FORMULAE FOR ESTIMATING AAR EXPASION IN CONCRETE STRUCTURES BASED ON ULTRASONIC PULSE VELOCITY MEASUREMENT

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Abstract

Ultrasonic pulse velocity (UPV) technique and core testing are common and effective means for appraisal of concrete structures. For concrete structures affected by alkali-aggregate reaction (AAR), these techniques seem not working so well. One of the major problems lies in the fact that when a concrete core is taken out of a structure, confinement to the core from surrounding concrete and reinforcement is removed. The properties of the core as determined by common tests do not reflect the actual properties of the concrete inside the structure. The assessment of mechanical properties of in-situ concrete is still a difficult task due to the lack of research on this aspect.

Earlier researches by the authors and others showed that AAR expansion of the concrete inside structure is the key factor affecting mechanical properties of the concrete and hence, the accuracy of structural analysis. Accurate assessment of AAR expansion of the concrete within the structure is crucial in structural appraisal.

This paper derives, based on a model of AAR affected concrete, formulae that could be used in estimating AAR expansion and concrete properties using UPV technique. An experiment verifying the formulae is also presented.

Keywords: structural appraisal, ultrasonic pulse velocity, finite element, AAR, concrete affected by AAR

1 INTRODUCTION

The common techniques for assessing concrete structures, such as core testing and ultrasonic pulse velocity measurement, may be working well for structures without AAR. For structures affected by AAR, these techniques seemed not working so well. There have been many evidences that properties obtained from core testing, or derived from UPV measurement on cores, did not reflect the behaviour of the structures. The following are two well-known cases.

Hanshin Expressway in Japan: The Hanshin Expressway runs between Osaka and Kobe in Japan [1]. In one elevated portion of the expressway supported on 500 piers, about 100 piers exhibited visual cracking due to AAR in 1979, four years after construction. In 1984, the surface cracking was considered to be severe, with crack widths up to 5 mm and depths up to 100 mm. Load tests were performed on both damaged and undamaged piers. The loads applied were up to 80% of the design maximum live load. UPV, compressive strength and Young's modulus were also tested on cores drilled from the piers. It was reported that the Young's modulus of concrete from affected piers was only 20% that of unaffected concrete with a value of only 6.2 kN/mm^2. However, the deflections measured on both affected and unaffected piers during the load tests were similar. It seems clear that the Young's modulus as measured from the cores did not reflect the actual behaviour of the concrete inside the pier.

Frame in South Africa: Blight and Alexander reported two load tests on a portal frame near Johannesburg, South Africa [2, 3, 4]. The first test was in 1982 and the second in 1988. It was reported that the estimated modulus of elasticity was 18 GPa, while the results of the load test indicated that the actual modulus of elasticity should be around 24 GPa.

The above two cases indicated that common method of core and UPV testing for normal concrete structure could not be directly used in structural appraisal of AAR affected structures, due to the fact that the properties of the cores have changed, often significantly, when they are taken out of the structure.

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Earlier researches [5, 6, 7] showed that the most influential factor affecting the properties of AAR affected concrete, and therefore affecting the reliability of structural analysis, is AAR expansion of the concrete as it is inside the structure. Once the expansion is determined, with reasonable accuracy, the capacity and deformation properties of the affected structure may also be estimated with acceptable confidence.

The structural analysis proposed by the Authors in earlier research for AAR affected structures involves two stages [7].

Stage 1: Assessment of AAR expansion of concrete inside the affected structure. For laboratory tested members, AAR expansion may be estimated using AAR expansion model and the information obtained from expansion of unrestrained concrete. No method for assessing AAR expansion for in-situ structures was proposed before. The formulae for UPV tests proposed in this paper may be used for this purpose.

Once AAR expansions are estimated, stresses in reinforcement and in the concrete may then be determined. Mechanical properties of the affected concrete are also depends on the expansion [7].

Stage 2: Analysis/prediction of structural capacity/performance of the structure. This could be done by means of finite element analysis. AAR expansion and properties of AAR affected concrete derived from the expansion are the input data for the analysis.

The formulae proposed in this paper are for the estimation of AAR expansion. This is done by calculating modulus of elasticity of affected and unaffected concrete, which, in turn, are determined by UPV measurement.

The model presented in this paper is a one-dimensional model, which is easy to understand. The formulae can be extended to cover three dimensional situations.

2 MODEL AND FORMULAE

Figure 1 shows a one-dimensional model of AAR affected concrete subjected to a compressive stress, σ_a. This model can be regarded as a composite of two constituent materials: sound concrete and gel-filled cracks surrounding the concrete. L_c is the average spacing between AAR cracks perpendicular to the direction of strain measurement. L_g is average thickness of the crack. Assuming strain of AAR expansion is ε_{ex}, and then the thickness of AAR gel is

$$L_g = L_c \varepsilon_{ex} \tag{1}$$

When a stress increment $\Delta\sigma_a$ is applied, the strain increment $\Delta\varepsilon_a$ is

$$\Delta\varepsilon_a = \frac{\Delta\sigma_a}{E_a} = \left(\frac{\Delta\sigma_a L_c}{E_c} + \frac{\Delta\sigma_a L_g}{E_g} \right) / L_c = \Delta\sigma_a \left(\frac{1}{E_c} + \frac{\varepsilon_{ex}}{E_g} \right). \tag{2}$$

The tangent modulus of elasticity of the composite is

$$E_a = \frac{1}{\dfrac{1}{E_c} + \dfrac{\varepsilon_{ex}}{E_g}} \tag{3}$$

In Equations (1) to (3)

ε_{ex} - strain due to AAR expansion of affected concrete at a point within the structure, and is subjected to a stress σ_a in the direction of the strain.

E_a - tangent modulus of elasticity of AAR affected concrete at the same point inside the structure, corresponding to an expansion of ε_{ex}.

E_c - tangent modulus of the concrete when it is not affected by AAR, subjected to a stress σ_a.

E_g - modulus of elasticity of AAR gel. This value will depend on the nature and condition of AAR gel. From the concrete tested by the authors in previous research [7], value of E_g for laboratory tested concrete is usually between 70 to 90 MPa.

Similarly when the concrete is taken out of the structure and is free from restraining stress, tangent modulus of elasticity becomes

$$E_{a0} = \frac{1}{\frac{1}{E_c} + \frac{\varepsilon_{ex0}}{E_g}}. \quad (4)$$

In Equation (4)

ε_{ex0} - strain of AAR expansion of affected concrete when the concrete (core) is taken out of the structure and is free from restraining stress.

E_{a0} - tangent modulus of elasticity of affected concrete when the concrete (core) is taken out of the structure and is free from restraining stress.

From Equation (3), AAR expansion within affected structure can be estimated using the following equations.

$$\varepsilon_{ex} = E_g\left(\frac{1}{E_a} - \frac{1}{E_c}\right) \quad (5)$$

Similarly

$$\varepsilon_{ex0} = E_g\left(\frac{1}{E_{a0}} - \frac{1}{E_c}\right) \quad (6)$$

Values of E_a, E_{a0} and E_c can be determined through UPV measurement on concrete structure, cores taken from the structure and unaffected part of the structure respectively as follows.

$$\frac{1}{E_a} = \frac{k}{\varrho (v_a)^2} \quad (7)$$

$$\frac{1}{E_{a0}} = \frac{k}{\varrho (v_{a0})^2} \quad (8)$$

$$\frac{1}{E_c} = \frac{k}{\varrho (v_c)^2} \quad (9)$$

In Equations (7) to (9),

k - function of Poison's ratio, γ, $k = \frac{(1-\gamma)}{(1+\gamma)(1-2\gamma)}$. Since for AAR affected concrete γ is between 0.15 and 0.25, so k is between 1 and 1.2.

v_a - UPV through concrete within affected structure subject to restraining stress σ_a.

v_{ao} - UPV through concrete core taken out of the structure and free from restraining stress.

v_c - UPV through concrete without AAR.

ϱ - density of concrete.

3 VERIFYING EXPERIMENT AND RESULTS

An experiment was derived to verify and demonstrate the proposed approach (Figure 2). The specimen used is a normal plain concrete beam 150mm x 150mm x 750mm. UPV was firstly measured along the longitudinal direction of the beam before the beam was split through its middle section by a bending action. The two broken pieces were then put back together, and the broken section resembles a major crack across the beam (Figure 2). Thin films of grease were spread over the broken surfaces to resemble AAR gel (Figure 3). Demec spots were then glued on the beam for measurement of strain. The assembled broken beam was then put in a testing machine, and a compression force up to 5 N/mm^2 was applied (Figure 4). UPV was measured and Demec reading was taken. A pair of steel benches was used to facilitate UPV measurement (Figure 4). After the compression reached 5 N/mm^2 and was maintained for ten minutes, the load was then released. The UPV measurement and Demec gauge reading were then repeated.

Results of the experiment were presented in Table 1.

4 DISCUSSION

1. Young's modulus of sound concrete, E_c, as determined from Equation (9) was 42.43 kN/mm^2. The apparent Young's modulus of the broken specimen under 5 N/mm^2 restraining stress was 41.94 kN/mm^2. The change of apparent Young's modulus was inconspicuous even though there was a major single crack in the middle of broken specimen. Apparent Young's modulus of the broken specimen reduced to 40.49 kN/mm^2 when the restraining force was removed.
2. The deformation property of the "gel" was not studied in this research. Previous research on laboratory produced concrete with AAR by the author found that the value of E_g is between 60 MPa and 80 MPa [7]. In the following calculation the value of 70 MPa was adopted for E_g.
3. The strain measured over a gauge length across the crack includes both deformation of sound concrete and deformation of gel-filled crack. The change of strain over 150 mm gauge length when the compressive stress of 5 N/mm^2 was removed was 385 μ, which includes a strain of 118 μ from the sound concrete (5 N/mm^2 / 42.43 kN/mm^2 x 10^6). The remaining strain of 267 μ was contributed from deformation of the crack, which was 0.04 mm (276 $\mu \times$ 150 mm). Average strain change due to the deformation of the crack over the total length of the specimen was 53 μ (0.04 mm / 750 mm), this value is close to the value of 59.4 μ calculated from Equations (5) and (6), i.e. $\varepsilon_{ex0} - \varepsilon_{ex}$. The comparison indicates that the formulae reflect the change of expansion well.

5 CONCLUSIONS

1. Confinement to cracked concrete significantly alters the properties of the concrete. This is manifested by the discrepancy of the properties of cores and the behaviour of the concrete inside affected structure. The discrepancy in properties of confined and non-confined concrete can be reflected sensitively by UPV measurements. For appraisal of AAR affected structures, UPV measurement directly on structure may yield more useful and reliable information.
2. Research has shown that the estimation of AAR expansion of concrete inside structure is crucial in structural appraisal. The estimation may be done by comparing properties of concrete when it is inside the structure and when it is taken out of the structure. The formulae proposed in this paper may be used for this purpose.

6 REFERENCES

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TABLE 1: Experimental data and results.

	Size	150mm x 150mm x 750mm
	Mass	40.4 kg
	Density	2394kg/m^3
Before beam is split	UP travelling time	169 μs
	Velocity (v_c)	4438 m/s
	Estimated E_c (Equ. (9))	42.43 kN/mm^2
When stress applied is 5N/mm^2	UP travelling time	170 μs
	Velocity (v_a)	4412 m/s
	Estimated E_a (Equ. (7))	41.94 kN/mm^2
	ε_{ex} (Equ. (5))	19.6μ
When beam is free from stress	UP travelling time	173 μs
	Velocity (v_{a0})	4335 m/s
	Estimated E_{c0} (Equ. (8))	40.49 kN/mm^2
	ε_{ex0} (Equ. (6))	79.0μ
When σ changed from 5N/mm^2 to 0.	Strain change over gauge length 150mm across crack	385μ
	Change of ε_{ex}, $\Delta\ \varepsilon_{ex}$	79μ– 19.6μ= 59.4μ

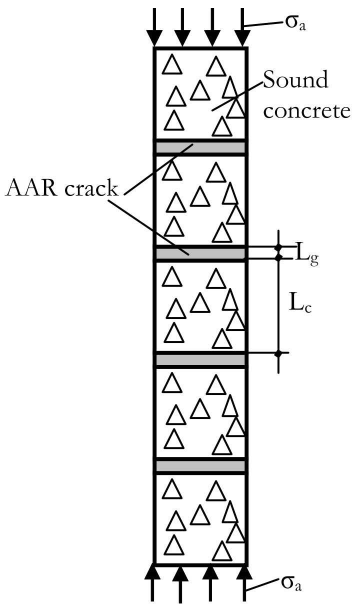

Figure 1: Model of AAR cracked concrete.

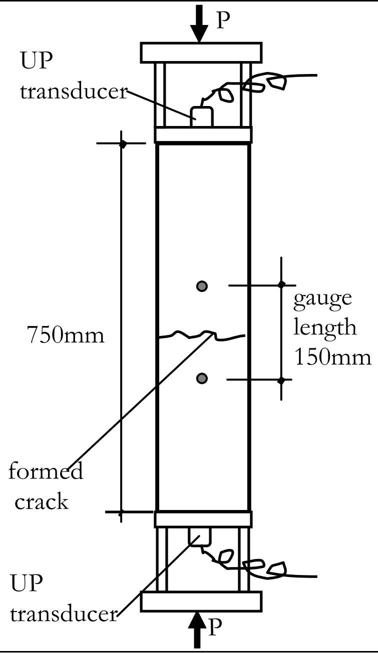

Figure 2: Experiment set up.

Figure 3: Grease applied on the broken surfaces.

Figure 4: Ultrasonic pulse velocity measurement.