

Civil Engineering FE CBT Exam

Knowledge: Materials Science & Engineering with 10 Example Problems

Contents

1 Mechanical Behavior & Material Properties	2
1.1 Engineering vs. True Stress and Strain.....	2
1.2 Key Points on the Engineering Stress-Strain Curve	2
1.3 Moduli Definitions	2
1.4 Elasticity, Plasticity, Poisson's Ratio, and Multi-Axial Deformation	3
1.5 Energy Properties: Modulus of Resilience & Toughness.....	3
1.6 Thermal Stresses & Deformation	3
2 Metals & Structural Steel Metallurgy.....	4
2.1 Steel Manufacturing & Carbon Content Effects	4
2.2 Steel Heat Treatments.....	4
2.3 Hardness Testing & Tensile Strength Correlations.....	4
2.4 Hardenability & The Jominy End-Quench Test (ASTM A255).....	5
2.5 Charpy V-Notch Impact Test & Corrosion.....	5
3 Aggregates & Portland Cement Concrete (PCC).....	6
3.1 Aggregate Moisture States.....	6
3.2 Concrete Mix Components & The Absolute Volume Method	6
3.3 Water-Cement Ratio (W/C) & Hydration Chemistry	6
3.4 ASTM C150 Cement Types & Admixtures.....	7
3.5 Hardened Concrete Mechanical Properties per ACI 318	7
4 Asphalt Concrete & Bituminous Binders	8
4.1 Bituminous Materials & Classification	8
4.2 Temperature Susceptibility & Pavement Distresses	8
4.3 Superpave Performance Grading (PG) System.....	8
5 Wood, Polymers & Composite Materials.....	9
5.1 Wood & Timber Mechanics	9
5.2 Fiber-Reinforced Composites & Rule of Mixtures.....	9
5.3 Polymers & Amorphous Solids.....	9
6 Example Problems and Solutions (10 Problems)	11

1 Mechanical Behavior & Material Properties

1.1 Engineering vs. True Stress and Strain

In structural engineering design, standard calculations utilize **Engineering Stress** (σ) and **Engineering Strain** (ϵ), which are based on the original un-deformed cross-sectional area (A_0) and gauge length (L_0):

$$\sigma = \frac{P}{A_0}, \quad \epsilon = \frac{\delta}{L_0} = \frac{L - L_0}{L_0} \quad (1)$$

Conversely, **True Stress** (σ_T) and **True Strain** (ϵ_T) account for instantaneous changes in cross-sectional area (A) and gauge length (L) during plastic deformation:

$$\sigma_T = \frac{P}{A} = \sigma(1 + \epsilon), \quad \epsilon_T = \ln\left(\frac{L}{L_0}\right) = \ln(1 + \epsilon) \quad (2)$$

Note: The conversion $\sigma_T = \sigma(1 + \epsilon)$ assumes uniform uniaxial deformation and approximately constant volume; global strain is not valid after necking.

1.2 Key Points on the Engineering Stress-Strain Curve

A typical ductile steel tensile specimen exhibits distinct physical regimes:

1. **Proportional Limit:** The highest stress at which stress is strictly proportional to strain (Hooke's Law: $\sigma = E\epsilon$).
2. **Elastic Limit:** The maximum stress the material can sustain without undergoing permanent plastic deformation upon unloading.
3. **Yield Strength (F_y):** The stress level at which significant plastic deformation occurs with little or no stress increase. For materials without a well-defined upper/lower yield point, the yield strength is determined via the **0.2% (0.002 in/in) Offset Method** by drawing a line parallel to the initial elastic tangent slope starting at $\epsilon = 0.002$.
4. **Ultimate Tensile Strength (F_u):** The maximum engineering stress achievable on the stress-strain curve. Beyond F_u , localized cross-sectional reduction (**necking**) begins.
5. **Rupture / Fracture Stress (F_r):** The engineering stress at which the specimen physically fractures.

1.3 Moduli Definitions

Depending on the linearity of the material's elastic behavior, multiple elastic moduli are defined:

- **Young's Modulus / Initial Tangent Modulus (E):** The initial linear slope of the stress-strain curve (σ/ϵ). For structural steel, $E \approx 29,000 \text{ ksi} = 200 \text{ GPa}$.
- **Secant Modulus:** The slope of a straight line drawn from the origin to any specified arbitrary point on the stress-strain curve.
- **Chord Modulus:** The slope of a line connecting two specific points on the stress-strain curve (commonly used for non-linear materials like concrete).
- **Tangent Modulus:** The instantaneous derivative slope ($d\sigma/d\epsilon$) at a given stress or strain level.

1.4 Elasticity, Plasticity, Poisson's Ratio, and Multi-Axial Deformation

When subjected to uniaxial axial load, materials undergo axial strain (ϵ_{axial}) and simultaneous transverse strain ($\epsilon_{lateral}$). **Poisson's Ratio** (ν) is defined as:

$$\nu = -\frac{\epsilon_{lateral}}{\epsilon_{axial}} = -\frac{\Delta d/d_0}{\Delta L/L_0} \quad (3)$$

Typical values of Poisson's ratio range from 0.10 to 0.20 for concrete, 0.25 to 0.30 for structural steel, and up to 0.50 for incompressible ideal elastomers (rubber).

Under generalized 3D stress states, normal strain components in orthogonal directions (x, y, z) are governed by Hooke's Law with Poisson's effect:

$$\epsilon_x = \frac{1}{E} [\sigma_x - \nu(\sigma_y + \sigma_z)] + \alpha \Delta T \quad (4)$$

$$\epsilon_y = \frac{1}{E} [\sigma_y - \nu(\sigma_x + \sigma_z)] + \alpha \Delta T \quad (5)$$

$$\epsilon_z = \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)] + \alpha \Delta T \quad (6)$$

Elastic Material Constant Relationships

For an isotropic, linear elastic material, the Modulus of Elasticity (E), Shear Modulus (G), Bulk Modulus (K), and Poisson's Ratio (ν) are inter-related:

$$G = \frac{E}{2(1 + \nu)}, \quad K = \frac{E}{3(1 - 2\nu)} \quad (7)$$

1.5 Energy Properties: Modulus of Resilience & Toughness

- **Modulus of Resilience (u_r):** The maximum elastic strain energy per unit volume that a material can absorb without permanent plastic deformation. It equals the area under the elastic portion of the stress-strain curve up to the yield point (F_y):

$$u_r = \int_0^{\epsilon_y} \sigma d\epsilon \approx \frac{\sigma_y^2}{2E} \quad (8)$$

- **Modulus of Toughness (u_t):** The total energy per unit volume required to cause complete material rupture. It equals the total integrated area under the entire stress-strain curve from zero to fracture strain (ϵ_f).
- **Ductility vs. High Strength:** High strength does **not** imply high toughness. High-strength materials often have reduced ductility (small strain to failure), resulting in lower total area under the stress-strain curve than lower-strength, highly ductile materials.

1.6 Thermal Stresses & Deformation

Unrestrained structural members undergoing a temperature change ($\Delta T = T_f - T_i$) experience thermal strain (ϵ_T) and axial elongation (δ_T):

$$\epsilon_T = \alpha \Delta T, \quad \delta_T = \alpha L \Delta T \quad (9)$$

where α is the Coefficient of Thermal Expansion ($10^{-6}/^\circ\text{F}$ or $10^{-6}/^\circ\text{C}$). If the member is fully restrained against expansion/contraction, internal thermal stress develops:

$$\sigma_T = -E\alpha\Delta T \text{ (tension positive)} \quad (10)$$

2 Metals & Structural Steel Metallurgy

2.1 Steel Manufacturing & Carbon Content Effects

Structural steel production reduces raw iron ore in a blast furnace to form **Pig Iron**, which contains high carbon content ($> 2.0\%$). Pig iron is further refined in oxygen furnaces to produce steel by dropping the carbon content.

Table 1: Classification of Iron-Carbon Alloys by Carbon Content

Category	Carbon Content (% C)	Mechanical Properties & Applications
Low Carbon / Structural Steel	0.15% – 0.27%	Ideal ductility, strength, weldability (A36, A992 s
Medium Carbon Steel	0.27% – 0.60%	Higher strength, reduced ductility (gears, structur
High Carbon Steel	0.60% – 2.00%	High hardness, wear resistant, brittle (tools, high-
Cast Iron	$> 2.00\%$	Gray iron: brittle; ductile grades differ.

Carbon Content & Modulus of Elasticity

A classic FE Exam concept question asks: "How does increasing carbon content affect the Modulus of Elasticity (E) of steel?"

Answer: Carbon content has relatively little effect on steel's modulus of elasticity ($E \approx 29,000$ ksi). Increasing carbon generally raises strength while reducing ductility and toughness.

2.2 Steel Heat Treatments

Heat treatment manipulates the crystalline microstructure (Austenite [FCC], Ferrite [BCC], Cementite [Fe_3C], and Martensite) to achieve desired mechanical behaviors:

1. **Annealing:** Heating steel above critical transformation temperature followed by very slow furnace cooling.
Result: Produces a soft, ductile, stress-free microstructure with high toughness and excellent machinability.
2. **Normalizing:** Heating steel above critical temperature followed by ambient air cooling.
Result: Relieves residual manufacturing stresses, refines grain size, and produces uniform mechanical properties.
3. **Quenching (Hardening):** Heating to the stable Austenite phase followed by rapid immersion cooling in water, brine, or oil.
Mechanism: Prevents the formation of equilibrium ferrite/cementite phases, trapping carbon in a body-centered tetragonal (BCT) lattice called **Martensite**.
Result: Maximum surface hardness and strength, but extremely brittle.
4. **Tempering:** Reheating previously quenched martensitic steel to an intermediate temperature below the critical point, then cooling.
Result: Restores ductility and fracture toughness while retaining high strength.

2.3 Hardness Testing & Tensile Strength Correlations

Hardness measures a surface's resistance to permanent indentation, scratching, or abrasion.

- **Brinell Hardness Test (BHN / HB):** Pressing a 10 mm hardened steel or carbide ball under a 3000 kg (or 500 kg) load into the surface and measuring the resulting indentation diameter.

- **Rockwell Hardness Test (HRB, HRC):** Applies a minor load followed by a major load (100 kg for HRB, 150 kg for HRC) and measures the **depth of indentation**. Smaller indentation depth indicates higher hardness.

Brinell Hardness to Tensile Strength (TS) Correlation

For plain carbon and low-alloy steels, empirical formulas convert Brinell Hardness Number (*BHN*) directly to ultimate tensile strength:

$$TS \text{ (psi)} \approx 500 \cdot BHN, \quad TS \text{ (MPa)} \approx 3.5 \cdot BHN \quad (11)$$

2.4 Hardenability & The Jominy End-Quench Test (ASTM A255)

Hardenability is the relative ease with which a steel alloy can attain a specified hardness depth during heat treatment. It is evaluated via the standardized **Jominy End-Quench Test**:

- A standard 1-inch diameter by 4-inch long cylindrical steel bar is fully austenitized, then mounted vertically and quenched at its bottom end with a standardized water jet.
- One-dimensional cooling produces a continuous gradient of cooling rates along the bar length: the quenched end cools instantly (maximum martensite formation), while points further from the end cool progressively slower.
- Hardness (*HRC*) is measured along the length of the bar to plot a **Jominy Hardenability Curve**.
- **Effect of Alloying Elements:** Adding alloying elements (such as Chromium, Molybdenum, Nickel, and Manganese) retards the rate of phase transformation, allowing high hardness to be maintained at deeper positions along the bar (flattening the Jominy curve).

2.5 Charpy V-Notch Impact Test & Corrosion

- **Charpy V-Notch Test:** Evaluates material impact toughness and determines the **Ductile-to-Brittle Transition Temperature (DBTT)**. As operational temperatures drop, structural steel transitions from ductile failure (high energy absorption) to catastrophic brittle failure (low energy absorption).
- **Galvanic Corrosion:** Occurs when two dissimilar metals are electrically coupled in the presence of an electrolyte. The more reactive (anodic) metal corrodes preferentially to protect the noble (cathodic) metal.
- **Sacrificial Anode Protection:** Buried steel pipelines or marine structures are connected to sacrificial blocks of **Zinc** or **Magnesium** (which act as anodes and corrode away, saving the steel pipe).

3 Aggregates & Portland Cement Concrete (PCC)

3.1 Aggregate Moisture States

Aggregates in concrete or asphalt mixtures exist in four distinct physical moisture states:

Table 2: Four Physical Moisture States of Aggregates

Moisture State	Internal Pores	Particle Surface	Engineering Significance
1. Oven Dry (OD)	Completely dry	Completely dry	Required benchmark for Hot Mix Asp
2. Air Dry (AD)	Partially filled	Dry surface	Absorbs water from concrete batch w
3. Saturated Surface Dry (SSD)	100% Saturated	Surface dry	Standard design benchmark for concre
4. Moist / Wet	100% Saturated	Excess free water	Contributes excess free moisture to co

Aggregate Moisture Equations

Standard aggregate moisture definitions based on dry solid weight (W_{OD}):

$$\text{Total Moisture Content (\%MC)} = \frac{W_{wet} - W_{OD}}{W_{OD}} \times 100 \quad (12)$$

$$\text{Absorption (\%Abs)} = \frac{W_{SSD} - W_{OD}}{W_{OD}} \times 100 \quad (13)$$

$$\text{Free Moisture (\%FM)} = \%MC - \%Abs \quad (14)$$

If $\%FM > 0$, the aggregate is wetter than SSD and contributes free surface water to the batch mix. If $\%FM < 0$, the aggregate absorbs water from the concrete mix.

3.2 Concrete Mix Components & The Absolute Volume Method

Concrete consists of Portland cement, water, fine aggregate (sand), coarse aggregate (gravel/crushed stone), and optional admixtures.

- Cement Paste = Cement + Water
- Mortar / Grout = Cement Paste + Fine Aggregate
- Concrete = Mortar + Coarse Aggregate
- **Specific Gravity of Portland Cement:** $SG_{cement} = 3.15$. Unit weight of water $w_w = 62.4 \text{ lb/ft}^3$ (1000 kg/m³).

Under the **Absolute Volume Method**, the sum of solid volumes of all constituents plus air volume must equal $1.0 \text{ yd}^3 = 27 \text{ ft}^3$ (1.0 m³):

$$V_{water} + V_{cement} + V_{coarse_agg} + V_{fine_agg} + V_{air} = 27.0 \text{ ft}^3 \quad (15)$$

where the volume of any component i is calculated from its weight W_i and bulk specific gravity SG_i :

$$V_i = \frac{W_i}{SG_i \cdot 62.4 \text{ lb/ft}^3} \quad (16)$$

3.3 Water-Cement Ratio (W/C) & Hydration Chemistry

Hydration is the exothermic chemical reaction between Portland cement and water that produces Calcium-Silicate-Hydrate (C-S-H) gel (the binding glue).

- **Stoichiometric Water Requirement:** Complete chemical hydration requires a W/C ratio of approximately 0.22 – 0.25 by weight.

- **Practical W/C Range:** Typical concrete mix designs utilize $W/C = 0.40 - 0.70$. The additional water provides necessary **workability** and placement slump.
- **Impact of Excess Water (W/C too high):** Dramatically decreases compressive strength, increases porosity and permeability, increases drying shrinkage cracking, and reduces bond strength to rebar.

3.4 ASTM C150 Cement Types & Admixtures

- **Type I (Normal):** General structural construction.
- **Type II (Moderate Sulfate/Heat):** General structures exposed to soil/water with moderate sulfate concentrations.
- **Type III (High Early Strength):** Rapid strength gain for cold weather or fast formwork removal.
- **Type IV (Low Heat of Hydration):** Mass concrete pours (e.g., gravity dams) to prevent thermal cracking.
- **Type V (High Sulfate Resistance):** Severe sulfate environments (sewage pipes, high-sulfate soils).

Chemical Admixtures:

- **Air-Entraining Agents:** Produce millions of microscopic air bubbles (0.01 – 0.1 mm) that relieve hydraulic pressure during freezing cycles, vastly improving **freeze-thaw durability**.
- **Water Reducers / Superplasticizers (HRWR):** Increase concrete slump/workability without adding extra water, allowing lower W/C ratios and higher strengths.
- **Retarders:** Slow down set time during hot weather or long transit times.
- **Accelerators (e.g., Calcium Chloride $CaCl_2$):** Speed up initial/final setting time in cold weather.
- **Supplementary Cementitious Materials (SCMs):** Fly ash, blast furnace slag, and silica fume replace portion of cement, lower hydration heat, and improve long-term strength and durability.

3.5 Hardened Concrete Mechanical Properties per ACI 318

1. **Target Strength** (psi; adequate adjusted test-data s):
 $f'_{cr} = \max(f'_c + 1.34s, f'_c + 2.33s - 500)$ for $f'_c \leq 5,000$;
 $f'_{cr} = \max(f'_c + 1.34s, 0.90f'_c + 2.33s)$ for $f'_c > 5,000$.
2. **ACI 318 Elastic Modulus (E_c):** For unit weight w_c between 90 and 160 lb/ft³:

$$E_c = 33 w_c^{1.5} \sqrt{f'_c} \text{ (psi)} \quad (17)$$

For standard normal-weight concrete ($w_c \approx 145$ pcf):

$$E_c = 57,000 \sqrt{f'_c} \text{ (psi)} \quad \left[\text{or } 4,700 \sqrt{f'_c} \text{ (MPa)} \right] \quad (18)$$

3. **Tensile Strength:** Concrete tensile strength is weak, approximately **10% of compressive strength** ($f_t \approx 0.10f'_c$), measured via Splitting Tensile Test (ASTM C496).
4. **Flexural Strength / Modulus of Rupture (f_r):** Governs flexural cracking capacity under 3-point or 4-point beam loading:

$$f_r = 7.5 \lambda \sqrt{f'_c} \text{ (psi)} \quad \left[\text{where } \lambda = 1.0 \text{ for normal-weight concrete} \right] \quad (19)$$

4 Asphalt Concrete & Bituminous Binders

4.1 Bituminous Materials & Classification

Asphalt binder is a complex hydrocarbon mixture; polymer-modified binders contain added polymers.

- **Asphalt Cement:** Refined semi-solid binder used in Hot Mix Asphalt (HMA).
- **Cutback Asphalts:** Asphalt cement dissolved in a petroleum solvent. Solvents evaporate leaving binder behind.
 - *Rapid Curing (RC):* Solvent is gasoline/naphtha.
 - *Medium Curing (MC):* Solvent is kerosene.
 - *Slow Curing (SC):* Solvent is heavy fuel oil.
- **Asphalt Emulsions:** Mixture of asphalt cement, water, and an emulsifying agent.
 - *Anionic Emulsions:* Negatively charged droplets (best with electropositive aggregates like limestone).
 - *Cationic Emulsions:* Positively charged droplets (best with electronegative aggregates like granite/quartzite).

4.2 Temperature Susceptibility & Pavement Distresses

Asphalt is a **viscoelastic material**—its behavior depends heavily on both temperature and loading rate.

- **High Temperature Behavior:** Asphalt acts as a viscous liquid. Excessive heat leads to **Rutting** (permanent plastic deformation along wheel paths).
- **Low Temperature Behavior:** Asphalt behaves as an elastic, brittle solid. Thermal contraction in cold weather leads to **Transverse Thermal Cracking**.
- **Fatigue Cracking:** Caused by repeated cyclic traffic loads, resulting in "alligator cracking" in the wheel paths.

4.3 Superpave Performance Grading (PG) System

The Superpave system specifies asphalt binders based on expected high and low pavement design temperatures. For example, a **PG 64-22** binder is designed to perform safely between:

- Maximum 7-day average pavement temperature of 64°C.
- Minimum pavement design temperature of -22°C.

Aggregate Condition for Hot Mix Asphalt (HMA)

A fundamental distinction on the FE Exam:

- Concrete mix calculations assume aggregates are in the **Saturated Surface Dry (SSD)** condition.
- Hot Mix Asphalt (HMA) mix design requires aggregates to be **Oven Dry (OD)** because high plant mixing temperatures (> 275°F) drive off all surface and internal moisture.

5 Wood, Polymers & Composite Materials

5.1 Wood & Timber Mechanics

Wood is a natural organic polymer characterized by an **orthotropic** / **anisotropic** microstructure (distinct mechanical properties along three mutually perpendicular axes: Longitudinal, Radial, and Tangential).

- **Anisotropic Behavior:** Tensile and compressive strengths **parallel to the grain** are significantly higher than strengths **perpendicular to the grain**.
- **Moisture Content & Fiber Saturation Point (FSP):**

$$MC = \frac{W_{wet} - W_{oven_dry}}{W_{oven_dry}} \times 100 \quad (20)$$

The **Fiber Saturation Point** ($FSP \approx 30\%$) represents the moisture content where cell walls are completely saturated with bound water, but cell cavities contain no free water.

Shrinkage in Timber

Volumetric shrinking and swelling in wood occur **ONLY below the Fiber Saturation Point** ($MC < 30\%$). Variations in moisture content above FSP cause no dimensional changes or strength variations.

- **NDS Design Load Duration Factor (C_D):** Wood exhibits creep under sustained loading. Allowable design stresses are adjusted using the load duration factor C_D :

Load Duration / Type	C_D Factor
Permanent / 100 years	0.90
Normal occupancy / 10 years	1.00
Snow / 2 months	1.15
Construction or roof live / 7 days	1.25
Wind / earthquake / 10 minutes	1.60

5.2 Fiber-Reinforced Composites & Rule of Mixtures

Composite materials consist of high-strength reinforcement fibers embedded in a polymer matrix.

Rule of Mixtures Equations

For continuous, unidirectionally aligned fiber composites, the density (ρ_c) and longitudinal Elastic Modulus (E_c) follow the Voigt parallel model (iso-strain condition: $\epsilon_c = \epsilon_f = \epsilon_m$):

$$\text{Composite Density: } \rho_c = f_f \rho_f + f_m \rho_m \quad (21)$$

$$\text{Longitudinal Modulus: } E_c = f_f E_f + f_m E_m \quad (22)$$

where f_f and f_m are volume fractions ($f_f + f_m = 1.0$), E_f, E_m are elastic moduli, and ρ_f, ρ_m are component densities.

5.3 Polymers & Amorphous Solids

- **Thermoplastics:** Linear or branched polymer chains held by weak secondary bonds. Can be repeatedly heated, softened, reformed, and cooled (e.g., Polyethylene, PVC, Polystyrene).
- **Thermosets:** Highly cross-linked 3D network polymer structures. Cannot be re-melted upon heating; decompose at elevated temperatures (e.g., Epoxies, Phenolics).

- **Glass Transition Temperature (T_g):** The critical temperature below which an amorphous polymer undergoes a transition from a ductile/rubbery state to a rigid, brittle glass solid.

6 Example Problems and Solutions

Problem 1: Concrete Batch Water Adjustment for Aggregate Moisture

A jobsite concrete mix design requires the following SSD baseline weights per cubic yard:

- Cement: 540 lbs
- Coarse Aggregate (SSD, $Abs = 0.5\%$): 1,700 lbs
- Fine Aggregate (SSD, $Abs = 1.0\%$): 1,545 lbs
- Mixing Water: 272 lbs

On a given batching day, the field moisture tests reveal that both coarse aggregate and fine aggregate have a total moisture content (MC) of 2.0%. Calculate the corrected amount of water (in lbs) that must be added to the batch mix per cubic yard.

- (A) 231.3 lb/yd³
(C) 272.0 lb/yd³

- (B) 246.6 lb/yd³
(D) 312.7 lb/yd³

Solution

Step 1: Determine the Free Moisture Percentage (%FM) for each aggregate.

$$\begin{aligned}\%FM_{coarse} &= \%MC_{coarse} - \%Abs_{coarse} = 2.0\% - 0.5\% = +1.5\% \\ \%FM_{fine} &= \%MC_{fine} - \%Abs_{fine} = 2.0\% - 1.0\% = +1.0\%\end{aligned}$$

Step 2: Calculate free surface water on the oven-dry (OD) basis.

Because moisture content and absorption are defined relative to oven-dry weight, first convert SSD weights to OD weights.

$$W_{OD,coarse} = 1,700 / 1.005 = 1,691.54 \text{ lbs}$$

$$W_{OD,fine} = 1,545 / 1.010 = 1,529.70 \text{ lbs}$$

$$W_{free,coarse} = 1,691.54(0.020 - 0.005) = 25.37 \text{ lbs}$$

$$W_{free,fine} = 1,529.70(0.020 - 0.010) = 15.30 \text{ lbs}$$

$$W_{free,total} = 25.37 + 15.30 = 40.67 \text{ lbs}$$

Step 3: Adjust the design mix water.

Since the aggregates contribute 40.67 lbs of free water, subtract it from the baseline mix water.

$$W_{added \text{ water}} = 272 - 40.67 = 231.33 \text{ lbs (approximately 231.3 lbs)}$$

Correct Answer: (A) 231.3 lb of water per cubic yard.

Problem 2: Water-Cement Ratio & Jobsite Water Limits

A concrete specification requires 593 lbs/yd³ of cement with a maximum allowable water-cement ratio (W/C) of 0.45. A 10 yd³ concrete ready-mix truck arrives on-site. The batch ticket indicates that 310 gallons of total water (added water plus aggregate free moisture) are already present in the drum. Determine the maximum additional volume of water (in gallons) that can be added at the jobsite before exceeding the $W/C = 0.45$ specification limit. (Unit weight of water = 8.34 lbs/gal).

- (A) 9.964 gal
(C) 20.0 gal

- (B) 10.04 gal
(D) 31.0 gal

Solution

Step 1: Calculate the maximum allowable total water weight for the 10 yd³ load.

$$W_{cement,total} = 593 \text{ lbs/yd}^3 \times 10 \text{ yd}^3 = 5,930 \text{ lbs}$$

$$W_{water,max_allowable} = (W/C)_{max} \times W_{cement,total} = 0.45 \times 5,930 \text{ lbs} = 2,668.5 \text{ lbs}$$

Step 2: Convert maximum allowable water weight to gallons.

$$V_{water,max_allowable} = \frac{2,668.5 \text{ lbs}}{8.34 \text{ lbs/gal}} = 320.0 \text{ gallons}$$

Step 3: Determine the remaining water volume that can be added.

$$V_{\text{additional}} = V_{\text{water, max allowable}} - V_{\text{ticket}} = 319.964 \text{ gal} - 310.0 \text{ gal} = 9.964 \text{ gal}$$

Correct Answer: (A) 9.964 gal of additional water.

Problem 3: Tension Test Stress-Strain Curve Analysis

A cylindrical steel bar with an initial diameter $d_0 = 0.505$ in and initial gauge length $L_0 = 2.00$ in is subjected to a tensile test. The experimental data yields the following observations:

- In the initial linear range, an axial force $P = 6,000$ lbs produces an elongation $\delta = 0.00206$ in.
- Plastic yield occurs at an axial load $P_y = 7,200$ lbs.
- Maximum peak load $P_{max} = 12,000$ lbs.
- Final length at fracture $L_f = 2.50$ in.

Calculate: (a) Young's Modulus (E), (b) Yield Strength (F_y), (c) Ultimate Strength (F_u), and (d) Percent Elongation (%EL).

(A) $E=29.1$ Mpsi; $F_y=35.95$ ksi; $F_u=59.91$ ksi; $EL=25\%$

(B) $E=29.1$ Mpsi; $F_y=35.95$ ksi; $F_u=59.91$ ksi; $EL=20\%$

(C) $E=29.1$ Mpsi; $F_y=35.95$ ksi; $F_u=49.91$ ksi; $EL=25\%$

(D) $E=24.1$ Mpsi; $F_y=35.95$ ksi; $F_u=59.91$ ksi; $EL=25\%$

Solution

Step 1: Calculate initial cross-sectional area A_0 .

$$A_0 = \frac{\pi}{4} d_0^2 = \frac{\pi}{4} (0.505 \text{ in})^2 = 0.2003 \text{ in}^2$$

Step 2: Calculate Young's Modulus (E). In the linear elastic region ($P = 6,000$ lbs):

$$\begin{aligned}\sigma &= \frac{P}{A_0} = \frac{6,000 \text{ lbs}}{0.2003 \text{ in}^2} = 29,955 \text{ psi} \\ \epsilon &= \frac{\delta}{L_0} = \frac{0.00206 \text{ in}}{2.00 \text{ in}} = 0.00103 \text{ in/in} \\ E &= \frac{\sigma}{\epsilon} = \frac{29,955 \text{ psi}}{0.00103} = 29,082,524 \text{ psi} \approx \mathbf{29.1 \times 10^6 \text{ psi}} \quad (29.1 \text{ Mpsi})\end{aligned}$$

Step 3: Calculate Yield Strength (F_y).

$$F_y = \frac{P_y}{A_0} = \frac{7,200 \text{ lbs}}{0.2003 \text{ in}^2} = 35,946 \text{ psi} \approx \mathbf{35.95 \text{ ksi}}$$

Step 4: Calculate Ultimate Tensile Strength (F_u).

$$F_u = \frac{P_{max}}{A_0} = \frac{12,000 \text{ lbs}}{0.2003 \text{ in}^2} = 59,910 \text{ psi} \approx \mathbf{59.91 \text{ ksi}}$$

Step 5: Calculate Percent Elongation (%EL).

$$\%EL = \frac{L_f - L_0}{L_0} \times 100 = \frac{2.50 \text{ in} - 2.00 \text{ in}}{2.00 \text{ in}} \times 100 = \mathbf{25.0\%}$$

Correct Answer: (A) $E=29.1$ Mpsi; $F_y=35.95$ ksi; $F_u=59.91$ ksi; $EL=25\%$.

Problem 4: Lateral Strain and Column Diameter Expansion

A solid cylindrical steel column ($E = 29,000$ ksi, Poisson's ratio $\nu = 0.30$) has an initial diameter $d_0 = 4.00$ inches and length $L = 10.0$ feet. The column is subjected to a compressive axial load $P = 250$ kips. Calculate the change in diameter (Δd) of the column and indicate whether the diameter increases or decreases.

(A) $+0.000823$ in; diameter increases

(B) -0.000823 in; diameter decreases

(C) $+0.000686$ in; diameter increases

(D) -0.000686 in; diameter decreases

Solution

Step 1: Calculate cross-sectional area A_0 and axial compressive stress σ_{axial} .

$$\begin{aligned}A_0 &= \frac{\pi}{4} (4.00 \text{ in})^2 = 12.566 \text{ in}^2 \\ \sigma_{axial} &= -\frac{P}{A_0} = -\frac{250 \text{ kips}}{12.566 \text{ in}^2} = -19.894 \text{ ksi} \quad (\text{compressive})\end{aligned}$$

Step 2: Calculate axial strain ϵ_{axial} .

$$\epsilon_{axial} = \frac{\sigma_{axial}}{E} = \frac{-19.894 \text{ ksi}}{29,000 \text{ ksi}} = -0.000686 \text{ in/in}$$

Step 3: Calculate transverse (lateral) strain $\epsilon_{lateral}$ using Poisson's ratio.

$$\epsilon_{lateral} = -\nu \epsilon_{axial} = -(0.30)(-0.000686 \text{ in/in}) = +0.0002058 \text{ in/in}$$

Step 4: Calculate change in diameter Δd .

$$\Delta d = d_0 \times \epsilon_{lateral} = 4.00 \text{ in} \times 0.0002058 = +\mathbf{0.000823} \text{ inches} \quad (\text{Increase in diameter})$$

Correct Answer: (A) The diameter increases by 0.000823 in.

Problem 5: Restrained Thermal Stress in Structural Steel

A structural steel beam ($E = 29,000$ ksi, $\alpha = 6.5 \times 10^{-6}/^{\circ}\text{F}$) is rigidly restrained against axial expansion at both ends. The beam is installed at an initial temperature $T_i = 40^{\circ}\text{F}$. During summer, the temperature rises to $T_f = 120^{\circ}\text{F}$. Determine the compressive thermal stress (σ_T) induced in the beam.

(A) 15.08 ksi tension

(B) 15.08 ksi compression

(C) 2.60 ksi compression

(D) 29.00 ksi compression

Solution

Step 1: Calculate the temperature change ΔT .

$$\Delta T = T_f - T_i = 120^{\circ}\text{F} - 40^{\circ}\text{F} = 80^{\circ}\text{F}$$

Step 2: Calculate restrained thermal strain ϵ_T .

$$\epsilon_T = \alpha \Delta T = (6.5 \times 10^{-6}/^{\circ}\text{F})(80^{\circ}\text{F}) = 0.000520 \text{ in/in}$$

Step 3: Calculate induced compressive thermal stress σ_T .

$$\sigma_T = E \epsilon_T = (29,000 \text{ ksi})(0.000520) = \mathbf{15.08 \text{ ksi}} \quad (\text{Compression})$$

Correct Answer: (B) 15.08 ksi in compression.

Problem 6: Brinell Hardness Number to Tensile Strength Estimation

A surface hardness test on a structural steel plate yields a Brinell Hardness Number $BHN = 180$. Estimate the ultimate tensile strength of the steel in: (a) psi and (b) MPa using the empirical NCEES Reference Handbook formulas.

(A) 90,000 psi; 630 MPa

(B) 90,000 psi; 620.5 MPa

(C) 180,000 psi; 630 MPa

(D) 500 psi; 3.5 MPa

Solution

Step 1: Apply NCEES Handbook empirical formula for U.S. Customary units.

$$TS \text{ (psi)} \approx 500 \cdot BHN = 500 \times 180 = \mathbf{90,000 \text{ psi}} \quad (90 \text{ ksi})$$

Step 2: Apply NCEES Handbook empirical formula for SI units.

$$TS \text{ (MPa)} \approx 3.5(180) = 630 \text{ MPa (separate empirical fit).}$$

Exact conversion of 90 ksi is about 620.5 MPa.

Correct Answer: (A) 90,000 psi and 630 MPa using the separate empirical fit.

Problem 7: ACI 318 Concrete Elastic Modulus & Modulus of Rupture

A normal-weight concrete specimen ($w_c = 145$ pcf) has a 28-day specified compressive strength $f'_c = 4,000$ psi. Calculate:

(a) The ACI 318 Elastic Modulus (E_c).

(b) The ACI 318 Modulus of Rupture (f_r) assuming normal-weight concrete ($\lambda = 1.0$).

(A) $E_c = 3.605 \times 10^6$ psi; $f_r = 474.3$ psi(B) $E_c = 3.605 \times 10^8$ psi; $f_r = 474.3$ psi(C) $E_c = 3.605 \times 10^6$ psi; $f_r = 300.0$ psi(D) $E_c = 4.743 \times 10^6$ psi; $f_r = 474.3$ psi**Solution**

Part (a): Elastic Modulus E_c

$$E_c = 57,000 \sqrt{f'_c} = 3,605,000 \text{ psi} = 3.605 \times 10^6 \text{ psi (3,605 ksi)}$$

Part (b): Modulus of Rupture f_r

$$f_r = 7.5 \lambda \sqrt{f'_c} = 7.5 \times 1.0 \times \sqrt{4,000} = 7.5 \times 63.2455 = \mathbf{474.3 \text{ psi}}$$

Correct Answer: (A) $E_c = 3.605 \times 10^6$ psi and $f_r = 474.3$ psi.

Problem 8: Fiber-Reinforced Polymer (FRP) Composite Rule of Mixtures

A continuous, unidirectionally aligned carbon-fiber reinforced epoxy composite is manufactured with a fiber volume fraction $f_f = 0.60$ (matrix volume fraction $f_m = 0.40$). The constituent properties are:

- Carbon Fibers: $E_f = 35.0$ Mpsi = 240 GPa, density $\rho_f = 0.065$ lb/in³
- Epoxy Matrix: $E_m = 0.50$ Mpsi = 3.45 GPa, density $\rho_m = 0.045$ lb/in³

Calculate: (a) Total composite density (ρ_c) and (b) Longitudinal Elastic Modulus (E_c).

(A) $\rho_c = 0.057$ lb/in³; $E_c = 21.2$ Mpsi

(B) $\rho_c = 0.057$ lb/in³; $E_c = 20.2$ Mpsi

(C) $\rho_c = 0.065$ lb/in³; $E_c = 21.2$ Mpsi

(D) $\rho_c = 0.057$ lb/in³; $E_c = 35.0$ Mpsi

Solution**Part (a): Composite Density ρ_c**

$$\begin{aligned}\rho_c &= f_f \rho_f + f_m \rho_m = (0.60)(0.065 \text{ lb/in}^3) + (0.40)(0.045 \text{ lb/in}^3) \\ &= 0.039 + 0.018 = \mathbf{0.057 \text{ lb/in}^3}\end{aligned}$$

Part (b): Longitudinal Elastic Modulus E_c (Voigt Model)

$$\begin{aligned}E_c &= f_f E_f + f_m E_m = (0.60)(35.0 \text{ Mpsi}) + (0.40)(0.50 \text{ Mpsi}) \\ &= 21.0 \text{ Mpsi} + 0.20 \text{ Mpsi} = \mathbf{21.2 \text{ Mpsi}} \quad (21.2 \times 10^6 \text{ psi})\end{aligned}$$

Correct Answer: (A) $\rho_c = 0.057$ lb/in³ and $E_c = 21.2$ Mpsi.

Problem 9: Steel Heat Treatment & Microstructure Selection

A mechanical component machined from medium-carbon steel requires maximum surface hardness and high wear resistance, but retains excessive brittleness after initial processing. Select the appropriate multi-step heat treatment sequence required to achieve high strength and high fracture toughness:

- (A) Annealing followed by Normalizing
- (B) Quenching followed by Tempering
- (C) Normalizing followed by Cold Working
- (D) Quenching followed by Annealing

Solution

Correct Answer: (B) Quenching followed by Tempering

Explanation:

- **Quenching** rapidly cools austenitized steel to form untempered Martensite, achieving maximum potential hardness and yield strength. However, untempered martensite is extremely brittle and prone to catastrophic cracking.
- **Tempering** reheats the quenched martensite to an intermediate temperature below the lower critical line (A_1), allowing trapped carbon to diffuse slightly and forming tempered martensite. This relieves internal stresses, dramatically improves fracture toughness and ductility, while preserving high strength.

Problem 10: Wood Orthotropic Properties & NDS Load Duration Factor

A select structural Douglas Fir sawn lumber column is designed to support three distinct loading combinations:

- (1) Permanent Dead Load only (100-year continuous duration)
- (2) Normal Occupancy Live Load (10-year cumulative duration)
- (3) Design Wind / Earthquake Load (NDS 10-minute load-duration category)

Identify the NDS Load Duration Factor (C_D) corresponding to each loading scenario and explain why timber permits higher allowable stresses under shorter-duration design loads.

- (A) $C_D=0.90, 1.00, 1.60$
- (B) $C_D=1.00, 1.25, 1.60$
- (C) $C_D=0.90, 1.00, 1.00$
- (D) $C_D=0.70, 0.90, 1.60$

Solution**Part (a): NDS C_D Values**

1. Permanent Dead Load: $C_D = 0.90$
2. Normal Occupancy Live Load: $C_D = 1.00$
3. Design Wind / Earthquake Load (10-minute category): $C_D = 1.60$

Part (b): Engineering Explanation

Wood exhibits time-dependent strength behavior under sustained loading. The NDS load-duration factor increases allowable design values for shorter-duration design loads. Wind and earthquake loads use the 10-minute category factor $C_D = 1.60$. This should not be interpreted as a universal factor for every arbitrary 10-second impulse load.

Correct Answer: (A) $C_D=0.90, 1.00$, and 1.60 , respectively.