DETERIORATING FRACTURE PROPERTY AND WAVE VELOCITY OF CONCRETE USED IN NUCLEAR POWER PLANT IN MARINE ENVIRONMENT

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ABSTRACT
An experimental study has been studied to investigate the mechanical properties of the concrete provided by the new Taipower’s nuclear power plant under construction in Taipei. Two typical concrete mixtures - with and without fly ash, were selected in this research. The compressive strength and modulus of elasticity were determined based on the ASTM Specifications. The fracture toughness of concrete, in terms of critical stress intensity factor $K_C$ was evaluated by the methods proposed by Jenq and Shah. Stress wave velocities were measured by impact-echo method. The concrete subjected to various deteriorating conditions were simulated by various curing durations under a cyclic process between in sea water solution and in an oven. The test results showed that compressive strength, modulus of elasticity, critical stress intensity factor and stress wave velocity of those concretes cured in regular water are higher in magnitude than those cured in seawater-oven cycles turn out higher than those regular cured for a given compressive strength.

Keywords: concrete, deterioration, fracture toughness, modulus of elasticity, wave velocity.

1. INTRODUCTION
Concrete is a primary material used for the containment in which a reactor vessel is located for the purpose of structural strength and radiation protection. The durability of the containment always depends on the fracture resistance and corrosion resistance of concrete, in particular, for those nuclear power plant built in the marine environment.
environment. In 1996, NRC requested the nuclear power plants in the States to embark on in-service inspection for concrete containment. In consequence, it is significant to know the failure mechanism of those concrete in their life cycle. In the last few decades, a great number of researches have employed the fracture mechanics in normal concrete to figure out its fracture toughness [1-2]; while few have been conducted for those corroded.

1.1 Degradation of Concrete
Concrete always deteriorates due to corrosion, cracking, chemical attack, and so on. In marine environment, concrete structures are always corroded from its embedded reinforcement or deteriorated due to sulfate attack from its surface. However, in concrete itself the chemical reaction due to seawater produces certain chemical products, such as aragonite, brucite and ettringite, which are insoluble and provide a sealant to reduce the permeability and prevent further ingress of seawater into the interior of the concrete [3]. While this may not be the case for those concretes in the tide zone whose chemical products may be washed away by the wave. In literatures, Type II Portland cement is always adopted as main binder in concrete which provides a moderate resistance to seawater.

1.2 Fracture Mechanics of Concrete
The application of fracture mechanics on concrete was first initiated by Kaplan in 1961 [4]. A crack in concrete is thought to begin when the fracture toughness that is always defined quantitatively in terms of critical stress intensity factor, $K_C$, or the fracture energy, $G_C$, has been exceeded. Much research has addressed the fracture toughness of normal concrete with various mixtures [5-6], but little research has addressed the strength and fracture properties of heavy concrete. A fracture process zone exists in front of the tip of a propagating crack. A number of proposals have recently been suggested to RILEM (1989), such as Hillerburg’s fracture model (1985) [7], Bazant’s size effect model (1986) [8], Jenq and Shah’s two-parameter model (1985) [9] and Karihaloo and Nallathambi’s effective crack model (1991) [10], all of which provide methods for determining the fracture properties of concrete. Since the deterioration of most of the concrete structures embarks on the initiation of crack, it is felt valid to figure out the fracture mechanism of concrete.

1.3 Non-destructive Evaluation of Concrete
The P-wave velocity measurement to concrete structure using either impact-echo method or ultrasonic method has been applied to monitoring or estimating material strength for years. It is valid and feasible to employ these techniques on concrete which is a porous and permeable material. Both of quality control and defect inspection such as crack (inside or outside concrete structure) can be easily investigated. The measurement and equipment used in this research mainly followed the requirement of the Procedure B in ASTM C1383 (Impact Echo Method) [11].

2. EXPERIMENTAL PROGRAM

2.1 Material Preparations

2.1.1 Cement
The cement used in the concrete construction project of the power plant is Type II Portland cement which performs moderate sulfate resistance and is the only kind used for the entire experiment following the ASTM C595 for concrete with minor sulfate resistance; the cement performance is suitable for concrete structures in marine environment or seashore [12].

2.1.2 Aggregate
Crushed limestone is adopted in concrete as coarse aggregate with a maximum particle size of 19 mm and a fine modulus of 6.82, both of which were supplied by the power plant. The fine aggregate has a fineness modulus of 3.23, according to ASTM C136 [13]. The specific gravities of coarse aggregate and fine aggregate are 2.73 and 2.70, respectively, measured following the ASTM C127 [14]and ASTM C128 [15]. The strength and toughness of concrete are thought being dominated significantly by the texture and strength of the aggregates.

2.1.3 Mixture of Concrete
An experimental study has been conducted to investigate the mechanical properties of the concrete provided by a new nuclear power plant in Taibei. Two typical concrete mixtures—without and with fly ash referred to FC and NC, were selected in this research and are shown in Table 1. The water-to-binder ratios of both mixtures are 0.52 and 0.48, respectively. The initial set retarder and water reducer of type D admixture complying with ASTM C 494 [16] were employed in both mixtures. It was used to improve the workability in the fresh concrete stage.

### Table 1 Mixtures of concretes

<table>
<thead>
<tr>
<th>Mixture</th>
<th>FC</th>
<th>NC</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/B</td>
<td>0.48</td>
<td>0.52</td>
</tr>
<tr>
<td>Water</td>
<td>194</td>
<td>194</td>
</tr>
<tr>
<td>Cement</td>
<td>345</td>
<td>370</td>
</tr>
<tr>
<td>Fly ash</td>
<td>64</td>
<td>-</td>
</tr>
<tr>
<td>Sand</td>
<td>1019</td>
<td>982</td>
</tr>
<tr>
<td>Aggregate</td>
<td>710</td>
<td>799</td>
</tr>
<tr>
<td>Admixture</td>
<td>2.03</td>
<td>1.85</td>
</tr>
</tbody>
</table>

Note: NC and FC stand for normal concrete and fly ash concrete, respectively. All units are in kg.

### 2.2 Testing Specimens

Four types of specimens made from the above two mixtures were fabricated in this testing program. The Φ10 x 20 cm cylinders were used to determine the physical properties of concrete including modulus of elasticity and stress wave velocity. The Φ10x 20 cm cylinders were mainly tested for compressive strength. Three-point bending beam specimen of 10 x 10 x 35 cm in dimension with a notch pre-cast in the middle of the beam was employed for fracture test. It follows the fracture mechanic tests recommended by the RILEM. All specimens were cured one day in the mold, then demolded and placed in the designated curing environments until being tested.

### 2.2.1 Deterioration Process

The concrete subjected to various deteriorating conditions were simulated and designated on various curing durations under a cyclic process between in seawater solution and in an oven at 60 °C. The concrete were tested after various curing durations of 28 days, 56 days and 91 days. The constituents of sea water solution include compositions such as NaCl, MgCl₂, Na₂SO₄, CaCl₂ and KCl, as listed in Table 2, which comply with ASTM D1141 [17].

### Table 2 Composition of seawater based on ASTM

<table>
<thead>
<tr>
<th>Component</th>
<th>Concentration (g / L)</th>
</tr>
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<tbody>
<tr>
<td>NaCl</td>
<td>24.5</td>
</tr>
<tr>
<td>MgCl₂.6H₂O</td>
<td>11.1</td>
</tr>
<tr>
<td>Na₂SO₄</td>
<td>4.1</td>
</tr>
<tr>
<td>CaCl₂</td>
<td>1.2</td>
</tr>
<tr>
<td>KCl</td>
<td>0.7</td>
</tr>
</tbody>
</table>

### 2.3 Testing Procedure

Testing procedures of all fundamental mechanical properties conform to the ASTM Specifications [18-19]. Fracture toughness of concrete was determined in terms of stress intensity factor \( K_{IC} \) which is provided by Jenq and Shah. This method is recommended by the RILEM [20]. In this method, single-edge-notched (SEN) beam was tested in three-point bending manner, as referred to Mode I fracture test, on a MTS testing system, as shown in Figure 1. While a beam is being loaded, load-point displacement (LPD) and crack mouth opening displacement (CMOD) are simultaneously monitored and recorded.
Fig. 1 Configuration setup of Mode I fracture test in MTS

The RILEM Technical Committee 89-FMT on Fracture Mechanics of Concrete-Test Methods has proposed in 1990 a recommendation to measure the material fracture parameter $K_{IC}$ using a three-point bend beam. The initial notch-to-depth ratio should be 1/3, and the notch width is about 2 mm. A closed-loop testing machine with the crack mouth opening displacement (CMOD) as feedback signal is employed to achieve a stable failure. The crack mouth opening displacement and the applied load were recorded continuously during the test. A clip gauge is used to measure the CMOD. The rate of loading was controlled by a constant rate of CMOD such that the peak load is reached in about 5 minutes.

To obtain the fracture parameters $K_{IC}$ for plain concrete, the maximum load $P_{m}$ and the corresponding elastic component of the CMOD were measured. These were used to estimate the effective elastic crack length $a_{e}$ so that the calculated CMOD (based on LEFM equations) is equal to the measured value. For a given initial notch length $a_{o}$ and depending upon the type of test, the two fracture parameters are determined as follows.

First, the modulus of elasticity $E_{c}$ is determined from cylinder tests or from the following formula based on initial beam compliance $C_{i}$ shown in Figure 2.

$$E_{c} = \frac{6S a_{o} V_{i}(\alpha_{o})}{C_{i} t b^{2}}$$  \hspace{1cm} (Eq. 1)

$$V_{i}(\alpha_{o}) = 0.76 - 2.28 \alpha_{o} + 3.87 \alpha_{o}^{2} - 2.04 \alpha_{o}^{3} + 0.66/(1-\alpha_{o})^{2}$$  \hspace{1cm} (Eq. 2)

and $\alpha_{o} = (a_{o} + h_{o}) / (b + h_{o})$, $h_{o}$ = clip gauge holder thickness.
Figure 2 Load versus crack-open-mouth displacement (COMD) curve

The effective crack length is determined from Equation 1 by replacing $a_o$ with $a_e$, $\alpha_o$ with $\alpha_e$ and $C_i$ with $C_u$ where $\alpha_e = (a_o + h_o) / (b + h_o)$ and $C_u$ as shown in Figure 2 is the unloading compliance at 0.95 $P_{\text{max}}$ on the softening branch. Thus it may be solved by iteration.

$$a_e = \frac{C_u V_i(\alpha_o)}{C_i V_i(\alpha_e)} \quad \text{(Eq. 3)}$$

Then the critical stress intensity factor is

$$K_{IC} = \frac{3 P_{\text{max}} S}{2 t b^2} \sqrt{m_e} F(\alpha) \quad \text{(Eq. 4)}$$

where $\beta = a_o / a_e$.

2.3.2 Stress wave velocity

In this study, the scale of specimen is a $\Phi 10 \times 20$ cm cylinder. The multiple reflections of the P-wave between the top and bottom surfaces of the specimen give rise to a transient longitudinal resonance with a frequency $f$ related to the specimen length $d$ (20 cm). Therefore, the Impact-echo test can be applied to compute the P-wave velocity using equation:

$$V_p = \frac{2 d f}{0.94} \quad \text{(Eq. 5)}$$

in which the 0.94 is a shape parameter to the specimen.

In this research, the testing equipments all comply with the requirement of the Procedure B in ASTM C1383 (Impact Echo Method). The system is a portable computer with a data-acquisition card of 500 kHz or higher sampling rate. However, for more stably operating and signal receiving, fixing accelerometer (sensor) was used instead of the displacement transducer. Three testing results (spectrums with longitudinal resonance frequency $f$) were obtained and recorded for each specimen. The average $f$ was used to compute $V_p$.

3. RESULTS AND DISCUSSIONS

From the test results, several mechanical properties such as fracture toughness, modulus of elasticity and stress wave velocity are observed and listed in Table 3, which are discussed as follows:
Table 3 Mechanical properties of normal concrete and fly ash concrete

<table>
<thead>
<tr>
<th>Type</th>
<th>Properties</th>
<th>Curing Condition</th>
<th>Curing duration</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>28 days</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Deteriorating</td>
</tr>
<tr>
<td>NC</td>
<td>$f_c'$ MPa</td>
<td></td>
<td>33.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>$E_C$ GPa</td>
<td></td>
<td>20.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>17.6</td>
</tr>
<tr>
<td></td>
<td>$K_{IC}$ MPa $\sqrt{m}$</td>
<td></td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>$V$ m/s</td>
<td></td>
<td>3922</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4015</td>
</tr>
<tr>
<td>FC</td>
<td>$f_c'$ MPa</td>
<td></td>
<td>37.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>35.3</td>
</tr>
<tr>
<td></td>
<td>$E_C$ GPa</td>
<td></td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>18.3</td>
</tr>
<tr>
<td></td>
<td>$K_{IC}$ MPa $\sqrt{m}$</td>
<td></td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.56</td>
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<tr>
<td></td>
<td>$V_p$ m/s</td>
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<td>4016</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>4000</td>
</tr>
</tbody>
</table>

Note: NC and FC stand for normal concrete and fly ash concrete, respectively.

3.1 Compressive strength

Compressive strengths of concretes – with or without inclusion of fly ash, increase with the curing duration as shown in Figure 3 and Figure 4, respectively. But most of the control sets of both concretes that were cured in regular water appear higher than those cured in seawater-oven cyclic process. Also, it turns out that concrete with lower water-to-binder ratio have higher compressive strength than those with higher water-to-binder ratio.

![Fig. 3 Compressive strength of fly ash concrete](image1)

![Fig. 4 Compressive strength of normal concrete](image2)

3.2 Fracture toughness

Test results showed that the fracture toughness of both concrete, in terms of stress intensity factor $K_{IC}$, increase with the seawater-oven cycles, as shown in Figure 5 and Figure 6. As compared with the control sets for a given curing duration, the $K_{IC}$ of concretes cured in seawater-oven turned out lower than those control sets. It also appeared out that concrete with lower water-to-binder ratio appears higher critical stress intensity factor than...
those with higher water-to-binder ratio.

![Fig. 5 Fracture toughness of fly ash concrete](image1)
![Fig. 6 Fracture toughness of normal concrete](image2)

**3.3 Stress wave Velocity**

Stress wave velocities of concrete – with or without inclusion of fly ash, increase with the wet-dry cycles. It turned out that concrete with lower water-to-binder ratio appears higher stress wave velocity than those with higher water-to-binder ratio, as shown in Figure 7 and Figure 8. It implies the permeability of concrete can be enlarged due to deteriorating process. Also, the existence of fly ash could improve the permeability of concrete.

![Fig. 7 Wave velocity of fly ash concrete](image3)
![Fig. 8 Wave velocity of normal concrete](image4)

**3.4 Modulus of elasticity**

In Table 3, it can be observed that moduli of elasticity for both concretes increase with seawater-oven cycles. As being correlated with compressive strength by the fitting curves, as shown in Figure 9 and Figure 10, it shows that the concrete cured in seawater-oven has a higher modulus of elasticity than that cured in water for a given compressive strength. However, both curves appear lower than that empirical formula to predict modulus of elasticity provided by ACI. This could attribute to the local characteristics of aggregate.
4. CONCLUSIONS

This experimental study investigated the deterioration in several mechanical properties of concretes of two typical mixtures – with and without the inclusion of fly ash as part of binder in concrete. Several conclusions are drawn from the test results.

1. Compressive strengths of concretes – with or without inclusion of fly ash, increase with the seawater-oven cycles. But they are all lower than the control sets that were cured in regular water for a given duration. It turns out that concrete with lower water-to-binder ratio appears higher compressive strengths than those with higher.

2. Test results revealed that moduli of elasticity for both concretes increase with seawater-oven cycles. As being
correlated with compressive strength by the fitting curves, it shows that the concrete cured in seawater-oven has a higher modulus of elasticity than that cured in regular water for a given compressive strength.

3. The fracture toughness of concrete – with or without inclusion of fly ash, in terms of stress intensity factor $K_{IC}$, increase with the seawater-oven cycles. But they are all lower than those control sets that were cured in regular water for a given curing duration. It turns out that concrete with lower water-to-binder ratio appears higher stress intensity factor than those with higher.

4. Stress wave velocities of concrete – with or without inclusion of fly ash increase with the wet-dry cycles. It turned out that concrete with lower water-to-binder ratio appears larger stress wave velocity than those with higher water-to-binder ratio. Those concretes cured in water have higher stress wave velocities than those cured in seawater-oven cyclic process. It implies that the permeability of concrete can be enlarged due to deteriorating process.

5. From the test results, it can be observed that for both concretes cured in seawater-oven cyclic process do not deteriorate; whereas it shows growing in compressive strength, modulus of elasticity, fracture toughness and stress wave velocity. This implies that concrete in marine environment may self-cure itself if no wave or other physical force, like corroding reinforcement embedded inside the concrete.

ACKNOWLEDGEMENT

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