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MECHANICS OF CEMENT-BASED COMPOSITES

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In the paper general outline is given of research performed during last years by the group working in the Laboratory of Strain Fields at the Institute of Fundamental Technological Research, Polish Academy of Sciences in Warsaw. The main subject of research is the mechanics of cement-based composite materials. Experimental and theoretical research are accompanied by applications realized in co-operation with building companies.

1. Introduction

The term "cement-based composites" covers a large group of materials made of Portland cement as a binder, of coarse and fine aggregate and of various kinds of admixtures, additives and dispersed reinforcement. All these components may be of different origin, properties and volume fractions, and their fabrication may proceed according to varied technologies. Cement-based materials correspond well to the widely accepted definition of composites.

Cement mortars and concretes are used extensively in their present form *since the beginning of the century.* However, traditional concretes cannot satisfy new demands, e.g. in high rise buildings, long span bridges, nuclear reactor vessels, etc. That is why we are now in a phase of rapid development of the Portland cement based materials, stimulated by application of new components and technologies, use of modern methods of investigation, and also by new requirements in building and civil engineering structures. Several kinds of new materials become more and more popular: fibre reinforced concretes, polymer concretes, high performance concretes, etc.

As it concerns new requirements, the durability is one of the most important aspects from both technical and economical viewpoints. Various non-classical phenomena like cracking, fracture, plastic deformation, fatigue, etc. should be also taken into consideration. The necessary knowledge as well as new kinds of approach to materials like fracture mechanics, damage theory, multicriteria optimization and many other are now available and can be also applied to cement based composites.

The mechanics of concrete-like composites is a system of experimental results, test methods and relations which are slowly bridging the traditional gap between the material scientists and civil engineers. Obviously, all particularities which characterize these materials should be taken into account. For example, large volumes of materials used and conditions in which they are produced impose special restrictions on material costs and manufacturing methods.

The aim of this paper is to review more important problems of investigations concerning cement-based composites, with special attention paid to research carried on in recent years in the Laboratory of Strain Fields at the Institute of Fundamental Technological Research. Selected references are added.

2. Composites and their components

The components of composite materials may be presented in a somewhat simplified way in four main groups: binders, activators, fillers and reinforcements. In cement based composites main activator is usually water. All those groups are not always represented in different materials, Brandt (1994). In another classification of components attention is paid to their characteristic form. The continuous phase (matrix) is embedding the dispersed phase (inclusions). The case when two phases are continuous – like in ferro-cement – is traditionally not considered to be a typical cement based composite, being rather a composed structure (like RC – reinforced concrete). The inclusions in cement based composites may have the form of more or less regular particles or grains, fibres and pores or voids, separated or interconnected. The terms matrix and inclusions are used at different levels: the matrix itself may be composed of lower level inclusions embedded in a binder.

Between matrix and inclusions an intermediary region exists called interface. The stresses are transmitted through that interface from matrix to inclusions (particles, grains or fibres) and vice versa. Local failures occurring there in form of plastic yieldings or cracks modify considerably the behaviour of the composite material under external actions.

Portland cements are materials which by their binding properties and bond to other components assure the transmission of stresses. Cement with water, called cement paste is used as a matrix of lowest level. Together with fine aggregate it can form another matrix at higher level.

There are several kinds of cements and they may be also combined with other types of binders, e.g. with polymers.

The fillers or inclusions are used as particles or grains of various shapes and dimensions. They are introduced into the matrix to improve mechanical properties, to fill voids, increase density, and to control crack propagation. Non-hydrated cement grains play also a role of fillers. Sometimes the cheap and porous inclusions are introduced to decrease the material cost, its unit weight, or to improve the thermal insulation properties.

The inclusions are made of natural gravel and crushed stone, sand, voids only filled with air or with specially produced gas, etc.

Special category is formed by microfillers which are by two orders smaller than cement grains. Since a decade so-called silica fume obtained as a waste condensate in production of ferrosilicon and silicon alloys is extensively used for high strength and high performance concretes.

As reinforcement thin fibres are applied, short or long, randomly dispersed or regularly distributed, also in the form of mesh or fabrics, which are all called dispersed reinforcement. When a system of interconnected pores in a hardened concrete matrix is filled with a polymer during impregnation process, then a special type of reinforcement is also created. In certain cases the hybrid reinforcement is used, which means that the reinforcement is composed of two or more types of fibres, carefully designed for their separate purposes.

There are three main groups of polymer concretes: PC (polymer concrete), PCC (polymer-cement concrete) and PIC (polymer impregnat concrete) according to definitions accepted by the American Concrete Institute. The role of polymers in these composites is entirely differentiated mainly by the fact that additive and synergistic mechanisms are different. Additive mechanisms depend on the properties of the components and on their fractional volumes. The rule of mixture is decisive on the macrostructural level and it determines the final composite properties. The synergistic mechanisms depend rather on the phenomena in the microstructure of the interfacial layers at the surface of the components and certain small quantities of an admixture may play a considerable role in final composite behaviour.

The list of cement-based composite materials which form the new generation of building materials should be completed by several kinds of special concretes, which by use of particular components and technology exhibit special properties and satisfy special requirements. Among the other, High Performance Concretes are at present rapidly developing and are subject of extremely numerous investigations.

3. Material design and optimization

In design of cement based composites traditionnally trial-and-error methods are applied, and the design is based rather on experience than on analysis and theoretical models. Detailed review on the design of mix composition of concrete is given by Kasperkiewicz in [54]. With increasing variety of possible components and with development of requirements and imposed conditions, the application of more rational optimization methods is necessary. In the last years the effort in research at the Laboratory was concentrated on development and application of appropriate methods of optimization of cement based composites.

The general formulation of the problem of optimization of a material is the same as in the structural optimization, cf [52] and [53].

An optimal material is described by a set of decisive variables x $(i = 1, 2, ..., n)$ which minimize or maximize an optimization criterion.

Variables x_i are assumed to be independent and together with arbitrary selected parameters they determine completely the object of optimization: a structure or a material. They are called material variables.

Optimization criteria describe basic properties of materials. They are called also objective functions; there may be more than one objective function. In material optimization the objective functions describe selected properties which are considered as important and decisive for the material quality and applicability. The solution consists of determination of these values of design variables which extremize these properties. As material properties all physical, chemical and other properties may be considered. For engineering materials particularly important are mechanical properties like strength, Young modulus, specific fracture energy, durability but also specific cost of the material.

In structural and material optimization there are several common features. The both groups of problems are correctly formulated when criteria, constraints and variables are defined analytically. Sometimes not best but only "better" design variants are unprecisely called "optimal solutions". But calculation of a few cases and selection of the best one among them is not an optimization approach. It is improper to speak about optimal solution without clear declaration concerning in what sense and within what domain (feasible region) is this solution valid.

It should also be emphasized that the optimization problem is always solved not in reference to real materials, but taking into account their approximate models. The result of an optimization procedure is therefore dependent on assumptions and approximations admitted in these models, for example an assumption of elasticity and homogeneity of the individual phases, uniform distribution of inclusions or fibres, etc.

The optimization does not replace entirely the procedure of material design, because it may not cover certain aspects and requirements, which determine the material completely. Disregarding various secondary aspects is justified by necessary simplification of the optimization problem. On the contrary, in the final design of the material, which follows the optimisation procedure, satisfied must be all conditions and requirements concerning safety, serviceability, economy, etc. Necessary modifications are then introduced to the material composition and structure. Like its analogue in constructions the optimization of the material is therefore only a part of the design, in which some intuitive procedures are replaced by objective calculations.

The sensitivity of the objective function with respect to changes of variables is a separate problem. For unequivocal optimization the objective function should not have too steep gradients. However when the objective function does not really depend on the decisive variables, then the variables are probably incorrectly selected.

Proper choice of constraints and objective functions is important in the formulation of the problem. The solution is based on given conditions, but sometimes an objective function should better be replaced by a constraint or vice versa. It occurs also that small modification of a constraint may influence considerably the objective function. In such a case the resignation of some preliminary assumptions concerning constraints may be justified.

If the optimization problem is formulated with one single criterion $F(x_i)$ and with the appropriate constraints, then the necessary conditions for a maximum are derived from the well known Kuhn-Tucker theorem.

Only in rare cases it is admissible to limit the optimization procedure to one single criterion, e.g. a structure of minimum cost or a material of maximum strength. Such a formulation has in general somewhat academic character and may be used only as a simplified example for preliminary explanation of the problem. In most cases the necessity of taking into account several criteria simultaneously is obvious although they are often introduced in an indirect way – as appropriate constraints. General procedure involves so called multiobjective or multicriteria optimization, in which several criteria are accompanied by appropriateconstraints.

The criteria or decisive functions are components of the vector $\boldsymbol{X}^N$ in n-dimensional space. Every point of this space corresponds to one particular material defined by n decisive variables. The feasible region Q is a part of the n-dimensional space and is determined by the constraints.

The space of the objective functions R^K is k-dimensional. Every point of this space corresponds to one vector of the objective function $F_j(x_i)$, and to the feasibility region Q corresponds region $F(Q)$, which incorporates among other all partly optimal solutions, that is such points which have no "better neighbours" from the point of view of whichever criterion. Such a set is called compromise set.

The compromise set is a rigorous and strict solution of the problem, but important is the next, final step involving selection of the preferable solution, based on a subjective decision. This may be done using different assumptions and methods. For example, when strength and cost are two conflicting objective functions, then the compromise set contains all solutions possible from the design point of view. For one application the cheapest solution may be selected, and for the other – the strongest one. In general, a system of arbitrary weights is assumed for each objective function, which means that some functions are considered as more important than the others. This leads to formulation of so called utility function, in which the weights of all criteria are introduced.

General formulation of optimization of cement based composites is presented in [54] together with a few examples. Numerical solutions concerning fibre distribution in fibre reinforced concretes are given by Brandt (1984), (1985a,b), (1986) and (1987), Marks (1988) and (1989), Brandt and Marks (1992), Brandt et al. (1992). Also composition of ordinary concrete is considered by Brandt and Marks (1993), Marks and Potrzebowski (1992), Kasperkiewicz (1993) and (1994). Problems of optimization of polymer concretes are considered by Czarnecki and Lukowski in [54]. The methods of optimization of concretes with controlled water permeability are proposed by Bajorek in [54].

All values characterizing the properties of the material components used in composite material manufacture are subject to random and systematic variations. The same concerns their effective volume fractions and their distributtion in the composite material. That is why experimental verification with actual materials and in local conditions of execution is necessary to test the assumptions and in most cases to introduce certain modifications into the set of design variables accepted for the optimization procedure.

Further development of optimization approach to cement based composites should be directed at various realistic objective functions and variables and at better formulation of objective functions. An important generalization takes into account stochastic nature of the variables and processes involved Piasta in [54].

4. Internal structure

Internal structure of the material is described by configuration of its various elements (grains, pores, cracks, fibres, etc.) that is by their spatial distribution. Most of mechanical properties are dependent upon structure; in this respect the material is then called "structure sensitive".Considerable research effort at the Laboratory was spent on description of idealised and real structures composed of short steel fibres dispersed in cement matrix, cf Kasperkiewicz (1978b,c), Kasperkiewicz et al. (1978). Analytical relations were then proposed to express influence of fibre distribution on mechanical properties of the composite material, cf Kasperkiewicz (1978a).

Observed was also dependence on the microstructure of the composite of a non-mechanical properties, like for example water diffusion constant D, cf Garbalińska and Kasperkiewicz (1994).

Structure of aggregate grains, pores and cracks are analysed by stereological methods mentioned below, but this research is not so much advanced yet to give formulae relating stereological characteristics to the mechanical properties of concrete materials. The test methods are used mainly for control purposes, e.g. well checked is correlation between frost resistance of concrete and its air-voids spacing, which can be now evaluated with computerized methods developed in the Laboratory.

5. Mechanical properties

Properties of composite materials depend upon their composition and internal structure. The most important mechanical problems of cement based composites which were considered at the Laboratory concern plain concrete, shotcrete and fibrous concrete.

Strength under various stress states as well as forms of fracture were determined experimentally and related to material composition and structure. Several papers were published on flexural behaviour of SFRC by Brandt et al. (1989), and on fracture energy of concrete by Kasperkiewicz (1986) and (1995), Kasperkiewicz et al. (1986) and (1989), Kasperkiewicz and Stroeven (1991), Tran and Kasperkiewicz (1994), on tensile strength of SFRC by Kasperkiewicz (1979), and on its behaviour in splitting by Potrzebowski (1983). The approach using fracture mechanics and analysis of crack propagation was investigated and basic relations have been established among the other in papers by Brandt (1980) and Kasperkiewicz (1983). In this approach increasing attention was paid to the energy consumption during cracking and fracture processes.

Considerable influence of fibre distribution and direction on mechanical properties was observed and practical conclusions for material design and optimization were proposed, cf Brandt (1982) and (1991). This direction of research led to formulation of optimal solutions.

Mechanical problems at interface between fibre and matrix are of importance for composite behaviour of FRC. Reinforcement with short fibres of different materials is effective provided that appropriate bond is assured between fibres and matrix. To determine the bond strength and distribution of bond stress along fibres a special test method was applied and developed in which a fibre or a group of fibres were pulled out of the matrix. The behaviour of such a system was observed by different means, among others applying holography. The obtained results were used to improve mechanical properties of the material. Several original results are published in papers by Burakiewicz (1979) and by Potrzebowski (1991), who proposed a general model for stress transfer between fibre and matrix.

Properties of cement composites under impact loading were investigated by Glinicki (1992) and (1993) who has shown how the tensile strength is increasing with the rate of loading and found out that the phenomenon is strongly related to the material structure.

Mechanical properties of composites reinforced with non-metallic fibres were also determined in special experiments. Carbon and polipropylene fibres were used by Brandt and Glinicki (1992), who shown that microcracks were efficiently controlled by carbon fibres due to their small dimensions and excellent distribution.

Durability of glass fibre reinforced composites was investigated in cooperation with Ecole des Mines de St.Etienne (France). The problem is related to the destructive influence of highly alkaline Portland cement paste on glass fibres. This influence comprises in fact two effects: corrosion of fibres and increase of brittleness of the fibre-matrix interface. As a result, ordinary E-glass fibres cannot be used with Portland cement based matrix, because after a few weeks all reinforcing effect disappears. There are various methods to reduce these effects or to slow them considerably. The newest approach to this problem is based on application of a new generation of alkali-resistant glass fibres together with special polymer based admixtures in the matrix. In a few papers the results of tests are presented and models of composite behaviour were proposed by Glinicki et al. (1994), Glinicki (1994).

Nonconventional approach to fracture of plain concrete elements was attempted by Brandt and Prokopski (1993), who tried to determine a relation between composition of concrete specimens and the shape of their fracture surfaces which may be quantified by their fractal dimension. The tests have shown that the fracture surfaces are fractal objects and that differences can be observed in fractal dimensions of these surfaces belonging to different kinds of concrete.

6. Test methods

Mechanical properties of specimens and elements are determined using modern, displacement controlled testing mashines. Various states of stress are investigated, by which mechanical properties like strength, flexural toughness, ability to absorb strain energy, impact resistance etc. are determined. The results of various material compositions and structures are compared with theoretical calculaltions and general relations are proposed together with practical formulae for design.

Internal structure may be observed on cross-sections, thin sections and on radiograms. There are many methods which may be applied: from macroscopical observation to most sophisticated investigations using scanning electron microscopy (SEM) or thermogravimetric analysis (TGA).

Over the years different test methodes have been applied in the Laboratory. They involved among others analysis of images of plates obtained by X-rays to describe distribution of steel fibres, cf Kasperkiewicz (1983). When the fibres are introduced to the fresh mix it is important to obtain their random or regular distribution according to prealably determined design. Using stereological approach it possible to analyse quantitatively the images of the fibres and to determine their spatial distribution. Similar stereological methods are applied to images obtained from cross-sections where individual fibres are visible. The image analysis was initially performed manually but at present special equipment for automatic image analysis is applied in the Laboratory. Knowing the distribution of fibres and the properties of the composite it is possible to propose conclusions concerning for example the quality of methods of composite material fabrication, e.g. randomness or regularity of fibre distribution.

Stereological formulae were developed for analysis of grain distributions in concrete by Brzezicki et al. (1994).

Similar methods were also applied to distribution of pores and aggregate grains, to analysis of the grain shape, etc., by Brzezicki (1993) and (1994).

Displacements between fibre and matrix during pull-out process were measured using laser interferometry by Potrzebowski (1991).

In most of tests performed in the Laboratory on specimens subjected to static loading the acoustic events related to microcracking are counted and recorded. It is then possible to observe correlations between all variations of measured parameters (load, displacement, strain) and development of microcracking. Using acoustic emission some interesting conclusion have been proposed as to the influence of carbon fibres on the microcracking, cf Brandt and Glinicki (1992).

7. Applications

In the Laboratory the research is always closely connected to possible application in building and civil engineering. Already in 70's and 80's first attempts were made to use steel fibre reinforced concrete (SFRC) for special parts of civil engineering structures and industrial buildings. In that aim seminars and conferences were organized to present new materials to professional engineers and building companies. A general review of properties of various cement based composites was given in a small monography by Brandt et al. (1983).

Since a few years High Performance Concretes (HPC) are attracting attention in various advanced laboratories in the world. It is in fact a new generation of cement based materials obtained by application of superplasticizers, reduction of water, use of various admixtures and microfillers and by careful selection of all components.

Mechanical properties and composition of HPC were considered in two review papers by Kucharska and Brandt (1993), Brandt and Kucharska (1993), in which main directions and methods were presented and discussed. In the same time tests were carried on with clear objective of direct application. As one of the results, after series of tests, several mix compositions of HPC have been obtained at IFTR and specimens were executed with compressive strength reaching $110 \div 120$ MPa. The compositions and technologies were presented by Glinicki et al. (1995) and are prepared for special publication.

Fibre reinforced concretes for special applications in construction of underground railway system in Warsaw were tested and successful mix compositions have been proposed, cf Brandt et al. (1994). Members of the Laboratory are involved in cooperation with several civil engineering companies in view of improving practical knowledge and technology used in construction.

A new idea of reinforcing concrete with aramid fabrics was tested, having in view the possibility of controlling shrinkage cracks in masive concrete elements cf Kasperkiewicz and Reinhardt (1993).

Very significant field of application of cement-based composites is repair of outdoor concrete structures which are exposed to various sources of corrosion and destruction. This is a very important problem from both technical and economical viewpoints, because large amount of money is spent every year from national and local budgets around the world for repair of existing structures. Close cooperation and financial support from the Institute of Road and Bridges (Ministry of Transportation) enabled to perform tests and to prepare compositions of fibre reinforced materials which may be used for repair of concrete structures. These works are continued and first results were delivered in the form of internal reports, practical recommendations and publications, e.g. Potrzebowski (1994).

Research activity of the Laboratory was completed by organization of several summer schools, teaching seminars, international symposia and series of lectures delivered at technical universities in Poland. Maintained are extensive links with leading laboratories abroad.

8. Conclusions

Cement-based materials form a large group of composite materials which are important for certain branches of Polish economy. Extensive development of these materials, especially improvement of their quality and developing various new applications is observed in all advanced countries. It is necessary to promote such research further to form basis to cope with all chalenges of present times.

Cement-based materials are composites of very complicated structure and of mechanical properties related to a multitude of parameters. To produce and apply them in a rational way extensive research effort is necessary. This cannot be replaced neither by information and products imported from abroad, nor by sophisticated but general considerations. For a success in this research, knowledge from different fields ranging from chemistry of Portland cement up to the fracture mechanics and mathematical morphology must be deliberately combined with the most advanced experimental methods and field applications.

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Mechanika kompozytów o matrycach cementowych

Streszczenie

W pracy przedstawiono tematykę badań i niektóre wyniki uzyskane w dziedzinie kompozytów o matrycach cementowych. Badania są prowadzone w Pracowni Pól Odkształceń IPPT PAN w Warszawie. Badania dotyczą głównie właściwości mechanicznych i kompozycji tych materiałów. Obok prac doświadczalnych i teoretycznych prowadzone są badania aplikacyjne we współpracy z przedsiębiorstwami budowlanymi.

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