Fracture Mechanics of Concrete and Concrete Structures -
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Study of the effect of alkali-silica reaction on properties of concrete by means of conventional test methods and non-destructive test methods

M.Hosein Eftekhar & Saman R.Moghadam
B.Sc Student, Research Assistant, Construction Materials Institute of University of Tehran

Mohammad Shekarchi
Assistant Professor, Director of Construction Materials Institute of University of Tehran

A.Mirdamadi
M.Sc Student, Research Assistant, Construction Materials Institute of University of Tehran

ABSTRACT: Development of non-destructive method, developed specifically for assessing the damage induced by alkali-silica reaction (ASR) in concrete structures, is needed in order to carry out a systematic evaluation of the concrete condition. The aim of this study is to monitor the evolution of the ASR damage in laboratory with concrete samples with NDT methods (Dynamic modulus of elasticity, Impact-Echo methods and Electrical resistivity). For this study result of Impact-Echo method were compared and correlated with expansion, mass variation. Two reactive concretes mixture were made with two kind of reactive aggregates and one other mixture incorporating non-reactive aggregate was made as a control. After 15 days, the expansion of non-reactive aggregate was 0.1% base on ASTM C 1260 and two kind of reactive aggregates were 0.59% and 0.44% respectively. Concrete specimens, made from aggregates sources in ARAS region, Iran, were subjected to 1 N NaOH at 38 °C. This work suggests that non-destructive techniques based on Impact-Echo and dynamic modulus of elasticity should be developed in order to evaluate the development of ASR in concrete structures. Petrographic examination confirmed the damage to concrete is associated with ASR.

1 INTRODUCTION

It has long been recognized that the durability of concrete is dependent upon the mineralogical and textural properties of the rock aggregate. In addition to well known reactive rocks, durability is influenced by the deleterious properties of rocks. Expansion and cracking leads to loss of strength and durability of concrete [Thomas, M.D.A. Sadri, A. Tesfamariam, S].The alkali–aggregate reaction is a chemical process involving alkaline oxides generally deriving from the alkalis in the cement and certain forms of reactive silica present in the aggregate. Damage due to alkali-aggregate-reaction in concrete are observed worldwide. A variety of structure such as dams, bridges, walls and pavements are affected [Thomas, M.D.A. Sadri, A. Tesfamariam, S].

Non destructive test (NDT) methods have been widely used to detect imperfections, weakness and deterioration and examination of structural distress. In this study a field investigation of ASR-affected concrete was carried out using three different NDT techniques, these were impact-echo, dynamic modulus of elasticity and electrical resistivity. This paper presents a brief review of these three methods.

A new inspection of impact-echo that is the first non-destructive technology to be part of a regulating standard for quality control in civil engineering in Germany. Impact-echo has been used to asses ASR on drilled cores, on small size sections like bridge pier, as well as on laboratory specimens [Shekarchi, M. & Tajari, M. & Sadri, A].

Carino and Sansalone provided a brief explanation of the impact-echo method and presented results that illustrate the capacity of the method to locate a variety of flaws in plain and reinforced concrete. It is based on monitoring the surface motion resulting from short-duration mechanical impact [Shekarchi, M. & Tajari, M. & Sadri, A].

Principal components of impact-echo test system are a cylindrical handheld transducer unit, a set of spherical impostors, a portable computer, a high-speed analog to digital data acquisition system, and a software program that controls and monitors the test and displays the result and numerical and graphic form [Sansalone, Mary J. Streett, William.B]. (In this study the software was used is PIES)

Determination of dynamic modulus of elasticity is based on the calculation of resonance frequency in concrete specimens. Stress wave velocity can be criteria of continuity of considered elements. Stress wave velocity in time amplitude and amplitude of frequency as impact-echo method can be usable in the detection of possible micro cracks consequent upon alkali silica reactions. In the other words the perfect and natural elements can transmit stress wave velocity more than the other elements.

Therefore decrease of stress wave velocity can be suitable criteria in the evaluation of circumstance in structures and this is a new method for experiment of materials in concrete. This will decrease the time of experiment of materials and cost of study on damaged structures.

Electrical resistivity is an important durability characteristic of concrete to resist the passage of electrical current.

Electrical resistivity is fundamentally related to the permeability of fluids and diffusivity of ions through porous materials such as concrete [Shekarchizadeh, Mohammad. & Tahersima, Mohammad. & Hajibabaee, Amir. & Layssi, Hamed]. Electrical resistivity may be considered as a function of concrete quality and pore structures. We can monitor development of cracks that has been made by ASR by electrical resistivity.

2 MATERIALS

2.1 *Aggregates*

Aggregates that used in this investigation are reactive aggregates and non-reactive aggregates. The aggregates from ARAS region, IRAN are reactive aggregates. JL and ML are two specimens that made with reactive concrete. The existence of cherts in aggregates shows us that aggregates from ARAS are potential reactive. We used aggregates from non-reactive mines for control specimen (CL). The criteria of reactivity of aggregates is based on ASTM C1260.The course aggregate in both reactive (JL, ML) and non-reactive (CL) specimens is non- reactive but fine aggregate in JL,ML is reactive and in CL is non-reactive.

2.2 *Concrete mixture proportions*

Three (JL, ML, CL) kind of mixture were designed with the same properties (Table 1).The difference is only related to the fine aggregates type (reactive and non-reactive).The cementitious materials used in this study were Portland cement (PC) equivalent to ASTM Type II, and a low-alkali cement used. 1% super plasticizer used was Fosroc Complast 430 (For suitable workability).

Table 1. Mixture proportions.

Mixtures	Non-reactive	Reactive
W/C	0.42	0.42
Gravel(Kg/m3)	900	900
Cement(Kg/m3)	420	420
Sand(Kg/m3)	900	900

2.3 *Casting and conditioning of test specimens*

A total 3 cylinders (150×300 mm) for each CL, JL, and ML were cast. These cylinders used for impact-echo and determination of dynamic modulus of elasticity. A total 3 prisms (75×75×285 mm) for each specimen used for determination of mass change and length variation were cast. We used 3 cubes (100×100×100 mm) for each specimen for determination of electrical resistivity. After 24 h in a curing room, specimens were taken out of moulds. Specimens were subjected to 1 N NaOH at 38±2 °C. The “zero” length of prisms was set just before immersion in to the NaOH solution.

3 TEST DETAILS

3.1 *AMBT (Accelerated Mortar Bar Test)*

This experiment was done for evaluation of reactivity in aggregates. This test was done based on ASTM C 1260.

3.2 *CPT (Concrete Prism Test)*

This test is used to evaluate the potential alkali reactivity of individual or proposed combinations of course and fine aggregates.

3.3 *Stress wave velocity*

In a classical rigid-body dynamics, if a transient force is suddenly applied to an elastic body in the form of transient stress, the corresponding displacements are propagated outwards as elastic waves. The three main types of elastic waves are p waves (compressive waves), S waves (Shear Waves), and R waves (Rayleigh waves).

The velocity of P wave and S wave are given as following:

$$C_P = \sqrt{\frac{E(1-\upsilon)}{\rho(1+\upsilon)(1-2\upsilon)}}$$

$$C_S = \sqrt{\frac{E}{2\rho(1+\upsilon)}}$$

Based on formula the velocity of P-wave relates to the modulus of elasticity, Poisson ratio and density of concrete. As ASR occurs in concrete, modulus of elasticity and thus velocity of P-wave decrease. By the fact, ASR can be evaluated as a function of P-wave velocity [Saint-Pier, Francois. & Rivard, Patrice. & Ballivy, Gerard], [Shekarchi, M. & Tajari, M. & Sadri, A].

In this test for calculation of stress wave velocity (P-wave velocity) we used PIES as software program that controls and monitors the test and displays the result and numerical and graphical form.

The shape of the electrical pulse signal sent to the transmitter transducer is a one period sinusoid a 200 kHz central frequency.

3.4 *Electrical resistivity*

Sudden temperature variations may lead to micro cracks in concrete. To prevent ignition of micro cracks, temperature of specimens should be slightly declined a few hours before testing. Specimens were tested a saturated surface dry condition.

It's important to dry the surface before testing as the moist surfaces may cause resistivity declining and inaccurate measurement. After drying the surfaces, electrical resistivity of concrete has been determined by two cuprous plates. Sufficient fresh cement paste has been injected between cuprous plate and specimen surfaces for complete connection.

3.5 *Dynamic modulus of elasticity*

In this study for determination of dynamic modulus of elasticity the longitudinal frequency of specimen in the free-free mode will be calculated. In this mode stress in both top and bottom of specimen will be zero. Based on the ASTM C 215, E_d is given as following:

$$E_d = \mathrm{D} \times \mathrm{M} \times f^2$$

where D is shape factor, M is mass, f is longitudinal frequency. For cylinders D is:

$$\mathrm{D} = 5.093 \times \mathrm{l} / d^2$$

where l is length and d is diameter of specimen.

4 RESULTS AND DICUSSIONS

4.1 *AMBT*

Figure 1 shows expansion of specimens based on accelerated mortar bar test (ASTM C 1260). This figure shows average of values. The ASTM limit is 0.1 % expansion a 14 days age. Therefore CL is non-reactive and JL, ML are too high reactive. Cracks on the surface of JL, ML confirm this effect. We can see the cracks on the surface of JL and ML obviously.

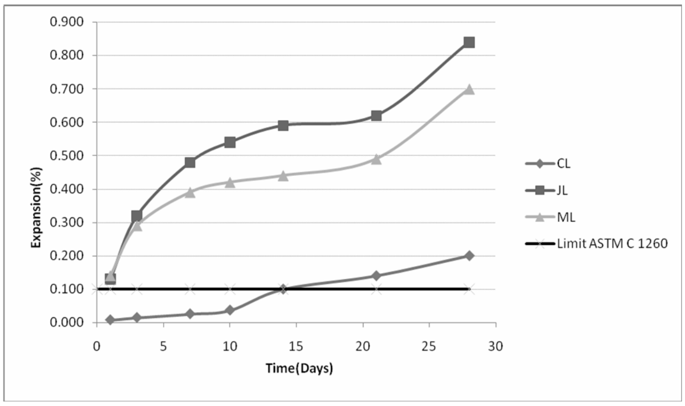

Figure 1. Expansion of prisms of mortar based on ASTM C 1260.

4.2 *CPT*

The period of this test is one year but the period of this evaluation is 90 days so we plotted the result of expansion in the period of evaluation. Figure 2 shows that after 90 days we can see the considerable expansion after this period. The expansion of JL is more than the criterion of ASTM C 1293(0.04%) and the expansion of ML is more than the CL. In this period cracks are not observable on the surface of specimens.

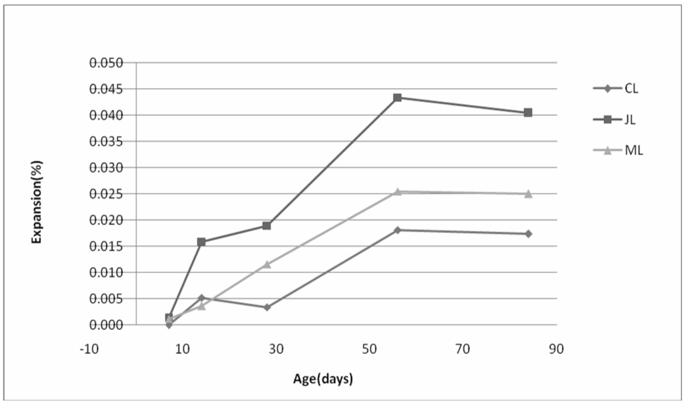

Figure 2. Expansion of prisms of mortar based on ASTM C 1293.

4.3 *Stress wave velocity*

Figure 3 shows the evolution of the stress wave velocity of three mixtures. Results show increase of stress wave velocity in all specimens. Stress wave velocity of JL is more than the others. It is because of difference between compressive strength of specimens. Therefore compressive strength of JL is more than others probably. (Table 2 indicates this subject)

The considerable note is increase of stress wave velocity of all specimens is approximately unchangeable after 28 days age. This matter shows that sensitivity of stress wave velocity to changing of micro-structure is too low. This study shows that to changing stress wave velocity, micro-structure should be changed considerably.

Table 2. Compressive Strength at age 84 days.

Specimens	Compressive Strength(Mpa)
CL	41
JL	44
ML	30

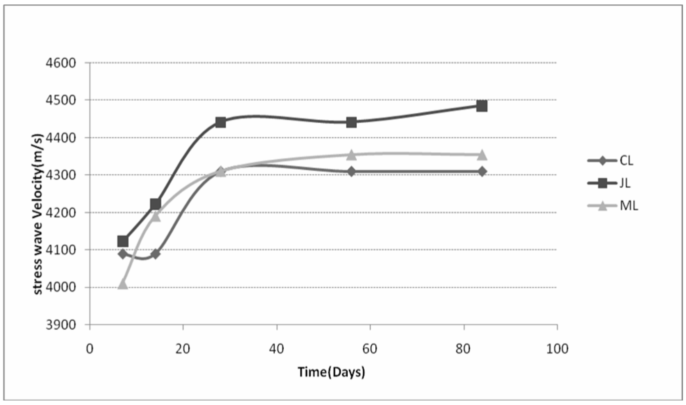

Figure 3. Stress wave velocity of specimens.

4.4 *Dynamic modulus of elasticity*

Figure 4 shows that the dynamic modulus of elasticity is more sensitive to ASR than the stress wave velocity. The non-reactive mixture (CL) shows a very slight increase after 60 days where as the value decreases after 60 days for the reactive mixtures (JL, ML).this decrease indicates that the stiffness of the concrete is reduced, and this has an influence on the physical properties measured with other non destructive techniques such as electrical resistivity.

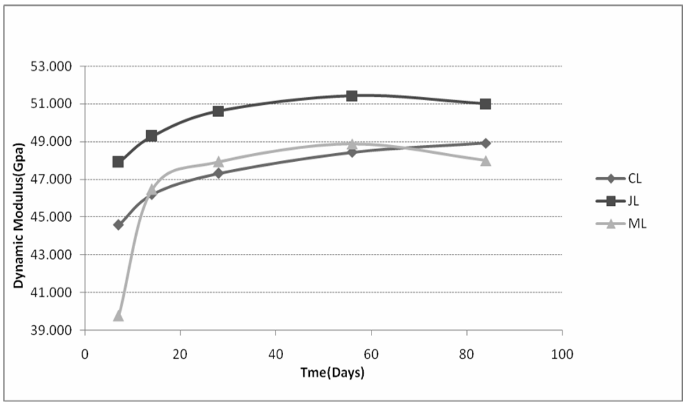

Figure 4. Dynamic modulus of elasticity of specimens.

4.5 *Electrical resistivity*

Figure 5 shows that changing of electrical resistivity of specimens during the study. Increase of electrical resistivity in all specimens is because of hydration and improvement of structure of concrete. That is decrease of porosity and ionic transmission but we have the ASR effect in this period too, however effect of hydration is more than the ASR effect in this period.

On the other hand, for JL and ML, during the late period of test the effect of ASR because of micro cracks progress is more than the effect of hydration so we see decrease of electrical resistivity. Aggregates in CL are non-reactive therefore electrical resistivity will be increase. It means ASR has not happened in CL.

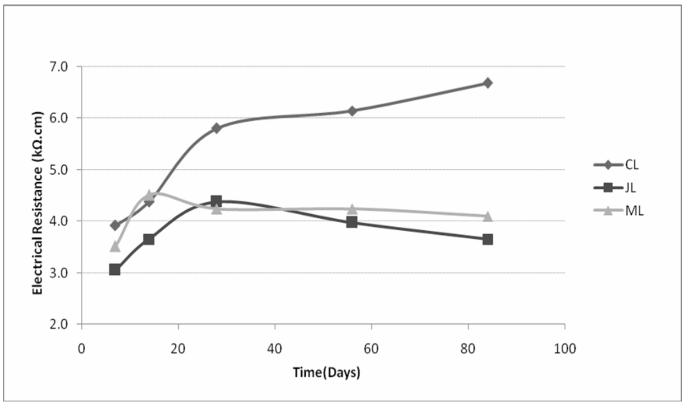

Figure 5. Electrical resistivity of specimens.

4.6 *Comparison between stress wave velocity and conventional tests*

Figure 6 shows that velocity with expansion change rapidly at first but at last this changing become slowly. CL will be flat approximately after this duration but after that expansion will increase slowly and velocity will be unchangeable. One important note in figure can be understood, it is the variation of expansion and velocity is equal approximately. It means correlation between variation of velocity and expansion is nearly one.

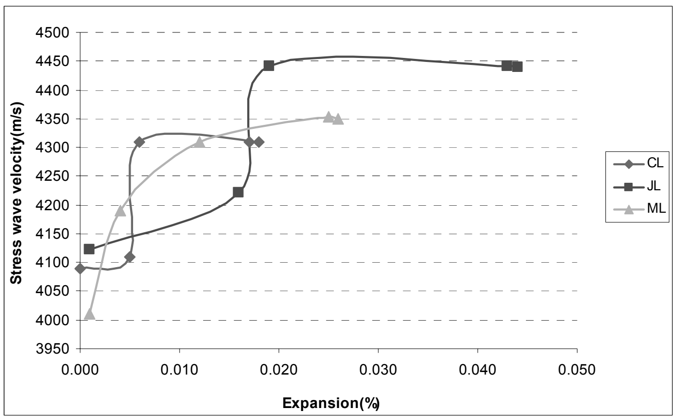

Figure 6.Comparison between stress wave velocity and expansion.

Figure 7 shows that mass change with stress wave velocity can be suitable parameters for investigation on ASR.

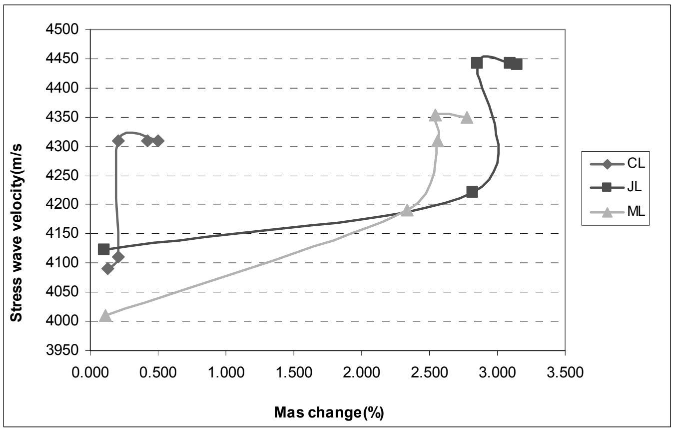

Figure 7. Comparison between stress wave velocity and mass change.

5 CONCLUSION

It was shown that the sensitivity of stress wave velocity method is too low to establish damage criteria associated with ASR especially in early age. Virtually no variation was observed after 84 days in NaOH on both reactive and non-reactive mixtures whereas the dynamic modulus of elasticity and electrical resistivity are more suitable parameters for evaluation of ASR.

Results of impact-echo and dynamic modulus of elasticity tests on specimens that constructed from same materials are similar. This matter shows the accuracy of these tests in determination of concrete properties.

Methods based on dynamic modulus of elasticity and electrical resistivity rather than stress wave velocities should be used to assess in-situ ASR affected concrete structure.

The results from NDT methods will be more reliable when combine with conventional tests such as mass change and expansion.

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