High Performance Concrete Engineering

Homework #3 (Deadline by 6pm on Oct 25th)

Submission of hand-written homework will be accepted.

Total 100 marks

(a) What effect does increasing the rate of loading have on (i) concrete strength (ii) the strain corresponding to peak stress? [10 marks]

(b) What does concrete response as described in the answer to Prob. (a)? [10 marks]

(c) What does the appearance of efflorescence on the surface of a structure imply? [10 marks]

(d) What strategies could you adopt to minimize the corrosion of reinforcing steel in concrete bridge decks? [10 marks]

(e) (Non-handwriting problem) Evaluate the prediction of chloride ion diffusion coefficient (D) given by KCI, ACI, and *fib*. Use below measured data of diffusion coefficients at specific dates to compute aging factor (*m* in KCI and ACI, *a* in *fib*) by linear regression from equation (1).

Days	91	180	365	730	1095
D (10^{-12} m^2/s)	8.3	4.76	4.79	4.24	3.69

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^{m} \qquad \text{Eq. (1)}$$

Compute the prediction of chloride ion diffusion coefficient up to 100 years and discuss the result based on the comparison of different standards. [30 marks]

(f) (Non-handwriting problem) Evaluate the expected service life of nuclear power plant structure made of below concrete mix proportion based on KCI standard.

Spec. Strength (Psi)	W/(C+P) (%)	Water (lb)	Cement (lb)	Fly ash (lb)	Sand (lb)	Coarse Agg. (lb)	HWA (lb)	AEA (lb)
4,000	50	269	435	109	1,347	1,712	2.72	0.14

Cover depth: 75 mm
C_{lim} (kg/m^3) = 1.289
Ci (kg/m^3) = 0.05
C_S (kg/m^3) = 3.0
D_R (10^{-12} m^2/s) = 8.3 at 91 days
m = use obtained value from Prob. (e)

If you need additional information, use appropriate assumptions and specify them. Also, attach relevant code or screen capture that you use for the computation.

High Performance Concrete Engineering HW #3

100

2018-31976
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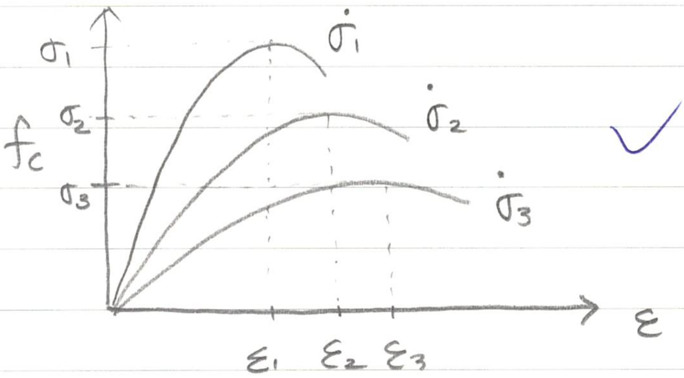
(a) What effect does increasing the rate of loading have on (i) concrete strength (ii) the strain corresponding to peak stress?

- As the rate of loading increases, the concrete strength also increases.
- And the strain corresponding to peak stress decreases as the loading rate increases as below.



loading rate = $\dot{\sigma}$
corresponding strain = ε

$\Rightarrow \quad \dot{\sigma}_1 > \dot{\sigma}_2 > \dot{\sigma}_3$

$\sigma_1 > \sigma_2 > \sigma_3$

$\varepsilon_1 < \varepsilon_2 < \varepsilon_3$

(b) What does concrete response as described in the answer to (a)?

- This is due to that progressive microcracking at sustain loads. A concrete subjected to sustained loading fails at a lower stress than under the instantaneous or short-term loading. Also, the concrete subjected ~~to~~ long-term loading shows the progressive microcracking which induces more deformation (large strain).

(c) What does the appearance of efflorescence on the surface of a structure imply?

- The efflorescemse is the calcium carbomate formation on the surface of a structure. This occurs when water can percolate through the concrete.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

- $CaCO_3$ is shown as a white crust on the surface
- The major problem of efflorescence that it causes an asthetic problem
- Also, it results in the increase of porosity and permeability as well as a decrease of the strength. This is due to that it makes other cementitious constituents decompose

(d) What strategies could you adopt to minimize the corrosion of reinforcing steel in concrete bridge decks?

- The corrosion of reinforcing steel is caused through the destroyed passive film by carbonation and chloride ions
- To prevent the corrosion, the things below can be adopted
  - i) Reduce the porosity of concrete by using mineral admixtures or reducing water-cememt ratio.
  - ii) Add the corrosion inhibitors such as calcium nitrite.
  - iii) Use stainless steel or other reinforcing materials
  - iv) Design the sufficient thickness of concrete cover
  - v) Make an epoxy coating on steel reinforcing bars.
  - vi) Install a protective layer on the top of the concrete.
  - vii) Cathodic protection by attaching the metals that are more reactive than the reinforcing steel.

(e) (Non-handwriting problem) Evaluate the prediction of chloride ion diffusion coefficient (D) given by KCI, ACI, and *fib*. Use below measured data of diffusion coefficients at specific dates to compute aging factor (m in KCI and ACI, a in *fib*) by linear regression from equation (1).

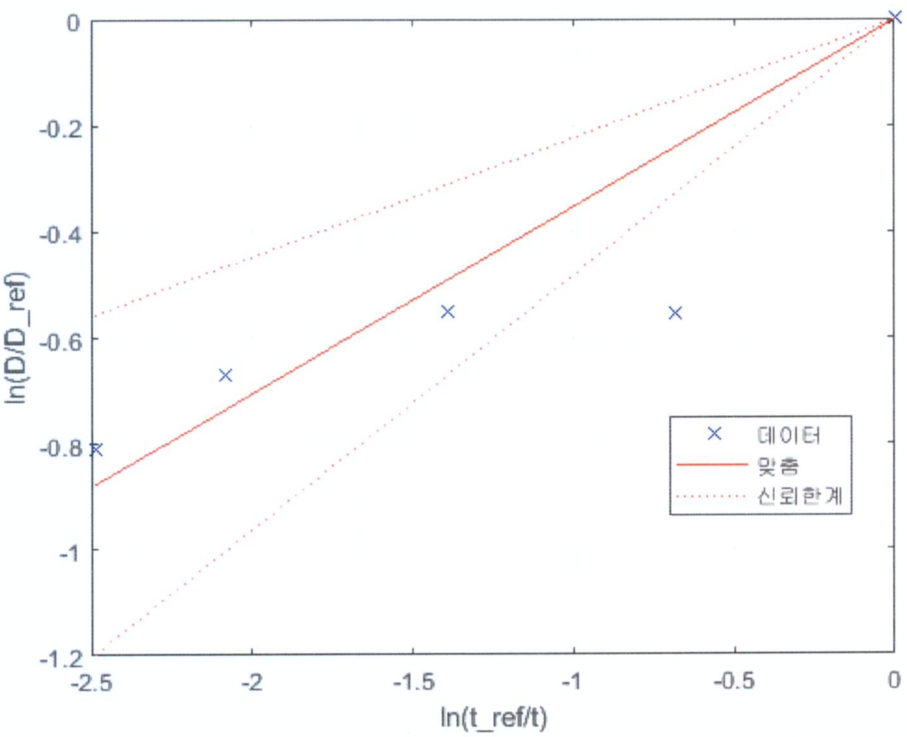
Days	91	180	365	730	1095
D (10^{-12} m^2/s)	8.3	4.76	4.79	4.24	3.69

$$D(t) = D_{ref}\left(\frac{t_{ref}}{t}\right)^m \qquad \text{Eq. (1)}$$

Compute the prediction of chloride ion diffusion coefficient up to 100 years and discuss the result based on the comparison of different standards. [30 marks]

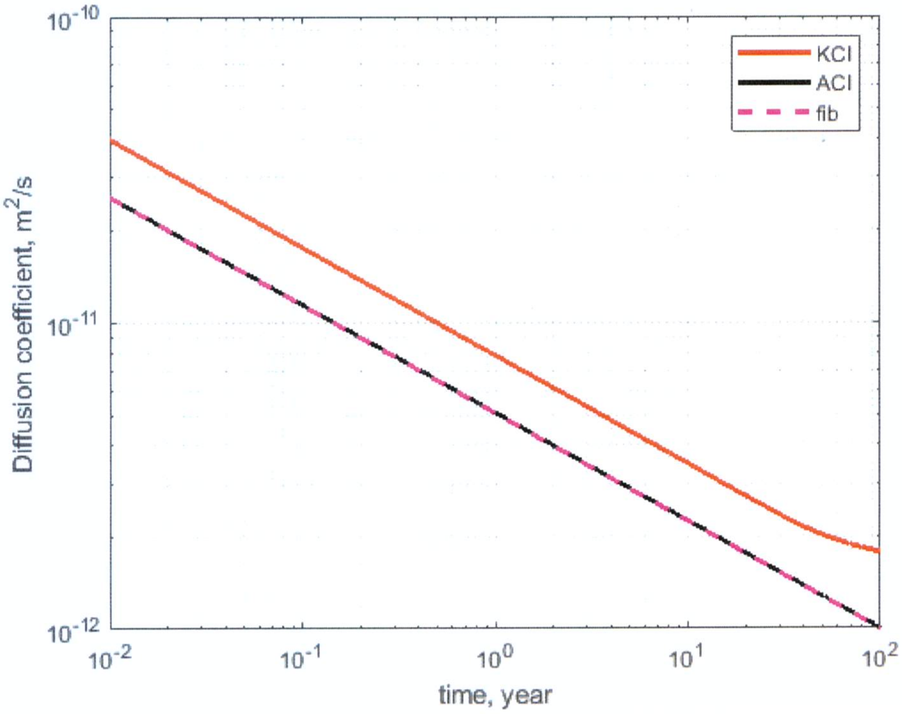
- The aging factor can be obtained by linear regression from equation (1) using the measured data of diffusion coefficients.

$$\ln D = \ln D_{ref}\left(\frac{t_{ref}}{t}\right)^m \rightarrow \ln\left(\frac{D}{D_{ref}}\right) = m \cdot \ln\left(\frac{t_{ref}}{t}\right)$$



- The obtained aging factor is $m = 0.3528$.

- Then, the prediction of chloride ion diffusion coefficient up to 100 years can be presented as below (Assume $k_e = 1, k_t = 1$, which denote the environmental and temperature effect, respectively).



- In the figure of the prediction of chloride ion diffusion coefficient, KCI shows much higher value than other design standards, and others show exactly same results.
- First of all, in cases of ACI and *fib*, the given equations of the prediction of chloride ion diffusion coefficient are exactly same when the coefficients $k_e = 1, k_t = 1$. This makes the same diffusion coefficient each other. If the effect of environmental and temperature effects being significant, the diffusion coefficients obtained by *fib* will be higher than those obtained by ACI.
- In case of KCI, it makes possible to design structures more conservative in terms of the corrosion by highly evaluating the diffusion coefficient.

Matlab code

(e)

```
%% High performance concrete engineering HW#3 - (e)

clc
clear

D = [8.3, 4.76, 4.79, 4.24, 3.69]*10^-12;  % m^2/s
t = [91, 180, 365, 730, 1095]; % days
Dref = D(1); % m^2/s
tref = t(1); % days

x = log((tref./t));
y = log(D./Dref);

mdl = fitlm(x,y,'y~x1-1'); % linear regression

figure(1)
plot(mdl)
xlabel('ln(t_ref/t)')
ylabel('ln(D/D_ref)')
title(' ')
grid on
m = table2array(mdl.Coefficients(1,1))
time = linspace(0,100,10000); % year

tc = 30; % year
for i = 1:length(time)
    % KCI
    if time(i) < tc
        Dp(i,1) = Dref/(1-m).*(tref/365/time(i)).^m; % m^2/s
    else
        Dp(i,1) = Dref/(1-m).*((1-m)+m*(tc/time(i)))*(tref/365/tc).^m; %
m^2/s
    end
    % ACI
    Dt(i,1) = Dref*(tref./365./time(i)).^m; % m^2/s
    % fib
    ke = 1;
    kt = 1;
    At(i,1) = (tref/365./time(i)).^m;
    Dappc(i,1) = ke*Dref*kt*At(i,1); % m^2/s
end

figure(2)
KCI = loglog(time,Dp*365*24*60*60,'r','linewidth', 2)
hold on
grid on
ACI = loglog(time,Dt*365*24*60*60,'k','linewidth', 2)
fib = loglog(time,Dappc*365*24*60*60,'m--','linewidth',2)
xlabel('time, year')
ylabel('Diffusion coefficient, m^2/s')
ylim([10^-5, 10^-2])
```

(f) (Non-handwriting problem) Evaluate the expected service life of nuclear power plant structure made of below concrete mix proportion based on KCI standard.

Spec. Strength (Psi)	W/(C+P) (%)	Water (lb)	Cement (lb)	Fly ash (lb)	Sand (lb)	Coarse Agg. (lb)	HWA (lb)	AEA (lb)
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D_R (10^{-12} m^2/s) = 8.3 at 91 days
m = use obtained value from Prob. (e)

If you need additional information, use appropriate assumptions and specify them. Also, attach relevant code or screen capture that you use for the computation.

- The concentration of chloride ion can be obtained by following equation on KCI standard.

$$C_d - C_i = (C_s - C_i)\left(1 - erf\left(\frac{x}{2\sqrt{D_d t}}\right)\right)$$

- In this equation, the cover depth can be applied on the distance x, and D_d can be obtained as follows with the given values.

$$m = 0.3528 \quad \text{(from Prob.(e))}$$

$$D_p = \begin{cases} \dfrac{D_R}{1-m}\left(\dfrac{t_R}{t}\right)^m & \text{for } t < t_c \\ \dfrac{D_R}{1-m}\left[(1-m) + m\dfrac{t_c}{t}\right]\left(\dfrac{t_R}{t_c}\right)^m & \text{for } t \geq t_c \end{cases}$$

where, $t_c = 30\ (year)$.

- Then, the minimum value of D_k can be obtained from $\gamma_p D_p \leq \phi_k D_k$, where $\gamma_p = 1.11$ and $\phi_k = 0.86$, which denote environmental coefficient and durability reduction factor of chloride attack.

$$(D_k)_{\min} = \frac{\gamma_p}{\phi_k} D_p$$

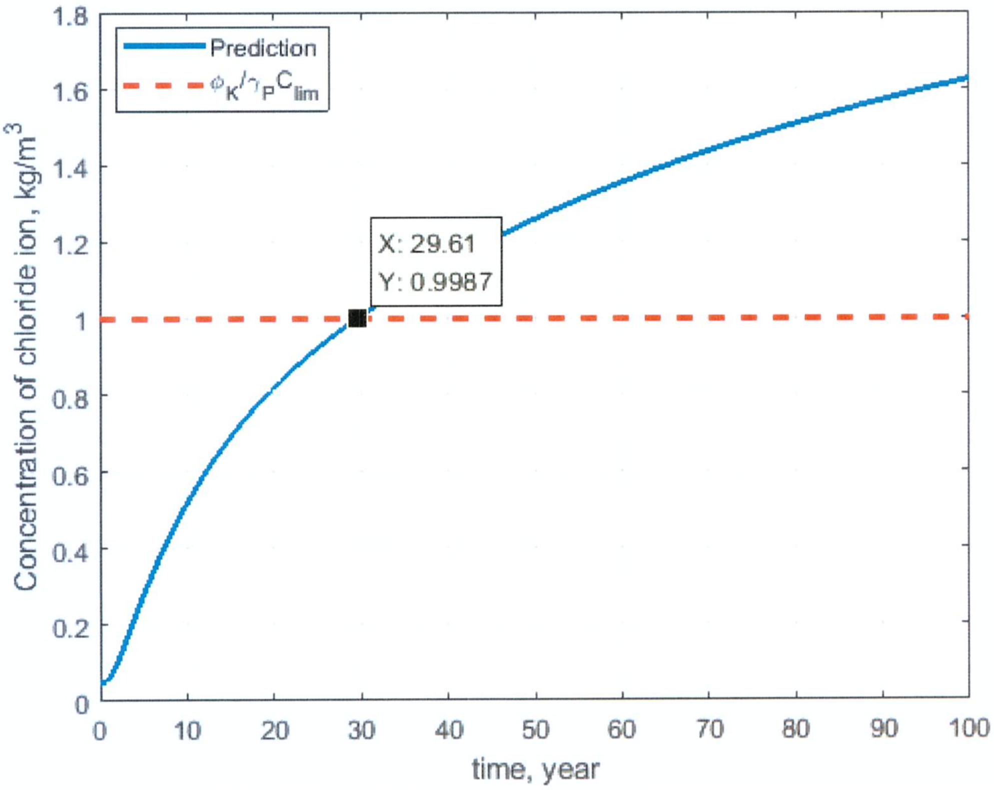
$$\therefore D_d = \gamma_c D_k$$

where, $\gamma_c = 1.0$.

- Therefore, the concentration of chloride ion, C_d, can be obtained along with the time.
- The expected service life is evaluated as the time when the concentration of chloride ion reach the $C_{\lim}$ which means the time when the rebar corrosion starts with considering the environmental coefficients (γ_p) and durability reduction factor (ϕ_k) of chloride attack as below.

$$\gamma_p C_d \leq \phi_k C_{\lim}$$

- The figure below shows C_d along with the time and $\frac{\phi_k}{\gamma_p} C_{\lim} = 0.9987$.
- As shown in the figure, the expected service life of nuclear power plant structure is about 30 years.



Matlab code

(f)

```
%% High performance concrete engineering HW#3 - (f)

clc
clear
load('hw3_e.mat')
phi_k = 0.86;
gamma_p = 1.11;
gamma_c = 1.0;
xd = 75*10^-3; % m
Ci= 0.05; % kg/m^3
Cs = 3.0; % kg/m^3
Clim = 1.289; % kg/m^3


Dk_min = (gamma_p/phi_k)*Dp; % m^2/s
Dd = gamma_c*Dk_min; % m^2/s

Cd = Ci+(Cs-Ci).*(1-erf(xd./(2.*sqrt(Dd'.*(time*365*24*60*60)))));

Cmax = phi_k/gamma_p*Clim;
Cmax_plot = Cmax*ones(length(time),1);
figure (1)
plot(time, Cd, 'linewidth', 2)
hold on
plot(time,Cmax_plot,'r--','linewidth',2)
xlabel('time, year')
ylabel('Concentration of chloride ion, kg/m^3')
legend('Prediction', '\phi_{K}/\gamma_{P}C_{lim}')
grid on
```