Q1(a) Reducing the carbon footprint of concrete

Modifications to the manufacturing process to reduce CO_2 production:

Cement replacement methods

1. Adopt 5-10% MgO (Magnesium oxide) mixed with remainder OPC.
   - this reduces amount of OPC used (i.e. cement replacement)
   - % of MgO can be increased significantly above these levels but strength & durability may decrease as a result.

2. Replace OPC by (up to 30%) pfa (pulverized fuel ash)
   - this is a by-product of coal-fired power stations.
   Can also replace % of OPC by ggbs (ground granulated blast-furnace slag) - typically up to ~40%.
   - this is a by-product of steel manufacturing process.

These replacements all lead to less OPC production, which is very carbon intensive.
If too large a % of replacement materials are used, it is possible that the strength of the resulting concrete will reduce.
In practice, the use of pfa & gbfs are replacement for OPC has been shown to improve the durability of concrete by providing a more impervious product. It also leads to reduced heat of hydration which decreases the potential for shrinkage cracking when cooling.

Energy reduction methods (no effect on WLP of concrete)

3. Adopt "dry process" for production of cement instead of "wet process" as this requires significantly less energy input.
   - can also slightly reduce kiln temperature to ~1300-1350°C. to reduce energy consumed in production.
4. Use recycled aggregates in concrete production, since considerable amount of energy is consumed in producing & transporting aggregates.

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Q1(b)(i) Reinforcement Corrosion

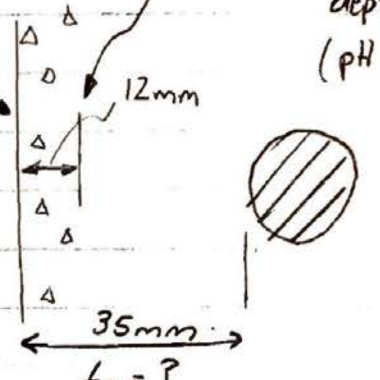
$t_0 = 1960$ Cover $= 35mm$

Assume $C_0 = $ constant

$D = $ constant.

Thresholds.

NB: $pH = 12$ + $Cl^- = 0.4\%$.



Carbonation Rate $\propto \sqrt{t}$

$$12mm \propto \sqrt{5}$$
$$35mm \propto \sqrt{t_2}$$

$$\sqrt{\frac{t_2}{5}} = \frac{35}{12} \Rightarrow t_2 = \left(\frac{35}{12}\right)^2 5 = 42.5yrs$$

Carbonation induced corrosion can be expected after 42.5 years

Chlorides

$x_1 = 10mm$ $C_1 = 0.2\%$ $t_1 = 2$ years
$x_2 = 10mm$ $C_2 = 0.6\%$ $t_2 = 8$ years.
$x_3 = 35mm$ $C_3 = 0.4\%$. $t_3 = ?$ years.

$$C = C_0\left(1 - erf\left(\frac{x}{2\sqrt{Dt}}\right)\right) = C_0(1 - erf(z))$$

$$C_1 = C_0\left(1 - erf\frac{10}{2\sqrt{D.2}}\right) = 0.002$$

$$C_2 = C_0\left(1 - erf\frac{10}{2\sqrt{D.8}}\right) = 0.006$$

$$\frac{0.006}{0.002} = \frac{1 - erf(z_2)}{1 - erf(z_1)} = 3 \quad ①$$

$$z_1 = \frac{10}{2\sqrt{D.2}} \quad z_2 = \frac{10}{2\sqrt{D.8}} \quad \therefore \frac{z_2}{z_1} = \frac{\sqrt{2}}{\sqrt{8}} = \frac{1}{2} \Rightarrow z_1 = 2z_2 \quad ②$$

From Tables use trial + error to guess $z_1 = 1$ $\therefore z_2 = 0.5$

$erf(z_1) = 0.84$ $erf(z_2) = 0.52$

Q1(b)(i) cont. $\frac{1-erf(z_2)}{1-erf(z_1)} = \frac{0.48}{0.16} = 3.$ as required.

$\therefore z_1 = 1$

Want to find dist. in from surface at which $C_4 = 0.4\%$ after 2 years.

$$C_1 = C_0\left(1 - erf\left(\frac{10}{2\sqrt{D.2}}\right)\right) = 0.002$$

$$C_4 = C_0\left(1 - erf\left(\frac{x_4}{2\sqrt{D.t_4}}\right)\right) = 0.004 \quad \text{where } t_4 = t_1 = 2 \text{ years.}$$

$$\frac{C_4}{C_1} = \frac{0.004}{0.002} = \frac{1-erf(z_4)}{1-erf(z_1)} \quad \text{where } z_1 = 1,\ erf(z_1) = 0.84.$$

$\therefore 1 - erf(z_4) = 2(1-0.84) = 0.32$

$erf(z_4) = 0.68$

From Tables for $erf(z_4) = 0.68$ $z_4 = 0.7$

$\therefore z_4 = \frac{x_4}{2\sqrt{D.2}} = 0.7$; $z_1 = \frac{10}{2\sqrt{D.2}} = 1.0.$

$\therefore z_4 = 0.7 \times 10 = 7mm$ $\therefore C_4 = 0.4\%$ at $x_4 = 7mm$ after $t_4 = 2$ yrs.

Want time until $C_3 = 0.4\%$ at $x_3 = 35mm$.

Diffusion $\propto \sqrt{t}$

$x_4 \propto \sqrt{t_4}$ $\quad \frac{7}{35} = \frac{\sqrt{2}}{\sqrt{t_3}} \Rightarrow t_3 = \left(\frac{35}{7}\right)^2 \times 2$

$x_3 \propto \sqrt{t_3}$

$= 50$ years

$\therefore$ Chloride induced corrosion can be expected after 50 years.

c.f. 42.5 years for carbonation $\Rightarrow$ Corrosion due to carbonation after 42.5 years.

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Q1(b)(ii) Factors affecting time to initiation + rate of corrosion

- Quality of surface concrete in cover region.
- Availability + concentration of CO_2 + Cl^- ions.
- Surface chloride concentration (+ initial concentration)
- Diffusion coefficient (D) of concrete (in practice non-linear)
- Permeability of concrete
- Degree of saturation of concrete (moisture content)

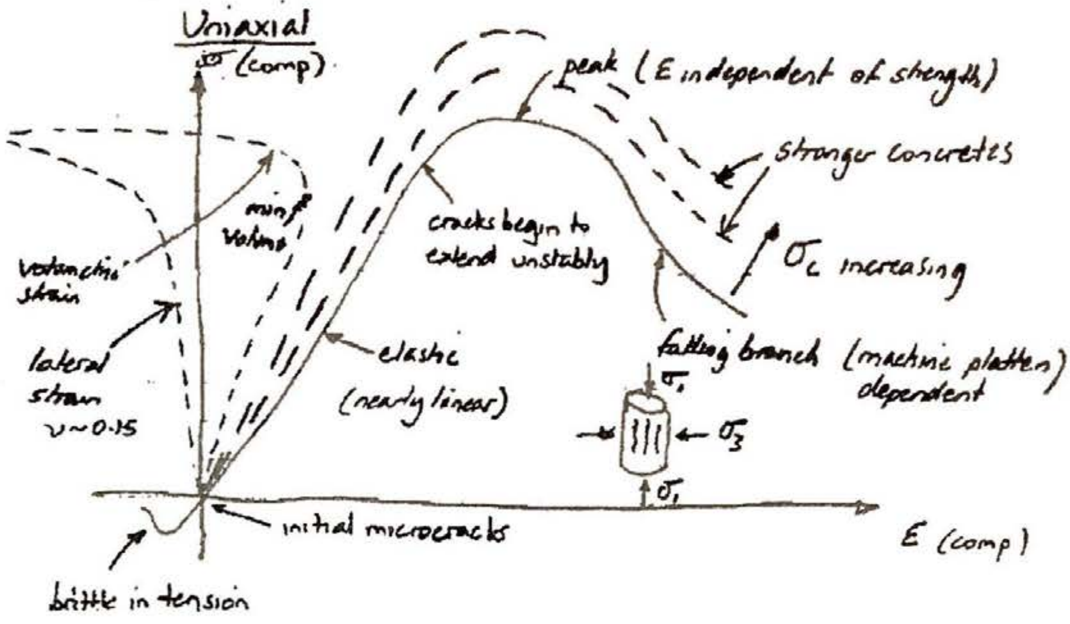
Also - Surface coatings on concrete (silane)
- expoxy coated / galvanised rebar
- stainless steel

Main durability factors - 4C's + W/C
i.e. - compaction
- curing
- cover
- cement content

Q1 Sustainability

This question was answered very well in general – students were able to provide excellent summaries of embodied carbon in the context of concrete structures and their whole life performance in (a). In (b) most students correctly undertook calculations for both carbonation and chloride ingress, marks were lost by those who only addressed one mode of deterioration.

Q2(a)(i)



Increasing lateral stress (σ_3) has the effect of increasing ductility (shows as a rise in falling branch of σ–ε graphs)

(ii) Triaxial — Crushing is inhibited in compression ∴ very strong

Also more ductile σ ~ ε curves
Can provide confinement in columns, members using links wrapped around members.

Examples where triaxial properties are exploited
① Lateral binding of columns e.g. in earthquake regions

② concrete hinges in columns.

Q2 (b)(ii)

$V_{Ed} = 750\text{kN}$

$V_{Rd,s} = \frac{A_s}{s} z\, f_{ywd} \cot\theta$

$\cot\theta = 2.5$ (check later)

$f_{ywd} = 450\text{ MPa}$

$A_s = \frac{\pi (12)^2}{4} \times 2 \text{ legs} = 226\text{mm}^2$

$s = 150\text{mm}$

$V_{Rd,s} = \frac{226}{150}(500)(450)(2.5) = \underline{848\text{kN}}$

$= 1.13\, V_{Ed}$

Check $V_{Rd,max} = \alpha_{cw} b_w z\, v_1 f_{cd} / (\cot\theta + \tan\theta)$

$\alpha_{cw} = 1$

$b_w = 300\text{ mm}$

$z = 500\text{mm}$

$v_1 = 0.6$

$f_{cd} = 50/1.5 = 33.3\text{ MPa}$

$V_{Rd,max} = \underline{1.03\text{MN}}$ $\cot\theta = 2.5$ $\underline{\text{ok}}$ ✓

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2(b)(ii) students should iterate the design such that $V_{Ed} \approx V_{Rd,s}$.

one example would be

ϕ12mm @ 169mm centres
→ round up to 170mm (slightly under)
165mm (slightly over)

ϕ8mm @ 75mm centres

- for revised design, calculate volume steel (using z = 500mm) and compare between options to reduce overall volume.

ϕ12 @ 165 = 685 x10³ mm³ /m length

2(~~b~~)(iii) ϕ8 @ 75 = 670 x10³ mm³ /m length

these two options have similar steel content.

The original design was = 754,000 mm³ /m length

2(b)(iii) The additional tensile force,

$$\Delta F_{td} = 0.5 V_{Ed} \cot\theta$$

↳ 938 kN.

This should be compared to the available

bars = 1257 mm^2

$$A_s f_y = 1257 (450)$$
$$= 566 \text{ kN}$$

⇒ therefore longitudinal bar sizes need to be increased

Q2 Shear design

Part (a) was answered well, with most students able to plot graphs of stress versus strain. Some students did not include comments or graphs on volumetric strain, and some missed the opportunity to explain the relationship between strength and Young's modulus. Part (b)(i) was generally well answered, some students over complicated their working. Most were able to show that the proposed arrangement of steel was sufficient to carry the shear force. In (b)(ii) at least one iteration of the design was required, and this was generally done adequately. In (b)(iii) many students did not appreciate the importance of the additional tensile force and how this can lead to additional longitudinal reinforcement.

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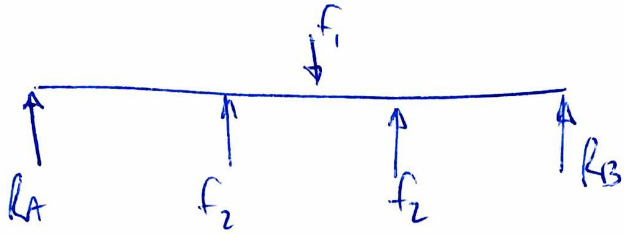
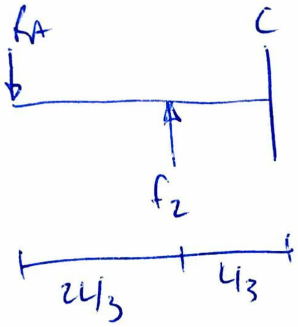
Q3(a)





$\delta_c = 0\,mm$

$$\frac{R_A (L)^3}{3EI} = \frac{f_2}{3EI}\left(\frac{L}{3}\right)^3 + \frac{f_2}{2EI}\left(\frac{L}{3}\right)^2\left(\frac{2L}{3}\right) = \frac{4}{81}\frac{f_2 L^3}{EI}$$

$$\therefore R_A = \frac{4}{27} f_2$$

$$R_A = R_B$$

$$f_1 = 2f_2 - 2R_A$$

$$\underline{\underline{f_1 = \frac{46}{27} f_2}}$$

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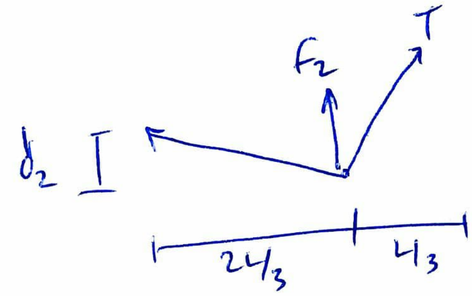
Q3(b)(i)

- cable is concordant if the forces cause no deflection at centre ∴ in same proportion as part (a)
- Force in cable = "T"

(1) at point D



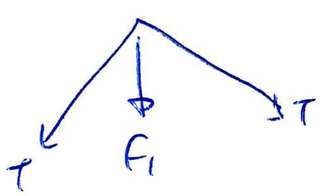
$\Big] (d_2 - d_1)$ (↑)

$$f_2 = \frac{T(d_2)}{2L/3} + \frac{T(d_2 - d_1)}{L/3}$$

$$f_2 = \frac{3T d_2}{2L} + \frac{3T(d_2 - d_1)}{L}$$

$$f_2 = \frac{T}{L}(4.5d_2 - 3d_1) \quad ①$$

(2) at B



$\Big] (d_2 - d_1)$

$$f_1 = 2 \times \frac{T(d_2 - d_1)}{L/3}$$

$$= \frac{6T(d_2 - d_1)}{L}$$

$$= \frac{2T}{L}(3d_2 - 3d_1) \quad ②$$

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Q3 (b)(ii)

from (a) we know $f_1 = \frac{46}{27} f_2$

& $\frac{2T}{L}(3d_2 - 3d_1) = \frac{46}{27}\frac{T}{L}(4.5\,d_2 - 3d_1)$

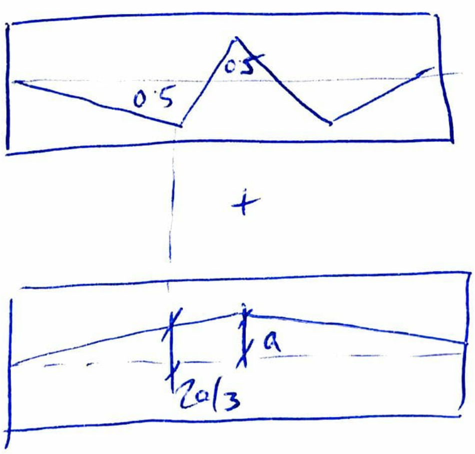
$$-5/3\, d_2 = 8/9\, d_1$$

$$d_1 = \frac{-15}{8} d_2$$

Q3(c)

actual profile $\frac{S_1}{S_2} = \frac{-0.5}{0.5} = -1$

we need to add a linear cable to get $\frac{S_1}{S_2} = \frac{-15}{8}$



$$\frac{S_1}{S_2} = \frac{-0.5-a}{+0.5-2a/3} = -\frac{15}{8}$$

$$-0.5-a = \frac{-15}{16} + \frac{5a}{4}$$

$$a = \frac{7}{36}$$

$$\therefore M = \frac{7}{36} \cdot T = \frac{7(2500)}{36} = 486 \text{ kNm} \quad \text{(high)}$$

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Q3(c)(ii)

- creep causes loss of prestress & additional deflections
- in-situ not prestressed so does not creep
- causes restraint stresses between the two - one wants to creep & the other does not.
- no analysis required.

Q3 Prestressed beam

This question was the least well answered of the paper. In (a) the application of data book cases tripped up a number of candidates. Part (b) was poorly answered, with many students getting into lost in the geometry of the beam, or not realising that the answer from (a) was helpful in answering (b)(ii). Part (c) was also not well answered, with only a few students correctly applying a linear transformation as requested by the question. Most students were able to provide a sensible comment in (c)(ii) about creep but only a few identified that restraint between the two elements would be important.