BASICS OF CONCRETE SCIENCE

L. Dvorkin and O.Dvorkin

St-Petersburg (Russia), Stroi-Beton, 2006

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L.Dvorkin and O.Dvorkin
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ABSTRACT

There are enlightened basic aspects of scientific concrete science. There is given summary of modern ideas about hardening and structure-forming of cement stone and concrete, rheological and technological properties of concrete mixes, strength, strain and other properties, which determine concrete operate reliability and durability. There are considered basic types of normal weight cement concrete, lightweight and cellular concrete, non-cement mineral binders concrete, mortars.

The book is addressed to students and post-graduate students of construction specialties of higher educational establishments, scientists and technologists.

BASIC MONOGRAPHS OF AUTHORS

1. L.I.Dvorkin "Optimum Design of Concrete Mixtures", Lvov, Vusha Skola, 1981, 159 p. (Rus.)
2. L.I.Dvorkin,.V.I.Solomatov, V.N. Vurovoi, S.M.Chydnovski "Cement Concrete with Mineral Admixtures", Kiev, Bydivelnik, 1991, 137 p. (Rus.)
3. L.I.Dvorkin, O.L.Dvorkin "Effective Cement - Ash Concrete", Rivne, Eden, 1999, 195 p. (Rus.)
4. O.L.Dvorkin "Design of Concrete Mixtures. (Bases of Theory and Methodology)", Rivne, NUWMNR, 2003, 265 p. (Rus.)
5. V.I.Bolshakov, L.I.Dvorkin "Building Materials", Dniepropetrovsk, Dnipro-VAL, 2004, 677 p. (Rus.)
6. V.I.Bolshakov, L.I.Dvorkin, O.L.Dvorkin " Bases of Theory and Methodology of Multi-Parametrical Design of Concrete Mixtures", Dniepropetrovsk, PGASA, 2006, 360 p. (Rus.)
7. L.I.Dvorkin, O.L.Dvorkin " Building materials from wastes of industry", Rostov-na-Dony, Phenics, 2007, 363 p. (Rus.)

CONTENTS

Leonid Dvorkin – Honored worker of science and technics of Ukraine, academician of Academy of Civil Engineering of Ukraine, Doctor of Technical Science, Professor, Head of Department of Building Material Science of National University of Water Management and Nature Resources (Ukraine).
Prof. L. Dvorkin is an author of a series of researches, monographs, manuals, textbooks and reference books.
His researches and scientific works are mainly devoted to chemistry and technology of binders and concrete, saving of resources in building materials production.

Oleg Dvorkin– Doctor of Technical Science, Professor of Department of Building Material Science of National University of Water Management and Nature Resources (Ukraine).

O. Dvorkin is an author of a series of researches, monographs and textbooks. His researches and scientific works are mainly devoted to concrete technology and saving resources in building materials production.

REFERENCE
on the manuscript of book
of Doct. of Tech. Science, Prof. L. Dvorkin and
Doct. of Tech. Science O. Dvorkin
"Basics of Concrete Science"

By now concrete science became one of the fundamental material sciences, at which modern construction technology is based. A large body of literature is devoted to certain problems and sections of concrete science.

In this connection famous monographs of V. Ramachandran, A. Neville, F. Lee, A. Sheykin and other authors should be mentioned. Chapter "Concrete science" in educational literature is adduced in manuals on concrete and reinforced concrete technology (manuals of O.Gershberg, Y.Bazhenov etc.).

Therewith wide theoretical and empirical date have been accrued till present time that makes preparation of the books with recital of general essentials of concrete science as independent discipline order of the day. Discipline subject is studying of concrete structure and properties of different types and influence of various factors on them.

Authors of the book under review attempted to solve this problem. The book consists of 10 chapters, comprising main subjects of material science and enlighting qualitative peculiarities of raw materials and admixtures, chemical and physical processes in concrete structure forming, complex of concrete properties which characterize concrete durability, types of cement and mostly wide-spread non-cement concrete and mortars. Distinctive features of the book accessible and in the same time deep enough recital of the data, generalization of wide experimental data, accent on the problems of forecasting and management of concrete properties, their proportioning.

To our opinion the book appeared to be "full-blooded" and original. Along with classical statements there are enlightened modern data and conceptions.

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P.V. KRIVENKO

REFERENCE
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"Basics of Concrete Science"

Basically concrete science is engineering science, development of which greatly defines a level of modern construction technology. The series of editions educational chiefly prepared by professors B.G. Scramtaev, Y.M. Bazhenov and others are devoted to recitals of concrete science essentials. Therewith dynamic development of concrete science in recent years causes necessity of preparation the works, where modern theoretical essentials of that science would be generalized and accessibly stated. The book prepared by famous specialists Doctors of Technical Science, Professors L.Dvorkin and O.Dvorkin subserves this purpose.

Therewith it should be mentioned that the book presented can be considered as in-depth course of concrete science basics which can be useful for wide readership – students, post-graduate students, scientists and technologists.

Structure of the course suggested is appeared to be straight enough; authors sequentially enlighten peculiarities of raw materials, rheological and technological properties of concrete mixes, issues of concrete structure forming, its influence on strength, deformability, concrete resistance to physical and chemical aggression effect. There are discovered interestingly and deeply enough the issues of concrete creep and shrinkage.

Accessible logical recital, wide range of the problems enlightened, generalization of wide experimental data obtained by large group of researchers including the authors themselves, high level of using diagrams, tables, quantitative dependences are characteristic for the book under reference.

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P.G. KOMOHOV

FOREWORD

L. Dvorkin and O.Dvorkin

Modern concrete science is dynamically developed applied science which subject is studying of structure and properties of the composite materials received at hardening of binders and aggregates.
The primary goal of concrete science is working out the theory of producing of concrete with given properties, maintenance of their working capacity and necessary durability in structures and constructions at influence of service factors.
Considering many-sided nature of concrete science, huge luggage of theoretical workings out and the practical experience, saved up by present time, the statement of concrete science essentials is an uneasy problem.
By preparation of the book authors pursued the goal to shine well and at the same time without excessive simplification such sections of concrete science as structure of a cement stone and concrete, its basic properties and types, design of concrete mixtures. Principal views of noncement concrete and mortars are considered in short also.
The offered book as authors hope, can be used not only by students of building specialities of universities, but also to be useful to post-graduate students, scientists, a wide range of technologists.
Authors are grateful to reviewers: Prof. P.Komohov, Prof. P. Krivenko and Prof. A.Ysherov-Marshak for valuable advices and remarks; and also PhD N.Lyshnikova who have assisted in preparation of presentation.

INTRODUCTION.
SHORT HISTORICAL ESSAY

L. Dvorkin and O.Dvorkin

Concrete science is a science about concrete, its types, structure and properties, environmental impact on it. Concrete science develops in process of development of construction technology, improving of experimental methods of research.

Concrete application in civil engineering can be divided conventionally into some stages:

1. The antique

2. Application of a hydraulic lime and Roman cement.

3. Portland cement technology formation and plain concrete application.

4. Mass application of concrete for manufacturing of reinforced concrete constructions.

5. Application of concrete for manufacturing of prestressed and precast reinforced concrete constructions

6. Wide use of concrete of the various types modified by admixtures.

1. Antique concrete

Fig.1. Pantheon in Rome.
Concrete domical building 43 m high (115-125 A.D.)

2. Pioneer research of cement concrete

Fig.2. A. Le Shatelye (1850-1936)
The author of crystallization theory of binders hardening

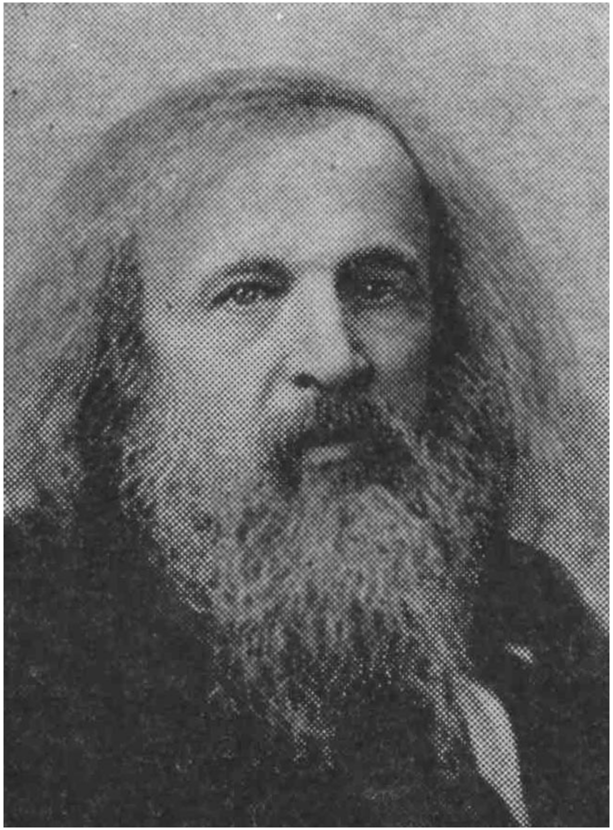


Fig.3. D. Mendeleev (1834-1907)
The great Russian chemist.
He has investigated a series of issues of cement chemistry

Fig.4. A. Shulyachenko (1841-1903)
The author of a series of famous works
on hardening theory
of hydraulic binders, concrete corrosion

Fig.5. N. Beleluskiy (1845-1922)
The author of a series of famous
works on methods of cement and
concrete testing, design of reinforced
concrete constructions

3. “Golden age” of concrete

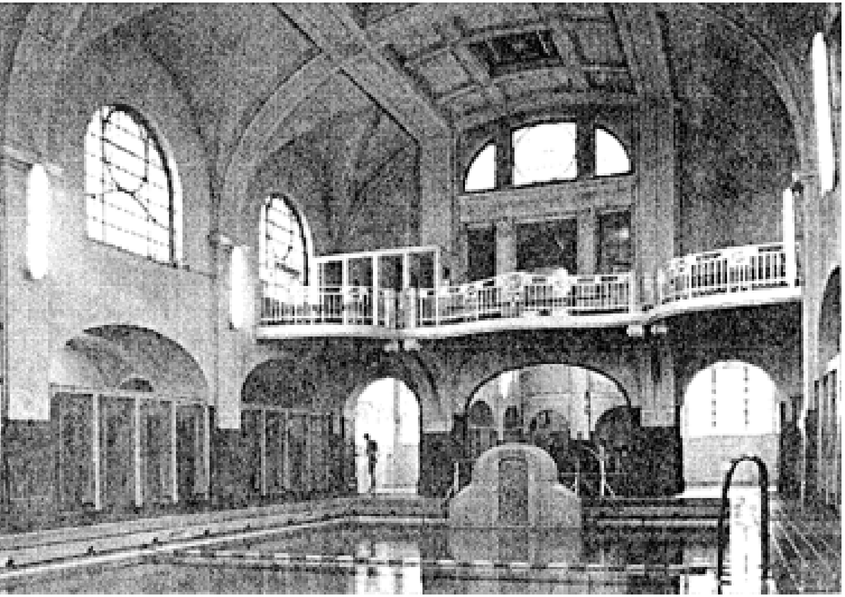


Fig.6. Roofed swimming pool, Hebveiler, France (1896)

Fig.7. Roofed market, Munich, Germany (1912)

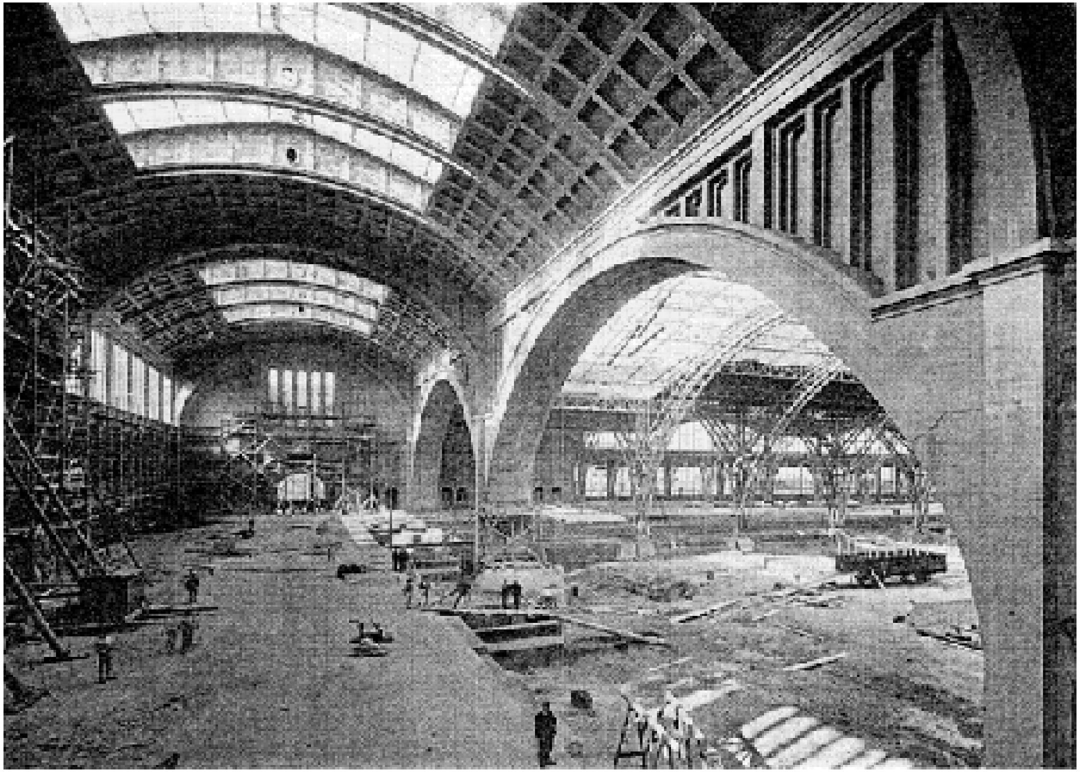


Fig.8. Central railway station, Leipzig, Germany (1915)

Fig.9. Exhibition hall, Brunn, Czech Republik (1928)

Fig.10. Empire State Building, New-York, USA (1931) 381 m high

Fig.11. Moscow subway station “Red Gates”. Monolithic concrete. The platform is ingrown 32.8 m (1935)

Fig.12. Concrete dam at Dnieper hydroelectric plant (1932)

Fig.13. Concrete dam at Sayano-Shushenskaya hydroelectric plant (1982)

Fig. 14. Ostankino television tower, Moscow, more than 530 m high (1967)

Fig.15. Project of reinforced concrete petroleum extraction platform

4. Concrete of XXI century

In XXI century concrete has entered as the basic building material appreciably defining level of a modern civilization. The world volume of application of concrete has reached 2 billion m^3. Advantages of concrete are an unlimited raw-material base and rather low cost, an environmental acceptance, application possibility in various performance conditions and achievements of high architectonic-building expressiveness, availability of technology and possibility of maintenance of high level of mechanization and automation of production processes, which cause attractiveness of this material and its leading positions on foreseeable prospect. Achievements concrete science and concrete technologies allow to project by present time concrete, products and designs with demanded properties, to predict and operate its properties.

CHAPTER 1

CONCRETE. RAW MATERIALS

L. Dvorkin and O.Dvorkin

1.1. Concrete. General

Concrete can be classified as composite material and that is a combination of different components which improve their performance properties.

In general case binder component which can be in hard crystalline or amorphous state is considered as the matrix of composite material.

In concrete matrix phase the grains of aggregates (dispersed phase) are uniformly distributed.

Concrete classification

Classification indication	Types of concrete
Types of binders	Cement, Gypsum, Lime, Slag-alkaline, Polymer, Polymer-cement
Density	Normal-weight, High-weight, Light-weight
Types of aggregates	Normal-weight, Heavy-weight, Light-weight, Inorganic, Organic
Size of aggregates	Coarse, Fine
Workability of concrete mixtures	Stiff and Plastic consistency
Porosity of concrete	High-density, Low-density, Cellular
Typical properties	High-strength, Resistance to action of acids or alkalis, Sulfate resistance, Rapid hardening, Decorativeness
Exploitation purpose	Structural concrete, Concrete for road and hydrotechnical construction, Concrete for thermal isolation, Radiation-protective concrete, White and Coloured concrete

1.2. Binders. Classification. Nature of binding properties

Concrete can be produced on the basis of all types of glues which have adhesion to the aggregates and ability for hardening and strength development.

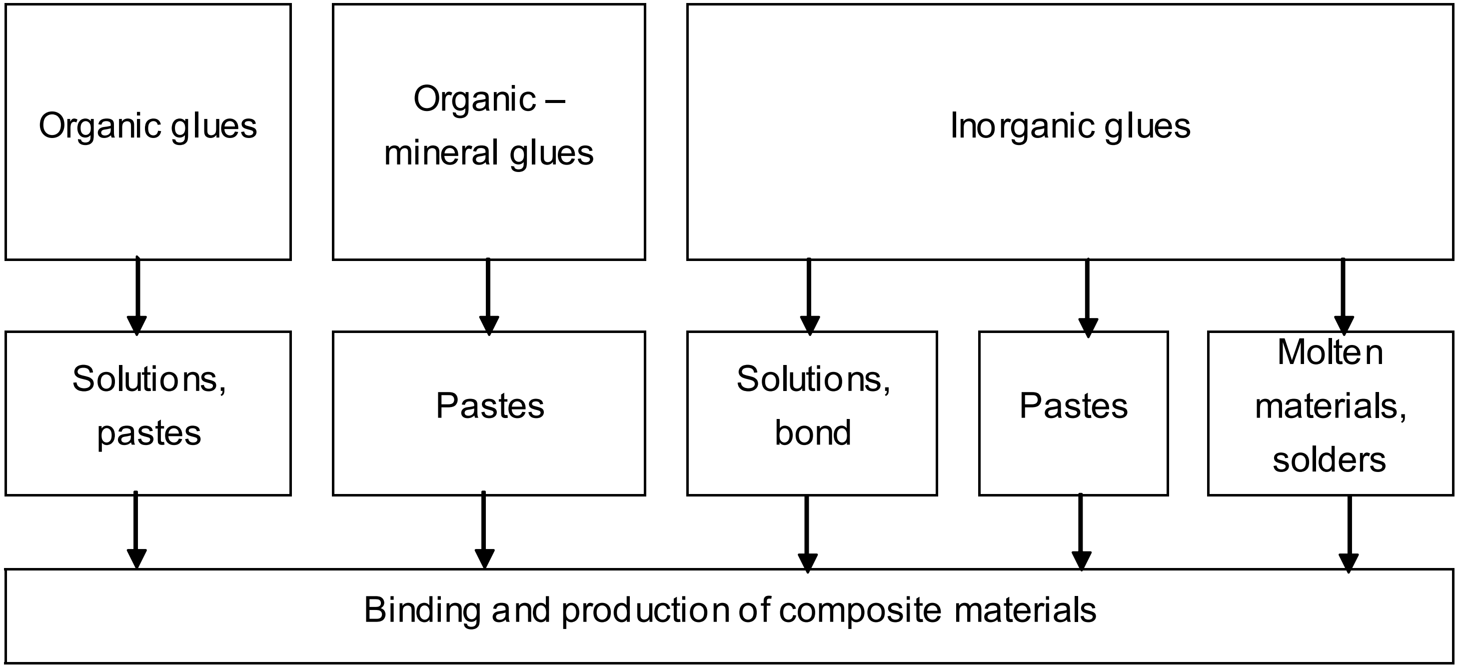


Fig.1.1. Types of adhesives

Periodicity of chemical compounds binding properties

Oxide of chemical element	Oxide						
	Al_2O_3	SiO_2	Fe_2O_3	Cr_2O_3	Mn_2O_3	GeO_2	SnO_2
BeO	--	--	-	-	-	-	-
MgO	--	--	--	-	-	-	-
CaO	++	++	++	++	++	++	++
ZnO	--	--	--	--	-	-	-
SrO	++	++	++	+	+	+	+
CdO	--	--	-	-	-	-	-
BaO	++	++	++	++	++	++	++

Note: fixed (++) and predicted (+) existence of binding properties; fixed (--) and foreseen (-) absence of binding properties.

1.3. Portland cement and its types

Chemical composition of portland cement clinker is as a rule within following range, %:

CaO- 63...66	MgO- 0.5...5
SiO_2- 22...24	SO_3- 0.3...1
Al_2O_3- 4...8	Na_2O+K_2O- 0.4...1
Fe_2O_3- 2...4	$TiO_2+Cr_2O_3$- 0.2...0.5

Fig. 1.2. Crystals of alite

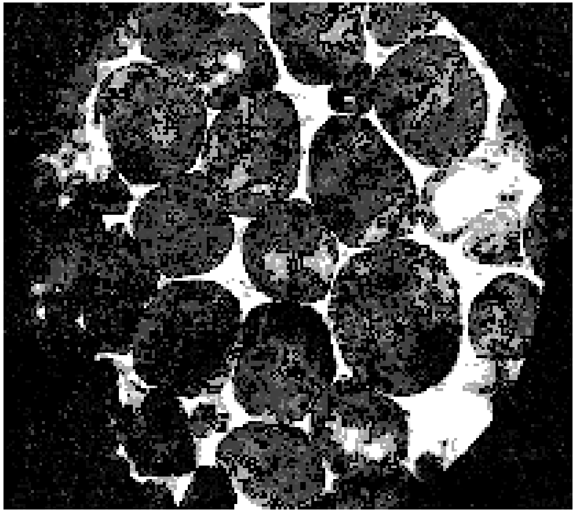


Fig. 1.3. Crystals of belite

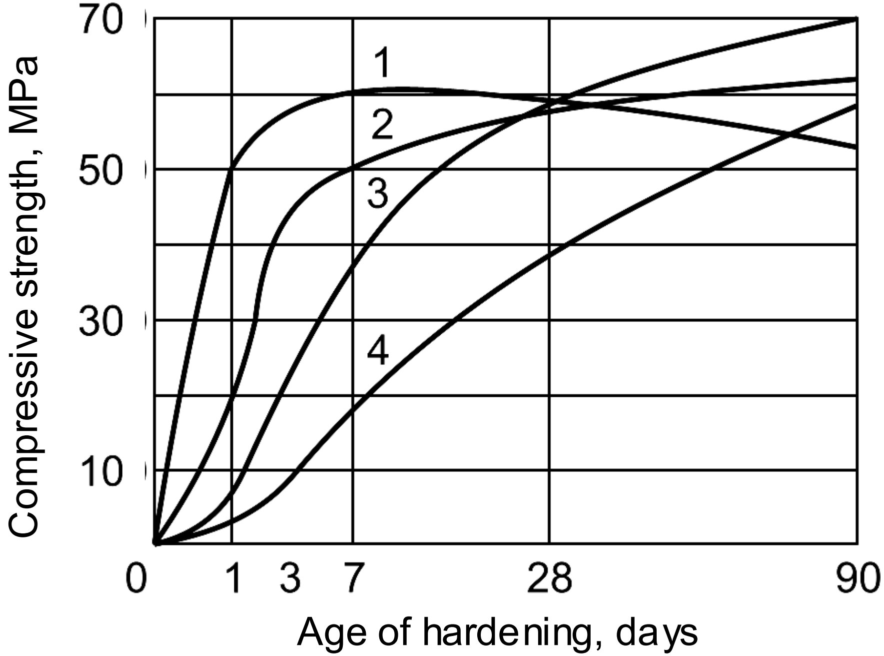


Fig. 1.4. Rate of cement paste hardening under using cements with different grain sizes:
1– <3 μm; 2 – 3…9 μm; 3 – 9…25 μm;
4 – 25…50 μm

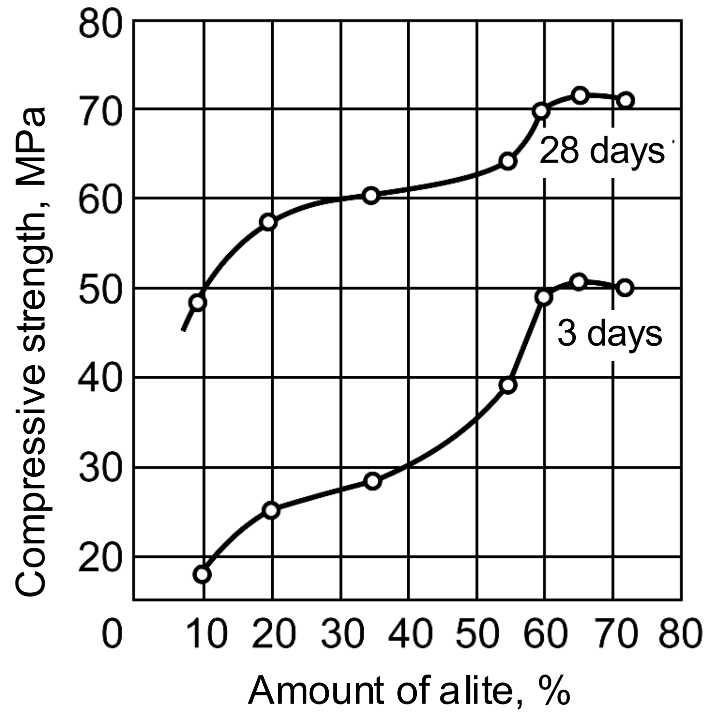


Fig. 1.5. Relationship between amount of alite and compressive strength of cement

1.4. Hydraulic non portland cement binders

Lime binders

Hydraulic lime binders contain materials produced by grinding or blending of lime with active mineral admixtures (pozzolans) — natural materials and industrial byproducts. At mixing of active mineral admixtures in pulverized form with hydrated lime and water, a paste which hardened can be obtained.

Typical hydraulic lime binders are lime-ash binders.

Slag binders

Slag binders are products of fine grinding blast-furnace slag which contains activation hardening admixtures. Activation admixtures must be blended with slag at their grinding (sulfate – slag and lime – slag binders) or mixing with water solutions (slag - alkaline binders). Activation admixtures are alkaline compounds or sulfates which contain ions Ca^{2+}, $(OH)^-$ and $(SO_4)^{2-}$.

Calcium - aluminate (high-alumina) cements

Calcium - aluminate (high-alumina) cements are quickly hardening hydraulic binders. They are produced by pulverizing clinker consisting essentially of calcium aluminates.

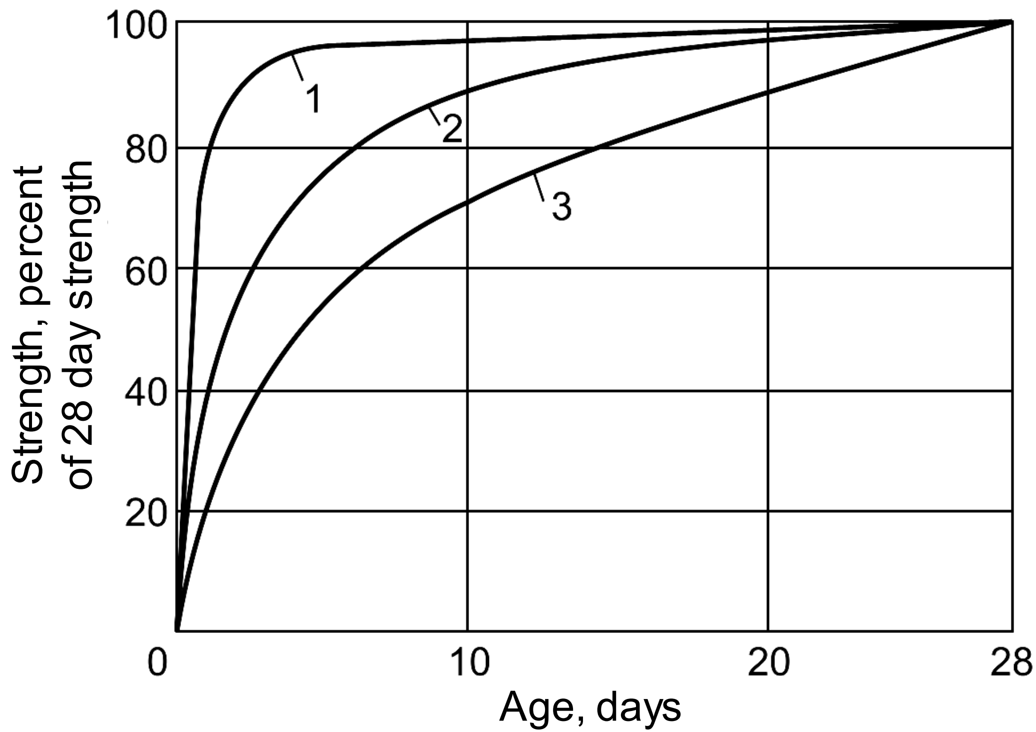


Fig. 1.6. Typical curves of cement strength increase:
1 - calcium - aluminate cement; 2 – high-early strength portland cement; 3 – ordinary portland cement

1.5. Concrete aggregates

Classification of aggregates for concrete

Classification indication	Kind of aggregates	Characteristics of classification indication
Grain size	Fine aggregates	≤5 mm
	Coarse aggregates	>5 mm
Particle shape	Gravel	Smooth particles
	Crushed stone	Angular particles
Bulk density (ρ_0)	Heavy	ρ_0>1100 kg/m^3
	Light	ρ_0≤1100 kg/m^3
Porosity (P)	Normal and high - density	P≤10%
	Low - density	P>10%
Exploitation purpose	Normal, high and low – density concrete, Concrete for hydrotechnical, road and other kinds of construction	Properties of aggregates must conform to the concrete properties

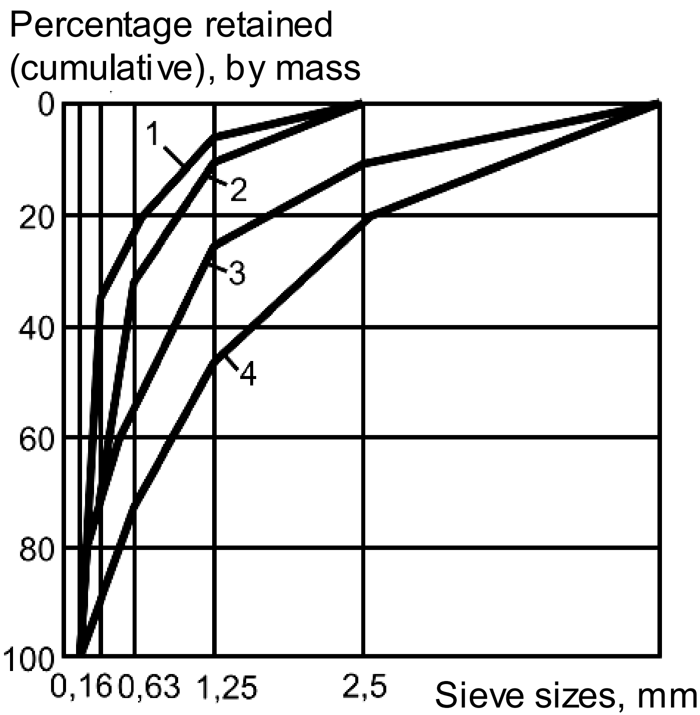


Fig. 1.7. Curves indicate the limits specified in Ukrainian Standard for fine aggregates:
1,2 - Minimum possible (Fineness modulus=1.5) and recommended (Fineness modulus=2) limits of aggregate size;
3,4 - Maximum recommended (Fineness modulus=2.25) and possible (Fineness modulus=2.5) limits of aggregate size

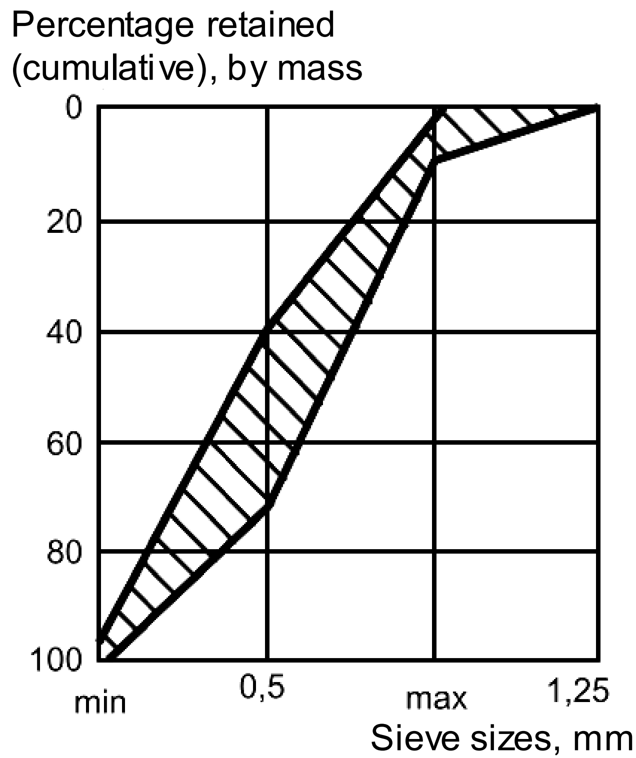


Fig. 1.8. Curves indicate the recommended limits specified in Ukrainian Standard for coarse aggregates

1.6. Admixtures

Chemical admixtures

European standard (EN934-2) suggested to classify chemical admixtures as follows.

Admixtures by classification (Standard EN934-2)

Type of admixture	Technological effect
Water reducer – plasticizer*	Reduce water required for given consistency or improve workability for a given water content
High water reducer – superplasticizer**	Essentially reduce water required for given consistency or high improve workability for a given water content
Increase bond of water in concrete mixture	Prevention of losses of water caused by bleeding (water gain)
Air-entraining	Entrainment of required amount of air in concrete during mixing and obtaining of uniform distribution of entrained-air voids in concrete structure
Accelerator of setting time	Shorten the time of setting
Accelerator of hardening	Increase the rate of hardening of concrete with change of setting time or without it.
Retarder	Retard setting time
Dampproofing and permeability-reducing	Decrease permeability
Water reducer/ retarder	Combination of reduce water and retard set effects
High water reducer/ retarder	Combination of superplasticizer (high water reduce) and retard set effects
Water reducer/ Accelerator of setting time	Combination of reduce water and shorten the time of setting effects
Complex effect	Influence on a few properties of concrete mixture and concrete

Note:

* Plasticizer reduces the quantity of mixing water required to produce concrete of a given slump at 5-12%.;

** Superplasticizer reduces the quantity of mixing water at 12-30 % and more.

Classification of plasticizers

Category	Type of plasticizer	Plasticizer effect (increase the slump from 2...4 sm)	Reduce the quantity of mixing water for a given slump
I	Superplasticizer	to 20 sm and more	no less than 20 %
II	Plasticizer	14-19 sm	no less than 10 %
III	Plasticizer	9-13 sm	no less than 5 %
IV	Plasticizer	8 and less	less than 5 %

Air-entrained admixtures are divided into six groups (depending on chemical composition):

1) Salts of wood resin;
2) Synthetic detergents;
3) Salts of lignosulphonated acids;
4) Salts of petroleum acids;
5) Salts from proteins;
6) Salts of organic sulphonated acids.

As gas former admixtures silicon-organic compounds and also aluminum powder are used basically. As a result of reaction between these admixtures and calcium hydroxide, the hydrogen is produced as smallest gas bubbles.

Calcium chloride is the most explored accelerating admixture. Adding this accelerator in the concrete, however, is limited due to acceleration of corrosion of steel reinforcement and decrease resistance of cement paste in a sulfate environment.
As accelerators are also used sodium and potassium sulfates, sodium and calcium nitrates, iron chlorides, aluminum chloride and sulfate and other salts-electrolytes.

Some accelerating admixtures are also anti-freeze agents which providing hardening of concrete at low temperatures.

In technological practice in some cases there is a necessity in retarding admixtures.

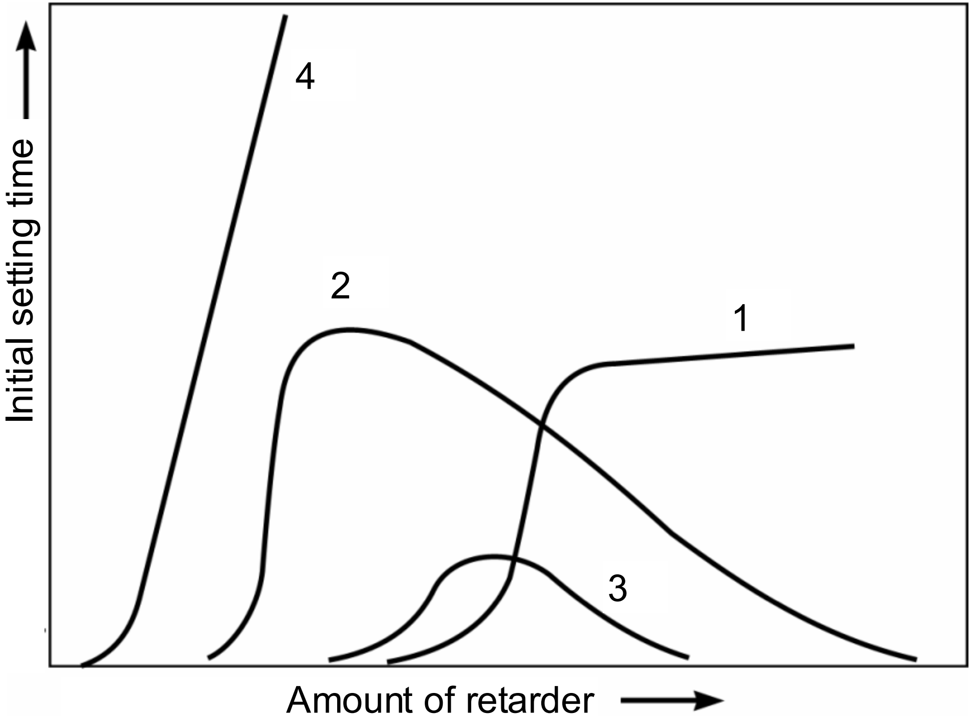


Fig.1.9. Effect of retarding admixrures on initial setting time (from Forsen)

Forsen has divided retarders into four groups according to their influence on the initial setting time:

1. $CaSO_4 \cdot 2H_2O$, $Ca(ClO_3)_2$, CaS_2.
2. $CaCl_2$, $Ca(NO_3)_2$, $CaBr_2$, $CaSO_4 \cdot 0.5H_2O$.
3. Na_2CO_3, Na_2SiO_3.
4. Na_3PO_4, $Na_2S_4O_7$, Na_3AsO_4, $Ca(CH_3COO)_2$.

Mineral admixtures

Mineral admixtures are finely divided mineral materials added into concrete mixes in quantity usually more than 5 % for improvement or achievement certain properties of concrete.

As a basis of classification of the mineral admixtures accepted in the European countries and USA are their hydraulic (pozzolanic) activity and chemical composition.

Fly ash is widely used in concrete mixes as an active mineral admixture. Average diameter of a typical fly ash particle is 5 to 100 μm. Chemical composition of fly ash corresponds to composition of a mineral phase of burning fuel (coal).

Silica fume is an highly active mineral admixture for concrete which is widely used in recent years. Silica fume is an ultrafine byproduct of production of ferrosilicon or silicon metal and contains particles of the spherical form with average diameter 0,1μm. The specific surface is from 15 to 25 m^2/kg and above; bulk density is from 150 to 250 kg/m^3.
The chemical composition contains basically amorphous silica which quantity usually exceeds 85 and reaches 98 %.

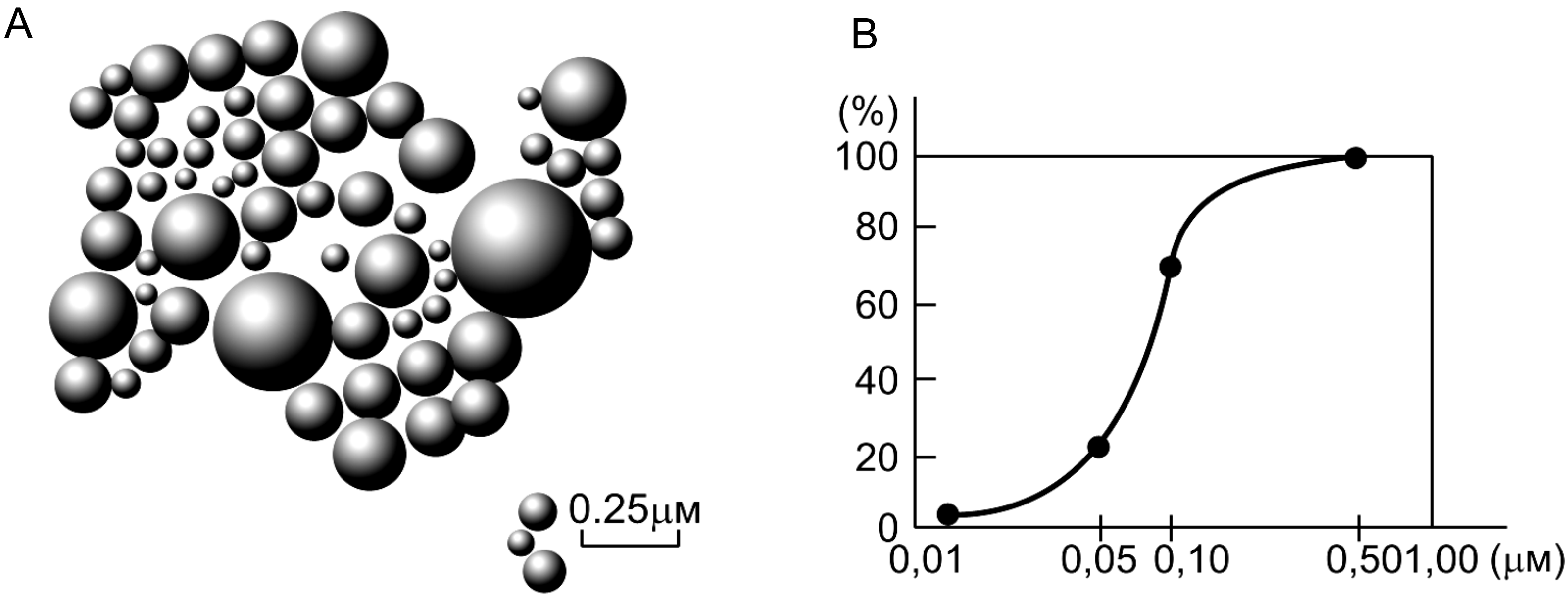


Fig.1.10. Basic characteristics of silica fume:

A – Particle shape and size; B – Grading curve

1.7. Mixing water

Mixing water is an active component providing hardening of cement paste and necessary workability of concrete mix.

Water with a hydrogen parameter pH in the range of 4 to 12.5 is recommended for making concrete. High content of harmful compounds (chloride and sulphate, silt or suspended particles) in water retards the setting and hardening of cement.

Organic substances (sugar, industrial wastes, oils, etc.) can also reduce the rate of hydration processes and concrete strength.

Magnetic and ultrasonic processing has an activating influence on mixing water as shown by many researchers.

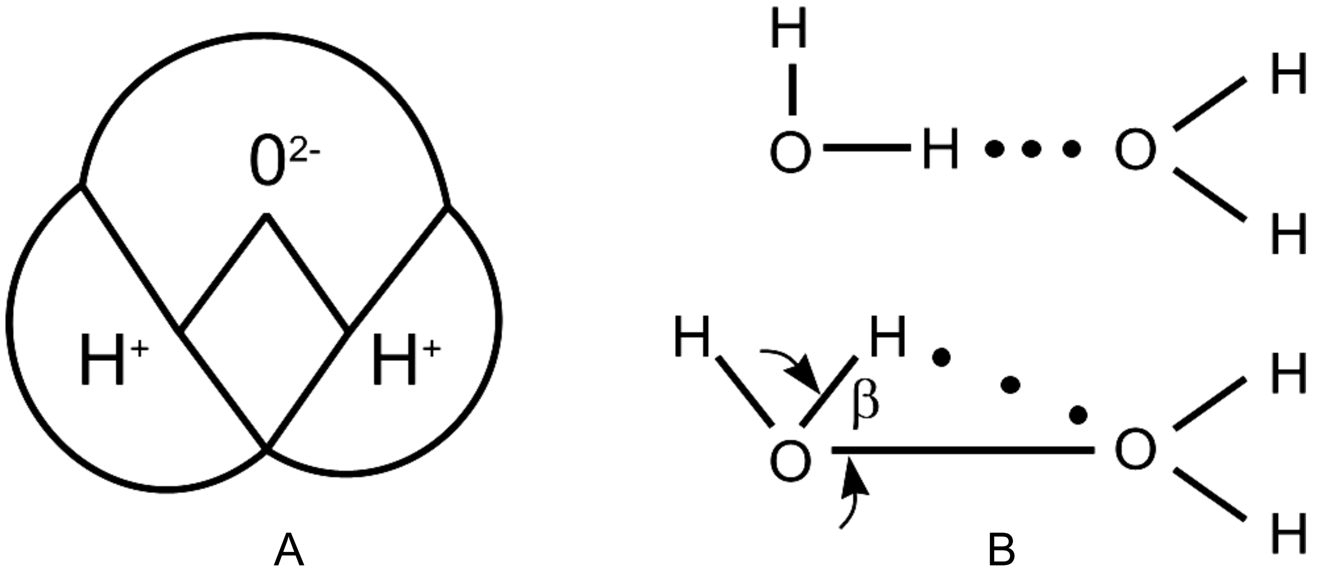


Fig. 1.11. Structure of a molecule of water (A) and types of hydrogen bonds (B)

CHAPTER 2

CONCRETE MIXTURES

L. Dvorkin and O.Dvorkin

2.1. Structure and rheological properties

Concrete mix is a system in which cement paste and water bind aggregates such as sand and gravel or crushed stone into a homogeneous mass.
The coefficient of internal friction relies mainly on the coarseness of aggregates and can be approximately calculated on the Lermit and Turnon formula:

$$f = \lg a d^{b}, \qquad (2.1)$$

where d - middle diameter of particles of aggregate; a and b - constants.

The rheological model of concrete mixture is usually characterized by the Shvedov-Bingam formula:

$$\tau = \tau_{max} + \eta_m \frac{dV}{dx}, \qquad (2.2)$$

where τ_{max} – maximum tension; η_m – plastic viscidity of the system with the maximum destructive structure; dV/dx – gradient of speed of deformation during flow.

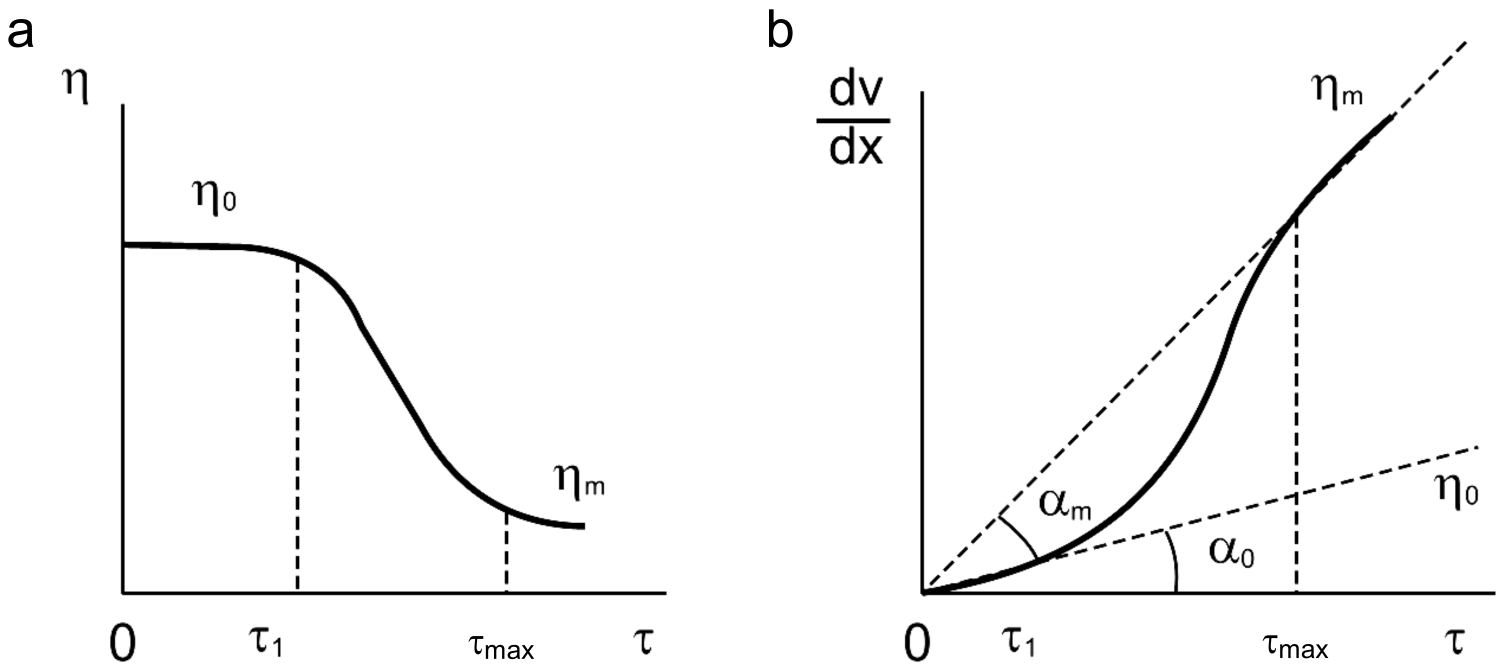


Fig. 2.1. Change of viscidly-plastic properties of concrete mixture depending on tensions:
a – change of structural viscosity; b – change of speed of deformation of flow (α_o and α_m – corners, which characterizing coefficients of viscosity of the system);
τ_{max} – maximum tension; η_o η_m – plastic viscosity of the system accordingly with nondestructive and destructive structure

The conduct of concrete mixtures at vibration approximately can be described by Newton formula :

$$\tau = \eta_m \frac{dV}{dx}. \qquad (2.3)$$

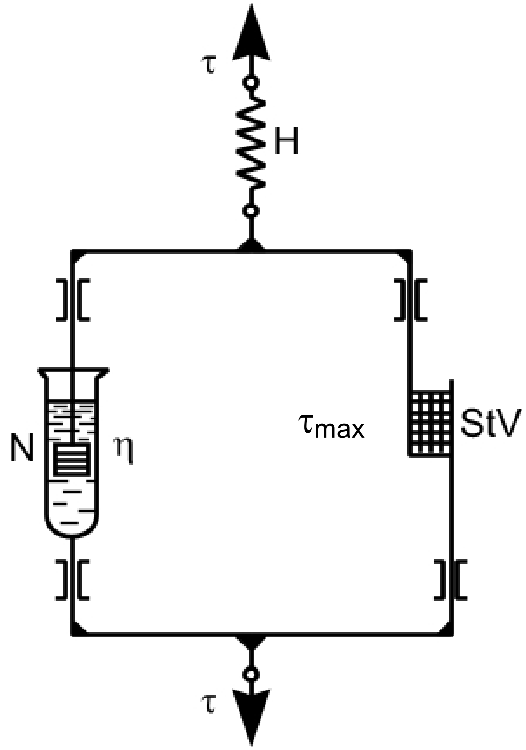


Fig. 2.2. Chart of rheological model of Bingam

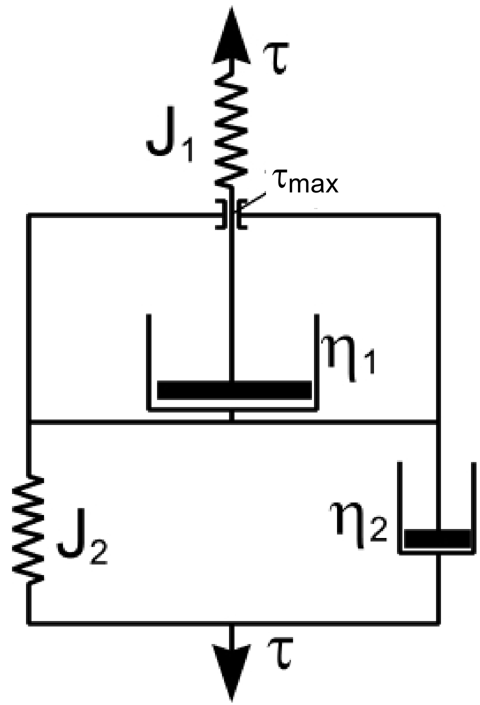


Fig. 2.3. Chart of the rheological model of Shefild-Skot-Bler

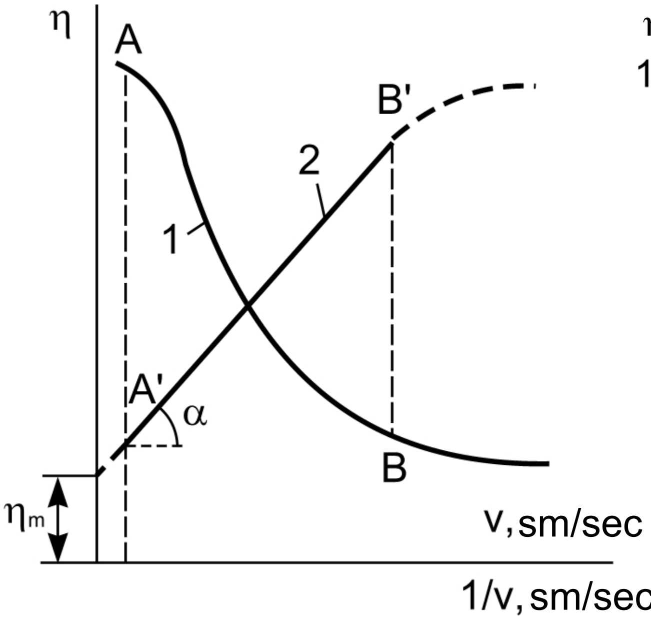


Fig. 2.4. Dependence of structural viscosity of concrete mixture on:

1- speed (v); 2 - reverse speed of vibrations (1/v)

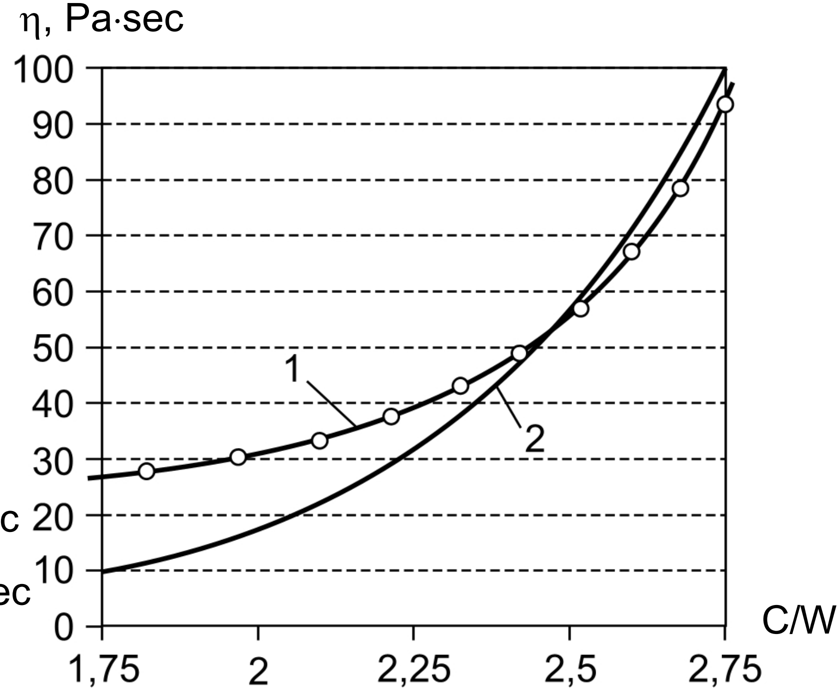


Fig. 2.5. Dependence of viscosity of concrete mixture on cement – water ratio (C/W):

1 – from formula (2.4);

2 – from A.Desov experimental data

Influencing of concentration of dispersed phase (φ) on viscosity of colloid paste (η) at first was described by A. Einstein:

$$\eta = \eta_0 (1 + 2{,}5\varphi), \qquad (2.3)$$

where η_0 – viscidity of environment.

Experimental data permitted to L.I.Dvorkin and O.L.Dvorkin to write down formula of viscosity of concrete mixture as follows:

$$\eta = K_0 e^{\eta_{c.p}\varphi_z}, \qquad (2.4)$$

where $\eta_{c.t}$ – viscosity of cement paste; φ_z –volume concentration of aggregates in the cement paste; K_0 – proportion coefficient.

2.2. Technological properties of concrete mixtures

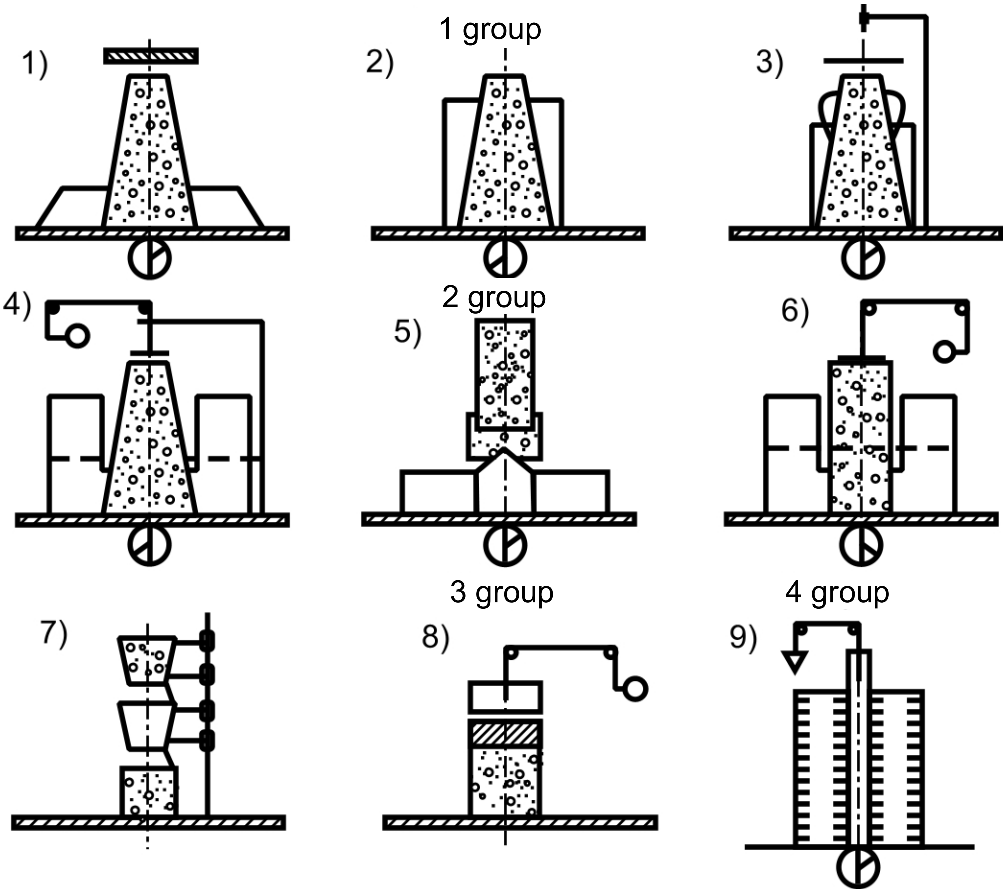


Fig. 2.6. Chart of methods of determination of structural-mechanical properties (workability) of concrete mixtures:
1 – cone; 2 –Skramtaev's method; 3– method Vebe;
4 – technical viscometer; 5 – Slovak method;
6 – modernized viscometer; 7 – English method;
8 – method of building NII; 9 – viscometer NIIGB

Formula of water balance of concrete mixture:

$$W = XК_{n.c}C + К_{m.s}S + К_{m.st}St + B_{pores} + B_{fm}, \qquad (2.5)$$

where W – the water quantity which determined to the necessary workability of mixture, kg/m^3; C, S and St – accordingly quantities of cement, sand and coarse aggregate, kg/m^3; $K_{n.c}$, $K_{m.s}$, $K_{m.st}$ – normal consistency of cement paste and coefficients of moistening of fine and coarse aggregates; $X = (V/C)_p/K_{n.d}$ – relative index of moistening of cement paste in the concrete mixture ($(V/C)_p$ – water-cement ratio of cement paste); V_{pores} – the water taken in by the pores of aggregates, kg/m3; V_{fm} – water which physically and mechanically retained in pores space between the particles of aggregates (free water), kg/m^3.

Approximately simultaneously (at the beginning of 30th of 20 century) and independently from each other V.I. Soroker (Russia) and F. McMillan (USA) had set the rule of constancy of water quantity (RCW). It was found that at unchanging water quantity the change of cement quantity within the limits of 200-400 kg/m^3 does not influence substantially on workability of concrete mixtures.

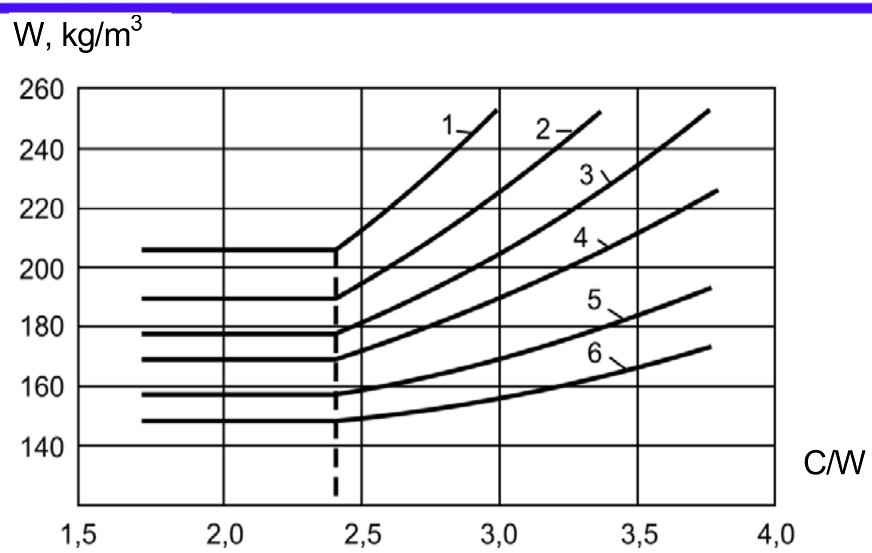


Fig. 2.7. Influence of cement-water ratio (C/W) on water quantity

1.3 – slump of concrete mixtures: 10, 5, 2 sm.
4.6 – workability (Vebe): 30, 60, 100 sec

The top limit $(W/C)_{cr}$ of the rule of constancy of water quantity(RCW) can be calculated by formula:

$$(W/C)_{cr} = (1{,}35\dots1{,}65)K_{n.c} + \frac{K_{m.s}S + K_{m.st}St}{C}, \qquad (2.6)$$

where $K_{m.s}$, $K_{m.st}$ – coefficients of moistening of fine and coarse aggregates; S and St – accordingly quantities of sand and coarse aggregate, kg/m^3

Application of aggregates substantially multiplies the water content of concrete mixtures, necessary for achievement of the set mobility (workability).

For the choice of continuous grading or particle-size distribution of aggregates different formulas, are offered:

Formula		Author
$У = 100\sqrt{\frac{d}{D}}$	(2.7)	Fuller
$У = A + (100 - A)\sqrt{\frac{d}{D}}$	(2.8)	Bolomey
$У = 100\left(\frac{d}{D}\right)^{n}$	(2.9)	Gummel

In formulas (2.7-2.9): d – size of particles of the given fraction of aggregate; D – maximum particle-size of aggregate; A – coefficient equal 8-12 depending on the kind of aggregate and plasticity of concrete mixtures; n – index of degree equal in mixtures on a crushed stone 0,2...0,4, on the gravel 0,3...0,5 (in Gummel's formula index of degree equal 0,1 to 1).

Correction of parameters of aggregates by mixing, for example, two kinds of sand can be executed by formula:

$$n = \frac{P_1 - P}{P_1 - P_2}, \qquad (2.10)$$

where R – the required value of the corrected parameter (fineness modulus of aggregate, specific surface, quantity of aggregate of definite fraction); P_1 and P_2 – values of the corrected parameter of aggregate accordingly with large and less its value; n –volume content of aggregate with the less value of the given parameter in the sum of volumes of the aggregates mixed up.

2.3. Consolidation (compaction) concrete

Achievement of necessary high-quality concrete is possible only at the careful consolidation of concrete mixtures.

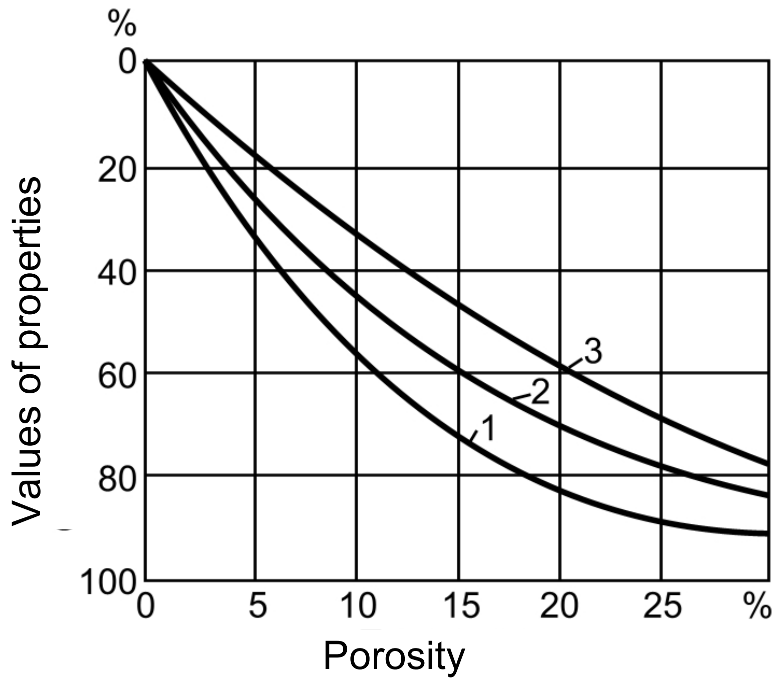


Fig. 2.8. Influence of porosity of concrete on compressive strength (1), tensile strength (2), dynamic modulus of elasticity (3)

The compacting factor (D_{cp}) of fresh concrete is determined by a compaction ratio:

$$D_{cp} = 1 - P, \qquad (2.11)$$

where P – porosity of compacting fresh concrete.

More than 90% of all concrete constructions and units are made by method of vibration.

A.Desov and V.Shmigalsky had offered the parameter of intensity of vibrations (I) as a criterion of efficiency of vibration (fig.2.9):

$$I = A^2 W^3, \qquad (2.12)$$

where A – amplitude of vibrations; W – frequency of vibrations.

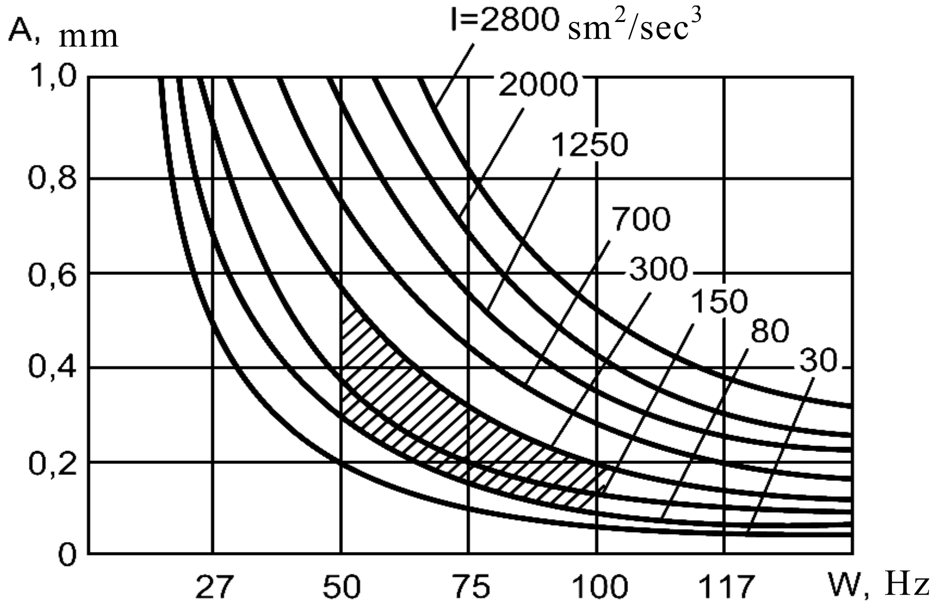


Fig. 2.9. Relationship between amplitudes (A) and frequency of vibrations (W) of a different intensity of vibration (I)

Duration of vibration (τ) for no-slump mixtures is offered to calculate by formula:

$$\tau = \alpha_c Vb \sqrt{I / I_u}, \qquad (2.13)$$

where I_u – minimum intensity of vibrations of mixture in the construction; I – intensity which workability (Vebe) of mixture is determined (Vb); α_c – coefficient relying on configuration of construction and degree of its reinforcement.

CHAPTER 3

CONCRETE HARDENING AND STRUCTURE-FORMING

L. Dvorkin and O.Dvorkin

Concrete hardening includes the complex of processes of cement hydration. Physical and chemical processes of structure formation of cement paste make substantial influence on concrete hardening. Concrete hardening and forming of concrete properties depend greatly on the mixing water, aggregates and admixtures used.

3.1. Hardening and structure of cement stone

Hydration of cement

A chemical process of cement hardening is the processes of hydration which occurs at mixing cement with water. Composition of new compounds is determined by chemical nature of waterless compounds, ratio between solid and liquid phase, temperature conditions.

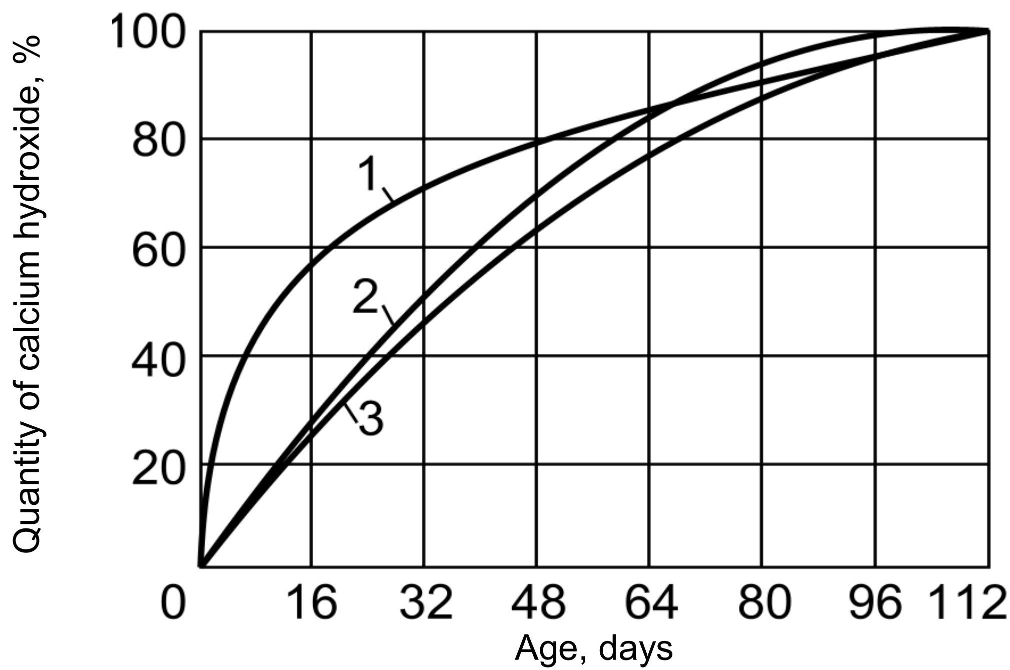


Fig.3.1. Rate of reaction of the calcium hydroxide $Ca(OH)_2$ forming during hydration of calcium silicates: **1** – tricalcium silicate ($3CaO{\cdot}SiO_2$); **2** - β - modification dicalcium silicate (β- $2CaO{\cdot}SiO_2$); **3** - γ - modification dicalcium silicate (γ -$2CaO{\cdot}SiO_2$)

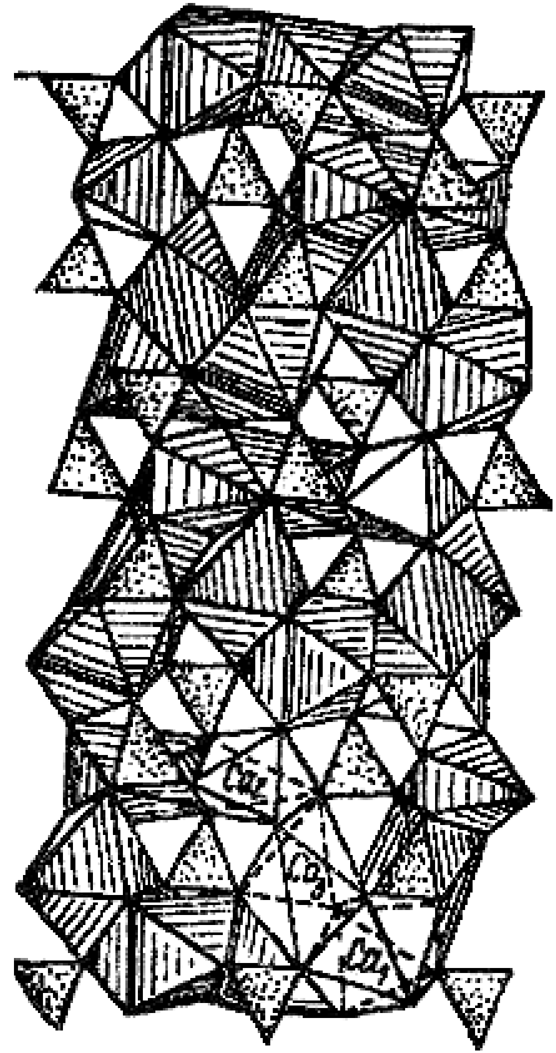


Fig.3.2. Plane section of tricalcium silicate (C_3S) structure

High hydration activity of aluminates minerals is caused by possibility of structural transformations due to the instability of the concentration of Al^{3+} ions in the crystalline grate of these minerals.

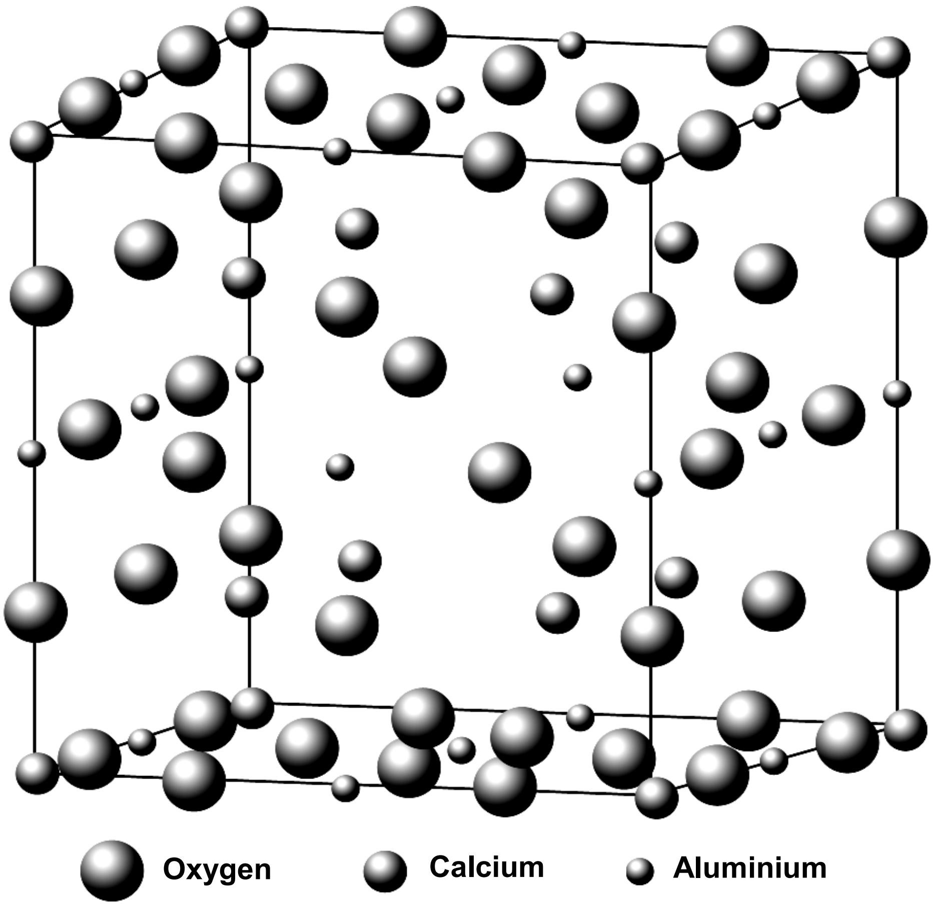


Fig.3.3. Structure of elementary cell of crystalline structure of tricalcium aluminate (C_3A)

All clinker minerals are disposed in a row concordant with their hydration activity: tricalcium aluminate (C_3A) – tetracalcium aluminoferrite (C_4AF) - tricalcium silicate (C_3S) - β dicalcium silicate (β- $2CaO{\cdot}SiO_2$).

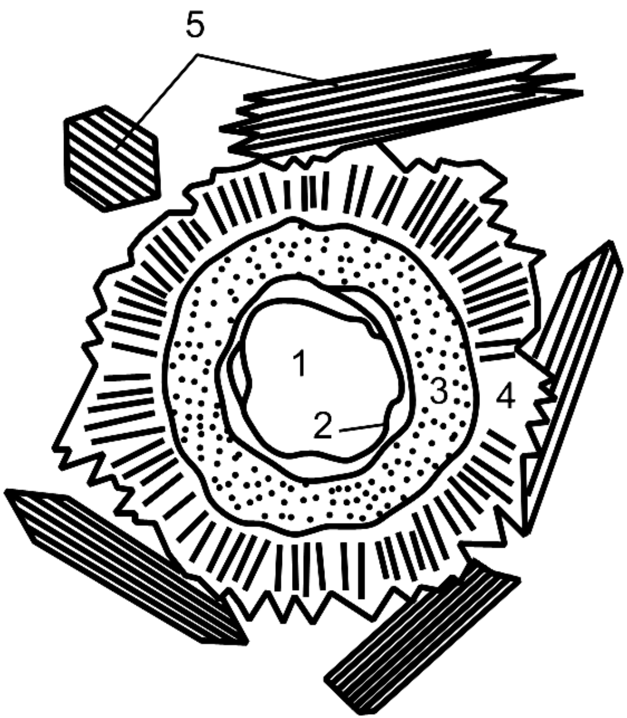


Fig.3.4. Schematic image of the reactive with water grain of tricalcium aluminate (C_3A):
1- non-hydrated kernel; 2- primary hydrate; 3- second finely crystalline calcium silicate hydrate (internal product); 4- third crystalline calcium silicate hydrate (external product); 5- separate large crystals

The rate of reaction between cement and water is accelerated if there is increasing in temperature, that is characteristic for all chemical reactions. Kinetics of hydration of compounds of portland cement clinker and their mixture in portland cement is described by formula:

$$L = k\,\lg\tau + B, \qquad (3.1)$$

where the L – level of hydration;
τ – time; k and B – constants.

<u>Level of hydration</u> determines quantity of cement reacting with water through the setting time.

Hardening and structure of cement stone

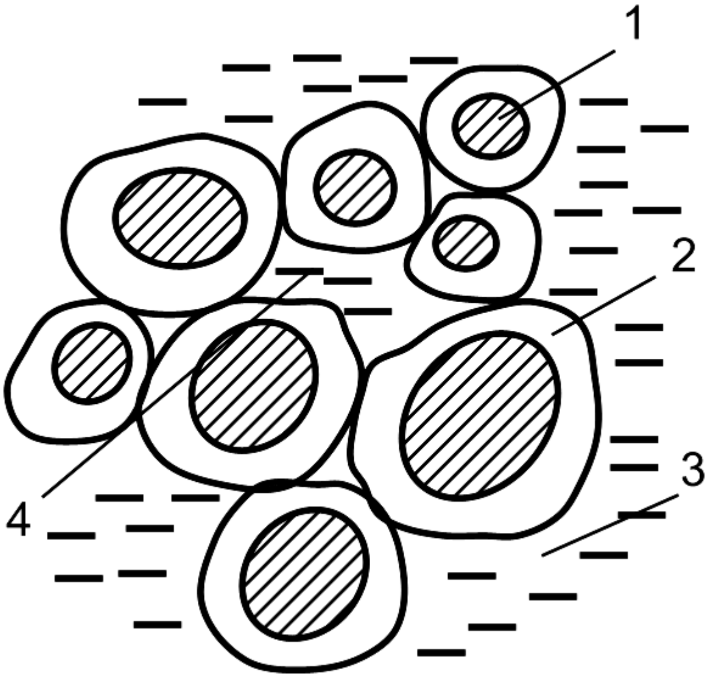


Fig.3.5. Chart of coagulate structure of cement paste (from Y.Bagenov):
1 – grain of cement; 2 - shell; 3 – free (mobile) water; 4 – entrapped (immobile) water

From positions of the physical and chemical mechanics P.Rebinder divides the process of hardening of cement paste on three stages:

a) Dissolution in water of unsteady clinker phases and selection of crystals;

b) Formation of coagulate structure of cement paste;

c) Growth and accretion of crystals.

A cement stone is pierced by pores by a size from 0.1 to 100 μm.

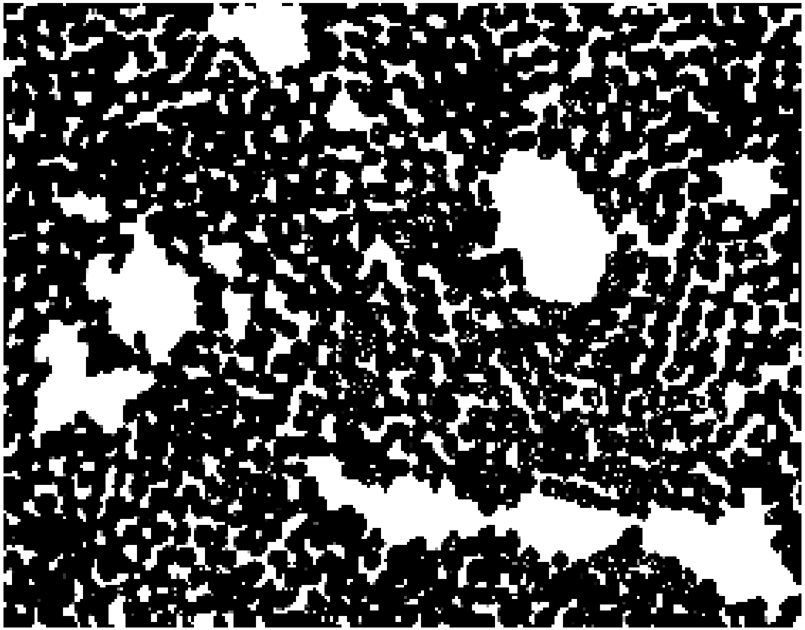


Fig.3.6. The simplified model of structure of cement stone

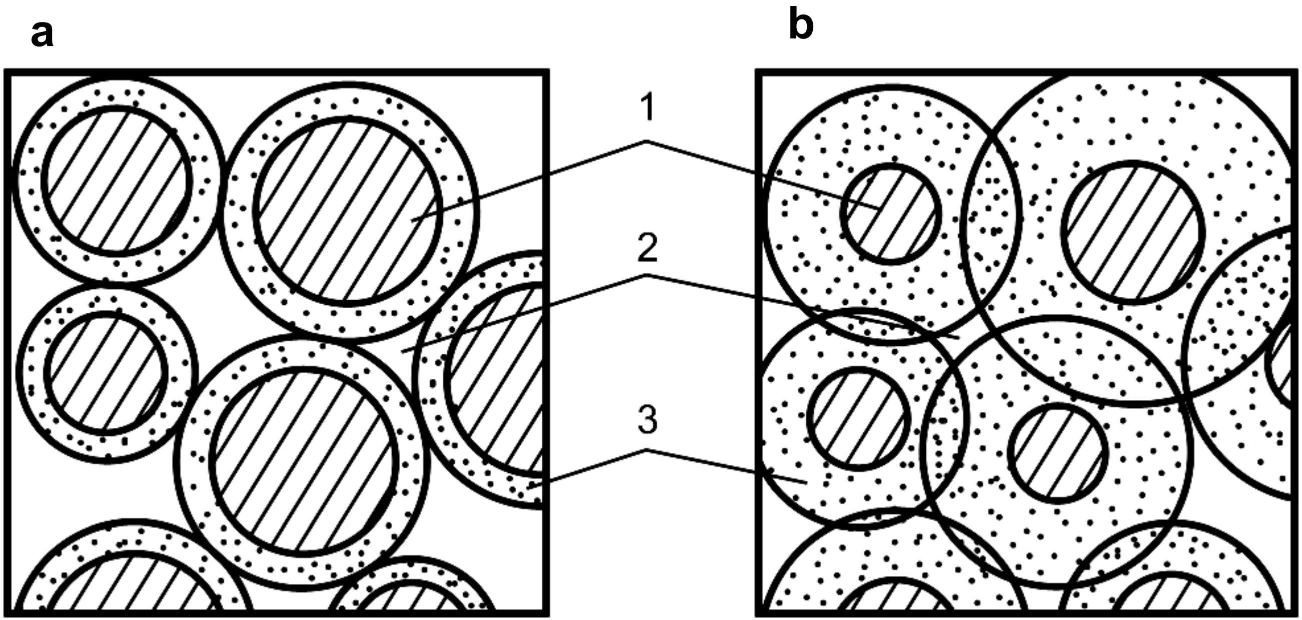


Fig.3.7. Change of capillary porosity in cement paste (stone) in the conditions of proceeding hydration of cement:

a- Level of hydration = 0.3; **b** – Level of hydration = 0.7

1- not fully hydrated grain of cement; **2**- capillary pores; **3**- cement hydrate gel

3.2. Influence of aggregates on forming of concrete structure

Aggregates along with a cement stone form the concrete structure of rocklike (conglomerate) mass.

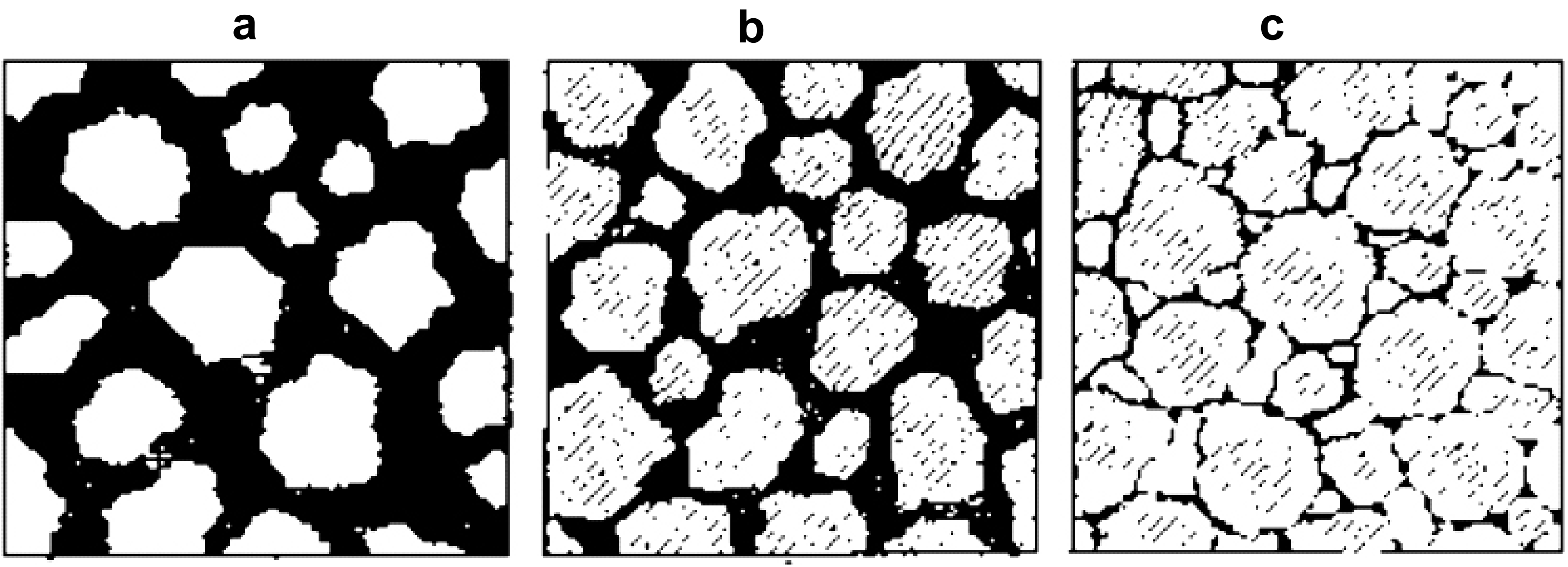


Fig.3.8. Charts of concrete structure:
a –floating structure;
b – intermediate structure; **c** – contact structure

The important structural elements of concrete which determining physical and mechanical properties are cracks.

In the real material always there is a plenty of microscopic cracks arising up on technological or operating reasons. Cracks are characterized by a length, width, radius, and front.

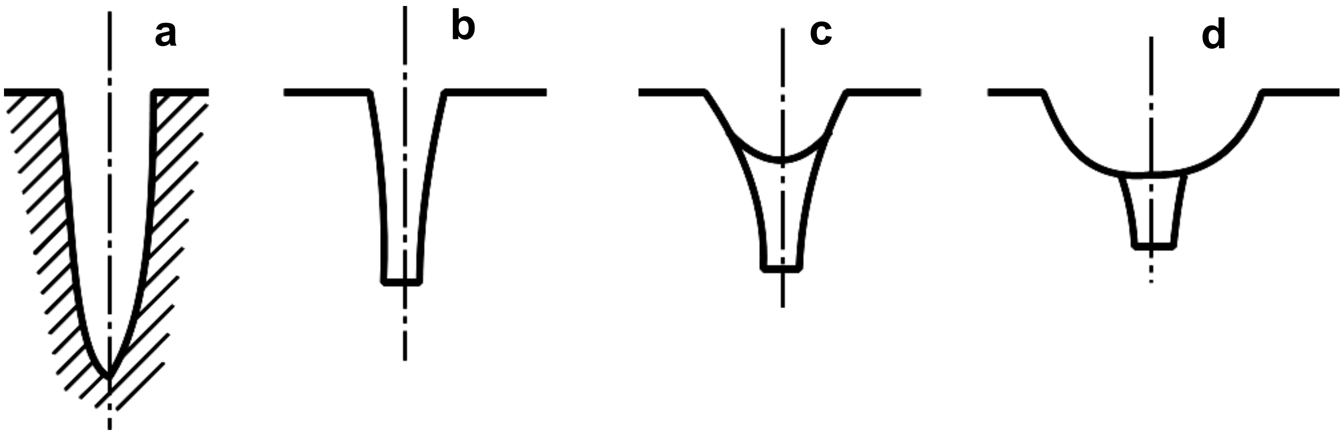


Fig.3.9. Models of cracks:
a – from Griffits; b – from P.Rebinder; c – from G.Bartenev (a, b, c – models of cracks in ideally easily broken material); d – crack in the real rocklike material (from G.Bartenev)

3.3. Influence of admixtures on concrete structure forming

Influence of chemical admixtures

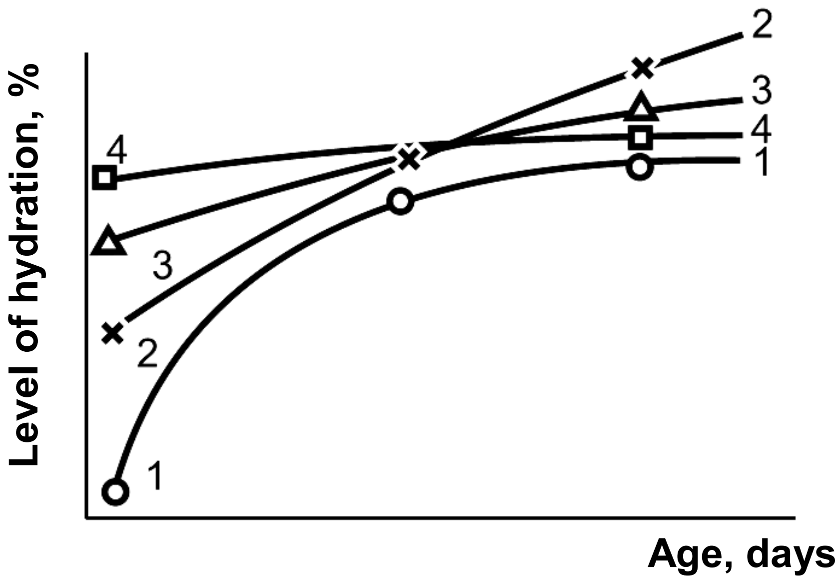


Fig.3.10. Kinetics of change of level of hydration of cement silicate phase:

1- without admixtures; **2**- calcium nitrite-nitrate (3%); **3**- calcium nitrite-nitrate–chloride (3%); **4**- calcium chloride (3%)

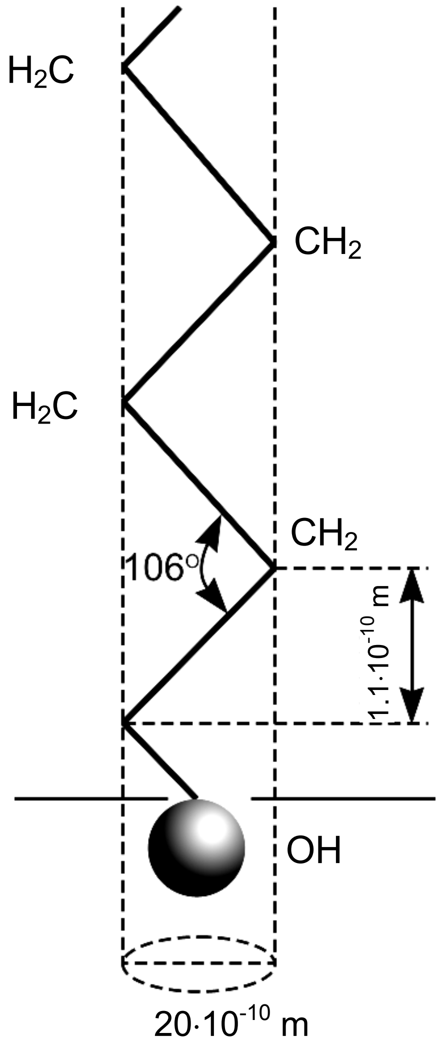


Fig. 3.11. Chart of molecule of surface-active substance

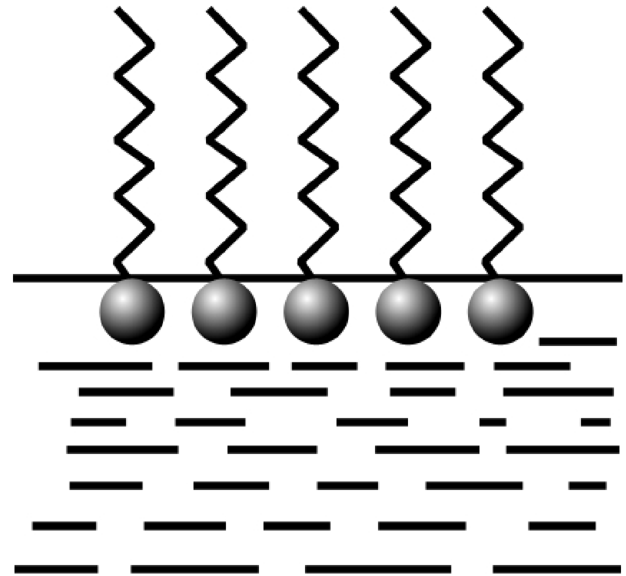


Fig.3.12. Adsorbed layer of surface-active substance at the surface of a solid

Influence of mineral admixtures

Finely divided mineral admixtures which are either pozzolanic or relatively inert chemically make active influence on the processes of hardening and forming of cement stone structure.

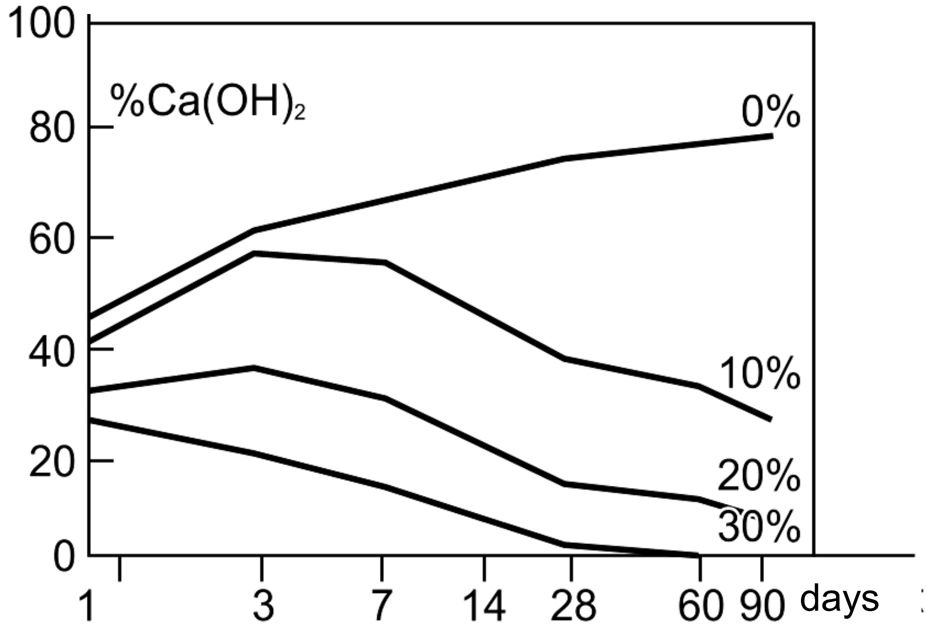


Fig.3.13. Change of the quantity of calcium hydroxide $Ca(OH)_2$ in solutions containing metakaoline (finely divided product that results from burning of kaolin)

3.4. Optimization of concrete structure

Concrete structure is a cover-up of its structure at a different levels from atomic - molecular for separate components to macro-structure as composition material.

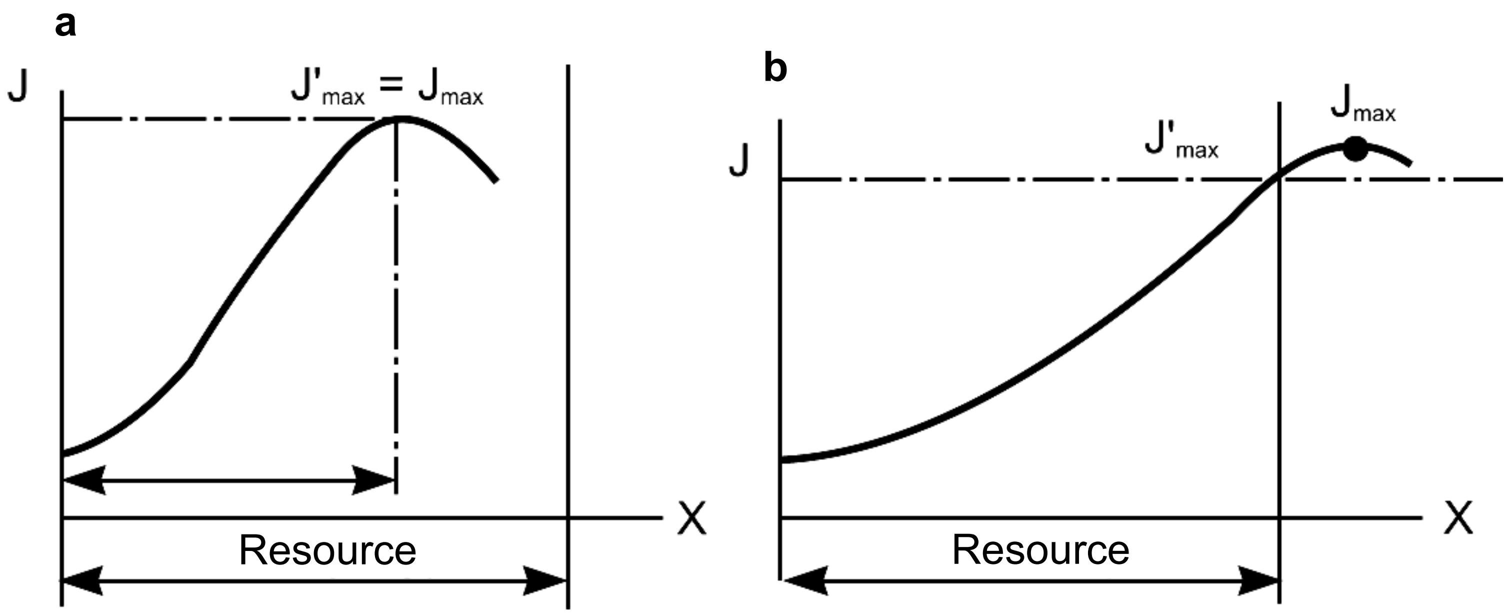


Fig.3.14. Kinds of optimization tasks (from V.Voznesensky):

a – achievement of the set level of criterion of efficiency (J) at the minimum expense of resources; **b** – achievement of maximal level of criterion of efficiency at the complete expense of resources for achievement of purpose

Some structural criteria of properties of concrete

Structural criteria	Formula	Denotations
Density of concrete (d)	$d = \frac{V_c}{V_c + W + V_{air}}$	V_c, W ,V_{air} - absolute volumes of cement, water and air in the general volume of concrete, liters per cubic meter (l/m^3)
General porosity of concrete (P_s)	$P_s = \frac{W - 0.23\alpha C + V_{air}}{1000}$	C - quantity of cement, kg/m^3; α - level of cement hydration
Volume concentration of cement paste (stone) in the concrete (C_p)	$C_p = \frac{C}{1000}\left(\frac{1}{\rho_c} + (W/C)\right)$	ρ_c – specific gravity of cement, kg per cubic liter (generally 3.1); W/C – water – cement ratio

Decision of tasks of concrete structure optimization is possible by mathematical methods supposing determination and analysis of mathematical models.

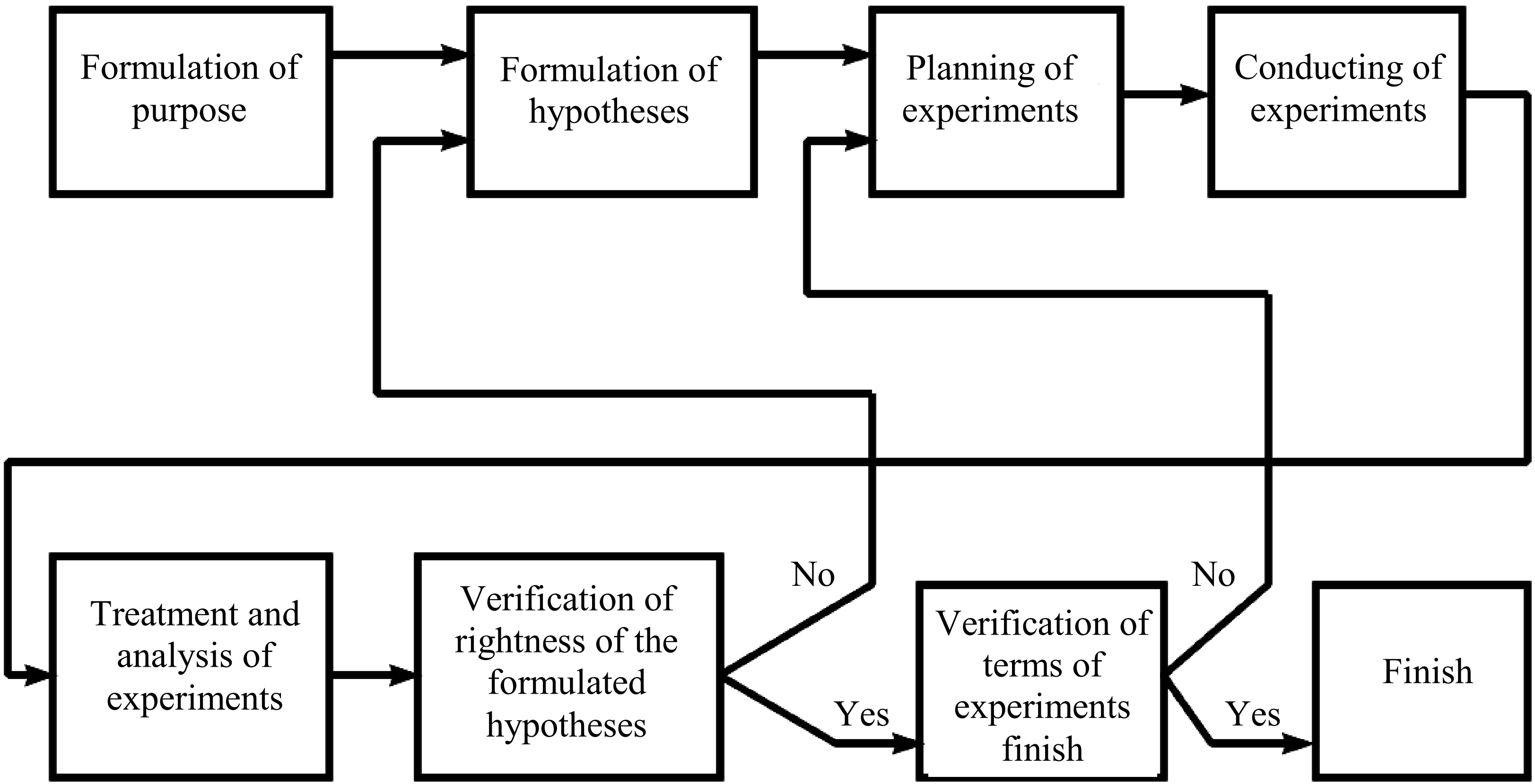


Fig.3.15. Strategy of determination of mathematical model

CHAPTER 4

CONCRETE STRENGTH

L. Dvorkin and O.Dvorkin

Strength is a property of materials to resist to destruction under action of the external loading.

4.1. Theories of strength and mechanism of destruction

The existing theories of concrete strength are divided into three groups: phenomenological, statistical and structural.

Phenomenological theories consider concrete, as homogeneous isotropic material. All attention is paid to dependence of strength on the external loading, they set reasons on which it is possible to judge about beginning of material destruction at the tense state, if the behavior at simple tension, compression or shear is known.

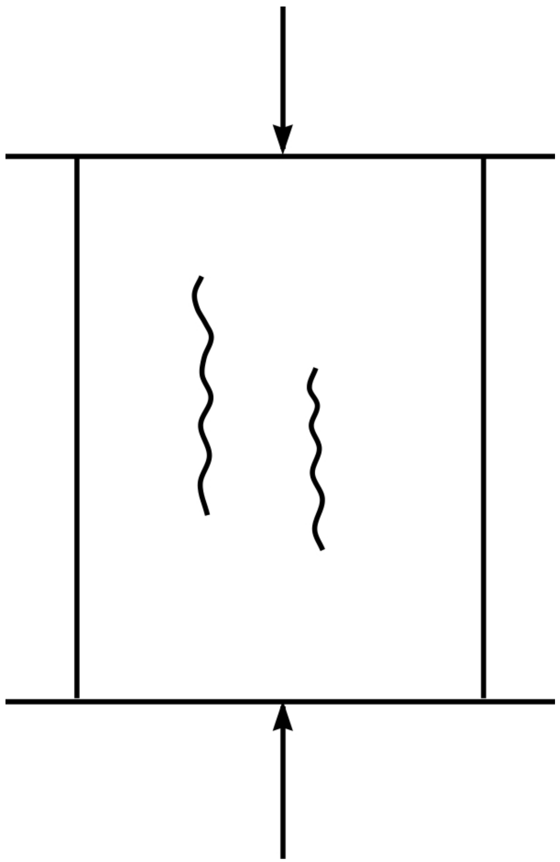


Fig. 4.1. Chart of destruction of easily broken material at the axial compression if there is default of friction on supporting flags of the press

According to statistical theories the existence in the concrete of continuous isotropic environment, in which there are microscopic cracks (conformable to the statistical laws) is also assumed. These theories allow to explain enormous distinction between theoretical and actual strength, determined by the defects of structure of substance, without consideration of structure.

Development of crack under action of the attached compression takes place at reduction of general energy of the system. Stability Criterion of easily broken material with a crack: can be calculated by the following formula:

$$\sigma = \sqrt{2E\nu / \pi l}, \qquad (4.1)$$

where σ- the attached compression; E- modulus of elasticity; ν- surface energy; *l*- length of crack.

In accordance with the statistical theory of the strength (from Weibull) tensile and flexural strength (R) changes inversely proportional to a volume υ:

$$R = \frac{A}{\upsilon^{1/m}}, \qquad (4.2)$$

where m – degree of homogeneity of material, taking into account the character of defects distributing; A – constant value.

Development of structural theory of concrete strength began at the end of the 19 century after establishment by Feret dependence between strength of concrete and density of cement paste, modified late by Powers taking into account the level of cement hydration. The Feret dependence became a basis for development of Abram's law (rule of water-cement ratio) - the fundamental dependence used at the calculation (proportioning) of concrete mixtures.

In accordance with Powers compressive strength (R) of the specimens of a different age and made at a different water-cement ratio can be calculated from:

$$R = AX^n, \qquad (4.3)$$

where X- ratio between volume of cement hydrate gel and the sum of volumes of cement gel and capillary space; A- coefficient characterizing strength of cement gel; n- constant (from 2.6 to 3).

The parameter X can be considered as a relative density of cement paste (stone).

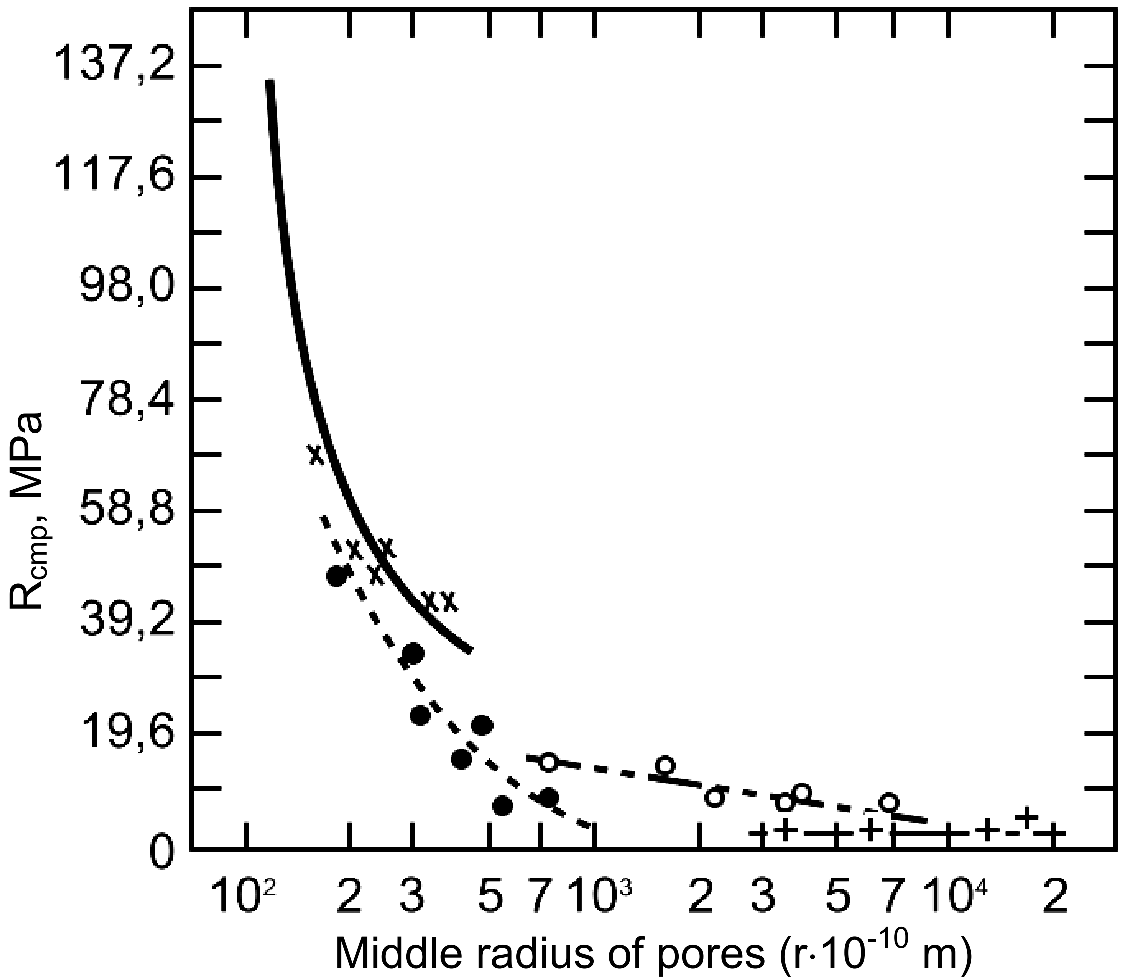


Fig. 4.2. Relationship between compressive strength (R_{cmp}) and middle size of pores of cement paste (stone)

The condition of development of crack in concrete can be determined from Griffith and Orovan formula:

$$\sigma = \sqrt{E\nu / d_{cp}} = k d_{cp}^{-1/2}, \qquad (4.4)$$

where σ- tensile stress; E- modulus of elasticity; ν- effective energy of destruction; d_{as} - average size of a crystal;

$k = (E\nu)^{-1/2}$ - coefficient of viscidity of destruction.

Strength of concrete depends on deformations arising up at loading.

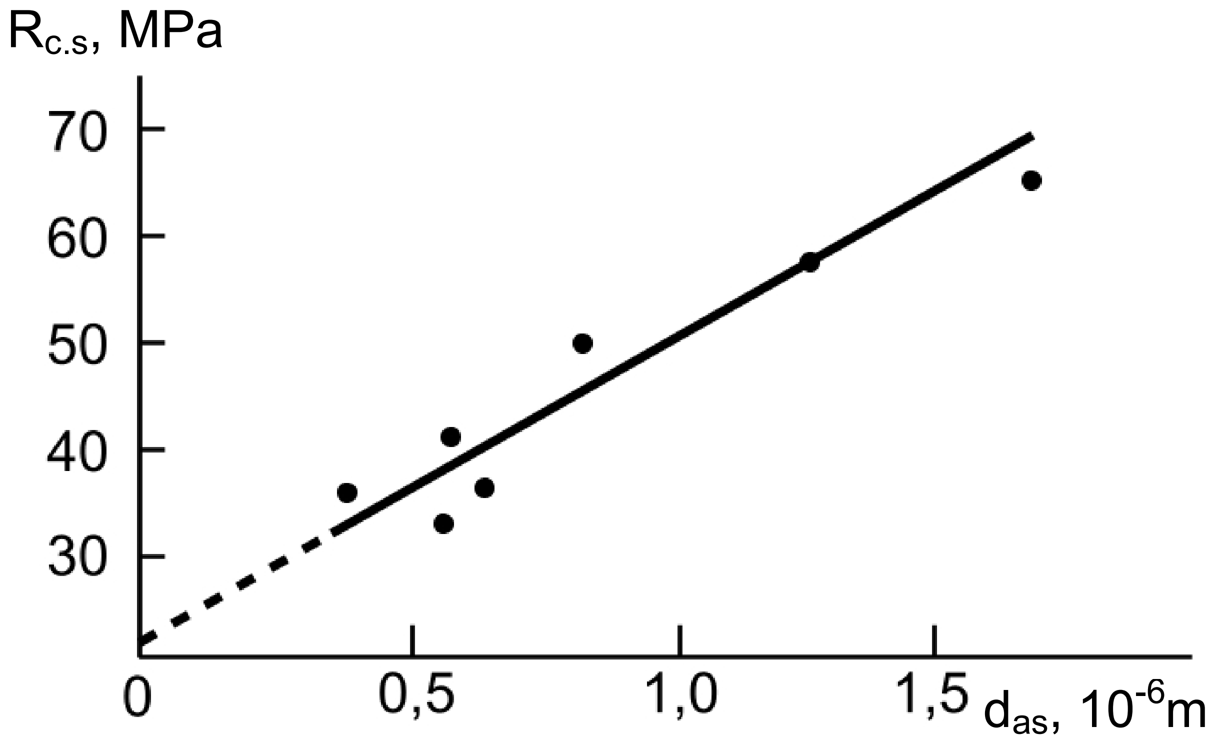


Fig. 4.3. Relationship of strength of the cement stone $R_{c.s}$ and average size of crystals d_{as}

4.2. Law (rule) of water-cement ratio

The fundamental works of Feret, Abrams, Bolomey and other researchers determined wide application in practical technology of the water-cement (W/C) law (rule) and based on it computation formulas.

After processing results more than 50 thousand tests, Abrams offered a formula:

$$R = \frac{k}{A^x}, \qquad (4.5)$$

where R- strength of concrete; k – strength coefficient, A – constant value, x – ratio between volume of water and volume of cement.

Graf offered at the end of 20th years of 20 century the formula of concrete strength (specifying the Abrams formula for practical calculations) as follows:

$$R = \frac{R_c}{A(W/C)^n}, \qquad (4.6)$$

where R_c – compressive strength of portland cement; A and n - coefficients (from Graf A=4...8, n=2); W/C – water-cement ratio.

Bolomey (based on Feret dependence) determined a formula:

$$R = K(C/W - 0.5), \qquad (4.7)$$

where R- strength of concrete; C/W– cement-water ratio;
K- coefficient.

After treatment of experimental researches B.Skramtaev and Y.Bagenov offered the formulas of concrete strength :

If C/W≥2.5 $$R = AR_c(C/W - 0.5), \qquad (4.8)$$

If C/W≤2.5 $$R = A_1 R_c(C/W + 0.5), \qquad (4.9)$$

where R- concrete strength; C/W– cement-water ratio; A and A_1 - coefficients.

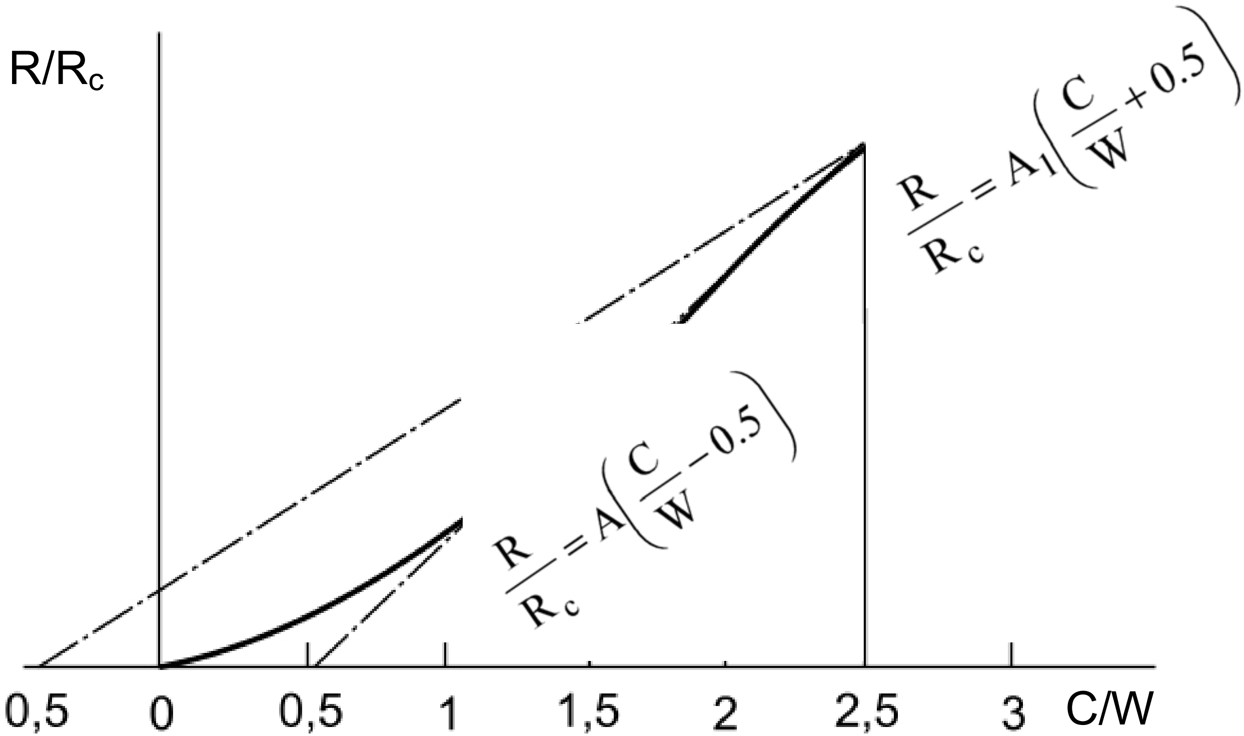


Fig. 4.4. Typical relationship between strength of concrete (R), strength of cement (R_c) and cement-water ratio (C/W)

4.3. Adhesion between aggregates and cement stone

Aggregates, making the bulk of concrete and forming the concrete structure as composite material, actively affect concrete strength foremost through strength of adhesion of cement paste (stone) with their surface.

Gordon produced the test of different kinds of aggregates. Strength distinctions of concrete arrived at 50%.

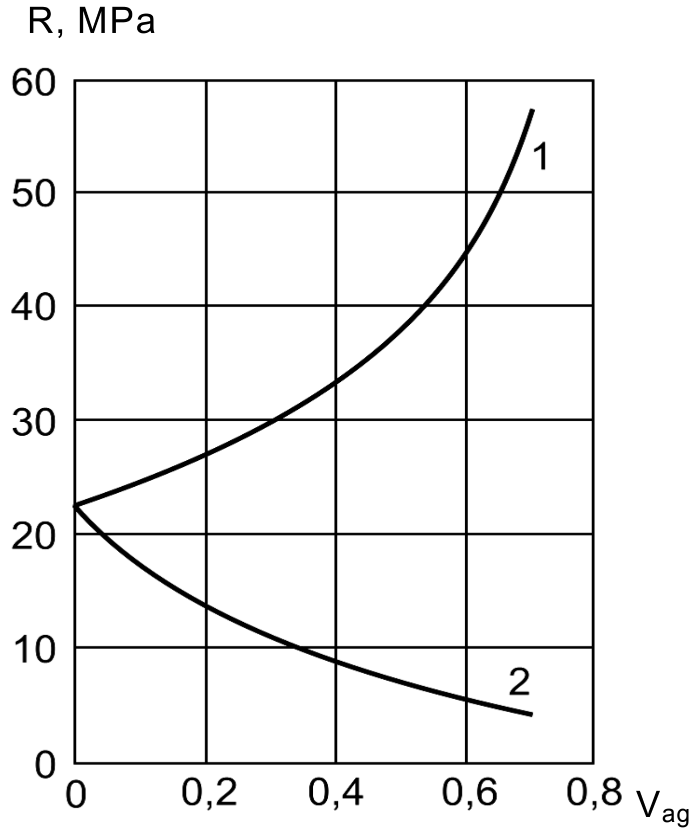


Fig. 4.5. Relationship between volume of aggregates in the volume of concrete (V_{ag}) and compressive strength (R) of concrete:

1 – complete coupling of aggregates and cement paste;
2 – coupling is fully absent

4.4. Influence of terms and duration of hardening concrete

Concrete strength in definite age is determined in accordance with Skramtaev formula:

$$R_n = R_{28} \frac{\lg n}{\lg 28}, \quad (4.10)$$

where n – duration of concrete hardening, R_{28} – concrete strength at 28 days.

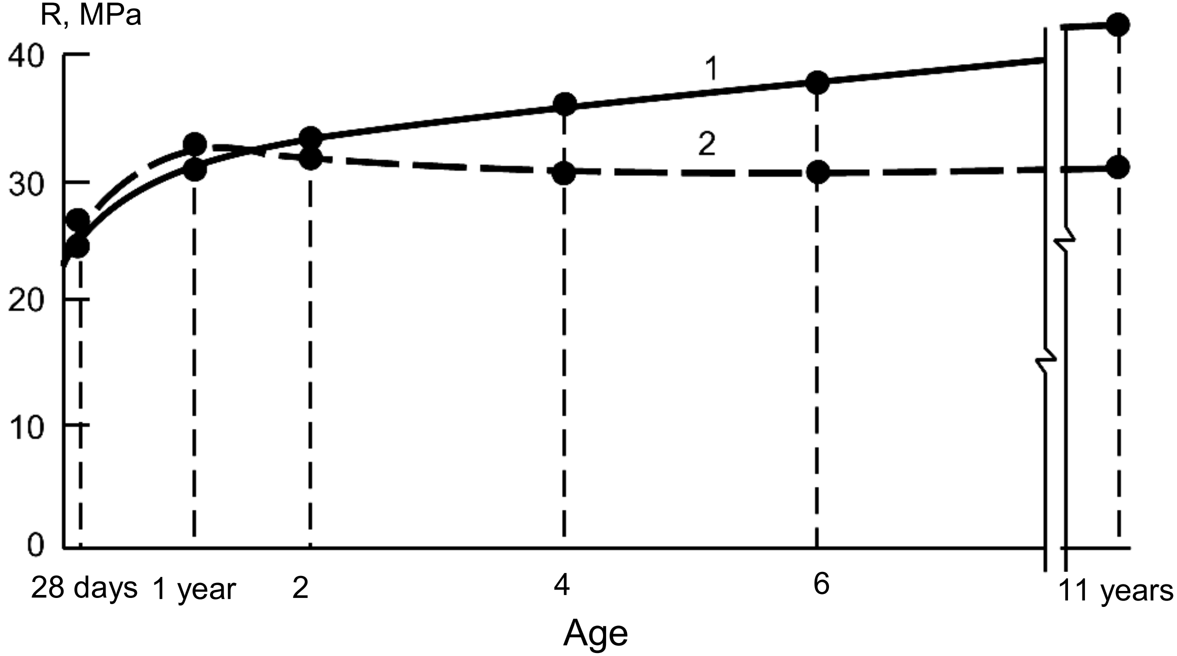


Fig. 4.6. Increasing of strength of concrete (R) in wet (1) and dry (2) conditions

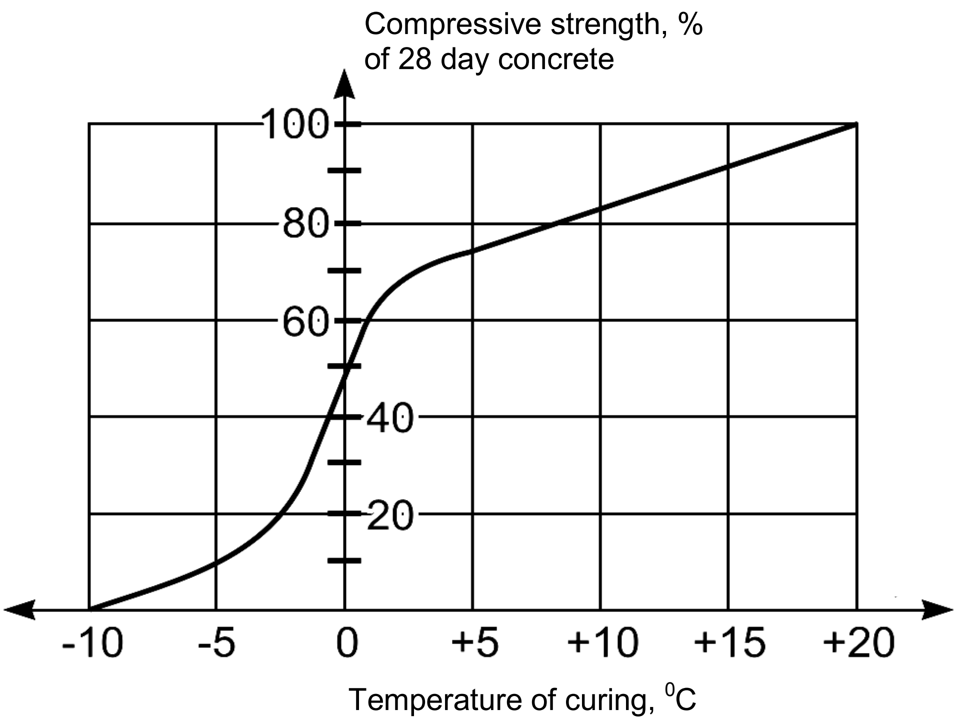


Fig. 4.7. Increasing of strength of fresh concrete during 28 days at temperature (t) from +20 to –10^{0}C

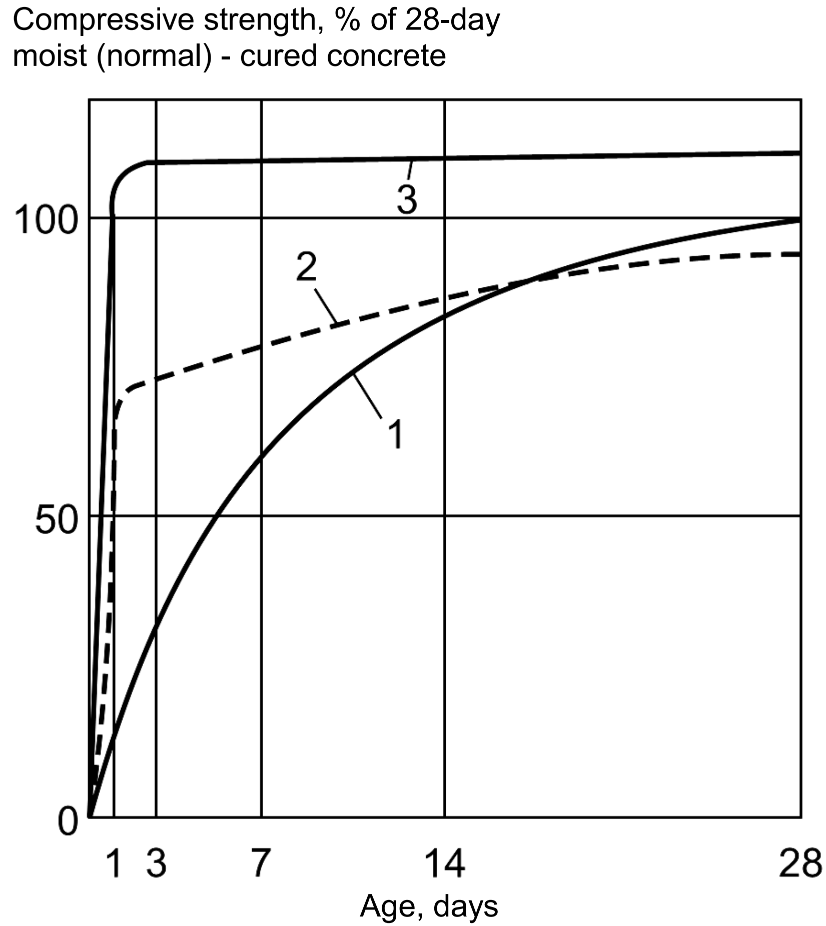


Fig. 4.8. Typical relationship between strength and duration of curing for different conditions:

1- moist (normal) curing; 2- curing in live stream at atmospheric pressure (80^{0}C max. steam temperature); 3- curing in high-pressure-steam autoclaves

4.5. Kinds of strength. Tests for concrete strength

The main kind of strength concrete is compressive strength that correlates with tensile strength, shear strength, flexural strength and other kinds of strength.

The values of concrete strength are greatly influenced by the features of tester machines, conditions of test, and form of specimens.

Various nondestructive tests (rebound, penetration, pullout, vibration and other methods) are widely used in practice for determination of strength of hardened concrete based on relationship between strength and indirect evaluations.

For strength evaluation of hardened concrete by nondestructive methods calibration charts are used, which related by measured indirect evaluation to the compressive strength of concrete.

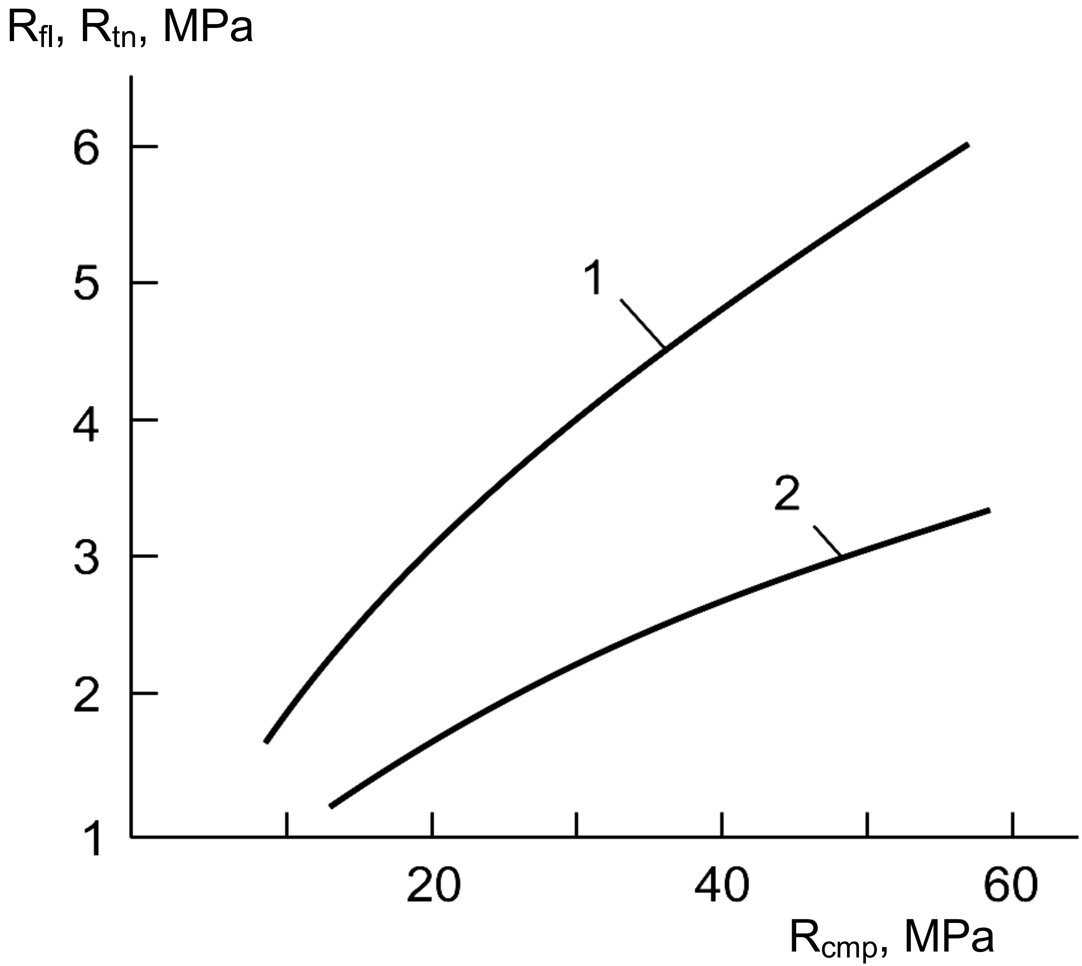


Fig. 4.9. Typical relationship between flexural strength R_{fl} (curve 1), tensile strength R_{tn} (curve 2) and compressive strength (R_{cmp}) of concrete

CHAPTER 5

DEFORMATIONS OF CONCRETE

L. Dvorkin and O.Dvorkin

Deformations of concrete arise up at hardening, exploitation and test of concrete.

Two kinds of deformations of concrete are:

1. Deformations due to applied external loads (power deformations);
2. Deformations due to volume changes under influencing of changes in temperature and moisture content (own deformations).

5.1. Concrete deformations at short-term load

Concrete Performance in constructions is determined by elastic and plastic deformations.

Complete deformation of concrete at a definite age of hardening ($\varepsilon\tau$) is calculated by the equation:

$$\varepsilon_{\tau} = \varepsilon_{el} + \varepsilon_{pl} + \varepsilon_{shr}, \qquad (5.1)$$

where ε_{el} - elastic deformation; ε_{pl} - plastic deformation; ε_{shr} - deformation of shrinkage.

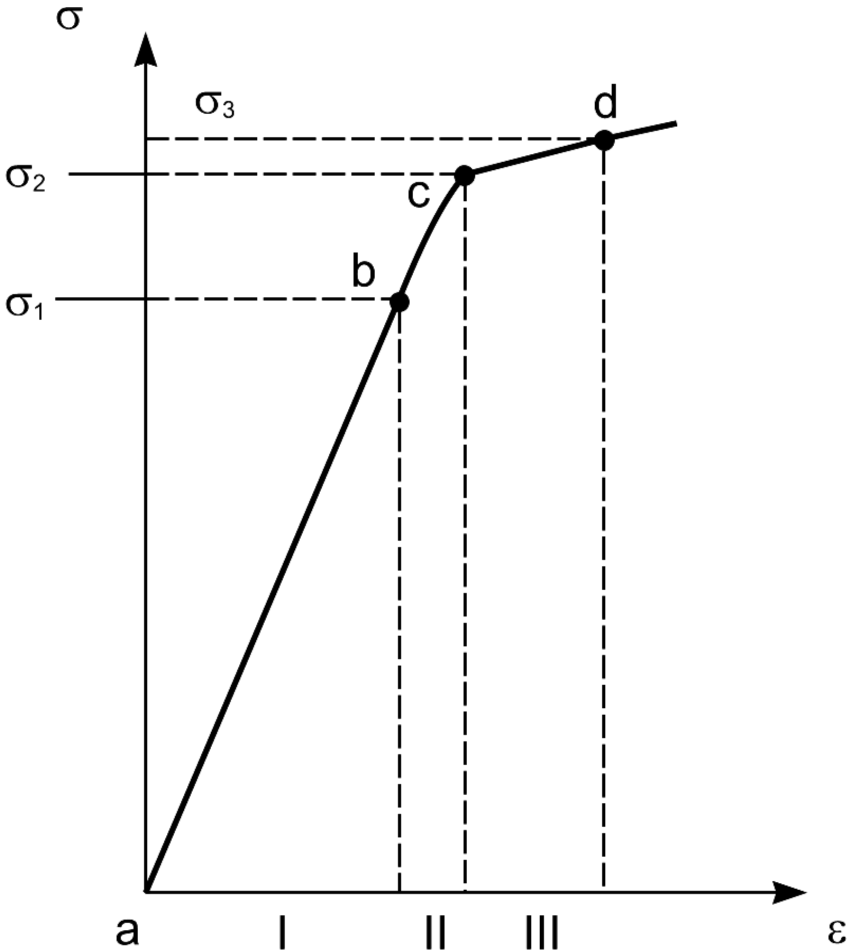


Fig. 5.1. The idealized chart of deformations in cement stone at the axial compression (at rapid loading)
ε - deformation; σ - stress

On the idealized chart of compression of cement stone it is possible to select three basic areas: a-b- absence of cracks in the structure of cement stone; b-c- appearance of microscopic cracks; c-d- destruction of cement stone as a result of spontaneous formation of growing cracks.

For description of cement stone and concrete deformation under loading a number of rheological models are offered.

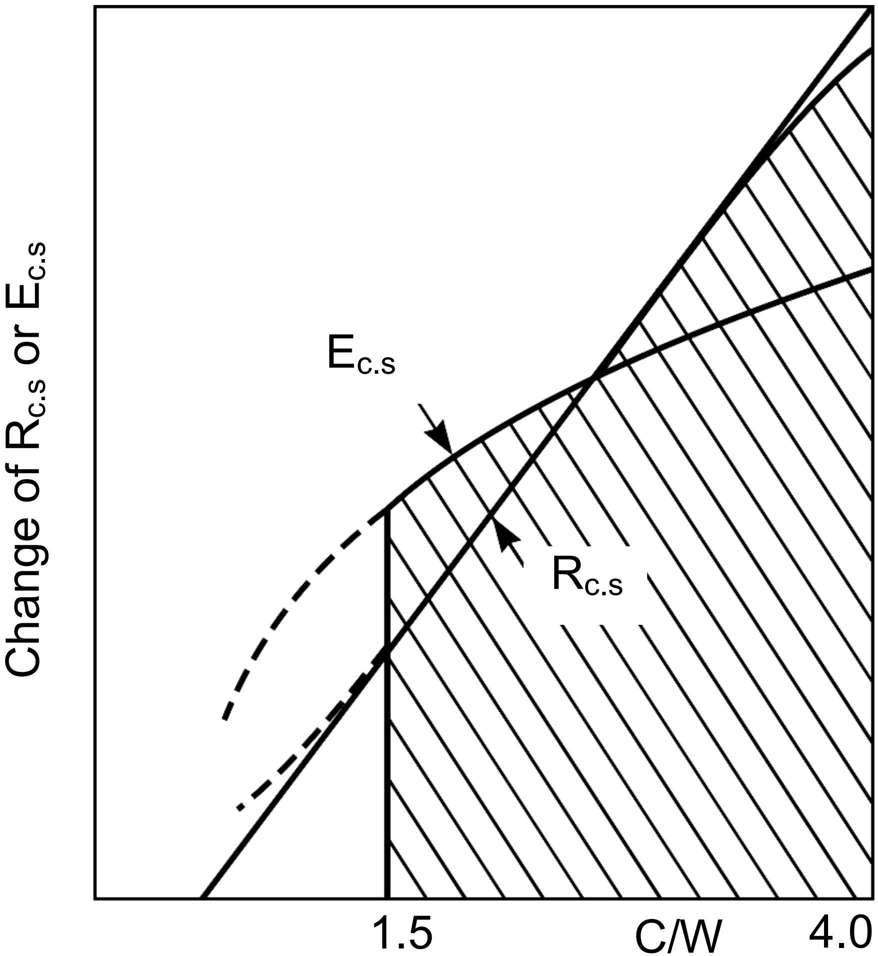


Fig. 5.2. Typical relationship between modulus of elasticity $E_{c.s}$, strength of cement stone $R_{c.s}$ and cement-water ratio (C/W)

There is a large number of formulas describing elastic properties of concrete. Their kind depends on the accepted model of stresses distributing, character of location of aggregates particles and other reasons.

Modulus of concrete elasticity (E) depends on concrete strength. For calculation of the modulus of elasticity at loading of concrete at age of hardening (τ) following equations are using:

$$E = \frac{E_m R_\tau}{S + R_\tau}, \qquad (5.2)$$

where R_τ - compressive strength (MPa) of concrete specimens - cubes after definite age of hardening (τ); E_m and S – constant values (E_m = 52000; S = 23).

Following equation is recommended by a European concrete committee:

$$E = C(R_\tau)^\gamma, \qquad (5.3)$$

where C=1900; γ = 0.5.

In the case of high-quality aggregates (crushed granite and quartz sand) using, as it is shown by E.Sherbakov the following formula can be used:

$$E \cdot 10^{-4} = \frac{5.3R_{\tau}}{85P_{c.s} + R_{\tau}}, \qquad (5.4)$$

where Pc.s - quantity of cement stone in the concrete (by mass).

Elastic properties of concrete can be characterized by static modulus of elasticity (E) and by dynamic modulus of elasticity (E_d) which taking into account stresses and strains in specimen at vibrations.

Relationship between dynamic modulus of elasticity (E_d) and compressive strength of concrete (R_{cmp}) is expressed by following formula:

$$E_d = \frac{4 \cdot 10^3 R_{cmp}}{1 + 0.07R_{cmp}}. \qquad (5.5)$$

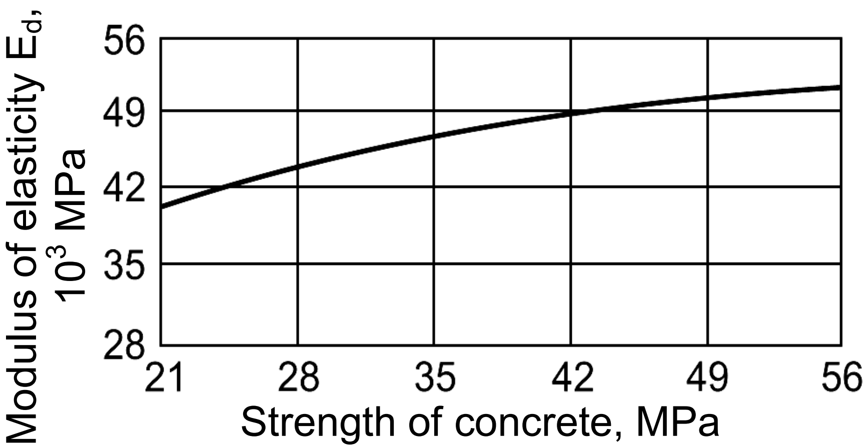


Fig. 5.3. Relationship between the dynamic modulus of elasticity (E_d) and compressive strength

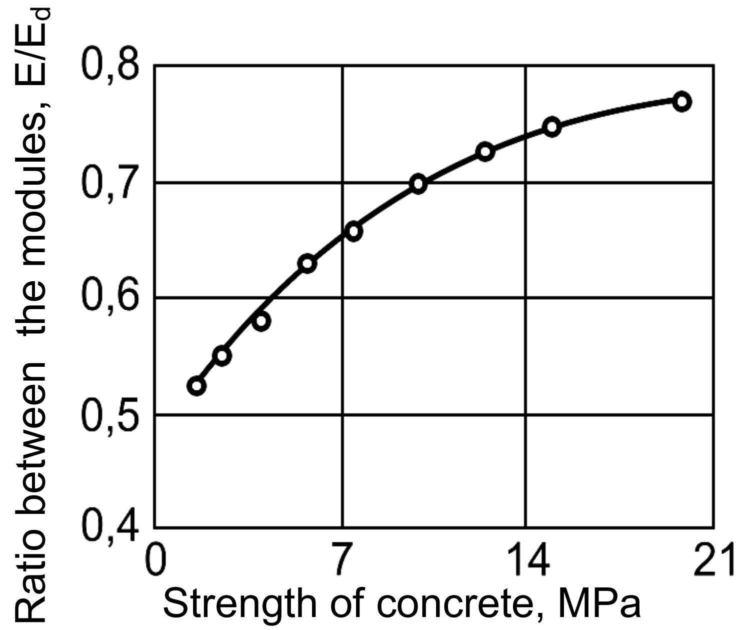


Fig. 5.4. Ratio between static modulus of elasticity (E) and dynamic modulus of elasticity (E_d) for different strength of concrete

Relative deformation (ε_r) is a ratio between tensile strength (R_t) and dynamic modulus of elasticity (E_d):

$$\varepsilon_r = R_t / E_d. \qquad (5.6)$$

At the time of laboratory testing the value of relative deformation (ε_r) can be calculated if compressive (R_{cmp}) and tensile (R_t) strength (MPa) are known:

$$\varepsilon_r = \frac{R_t(1 + 0.07R_{cmp})}{4 \cdot 10^3 R_{cmp}}. \qquad (5.7)$$

5.2. Concrete deformations at long-term load. Creep

Relationship between loading and deformations in concrete changes with time the concrete is stressed. Deformation of concrete caused by long - time loading is called creep.

There is a number of hypotheses which considering the mechanism of creep deformations under action of the external loading.

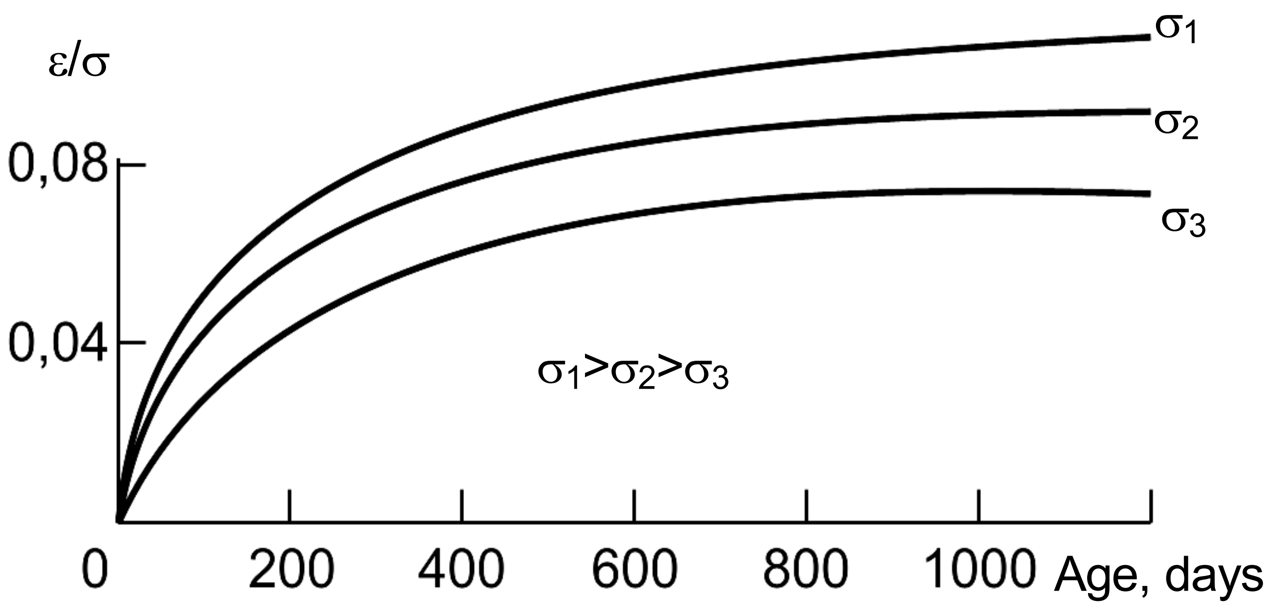


Fig. 5.5. Relationship between time-dependent deformation of creep of concrete (ε) and stresses (σ)

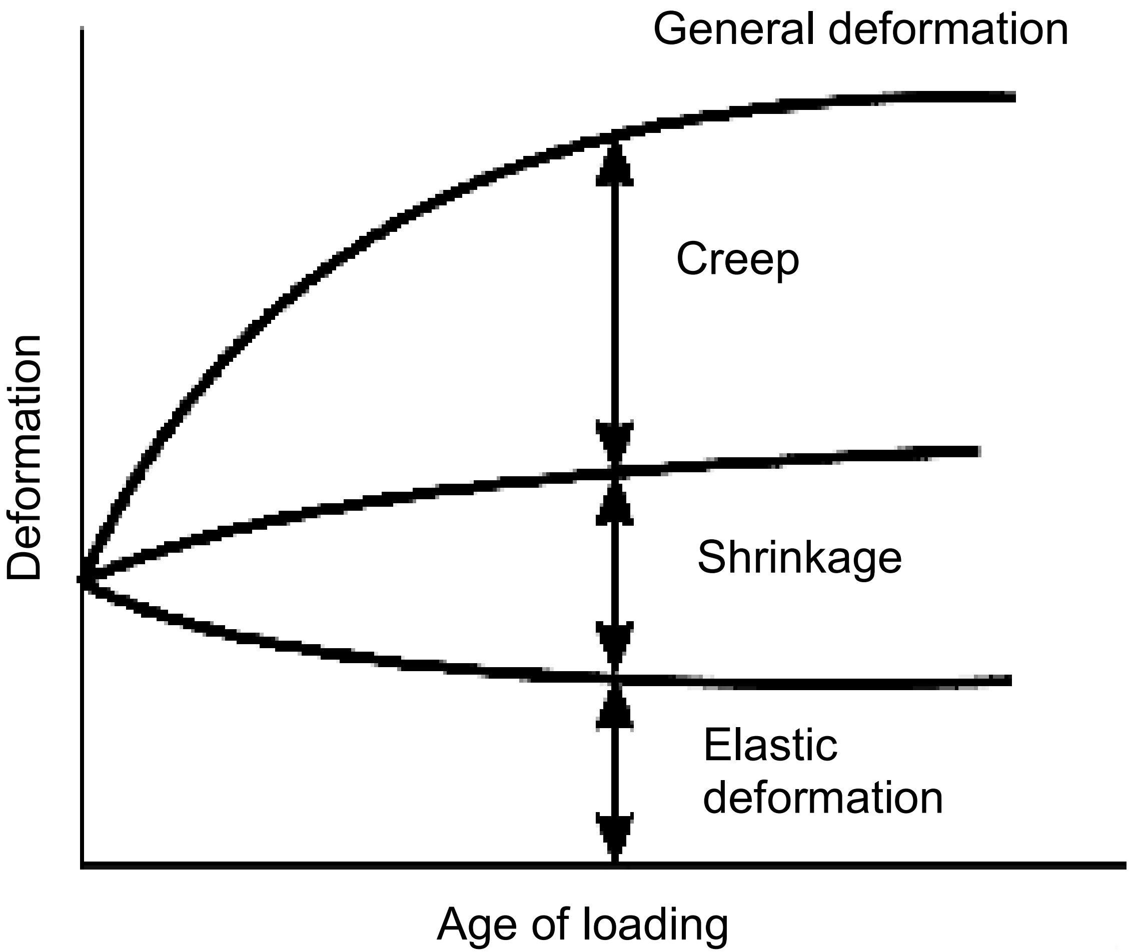


Fig. 5.6. Kinds of time-dependent deformations of concrete at action of continuous loading

Some calculating formulas for determination of creep ($C_m(28)$) of normal-weight concrete (age of loading 28 days)

Formula	Author
$$C_{m(28)} = \frac{K}{R_{cmp}}, \qquad (5.8)$$ R_{cmp}- compressive strength (MPa) of concrete specimens - cubes after 28 days of hardening, MPa; $K=25 \cdot 10^{-5}$	A.Velmi
$$C_{m(28)} = \frac{KW}{R_{cmp}}, \qquad (5.9)$$ W- quantity of water, liters per cubic meter; $K= 16 \cdot 10^{-6}$	E.Sherbakov

Deformation of creep at definite age of loading ($C_{m(\tau)}$) can be calculated as a follows:

$$C_{m(\tau)} = C_{m(28)} \xi_{\bar{r}} \xi_{\theta} \xi_{\tau}, \qquad (5.10)$$

where $C_{m(28)}$ – deformation of creep at 28 days loading;

$\xi_{\bar{r}} \xi_{\theta} \xi_{\tau}$ - coefficients taking into account influencing of size of unit, humidity of environment and age of concrete in the moment of loading began.

Also, deformation of creep at definite age of loading ($C_{m(\tau)}$) is obtained by use of the following formula:

$$C_{m(\tau)} = C_{m(max)} \left(\frac{\tau}{a + \tau}\right), \qquad (5.11)$$

where a – age of loading; τ - age of concrete hardening; $C_{m(max)}$ – maximally possible creep.

After rapid deformation at the beginning of load, deformation of creep continues at a decreasing rate.

Amount of creep depends on the technological reasons and reasons characterizing conditions of loading.

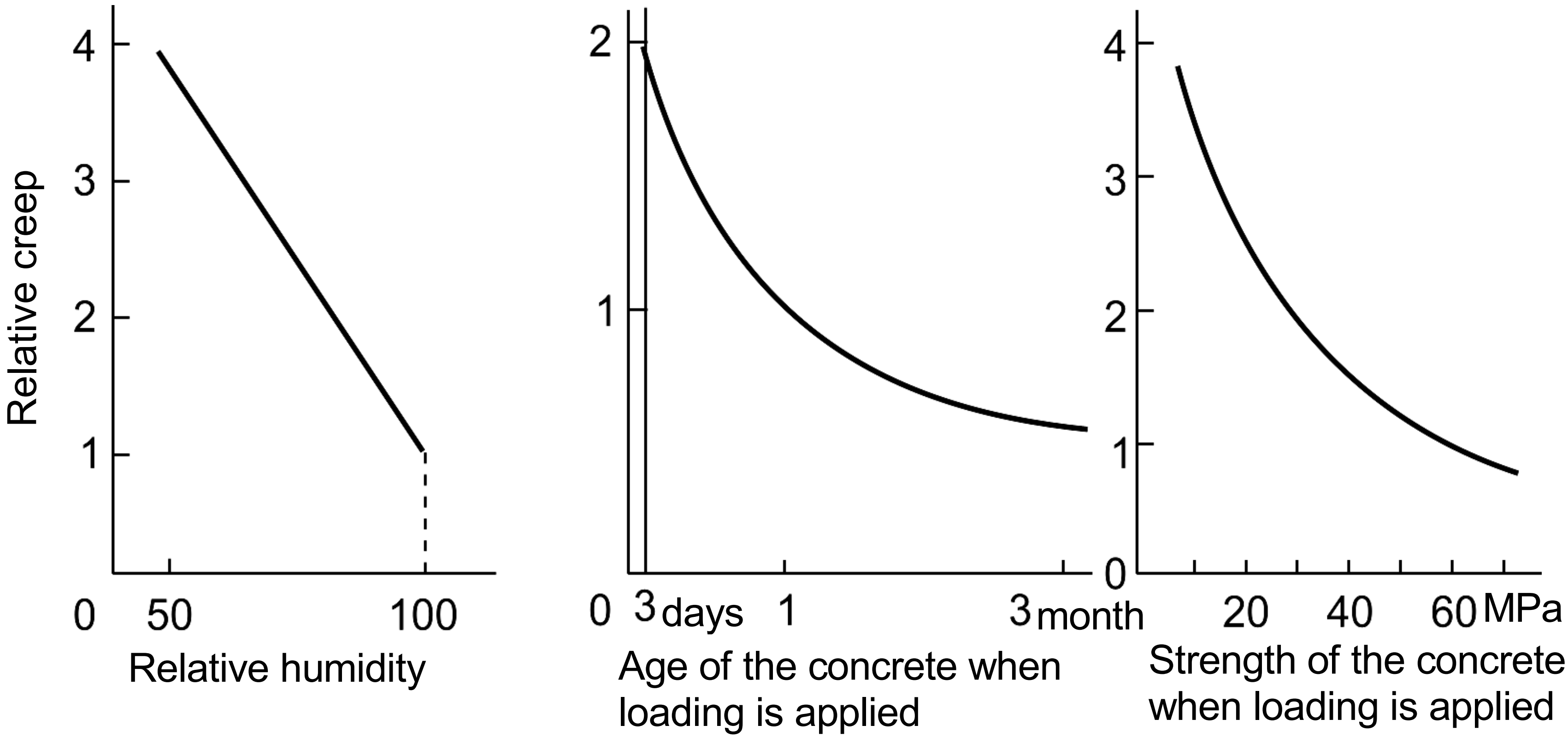


Fig.5.7. Effect of conditions of loading on magnitude of creep for typical normal-weight concrete

5.3. Own deformations. Concrete shrinkage

Own deformations of concrete are caused by moisture, temperature and other influences on a concrete without applying of the external loading.

The change of concrete humidity can cause decrease or increase in volume and accordingly deformations of shrinkage or expansion.

Deformations of expansion in cement stone and concrete at hardening are results of formation of the crystallization stone structure.

The expanding (swelling) of concrete volume occurs during continuous storage of the specimens in the water.

Deformation of contraction and drying shrinkage are developed due to processes of concrete hardening.

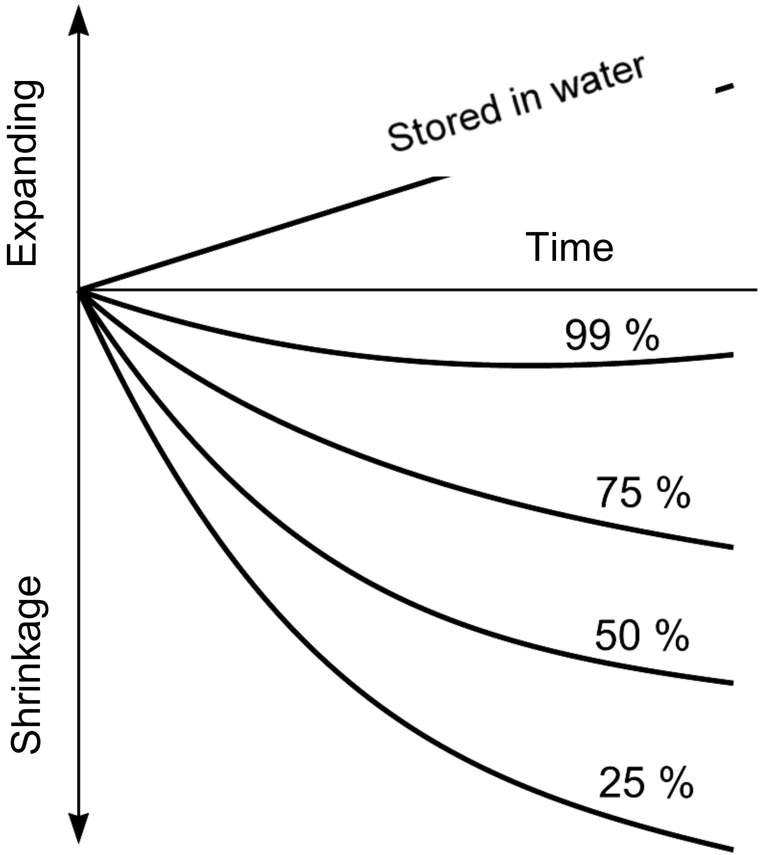


Fig. 5.8. Swelling and drying shrinkage of cement specimens which hardened and stored in water and in air with a different relative humidity

Contraction is the result of reactions of hydration of chemical cement compounds with water, therefore absolute volumes of hydrates less than total volumes of initial waterless compounds and water which necessary for hydration.

Contraction shrinkage of concrete in 5...10 times less than drying shrinkage.

Shrinkage of concrete at the change of humidity develops in two stages:

1. when a fresh concrete mixture has initial plastic consistency (plastic shrinkage);
2. at the time of continuing hardening and drying of concrete.

Drying shrinkage has the most influence on quality and exploitation of concrete constructions.

Internal tensions, stresses and cracks can occur due to the shrinkage deformations. Shrinkage deformation has also a negative effect on frost resistance and watertightness of concrete.

Amount of shrinkage of cement paste and concrete depends on age of hardening, composition, specific surface and quantity of cement, quantity of aggregates, water-cement ratio and other factors.

Some calculating formulas for determination of concrete shrinkage (ε_{shr})

Formula	Author
$\varepsilon_{shr} \cdot 10^6 = 0.125W\sqrt{W}$, (5.12) W- quantity of water, liters per cubic meter	E.Sherbakov
$\varepsilon_{shr} \cdot 10^6 = \frac{5W/C}{1+m}(667+C)$, (5.13) W/C – water – cement ratio; C – quantity of cement, kg per cubic meter; m- mass ratio between aggregates and cement	A.Velmi

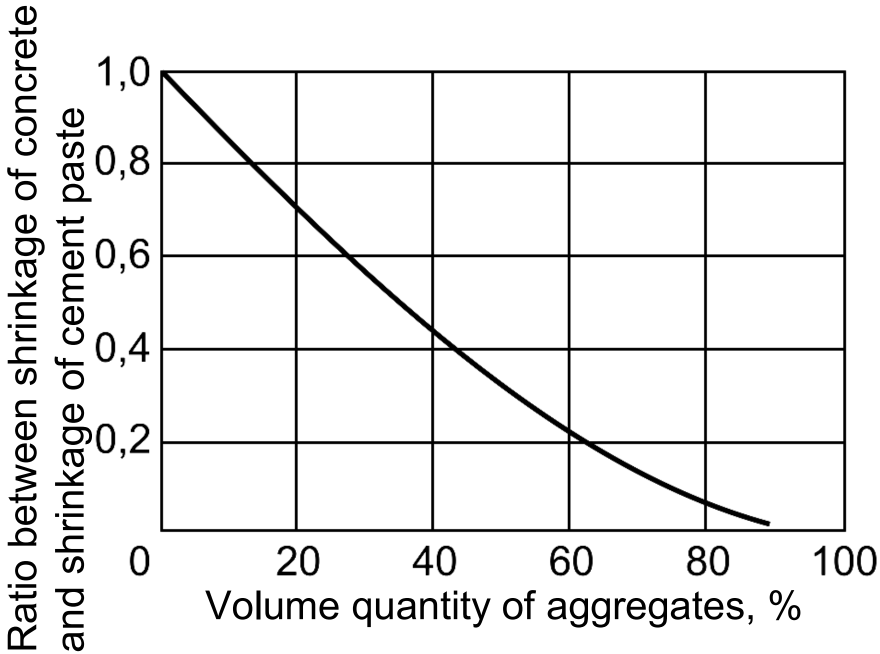


Fig. 5.9. Effect of volume quantity of aggregates on ratio between shrinkage of concrete and shrinkage of cement paste

Along with drying shrinkage, concrete is exposed to carbonation shrinkage due to carbon dioxide which presents in an air. Carbon dioxide reacts with the products of hydration of cement and that is accompanied by the increase of general shrinkage of concrete.

Thermal shrinkage is caused by the decrease of the temperature of concrete. The high changes of temperature in summer and in a winter can be a reason of concrete changes of unit length to 0.5 mm per m.

CHAPTER 6

CONCRETE RESISTANCE TO TEMPERATURE-HUMIDITY INFLUENCE.
CORROSION RESISTANCE

L. Dvorkin and O.Dvorkin

Concrete durability is provided at accordance its composition and structure to conditions of constructions performance.

6.1. Frost resistance of concrete

Reasons of frost destruction of concrete. Frost resistance of concrete is ability to keep strength and working ability at action of cyclic freezing and thawing in the water saturating conditions.

At present, there is no general theory explaining the reason of frost destruction of concrete though it is obvious that finally, strength decrease of damp concrete at cyclic freezing and thawing is caused basically by formation of ice in concrete pores. As the volume of ice is about 9 % more than volume of water, there is significant pressure that can rupture concrete and gradually loosen its structure.

According to a T.Powers hypothesis of hydraulic pressure the main reason of concrete destruction at cyclic freezing and thawing is the hydraulic pressure created in pores and capillaries of concrete under influence of freezing water. At enough volume of entrained air voids excess water gets in air voids and prevents concrete damage.

According to modern representations hydraulic pressure is not the unique reason of frost destruction. Destruction is also developed by the action of osmotic phenomena. They result increase in concentration of the dissolved substances ($Ca(OH)_2$, alkalies, etc.) in a liquid phase of concrete on border with an ice. Diffusion of water to area of freezing creates additional pressure.

Factors affecting frost resistance of concrete. Influence of cyclic temperature change additionally increases due to action of salts solutions. For example, different deicing chemicals ($NaCl$, $CaCl_2$) used for ice removal from road surfaces.

At presence of salts the osmotic phenomena in frozen concrete increases and viscosity of a liquid phase raises. As a result hydraulic pressure increases and destruction of concrete is accelerated.

Frost resistance of concrete is caused basically by its porous structure.

The temperature of freezing of water in concrete depends on the sizes of capillaries. For example, in capillaries 1,57 mm in diameter water freezes at -6,4^{0}C; 0,15 mm at -14,6^{0}C; 0,06 mm at -18^{0}C. In capillaries less than 0,001 mm in diameter water almost does not freeze.

The air voids received by adding in concrete mix an air-entraining admixture, essentially change structure of a cement stone. The number of air voids per 1 cm^3 of cement stone can reach one million and a surface of these voids may be within the range of 200 to 250 cm^2. Protective action has only small enough in size air voids — less than 0,5 or 0,3 mm in diameter.

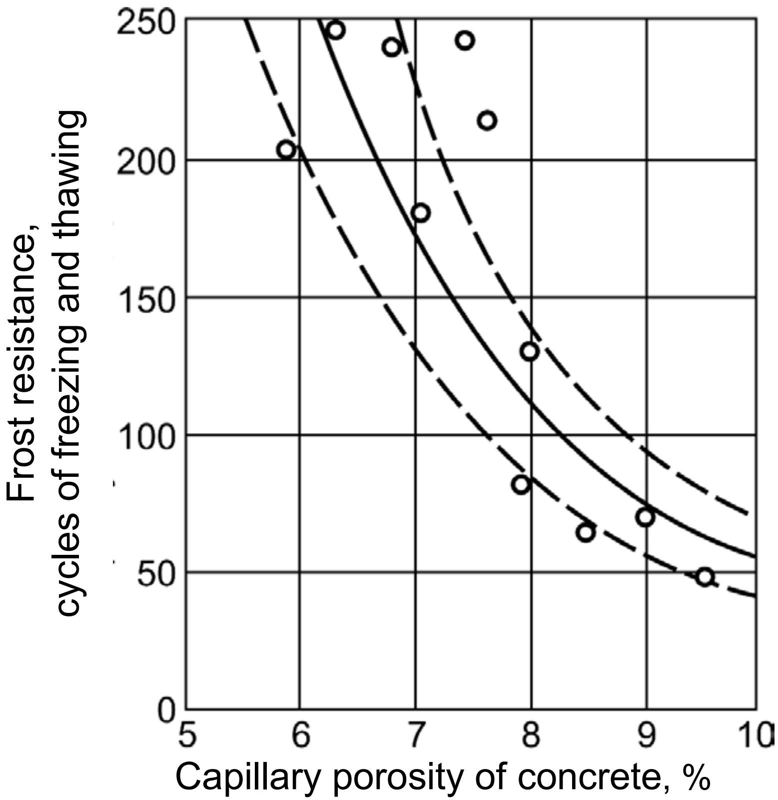


Fig.6.1. Effect of capillary porosity on frost resistance of concrete (from Gorchakov)

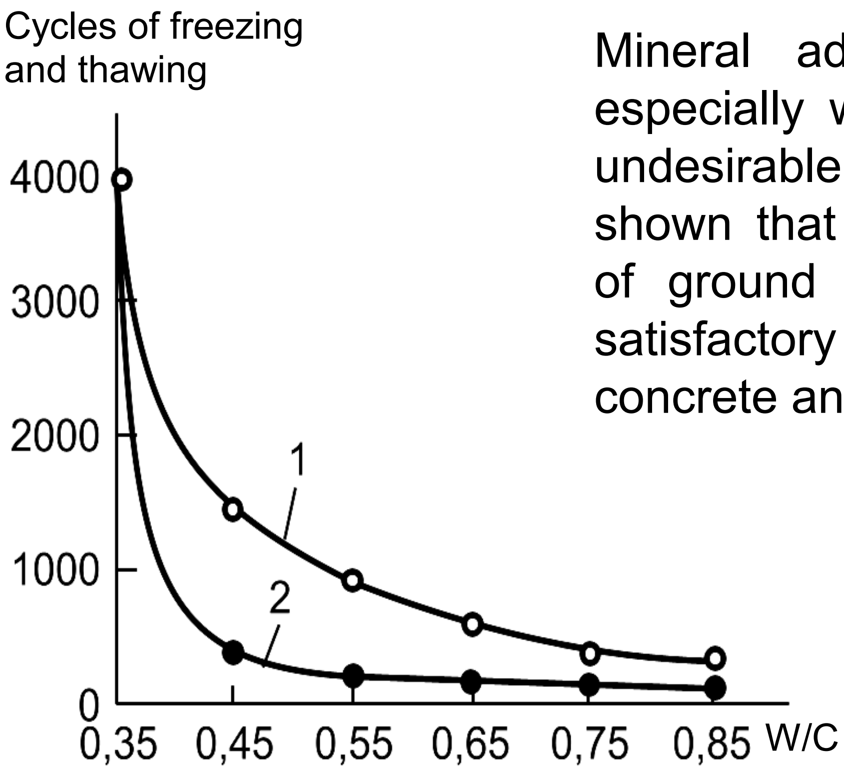
It is possible to divide all technological factors governing frost resistance of concrete on two groups:

1. Factors defined by conditions of construction exposures;
2. Factors considering features of initial materials, structure, composition of concrete and its hardening conditions.

Very important factors defining frost resistance are also the degree of water-saturation and temperature of freezing of concrete.
Strength decrease of concrete after freezing and thawing is possible only at its water-saturation above the certain value.
Comparative determination of frost resistance of concrete by freezing at -17 and -50°C has shown that destruction of concrete in the second case is accelerated significantly (6 to 10 times).

Design of frost-resistant concrete. The volume of the open capillary voids influencing quantity of frozen water, depends on the water-cement ratio (W/C) and degree of cement hydration.
With increase W/C increases both total volume of open capillary voids and their average diameter, that also worsens frost resistance.

The second characteristic defining capillary porosity of concrete is degree of cement hydration which depends on cement strength, rate of hardening, time and conditions of concrete hardening.



Mineral admixtures in frost-resistant concrete especially with the large water requirements are undesirable. At the same time, it is experimentally shown that concrete with non-large maintenance of ground granulated slag or fly ash may be satisfactory frost-resistant, especially at adding in concrete an entrained air.

Fig.6.2. Relationship between frost resistance and water-cement ratio (W/C) of concrete:
1 – Air-entrained concrete;
2 - Non-air-entrained concrete

Increase of specific surface of cement over 400 m^2/kg reduces frost resistance of concrete. Such super-fine cements are characterized by large shrinkage.

Air-entraining admixtures are produced in the form of the concentrated solutions, pastes or in the form of dry and easily soluble powder.

Measurement of frost resistance. The standardized method of an estimation of frost resistance of concrete is characterized by number of cycles of freezing and thawing of specimens under standard conditions of test without essential strength decrease.

The system of normalization of frost resistance offered by us according to which number of cycles of freezing and thawing (F) of laboratory specimens is not given; a class of frost resistance of concrete is more rational. For example:

1 class – non-large frost resistance (F=50 to 150),
2 class - large frost resistance (F =150 to 300),
3 class - high frost resistance (F=300 to 500),
4 class - especially high frost resistance (F> 500).

All methods of definition of concrete frost resistance can be divided in experimentally-calculated and calculated methods.
Experimentally-calculated methods define corresponding experimental parameters (strength, modulus of elasticity, water absorption, etc.) and then approximate number of cycles of freezing and thawing of concrete.

Calculated methods allow to define approximately frost resistance of concrete "a priori" that is without preliminary trial mixes. Such methods represent special interest at designing (proportioning) of frost-resistant concrete mixtures. At the same time, calculated concrete mixtures necessary to check experimentally.

As a result of statistical processing experimental data we offered the following formula for determination of frost resistance of concrete (F):

$$F = K\left(10^{F_k} - 1\right), \qquad (6.1)$$

where К - factor depending on the kind of cement (for ordinary normal Portland cement K=170);

F_k - modified compensatory factor can be determined by the formula:

$$F_к = \frac{V_{air} + V_{contr}}{V_w}, \qquad (6.2)$$

where V_{air} – volume of entrained air voids, %; V_{contr} – volume of concrete voids occurring as the result of cement contraction, %; V_w - volume of water freezing at -20^{0}C in the concrete.

The equation of the compensatory factor can be modified as follows:

$$F_k = \frac{10V_{air} + 0{,}06\alpha C}{W - 0.5\alpha C + 1000(1 - K_{c.f})}, \qquad (6.3)$$

where $K_{c.f}$ – compacting factor of concrete; C, W- quantities of cement and mixing water, kg/m^3; α - degree of cement hydration.

For calculation of a degree of cement hydration (α) its relationship with compressive strength of the cement stone can be used. For example, T.Pawers presented this dependence in the form of the formula:

$$R_{c.s} = 238\alpha^3, \qquad (6.4)$$

where $R_{c.s}$ - compressive strength of the cement stone (MPa).

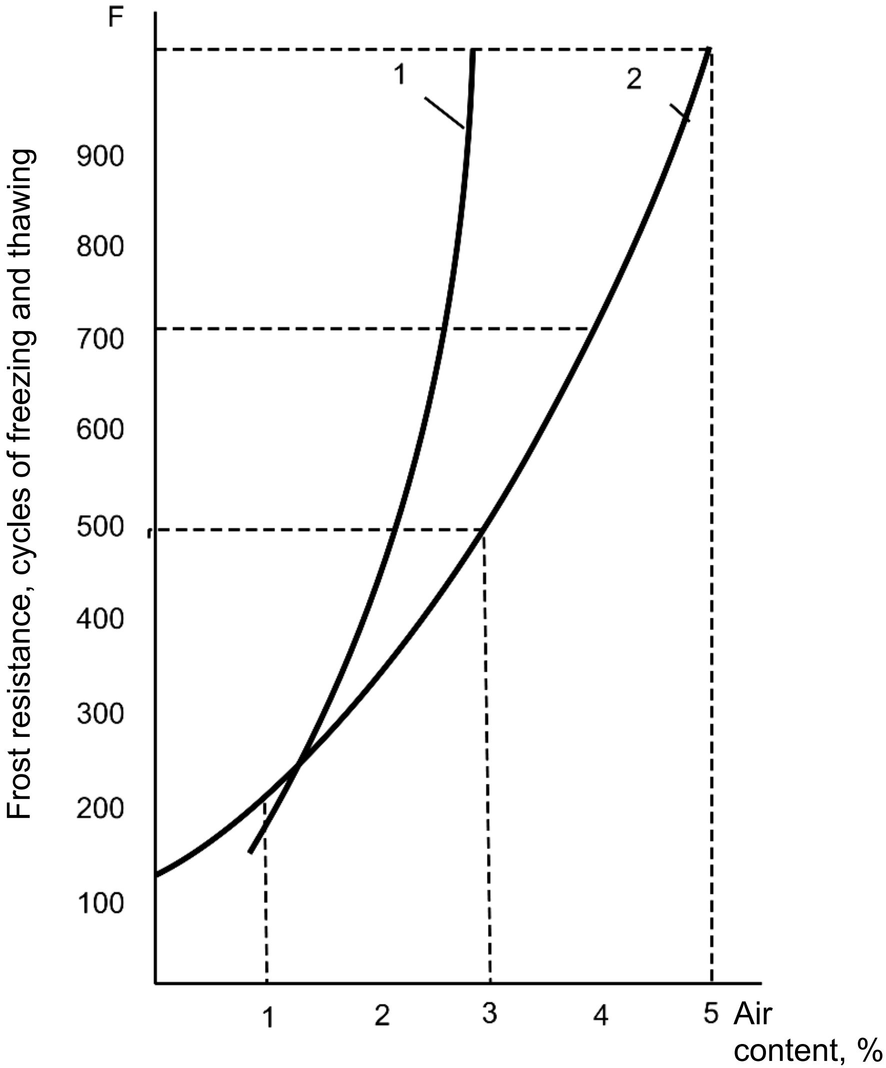


Fig.6.3. Effect of entrained air on frost resistance of concrete:

1 – from laboratory tests (PCA data); 2 – from formula (6.1) (α = 0,7, K= 170, C = 400 kg/m^3, W = 200 kg/m^3)

Comparison of calculated values of frost resistance under the formula (6.1) and experimental values of Portland Cement Association are shown in Fig.6.3.

The American data differ higher values of frost resistance at V_{air}≥2%, that it is possible to explain higher normalized decrease of strength of concrete specimens - 25 % instead of 5 %.

6.2. Concrete resistance to temperature influences

Temperature rise at hardening of concrete accelerates chemical reactions of hydration and positively influences on growth of concrete strength. Essential acceleration of hardening processes begins at temperatures from 70 to 95°C and especially at 170 to 200°C. However at not enough quantity of mixing water in concrete mixture influence of the raised temperatures slows down process of hydration and reduces strength of concrete.

For production of durable concrete it is important to reduce to minimum its deformation at temperature influence.

Occurrence of thermal strains in concrete probably not only at its external heating, but also as a result of a self-heating due to exothermic reaction of hydration.

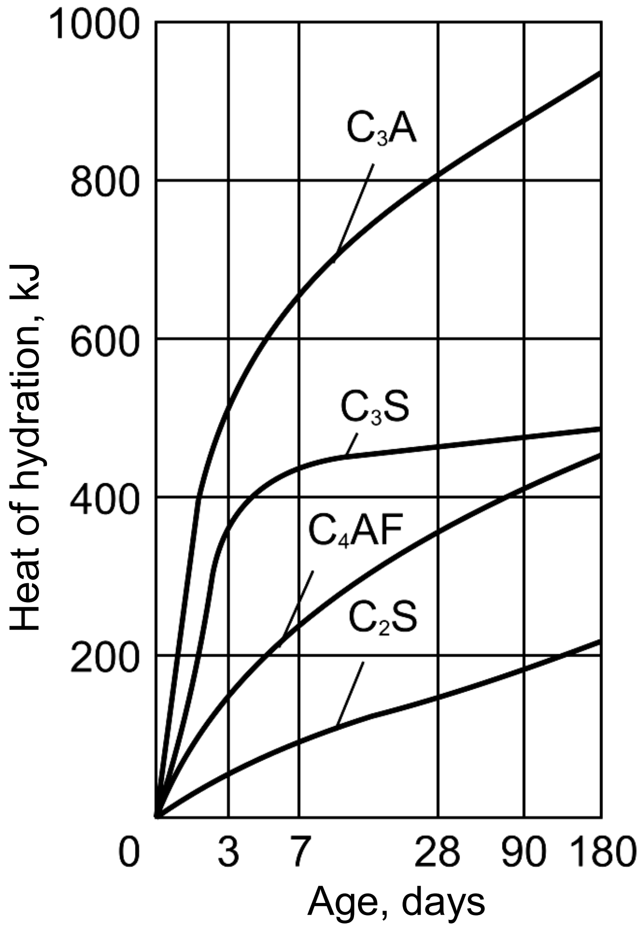


Fig.6.4. Heat evolution at hydration of compounds of cement clinker

Formation of cracks in massive concrete structures usually has thermal character. Criterion $К_t$ characterizes thermal cracks resistance:

$$К_t = \frac{\varepsilon_{m.s} \cdot C \cdot \rho}{Q \cdot \alpha}, \qquad (6.5)$$

where $\varepsilon_{m.s}$ - maximal deformation of a stretching; C – specific heat capacity of concrete kJ/kg·K ; ρ – concrete density, kg/m³; Q – heat of hydration (heat evolution), kJ/m³; α – factor of linear temperature expansion.

The normalized heat evolution (kJ/m^3) for massive concrete structures can be determined from a condition of limitation of concrete temperature to the certain age of hardening by the following:

$$Q = \frac{C\rho}{K}(t_{cr} - t_o), \qquad (6.6)$$

where C – specific heat capacity of concrete kJ/kg·K; t_{cr} – maximal (critical) temperature (Celsius) of hardened concrete; К – factor depending on conditions of concrete cooling ($K \leq 1$); t_o – temperature (Celsius) of the fresh concrete after its finishing; ρ – concrete density, kg/m^3.

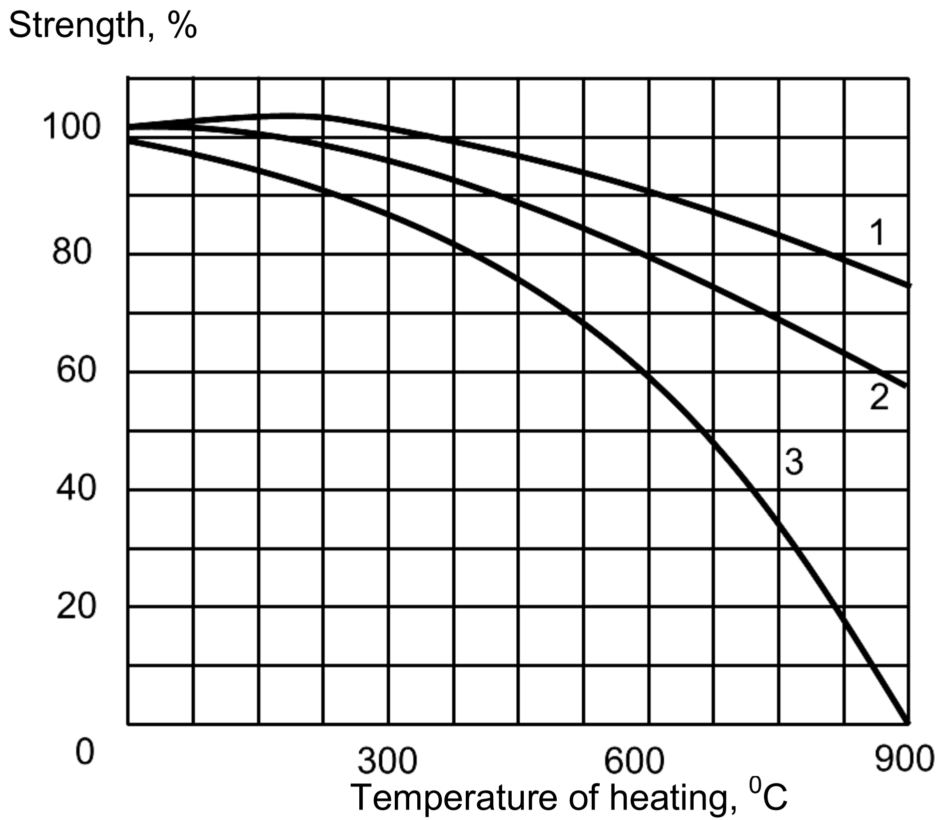


Fig.6.5. Effect of temperature on strength of concrete:

1 – Portland cement 70% + Trepel 30%;
2 – Portland cement 70% + Pumice 30%;
3 – Portland cement

Intensive destructive processes begin at heating concrete to temperature more than 200°C.

For heat resistance increase, finely divided mineral admixtures can be added into cement or concrete mixes, that chemically react with calcium oxide, resist to heats and reduce shrinkage of cement stone at heating.

6.3. Permeability

Permeability of concrete characterizes its ability to conduct gases and liquids at a certain pressure difference. Permeability of concrete is defined by a factor of permeability - the quantity of a liquid getting through unit of the area of the specimen in unit of time at a gradient of a pressure equal 1.
In concrete there are capillaries of the various size, therefore various mechanisms of moving of gas and liquids can simultaneously operate.

Watertightness

Two normative characteristics of watertightness are possible to use:

1. Maximal pressure of water (W, MPa) which standard specimens with height and diameter 150 mm can sustain without water infiltration.
2. Coefficient of water filtration through a concrete defines the quantity of water getting through unit of the area for a time unit, at a gradient of water pressure equal 1.

The coefficient of water filtration through concrete can be used for determination of permeability for other liquids:

$$(K_f/K) = (\eta/\eta_w), \qquad (6.7)$$

where К and η - coefficient of permeability and viscosity of liquid different from water; K_f and η_w - coefficient of filtration and water viscosity.

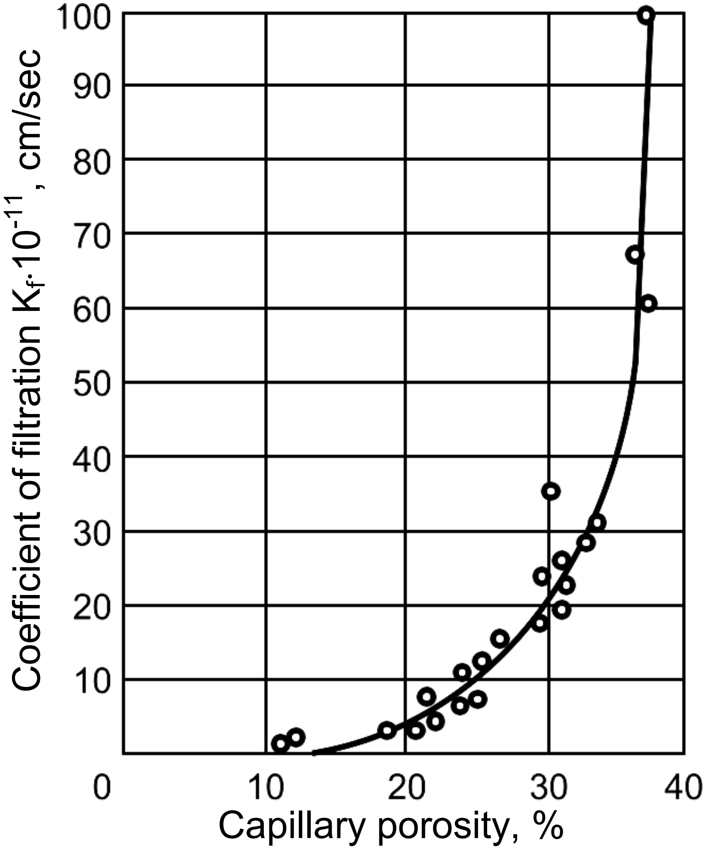


Fig.6.6. Relationship between permeability and capillary porosity of the cement stone

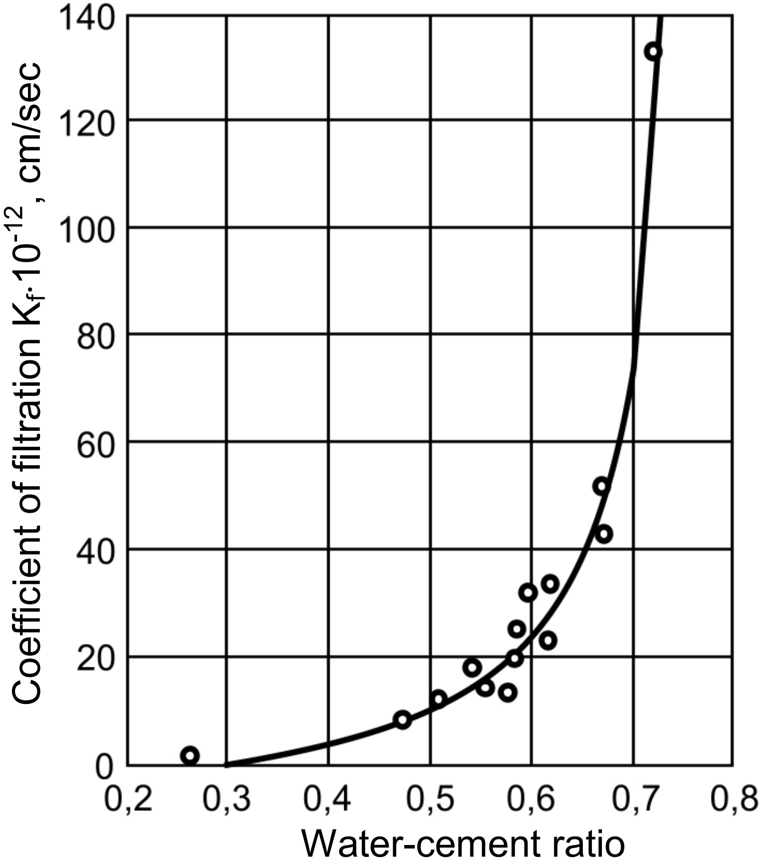


Fig.6.7. Relationship between permeability and water-cement ratio of the cement stone

As it is experimentally shown, relationship between coefficient of concrete filtration (K_f) and its compressive strength (R_{cmp}) is defined as:

$$K_f = K_w R_{cmp}^m , \qquad (6.8)$$

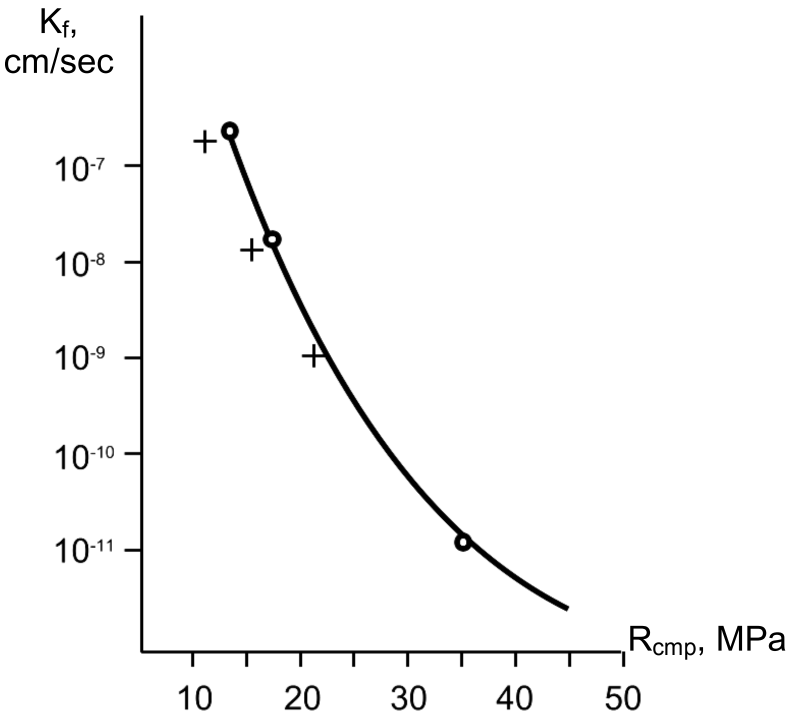


Fig. 6.8. Relationship between coefficient of filtration of concrete (K_f) and compressive strength (R_{cmp}):
"+" – From Elbakidze,
"o"– Our experimental data

where K_w and m - factors which values are determined by features of concrete mixtures, conditions and duration of hardening, etc.

Effective way of decreasing of concrete permeability is adding organic or inorganic admixtures into concrete mix.
As organic materials apply surface-active and polymeric admixtures .
Inorganic materials for decrease of permeability are presented by various salts, clays and active mineral admixtures (pozzolans).

After producing concrete's constructions, decrease in its permeability can be reached by processing of concrete surface by waterproof substances and the substances chemically reacting with minerals of cement stone with formation of insoluble compounds or covering surface by protective materials.

6.4. Corrosion resistance

Degree of aggressive effect of an environment is defined by its chemical composition and a complex of the factors describing conditions of contact of environment and concrete.

Cement stone consists of alkaline chemical compounds, therefore the most intensive corrosion of concrete occurs at influence of the environment containing water solutions of acids on it. Salts, inorganic and organic substances can be also aggressive to concrete.

The degree of aggressive influence of liquids depends on concentration of hydrogen ions (pH), amount of carbonic acid (CO_2), salts, caustic alkalis, sulfates. Oils and solvents also are aggressive liquids.

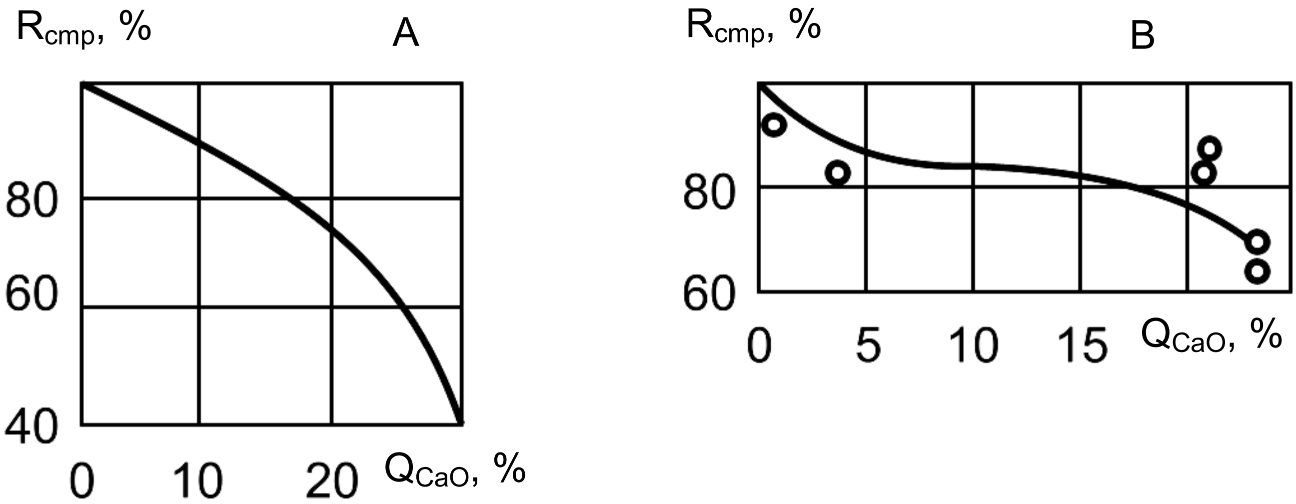


Рис. 6.10. Effect of dissolution of calcium hydroxide on compressive strength of cement stone (A) and concrete (B):
Q_{CaO} - Amount of dissolved calcium hydroxide, %;
R_{cmp} – Compressive strength of cement stone and concrete, %

From Moskvin classification, dissolution processes of lime and its washing away from concrete concern to corrosion of first type.

Corrosion of the second type is caused by chemical reactions between the products of hydration of cement and acids or salts which affect concrete. Calcium salts of usually well water-soluble appear as a result of action of acids.

Corrosion of the second type is also caused by magnesium salts, often presents in large amount in underground and sea water (15.5...18% from total salts content). At magnesia corrosion appears amorphous mass of $Mg(OH)_2$ decreasing strength of concrete along with soluble salts.

Corrosion of the third type develops in concrete from internal stress due to accumulation of insoluble salts in the capillaries of concrete.

The most widespread corrosion of this type is sulfate corrosion which takes place in cement stone under action of ions. SO_4^{2-}

Ettringite appears in the cement stone under the action of sulfate water:

$$3CaO \cdot Al_2O_3 \cdot 6H_2O + 3(CaSO_4 \cdot 2H_2O) + 19H_2O =$$
$$3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$$

Volume expansion and concrete destruction are often caused by ettringite formation.
Active mineral admixtures (pozzolans) essentially increase sulfate resistance due to chemical reaction with calcium hydroxide.

Water containing more than 1000 mg/Litre ions SO_4^{2-} cause mainly gypsum corrosion due to accumulation of gypsum in capillaries of the cement stone.

Destructions of concrete under influence of vegetative and animal organisms are called biological damages.

Durability of concrete in the terms of influence of aggressive environment is provided by application of concrete with a high density, by use initial components with the proper chemical composition and application at a necessity the special measures of concrete's defense (application of isolating materials, admixtures etc.).

Special kind of the aggressive environment for concrete is ionizing radiation. Structures of nuclear reactors are exposed to the greatest degree ionizing radiation. Ability of concrete to keep their properties after radiation action is called radiating resistance.

CHAPTER 7

DESIGN OF NORMAL CONCRETE MIXTURE

L. Dvorkin and O.Dvorkin

7.1. General and tasks

Design of concrete mixtures - the main technological problem, which decision defines a level of operational reliability of constructions and degree of rational use of the resources spent for their manufacturing and installation.

The founder of practical methodology of design of concrete mixtures is D.Abrams. He summarized results of extensive experimental researches in Chicago Laboratory of Portland cement Association and formulated the primary tasks of design of concrete mixtures and methods of their decision.

In modern technology designing of concrete mixture means a substantiation and choice of a kind of initial materials and their ratios providing at set criterion of an optimality given requirements to a concrete mix and concrete.

Actual directions of development of methodology of concrete mixtures design are:

- increase in "predicting ability" of calculated methodology that is an opportunity of full comsideration of technological factors and given requirements to concrete;
- increase in efficiency of algorithms of concrete mixtures design, their accuracy and speed.

In technological practice method of designing concrete mixtures with the required compressive strength is the most common. Many properties of concrete are simply linked with compressive strength such as flexural and tensile strength, resistance to abrasion, etc. However, dependence between strength and frost-resistance or strength and creep, etc. is not always straight proportional. Their calculated determination must be based on the complex of the special quantitative dependences.

Most developed and realized in practice there are 2-factor tasks, it means that the given properties of concrete are compressive strength (R_{cmp}) and consistency of the mix (Slump or Vebe).

If there is a necessity in normalization of some other technical properties of concrete, except for compressive strength, the problem of concrete mixtures design becomes essentially complicated.

At designing mixtures of various and in particular special kinds of concrete (hydrotechnical, road, etc.) there are multi-factors tasks. They can be divided into three subgroups:

1- With the normalized parameters unequivocally connected with compressive strength of concrete;

2- With the normalized parameters uncertainly connected with compressive strength of concrete;

3 - With the normalized parameters which have been not connected with compressive strength.

For example, tasks with various given parameters of strength of concrete belong to the first subgroup. At calculation of compositions of such concrete mixture the defining parameter from given properties of the concrete and its corresponding compressive strength are determined and established minimally possible cement-water ratio (C/W) which providing all set of properties.

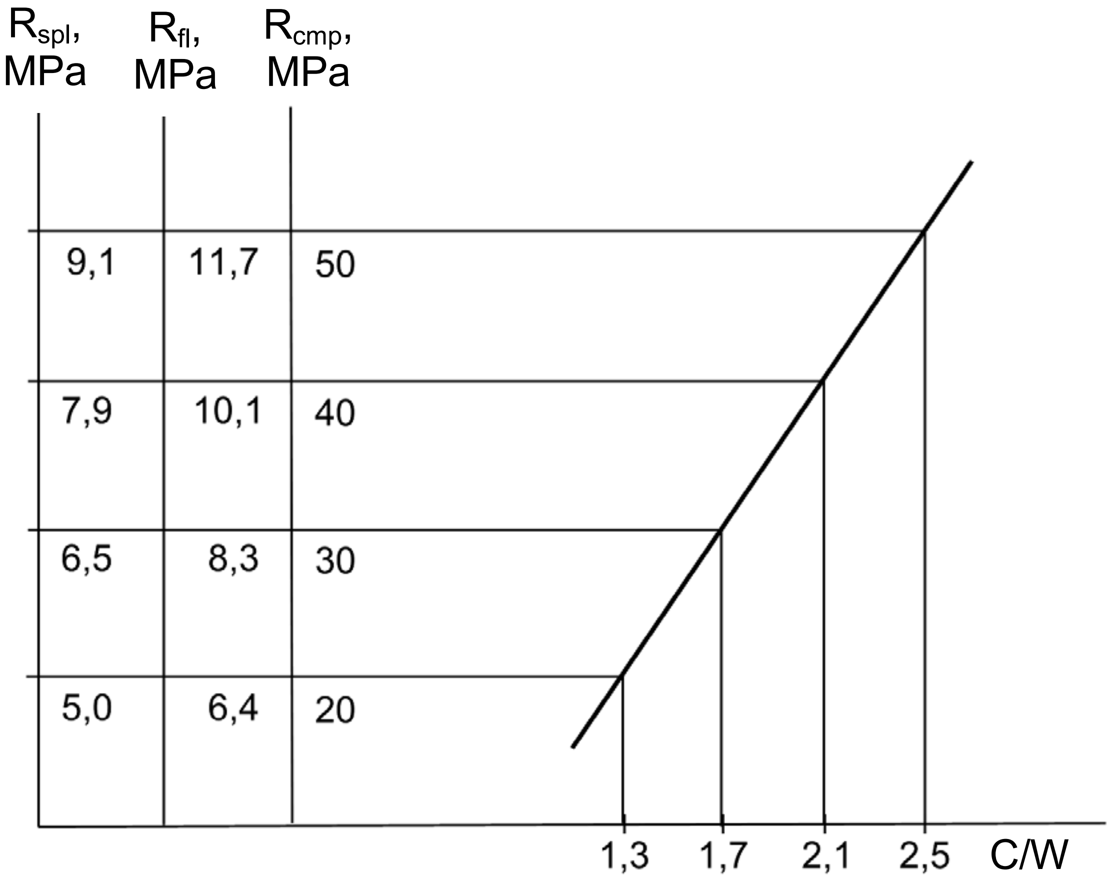


Fig. 7.1. Effect of cement-water ratio (C/W) on the compressive strength (R_{cmp}), flexural strength (R_{fl}) and splitting tensile strength (R_{spl})

For example, from Fig. 7.1 follows, that if are normalized: compressive strength $R_{cmp} \geq 20$ MPa, flexural strength $R_{fl} \geq 8{,}3$ MPa and splitting tensile strength $R_{spl} \geq 7{,}9$ МПа, that, obviously, the defining parameter is R_{spl} and necessary cement-water ratio providing all three parameters of properties, is equal 2.1.

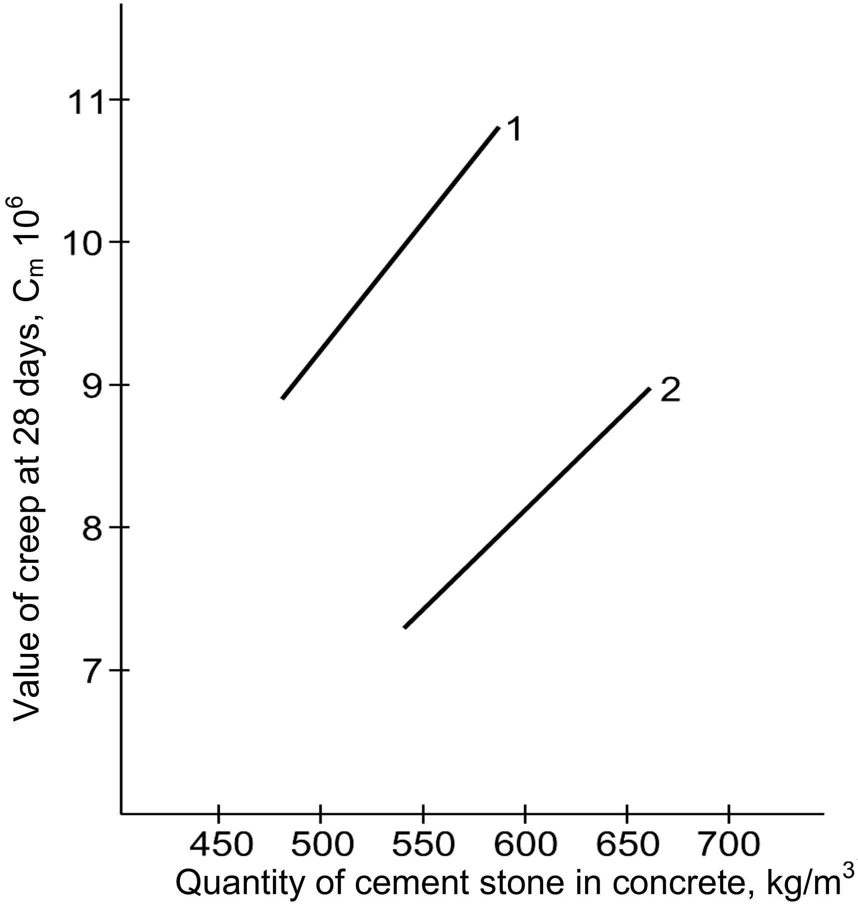


Fig. 7.2. Effect of quantity of the cement stone in concrete on the value of creep:
1 – Compressive strength of concrete = 20 MPa;
2 – Compressive strength of concrete = 30 MPa

Normalized parameters in tasks of the second subgroup of designing concrete mixtures alongside with compressive strength can be creep, frost resistance, heat generation, etc.

Fig. 7.2 shows the example of relationship between creep and quantity of the cement stone in concrete at constant compressive strength. At constant water-cement ratio and therefore concrete strength, concrete creep can essentially differ depending on quantity of the cement stone in concrete.

For the tasks of concrete mixtures design of the third subgroup (for example, light concrete) water-cement ratio is not a determinative factor, providing the complex of the normalized properties. For such tasks is necessary to find other, substantial for all normalized properties factor. Determination of necessary value of this factor becomes the main task of concrete mixtures design.

7.2. Selection of raw materials and admixtures

Task of a choice of initial materials is the technical and economic problem defining efficiency of designed concrete mixtures and an opportunity of achievement of demanded properties of concrete.

The basic technical parameters at a choice of a kind of cement are: chemical composition, strength, rate of hardening, normal consistency and fineness.
For an estimation of efficiency of use of cement the relative parameters describing the quantity of cement or its cost on unit of strength and also ratio between strength of concrete and the quantity of cement are offered.

Active mineral admixtures (pozzolans) are added directly in concrete mixes and widely applied to economy of cement and their most power-intensive component - cement clinker.

"Cementing efficiency" or amount of cement saved at adding active mineral admixtures depends on many factors characterizing their composition, structure, fineness, terms of hardening, age of concrete, etc.

The characteristic feature of a modern concrete technology is wide application of chemical admixtures for achievement of necessary concrete properties, declines of expense of financial and power resources at making concrete and at its application for constructions.

Expenses for the admixture (E_{xa}) at production of concrete can be calculated as follows:

$$Ex_a = C_a A + Ex_a^{adt}, \qquad (7.1)$$

Where C_a - cost of the admixture per 1 m^3 of concrete including necessary transport costs; A - the specific amount of the admixture;

Ex_a^{adt} - the specific costs connected with additional processing of the admixture, its storage, batching, change of the composition of concrete mixture, etc.

For manufacturers of concrete (concrete mix, products and structures) is important to distinguish the economic effect provided by the admixture due to economy of other resources during manufacture and effect reached at concrete application.

Expenses on admixture (E_{xa}) at the production of concrete mix are justified, if the following condition is executed:

$$Ex_a < Ex_i + Ex_{pr} - Ex_i{}' - Ex_{pr}{}', \qquad (7.2)$$

Where Ex_i and Ex_i' - expenses on initial materials of concrete mix without admixture and with admixture; Ex_{pr} and Ex_{pr}' - other production expenses on concrete mix without admixture and with admixture.

7.3. Calculations of basic parameters of concrete mixture composition

Calculation of cement-water ratio.

Most widely used formula for determination of cement-water ratio (C/W) is following:

$$R_{cmp} = AR_c\left(C/W - 0.5\right), \qquad (7.3)$$

Where A- coefficient, specified in Table 7.1 depending on the different factors; R_c – strength of cement at 28 days, MPa; R_{cmp} – compressive strength of concrete at 28 days, MPa.

Additional possibilities are opened at the use in the formula of strength in place of ordinary multiplicative coefficient pA.

Equation of multiplicative coefficient pA can be presented as follows:

$$pA = A\,A_1 \ldots A_i \ldots A_n, \qquad (7.4)$$

Where A_i is a coefficient, taking into account additional influence on the value of strength of i-factor (i=1…n).

Ordinary technological information allows to take into account in the multiplicative coefficient pA to 2 or 3 additional coefficients A_i.

Table 7.1

Recommended values of coefficient A (from V.Sizov)

Kind of aggregates	Contents of harmful substances (clay, silt, soft particles) in crushed stone (gravel) and sand, %	Value of coefficient A for concrete made with the use of		
		Crushed stone	Gravel mountain	Gravel river and marine
Crushed stone (gravel) Sand	0 0	0.64	0.6	0.57
Crushed stone (gravel) Sand	0 3	0.61	0.56	0.53
Crushed stone (gravel) Sand	1 3	0.58	0.53	0.5
Crushed stone (gravel) Sand	2 3	0.55	0.5	0.47
Crushed stone (gravel) Sand	2 5	0.52	0.47	0.44

Additional possibilities for expansion of range of the decided tasks of designing concrete mixtures are possible at the use of the “modified cement-water ratio $(C/W)_{mod}$”:

$$(C/W)_{mod} = \frac{C + K_{c.e} D}{W + V_{air}}, \qquad (7.5)$$

Where $K_{c.e}$ - coefficient of "cementing efficiency" of mineral admixtures, that is content of cement in kg, commutable by 1 kg of mineral admixture: D - content of mineral admixture, kg/m^3; C and W – accordingly contents of cement and water, kg/m^3; V_{air} - volume of the entrained air, liters per m^3.

In this case, formula (7.3) can be presented as follows:

$$R_{cmp} = pAR_c \left(\frac{C + K_{c.e} D}{W + V_{air}} - 0.5 \right). \qquad (7.6)$$

Where R_c – strength of cement at 28 days, MPa; R_{cmp} – compressive strength of concrete at 28 days, MPa.

The coefficient of "cementing efficiency" can be easily defined from experimental data for the concretes with identical strength by the following:

$$K_{c.e} = \frac{C_1 - C_2}{D}, \qquad (7.7)$$

Where C_1 - content of cement in the concrete without mineral admixture; C_2 - content of cement in the concrete with mineral admixture; D - amount of mineral admixture.

Application of the "modified cement-water ratio" is rational and useful in particular for the concrete mixtures design with the limited or small amount of cement at adding of mineral admixtures.

Calculation of water content.

In practice of designing concrete mixtures the water content of concrete mixtures is determined usually from empiric data by the graphs (Fig.7.3) or tables which offer some base values of water content (kg/m^3) depending on the indexes of consistency of concrete mix and specified depending on the features of initial materials. The rule of constancy of water content, in accordance with which the water content for achievement necessary consistency of concrete mix remains practically permanent in the certain range of cement content or cement-water ratio, is widely used thus.

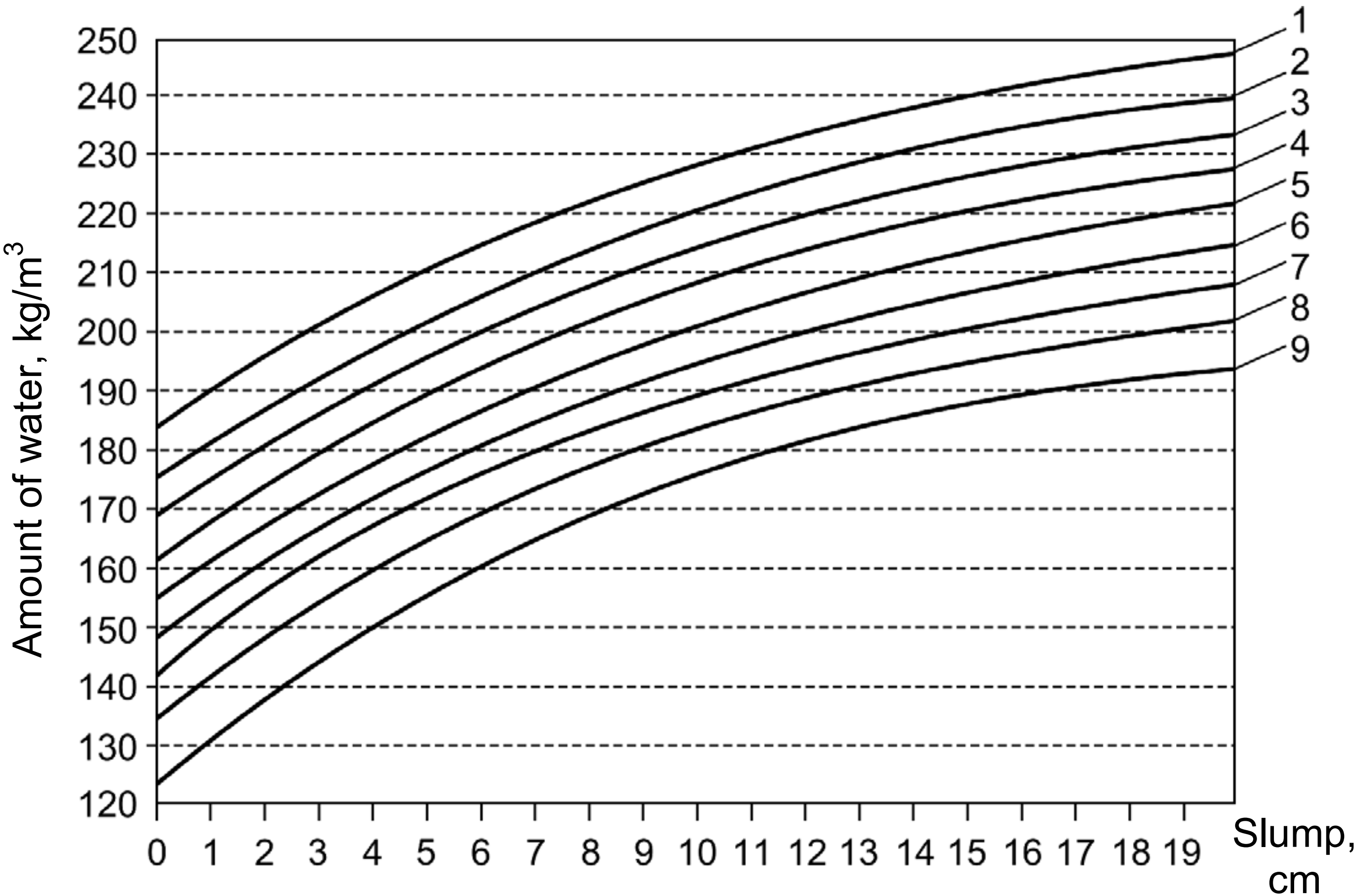


Fig. 7.3. Relationship between amount of water per cubic meter and slump of concrete mix:

1 – Sand (Fineness modulus is equal 3); 2-9 – Granite crushed stone (Particle sizes are 10, 15, 20, 30, 40, 60, 80 и 150 mm)

Calculation of aggregates content.

One of basic tasks of optimization of concrete mixtures is determination of aggregates ratio, which provides the minimum amount of cement.

Widely applied in Russia and Ukraine the calculation-experimental methods of designing concrete mixtures, use the coefficient (α) which characterizes filling of voids between crushed stone (gravel) particles with cement-sand pastes (mortar) (taking into account some stock of the paste for achievement demanded consistency of the concrete mix) for determination of quantities of sand and crushed stone (gravel).

Quantities of coarse and fine aggregates can be easily defined by decision of system of two equations of material balance. The first equation expresses equality of volume of the concrete mix to the sum of absolute volumes of the initial components of concrete, the second - conformity of volume of the cement - sandy paste (mortar) to volume of voids in the coarse aggregates (taking into account some stock of the paste for achievement demanded consistency of the concrete mix):

$$\frac{C}{\rho_c} + \frac{W}{\rho_w} + \frac{F_{ag}}{\rho_{f.ag}} + \frac{C_{ag}}{\rho_{c.ag}} = 1000$$

$$\frac{C}{\rho_c} + \frac{W}{\rho_w} + \frac{F_{ag}}{\rho_{f.ag}} = \alpha P_{c.ag} \frac{C_{ag}}{\rho_{b.c.ag}}, \qquad (7.8)$$

Where C, W, F_{ag}, C_{ag} – accordingly quantities of cement, water, fine and coarse aggregates, kg/m^3; ρ_c, ρ_w, $\rho_{f.ag}$ и $\rho_{c.ag}$ – accordingly specific gravity (weight per unit absolute volume of ingredients of concrete) of cement, water, fine and coarse aggregates, kg per liter; $P_{c.ag}$ – volume of voids in coarse aggregates, including space between particles; $\rho_{b.c.ag}$ – bulk density of coarse aggregates, kg per liter.

Therefore:

$$C_{ag} = \frac{1000}{\frac{1}{\rho_{c.ag}} + \frac{\alpha \rho_{c.ag}}{\rho_{b.c.ag}}}, \qquad (7.9)$$

$$F_{ag} = \left(1000 - C/\rho_c - W/\rho_w - C_{ag}/\rho_{c.ag}\right) \rho_{f.ag}. \qquad (7.10)$$

From Table 7.2 the coefficient α can be found.

Table 7.2

Coefficient α (plastic consistency of concrete mixes)

Cement content, kg/m^3	Value of α at water-cement ratio					
	0.3	0.4	0.5	0.6	0.7	0.8
250	–	–	–	1.26	1.32	1.38
300	–	–	1.3	1.36	1.42	–
350	–	1.32	1.38	1.44	–	–
400	1.31	1.4	1.45	–	–	–
500	1.44	1.52	–	–	–	–
600	1.52	1.56	–	–	–	–

Notes: 1. Water demand of fine aggregates is equal 7%.

2. For stiff concrete mixes ($C < 400$ kg/m3) $\alpha = 1.05...1.15$.

7.4. Correction of design concrete compositions

Inevitable deviations of actual indexes of properties of concrete mixes and concretes from a calculated stipulate certain approximations of calculated compositions of concrete. Adjustment of calculated compositions is made experimentally in a laboratory. Depending on possibilities of testing laboratory and terms of construction works, an amount of laboratory works at experimental correction of composition of concrete can be different. Complete adjustment can be at experimental correction of all parameters of concrete mixture: water content, water-cement ratio, ratio between different aggregates, volume of the entrained air. Sometimes, incomplete laboratory adjustment is possible (for example, only correction of water content, providing given consistency with subsequent correction of other parameters of mixture after production of concrete).

It is necessary to take into account that at production conditions, sand and crushed stone (gravel) have some humidity unlike laboratory (nominal) compositions of concrete, which define for dry initial materials.

At manufacture of concrete, the quantities of fine ($F_{p.ag}$, kg/m^3) and coarse ($C_{p.ag}$, kg/m^3) aggregates increase on mass of water which is:

$$F_{p.ag} = F_{ag} \cdot (1 + H_{f.ag}), \qquad (7.11)$$

$$C_{p.ag} = C_{ag} \cdot (1 + H_{c.ag}), \qquad (7.12)$$

where F_{ag}, C_{ag} – quantities of dry sand and crushed stone (gravel) in laboratory (nominal) concrete mixture, kg/m^3; $H_{f.ag}$, $H_{c.ag}$ – humidity of sand and crushed stone (gravel), parts of unit.

Accordingly for manufacture of concrete, quantity of water (W_p) is diminished as compared to laboratory mixture on mass of water in aggregates:

$$W_p = W - F_{ag} \cdot H_{f.ag} - C_{ag} \cdot H_{c.ag}, \qquad (7.13)$$

where W – quantity of water in laboratory (nominal) concrete mixture, kg/m^3.

CHAPTER 8

TYPES OF CONCRETE

L. Dvorkin and O.Dvorkin

Along with ordinary coarse aggregate concrete, in construction are also used types of concrete which differ from their structural peculiarities, composition and properties.

There are considered fine-grained concrete, high-strength concrete, concrete, modified by polymer admixtures and fiber reinforced concrete, concrete for special purposes – hydrotechnical, high-strength, heat-resistant, facing and concrete for nuclear radiation protection in the given chapter.

8.1 Fine-grained concrete

Maximum coarseness of the aggregate in fine-grained concrete is 10 mm. Sand concrete that does not contain coarse aggregate is prevalent type of the concrete.

Y. Bagenov suggested dependence of sand concrete strength as empirical formula:

$$R = AR_c\left(\frac{C}{W + V_a} - 0.8\right), \qquad (8.1)$$

Where A is a coefficient: for high quality materials A=0.8, medium quality – 0.75 and low quality – 0.65; V_a is volume of entrained air; C, W – contents of cement and water, kg/m^3; R_c –strength of cement, MPa.

Numerous experimental data shows, that there are a lot of factors besides cement-water ratio (C/W), cement strength and aggregate quality such as placeability of fresh concrete, hardening conditions, presence and quantity of admixtures etc. which make influence on fine grained concrete strength.

Quality of the aggregate for fine grained concrete make much more influence on its basic properties than those for conventional heavy concrete. According to Y.Bagenov data replacement coarse sand for fine sand in concrete can reduce strength for 25...30%, and sometimes in 2...3 times.

Concrete placeability parameter defines sand - cement ratio at given water-cement ratio (Fig. 8.1).

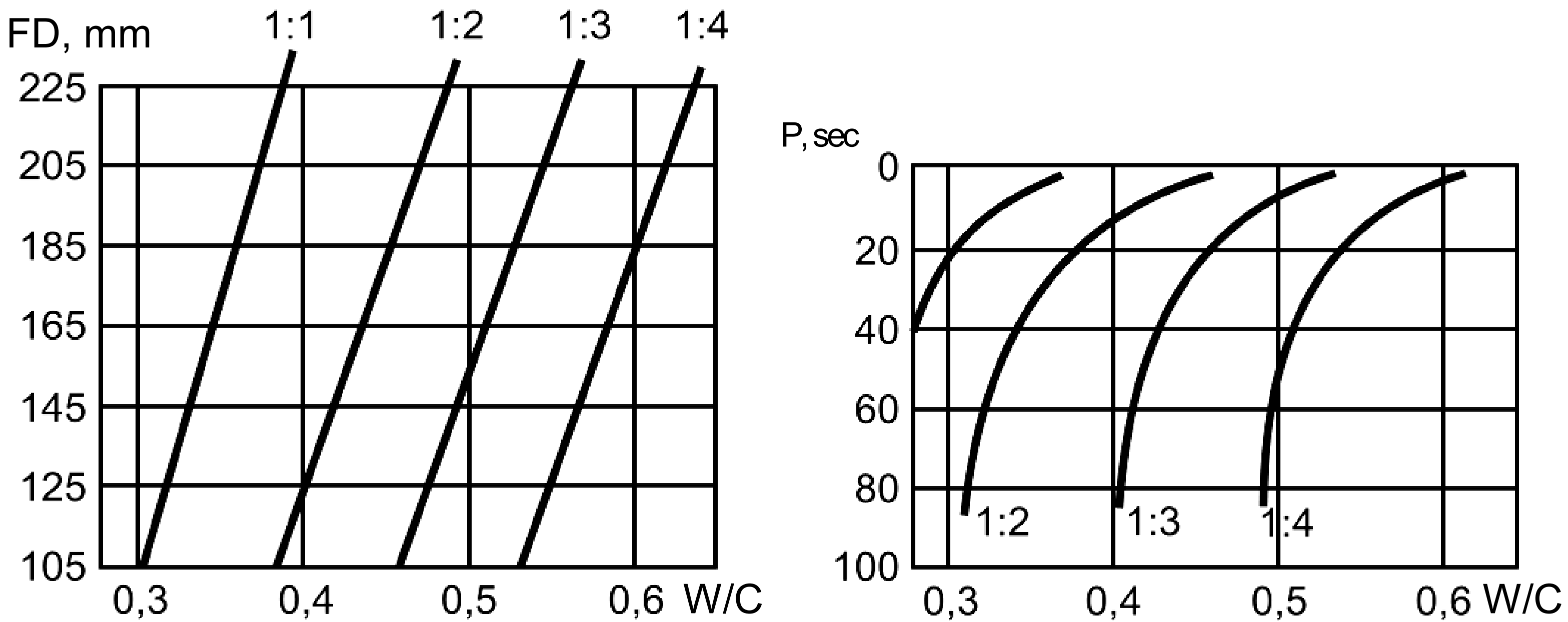


Fig. 8.1 Curves for selection of cement and medium coarseness sand ratio, that provides given value of flow diameter (FD) and placeability (P) of cement-sand mixtures (according to Y.M.Bagenov)

Raised tensile (flexural) strength and compressive strength ratio is distinctive feature for fine grained concrete (Fig. 8.2).

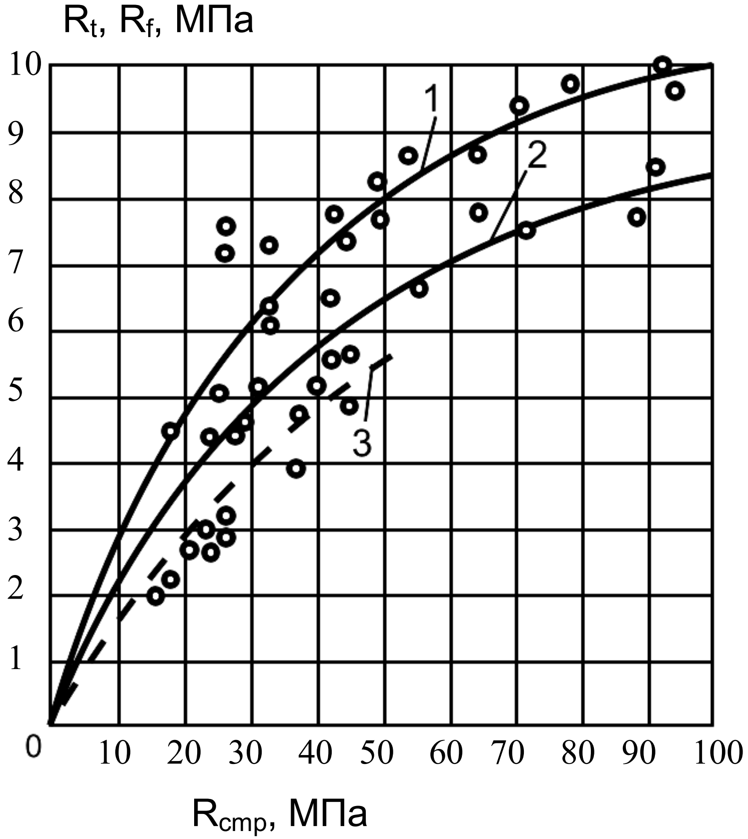


Fig.8.2. Dependence of concrete flexural strength (R_f) and tensile strength (R_t) on compressive strength (R_{cmp}):
1 - R_f of sand concrete, 2 - R_f of ordinary concrete, 3 – R_t of sand concrete

Structure peculiarities make influence on deformation properties of fine grained concrete. They have modulus of elasticity at 20...30% lower and higher shrinkage and creep than ordinary concrete. Deformability and creep can be reduced considerably due to the harshness of concrete mix, application of force compacting method.

8.2. High-strength concrete

Until present there is no direct definition for the types of concrete, which can be considered as high-strength ones. Conditional border between conventional and high-strength concrete varies as concrete technology develops. In the fifties of last century concrete grades 25-40 MPa considered to be high-strength, in the sixties – 50-60 MPa. Now normally high-strength concrete is ranged as concrete with compressive strength at the age of 28 days 70-150 MPa. European standard EN206 envisage possibility of concrete production and application including 115MPa concrete grade. Mostly due to effective modifiers (superplasticizers and silica fume) industrial technology of concrete production at given strength range have been developed and appropriate standards were worked out. Such concrete is used widely for load-carrying structures, monolithic framework of high-rise constructions (Table 8.1), bridges, platforms, vibrohydropressed tubes. There has been obtained concrete with compressive strength up to 200 MPa.

Table 8.1

Examples of high-strength concrete application at the high-rise buildings construction

City	Year of construction	Number of floors	Concrete strength, MPa
Montreal	1984	26	119.6
Toronto	1986	68	93.6
New York	1987	72	57
Toronto	1987	69	70
Paris	1988	36	70
Chicago	1989	82	78
Guangow, China	1989	63	70
Chicago	1990	65	84
Frankfurt	1990	58	45
Seattle	1990	58	133
Frankfurt	1991	51	112

High-performance concrete is a type of high-strength concrete which has compressive strength at the age of 2 days 30-50 MPa, at the age of 28 days – 60-150 MPa, frost resistance – more than 600 cycles of freezing and thawing, water absorption – less than 1-2%, abrasiveness – no more than 0.3-0.4 g/cm^2, adjustable deformability parameters.

Obtaining high strength of heavy concrete at high-strength aggregates is possible due to increasing in concrete density and strength of cement stone (cohesive factor) and contact zone (adhesive factor). The main direction of high-strength concrete obtaining is providing extremely low water-cement ratio (W/C) at comparatively high hydration degree of cement and necessary compacting of concrete mix. At low W/C ratio obtaining of optimal ratio between crushed stone and mortar content makes positive influence on concrete strength.

Cardinal way of W/C ratio reduction without significant workability degradation of concrete mix are superplasticizers (SP) adding. Unlike ordinary plasticizers reducing water consumption up to 10-5%, superplasticizers permit to reduce water consumption at 20-30% and more and to increase concrete strength. Concrete with high early age strength can be obtained by regulation of SP and W/C ratio. It can be increased in 2-3 times at adequately high dosage of the admixture.

Concrete strength changes almost linearly with cement strength increasing.

Binders of low water requirement (BLWR) obtained by fine milling of portland cement clinker and mineral admixture with adding powdered superplasticizer belongs to the effective binders for high-strength concrete. BLWR have high specific surface (4000-5000 cm^2/g), low water requirement (16-20%) and strength up to 100 MPa. Water amount of concrete mixes on the basis of binders of low water requirement (BLWR) is lower at 35-50% than at the ordinary Portland cement (Fig.8.3).

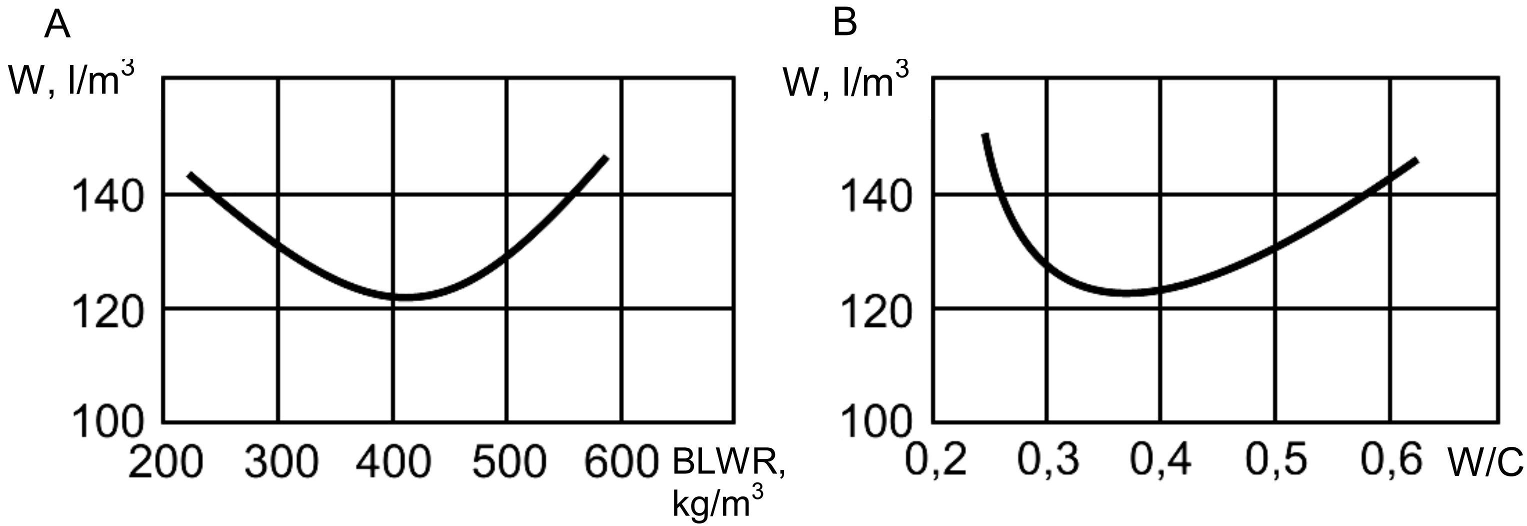


Fig.8.3 Relationship between water amount of concrete mixes (slump 1-4 cm) and BLWR content (A), water-cement ratio W/C (B)

In the fifties of the last century in Norway it has been suggested to improve concrete properties by adding ultra fine byproducts of metallurgy industry – silica fume (SF) and it have been started wide production of concrete with SF since the middle seventies. It was found out that the most effective microsilica admixtures are byproducts of crystalline silica and ferrosilicium. They basically consist of amorphous silica (85-95% SiO_2) in the form of particles with diameter 0.1 mkm and have specific surface 1500-2000 m^2/kg.

Silica fume adding to the concrete is effective in complex with superplasticizer admixture taking into consideration increasing in mix water requirement.

Also other ultra fine silica and aluminosilica materials can be effective in the composition with superplasticizer.

8.3. Polymer-impregnated and polymer-cement concrete

Polymer-impregnated concrete. Polymer-impregnated concrete is concrete impregnated by polymer compositions or monomers with subsequent polymerization. Polymer-impregnated concrete is included into “P-concrete” group collecting different types of concrete where polymers are used both as admixtures and basic components. Polymer-impregnated concrete divides depending on impregnating material type: monomers (styrene, methylmetacrylate etc.), viscous organic binders (bitumen, paraffin etc.).

At concrete impregnation its structure changes, at first open capillary porosity decreases drastically, cement stone and aggregate contact zone is condensed. As a result water absorption reduces and compressive strength and other mechanical properties increase significantly.

There are shown comparison of the properties of ordinary initial concrete and impregnated concrete at polymerization by metylmetacrylate (according to Y.Bagenov data) in Table 8.2.

Table 8.2

Properties of ordinary initial concrete and polymer-impregnated concrete

Parameter	Initial concrete	Polymer-impregnated concrete
Strength, MPa:		
compressive	30...50	100...200
tensile	2...3	6...19
flexural	5...6	14...28
Modulus of elasticity at compression, MPa	$2.5 \cdot 10^4 ... 3.5 \cdot 10^4$	$3.5 \cdot 10^4 ... 5 \cdot 10^4$
Limit deformation at compression	0.001	0.002
Bond strength with reinforcement, MPa	1...2	10...18
Shrinkage	$50 \cdot 10^{-5}$	$0...5 \cdot 10^{-5}$
Creep	$(40...60) \cdot 10^{-5}$	$(6...8) \cdot 10^{-5}$
Electrical resistance, Om	10^5	10^{14}
Water absorption, %	3...5	1
Frost resistance, cycles of freezing and thawing	200	5000
Corrosive resistance to sulfates and acids	Insufficient	High

Polymer-cement concrete. Polymer-cement concrete is concrete modified with polymer admixtures. Cresson had received first patent on application of polymer cement with latex admixture in 1923.

Modified cement mixes differ from ordinary mixes due to their ability to water keeping that increases when polymer-cement ratio increases. That permits to improve placeability, prevent “drying” and reach good adhesion with porous base.

One of the main results of polymer admixtures adding is tensile strength increasing of cement concrete and their deformability. At adding of polyvinylacetate (PVA) and latexes admixtures flexural strength increasing in 2-3 times. There is also observed increasing in limit extensibility and adhesion to old concrete and reinforcement. PVA adding as an admixture to mortars increases extensibility up to 2 times.

At selection of the application area of polymer-cement mortars and concrete there are taken into consideration their specific properties and advantages (Tab.8.3).

Table 8.3

Technical application areas of mortars and concrete modified by latex (according to I. Okama)

Materials group	Materials assignment
Floor coverings	Floors for public buildings, storages, administration buildings, shops, toilets
Road and abrasion resistance coverings	Crosswalks, stairs, railway platforms, road coverings
Watertight structures	Concrete flat roofs, masonry blocks, water cisterns, swimming pools, dikes for silage
Binding compositions	Mortars for adhesion of finishing, heat-insulating and other materials; Bonding new concrete to old one and new mortar to old one
Anticorrosive compositions	Drainpipes, floors of chemical plants, mortars for acid resistant tiles, basements for machinery, floors for chemical laboratories, drug-store storages
Toppings	Ship decks, bridges coverings, trains floors, coverings for pedestrian overpasses

8.4. Fiber reinforced concrete

Fibrous or fiber reinforced concrete is a group of composite materials including short chopped fibers in cement matrix. There are different types of fiber made of steel, glass, synthetic materials, asbestos, carbon etc.

For composite materials with discrete fibers modulus of elasticity (E) and flexural strength (R_{fl}) can be approximately calculated from following:

$$E=K_r E_f V_f + E_m V_m, \qquad (8.2)$$

$$R_{fl}= K_r R_f V_f + R_m V_m \quad , \qquad (8.3)$$

Where K_r – reinforcement coefficient of concrete, E_f and E_m – modulus of elasticity of fiber and matrix, R_f and R_m – flexural strength of fibers and matrix, V_f and V_m – volume content of fibers and matrix.

Typical stress – strain diagram of fibrous concrete consists of 3 zones (Fig.8.4, 8.5).

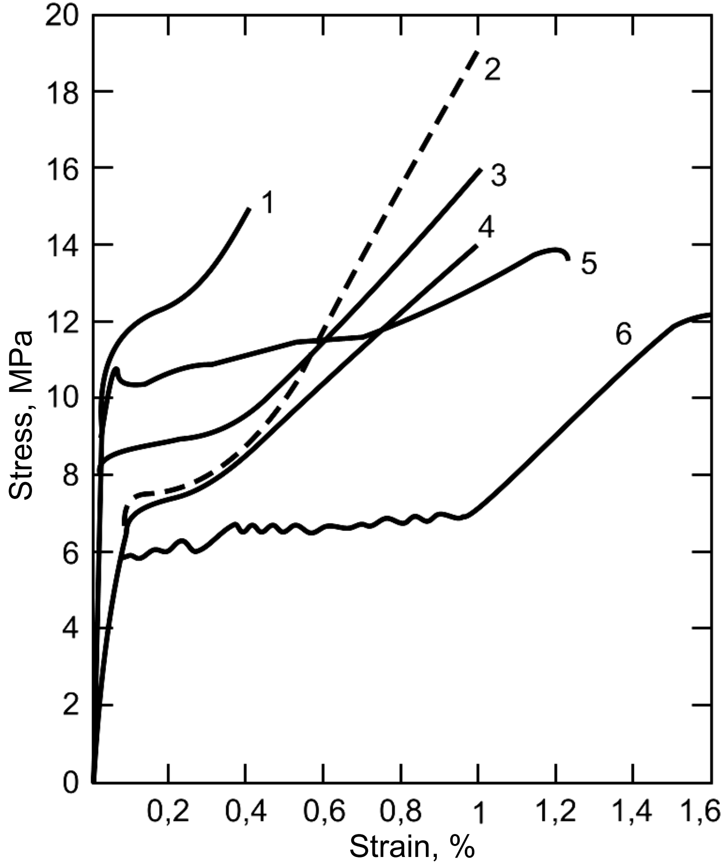


Fig. 8.5. Curves of stress – strain dependences for several fiber reinforced cement composites:
1 – Portland cement – steel wire, 1.5% by volume; **2** – The same, 1% by volume, **3** – High-alumina cement – fiberglass, 0.067% by volume; **4** – Portland cement – zirconium fiberglass, 5% by volume; **5** – Portland cement – polyamide fiber, 1.93% by volume; **6** – gypsum – fiberglass, 1% by volume

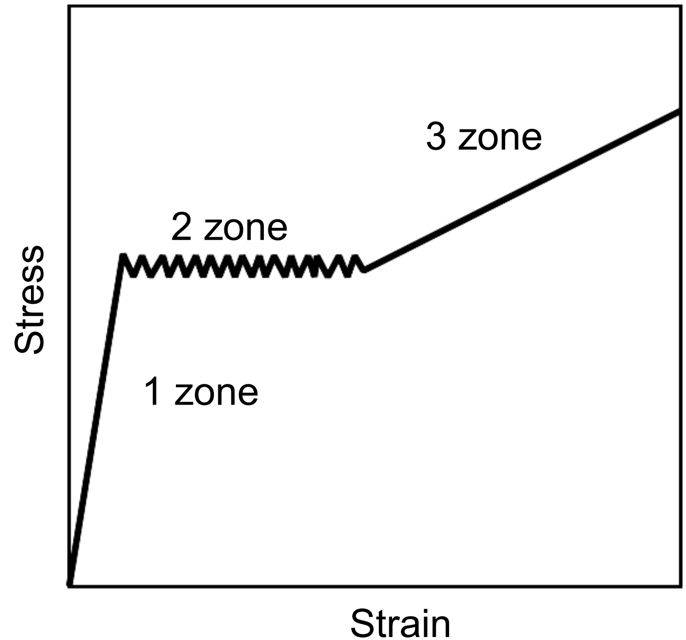


Fig. 8.4. Typical curve of stress – strain dependence for cement compositions reinforced by fiber

At fibrous concrete destruction maximum work done at burst (W_b) is expressed by formula:

$$W_b=V_f R_f l_{cr}/12, \qquad (8.4)$$

Where R_f – flexural strength of fibers, V_f – volume content of fibers; l_{cr} is critical length of fiber.

Steel fibrous concrete. Steel fibrous concrete is the most common fibrous concrete on the basis Portland cement reinforced by steel fiber. Steel fiber is presented usually by cuts of wire. Fibers can have different cross-area – round, oval etc. with dimensions from 0.2 to 1.6 mm and length from 10 to 160 mm. Fibers surface can be sectional and smooth. Amount of added fibers mostly varies from 0.5 to 2 % by volume. Adding into concrete steel fibers in the amount of 1-1.5% by volume increases its tensile strength up to 100%, flexural strength – up to 150-200%, compressive strength increases at 10-25%.

Glass-fiber reinforced concrete. Along with steel fibrous concrete there is positive experience of application of glass-fiber reinforced concrete (glass-fiber reinforced cement) that allows reducing additionally weight of constructions. Their production is based on adding into cement paste or cement mortar alkaline-resistant fiber in the amount of 5% by mass. Tensile strength and flexural strength of glass-reinforced mortar increases the strength of non-reinforced mortar in 2-3 times even after 10 years of air-dry hardening. Maximum deformation caused by limit tensile stress in glass-reinforced mortar is in 10 times more than in non-reinforced mortar.

There are combined successfully properties of initial materials and high strength and durability is reached in the composites on the basis of mineral binders reinforced by glass fiber.

Fiber made of non-alkaline aluminoborosilicate glass has the largest strength. Alkaline oxides reduce strength of a fiber.

Tensile strength of glass-reinforced cement increases linearly when glass fiber content increases (Fig. 8.6).

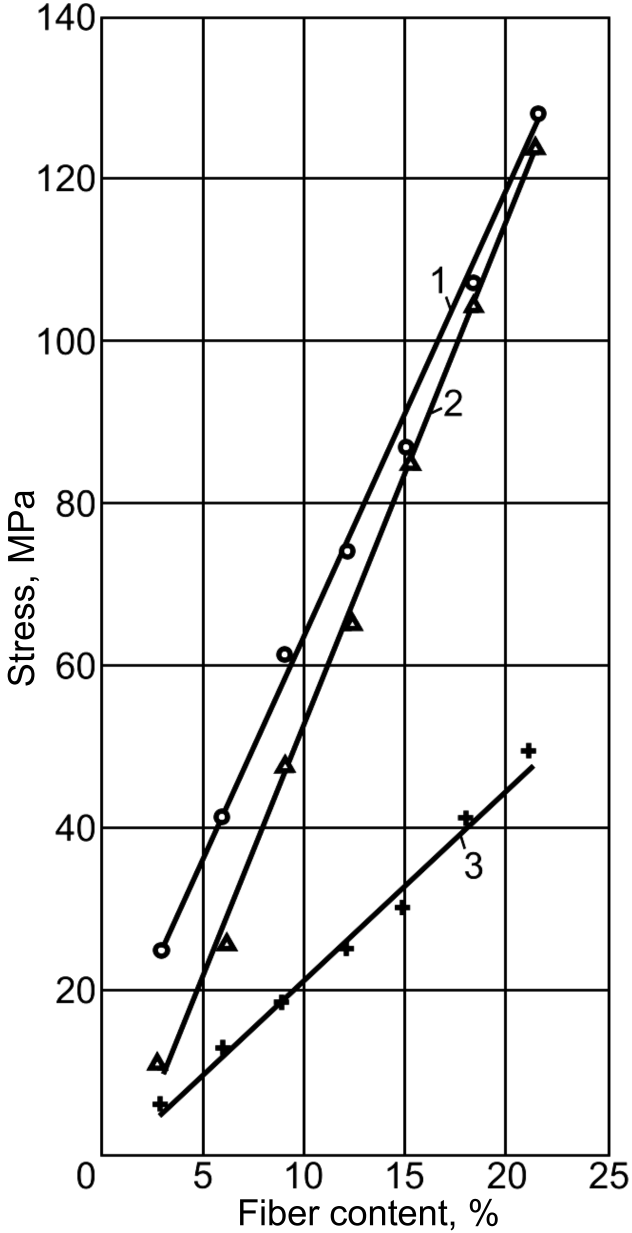


Fig.8.6. Variation of tensile strength characteristics (endlong) of glass-reinforced cement depending on glass fiber content:

1 – limit strength, 2 – stress that causes cracks formation in cement stone, 3 – conventional proportional limit

Fiber-reinforced concrete with polypropylene fibers. Polypropylene fibers are widespread for concrete reinforcement. Their distinctive features are good compatibility with Portland cement and high resistance to hardening binders.

Adding to concrete mix 0.1 – 1% (by volume) propylene fibers allows to reduce segregation of the mix and improve it pumpability, to increase significantly deformability and crack resistance.

8.5 Special concrete

Hydrotechnical concrete. Hydrotechnical concrete is used for constructions manufacturing and installation structures that periodically or constantly are in the water. This type of concrete use widely at installation hydropower, irrigation, transport structures, structures of industrial hydraulic engineering, water supply, sewerage etc.

Requirements to hydrotechnical concrete are differential taking into consideration zonal distribution of concrete into structures (Tab. 8.4).

Table 8.4

Requirements to hydrotechnical concrete by zones

Requirements to concrete	Massive structures						Non-massive structures		
	External zone			Internal zone					
	Zones concerning water level								
	underwater	variable level	overwater	underwater	variable level	overwater	underwater	variable level	overwater
Water resistance	+	+	+	+	+	–	+	+	+
Watertightness	+	+	+	+	+	–	+	+	+
Frost resistance	–	+	+	–	–	–	–	+	+
Low heat generation	+	+	+	+	+	+	–	–	–

Notice. Sign "+" means that the requirement demands.

Complex of specified requirements to hydrotechnical concrete has been provided by choice of initial materials and admixtures and design of concrete mixtures according to service conditions taking into consideration recommended restrictions (Table 8.5).

Table 8.5

Recommended limit values of water-cement ratio for hydrotechnical concrete

Zone and performance conditions	Non-massive reinforced concrete structures in the water		External zone of structures of massive constructions in the water	
	sea	fresh	sea	fresh
Zone of variable level at climate conditions:				
very severe	0.42	0.47	0.45	0.48
severe	0.45	0.50	0.47	0.52
moderate	0.50	0.55	0.55	0.58
Underwater zone:				
pressure	0.55	0.58	0.56	0.58
nonpressure	0.60	0.62	0.62	0.62
Overwater zone, washed episodically	0.55	0.60	0.65	0.65

Heat resistant concrete. Heat resistant concrete is used for facing the fireboxes, in the construction of flues, chimneys, at thermal stations construction, in the elements of protective walls and floors of nuclear power plants. Conventional heavy cement concrete is applicable for production of concrete structures exposed to long lasting influence of temperatures up to 200° C. Depending on limit allowable temperature of application heat resistant concrete are divided into classes – from 3 to 16 (limit temperature of application is correspondingly from 300 to 1600 °C). It is also classified:

- by fireproofness – heat proof with fireproofness up to 1580°C, fire proof – from 1580 to 1770°C and high fire proof – more 1770°C;

- by density in dry state – heavyweight (density>1500 kg/m^3) and lightweight (density ≤1500 kg/m^3);

- by type of applied binder – portland cement, slag portland cement, aluminous cement, magnesia cement, aluminophosphate binding agent etc.

Architectural concrete. Polymer concrete and mortars have improved finishing properties and raised adhesion to different bases. They are used for flooring in the premises with intensive movement and high requirements to purity. Polymer cement mortars are used also for adhesion of different facing materials, plasters and facade decorations.

Architectural expression of concrete can be achieved by special treatment to reach necessary texture.

Radiation shielding concrete. γ - radiation and neutrons have the highest penetrability among all the radiation. Ability of material to absorb γ - radiation is in proportion to its density. For decreasing neutrons flow in a material there must be elements with low atomic weight, as hydrogen for example. Concrete is effective material for biological protection of reactor as if it combines successfully at comparatively low cost high density and specified hydrogen content in chemically bound water. To reduce thickness of shrouds of atomic power stations and factories that produce isotopes along with normal weight concrete extra heavy concrete with specific gravity from 2500 to 7000 kg/m^3 and hydrated concrete with high content of chemically bound water are used. For this purpose there are used heavy aggregates: magnetite, hematite or limonite iron ores, barite, waste metal, lead shot, etc.

As a result of ionized radiation qualitative changes in concrete structure come about, character and depth of which depend on concrete properties, type of initial materials and exposure dose.

Concrete expose causes density decreasing and enlarging linear dimensions of aggregate grains. There is also possible transformation of minerals from crystalline to amorphous state that is accompanied by deformations of expansion. When exposure occurs different defects of crystalline structure of aggregates are formed and accumulated. When amorphous fazes content increases in the structure of rocks and crystal dimensions reduce radiation resistance of the rocks increases.

Modulus of elasticity of concrete reduces with exposure dose increases because of accumulation of structural defects in aggregates and cement stone.

CHAPTER 9

LIGHT-WEIGHT CONCRETE

L. Dvorkin and O.Dvorkin

Lightweight concrete is concrete with density up to 2000 kg/m^3. Lightweight concrete is divided by structure on dense, aerated, no-fine concrete and cellular concrete.

9.1. Concrete on non-organic porous aggregates

Lightweight concrete by purpose is divided on heat insulating, structural-heat insulating and structural (Tab.9.1). There are also special types of lightweight concrete according to conditions of their performance – heat resistant, decorative, corrosively resistant, etc.

Table 9.1

Technical characteristic of lightweight concrete

Concrete	Density, kg/m^3	Compressive strength, MPa	Heat conductivity, W/m·^{0}C	Purpose
Heat insulating	300-500	1.5-2.5	0.12-0.24	For heat insulation
Structural-heat insulating	500-1400	3.5-10	0.17-0.40	For enclosing structures
Structural	1400-1800	15-50	0.58-0.4	For load-carrying structures

Density of lightweight concrete can be expressed by the formula:

$$\rho_c = \rho_a \varphi + \left(1 - \varphi - \frac{V_v}{100}\right)\rho_m, \qquad (9.1)$$

where ρ_a and ρ_m – density of porous aggregate grains and cement-sand mortar, V_v – volume of voids between grains, φ - volume concentration of porous aggregate.

Strength of lightweight concrete is correlated with their density (Fig. 9.1). Great influence makes volume of voids between aggregate grains not filled with cement paste.

Most of the formulas for lightweight concrete strength are based on the hypothesis of stresses distribution between components of lightweight concrete under their destruction.

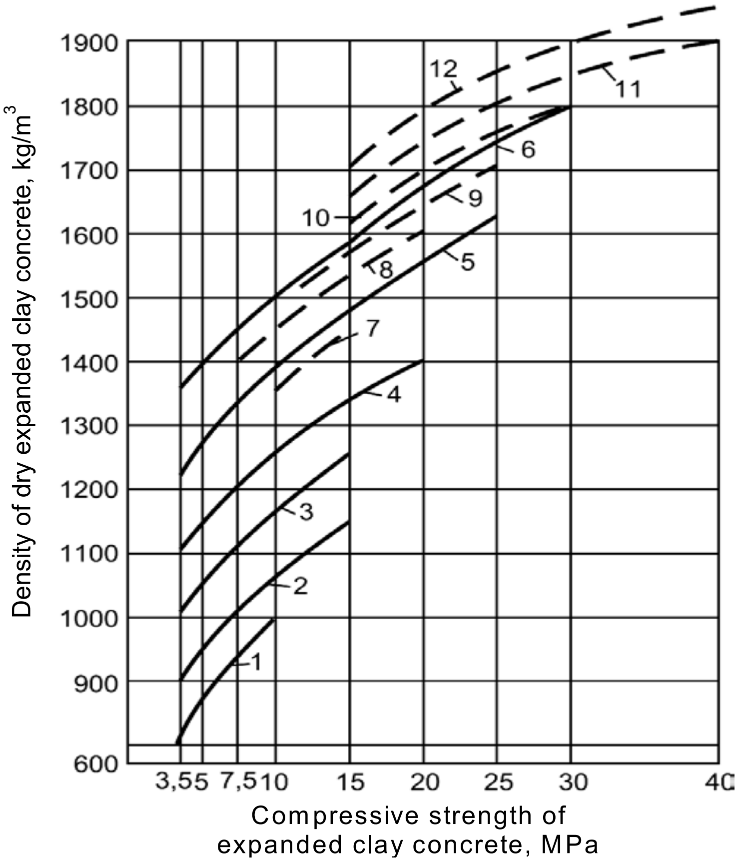


Fig. 9.1 Effect of bulk density of aggregate on density and strength of expanded-clay concrete on porous and quartz sand.
On expanded clay sand at bulk density of expanded clay gravel, kg/m^3:
1 – 300; 2 – 400; 3 – 500; 4 – 600; 5 – 700; 6 – 800;
On quartz sand at bulk density of expanded clay gravel, kg/m^3:
7 – 300; 8 – 400; 9 – 5--; 10 – 600; 11 – 700;
12 - 800

Their application for concrete design is impossible or difficult as if they are not connected single-valued with certain definite mix parameter.

Mix parameter single-valued with strength for lightweight concrete is “modified cement-water ratio (Z)”:

$$Z = \frac{V_c}{W + P_a V_a + V_{air}}, \qquad (9.2)$$

Where V_c, W, V_a, V_{air} - are correspondingly absolute volumes of cement, water, porous aggregate and air per 1 m^3 of concrete mix, P_a is aggregate porosity.

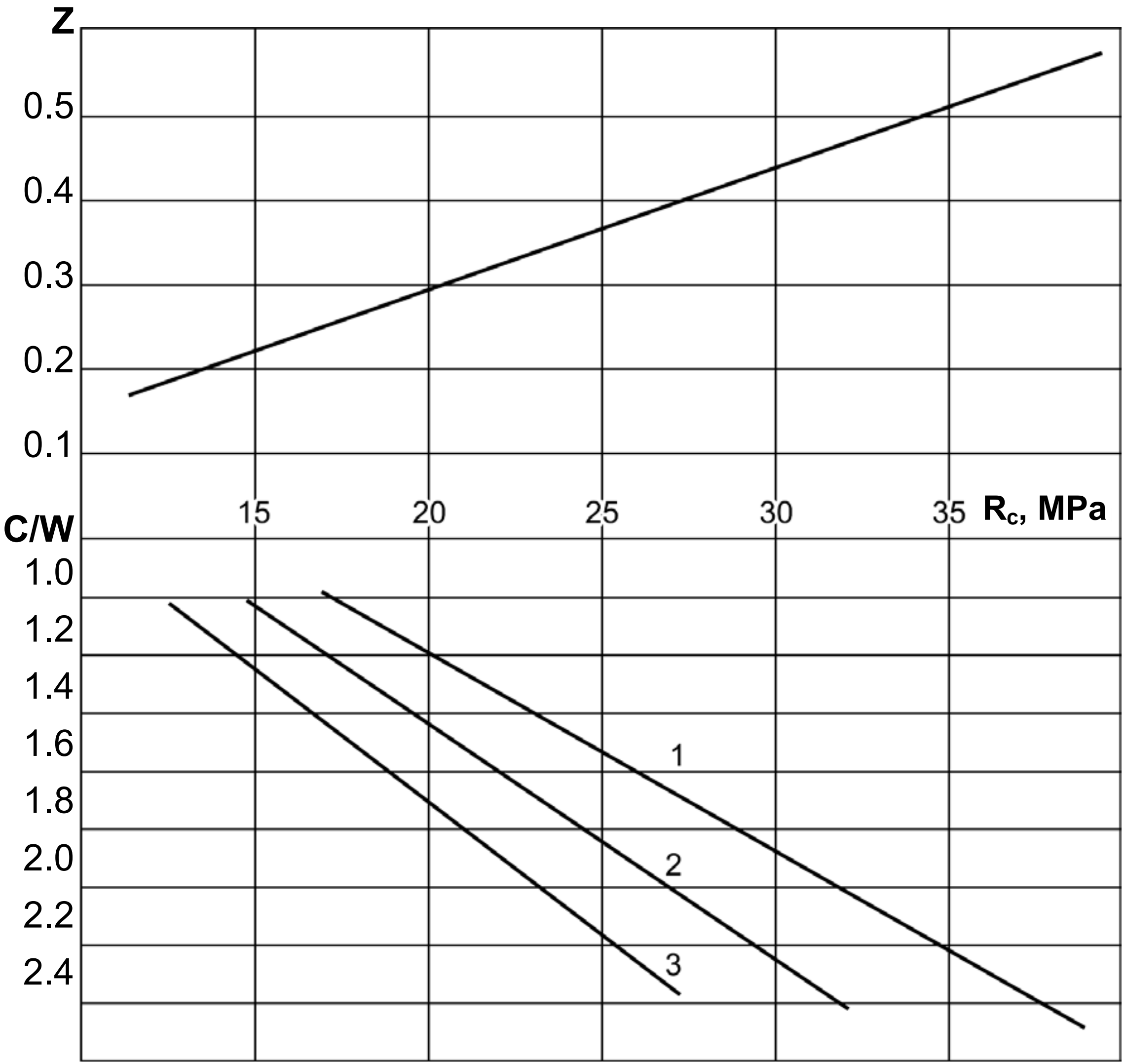


Fig.9.2. Strength (**R_c**) dependences of structural expanded clay concrete on cement-water ratio (**C/W**) and modified cement-water ratio (**Z**):
1 – porosity of expanded clay = 0.4; **2** – 0.55; **3** – 0.7

Reference books and experimental data processing (Fig. 9.2) has shown that strength of lightweight concrete on porous aggregates is connected with Z parameter by linear dependence.

9.2. Design of lightweight concrete with porous aggregates

Design of lightweight concrete is oriented on preliminary determination of components content that provides obtaining specified parameters at given conditions. In all cases design of lightweight concrete with compressive strength must provide specified density.

Design of lightweight concrete can be done:

- at specified types of coarse and fine aggregates with given values of their density;
- at specified type and density of coarse porous aggregate with possible selection of sand type;
- at selection both coarse and fine aggregates.

Selection of coarse porous aggregate is conducted on the basis of empirical data that link their bulk density with density (ρ_c) and strength of concrete (R_c).

Statistical treatment of known experimental data shows the possibility of connection equation application:

$$R_{c.a} = 0.008\rho^{b}_{c.a} - 1.88, \qquad (9.3)$$

Where $R_{c.a}$ is strength of expanded clay gravel; $\rho^{b}_{c.a}$ is bulk density of expanded clay gravel.

Maximal possible density of coarse porous aggregate at volume concentration of porous aggregate φ=const is limited by concrete density (ρ_c) and density of their mortar component. It can be found from the equation:

$$\rho_c = \rho_{c.a}\varphi + \rho_m(1-\varphi) - W_{evp}, \qquad (9.4)$$

Where $\rho_{c.a}$ and ρ_m are correspondingly density of coarse aggregate grains in cement paste and mortar density; W_{evp} is weight of evaporated water that forms additional pores volume.

W_{evp} value can be found by general water content (W) of concrete mix and its part, chemically bound with cement:

$$W_{evp} \approx W - 0.15C, \qquad (9.5)$$

Where C is quantity of cement.

Density of mortar part of lightweight concrete can be reduced by its porisation due to adding of air-entraining admixture. Required air content (V_{air}) in % to transformation of mortar with density ρ_m to ρ'_m can be found from condition:

$$V_{air} = 100 - \frac{100\rho'_m}{\rho_m}. \qquad (9.6)$$

Traditional methods of lightweight concrete design are based on preliminary assignment of cement consumption and volume concentration of porous aggregate on the basis of empirical data, which take into consideration strength and density of concrete, fresh concrete workability, density and strength of aggregate. For this purpose both tabulated reference data and corresponding regression equations can be used.

Volume concentration of coarse porous aggregate in lightweight concrete (φ) can be found by formula (9.7) taking into consideration necessary stock of cement-sand mortar between coarse aggregate grains (K_m):

$$\varphi = \frac{\rho_c}{K_m V^g_{c.a} \rho_m + \rho^b_{c.a}}, \qquad (9.7)$$

Where ρ_c is density of concrete, kg/m^3; $V^g_{c.a}$ is volume of voids between grains of coarse aggregate; $\rho^b_{c.a}$ is bulk density of coarse aggregate; ρ_m is mortar density, kg/m^3.

For concrete with dense sand, its consumption can be found from condition of absolute volumes:

$$F_a = \rho_c - 1.15C - C_{p.a}, \qquad (9.8)$$

Where F_a, C, $C_{p.a}$ are correspondingly quantities of dense sand, cement and coarse porous aggregates, kg/m^3; ρ_c is density of concrete, kg/m^3.

9.3. Concrete on the basis of organic (wood) aggregates

Wood wastes without preliminary treatment (sawdust, chips) or after grinding (slips, hogged chips, wood wool) can be used as aggregates in building materials on the basis of mineral binders. These materials can be subsumed to lightweight concrete are characterized by low density (300-800 kg/m^3) and heat conductivity (0.093-0.23 W/(m°C)), and also sufficient workability. Biological resistance and hard combustibility of the materials on their basis of mineral binders is provided by impregnation wood aggregates by mineralizers and their subsequent mixing with mineral binders. Concrete with wood aggregates blemishes are high water absorption and comparatively low water resistance.

Concrete on the basis of organic aggregates as other types of concrete divides by application on heat insulating, structural-heat insulating and structural.

All types of mineral binders from which Portland cement is the basic one can be used in the composition with wood aggregates.

For reduction of harmful extractive materials quantity, initial product for wood aggregates production are seasoned in the storages for a certain time (soft wood – not less than 2 months, hard wood – 6 months).

At positive temperature seasoning reduces to 1 months at conditions of subsequent grinding of wood into chips. Hogged chips of soft and especially hard wood are necessary steeped in the water or solutions of mineral. The last ones neutralizing action of harmful substances in the wood and fasten cement hardening in the same time.

9.4. No-fines and aerated concrete

Both lightweight porous and ordinary heavy gravel and crushed stone aggregates are used for obtaining no-fines concrete. Along with other types of lightweight concrete no-fines concrete can be used as material for monolithic and precast wall structures and also for drainage systems and filters.

Strength of no-fines concrete depends both on quantity and strength of their cement content. Last one is defined basically by cement strength and water-cement ratio.

Optimal content of cement paste ($V_{c.p}$) in no-fines concrete can be found from the condition:

$$V_{c.p} = \delta S, \qquad (9.9)$$

Where δ is thickness of cement paste that film and glue aggregate's grains; S is total surface of aggregate's grains.

Fineness and gradation of the aggregate make influence on formation of structure and properties of no-fines concrete. Volume of voids between grains also depends on cement content.

Unlike no-fines concrete, aerated lightweight concrete has porous structure formed by component forming pores. By properties this type of lightweight concrete takes intermediate place between concrete of dense structure and cellular concrete. Forming pores of lightweight concrete mix permits to use heavier porous aggregate without density increasing, to reduce quantity or to refuse to use porous sand, to apply aggregate with gap grading. Raised viscosity and workability are characteristic for aerated concrete mixes.

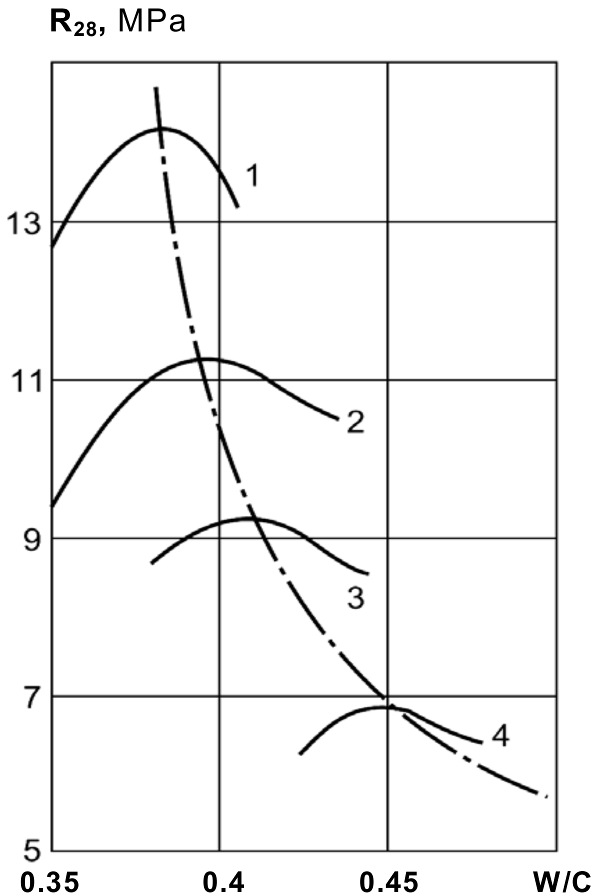


Fig. 9.3. Relationship between no-fines concrete strength at 28 day (R_{28}) and water-cement ratio (W/C):
1– concrete composition (cement: gravel by volume) 1:6;
2– idem 1:7; **3**– idem 1:8;
4– idem 1:10

Forming pores for concrete can be done by foam, gas or air-entraining admixture. Foam makes pores usually in no-aggregates concrete, air-entraining admixtures make pores in mixtures with sand, gas – both mixtures with and without sand.

9.5. Cellular concrete

Cellular concrete (gas concrete) has been suggested at first in 1889 by Czech researcher Hoffman which used for mortars effervescence carbon dioxide. In 1914 Owlswort and Dyer (USA) were issued the patent on application of aluminum and zinc powders to form hydrogen bubbles in cement stone, making principles of modern gas concrete technology.

Cellular concrete is manufactured from binder, silica component, gas formers or foaming agents and water. Both clinker and non-clinker (slag-alkaline and others) cements, lime, gypsum are binders for cellular concrete production.

Cellular concrete is referred to mostly effective materials for enclosing structures. At density 500-700 kg/m^3 they permit to reach strength 3-5 MPa at optimal structure. Basic factors of cellular concrete strength increasing at keeping their density are more high fineness of components grinding and their grading, thorough mixing, selection of optimal mixes compositions and curing regime.

Aluminum powder is most common gas former. Powder adding provides start of gas emission in alkaline environment after 1...2 min. Aluminum paste is used along with powder. Gas forming reaction proceeds in following way:

$$3Ca(OH)_2 + 2Al + 6H_2O \Leftrightarrow 3CaO \cdot Al_2O_3 \cdot 6H_2O + 3H_2 \uparrow$$

As the result of chemical reaction from 1 g of aluminum at normal conditions 1.254 litres of hydrogen is formed, at 50°C hydrogen volume is 1.48 litres.

As foaming agents there are used different surface-active agents (sulphite yeast, soap agent, etc.) and other substances, which at intensive mixing with water make stable foams.

Cellular concrete strength (R_c) correlates closely with its density (ρ_c). Practice for strength prediction of these materials there are used different empirical equations, for example:

$$R_c = A\rho_c^2, \qquad (9.10)$$

Where A is strength-density ratio, that can vary within wide limits. For autoclaved cellular concrete A≈10, for non-autoclaved cellular concrete A≈7,5...8,5.

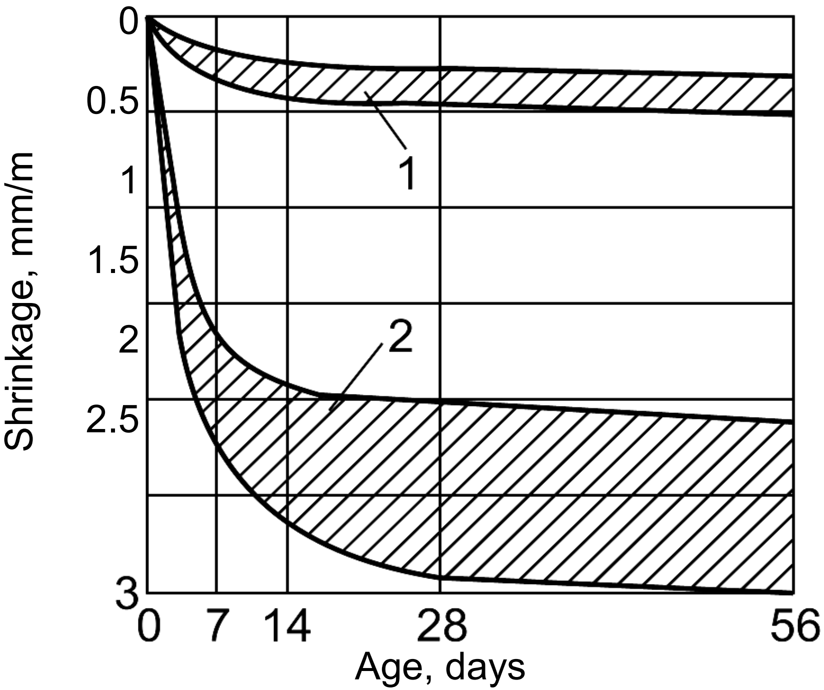


Fig. 9.4. Relationship between shrinking deformations of cellular concrete and age of hardening:
1 – autoclaved concrete;
2 – non-autoclaved concrete

Shrinking deformations of autoclaved cellular concrete made on the basis of cement and sand reach 0.5-0.7 mm/m and more, and for non-cement and non-autoclaved concrete 2 mm/m and more (Fig.9.4); swelling deformations depend on storage conditions and are 0.4-1.6 mm/m.

CHAPTER 10

CONCRETE ON THE BASIS OF NON-CLINKER BINDERS. MORTARS AND DRY PACK MIXES

L. Dvorkin and O.Dvorkin

Along with concrete on the basis of Portland cement and high-alumina cement there are used different concrete on the basis of other non-organic and organic binders in construction industry.

Mortars are composite heterogeneous materials which differ from concrete only by absence of coarse aggregate and poured as a rule on the basis with thin layer.

10.1. Silicate concrete

Unlike ordinary concrete, silicate concrete is produced on the basis of lime-sand binders of autoclave curing. The same classification by structural features and purposes as for ordinary concrete is appropriate for silicate concrete.

Extension of silicate materials started from 1880 when V.Michaelis has suggested silicate brick. Foundational idea of silicate materials obtaining is lime-sand composites hardening as a result of hydrosilicate synthesis at raised temperature and pressure of vapour.

Fine powder lime-sand binder that has as a rule high activity (25-35% of active CaO+MgO) can be substituted by lime-slag or fly ash binder with lower activity by content of active calcium and magnesium oxides (10-15%). At that lime content reduces in the mix approximately in 2-3 times.

Silicate concrete strength varies within wide range: from 5-10 MPa for lightweight concrete to 80-100 MPa for high-strength heavyweight concrete.

Dense silicate concrete strength at anhydrous lime application can be determined approximately by formula:

$$R_c = 4.05\left(\frac{S_{g.s}}{100} + \frac{1,6}{C/W - 1}\right) + 18, \qquad (10.1)$$

Where $S_{g.s.}$ is specific surface of sand, m^2/kg; C/W is cement-water ratio.

When hydrated lime is used:

$$R_c = 16\left(\frac{C_l}{W} - 1\right) + 14, \qquad (10.2)$$

Where C_l is lime-sand binder content, kg/m^3; W – quantity of water, kg/m^3.

Content of active calcium oxide in silicate concrete mixture varies depending on required concrete strength taking into consideration fineness modulus of sand (Tab.10.1, Fig.10.1, 10.2).

Table 10.1

Content of active CaO, % by mass of compacted silicate concrete mix

Strength of concrete, MPa	Sand			
	ultra fine	fine	medium	coarse
15	6.5	6.2	6	5.8
25	7.5	7.2	7	6.5
30	9	8.5	8	7.5
40	10.5	9.5	8.5	8

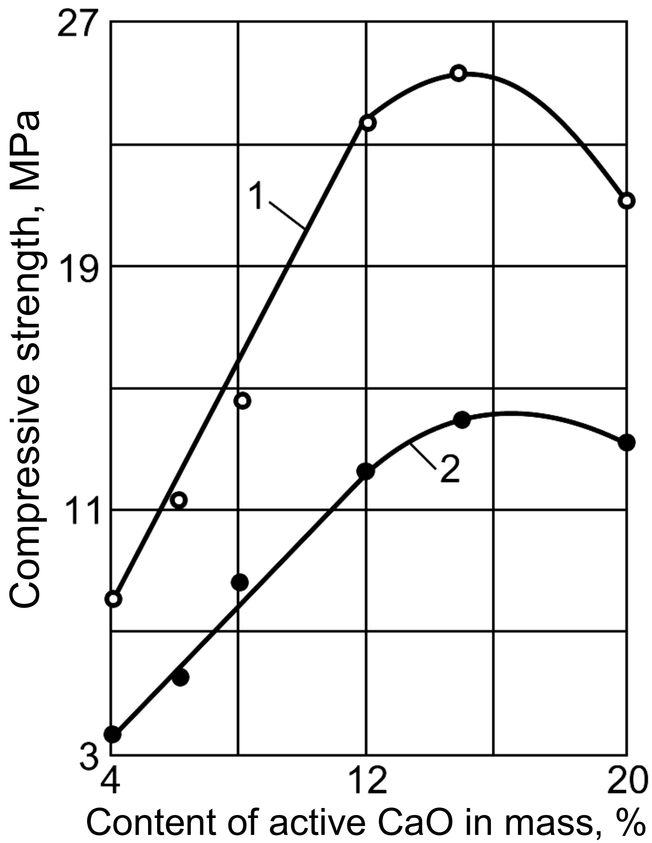


Fig. 10.1. Effect of active CaO in the mixture on compressive strength of lime-sand specimens:

1 – on the basis of quartz sand;
2 – on the basis of feldspar sand.

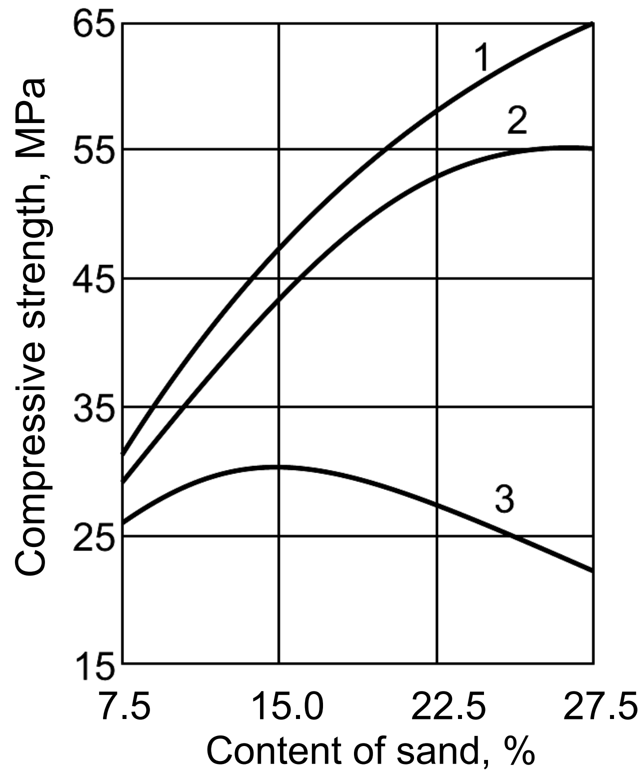


Fig. 10.2. Relationship between silicate concrete strength and sand content with specific surface:

1 - 4500 cm^2/g; **2** - 2500 cm^2/g;
3 - 1500 cm^2/g.
Content of active CaO in the mixture is 12.5%

10.2. Slag and fly-ash concrete

Concrete on the basis of lime-slag and lime-ash binders, gypsum-slag, sulfate slag and slag non-clinker cements can be classified as such concrete. Slag-alkaline concrete can be referred to a separate group.

Chemical activity of slag is defined by quality coefficient К, calculated according to following formulas:

- at magnesium oxide (MgO) content up to 10%

$$К = \frac{CaO + Al_2O_3 + MgO}{SiO_2 + TiO_2}, \qquad (10.3)$$

- at magnesium oxide (MgO) content more 10%

$$К = \frac{CaO + Al_2O_3 + 10}{SiO_2 + TiO_2 + (MgO - 10)}. \qquad (10.4)$$

Ash is divided on high-calcium ($CaO > 20\%$) and low-calcium ($CaO < 20\%$). Crystalline phases are prevalent for the first one, and glass and amorphous-like clay material is dominant for the second one. High-calcium ash can be divided on low- sulfate ($SO_3 < 5\%$), obtained by coal and peat burning and sulfate ($SO_3 > 5\%$) obtained by shale's burning.

Slags and ash acquire ability to harden at alkaline, line, sulfate and combined types of activation. Slag and fly ash materials with different intensity harden in normal conditions and at steam curing depending on their mineralogical composition, chemical composition and active phases content, fineness, type and concentration of activator.

As activators of slag and fly-ash binders are used anhydrous lime, calcium sulphate hydrate or hemihydrate are used. Application of hydrated lime gives worse results than lump quicklime.

Cellular, fine-grained, light-weight and heavy-weight concrete are manufactured on the basis of slag and fly ash binders. Comparatively high quality of these materials is obtained at steam curing.

10.3. Slag- alkaline concrete

Concretes for which common feature is slag-alkaline binders application are included into group of slag-alkaline concrete. Fundamentals of theory and technology of National University of Construction and Architecture (Kiev, Ukraine) have been worked out by V. Glukhovsky.

Approximate composition of heavy-weight concrete, %: ground granulated slag - 15...30; alkaline component – 0.5...1.5; aggregates - 70...85.

Physical and mechanical properties of slag-alkaline concrete can vary with wide range by selecting raw materials, varying concrete mix composition and applying different technological processes. Parameters of the most of these type concrete properties are close to parameters of cement concrete and in some instances they can be appreciably higher.

Until present almost forty years experience is gathered in application of slag-alkaline concrete in construction industry. There is shown effectiveness of production of wide range constructions, assigned for service in different including hard conditions.

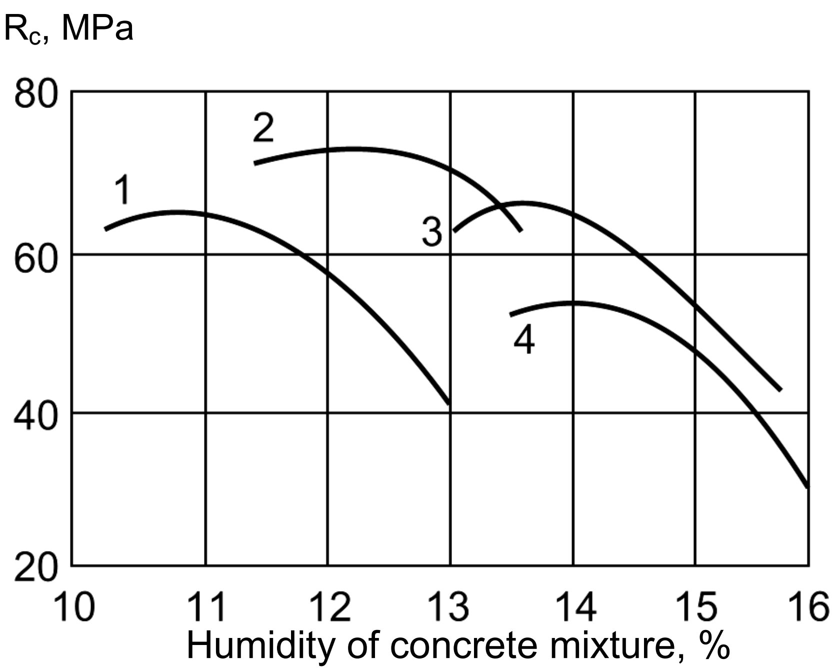


Fig. 10.3. Relationship between slag alkaline concrete compressive strength (R_c), humidity of mixture and weight part of clayey particles in the aggregate:

1 – weight part of clayey particles in the aggregate 1.2 %; **2** – idem 5.2 %; **3** – idem 6.4 %; **4** – idem 8.8 % (according to G.Skurchinskaya data)

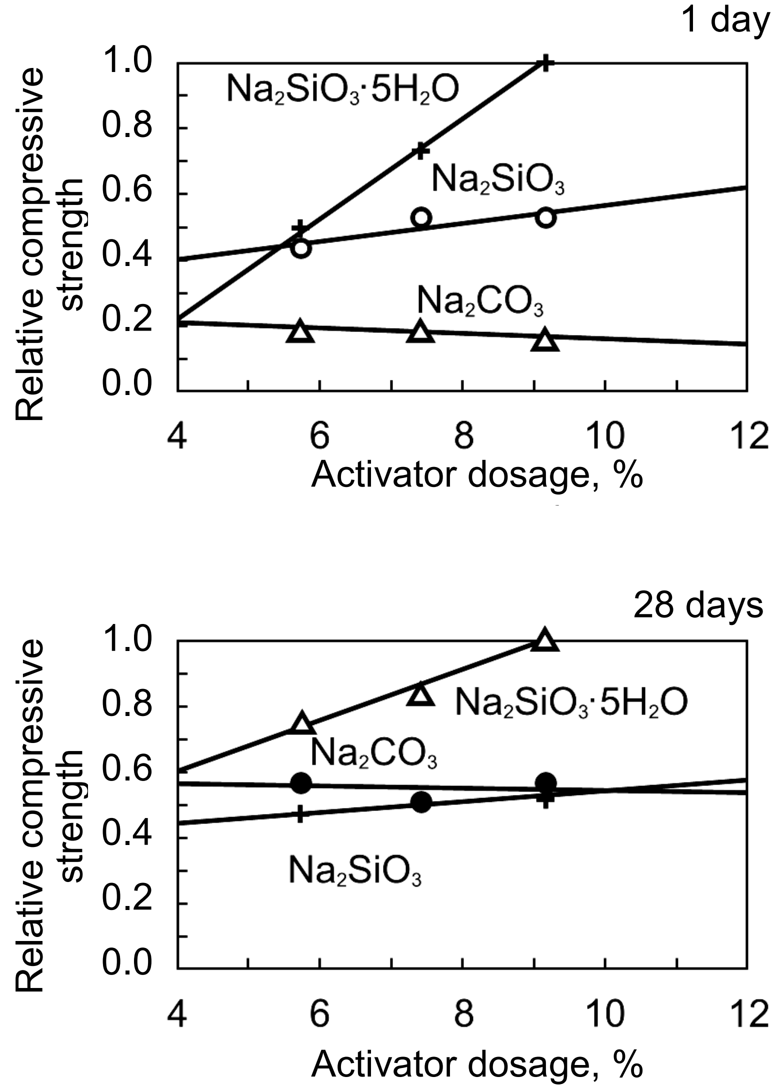


Fig.10.4. Relative strength of alkaline slag binder depending on type and content of activator (from I.Blackmeyer data)

10.4. Gypsum concrete

Gypsum concrete is concrete produced on the basis of gypsum binders. Building blocks, masonry blocks, panels, assigned particularly for internal walls and crosswalls are produced from gypsum concrete. Application area of such concrete is limited mostly because of their insufficient water resistance.

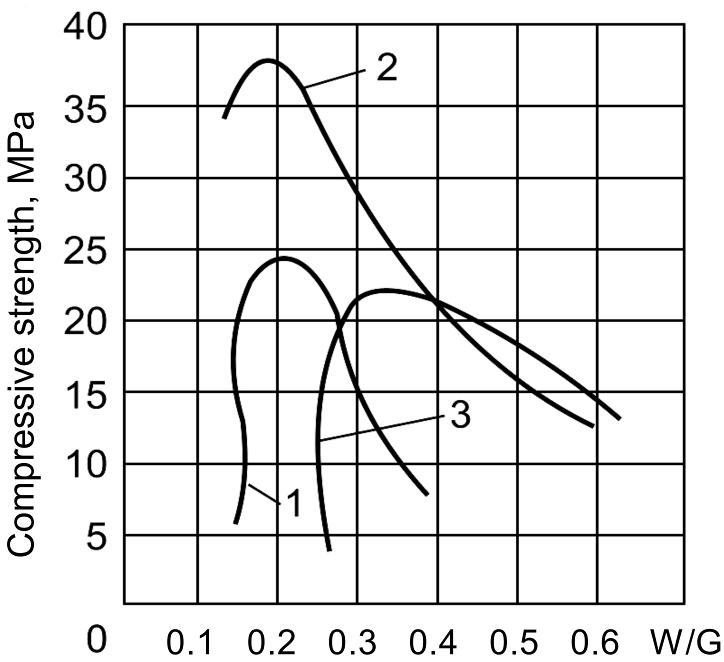


Fig.10.5. Influence of water-gypsum ratio (W/G) on gypsum strength:

2- α- hemihydrate gypsum;
1, 3 - β- hemihydrate gypsum.

According to data obtained by A.Volgensky and A.Ferronskaya, the effect of water-gypsum ratio (W/G) on gypsum concrete strength is similar to effect of water-cement ratio on cement concrete strength (Fig.10.5).

Water-gypsum ratio depends on gypsum binder type, temperature of mixing water and method of forming of elements.

There are obtained concrete with strength 5-10 MPa on the basis of gypsum binder. Application of high-strength gypsum, anhydrous gypsum and estrich gypsum permits to increase strength up to 20 MPa. Concrete strength at application of composite gypsum-cement-pozzolanic and gypsum-slag-cement-pozzolanic binders on the basis of alabaster is 7.5-20 MPa, on the basis of alpha gypsum is 15-40 MPa.

Quality and nature of aggregates make significant influence on strength of gypsum concrete.

10.5 Mortars

Lime, gypsum, cement and composite (cement-lime, cement-clay) mortars are the most common in construction.

Basic properties of mortars are workability and water-retaining capacity. Providing of required workability of mortar mixtures without segregation can be reached by adding of plastizing admixtures and fillers.

Water-retaining capacity prevents segregation of mortar mixture. In view there, are reduced water-binder ratio (due to right proportion), ultra-fine mineral fillers, plastizing and special water-retaining admixtures.

For strength forecasting of cement-lime mortars are widely used N.Popov formula. At pouring on dense basement, mortars strength (R_m) is calculated by formula:

$$R_m=0.25R_{cem}(C/W-0.4), \qquad (10.5)$$

Where R_{cem} – strength of cement, MPa; C/W – cement-water ratio.

At water drawoff by porous base in the mortars with different C/W, strength of mortars (R_m) can be calculated as follows:

$$R_m=KR_{cem}(C-0.05)+4, \qquad (10.6)$$

where К - coefficient of sand quality: for coarse sand К=2.2; medium sand К=1.8; fine sand К=1.4; C - cement content.

Composites of mortars are selected by tables or calculation and specified by experimental way in the context of specific materials.

Strength increase of masonry mortars at cold-weather construction can be provided by adding of a series of chemical admixture.

10.6 Dry pack mixes

Modern construction industry is characterized by more wide application of dry pack mixes, accurately batched and mixed in plant conditions mortars and concrete mixes, with adding water at building site.

At construction work effectiveness of dry pack mixes is demonstrated in high level of mechanization, significant reduction of construction terms, decreasing labour content and working costs, providing high quality.

Dry pack mixes are classified by:
- main purpose (type of work);
- type of binder in the mixture;
- modification level of the mixture by admixtures;
- the most significant feature in hardened state;
- conditions of application.

There are identified different mixes by purpose: masonry, facing, jointing, stopping, plastering, gluing, sealing mixes etc.; by type of basic binder – gypsum, anhydrate, lime, magnesium, cement, cement-lime, polymer etc.; by modification level – cost-effective, standard, high-quality; by characteristic feature in hardened state - adhesive, weather-proof, fast-hardening, waterproof, frostproof, high-strength, self-leveling, elastic etc.; by application conditions – hand and machine coating, for porous materials etc.

The same mix can be often used at different construction.

Adjustment of technological and performance properties of dry pack mixes is reached by adding different chemical admixtures

Thickening, dispersing, foaming, defoaming, water-repelling, conservative agents etc. are included into the complex of special chemical admixtures.