Chapter 2
General Characteristics of Concretes and Reinforced Concretes

Abstract The Chapter presents general characteristics of concretes and reinforced concretes, their classification, grading and designations. Definition of structure inhomogeneity in these materials and its effect on service characteristics are given. The Chapter contains typical diagrams of concrete deformation and fracture as well as nominal strength values for different concrete grades in tables. Besides strength, other important mechanical characteristics, such as fracture toughness, are of no less importance in concretes. The authors provide a summary of existing fracture toughness criteria and methods for experimental fracture toughness determination. At present, concrete science can formulate only individual aspects of a concrete strength and deformation theory. Considering concrete as a composite material with hierarchical structure (at micro, meso, and macro levels) and analyzing these structure levels, the authors propose a mathematical model enabling the establishment of quantitative relations between breaking (tensile) and compressive strength values for a porous material such as concrete.

The Chapter contains classification and mechanical properties of concrete reinforcement as well.

Concretes are conglomerates formed through the solidification of a mix of cement solution, water, fillers, and modifying additions, if needed. A wide diversity of binding cement materials and concrete fillers (aggregates) as well as physical and mechanical characteristics of the concrete components significantly complicates the development of generalized microstructure models and strength theories for concrete [1]–[6].

Reinforced concrete is concrete enhanced with steel rods. While the elastic moduli of the cement stone and aggregate differ significantly but within one order of magnitude, the elastic modulus of a steel is nearly a full order higher than the integrated elastic modulus of concrete as a whole.

Concrete intended for use in reinforced structures must possess the following mandatory pre-determined physical and mechanical properties: high strength; good adhesion to reinforcement; sufficient density (moisture impermeability) for protection of reinforcement from corrosion, etc.

Depending on the intended application and operation conditions, the concrete must comply with the following special requirements: resistance to corrosive environments (e.g., reservoirs in the chemical industry); heat resistance (including long-term operation at high temperatures); high fracture toughness (i.e., resistance to crack propagation), etc.

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As adopted in the practice of engineering, the short names of concrete grades intended for use in reinforced structures are as follows:

a. *Heavy concrete* is concrete with a dense microstructure containing heavy aggregates bonded at the cement mortar solidification.
b. *Fine concrete* is concrete with a dense microstructure containing fine aggregates bonded at the cement mortar solidification in any ambient conditions.
c. *Lightweight concrete* is concrete with a dense microstructure containing porous aggregates bonded at the cement mortar solidification in any ambient conditions.

Heavy aggregates may consist of crushed rocks (sandstones, granite, diabase, etc.) and natural quartz sand. Porous aggregates may be natural (pearlite, shell limestone, etc.) or artificial (expanded clay, slag, etc.). Depending on the type of porous aggregate, there exists expanded-clay (ceramsite) concrete, slag concrete, pearlite concrete, etc.

Cellular concretes, or concretes with porous aggregates and medium density 1400 kg/m^3 or lower, are mainly applied in shielding structures. Heavy concretes are most commonly applied for protection from harmful radiation.

To prepare concretes satisfying certain special requirements, for example, of a specified mechanical strength, the concrete should have certain components in a predetermined quantitative ratio including various cements, coarse and fine aggregates, modifying additions, etc.

The strength of a concrete depends on many factors including aggregate particle size; aggregate strength and surface condition; cement brand and proportion; water content during solidification; aggregate roughness and adhesion to the cement mortar, etc. [7].

2.1 Concrete Microstructure and Its Effect on Strength and Deformation Behavior

A concrete's microstructure has a strong effect on its strength and deformation behavior. In order to understand the mechanisms underlying this effect, let us consider the process of concrete formation. After flooding a dry mixture of aggregates and cement with water, a chemical reaction occurs between the cement minerals and water resulting in the formation of a gel being the fluid mass, which consists of cement particles and various crystalline compounds suspended in water. During agitation of the concrete mix, the gel envelops aggregate particles and gradually solidifies, while suspended crystallites combine into progressively growing crystals. The solidified gel transforms into the cement stone, binding all coarse and fine components into the monolithic solid material referred to as concrete.

In the resulting microstructure, solid aggregates occupy more than 80 % of the volume, depending on the grade of concrete. The composition of the basic cement mass (gel or cement stone) comprises both minerals formed in initial reactions of the dry cement minerals with water and compounds forming in subsequent reactions

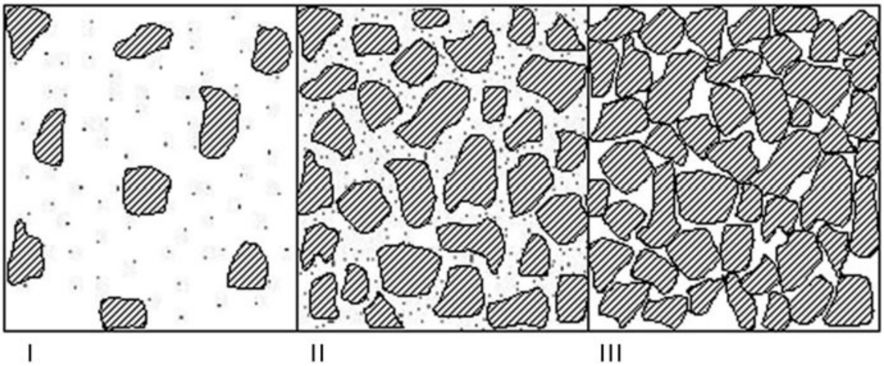

Fig. 2.1 Typical classes of concrete microstructure

between the so-formed products. The microstructure of the cement stone is generally crystalline and consists of various calcium compounds, namely, calcium hydroxide, hydrosilicates, hydroaluminates, and hydroferrites.

The characteristics of the concrete depend to a considerable extent on the microstructure density or porosity, as well as the porosity type. Using the criterion of porosity, one can define the following typical concrete classes (see Fig. 2.1):

- concrete with 'floating' aggregates (I);
- concrete with closely packed aggregates (II);
- high-porous concrete with a deficient cement binder (III)

Thus, the microstructure of concretes is very heterogeneous. From a physical point of view, the concrete is a capillary-porous material containing three phases: solid, liquid, and gaseous. The cement stone, in turn, is very heterogeneous too.

Prolonged processes that continue in solid concrete due to changes in water balance, solidifying gel volume, and crystal size, impart specific elastoplastic properties to the material expressed in the deformation behavior of the concrete under action of loads and conditions of temperature-humidity.

The deformation behavior of the concrete implies its densification (compaction), swelling, and creep. In particular, concrete hardening in ambient air conditions leads to shrinkage (compaction) whereas hardening in water causes dilatation (swelling). As experiments show, the magnitude of shrinkage of a concrete depends on the following factors:

a. cement proportion and grade: lower proportion of cement volume results in greater shrinkage, highly active or alumina cements causing great shrinkage;
b. proportion of water: higher water-cement ratio (w/c) results in greater shrinkage;
c. aggregate particle size: fine sand and porous aggregates cause greater shrinkage

Concrete swelling takes place when the material hardens in humid conditions or contains special expansion agents.

Concretes prepared using certain special cement brands are non-shrinking [6].

If the element of structure of a concrete is loaded, the load will induce certain initial deformation, and thereafter, the element will change its form over time, while stresses created by the load will relax. The phenomenon of inelastic deformation under long-term loading is known as concrete creep.

2.2 Concrete Strength and Stress-strain Behavior

Concretes as structural materials are distinguishable by their high microstructure heterogeneity. Therefore, certain simplifications or approximations are required in the development of physical and mechanical models for stress state analysis and prediction of the strength and deformability of concretes. In particular, such models treat the concrete as elastic homogeneous continuum with some averaged Young modulus (E), Poisson ratio (ν), specific fracture energy (γ) (that is, energy spent in the formation of the fracture surface unit), ultimate tensile (or bending) strength (R_{bt}), and ultimate compression strength (R_{b}). The above characteristics are subject to experimental measurement. In the elastic continuum approximation, they describe the elastic medium and serve as the base in estimating strength and durability of the elements of concrete structures. Obviously, estimations of durability require knowledge of the above characteristics as functions of time, temperature, and diffusion processes running during longtime material operation under given conditions.

In addition to continual mechanical models, there exist analytic local models accounting for structural inhomogeneity (pores, voids, interlayers between aggregate particles, cracks and other stress concentrators) and determining resistance of the material to local crack nucleation. Crack growth from such nuclei can lead to the complete breakage of concrete and reinforced concrete structures.

Such data are necessary for the engineering practice of the renewal of the impaired structural elements in the selection of appropriate healing materials and methods and serviceability estimations.

Concretes usually demonstrate nonlinear stress-strain dependence at both tension and compression. A generalized stress-strain curve for concrete is linear at small strains and passes extremes at larger strains in areas of both tension and compression (Fig. 2.2).

Extreme stress values in the experimental plots (Fig. 2.2) represent the ultimate tensile strength (R_{bt}) and ultimate compression strength (R_b), which are measured using the testing schemes shown in Fig. 2.3.

The Young modulus is measurable in accordance with Hooke's law as a tangent of the curve angle α_0 with the strain axis within the limits of elasticity (Fig. 2.2):

$$E = k \tan \alpha_0, \tag{2.1}$$

where k is the unit conversion factor.

Since stress-strain curve is nonlinear at high (breaking) stresses (Fig. 2.2), the elastic modulus may be determined at any load value as the tangent slope at respective points of the stress-strain curve:

$$E' = k_1 \tan \alpha_1. \tag{2.2}$$

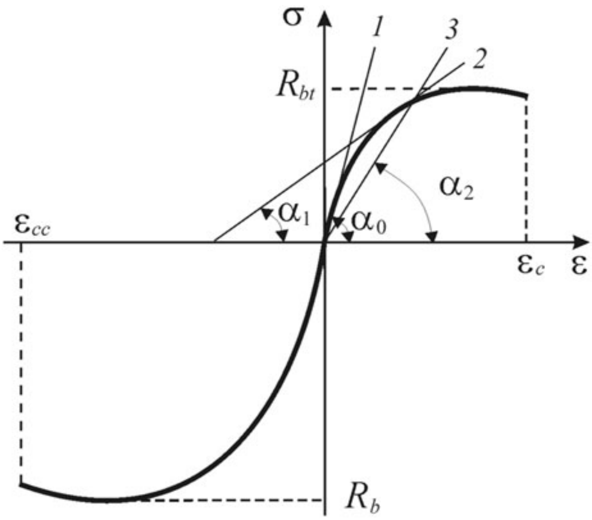

Fig. 2.2 Stress-strain curve for concrete in areas of tension and compression

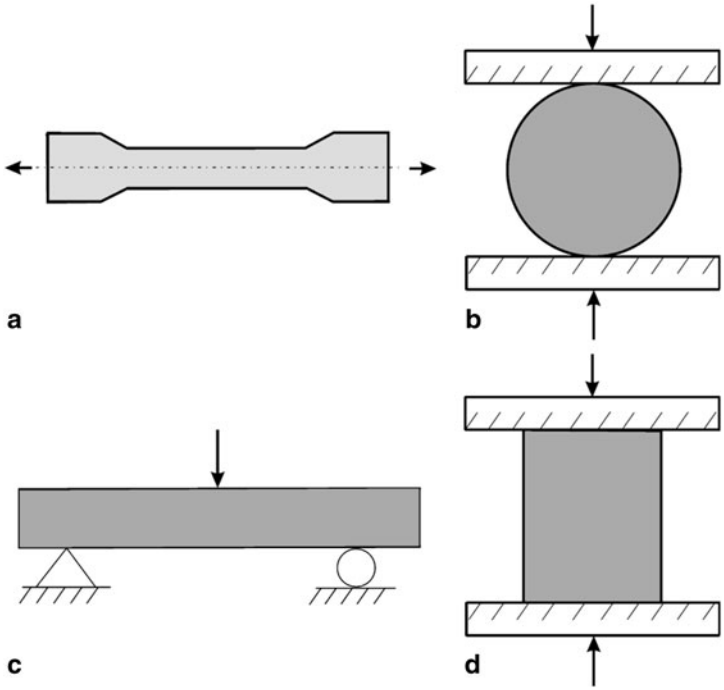

Fig. 2.3 Testing schemes for determining the tensile strength (*a*–*c*) and compressive strength (*d*)

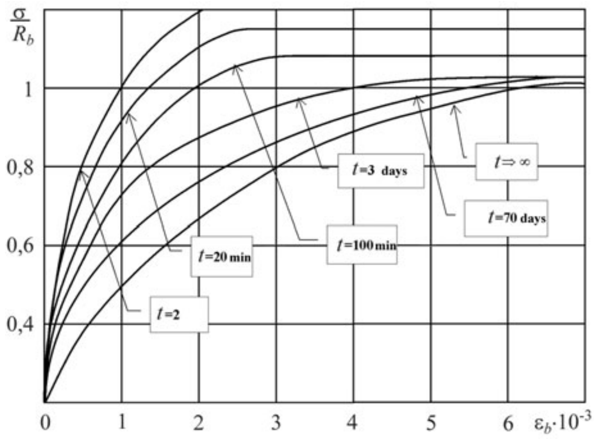

Fig. 2.4 Stress-strain curves for concrete at various loading times. [1]

An average elasticity modulus needed for calculations of the stress state is proportional to the slope of straight line *3* (Fig. 2.2) passing through the particular point at the given stress level:

$$E'' = k_2 \tan \alpha_2. \tag{2.3}$$

It is clear that so-defined elasticity moduli have variable values since angles α_1, α_2 depend on the concrete load time (Fig. 2.4).

The relationship between the elasticity modulus at tension or compression and the shear modulus is as follows:

$$G = \frac{E}{2(1+\nu)}, \tag{2.4}$$

where ν is the Poisson ratio. Shear modulus (G) is an important characteristic of concrete because combined stress states, for example, shear combined with tension (beams), shear combined with compression (arches), are very common in practice. At $\nu = 0.2$, the shear modulus amounts to $G \approx 0.4E$.

Consequently, only the initial elastic modulus determined in the initial stage of a specimen loading within limits of elastic deformation is the physical characteristic of concrete (Fig. 2.2; Eq. 2.1). Table 2.1 presents values of the elastic modulus for certain grades of concrete [1].

2.3 Compressive Strength of Concretes

Compressive strength is the most common and important characteristic of concretes. During compression, stresses in a concrete specimen concentrate either in aggregates, which have higher elastic nodulus values (are harder), or around holes and

Table 2.1 Elastic moduli of concretes at tension or compression $E_b 10^{-3}$, MPa

Concrete	Concrete class according to compressive strength (MPa)										
	B12.5	B15	B20	B25	B30	B35	B40	B45	B50	B55	B60
Heavy, natural hardening	21	23	27	30	32.5	34.5	36	37.5	39	39.5	40
Heavy, heat treated	19	20.5	24	27	29	31	32.5	34	35	35.5	36
Fine type A, natural hardening	17.5	19.5	22	24	26	27.5	28.5	–	–	–	–
Fine type A, heat treated	15.5	17	20	21.5	23	24	24.5	–	–	–	–
Fine type B, natural hardening	15.5	17	20	21.5	23	–	–	–	–	–	–
Fine type B, heat treated	14.5	15.5	17.5	19	20.5	–	–	–	–	–	–
Fine type C	–	16.5	18	19.5	21	22	23	23.5	24	24.5	25
Lightweight, graded by density:											
1400	11	11.5	12.5	13.5	14.5	–	–	–	–	–	–
1800	14	15	16.5	18	19	20	20.5	–	–	–	–

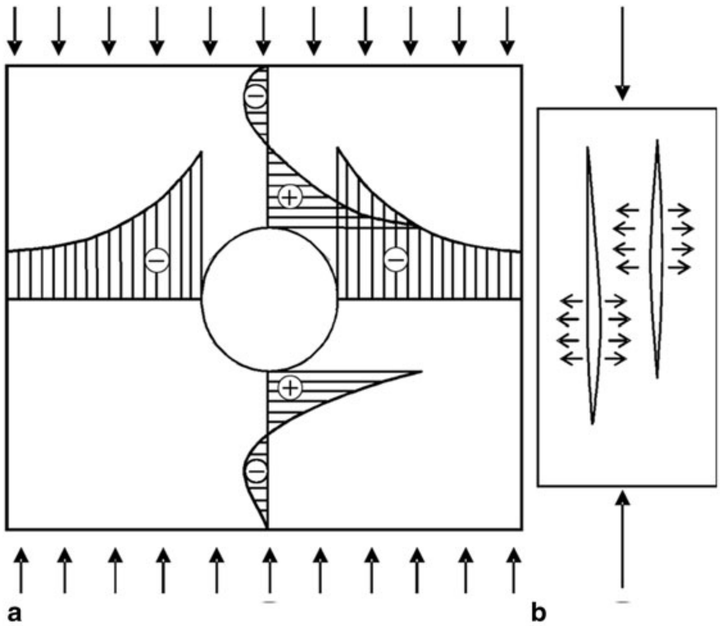

Fig. 2.5 Stress state pattern near micropores (**a**) and genesis of cleavage cracks in a concrete specimen under compression (**b**) [8]. The symbol ⊕ here depicts tensile stresses, symbol ⊖ compressive stresses

cracks. For this reason, a complicated stress state arises in the mechanically inhomogeneous conglomerate (Fig. 2.5) including both compressive stresses and tensile stresses, especially near cavities or voids. Under a compressive loading mode, the primary cracks parallel to the compression axis open first, becoming cleavage cracks (Fig. 2.5b).

Table 2.2 Values of the size correction factor β for compressive strength determination of concrete. [8]

Shape of specimen	Cube					Cylinder			
Size of specimen (cube edge or cylinder diameter), cm	7	10	15	20	30	7 × 14	10 × 20	15 × 30	20 × 40
β value	0.85	0.91	1.0	1.05	1.10	1.16	1.16	1.20	1.24

Thus, tensile stresses adjacent to the compressive ones originate in a concrete specimen under compression around defects like voids or cracks, which, therefore, determine the strength of the concrete.

In addition to primary cracks, factors affecting the strength of the concrete include the process-dependent parameters and age and hardening conditions, as well as the size and shape of the concrete body. Let us consider some of them in more detail.

Cube strength of concrete Cube specimens break under uniaxial compression by the concrete cracking in planes parallel to the compression axis. Cube-shaped concrete specimens with the cube edge size 7; 10; 15, 20 or 30 cm are suitable for compressive strength measurements. Cube specimens of 15 × 15 × 15 cm in size represent the general reference. The results obtained in the testing of cube specimens require correction using an empirically determined factor β (see Table 2.2).

Also suitable for compressive strength measurements are the cylinder-shaped concrete specimens with diameters of 7; 10; 15, or 20 mm, with height twice as high as the diameter.

Prismatic strength of concrete Since reinforced concrete structures mostly have a prismatic rather than cubic shape, the prismatic strength is more common in engineering practice as well [1], [4], [6] , [8], [9]. Comparative tests of concrete prismatic vs. cubic specimens (Fig. 2.8) have shown that the prismatic strength of concrete is lower than the cubic, and diminishes with an increase in height to base edge ratio (h/a). At the value $h/a = 4$, the prismatic strength R_b stabilizes and amounts to about 0.75 of the cube strength. Table 2.3 presents average and generalized (standard) values of prismatic strength for certain grades of concrete.

Table 2.4 presents the tensile and compressive strength values of concrete applicable in designing the elements of concrete structures.

Comparison of the data presented in Tables 2.4 and 2.3 for the same types of concrete shows that the strength values applicable in engineering designing are lower than the prismatic strength values, which, in turn, are lower than cube strength values (Table 2.2).

2.4 Concrete Grades and Types: Concrete Classification [5]

The following attributes constitute the base of concrete classification:

a. Microstructure grading:

Table 2.3 Standard values of tensile and compressive strength of concrete, MPa. [8]

Deformation mode	Concrete type	Concrete class according to compressive strength (MPa)										
		B12.5	B15	B20	B25	B30	B35	B40	B45	B50	B55	B60
Uniaxial compression (prismatic strength) R_b	Heavy or fine	9.5	11	15	18.5	22	25.5	29	32	36	39.5	43
	Lightweight	9.5	11	15	18.5	22	25.5	29	–	–	–	–
Uniaxial tension R_{bt}	Heavy	1	1.15	1.4	1.6	1.8	1.95	2.1	2.2	2.3	2.4	2.5
	Fine type:											
	A	1	1.15	1.4	1.6	1.8	1.95	2.1	–	–	–	–
	B	0.85	0.95	1.15	1.35	1.5	–	–	–	–	–	–
	C	–	1.15	1.4	1.6	1.8	1.95	2.1	2.2	2.3	2.4	2.5
	Lightweight with fine aggregates:											
	Dense	1	1.15	1.4	1.6	1.8	1.95	2.1	–	–	–	–
	Porous	1	1.1	1.2	1.35	1.5	1.65	1.8	–	–	–	–

Table 2.4 Concrete strength values applicable in engineering designing, MPa. [8]

Deformation mode	Concrete type	Concrete class according to compressive strength (MPa)										
		B12.5	B15	B20	B25	B30	B35	B40	B45	B50	B55	B60
Uniaxial compression (prismatic strength) R_b	Heavy or fine	7.5	8.5	11.5	14.5	17	19.5	22	25	27.5	30	33
	Lightweight	7.5	8.5	11.5	14.5	17	19.5	22	–	–	–	–
Uniaxial tension R_{bt}	Heavy	0.66	0.75	0.9	1.05	1.2	1.3	1.4	1.45	1.55	1.6	1.65
	Fine type:											
	A	0.66	0.75	0.9	1.05	1.2	1.3	1.4	–	–	–	–
	B	0.565	0.635	0.765	0.90	1.0	–	–	–	–	–	–
	C	–	0.75	0.9	0.5	1.2	1.3	1.4	1.45	1.55	1.6	1.65
	Lightweight with fine aggregates:											
	Dense	0.66	0.75	0.9	1.05	1.2	1.3	1.4	–	–	–	–
	Porous	0.66	0.735	0.8	0.9	1.0	1.1	1.2	–	–	–	–

- dense (space between aggregate particles is completely filled by solid cement);
- macro porous or popcorn (low-sandy or high-sandy);
- high-porous (with porous aggregates and artificial porosity of solid cement)

b. Average density grading:
   - extra-heavy with density over 2500 kg/m^3;
   - heavy with density from 2200 to 2500 kg/m^3;
   - lightened with density from 1800 to 2200 kg/m^3;
   - lightweight with average density from 500 to 1800 kg/m^3;

c. Particle size grading: coarse concretes or fine concretes;

d. Aggregate grading:
   - dense aggregates;

  - porous aggregates;
  - special aggregates;
  - biologically resistant;
  - heat resistant, etc.

e. Hardening grading:
  - natural hardening;
  - heat treatment at ambient pressure;
  - high-pressure steam treatment

f. Binder grading:
  - gypsum;
  - silica;
  - acid-proof;
  - polymer-cement or polymer;
  - cement

g. General purpose in construction:
  - structural:
    - heavy concrete;
    - fine medium-density concrete;
    - lightweight concrete with dense or porous microstructure;
    - spongy concrete of high-pressure or natural hardening;
    - strained special-purpose concrete [5];
  - special concretes (heat-resistant, road, hydraulic, chemical-resistant, artificial stone, radiation-protective, heat-insulating, etc.)

Concrete quality The following classes and grades determine the main quality rating of concrete:

a. Concrete class according to compressive strength "B";
b. Concrete class according to tensile strength "B_t";
c. Frost resistance grade "F";
d. Water tightness grade "W";
e. Average density grade "D";
f. Self-stressing grade of strained concrete "S_p"

The most valuable feature of concrete is its high compressive strength, which finds wide application in concrete and reinforced concrete structures. Compressive strength is the principal parameter determining grades and classes of concretes.

The compressive strength class "B" of a concrete reflects the guaranteed compressive strength in MPa. The concrete class limits reflect the variability of measured concrete strength values with the rated coefficient of variation 13.5 %. The grade of heavy concretes expresses the ultimate compressive strength in kilogram-force per square centimeter (kgf/cm^2) measured using the reference cube specimens with edge size 15 cm after 28 days of "standard" hardening at a temperature of 20 ± 2 °C and relative humidity 80...100 % [9].

2.5 Fracture Toughness Characteristics of Concretes

Fracture toughness (or crack growth resistance) is the characteristic of material determining its resistance against breakage by crack propagation [10]. The fracture toughness characteristic is especially important for concretes since they are brittle materials and cracking is an intrinsic phenomenon for them. Many reinforced concrete structures, therefore, work in the presence of cracks. The crack opening displacement is therefore one of the primary parameters determining the permissible conditions for the use of a reinforced concrete structure, including the presence of corrosive operation environments (see Chap. 3 and [11]). In this view, the critical crack tip opening displacement δ_{IC} proposed in [12] as a criterion of fracture toughness has a particular importance for the concrete and is one of its principal physical and mechanical characteristics.

The maximal (critical) value of the stress intensity factor (SIF), K_{IC}, is another important and commonly accepted characteristic of concretes that determines the highest permissible stress state near a cleavage crack tip in a strained body. The limiting value of this factor indicates that the stress state near the crack tip in the body (concrete structure) containing the crack proportional to K_{I} has risen up to the highest possible value K_{IC}, and the crack begins catastrophic propagation with possible complete breakage of the structural element. K_{IC} values are subject to experimental measurement [13].

Besides the above-mentioned, fracture mechanics applies certain other parameters, such as the critical value of specific fracture energy per fresh surface formation unit (γ), critical intensity of the release rate of strain energy (G_{IC}), as well as the critical value of Cherepanov-Rice's J-integral [13]. A simple interrelation exists between all these characteristics of fracture toughness valid for conditions of plane strain and localized plasticity near the crack tip:

$$2\gamma = \sigma_0 \delta_{IC} = J_{IC} = \frac{1 - \nu^2}{E} K_{IC}^2, \tag{2.5}$$

where σ_0 is the ultimate tensile stress (strength) of the material [12]; ν is the Poisson ratio, and E is the elastic modulus of concrete experimentally determined using respective techniques [14], [15].

Methods of determination of fracture toughness characteristics for concretes generally include [13]:

a. Methods based on experimental data on crack growth and theoretical solutions of respective mathematical crack theory problems;
b. Direct methods for determination of fracture toughness;
c. Methods based on establishing the correlating relationships between the fracture toughness and service characteristics easily measurable by standard techniques (e.g., hardness, ultimate strength, ultimate yield point, impact toughness, etc.).

Implementation of these methods requires specimens of respective shape and size with artificial cracks, as well as the necessary accuracy of crack size and critical load measurements in experiments.

The shape and size of specimens is, in many cases, dictated by the mode of material service in a structure and operational conditions.

Methods of the first group (a) are most common in practice. They are based on the following principle. Solution of a boundary problem for a cracked body of strictly defined shape and size in the mathematical crack theory yields a dependence of the form:

$$K_I = PF(l,\ E,\ \nu,\ H_1,\ H_2,\ H_3), \tag{2.6}$$

where $F\ (l, E, \nu, H_1, H_2, H_3)$ is a known function; l is crack length; H_1, H_2, and H_3 are geometric parameters of the specimen; P is the applied load.

The specimen is manufactured in accordance with the mathematical conditions. The load application to this specimen under a minor loading rate allows for registering the critical load value $P = P_C$ corresponding to the beginning of crack propagation and calculating the critical value of the stress intensity factor K_I using Eq. (2.6). So obtained, the SIH value at the load $P = P_C$ is nothing other than the critical stress intensity factor K_{IC} for the chosen material.

In order that the fracture toughness value K_{IC} be representative of the material rather than the tested specimen, the stress state of the material near the crack tip must exactly correspond to the mathematical model. One condition of such correspondence consists of a specimen with thickness H_3 large enough to obey the relation [13]:

$$H_3 \geq \beta_0 \frac{K_{IC}^2}{\sigma_{0.2}^2}, \tag{2.7}$$

where coefficient β_0 is subject to experimental or theoretical determination.

Under violation of condition (2.7), the Eq. (2.6) yields a conditional critical stress intensity factor K_C that varies depending on the thickness of the specimen.

The following specimen and loading configurations are the most widely used: prismatic eccentrically tensile specimen with lateral crack (Fig. 2.6a); prismatic specimen for three-point bending (Fig. 2.6b); cylindrical specimen with outward circumferential crack for axial tension (Fig. 2.6c) or three-point bending (Fig. 2.6d); cylindrical specimen with inner crack for transverse compression along the crack plane (Fig. 2.6e).

Determination of another characteristic of fracture toughness, the specific fracture energy γ, is more convenient when using direct experiments. This method implies measurements of the work A spent for the crack length increment Δl. The loading mode must ensure a stable crack growth. In this case, the spent work (or consumed energy) is equivalent to the area under curves of loading a specimen with crack length $2\ l$ and unloading the specimen with crack length $2\ l + 2\Delta l$ in the experimental diagram of load P vs. crack opening u (Fig. 2.7).

The fracture toughness characteristic γ results from the formula:

$$\gamma = \frac{A}{4\Delta l H_3}. \tag{2.8}$$

The advantage of such an approach is in the freedom from any mathematical solutions, which is important for engineering practice and measurement of independent fracture

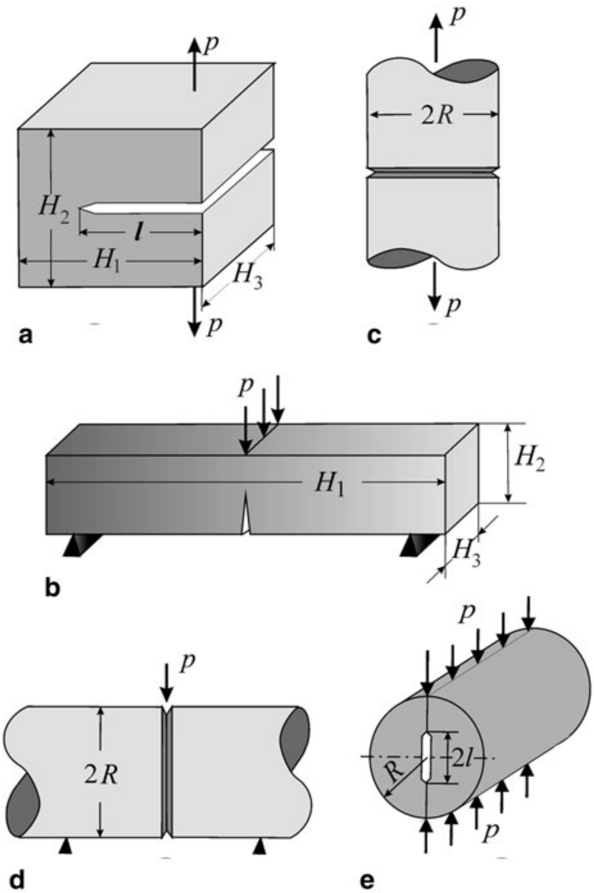

Fig. 2.6 Concrete specimen geometry for the fracture toughness experimental determination

toughness. The evaluation method of the fracture toughness characteristic, J-integral, closely resembles the determination method of γ. A direct interrelation exists between both methods within linear fracture mechanics: $2\gamma = J_{IC}$.

The third group (c) of methods for measuring fracture toughness envisages measurements of standard mechanical properties and microstructure parameters with further calculation of the required value using respective correlation expressions. The analytical formula for calculation of K_{IC} derived in [13] can serve as an example of this approach:

$$K_{IC} = \sqrt{\frac{\rho \tau_T E}{(1 - \nu^2)\varepsilon_C}}, \tag{2.9}$$

where ρ is an intrinsic microstructure parameter; ε_c is the ultimate tensile strain; and τ_T is the ultimate shear stress of the material.

Monograph [13] contains more information about the evaluation methods for fracture toughness.

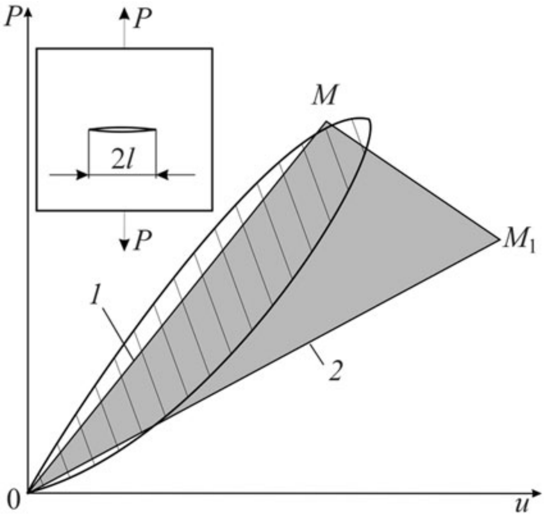

Fig. 2.7 Experimental diagram load–crack opening: curve 1 depicts loading, curve 2 unloading

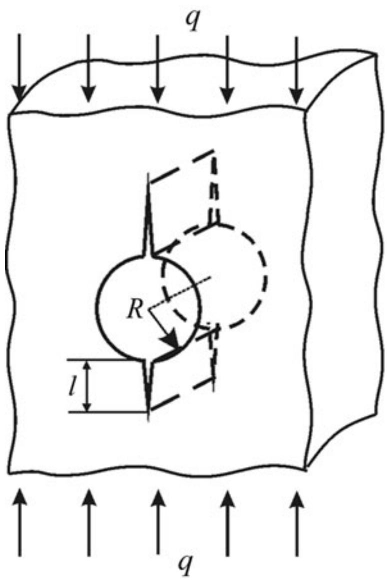

Fig. 2.8 Cracks nucleated near pore under compression

2.6 Compressive and Tensile Strength of Concrete Prisms[1]

Concrete is an inhomogeneous material, a conglomerate of cement stone and aggregates of various sizes and hardness. The compressive or tensile strength is one of the most important physical and mechanical characteristics of concretes. At present,

[1] The authors are grateful to N.V. Onischak for participation in the obtaining of the present results.

concrete science can formulate only individual aspects of a strength and deformation theory of concrete. The following is important in this regard.

Solids with perfect microstructure are indestructible in compression because, in their case, interactive forces between their constituents grow infinitely. A solid breaks down only when areas of tensile stress and strain arise during deformation and its constituents have the opportunity to separate one from another, with interactive (attraction) forces diminishing as the distance increases (after some critical distance). If bond stresses (interactive forces between constituents in an inhomogeneous material) begin to diminish while tensile stresses still grow, then, in some circumferences, a limiting equilibrium state arises between the constituents. That is, increments of infinitesimal tensile stress cause fractures in the given area, i.e., breakage between neighboring solid constituents. In such a way, microcracks nucleate in the above area. Further fracture development proceeds by growth and propagation of these cracks. A theory of inhomogeneous body strength based on similar concepts must derive a certain relation between tensile and compressive strengths of a concrete being the inhomogeneous material. Let us consider a simple (approximate) model of a deformed inhomogeneous body in order to obtain such a relation.

Cement stone is a key factor in determining the strength of concrete [1]. The structure of concrete as a composite material has three levels of hierarchy, namely [5], [16]: microstructure (structure of the cement stone); mesostructure (structure of cement/sand mortar), and macrostructure (structure of aggregate/mortar composite). Each level introduces its own contribution into the strength of the concrete. Analysis of these structure levels results in the following expression for the tensile strength of concrete proposed in [17]:

$$R_{bt} = A_1 R_{bt}^{m} = A_1 \cdot A_2 \cdot R_{bt}^{c}, \tag{2.10}$$

where A_1 and A_2 are dimensionless coefficients accounting for the quality of the concrete's macrostructure and mesostructure, respectively; $R_{\mathrm{bt}}^{\mathrm{m}}$ and $R_{\mathrm{bt}}^{\mathrm{c}}$ are strengths of cement/sand mortar and cement stone, respectively.

Experimental measurements have shown [5] that the similar relation for the compressive strength of concrete contains the same coefficients A_1 and A_2:

$$R_b = A_1 A_2 R_b^c, \tag{2.11}$$

where $R_{\mathrm{b}}^{\mathrm{c}}$ is the compressive strength of cement stone.

It follows from Eqs. (2.10) and (2.11) that the strength of cement stone to a significant extent determines the strength of concrete. The cement stone has a capillary porous microstructure with typical pore size below 100 μm. Its tensile or compressive strength depends on porosity.

Let us accept a plate with a system of round bores with the radius R as the cement stone calculation model. Let us consider an isolated bore assuming low pore concentration so that pore interaction is negligible. Let such a plate undergo compression with uniform force q applied at large enough of a distance from the bore (Fig. 2.8).

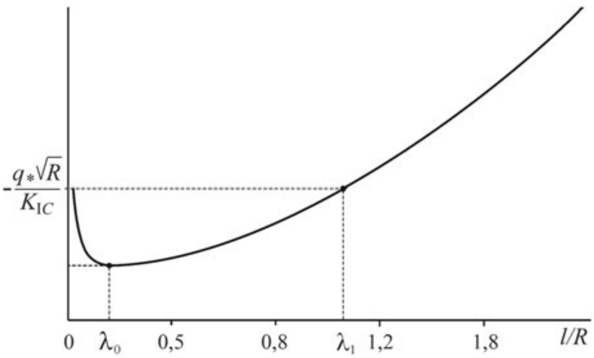

Fig. 2.9 Limiting load dependence on the crack length

Such loading creates tensile stresses at the bore circumference. A high enough load will initiate nucleation of cracks growing out of the bore (Fig. 2.8). The work [10] presents the solution of a mathematical problem for the plate with a bore and outgoing cracks. In particular, the limiting loads value for the pattern in Fig. 2.8 amounts to [16]:

$$q* = \sqrt{\frac{\pi \cdot (1+\lambda)^7}{4R[(1+\lambda)^2 - 1]}} \cdot K_{IC}; \lambda \equiv \frac{l}{R}. \tag{2.12}$$

Figure 2.9 shows the limiting load dependence on the normalized crack length l/R plotted on the base of Eq. (2.12).

The plot shows that the growth of cracks nucleated at the bore circumference under compressive load $q^* = -R_b$ is initially unstable, since they propagate up to length value $l = \lambda_1 R$ requiring no loading increase. Further crack growth requires a loading intensity increase ($|q^*| > -R_b$).

In this way, numerous system defects/cracks emerge in a body with bores under compression (Fig. 2.10). Since the bore spacing is large enough to neglect their interaction, interaction of cracks arranged along the compression axis is negligible as well.

So, let us suppose that our material has bores spaced at a distance $2d$ and cracks growing from the surface of each bore. The applied compressive load value q, at which the cracks merge into a single crack intercepting the whole body, corresponds to the ultimate compressive strength of the cement stone R_b^c. This material characteristic is determinable from Eq. (2.12) if we put the crack length l equal to half pore spacing d. Then,

$$R_b^c = \sqrt{\frac{\pi \cdot (1+d/R)^7}{4R[(1+d/R)^2 - 1]}} \cdot K_{IC}^c. \tag{2.13}$$

Fracture mechanics determines the tensile strength of material as:

$$R_{bt}^c = \frac{K_{IC}^c}{Y\sqrt{\pi l_0}}, \tag{2.14}$$

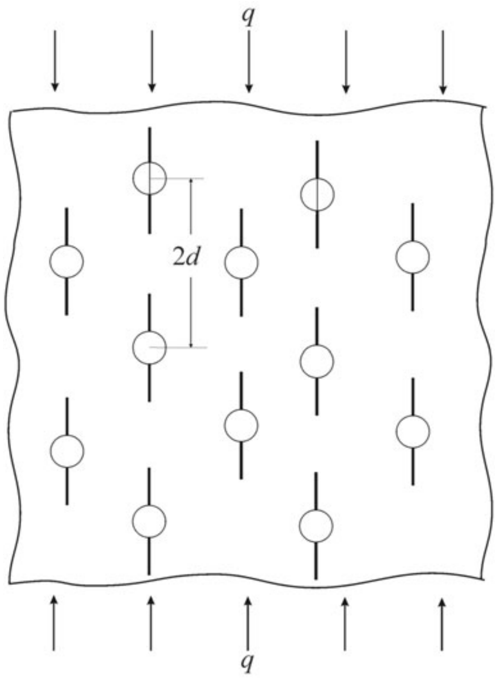

Fig. 2.10 Sketch illustration of pores with cracks in a concrete under compression

where Y is a parameter depending on crack geometry, spatial arrangement, etc.; l_0 is the half crack length assumed as being a characteristic of the material, in the given case, the cement stone. This formula allows for calculation of the crack length from experimentally measured values $R^{\rm c}_{\rm bt}$ and $K^{\rm c}_{\rm IC}$,

In compliance with the above assumptions, Eqs. (2.13) and (2.14) give the following expression interconnecting the ultimate compressive and tensile strengths:

$$R^c_b = R^c_{bt} Y \sqrt{\frac{\pi l_0}{4R}} \cdot \sqrt{\frac{\pi \cdot (1 + d/R)^7}{(1 + d/R)^2 - 1}}. \tag{2.15}$$

The ultimate tensile strength of cement stone aged over 28 days can vary from 3 to 7 MPa depending on the water-cement ratio. Fracture toughness $K_{\rm IC}$ of the same cement stone varies within the range of 0.11. . . 0.4 MPa·m$^{1/2}$. The value of coefficient Y for linear cracks in the plane problem is close to 1.0. Under such conditions, Eq. (2.14) yields the range of l_0 variation from 0.2 to 0.4 mm. Let us put a mean pore size equal to 0.1 mm. Total porosity is about 20 % of that corresponding to mean pore spacing $d \approx R$. Substitution of the above values into the relationship (1.15) permits for calculation that $R^{\rm c}_{\rm b} \approx (14. . . 20)\ R^{\rm c}_{\rm bt}$ in good agreement with experimental results.

The combination of Eqs. (2.10), (2.11), and (2.15) yields a similar relation between compressive strength (R_b) and tensile strength (R_{bt}) for concretes:

$$R_b = R_{bt} \cdot \frac{\pi Y}{2} \sqrt{\frac{l_0 \cdot (1 + d/R)^7}{R[(1 + d/R)^2 - 1]}}. \tag{2.16}$$

Table 2.5 Classification and mechanical properties of concrete reinforcement. [8]

Reinforcement designation and grade	Steel grade	Cross-section diameter, mm	Yield point, MPa	Ultimate strength, MPa	Tensile strain, %
1	2	3	4	5	6
Round hot-rolled reinforcing bar, grade A-1	St3. BSt3	6...40	230	380	25
Periodic profile, grades:					
A-I I	BSt5	10...40			
	10GT	10...32	300	500	19
	18G2S	40...80			
A-I I I	25G2S	6...40			
	35GS	6...40	400	600	14
	32G2R	6...22			
A-I V	20CrG2Z	10...22			
	80S	10...18	600	900	8
A-V	23Cr2G2T	10...22	800	1050	7
A-VI	20Cr2G2SR	10...22	1000	1200	6
Heat refined reinforcing bar, grades:					
At-I I I S	BSt5SP	10...38	400	600	–
At-I VS	25G2S	10...28	600	900	8
At-V	20GS	10...22	800	1050	7
At-VI	20GS	10...22	1000	1200	6
Ordinary reinforcing wire with periodic profile, Grade Vr-I	–	3...5	–	550...525	–
High-strength reinforcing wire:					
Smooth, grade V-II	–	3...8	–	1900...1400	4...6
Periodic profile, grade Vr-II	–	3...8	–	1800...1300	4...6
Reinforcing rope:					
Grade K -7	–	6...15	–	1850...1650	–
Grade K -19	–	14	–	1800	–

2.7 Classification and Mechanical Properties of Concrete Reinforcement

The purpose of concrete structure reinforcement consists mainly in resistance to tensile forces arising in its elements. The necessary reinforcement amount is subject to estimation based on the operational loading of the structural elements.

Reinforcement classification is comprised of four classes:

a. Steel reinforcement for reinforced concrete structures, including hot rolled rod and cold-drawn wire or rod (with any diameter) reinforcement;
b. Hot rolled reinforcement, including heat refined rods or rods hardened by cold drawing, dragging, etc.;

Table 2.6 Standard and engineering design values of strength and elastic modulus for reinforcing bars. [8]

Reinforcement grade	Standard strength R_{sn}, MPa	Strength values for engineering design, MPa			Elastic modulus E_s, MPa
		Tensile		Compressive R_{sc}	
		Either (a) longitudinal or (b) transverse strength per skew section under bending moment R_s	Transverse strength per skew section under transverse force R_{sw}		
A-1	235	225	175	225	210,000
A-1 1	295	280	225	280	210,000
A-1 1 1, 6. . . 8 mm dia	390	355	285	355	200,000
A-1 1 1 and At-1 1 1, 10. . . 40 mm dia.	390	365	290	365	200,000
A-1V and At- 1VS	590	510	405	390	190,000
A-V and At-V	785	680	545	390	190,000
A-V1 and At-V1	980	815	650	390	190,000

c. According to surface relief, reinforcement may include rods of periodic profile or plain wire; periodically, ribbed profile of rods as well as ledges and dents on a wire surface essentially enhance the adhesion with the concrete;
d. According to method of use in concrete structures, reinforcement may include pre-stressed (pre-stretched) or unstressed reinforcement

The hot-rolled reinforcing rods have six grades depending on the main mechanical characteristics (Table 2.5) [8] conventionally designated as A-I, A-Ð†Ð†, A-III, A-IV, A-V, and A-VI.

Heat refined reinforcing bars have an additional symbol "t" in their designation, namely At-1 1 1, At-1V, At-V, and At-V1. The reinforcing bars intended for placement by cage welding have an additional letter "S" in their designation after the Roman numeral. If the reinforcement has an enhanced corrosion resistance, its designation has the letter "K". Cold drawing hardened reinforcement is marked with an additional letter "V" in the grade name.

Each reinforcement grade covers steels with different chemical composition but similar values of yield point (Table 2.5). Table 2.6 presents standard and engineering design values of the strength and elastic modulus for reinforcing bars.

Table 2.7 shows the same characteristics for the reinforcing wires.

Table 2.7 Standard and engineering design values of strength and elastic modulus for reinforcing wires and wire ropes. [8]

Grade	Diameter, mm	Standard strength R_{sn}	Strength values for engineering design, MPa			Elastic modulus E_s, MPa
			Tensile		Compressive R_{sc}	
			Either (a) longitudinal or (b) transverse strength per skew section under bending moment R_s	Transverse strength per skew section under transverse force R_{sw}		
Vr-	3	410	375	270	375	
	4	405	370	265	370	
	5	395	360	260	360	170,000
V-	3	1490	1240	990	390	200,000
	4	1410	1180	940	For all grades in bonding with concrete	
	5	1330	1100	890		
	6	1250	1050	835		
	7	1180	980	785		
	8	1100	915	730		
B-	3	1460	1200	970	–	200,000
	4	1370	1140	910		
	5	1250	1050	830		
	6	1180	980	785		
	7	1100	915	735		
	8	1020	850	675		
K -7	6	1450	1200	970	–	180,000
	9	1370	1140	910		
	12	1330	1100	890		
	15	1290	1080	865		
K -19	14	1410	1180	940	–	180,000

The above-presented classification and properties of reinforcing steels correspond to the Standard of Ukraine DSTU 3760-98 issued in the year 1998 [18] and supplemented in the year 2006 [19]. These new Ukrainian standards introduced the classification adapted to international standards ISO 6934, ISO 6935, DIN 488, and ENU 10080 in respect to size, chemical composition, mechanical characteristics, and testing methods.

The new standard divides the reinforcing bars (A) into grades according to the physical yield point expressed in MPa (N/mm^2).

Finally, according to service characteristics, reinforcement can be as follows:

- Welding (letter “S”);
- Stress corrosion cracking resistant (“K”);
- Unweldable (without the letter “S”);
- Corrosion nonresistant (without the letter “K”)

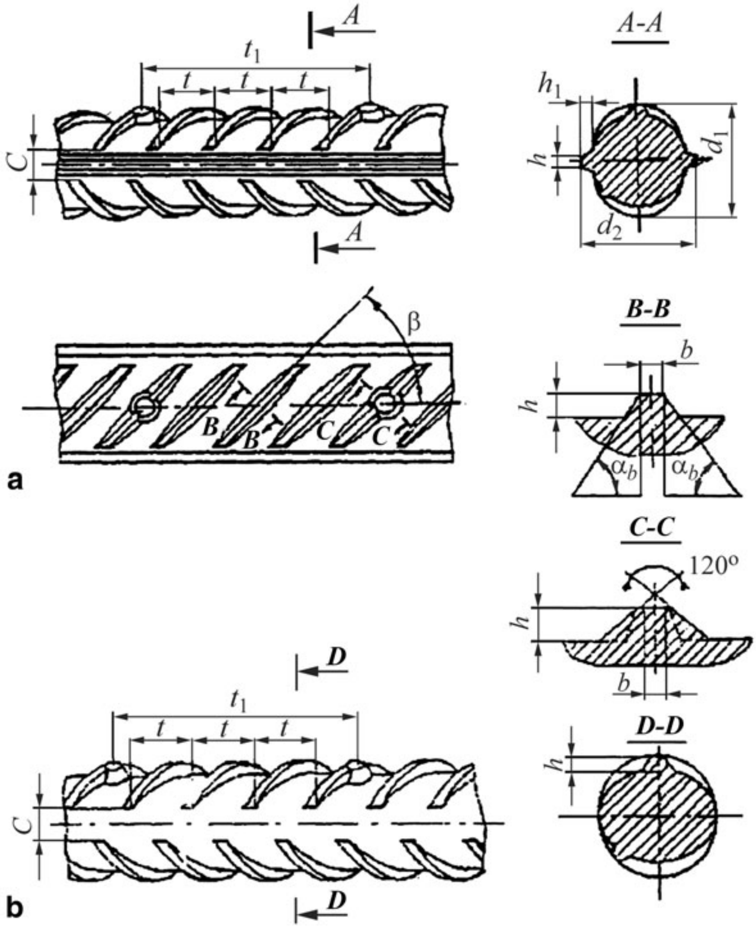

Fig. 2.11 Geometry of periodic hardened profile for rolled reinforcing bars

Ukrainian manufacturers produce ten different grades of reinforcing bars, namely: A240C with plain profile; A300C, A400C, A500C, A600, A600C, A600K, A800, A800K. and A1000 with periodic hardened profile (Fig. 2.11). Table 2.8 exhibits the technical characteristics of the reinforcing bars.

In the past, yield point was the only criterion of a steel grade selection for producing the reinforcement of a specified grade (see Table 2.5). Now, in compliance with Ukrainian standard DSTU 3760-98, the reinforcement production procedures rely on chemical elemental weight composition specified for each reinforcement grade (Table 2.9).

Weight percentage of other alloying elements (chromium, copper, nickel) for welding reinforcement should be less than 0.3 % for each. Chromium weight content 0.90 % or less is admissible for high-strength reinforcing bar grade A800K or A1000.

Table 2.8 Standard values of diameter, cross-section area, and running meter mass for reinforcing bars. [18]

Standard rod diameter d_n, mm	Standard cross-section area, mm^2	Running meter mass of reinforcing bars:	
		Design value, kg	Tolerance, %
1	2	3	4
5.5	32.8	0.187	
6.0	28.3	0.222	± 8.0
8.0	50.3	0.395	
10.0	78.5	0.617	
12.0	113.0	0.888	± 5.0
14.0	154.0	1.210	
16.0	201.0	1.580	
18.0	254.0	2.000	
20.0	314.0	2.470	
22.0	380.0	2.980	
25.0	491.0	3.850	± 4.5
28.0	616.0	4.830	
32.0	804.0	6.310	
35.0	1018.0	7.990	
40.0	1255.0	9.860	

Running meter mass of bars in kg is calculated based on nominal (standard) diameter and steel density 7.85 MT/m^3

Table 2.9 Chemical composition of reinforcing steels. [18]

Reinforcing bar grade	Highest permissible content of chemical elements, wt. %						
	Carbon	Silicon	Manganese	Phosphorus	Sulfur	Nitrogen	Arsenic
A240S	0.22	–	–	0.045	0.045	0.012	0.08
A300S	0.22	–	–	0.045	0.045	0.012	0.08
A400S	0.22	–	–	0.045	0.045	0.012	0.08
A500S	0.22	–	–	0.045	0.045	0.012	0.08
A600; A600S; A600K	0.28	1.00	1.6	0.045	0.045	0.012	0.08
A800; A800K	0.32	2.40	2.3	0.040	0.040	0.012	0.08
A1000	0.32	2.40	2.3	0.040	0.040	0.012	0.08

The most recent Ukrainian standard DSTU 3760:2006 (Appendix A) [19] defines specific steel grades appropriate for producing reinforcing bars of certain grades (see Table 2.10).

Note that the standard DSTU 3760:2006 (Appendix D) [19] establishes the following corrosion cracking requirements for the corrosion resistant grades of reinforcing bars. The time for a corrosion cracking rupture of a corrosion-resistant reinforcing bar specimen in the nitrate solution consisting of calcium nitrate, ammonium nitrate and water in weight proportion 600:50:350 must be at least 100 h at a temperature of 98... 100 °C and at applied stress $0.9\sigma_{0.2}$ (as calculated from Table 2.11).

Table 2.10 Steel grades recommended for producing reinforcing bars. [19]

Reinforcing bar grade	Steel grades acc. Ukrainian standards DSTU 2651:2005 (GOST 380-2005, GOST 5781-82, GOST 10884-94)	Bar forming method	Bar diameter, mm
A240S	St3sp, St3 ps, St3kp	Hot rolled	5.5–40
A400S	St3sp, St3 ps, St3Gps, St5sp, St5 ps, 25G2S, 35GS	Thermomechanically hardened hot rolled	6–40
A500S	St3sp, St3 ps, St3Gps, St5sp, St3Gps, 25G2S	Thermomechanically hardened	6–16, 18–22, 25–40
A600	20GS	Thermomechanically hardened	10–32
A600S	25G2S, 35GS		
A600K	10GS2. 08G2S		
A800	20GS, 20GS2, 08G2S, 10GS2	6–40	
A800K	35GS		
A800SK	20CrGS2		
A1000	25G2S, 20CrGS2	6–40	

Table 2.11 Mechanical characteristics of reinforcing bars. [18], [19]

Reinforcing bar grade	Temperature of electrical heating, °C	Ultimate tensile strength σ_B, MPa	Ultimate yield point $\sigma_{0.2}$, MPa	Ultimate tensile fracture strain δ_s, %	Ultimate uniform fracture strain δ_p, %	Total strain at maximum loading $\delta_{\max}$, %	Initial elastic modulus $E \times 10^{-4}$, MPa	Bending angle during bending tests, deg.	Boring bar diameter (in relation to nominal bar diameter d_n)
		Equal or higher than							
A240S	–	370	240	25	–	–	21	180	0.5 d_n
A300S	–	490	290	19	–	2.5	21	180	3 d_n
A400S	–	500	400	16	–	2.5	20	90	3 d_n
A500S	–	600	500	14	–	2.5	19	90	3 d_n
A600 A600S A600K	400	800	600	12	4	2.5	19	45	5 d_n
A800 A800K	400	1000	800	8	2	3.5	19	45	5 d_n
A1000	450	1250	1000	7	2	3.5	19	45	5 d_n

However, maximum permissible fracture toughness values for both corrosion static and corrosion cyclic cracking remain unrestricted, although these characteristics are very important, especially for structures in long-term operation requiring rehabilitation [20].

Table 2.11 demonstrates the mechanical properties and elastic modulus values for various grades of reinforcing bars.

References

1. Berg OY (1961) Fizicheskiye osnovy prochnosti betona i zhelezobetona (Physical fundamentals of concrete and reinforced concrete strength). GSI, Moscow
2. Vinogradov BN (1979) Vliyaniye zapolniteley na svoystva betona (The effect of aggregates on concrete properties). Stroyizdat, Moscow
3. Bazhenov YM (1978) Tehnologiya betona (The concrete technology). Vyssh.shkola, Moscow
4. Ahverdov IN (1981) Osnovy tehnologii betona (Basics of concrete physics). Stroyizdat, Moscow
5. Grushko IM, Illyin AG, Chikhladze ED (1986) Povysheniye prochnosti i vynoslivosti betona (Advance in concrete strength and durability). Vyssh.shkola, Moscow
6. Gotz VI (2003) Betony i budivel'ni rozchiny (Concretes and building mortars). KNUBA, Kyiv
7. Shishkin AA (2001) Fizicheskaya khimiya kontaktnoy zony betonov (Physical chemistry of contact zone in concretes). Mineral, Krivoy Rog
8. Baikov VN, Sigalov EE (1984) Zhelezobetonnyye konstruktzii (Reinforced concrete structures). Stroyizdat, Moscow
9. Petzold TM, Tur VV (2003) Zhelezobetonnye konstruktzii. Osnovy teorii rascheta i konstruirovaniya (Reinforced concrete structures: basics of design and development). BGTU, Brest
10. Panasyuk VV (1991) Mehanika kvazikhrupkogo razrusheniya materialov (Mechanics of quasi-brittle fracture of materials). Nauk. dumka, Kyiv
11. Moskvin VM, Alexeev SA, Verbitskiy GP, Novgorodskiy VI (1971) Treshchiny v betone i korroziya armatury (Cracks in concrete and corrosion of reinforcement). Stroyizdat, Moscow
12. Panasyuk VV (1968) Predel'noye ravnovesiye khrupkikh tel s treshchinami (The limiting equilibrium of brittle bodies with cracks). Nauk. dumka, Kyiv
13. Panasyuk VV, Andreikiv AE, Kovchik SE (1977) Metody otsenki treshchinostoykosti konstruktsionnykh materialov (Methods of fracture toughness estimation in structural materials). Nauk. dumka, Kyiv
14. Betony. Metody opredeleniya prizmennoy prochnosti, modulya uprugosti i koefficienta Puassona (1980) Concretes: methods for determining the prismatic strength, elastic modulus, and Poisson ratio. Gos. kom. po delam stroitelstva, Moscow
15. Zaitsev YV (1982) Modelirovaniye deformatsiy i prochnosti betona metodami mekhaniki razrusheniya (The concrete deformations and strength simulation using fracture mechanics methods). Stroyizdat, Moscow
16. Standard of Ukraine DSTU 3760-98. Prokat armaturnyi dlya zhelezobetonnykh konstruktsiy (1998) Reinforcing bars for concrete structures. Gosstandart Ukrainy, Kyiv
17. Grushko IM, Illyin AG, Rashevskiy ST (1965) Prochnost' betonov na rastyazheniye (Tensile strength of concretes). Vyssh.shkola, Kharkiv
18. USSR Standard GOST 29167-91. Betony. Metody opredeleniya treshchinostoykosti (vyazkosti razrusheniya) pri staticheskom nagruzhenii (1994) Concretes: methods for determining fracture toughness under static loading. Gosstroyizdat, Moscow
19. Standard of Ukraine DSTU 3760:2006. Prokat armaturnyi dlya zalizobetonnykh konstruktsiy. Zahal'ni tekhnichni umovy (2006) Reinforcing bars for concrete structures: general technical conditions. Derzhspozhivstandart Ukrainy, Kyiv
20. Romaniv ON, Nikiforchin GN (1986) Mekhanika razrusheniya konstruktsionnykh splavov (Fracture mechanics of structural alloys). Metallurgiya, Moscow

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