**Structural Engineering and Mechanics**, *Vol. 64, No. 6 (2017) 793-802*
DOI: https://doi.org/10.12989/sem.2017.64.6.793


# Numerical prediction of stress and displacement of ageing concrete dam due to alkali-aggregate and thermal chemical reaction

Nik Zainab Nik Azizan*[1,2], Angshuman Mandal[3a], Taksiah A. Majid[1b], Damodar Maity[3c] and Fadzli Mohamed Nazri[2d]

[1]*School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia*
[2]*School of Environmental Engineering, Universiti Malaysia Perlis, Perlis, Malaysia*
[3]*Department of Civil Engineering, Indian Institute of Technology, Kharagpur, India*

*(Received July 13, 2016, Revised September 24, 2017, Accepted October 11, 2017)*

**Abstract.** The damage of concrete due to the expansion of alkali-aggregate reaction (AAR) and thermal-chemical reactions affecting the strength of concrete is studied. The empirical equations for the variations of expansion of AAR, compressive strength and degradation of the modulus of elasticity with time, and compressive strength with degradation of the modulus of elasticity are proposed by analysing numerous experimental data. It is revealed that the expansion of AAR and compressive strength increase with time. The proposed combination of the time variations of chemical and mechanical parameters provides a satisfactory prediction of the concrete strength. Seismic analysis of the aged Koyna dam is conceded for two different long-term experimental data of concrete incorporating the proposed AAR based properties. The responses of aged Koyna dam reveal that the crest displacement of the Koyna dam significantly increases with time while the contour plots show that major principal stress at neck level reduces with time. As the modulus of elasticity decreases with ages the stress generated in the concrete structure get reduces. On the other hand with lesser value of modulus of elasticity the structure becomes more flexible and the crest displacement becomes very high that cause the seismic safety of the dam reduce.

**Keywords:** degradation of concrete; alkali-aggregate reaction; aged concrete dam; thermo-chemical reaction; compressive strength of aged concrete; numerical modeling

## 1. Introduction

A huge lifeline structure like concrete gravity dam is constructed of plain cement concrete. One of the main purposes of constructing a concrete gravity dam is to support the reservoir water lying adjacent to the dam. Due to the direct contact of the concrete with the supporting reservoir water over a long period (generally the design life of the gravity dam is considered to be 100 years), a severe degradation in the concrete strength is observed by the hydro-chemo-mechanical actions. Therefore, the degradation effects to the concrete strength need to consider in the concrete design to analyse the safety of the structure dam. Another important phenomenon is that the concrete gains strength with time. In general, the strength gaining after 28 days is considered as the full strength of the concrete.

However, several studies showed that the strength of the concrete develops beyond 28 days, and it progresses with time attaining a constant value. Therefore, to investigate the behavioural characteristics of an aged concrete gravity dam, both of the issues above need to be carefully considered.

Theoretically, the strength of concrete enhances due to its age. This concept was developed by Washa *et al*. (1989) based on the experimental observations on cylindrical mould where the concrete was stored for 50 years. Later on, this pioneering work of Washa *et al*. (1989) was followed by several researchers to obtain empirical relationships between the compressive strength and age of the concrete to study the strength gaining process of concrete gravity dams over time. In proposing the empirical equations, the previous investigators did not consider the degradation effect due to thermal or chemical factors to the concrete.

The durability of concrete occurs due to the environmental effects, such as moisture, thermal and chemical processes on the long-term behaviour structures. Bangert *et al*. (2003) developed a mathematical model to study the effects of moisture, heat and chemical dissolution process on the long-term behaviour of concrete structures. Kuhl *et al*. (2004b) focused on the coupled chemo-mechanical model relating the relations of mechanical damage and calcium leaching in cementitious materials on a macroscopic level. They developed their model based on the porosity concept which was described in terms of the chemical dissolution, mechanical damage and the

*Corresponding author, Ph.D.
E-mail: nikzainabnikazizan@gmail.com
[a]Ph.D.
E-mail: angshuman.mandal8@gmail.com
[b]Professor
E-mail: taksiah@usm.my
[c]Professor
E-mail: dmaity@civil.iitkgp.ernet.in
[d]Ph.D.
E-mail: cefmn@usm.my


http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

assumptions of chemical and mechanical potentials within the theory of mixtures and thermodynamics.

Gogoi and Maity (2007) used the experimental data of Washa *et al*. (1989) and constructed an empirical expression to predict the gain in compressive strength in concrete over a long period of time. They also followed the mathematical model given by Kuhl *et al*. (2004b) to evaluate the degradation index for varying time and proposed the relationship between the degraded elastic modulus and the initial elastic modulus. They further extended their study by implementing the degraded elastic modulus value into the numerical model of concrete gravity dams and the dam-reservoir coupled system. Their study indicated that a proper assessment of the ageing effect is crucial for the safety evaluation of concrete gravity dams during their lifetime. Burman *et al*. (2011) studied the long-term impact to the concrete by considering the correlation between dam and foundation. Their model is capable of capturing the time-dependent deterioration caused by the aspects of environmental and mechanical loadings that affect to concrete.

The Alkali-aggregate reaction (AAR) is the chemical reaction of alkali in concrete and alkaline mineral in aggregate to form the hygroscopic gel. The hygroscopic gel absorbs water causing the expansion of AAR and creates the cracking in concrete. The expansion of AAR takes place when the structure is surrounded with moisture, such as in the case of a concrete gravity dam. The structures exposed by the expansion of AAR affect the workability and stability of concrete that may cause the catastrophic failure. The rate of deterioration of concrete enhances due to the expansion of AAR, freezing and thawing processes.

There is a few way to consider the AAR effects to concrete either experimental test or mathematical model. The experimental test was conducted by Larive (1998) to identify the expansion of AAR over time by considering the thermal effect. The experimental observation of Larive (1998) showed that the AAR enhances with time. This fact also was also approved by Latifee and Kabir (2015). They presented a mathematical model to predict the long-term alkali-silica reaction (ASR) based on the experimental test which was Miniature Concrete Prism Test (MCPT). The concrete was tested from 3 to 84 days to find the percentage the expansion of ASR. The spline function proposed by the authors is one of the methods to generate the parametric curve, which is close to the experimental data. The duration of the expansion of ASR in their experiment was from 56 to 84 days to predict the long-term ASR in concrete.

A few researchers developed their numerical model based on this experimental test. Grimal *et al*. (2010) developed a numerical model based on finite element method in order to assess the mechanical behaviour of the damaged structures. The phenomena involving concrete creep, the stress induced by the formation of AAR gel and the mechanical damage were incorporated into their model. Cusatis *et al*. (2015) proposed a mathematical model based on a multi-scale multi-physics framework to simulate of ASR for concrete structures which are exposed to wet environments, for example, the dam structures are usually attacked by the ASR. In their study, they accounted for the effect of humidity by combining the mechanical behaviour of concrete with ASR, creep, and shrinkage. The different environmental conditions were considered as temperature, moisture and concrete ageing. Saouma *et al*. (2014) proposed a numerical model for the kinetics of ASR with time by using a petrographic method to identify the reactions rate of ASR. There are two major groups in the micromechanical model of ASR in concrete, namely (i) early-expansion ASR with reaction rims and (ii) late-expansion ASR without reaction rim but with localised reaction inside the aggregate.

Pan *et al*. (2013b) initiated the chemo damage modelling and cracking analysis of AAR-affected concrete dams. They studied the combination of the plastic-damage model for concrete with the AAR kinetic law. The Fontana Dam was analysed based on expansion deformation and the cracking process of AAR. It was found that the AAR is increased with time by considering the data from Fontana Dam over a period of 20 years. The studies were continued on 2013 (Pan *et al*. 2013a) by proposing a mathematical model to predict anisotropic swelling and cracking of AAR-affected to concrete arch dams. The model combined the chemical and mechanical effect by considering the AAR kinetic and the plastic-damage model. The case study for this research was the Kariba dam, in which a severe crack occurred after the dam operation for 52 years on the downstream area close to foundation dam. Pan *et al*. (2014) presented an integrated approach to the long-term behaviour and the consequence of seismic to the concrete dam influenced with AAR. The analysis was carried out using the finite element method combining the AAR kinetic, the creep impacts and the plastic-damage. This study considered the temperature effect, environmental moisture, and also the condition of stress by the AAR expansion.

The present study focuses on the various strength of concrete over time affecting the workability of concrete gravity dam under the action of several environmental processes over time. The parameters included in this study are the chemical and mechanical damage that can reduce the strength of concrete. Finally, the empirical equations for the variations of (i) expansion of AAR with time, (ii) compressive strength with time (without considering the chemical and mechanical damage), (iii) modulus of elasticity with time and (iv) modulus of elasticity with compressive strength are proposed. Thus, the novelty of this study is to propose empirical relationship to identify the concrete strength due to degradation, which is influenced by AAR and mechanical loading depending on the age of concrete.

## 2. Numerical modelling

### *2.1 Modelling of dam*

The structure of the dam has an elongated geometry with constant cross section. The structure of dam can be determined with plane strain condition cause of the loading position do not differ in along the trend. The stress-strain relationship can be written as

$$\{\sigma\} = [D]\{\varepsilon\} \tag{1}$$

Here, $\{\sigma\}^T=\{\sigma_x, \sigma_y, \tau_{xy}\}$ is the stresses and $\{\varepsilon\}^T=\{\varepsilon_x, \varepsilon_y, \gamma_{xy}\}$ is the strains. $[D]$ is the constitutive matrix described as

$$[D] = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix} 1-\nu & \nu & 0 \\ \nu & 1-\nu & 0 \\ 0 & 0 & (1-2\nu)/2 \end{bmatrix} \tag{2}$$

where $v$ is the Poisson's ratio, and $E$ is the modulus of elasticity. The response of degradation concrete strength is based on the decrease in the net area being able of supporting the stresses. The measurement of the extent of damage in concrete to determine the orthotropic index as Ghrib and Tinawi (1995)

$$d_{gi} = \frac{\Omega_i - \Omega_i^d}{\Omega_i} = 1 - \frac{\Omega_i^d}{\Omega_i} \tag{3}$$

where $\Omega_i$ is the small space of the face in the $i$-th direction and $\Omega_i^d$ is the space influenced by deterioration. The ratio of degradation lies between 0 and 1, in which $d_i$=0 represent no degradation and $d_i$ = 1 signifies fully degraded material. The index $i$ for $i$=1, 2 relates to the Cartesian axes $x$ and $y$ in the two-dimensional case. The proportion of the net area over the geometrical area may differ for each direction for this case. The equation below showed the effective plane strain material matrix

$$[D_d] = \frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix} (1-\nu)\Lambda_1^2 & \nu\Lambda_1\Lambda_2 & 0 \\ \nu\Lambda_1\Lambda_2 & (1-\nu)\Lambda_2^2 & 0 \\ 0 & 0 & (1-2\nu)\Lambda_1^2\Lambda_2^2/\left(\Lambda_1^2+\Lambda_2^2\right) \end{bmatrix} \tag{4}$$

where $\Lambda_1$=(1–$d_{g1}$) and $\Lambda_2$=(1–$d_{g2}$). In Eq. (4), $E_d$ is the modulus of elasticity of material without degradation. If $d_{g1} = d_{g2} = d_g$, the isotropic degradation model is stated as

$$[D_d] = (1-d_g)^2[D] \tag{5}$$

where $[D_d]$ and $[D]$ are the degraded and without degraded model of the constitutive matrices.

### *2.2 Evaluation of degradation index*

By considering the chemical and mechanical effects to the concrete, the compressive strength of concrete is predictable to decline with age. However, the compressive strength of concrete increases with its age. In this study, by considering the factors above as experimental data to simulate the concrete strength.

To consider the damaging of concrete dam effect by chemical and mechanical degradation, the total porosity of concrete is considered as a measure to determine the degradation parameter. The total porosity ($\phi$) is defined as the sum of the initial porosity ($\phi_0$), the chemical porosity resulting from skeleton dissolution ($\phi_c$) and the apparent mechanical porosity ($\phi_m$). Kuhl *et al*. (2004a) proposed a procedure to estimate the total porosity as follows

$$\phi = \phi_0 + \phi_c + \phi_m \tag{6}$$

The consideration of apparent mechanical porosity $\phi_m$ is due to the opening and propagation of micro-cracks in the material. The $\phi_m$ is defined as

$$\phi_m = [1-\phi_0-\phi_c]d_m \tag{7}$$

where the scalar degradation factor is $d_m$. The strain-based exponential degradation function as evaluated by Gogoi and Maity (2007) is expressed as

$$d_m = a_s - \frac{K^0}{K}\{1-\alpha_c+\alpha_c\exp[\beta_c(K^0-K)]\} \tag{8}$$

where $K^0$ is the variable representing the initial degradation status, and $K$ is the internal variable defining the current degradation status. The internal variable $K$ depends on the loading history of the material, whereas $K^0$ is determined by $f_t/E_0$, where $f_t$ is the static tensile strength and $E_0$ is the elastic modulus without degraded material afore several of mechanical loading applied. The $\beta_c$ appearing in Eq. (4) can be obtained experimentally (Bangert *et al*. 2003).

Then by considering chemical porosity resulting only due to AAR, then $\phi_c$ can be expressed as

$$\phi_c = d_{aar} \tag{9}$$

where, $d_{aar}$ is the damage due to the AAR in terms of the expansion strains. The $d_{aar}$ can be determined as Capra and Sellier (2003)

$$d_{aar} = \frac{\varepsilon_{aar}}{\varepsilon_{aar}+0.003} \tag{10}$$

The AAR kinetics controls the volumetric expansion of concrete during the reaction period. In this study, the AAR extent $\xi$ reaction concrete verified by Pan *et al*. (2014) is as follows

$$\xi(t,T,h) = f(h)\frac{1-\exp\left[-\dfrac{t}{\tau_c(T)}\right]}{1+\exp\left[-\dfrac{(t-\tau_L(T))}{\tau_c(T)}\right]} \tag{11}$$

where the real physical time is t, the responsive temperature is $T$, and the environmental moisture represents $0 \le h \le 1$, $\tau_c$ is the characteristic time and $\tau_L$ is the latency time of the AAR expansion. The scale of the AAR extent $\xi$ lies between 0 and 1, in which is $\xi$=0 and $\xi$=1 represent the initiation and the completion of AAR, respectively.

The time constants are specified based on the Arrhenius relation from the experimental conducted by Ulm *et al*., (2000)

$$\tau_c(T) = \tau_c(T_0)\exp\left[U_c\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \tag{12}$$

$$\tau_L(T) = \tau_L(T_0)\exp\left[U_L\left(\frac{1}{T}-\frac{1}{T_0}\right)\right] \tag{13}$$

where $T_0$ is the temperature at which the test is conducted, $U_c$ and $U_L$ are the activation energies at the characteristic time $\tau_c$ and at the latency time $\tau_L$, separately. The values of the activation energies are determined based on Pan *et al*. (2013a)

$$U_c = 5400 \pm 500K \tag{14}$$

$$U_L = 9400 \pm 500K \tag{15}$$

It is observed that the state of stress for the AAR influenced to the concrete has a long-lasting impact on the expansion performance (Multon and Toutlemonde 2006). The expansion of AAR strains is described by restructuring the volumetric expansion strain by considering a weight function Pan *et al*. (2014) as given by

$$\varepsilon_{aar}(t) = \xi(t,T)\varepsilon_v^\infty W(\sigma) \tag{16}$$

where $\varepsilon_v^\infty$ is the material constant that specifies the maximal volumetric expansion strain induced by AAR in the stress-free experiment and $W(\sigma)$ is the weight function of the principle stress, $\sigma$.

According to Pan *et al*. (2014), the degradation of the modulus elasticity $E_m$ and the tensile strength $f_t$ are studied based on the AAR damage factor as follows

$$E_m = E_0\left(1 - d_{aar}\right) \tag{17}$$

$$f_t = f_{t0}(1 - d_{aar}) \tag{18}$$

Following Atkins (2006), the variation of the degradation index $d_g$ with respect to time is expressed as

$$d_g = 1 - \exp\left(\frac{t_a}{\tau_a}\right) \tag{19}$$

Here, $\tau_a$ corresponds to the characteristic age or the design life of the structure and $t_a$ indicates the age at whichever the degradation index is to be defined. The relation between $E$ and $E_0$ can be established as $E_m=(1-d_g)E_0$. Here, $E_m$ is the degraded elastic modulus expected effect by the porosity of concrete and $E_0$ is the elastic modulus of without degradation concrete, counting the strength increase at a certain age. Referring to Gogoi and Maity (Gogoi and Maity 2007), the difference of degradation over the time is defined as

$$E_m = (1-\phi)^{t_a/\tau_a} E_0 \tag{20}$$

The isotropic degradation index as defined in Eq. (14) can be modified using Eq. (15) as

$$d_g = 1 - \frac{E_m}{E_0} \tag{21}$$

The static elastic modulus (SI units) of the concrete can be determined from the following relationship

$$E_0 = 4733\sqrt{f(t_a)} \tag{22}$$

where $t$ is the age in years and $f(t_a)$ is the gain in compressive strength. The gain in compressive strength of concrete in SI units was experimentally determined by Washa *et al*. (1989), Dolen (2005) in the following forms

Washa *et al*. (1989); $f(t_a) = 3.57\ln(t_a) + 44.33$ (23)

Dolen (2005); $f(t_a) = 1.51\ln(t_a) + 31.79$ (24)

### *2.3 Gain in expansion of AAR, $\varepsilon_{aar}$ and compressive strength with Age*

According to Pan *et al*. (2013b) the expansion of AAR increases due to age. The curve fitting method was used to predict empirically by counting this phenomenon. The 52 years of Kariba arch dam data published by Pan *et al*. (2013a) were studied. The parameters concerning to the AAR kinetics, as utilized in this study are as follows: $\tau_L$=25 years, $\tau_c$=22 years and $\varepsilon_v^\infty$=0.0028. The average yearly temperature at the site is considered as 27°C with low seasonal variations. The incremental time step is selected as 14 days for the entire duration of 52 years.

The data for expansion of AAR were analysed using a least square curve fitting produced by Pan *et al*. (2013a, 2014). Here a brief overview of the least square curve fitting approach is demonstrated briefly. In engineering problems, an experiment produces a set of data points ($x_1$, $y_1$),…, ($x_n$, $y_n$), where the perpendicular distance of a point from the vertical axis $\{x_k\}$ are different. Whereas selecting the specific mathematical function using the sets of experimental data to produced the curve fitting, the physically meaningful parameters are necessary to include in the mathematical function. The current study, we obtain to propose a mathematical function occupying the time (in years) and the expansion of AAR. The experimental data was extracting by a mathematical function of the form $y=f(x)$, some errors are predictable due to the test conditions. Therefore, the actual value of $f(x_k)$ satisfies (Mathews 1992)

$$f(x_k) = y_k + e_k \tag{25}$$

where $e_k$ is the measured error. Some of the methods that provide a quantitative understanding of the data scatter from the curve $y_{ls}=f(x)$ are as follows

Maximum error: $E_\infty(f) = \max_{1\le k\le N}\{|f(x_k) - y_k|\}$

Average error: $E_1(f) = \frac{1}{N}\sum_{i=1}^{N}|f(x_k) - y_k|$

Root-mean-square error: $E_2(f) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}|f(x_k) - y_k|^2}$ (26)

By selecting one on the quantities in Eq. (26), the best curve fitting line is identified. Between the three options are given in Eq. (26), $E_2(f)$ is chosen because of the minimum errors compare to the others. The least squares line is the line that minimises the root-mean-square error $E_2(f)$, and it is given by

$$y_{ls} = f(x) = Ax + B \tag{27}$$

In Eq. (28), the $N$ sets of experimental data can be identify $A$ and $B$ as given by

$$\begin{Bmatrix} B \\ A \end{Bmatrix} = \begin{pmatrix} N & \sum_{i=1}^{n} x_i \\ \sum_{i=1}^{n} x_i & \sum_{i=1}^{n} x_i^2 \end{pmatrix}^{-1} \begin{Bmatrix} \sum_{i=1}^{n} y_i \\ \sum_{i=1}^{n} (x_i y_i) \end{Bmatrix} \tag{28}$$

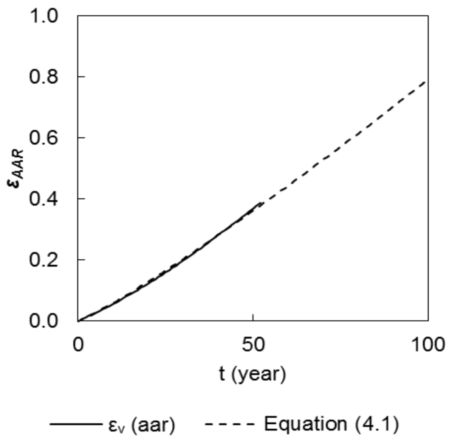



Fig. 1 Curve fitting of experimental data from Pan *et al*. (2013a) for expansion of AAR

The proposed equation for the curve fitting is considered as follows

$$y = Cx^{A} \tag{29}$$

where, $C$=exp($A$). The data linearization for curve is carried out by transforming the points ($x_k$, $y_k$) in the $xy$ plane to ($X_k$, $Y_k$) in the $XY$ plane applying ($X_k$, $Y_k$)=(ln$x_k$, ln$y_k$). Then, the least squares line is fitted to the points ($X_k$, $Y_k$) to obtain the prediction results. The prediction results using Eq. (30) are plotted in Fig. 1, which depicts that the curve has a satisfactory figure with the expansion of AAR data from Pan *et al*. (2013a) for 52 years. As a result, it is determined that equation in the curve can be used to calculate the progression of expansion of AAR over age. The new equation is identified as

$$\varepsilon_{AAR} = 0.00435t^{1.1163} \tag{30}$$

The expectation for compressive strength of concrete over age is gain by interpolating the data for compressive strength reported by Washa *et al*. (1989), Dolen (2005). The experimental data based on aged concrete gravity dam is considered as 50 years data for Washa *et al*. (1989) and 60 years data from Dolen (2005). The resulting curves are shown in Fig. 2. It is evident that the $f(t_a)$ curves as depicted in Fig. 2, obtained from the regression fittings of the experimental data have the same pattern. The equations for the proposed curve fittings using the experimental data are

$$f(t_a) = 2.54 \ln t_a + f_{ck} \tag{31}$$

## 3. Results and discussion

### 3.1 Numerical equations

The time variations of the modulus of elasticity $E$ of concrete without considering and with considering degradation from several studies along with the present study are plotted in Figs. 3 and 4. To construct Figs. 3 and 4, the experimental data are taken from Washa *et al*. (1989) and Dolen (2005), respectively. Both of the figures show

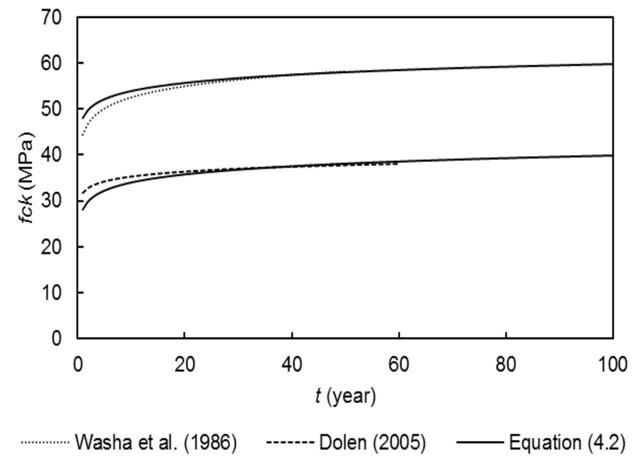



Fig. 2 Curve fitting of experimental data from Washa *et al*. (1989), Dolen (2005) for compressive strength

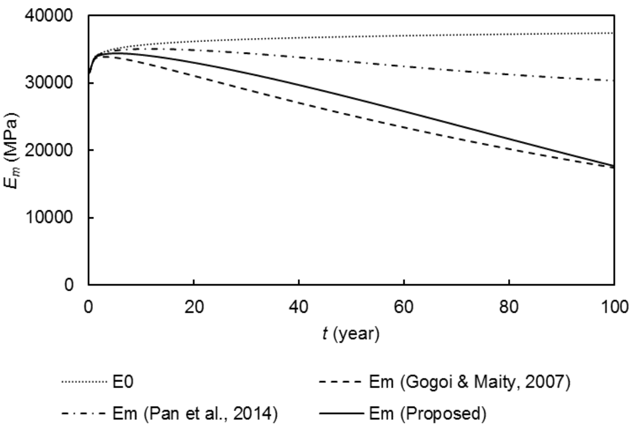



Fig. 3 Modulus of elasticity based on Washa *et al*. (1989) data

Table 1 Summary of the results of modulus of elasticity

| Eq. | Modulus of elasticity (in MPa) | 28 days | 1 yr | 25 yrs | 50 yrs | 75 yrs | 100 yrs |
|---|---|---|---|---|---|---|---|
| Washa *et al*. (1989) | $E_0$ | 30485.83 | 32794.60 | 35477.28 | 36028.84 | 36347.60 | 36572.08 |
| | $E_m$ (Gogoi and Maity 2007) | 30467.94 | 32544.55 | 29298.64 | 24572.22 | 20472.32 | 17011.32 |
| | $E_m$ (Pan *et al*. 2014) | 30482.10 | 32741.91 | 33801.26 | 32311.95 | 30739.05 | 29581.44 |
| | $E_m$ (Proposed) | 30476.30 | 32660.47 | 31439.23 | 27100.28 | 22171.13 | 17266.74 |
| Dolen (2005) | $E_0$ | 21990.92 | 25093.83 | 28510.56 | 29194.03 | 29586.52 | 29861.87 |
| | $E_m$ (Gogoi and Maity 2007) | 21978.01 | 24902.49 | 23545.22 | 19910.78 | 16664.23 | 13890.10 |
| | $E_m$ (Pan *et al*. 2014) | 21988.23 | 25053.51 | 27163.66 | 26182.25 | 25021.23 | 24153.87 |
| | $E_m$ (Proposed) | 21984.04 | 24991.19 | 25265.47 | 21959.26 | 18047.04 | 14098.66 |

that the pattern of the curve is similar. It is to be noted that Pan *et al*. (2014) studied the degradation of concrete only by considering the AAR effect with time. On the other hand, Gogoi and Maity (2007) studied the combination of AAR and the mechanical effect on the concrete. However, Gogoi and Maity (2007) considered the chemical parameter as a fixed value over the age. In this study, a combination of the parameters defining the chemical and mechanical

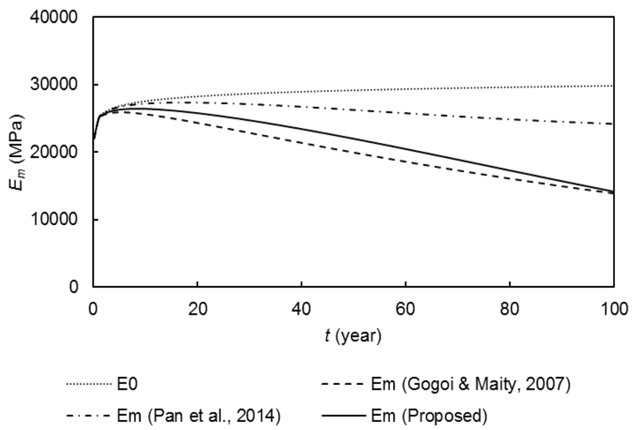



Fig. 4 Modulus of elasticity based on Dolen (2005) data

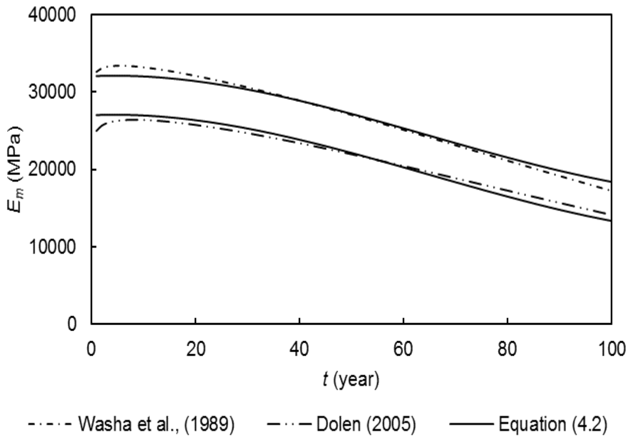



Fig. 5 Degradation concrete with time

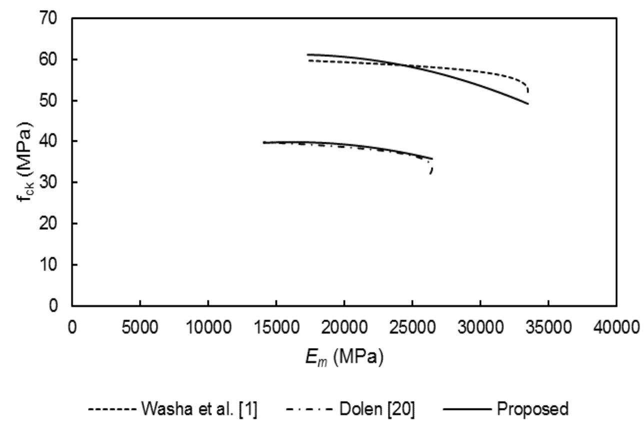



Fig. 6 Degradation concrete with compressive strength

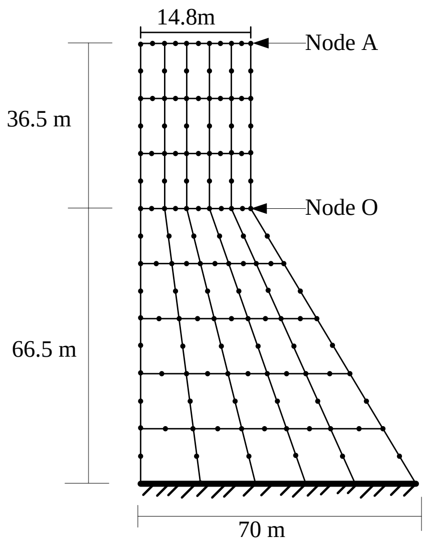



Fig. 7 Geometry and finite element discretization of Koyna dam

effects with time are studied to identify the degradation of concrete. The combination mention before is more reasonable because of the damage due of concrete gain over the age. Table 1 summarises the results of the modulus of elasticity based on the experimental data of compressive strength reported by Washa *et al*. (1989), Dolen (2005).

The variations of the modulus of elasticity resulting from the degradation of concrete due to the chemical and mechanical effects over time are shown in Fig. 5. The results of the abovementioned plot are based on a mathematical model from Washa *et al*. (1989), Dolen (2005) and used to identify the compressive strength without degradation over the age. The data were analysed by using curve fitting to predict the suitable mathematical equation for the modulus of elasticity over the age as shown in Fig. 5. Eqs. (32) and (33) can be used to predict the strength of the concrete based on the aged of concrete. The unit of time in this study is considered in years.

$$E_m(t_a) = 0.0175t_a^3 - 3.4054t_a^2 + 29.807t_a + E_m \qquad (32)$$

Furthermore, the equations of compressive strength of concrete as a function of the modulus of elasticity due to degradation are obtained based on the studies of Washa *et al*. (1989), Dolen (2005). They are given by

$$f_{ck}(t_a) = -4\times10^{-8} E_m^2(t_a) + 0.0013E_m(t_a) + f_{ck} \qquad (33)$$

Eq. (33) are plotted in Fig. 6. These equations can be used to predict the compressive strength of concrete for five years and above

### *3.2 Numerical investigation of the Koyna dam responses*

In order to investigate the dynamic response for the old concrete gravity dam which is Koyna dam and plane strain formulation has been considered.

The simplified geometry as proposed by Gogoi and Maity (2007) has been considered for the present study. The geometric configuration and the finite element discretization are shown in Fig. 7. The crest displacement response (node A) and the neck level (node O) major and minor stress responses are evaluated. The stress contours at different age level are also obtained. The material properties are considered as: mass density $\rho_d$=2415.816 kg/m$^3$ and Poisson's ratio $\nu_d$=0.235. Structural damping is considered as 3%, and the modulus of elasticity $E_m$ is considered from the proposed values of Table 1. The dam base is considered to be rigid, and the reservoir effect has been neglected in the present study.

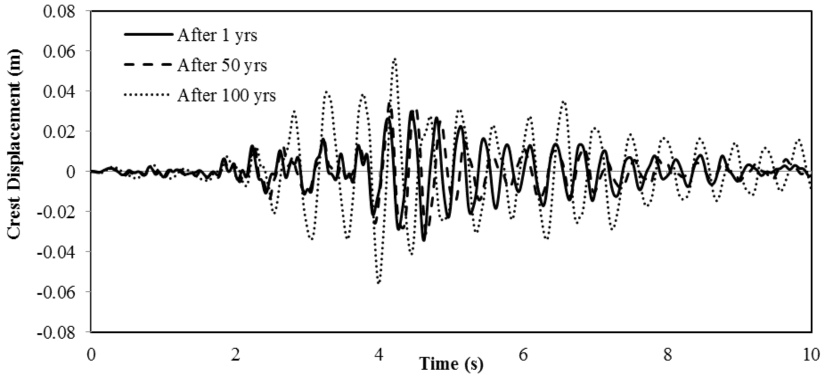



Fig. 8 Crest displacement of the Koyna dam at different age level from Washa *et al*. (1989)

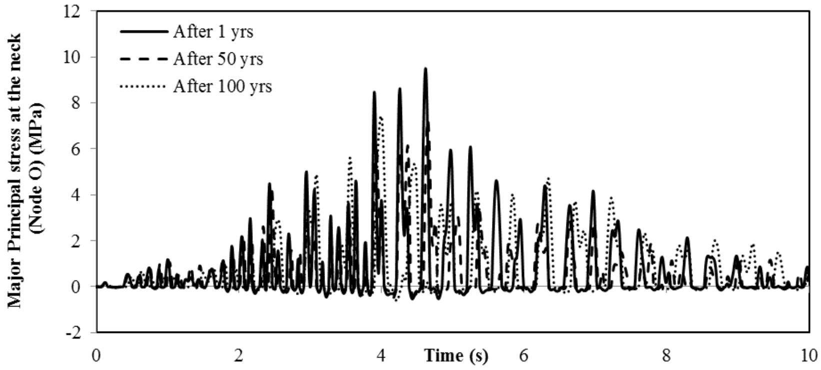



Fig. 9 Major principal stress for different age level from Washa *et al*. (1989)

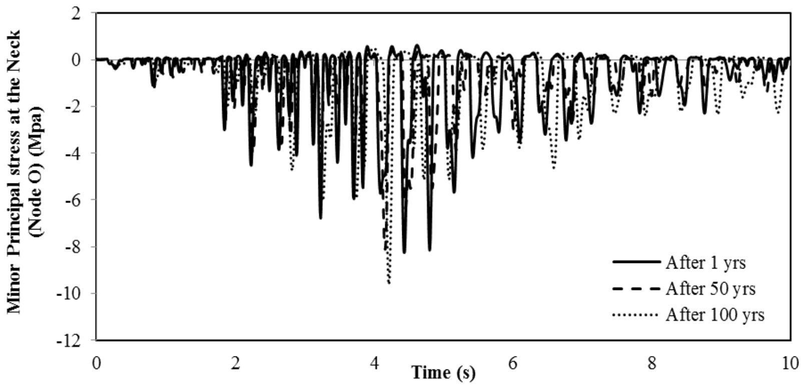
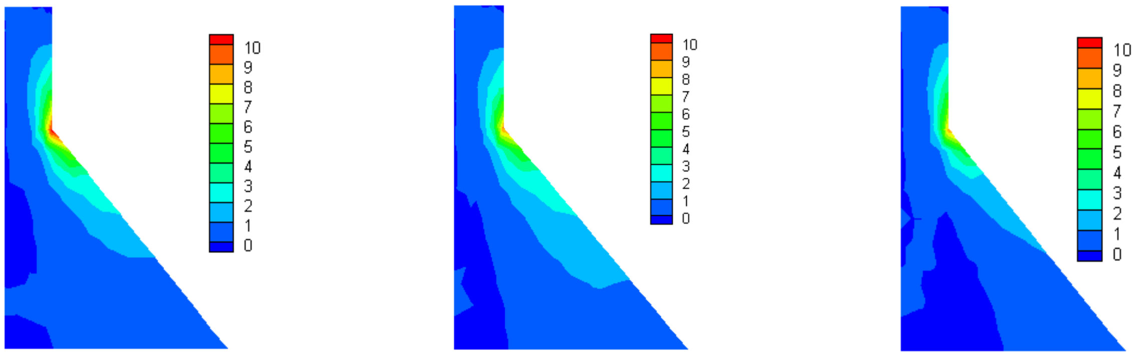



Fig. 10 Minor principal stress for different age level from Washa *et al*. (1989)

Now in order to investigate the dynamic behaviour for Koyna dam the limitation degradation of the concrete material is considered based on the environmental factors and mechanical loadings that effect to the structure for 100 years of design life. Initially, the structure without any degradation analysis is carried by considering the concrete strength for 28 days as the completion of the construction. For the first numerical investigation the degraded elastic moduli $E_m$ from the proposed values of Table 1 based on Washa *et al*. (1989) study.

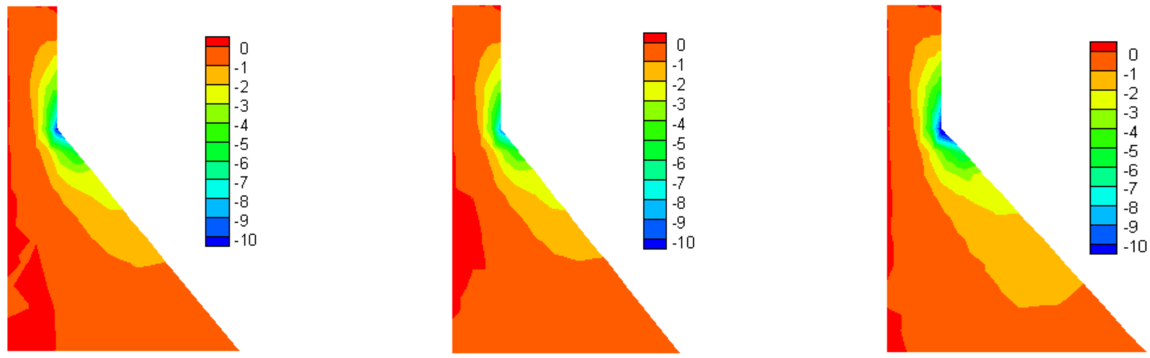
Crest displacement, neck level major and minor principal stresses for the three different age levels such as 1yrs, 50yrs and 100yrs have been plotted in Figs. 8-10. Fig. 8 shows the maximum crest displacement after 1 years is 31.04 mm and then the crest displacement increase about 3 percent which is approximately 31.84 mm for the dam aged after 50 years. When the concrete dam reached 100 years, the maximum crest displacement increase drastically to 53.43 mm which is the different with 50 years about 66 percent. The results of crest displacement shows that the displacement increase drastically with age due to mechanical and chemical reactions affecting the strength of the concrete. Contour plots for maximum major and minor principal stresses for three different age levels are provided in Figs. 11-12. The figures illustrate more clearly the behaviour of concrete dam due to aged which are the maximum principal stress contour reduce and increase for the minimum principle stress with age of concrete.

For the sec nd numerical investigation has been carried out considering the degraded elastic moduli $E_m$ from the




After completion of construction After 50 years After 100 years

Fig. 11 Maximum major principal stresses contours of Koyna dam for three different age level (Washa *et al*., 1989)




After completion of construction After 50 years After 100 years

Fig. 12 Maximum minor principal stresses contours of Koyna dam for three different age level (Washa *et al*., 1989)

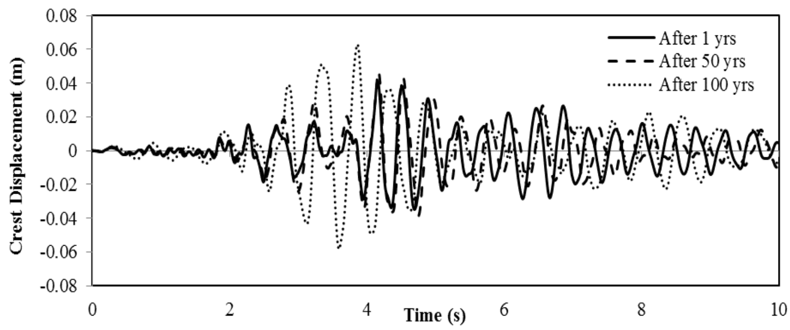



Fig. 13 Crest displacement of the Koyna dam at different age level from Dolen (2005)

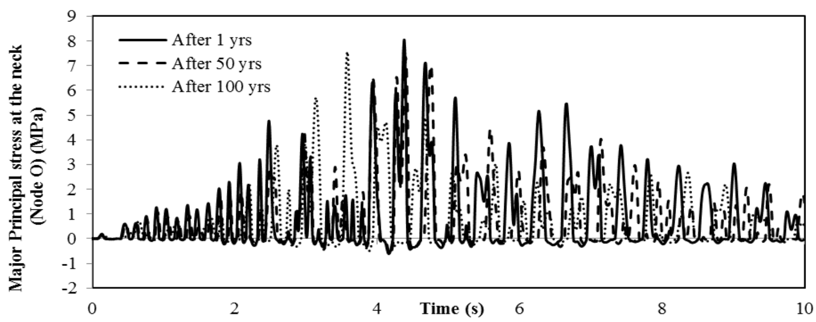



Fig. 14 Major principal stress for three different age level from Dolen (2005)

proposed values of Table 1 based on Dolen (2005) study. Crest displacement, neck level major and minor principal stresses for the three different age level have been plotted in Figs. 13-15. Fig. 13 shows the maximum crest displacement after 1 years is 40.03 mm and then the crest displacement increase about 9 percent which is approximately 37.03 mm for the dam aged after 50 years. When the concrete dam reached 100 years, the maximum crest displacement

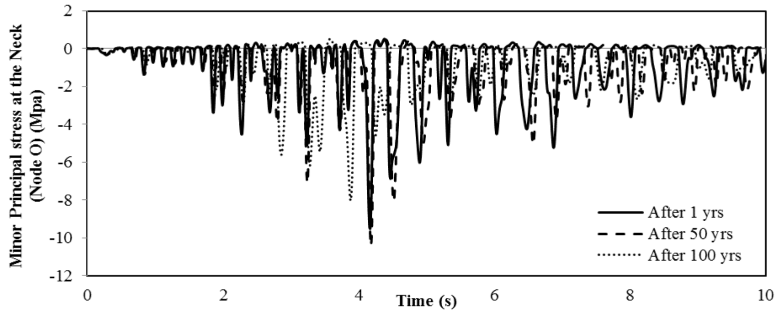
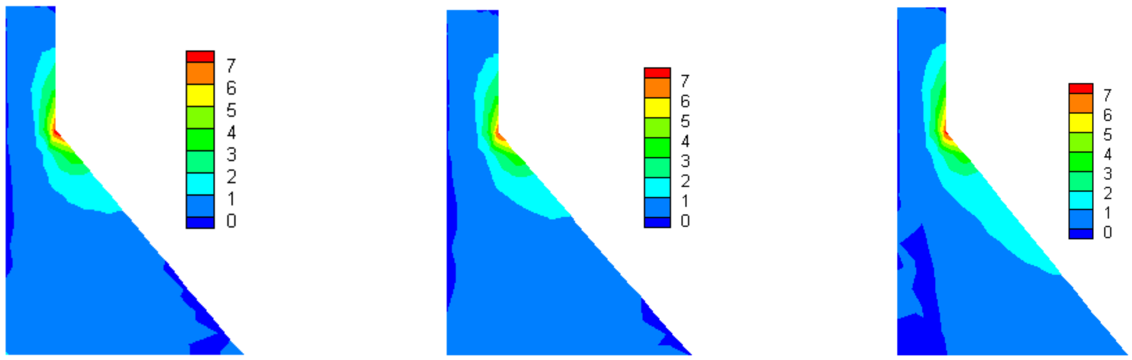
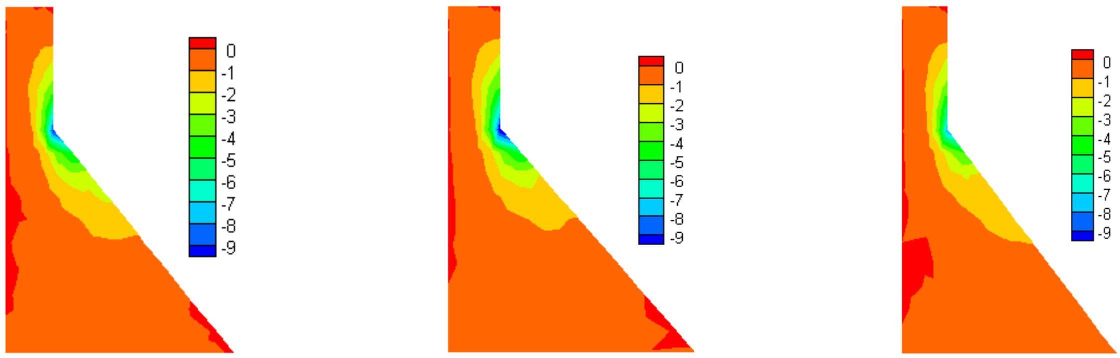



Fig. 15 Minor principal stress for three different age level from Dolen (2005)




After completion of construction After 50 years After 100 years

Fig. 16 Maximum major principal stress contours for three different age level from Dolen (2005)




After completion of construction After 50 years After 100 years

Fig. 17 Maximum minor principal stress contours for three different age level from Dolen (2005)

increase drastically to 63.09 mm which is the different with 50 years about 45 percent. The results of crest displacement shows that the displacement increase drastically with age due to mechanical and chemical reactions reduce the strength of the concrete. As the strength of concrete decrease with ages the structure become more flexible and the crest displacement becomes very high. Contour plots for maximum major and minor principal stresses for three different age levels are provided in Figs. 16-17. The figures illustrate more clearly the behaviour of concrete dam due to aged which are the principal stress contour reduce with age of concrete. As the concrete strength decreases with ages, the stress generated in the concrete structure reduce. This results shows that the deterioration effect to the concrete gravity dam reduce the concrete strength that cause the crest displacement very high and the structure may collapse due to seismic loadings.

## 4. Conclusions

The study focuses on the degradation of concrete with age due to the expansion of AAR that affects the strength of concrete. The expansion of AAR increases with time (Fig. 1). The experimental data taken from the previous researchers are analysed by using curve fitting method to obtain suitable mathematical equations. The first numerical relation was $\varepsilon_{AAR}$=0.00435 $t^{1.1163}$ is easily identified due to the expansion of AAR at various ages of concrete. This finding provides a new understanding of the effects of amplified ARR with the time. The change of modulus elasticity of concrete with and without degradation is studied. The equations for the variations of the modulus of elasticity with time for the degraded concrete are proposed by considering the chemical and mechanical damage over the ages (Figs. 3 and 4). The combination of the time variations of chemical and mechanical parameters provides a reasonable prediction of the concrete strength. The second proposed equation is $f(t_a)=2.54\ln t_a+f_{ck}$ to predict the compressive strength of concrete as a function of the age of the concrete in the design stage or to check the concrete strength for existing structure. The third proposed equation is $E_m(t_a)=0.0175t_a^3-3.405t_a^2+29.807t_a+E_m$ to predict the modulus of elasticity with time by considering the chemical and mechanical damage over the ages. The developed mathematical expressions predict the concrete strength as a function of the age of the concrete. The modulus of elasticity over ages represents the combined action of mechanical porosity and AAR show that the strength of concrete reduce with age. Seismic analysis of the aged Koyna dam has been carried out using two different long-term experimental data of concrete. From the aged Koyna dam responses, it is observed that the crest displacement of the Koyna dam is increased over the ages and on the other hand from the contour plots it is noted that neck level major principal stress gets reduced over the ages. As the modulus of elasticity decreases with ages the stress generated in the concrete structure get reduces. On the other hand with lesser value of modulus of elasticity the structure becomes more flexible and the crest displacement becomes very high that cause the seismic safety of the dam reduce. It may concluded that by applying the proposed AAR based degradation evaluation process to predict the safety level of the old concrete gravity dam in order to remedial measures can take action at the early stages of the existing dam for surviving from future earthquakes.

## Acknowledgments

The Authors wish to thank the Universiti Malaysia Perlis (UniMAP) and Minister of High Education (MOHE) for supporting the research. We would like to thank the anonymous reviewers for suggestions and comments.

## References

Atkins, P. (2006), *Physical Chemistry*, W.H Freeman and Company, New York.

Bangert, F., Grasberger, S., Kuhl, D. and Meschke, G. (2003), "Environmentally induced deterioration of concrete: physical motivation and numerical modeling", *Eng. Fract. Mech.*, **70**, 891-910.

Burman, A., Maity, D., Sreedeep, S. and Gogoi, I. (2011), "Long-term influence of concrete degradation on dam-foundation interaction", *Int. J. Comput. Meth.*, **8**(3), 397-423.

Capra, B. and Sellier, A. (2003), "Orthotropic modelling of alkali-aggregate reaction in concrete structures: Numerical simulations", *Mech. Mater.*, **35**(8), 817-830.

Cusatis, G., Alnaggar, M. and Rezakhani, R. (2015), "Multiscale modeling of alkali silica reaction of concrete", *RILEM International Symposium on Concrete Modelling*, Eds. K. Li, P. Yan, and R. Yang, RILEM Publication SARL.

Dolen, T.P. (2005), *Materials Properties Model of Aging Concrete*.

Ghrib, F. and Tinawi, R. (1995), "An application of damage mechanics for seismic analysis of concrete gravity dams", *Earthq. Eng. Struct. Dyn.*, **24**, 157-173.

Gogoi, I. and Maity, D. (2007), "Influence of sediment layers on dynamic behavior of aged concrete dams", *J. Eng. Mech.*, ASCE, **133**(4), 400-413.

Grimal, E., Sellier, A., Multon, S., Le Pape, Y. and Bourdarot, E. (2010), "Concrete modelling for expertise of structures Affected by alkali aggregate reaction", *Cement Concrete Res.*, **40**, 502-507.

Kuhl, D., Bangert, F. and Meschke, G. (2004a), "Coupled chemo-mechanical deterioration of cementitious materials. Part I: Modeling", *Int. J. Solid. Struct.*, **41**(1), 15-40.

Kuhl, D., Bangert, F. and Meschke, G. (2004b), "Coupled chemo-mechanical deterioration of cementitious materials. Part II: Numerical methods and simulations", *Int. J. Solid. Struct.*, **41**(1), 41-67.

Larive, C. (1998), "Apports combin'es de l' experimentation et de la modélisation à la comprehen- sion del alcali- réaction et de ses effets mécaniques", Laboratoire Central des Ponts et Chaussées, Paris. (in French)

Latifee, E.R. and Kabir, M.R. (2015), "Predicting ASR long term expansion through existing test method", *Malaysia J. Civil Eng.*, **27**(2), 180-192.

Mathews, J.H. (1992), "Curve fitting", *Numerical Methods for Mathematics, Science and Engineering*, Prectice-Hall of India, New Delhi.

Multon, S. and Toutlemonde, F. (2006), "Effect of applied stresses on alkali-silica reaction-induced expansions", *Cement Concrete Res.*, **36**(5), 912-920.

Pan, J., Feng, Y., Jin, F. and Zhang, C. (2013a), "Numerical prediction of swelling in concrete arch dams affected by alkali-aggregate reaction", *Euro. J. Environ. Civil Eng.*, **17**(4), 1-17.

Pan, J., Feng, Y., Xu, Y., Jin, F., Zhang, C. and Zhang, B. (2013b), "Chemo-damage modeling and cracking analysis of AAR-affected concrete dams", *Sci. Chin. Technol. Sci.*, **56**(6), 1449-1457.

Pan, J., Xu, Y., Jin, F. and Zhang, C. (2014), "A unified approach for long-term behavior and seismic response of AAR-affected concrete dams", *Soil Dyn. Earthq. Eng.*, **63**, 193-202.

Saouma, V.E., Martin, R.A., Hariri-Ardebili, M.A. and Katayama, T. (2014), "A mathematical model for the kinetics of the alkali-silica chemical reaction", *Cement Concrete Res.*, **68**, 184-195.

Ulm, F.J., Coussy, O., Kefei, L. and Larive, C. (2000), "Thermo-chemo-mechanics of ASR expansion in concrete structures", *J. Eng. Mech.*, **126**(3), 233-242.

Washa, G.W., Saemann, J.C. and Cramer, S.M. (1989), "Fifty-year properties of concrete made in 1937", *ACI Mater. J.*, **86**(4), 367-371.

*CC*