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Material structures of cement-based composites

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1. Introduction

The term "structure of a material" covers the distribution of its particular components in space and the set of relations between them that are characteristic for the whole structure. The characterization of a material structure is also completed by description of the properties of the components.

The description of material structure may be based either on assumptions related to an idealized perfect structure or on an analysis of a real structure. In most cases, both approaches are considered and their results are combined. The differences between these two approaches are caused by deviations from ideal models and by local imperfections. For example, the homogeneity of a material is often assumed as an approximation at a given level of analysis and when a material at corresponding lower level is considered then its heterogeneous nature becomes obvious. When the models of materials at various levels of dimensions are built, they are interrelated in a systematic way, or more precisely, the models on a considered level are deduced from the results observed at a lower level. It should be noted that all composite materials, including concrete, are heterogeneous by definition.

There is no one generally accepted classification of composites according to their structures. Composites used for construction may be described in terms of the matrix that is a continuous phase, and inclusions – which are embedded in the matrix. Usually, the structures composed of inclusions strengthen the matrix (reinforcing inclusions), but also fillers of low strength are used to enhance other properties e.g., thermal insulation, lower weight, etc. Special fillers may improve wear resistance or protection against fire.

The composites may be classified according to their internal structure, and to the type of inclusions and their dispersion in the matrix, e.g.:

- composites with dispersed phase composed of very small particles (10 nm÷100 μm),
- particulate composites with dispersed grains of larger size (100 μm÷50 mm),
- fibrous composites with dispersed fibres of various dimensions and materials,
- laminate composites, composed of layers made of various materials, stacked at different sequence.

Structure-property relations of materials describe the way in which a change in some structural feature of a material affects its properties. It appears that most of material properties depend on material structure and their values vary considerably with changes in certain structural variables. These so-called structure-sensitive properties are for example strength, Young modulus, permeability, etc. Among the independent ones is the density: for the density the so-called law of mixtures is valid. For all other properties, the law of mixtures is only an approximation, however frequently used with appropriate correcting coefficients.

The understanding of the relations between the structure and properties of material is a basis for material engineering. The necessary elements of the design of materials are: selection of components with their characteristic properties and decision of their volume or mass proportions. The rational distribution of inclusions in space and their reciprocal actions should be also determined, e.g chemical affinity or mechanical bond.

The paper presents a survey of the structures of cement-based composites. Structure determines the final material properties. The analysis of structure of a hardened concrete is the basic approach to satisfy the requirements for Quality Assurance and Quality Control of civil engineering structures made of ordinary and high performance concretes, including fibre reinforced concretes. The holistic approach to that subject was suggested by Mehta already in 1994 by following words:

> *The most serious problem in concrete technology today is the premature deterioration of concrete structures that are subjected to harsh environments. There is overwhelming evidence from field experience that many of the durability problems, such as sulfate attack, carbonation, alkali-silica reaction, and corrosion of reinforcing steel in concrete would not have occurred had the concrete been impermeable during the intended service life. Therefore, to address the durability related issues in selecting materials, mix proportions and construction practice for concrete, we must develop new, comprehensive models on concrete deterioration show-*

ing the effect of environmental influences on the permeability of concrete, cf. Mehta (1994).

In the paper the traditional reinforcing steel and FRP bars and tendons are not considered as components of the material structures.

2. Structure of concretes

The structures of concretes are considered at different levels that are conventionally defined as follows:

- molecular level in which atomic bonds are considered, the characteristic dimensions are of the order of 10^{-10}–10^{-12} ($10^{-10}\,\mathrm{m} = 0.1\,\mathrm{nm} = 1\,\text{Å}$);
- at the micro-level, the structure of hardened cement paste is treated (distribution of ions, atoms, particles, microdefects), in which single crystals may be observed with dimensions of the order of $1\,\mu\mathrm{m} = 10^{-6}\,\mathrm{m}$;
- at the mezo-level, the main characteristics are big pores, cracks and inclusions that mesure about $1\,\mathrm{mm} = 10^{-3}\,\mathrm{m}$;
- at the macro-level, concrete is treated as a continuum and homogeneous medium and the smallest characteristic dimensions are between 10^{-3} and $10^{-2}\,\mathrm{m}$.

Observations and measurements are frequently conducted at intermediary levels. The selection of an appropriate level for consideration and observation of the structure of a given concrete-like composite is important for the results and depends considerably on the aims of investigation. At every level, different objects appear and different processes may be observed while other cannot be recognized and are neglected. Moreover, without entering to lower levels, certain phenomena are difficult to be explained and modelled.

The following components of the structure of concrete may be distinguished:

- hardened cement paste, including various admixtures and additives that influence its various properties,
- aggregate grains of different origin and dimensions, also all kinds of micro-fillers,
- pores and voids, either pores due to evaporated water and systems of pores entrained by special air-entraining agents or caused by entrapped air during casting and mixing,
- reinforcement of all kinds: steel or FRP bars, tendons and cables, randomly or regularly distributed short and long fibres, micro-fibres, grids and mats,

- cracks and flaws due to various reasons and created during hydration processes, later by hardening, exploitation and exposure to varying temperature and moisture.

These components are described more in detail in subsequent Sections.

Special category of components are also interface contact zones and various kinds of interfaces (ITZ – interface transition zone):

- between aggregate grain and cement paste,
- between reinforcement (fibres, mats, etc.) and cement paste,
- between old and new concrete (repair and retrofiting).

3. Cement paste

The structure of hardened cement paste is created after the transition from a fluid to a rigid material. That is a continuous process resulting from progressive hydration of cement components. The approximate composition of the hardened cement paste is shown in Table 1 and the components indicated in the first column may be recognized in well-known images of the structure of hardened cement paste.

TABLE 1. Approximate composition of cement paste (w/c = 0.5), after Young (1985), Young et al (1998).

Component	Volume percent (appr.)	Remarks
C-S-H $CaO.SiO_2.1.7H_2O$	55	Continuous matrix, highly intrinsic microporosity
CH $Ca(OH)_2$	20	Large crystals (0.01÷1.0 mm)
Calcium sulfoaluminate hydrates	10	Small crystals (1÷10μm)
Capillary porosity	15	Depends on the amount of water (w/c)

When concrete is analysed between the micro- and mezo-levels, the hardened cement paste is treated as a continuous homogeneous matrix in which there are structures of inclusions. These inclusions are the grains of fine and coarse aggregate, nonhydrated cement grains, voids of various nature like pores and cracks, different forms of reinforcement and micro-reinforcement. Voids are partly or totally filled with water, air or other gases.

The structure of the microcracks that develops in the hardened cement paste is caused by hydration shrinkage and thermal and single microcracks are normally less than 10 μm wide. The microcracks may be observed and recorded in specially prepared concrete specimens – so-called thin sections. In plane sections analysed in reflective light the quantification of microcracks presents serious difficulties, but their overall pattern and connectivity may be determined, provided that the specimens are specially prepared.

4. Structures made with inclusions – grains of aggregate and small particles

In the continuous matrix made with the hardened cement paste the grains of aggregate of different origin are considered as inclusions. Between large grains there are packed small grains and particles of various micro-fillers. A few kinds of small particles are presented in Table 2 showing how many single particles are packed in 1 cm^3. Nonhydrated Portland cement grains belong also to the category of hard inclusions. The role of various small particles (micro-fillers) is to fill spaces between grains of sand, to create a rigid structure of concrete, to improve concrete density and impermeability and to increase its strength. It is to be mentioned that fine particles influence

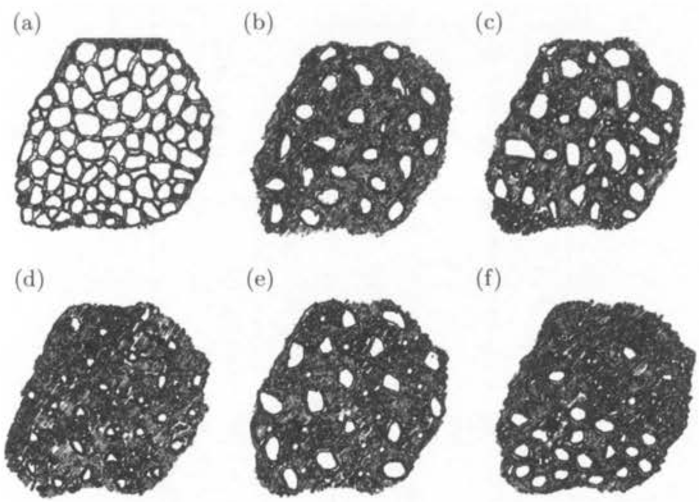

FIGURE 1. Examples of the aggregate grain structures; (a) similar size grains, large volume fraction of voids, only partly filled with matrix, (b) more paste and also lack of smaller grains, (c) continuous distribution of grains, most of concretes are designed to obtain such a structure, (d) structure without the biggest grains, (e) no intermediary size grains, so-called "gap-grading", (f) segregation of grains and upper part is rather a mortar; after Brandt (1995).

Table 2. Small particles in concrete.

Component	*Average diameter* [μm]	**Specific surface**	**Volume of one particle**	**Mass of one particle**	**Numbers of particles in 1 cm^3 of concrete** (for following mass of the component)		
Diameter [μm]	**Density** [g/m^3]	[m^2/kg]	[mm^3]	[g]	[400kg/m^3]	[40kg/m^3]	[120kg/m^3]
Portland cement	*50*	250÷450	$6.5 \cdot 10^{-5}$	$2.03 \cdot 10^{-7}$	1970 000	NA	NA
1÷100	3.1						
Fly ash	*45*	130÷230	$4.8 \cdot 10^{-5}$	$1.10 \cdot 10^{-7}$	NA	1090 000	360 000
1÷150	2.3						
Silica fume	*0.2*	18000÷24000	$4.2 \cdot 10^{-12}$	$9.30 \cdot 10^{-15}$	NA	$12.9 \cdot 10^{12}$	$4.3 \cdot 10^{12}$
0.1÷0.3	2.2						

NA – not applicable

considerably the rheological properties of the concrete mix and application of chemical admixtures may be necessary to maintain appropriate workability.

Grains of aggregate form so-called "concrete skeleton". The grain size distribution is carefully designed and experimentally checked for concretes of good quality. However, also their distribution should be homogeneous, otherwise regions with voids between aggregate grains or regions without paste are the weak points and the origins of future cracks and local destructions.

Examples of the aggregate grain structures are shown in Fig. 1, each of them is a result either of special design and selected grading or of incorrect preparation and execution of the concrete.

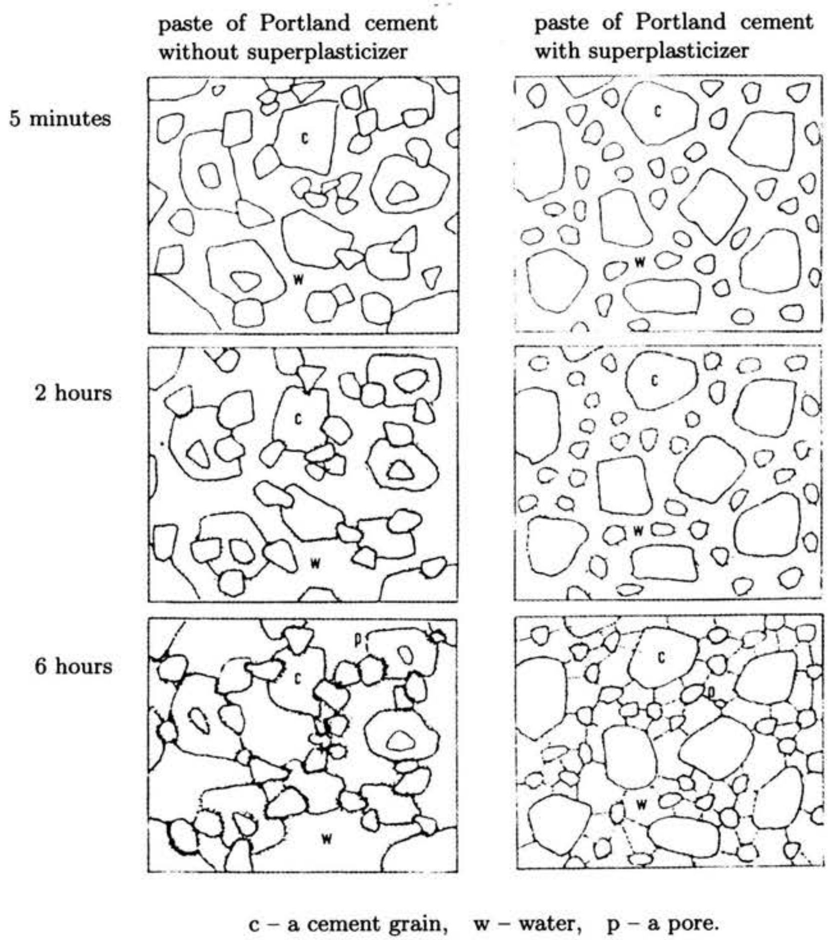

FIGURE 2. Defloculation of cement grains due to action of a superplasticizer; after Uchikawa (1986).

The composition of coarse and fine aggregate grains, completed if necessary by micro-fillers, should be carefully designed to obtain a densely packed structure, e.g., following the "Fuller curves concept". In such a composition, low paste content is needed to ensure appropriate workability of the concrete mix with low water/cement ratio (w/c). In most cases, for high quality concretes, it is necessary to use superplaticizers for better workability.

The action of a superplasticizer on a structure of cement particles during hydration is schematically shown in Fig. 2. After 5 minutes, 2 and 6 hours the hydration advances with a strong tendency of cement particles to join each other due to their electric charges (left side). When a superplasticiser is added to the mix (right side), then repulsion between the particles results in their defloculation and dispersion that is stabilized during hardening. The final structure of cement particles in these two cases is different. The mechanisms of the defloculation of cement grains by superplasticizers are described and explained by several authors, cf. Kucharska (2000).

The aggregate grains as element of the concrete skeleton are characterized by their shape, surface texture, porosity, strength, frost resistance, etc.

It is possible to recognize different kinds of the grain structure on correctly prepared plain cross-sections of concrete specimens, cores or elements. The preparation and analysis of the plain sections (both qualitatively and quantitatively) are described elsewhere, e.g. Kasperkiewicz and Załocha (2002).

The structure composed of grains may be modified at the stage of a fluid mix by impenetrable boundaries; this is called "wall effect". This phenomenon is observed at various levels: structure of coarse aggregate grains may be

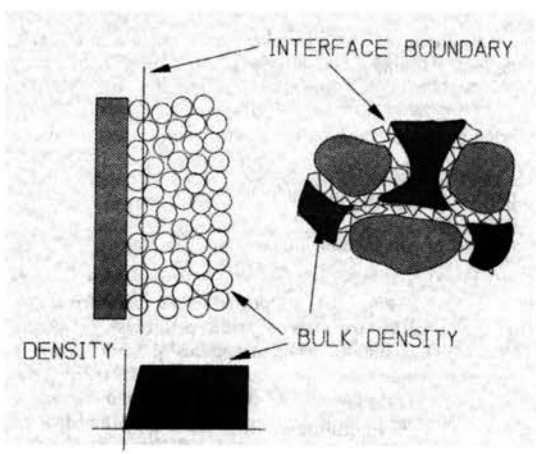

FIGURE 3. Schematic presentation of the wall effect; after Johansen and Andersen (1991).

modified by the sides of a formwork; small grains and particles during mixing and various stages of compaction processes encounter surfaces of the larger ones. Also surface of reinforcing bars plays a role of a boundary. Main result of the wall effect is lower density of packing, cf. Fig. 3.

Important problems are related to the structure formed with coarse aggregate grains that produce high stress concentrations. It has been experimentally shown by Dantu already in 1957 that effective local stresses at the tips of large aggregate grains are much higher than mean values of the stresses calculated from formulae, based on simplified assumptions concerning stress distribution. In Figs. 4 and 5 the results of these experiments are

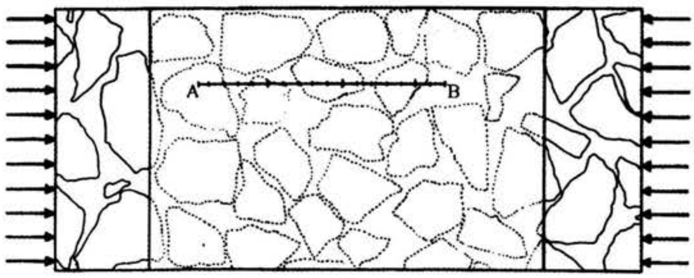

FIGURE 4. Structure of large aggregate grains analysed by photoelasticity (the measures were performed along the indicated line AB); after Dantu (1957).

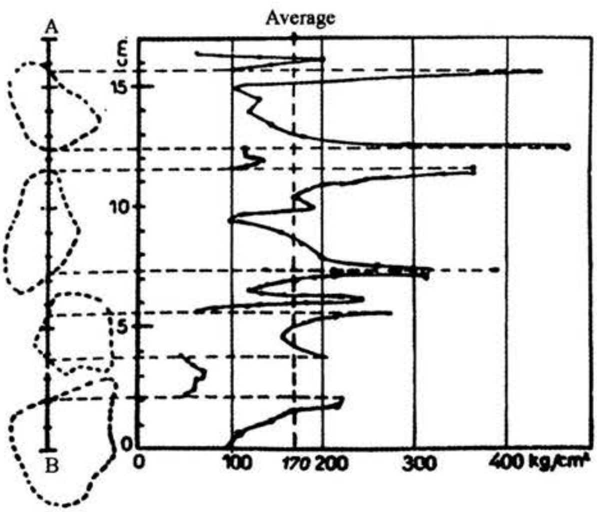

FIGURE 5. Stress concentrations produced by the structure of hard aggregate grains in the hardened concrete; after Dantu (1957).

summarized. It is to be mentioned that all cracks and microcracks are initiated by stress concentrations of various origin. Therefore, structure of coarse aggregate grains may determine initiation of fracture processes of concrete elements. That is the reason that for High Performance Concretes usually small diameter grains are used.

Specimens made of concretes with the same compressive strength but using different kinds of aggregates and inclusions were tested by Glinicki (1992). It has been shown that the internal structure influenced considerably the behaviour of these specimens.

5. Structures of pores and voids

There are various kinds of pores in concretes and they are classified according to their origin and size, Table 3.

Scheme of a pore-size distribution curve in Portland cement concrete is shown in Fig. 6.

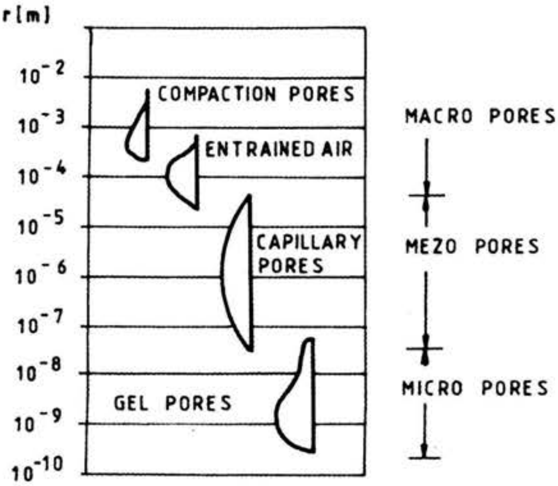

FIGURE 6. Pore-size distribution in ordinary PC concrete; after CEB (1989).

In the hydrated paste there are two distinct classes of pores: gel pores in interstitial spaces and capillar pores. They are different by their dimension and origin. The gel pores form a part of CSH (calcium silicate hydrate) and are much smaller than the capillary ones and their characteristic dimension is between 1 and 2 nm. They are too small to be filled by the hydration products and for capillary effects. The gel pores occupy up to 55% of the total volume of gel, this is related to the quality of cement and basically

TABLE 3. Pores in cement paste.

Classification	Size	Methods of analysis	Origins	Importance
Large pores	$> 500\,\mu$m	Optical microscopy	Air entrainment, entrapped air, inadequate consolidation or curing, excessive mix water	Limit strength
Air-entrained pores	$< 500\,\mu$m	Optical microscopy	Air entrainment	Slightly lower strength, improved frost resistance
Capillary pores:				
Macropores	> 50 nm	Mercury porosimetry	Remnants of water-filled space in fresh paste	Control permeability and durability
Mesopores	$2.5 \div 50$ nm	Mercury porosimetry, gas adsorption-desorption	Remnants of water-filled space, smaller pores associated with C-S-H	Capillary effects create stresses during drying
Micropores	< 2.5 nm	Gas adsorption-desorption	Associated with C-S-H	Disjoining effects may occur during wetting and drying

independent of the w/c ratio and of the level of hydration. They are not active in water permeating through cement paste and they do not influence the concrete strength, but are decisive for shrinkage and creep.

Capillary pores are partly filled with water that was not used for hydration processes and their volume is directly related to the w/c ratio and gradually decreases with hydration progress. They are interconnected and their influence on concrete permeability and durability is decisive.

Three examples of pore structures in cement paste are shown in Fig. 7, they are different as to their connectivity and ability of water permeability and capillarity.

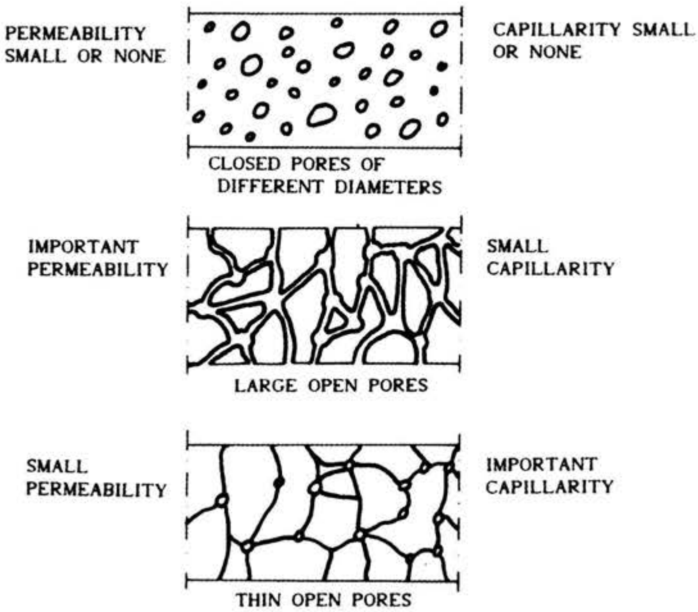

FIGURE 7. Examples of pore structures, their permeability and capillarity; after Venuat (1984).

The pore size distribution, i.e. cumulative pore volume vs. pore radius curve in Portland cement pastes can be measured using mercury intrusion porosimetry (MIP). The results may be influenced by the applied pressure and are obtained on small specimens. Other methods for the determination of pore structure and their distribution are also available.

The use of various kinds of micro-fillers results in refinement of the pore structure and therefore in reduction of the long-term concrete permeability. The application of binary and ternary blended cement is justified by creation microstructures better adapted to the purpose.

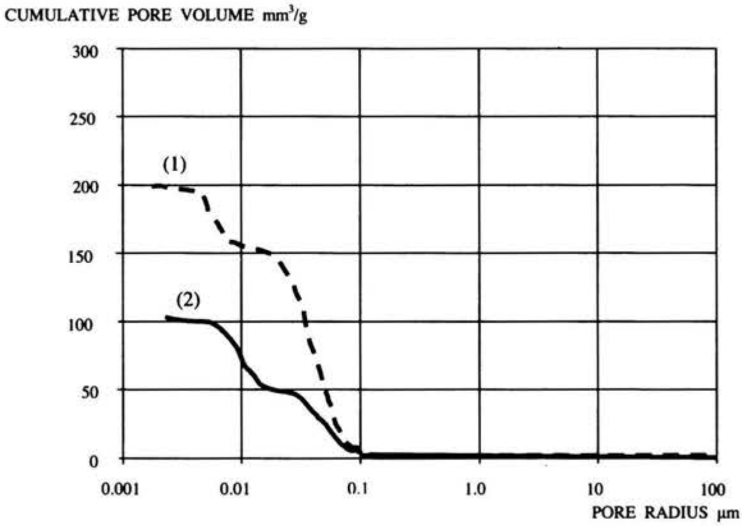

FIGURE 8. Pore size distribution in two concretes: (1) with pure Portland cement and w/c = 0.5; (2) with 55% replacement of Portland cement by (GGBS); after Wee et al. (1999).

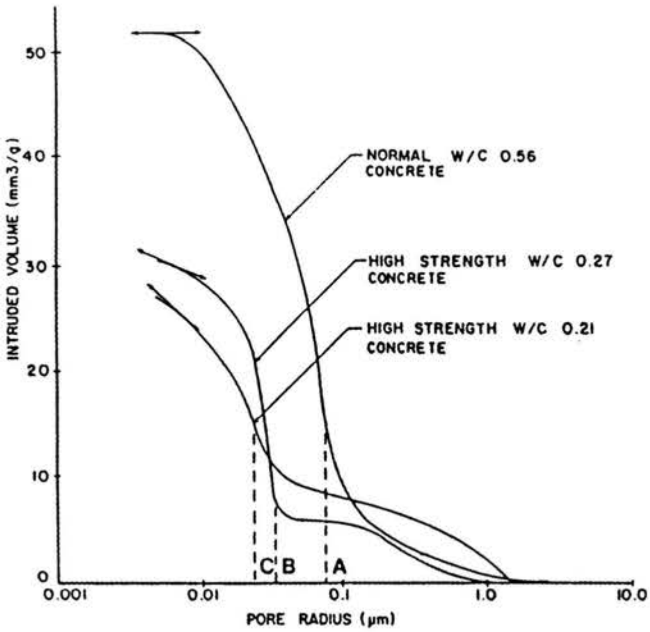

FIGURE 9. Pore size distribution curves of two High Performance Concretes in comparison with a normal (ordinary) concrete; after Moranville-Regourd (1992).

TABLE 4. Pore volume of hardened cement paste, mortar and concrete.

age			Similar workability						Constant water cement ratio								Measuring method
			Paste		Mortar S/C = 2		Concrete		Paste		Mortar S/C = 0.9		Concrete AE		Concrete Plaine		
		W/C =	0.30		0.55		0.60		0.50		0.50		0.50		0.50		
			**	***	**	***	**	***	**	***	**	***	**	***	**	***	****
7 days	Total pore volume	1 nm – 10 mm	27.4	27.4	29.0	54.5	19.1	61.1	40.6	40.6	28.0	40.0	18.7	65.8	14.6	51.4	1+2+3+4
	Gel pore space	1 – 3 nm	7.5	7.5	4.1	7.7	3.1	9.9	11.9	11.9	4.0	5.7	2.0	7.0	2.1	7.4	1
	Capillary	3 – 5 nm	4.6	4.6	2.4	4.5	0.6	2.0	4.6	4.6	1.5	2.1	0.5	1.8	1.1	3.9	2
	Water pore space	5 – 50 nm	10.4	10.4	9.3	17.5	4.7	15.0	15.8	15.8	10.9	15.6	4.3	15.1	4.2	14.8	
	Void	50 – 100 nm	0.8	0.8	3.6	6.9	1.6	5.1	3.0	3.0	4.9	7.0	1.9	6.7	1.5	5.3	
		100 nm – 2 μm	1.9	1.9	8.1	15.2	7.8	24.9	4.9	4.9	6.3	9.0	5.8	20.4	4.2	14.9	
		3 nm – 2 μm	17.7	17.7	23.4	44.1	14.7	47.0	28.3	28.3	23.6	33.7	12.5	44.0	11.0	38.7	
	Sum of water void	1 nm – 2 μm	25.2	25.2	27.5	51.8	17.8	56.9	40.2	40.2	27.6	39.4	14.5	51.0	13.1	46.1	1+2
	Air void	30 μm – 1 mm	1.7	1.7	0.6	1.1	0.4	1.3	0.4	0.4	0.4	0.6	*2.1	*7.4	0.4	1.4	3
	(Entrapped air)	1 – 10 mm	0.5	0.5	0.9	1.6	0.9	2.9	0	0	0	0	2.1	7.4	1.1	3.9	4
	Sum of air void	30 μm – 10 mm	2.2	2.2	1.5	2.7	1.3	4.2	0.4	0.4	0.4	0.6	4.2	14.8	1.5	5.3	3+4
28 days	Total pore volume	1 nm – 10 mm	24.2	24.2	26.0	47.9	19.2	61.3	37.5	37.5	23.0	32.3	20.4	71.7	15.9	56.0	1+2+3+4
	Gel pore space	1 – 3 nm	8.2	8.2	7.1	13.4	4.6	14.7	14.7	14.7	5.4	7.7	4.1	14.4	3.9	13.7	1
	Capillary	3 – 5 nm	2.8	2.8	3.6	6.7	0.8	2.6	5.8	5.8	3.7	5.3	1.5	5.2	1.3	4.6	2
	Water pore space	5 – 50 nm	10.0	10.0	5.8	11.0	5.6	17.8	15.6	15.6	8.8	12.6	4.7	16.5	4.1	14.4	
	Void	50 – 100 nm	0.3	0.3	1.3	2.5	1.6	5.1	0.2	0.2	1.4	2.0	0.7	2.5	0.8	2.8	
		100 nm – 2 μm	0.7	0.7	6.7	12.6	5.3	16.9	0.8	0.8	3.3	4.7	5.2	18.3	4.3	15.2	
		3 nm – 2 μm	13.8	13.8	17.4	32.8	13.3	42.4	22.4	22.4	17.2	24.6	12.1	42.5	10.5	37.0	
	Sum of water void	1 nm – 2 μm	22.0	22.0	24.5	46.2	17.9	57.1	37.1	37.1	22.6	32.3	16.2	56.9	14.4	50.7	1+2
	Air void	30 μm – 1 mm	1.7	1.7	0.6	1.1	0.4	1.3	0.4	0.4	0.4	0.6	*2.1	*7.4	0.4	1.4	3
	(Entrapped air)	1 – 10 mm	0.5	0.5	0.9	1.6	0.9	2.9	0	0	0	0	2.1	7.4	1.1	3.9	4
	Sum of air void	30 μm – 10 mm	2.2	2.2	1.5	2.7	1.3	4.2	0.4	0.4	0.4	0.6	4.2	14.8	1.5	5.3	3+4

W/C – Water cement ratio, S/C – Sand cement ratio, * Volume of entrained air, ** Pore volume per volume of hardened cement paste, mortar and concrete (volume %), *** Pore volume per volume of paste part of hardened cement paste, mortar and concrete (volume %), **** Measuring methods: 1 – Measured by N_2 adsorption-desorption method, 2 – Measured by mercury intrusion porosimetry, 3 – Measured by optical microscopy and image processing, 4 – Measured by X-ray computed tomography and image processing.

In particular, use of silica fume, fly ash and other micro-fillers allows to obtain a very small average capillary pore size and to enhance the durability of concrete elements.

The pore structure in hardened concrete may be also modified by addition of ground granulated blast-furnace slag (GGBS): the cumulative pore volume is decreased as well as the average pore diameter, leading to a denser microstructure. In Figs. 8 and 9 examples of the pore size distribution in cement paste characteristic for ordinary and High Performance Concretes are shown. The mean size of pore system and their total content depends mainly on water to binder ratio.

In Table 4 taken from Uchikawa (1988), examples of various pore structure characteristics for different concretes are presented. It is interesting to observe what percentage of total void volume is occupied by different categories of pores in concretes of w/c varying from 0.3 up to 0.5, with and without air entrainement.

The resistance of concrete against cyclic freezing and thawing in winter season is considerably improved when a structure of air voids (air bubbles) is formed during mixing, uniformly distributed and maintained in the hardened state. A special admixture called air entrainer is necessary for that aim and is added during mixing of concrete components. The effective air void structure in hardened cement matrix is described by:

- total air content, usually between 4 and 7%, depending on the aggregate grain diamete;
- spacing factor that expresses the mean distance from a given point in the cement paste to the nearest free surface of an air void, below 0.2 or 0.22 mm;
- specific surface of air voids, over 15 or 20 mm^2/mm^3;
- percentage of pores smaller than 0.3 mm, so-called A_{300}, over 1.5 or 1.8%.

The spacing factor is low when the total air content is sufficiently high and single air bubbles are small and uniformly dispersed in the matrix. Pores $> 5\,\mu m$ are recognized using optical microscopy on specially prepared cross-sections, counted and recorded manually or using computer image analysis procedure, in both cases basing on ASTM C 457. For various conditions of exploitation, different limits are imposed on these parameters. The technique of measurement and discussion of results are described elsewhere.

6. ITZ – Interfacial Transition Zones

The question is whether the interface between cement paste and aggregate grains may be considered as a special phase in the concrete. Since over 40 years many researchers are of that opinion, cf. MRS (1995). Some doubts are however based on more recent investigations, e.g., Diamond and Huang (1998) who obtained SEM images of the layers 10 μm thick around the grains and performed their quantitative analysis considering distance from the grain.

There are multiple reasons that zones around aggregate grains are different from the bulk hardened paste. These are among the others:

- wall effect, it means different arrangement of small particles and voids in the neighbourhood of quasi impenetrable surface of an aggregate grain, (cf. Fig. 3),
- vibration of the grain during compacting of the fresh mix,
- different flow of water in the regions close to the grains.

Whether material in ITZ is different from bulk matrix and to what extent in various kinds of concrete – that is the question for which different authors offer slightly different answers. According to a more traditional viewpoint every grain is surrounded by a kind of a shell made with cement paste of basically different composition and properties: it is more porous and less strong. The properties of the ITZ are functions of distance from the grain surface and the depth of ITZ may reach approximately 40-60 μm.

According to Diamond and Huang (1998) ITZ is characterized by:

- higher contents of pore space,
- lower contents of nonhydrated cement grains,
- more calcium hydroxide than in bulk hardened paste,

but local variations in composition of ITZ are high and often more important than their variation with the distance from aggregate. Therefore, according to these authors, ITZ effects may be overestimated, particularly for High Performance Concretes (HPC) where small grains of coarse aggregate are used. The influence of ITZ depends on the type and quality of concrete: the lower w/c the smaller influence of ITZ is observed, usually as a limit value for (HPC) w/c = 0.4 is considered. The depth of ITZ varies from 10 to 40 μm, according to what property is considered: pore colume, CH content or nonhydrated cement grains.

Another problem is the influence of silica fume; after addition of 5-10% of cement mass the workability of the fresh mix is improved. According to investigations by Goldman and Bentur (1989) concretes exhibit higher strength when either SF or carbon black is added and that effect was explained by increased density of ITZ; particles of carbon black are approximately the same size as SF but are chemically inert. These test results and opinions were discussed by Darwin (1995) who argued that both kinds of micro-fillers decreased the dimensions of pores in the bulk paste and therefore its resistance against crack propagation was improved, taking into consideration basic assumption of fracture mechanics. According to that opinion the bulk hydrated cement paste strongly influence on the mechanical properties and not only ITZ. The question is to what extent addition of SF does influence exactly ITZ and not mainly bulk cement paste properties.

Role of interface is to transfer forces from one phase to another. At rupture of concrete, the cracks propagate across aggregate grains or around the grains – in ITZ; this depends on the strength of the grains and quality of paste-aggregate bond. It should also be noted that not only the strength of the grains is important but also their properties: whether are more or less porous, permeable, soaked with water, etc.

It is generally accepted that ITZ influences the permeability of the composite material and percolation goes through interconnected layers around grains.

The structure of ITZ along steel fibres was analyzed experimentally by Potrzebowski (1991) as to its influence on the transfer of forces through bond and friction. It has been shown that after debonding between a fibre and cement matrix, the forces were transferred by friction in a continuous way and these forces decreased appreciably only after quite large opening of the crack along the fibre.

7. Fibre structures

The main role of structures composed of regularly or randomly dispersed fibres is to control cracks and micorcracks, their opening and propagation. In Figs. 10 and 11 it is schematically shown how the fibres influence cracks and what is their expected influence on the stress-strain or stress-crack opening curves.

There are different kinds of fibres as to their material and shape. They are single fibres in the matrix or bundles of fibres, mats with fibres or regular grids. In most cases of practical application, the fibres are randomly distributed, but for certain purposes they may be linearized and the fibre structure may be adapted to the predicted distribution of internal stress and strain, provided that it is known. It is interesting to learn how many single fibres are in 1 cm^3 of paste; this explains their efficiency in controlling the microcracks. Data on selected fibres and microfibres are given in Table 5.

An example of a regular structure of continuous fibres is shown in Fig. 12. Short fibres are dispersed in the cement matrix but their distribution depends on the aggregate grains dimensions and on the fibre length, as it is schematically shown in Fig. 13.

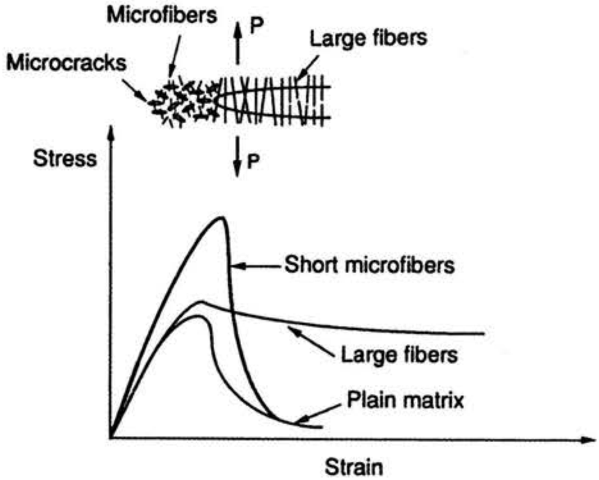

FIGURE 10. Structures of long and short steel fibres controling the crack propagation; after Betterman et al. (1995).

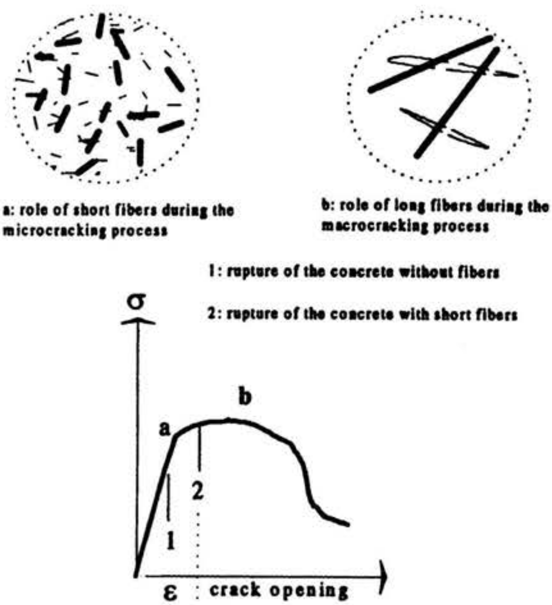

FIGURE 11. Structure of short fibres controlling microcracks and its influence on the stress-crack opening curve; after Rossi (1982).

TABLE 5. Microreinforcement of concretes and mortars.

Fibres	**Average dimensions** / ***Volume of a single fibre***	**Numbers of fibres in 1 cm³** 0.5%	1.0%	2.0%	3.0%
Asbestos fibres	$0.1\,\mu m \times 4\,mm$ / *$3.14 \cdot 10^{-8}\,mm^3$*	$1.59 \cdot 10^8$	$3.18 \cdot 10^8$	$6.36 \cdot 10^8$	$9.55 \cdot 10^8$
PAN carbon fibres	$6\,\mu m \times 3\,mm$ / *$8.5 \cdot 10^{-5}\,mm^3$*	59 000	118 000	236 000	354 000
Pitch carbon fibres	$14.5\,\mu m \times 3\,mm$ / *$0.000495\,mm^3$*	10 100	20 200	40 400	60 600
PVA fibres	$24\,\mu m \times 7\,mm$ / *$0.00317\,mm^3$*	1580	3160	6320	9480
Steel micro-fibres	$0.15\,mm \times 6\,mm$ / *$0.106\,mm^3$*	49	94	189	283
Steel fibres	$0.4\,mm \times 30\,mm$ / *$3.77\,mm^3$*	1.33	2.65	5.31	7.96

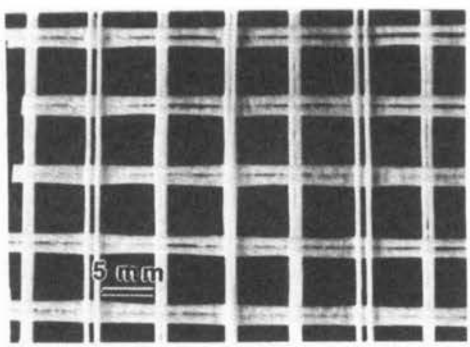

FIGURE 12. Example of regular structure of continuous glass fibres; after Bentur and Mindess (1990).

Three types of idealized structures of short dispersed fibres may be distinguished (Fig. 14):

- linearized fibres, i.e. single fibres are all parallel to a selected axis, denoted 1D,
- random distribution in parallel planes, denoted 2D,
- random distribution in space, 3D.

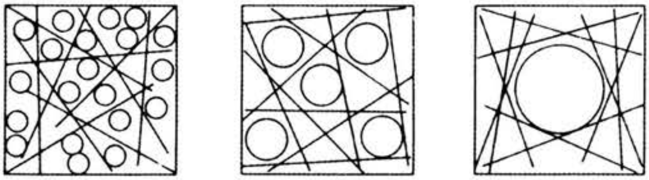

FIGURE 13. Effect of aggregate size on the fibre structures and distribution within a square of side length equal to fibre length (40 mm); after Hannant (1978).

FIGURE 14. Ideal structures of short dispersed fibres.

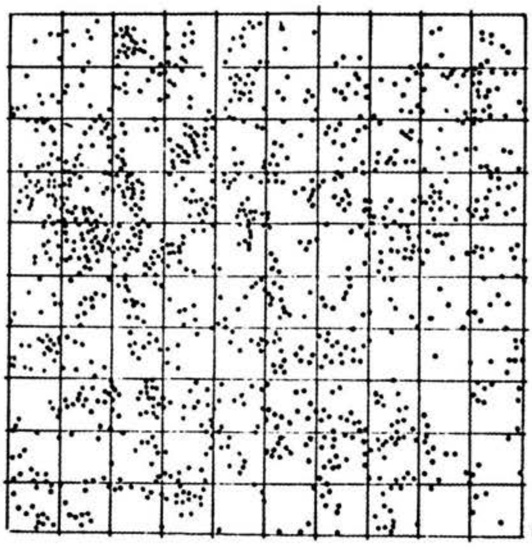

FIGURE 15. System of points representing traces of fibres in a cross-section, prepared for analysis in a computer image analyser; after Brandt (1995).

In most cases, where direction of principal internal forces is not known, random distribution of fibres (3D) is the most appropriate. In real structures, however, deviations from ideal distribution always occur, e.g., in horizontal elements the steel fibres may have tendency to take horizontal position and in thin layers of mortar the majority of long fibres are parallel to the surface; then intermediary structure 2D-3D occurs. The effective fibre distribution, i.e. fibre structure may be recognized experimentally on cores or cross-sections of the elements.

The traces of fibres in a cross-section may be counted and it is a reliable experimental method to evaluate the effective fibre structure in the element, cf. Fig. 15.

Homogeneity of fibre distribution may be estimated quantitatively, e.g., from comparison of numbers of fibres in the lower and upper parts of the cross-section, or in its other regions. Total number of fibres in a unit area may be also calculated from the formulae derived by Aveston and Kelly (1973), and Kasperkiewicz (1995) for three ideal fibre distributions:

$$\text{for 1D}: \; N^{1D} = \frac{4V_f}{\pi d^2},$$

$$\text{for 1D}: \; N^{2D} = \frac{8V_f}{\pi^2 2d^2},$$

$$\text{for 1D}: \; N^{3D} = \frac{2V_f}{\pi d^2}.$$

Here V_f is the fibre volume and d is the fibre diameter. The values from the above formulae and from counting may be compared and estimation of the effective number and distribution of fibres may be derived.

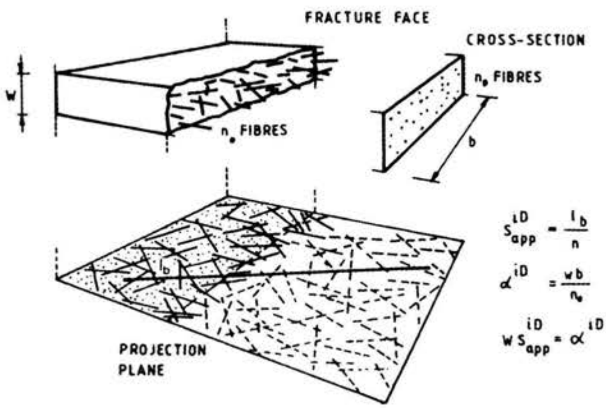

FIGURE 16. Parameters describing the fibre structure; after Kasperkiewicz (1983).

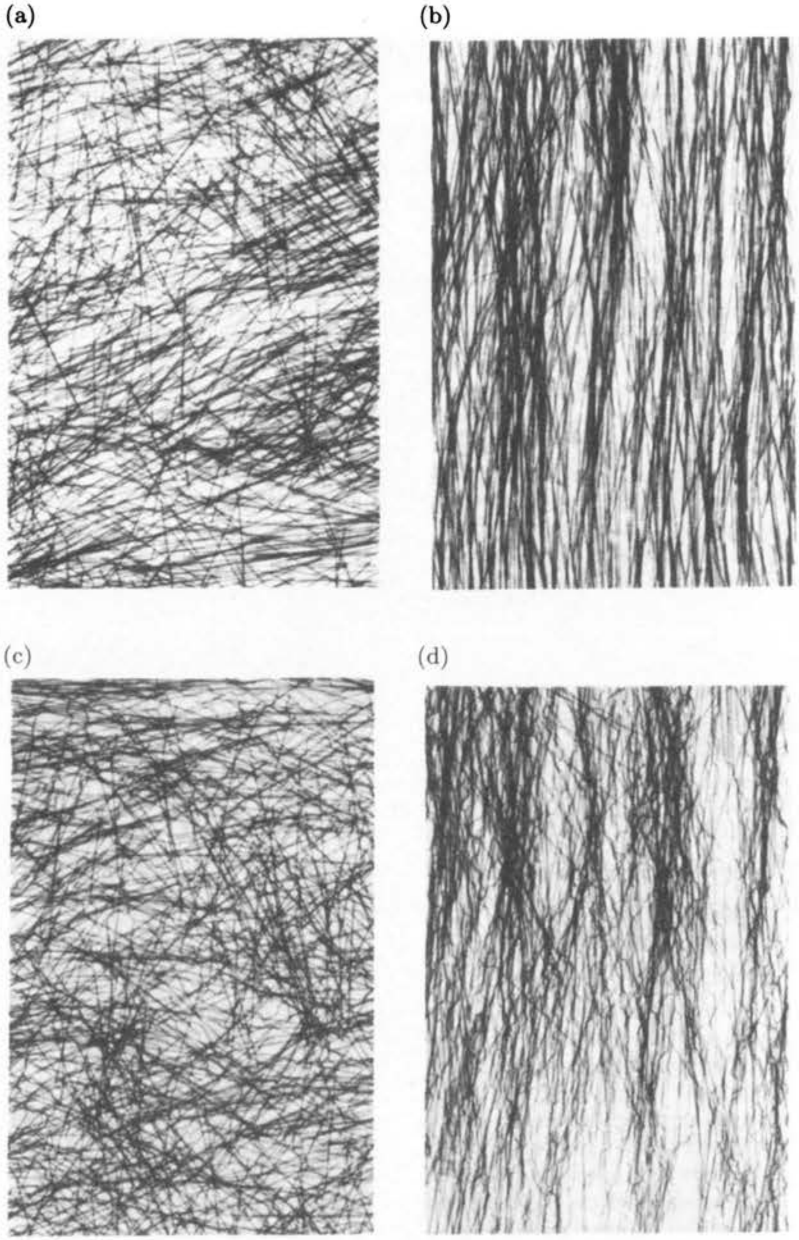

FIGURE 17. Examples of X-radiograms of cement mortar plates reinforced with steel fibres, $V_f = 2\%$, (a) plain straight fibres 2D, (b) plain straight fibres linearized 1D, (c) fibres with hooks 2D, (d) fibres with hooks 1D; after Brandt (1995).

Real structures of steel fibres are shown in Fig. 17. Four different fibre structures are represented by X-radiograms and some deviations from ideal structures are clearly depicted. For random distribution 2D, regions with more or less dense fibre structures occur (Figs. 17(a) and (c)). For linearized fibres (Figs. 17(b) and (d)), there are single fibres that do not follow principal direction and are not exactly parallel to the others.

8. Defects in the structures of concrete

Defects in the material structure of hardened concrete determine in fact the strength and durability of that composite material and finally, the safety and serviceability of concrete elements, structural or non-structural, e.g. cladding. Weak regions, local increased porosity, accidental voids and cracks concentrate internal stresses and facilitate the action of various external agents. As a result, the crack opening and crack propagation are initiated, leading to fracture and final destruction.

Similar kinds of defects increase also local permeability of concrete. Therefore, various processes of corrosion, leaching, carbonation, etc. are initiated or accelerated. The possibility of frost damages is also considerably enhanced when water is submitted to repeated cycles of freezing and thawing in the regions of increased porosity or in cracks and flaws that are open to external humidity.

Cracks and microcracks are the most frequently observed, recorded and controlled defects in the concrete structure. Their pattern, length, width, density and connectivity can be determined using computer image analysis methods. Results of such an investigation may be considered as a basis for the diagnosis of the concrete, its quality and durability, possible sources of deficiencies or serious defects (Wittman 1983).

The main aim of analysis of the structure of the hardened concrete by all methods is to record cracks and structural defects. Their analysis allows to define how serious and dangerous the defects are with respect to safety and serviceability of the structure. It is also possible to determine the origin and reasons of the defects, e.g.:

- low quality of the concrete components or their incompatibility,
- incorrect composition, i.e. wrong proportions derived from the material design,
- mistakes in material preparation, transportation, casting, vibration, etc.,
- inadequate curing and disturbed process of cement hydration,
- unexpected external actions or inappropriate structural detailing.

Defects in a concrete structure may be recognized by an analysis of specimens cast during execution but the most reliable source of information is the analysis of cores sawn out of the structural elements that are submitted to control. Methods of analysis of the concrete structure on plain sections are presented elsewhere, e.g. Załocha and Kasperkiewicz (2002) as concerned air-entrained pore systems.

9. Conclusions

Analysis of material structure reveals basic relations between its characteristics and material properties. Such an analysis is a powerful tool for investigations since that time when computer image analysis was used and quantitative results were obtained for all kinds of material properties.

Microstructure and structure is a critical factor in determining all mechanical properties and durability of concrete. Traditional methods for the structural characterization of concretes include description studies and various methods of analysis of the pore system. However, the descriptive methods have obvious disadvantages and only application of quantitative computer based image analysis may furnish really useful results.

Computerized image analysis was developed primarily for the study of metal structures and biomaterials. It appeared to be very fruitful for cement based composites at various levels: from the lowest level of nanometers that can be recorded with sophisticated equipment up to macroscopic images of plain sections of concrete cores and specimens, analysed in reflective light.

The details of that technique and selected results are given elsewhere. Here it suffices to stress the importance of the quantitative analysis of the structure of concrete in many kinds of investigations of concretes in civil engineering structures and their quality.

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