFE}\frac{x_d - \alpha\sqrt{x_d}}{t} \tag{3}$$

Where α can be taken as laboratory constant

$$\alpha = 2\sqrt{\frac{RT}{zFE}}.\mathrm{erf}^{-1}\left(1 - \frac{2c_d}{c_0}\right) \tag{4}$$

where c_d is the chloride concentration at which colour changes (0.07N for OPC concrete), c_o is chloride concentration in cathode chamber (2N). The chloride migration coefficient can be calculated using Eq. (3) and is presented in Table 4.

3.2. Chloride Migration coefficients from ACMT

In the ACMT, chloride ions transport the concrete sample under a constant applied voltage (24V). Same Eq. (3) can be used to calculate the chloride migration coefficient and is listed in table 3. In which c_0 value from Eq. (4) is changes to 0.52N, because we are using 3% NaCl in the Catholyte solution. Rate of penetration (R_p) is calculated using Eq. (5) and is presented in Table 3,

TABLE 4
TEST RESULTS OF RCMT AND ACMT

Concrete	RCMT			ACMT		
	x_d (cm)	M_{ns} ($1\times10^{-12} m^2s^{-1}$)	R_p (mm/v-hr)	x_d (cm)	M_{ns} ($1\times10^{-12} m^2s^{-1}$)	R_p (mm/v-hr)
S1	4.27	24.97	0.0593	2.38	12.65	0.0413
S2	2.25	12.68	0.0375	1.70	9.55	0.0295
S3	2.06	9.613	0.0286	1.30	7.21	0.0226

3.3. Chloride Migration coefficients from ACMT

In the ACMT, chloride ions transport the concrete sample under a constant applied voltage (24V). Same Eq. (3) can be used to calculate the chloride migration coefficient and is listed in table 3. In which c_0 value from Eq. (4) is changes to 0.52N, because we are using 3% NaCl in the Catholyte solution. Rate of penetration (R_p) is calculated using Eq. (5) and is presented in Table 3,

$$R_p = \frac{x_d}{V.t} \tag{5}$$

where xd is the Average penetration depth (mm), V is applied voltage, t is test duration (hr).

IV. EFFECT OF WATER-CEMENT RATIO ON MIGRATION COEFFICIENT

The chloride migration obtained from two accelerated test methods is evaluated based on colourimetric method. A good correlation is obtained between w/c ratio and migration coefficient, is shown in Fig. 4. It has been observed that as water-cement ratio increases, migration coefficient increased. By linear regression analysis, the correlation coefficient R^2 value for RCMT and ACMT is 0.8927, 0.9935 respectively.

V. CORRELATION BETWEEN RCMT AND ACMT MIGRATION COEFFICIENTS

Chloride migration coefficient between two test methods is presented in Fig. 5(a-c). As the water-cement ratio increases correlation coefficient R^2 value is decreased and highest R^2 value is observed for w/c ratio 0.35. Since, two migration coefficients showing good correlation, ant one method may be used in the evaluation of the chloride migration coefficient.

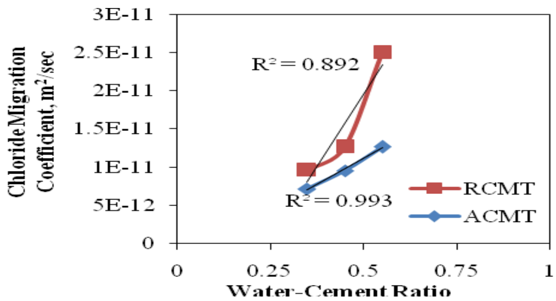

Fig. 4 Graph between Water- cement ratio and Chloride migration coefficient.

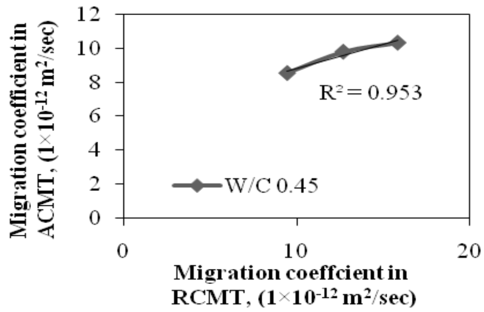

Fig 5b Correlation between migration coefficient in RCMT and ACMT for water-cement ratio 0.45

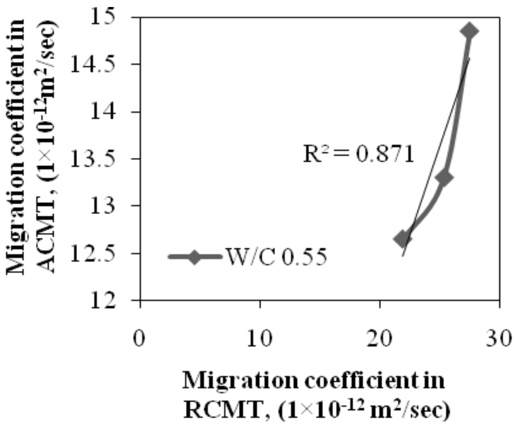

Fig 5a Correlation between migration coefficient in RCMT and ACMT for water-cement ratio 0.55

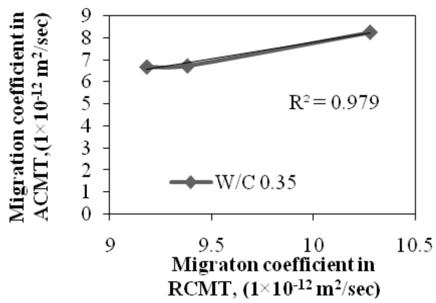

Fig 5c Correlation between migration coefficient in RCMT and ACMT for water-cement ratio 0.35

VI. CONCLUSIONS

The average penetration depth and chloride migration coefficient were evaluated by two acceleration migration test methods. The conclusions derived from the experimental investigation are presented:

1. The chloride migration coefficient of concrete is influenced by the w/c ratio. The migration coefficient increases with increasing w/c ratio.
2. The chloride penetration depth was observed more in RCMT compared to ACMT.
3. Highest R^2 value was observed for w/c ratio 0.35 between RCMT and ACMT. Any one method can be used to evaluate the chloride migration coefficient.

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