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ON THE APPLICATION OF DISPERSED FIBRES AS REINFORCEMENT FOR CONCRETE SHIELDS AGAINST RADIATION

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Abstract

The application of fibre reinforced concrete (FRC) in the various constructions in Nuclear Power Plants and particularly in the shields for protection against γ and neutron radiation seems possible and useful. A few examples of shields built with FRC are described and reviewed and the question is formulated why this kind of cement based composites are rather infrequently used in that area.

1. INTRODUCTION

Since a few years the problems related to the use of concrete as a basic material for construction of nuclear reactors are nearly disappeared from technical magazines. The containments and various auxiliary buildings in Nuclear Power Plants (NPPs) are at present under construction in many countries around the world and it seems apparently that there are neither technical nor scientific difficulties related to building structures and shields against radiation. However, after a thorough study in the information services we learn that multiple failures at different scale are encountered in many countries. In fact, there are several problems that were observed in NPPs and particularly the durability problems of concrete are apparently not completely solved.

Concrete structures are used extensively in all kinds of buildings around a reactor, in the main containment structure and in auxiliary buildings. Prestressed and reinforced concrete structures are built in order to protect people and environment against all kinds of radiation, to ensure safety in normal exploitation, against climatic actions, ageing and also to ensure safety in the case of terrorist attacks, falls of airplanes, etc., [1]. Application of cement based composites, e.g. in the form of High Performance Fibre Reinforced Concretes (HPFRC) seems to be very appropriate in order to increase resistance against local cracking and lose of tightness, but there are rather few information on that subject.

These problems in research publications in the magazines since some time are scarce and it may be explained by the fact, that the technology related to construction of NPPs, storages for radioactive materials, etc. is covered by restricted knowledge of specialized companies that are prepared to supply all kinds of these installations ready for exploitation. Various advanced technologies are applied and developed by these companies that are not so interested in diffusing the new solutions but in selling them round the world.

In Poland the safety and durability of concrete structures used in industrial application of nuclear energy are of high interest for society and government. In 1990 the construction of a NPP was closed in the social atmosphere created by the Chernobyl disaster. However, in 2010 a decision was adopted to build a NPP for production of energy based on nuclear fission and preparatory actions started. That is why the application of high quality concrete with fibre reinforcement is of importance.

In the paper possible use of Fibre Reinforced Concrete (FRC) in various structures in a NPP is considered and a few applications are reviewed. Special concrete structures built for storage of fission materials and of therapeutic application of isotopes also deserve attention.

2. ACTIONS ON CONCRETE STRUCTURES IN A NUCLEAR POWER PLANT

There are a few groups of conditions that should be satisfied when concrete is applied in various kinds of structures in a NPP's:

1. Reduction of influence of external climatic actions on buildings and on foundations;
2. Reduction and control of internal actions related to Alkali Aggregate Reaction (AAR), Delayed Ettringite Formation (DEF), etc.;
3. Attenuation and absorption of radiation from nuclear reactor in order to ensure safety;
4. High resistance to cracking in elevated temperature together with resistance against ionization radiation from nuclear reactor and from nuclear isotopes in different kinds of magazines.

The conditions 1 and 2 concern structures in a NPP as in all other kinds of concrete structures, however the durability is expected at least for 60 years and any control and repair operations may be particularly difficult and expensive.

For requirements 3 and 4 the situation is more complicated. The main function of concrete shields is to attenuate and to absorb ionizing radiation and that should be obtained with minimum thickness of the concrete cover. That is why particular compositions of concrete are designed with special aggregates, depending on the kind of radiation expected.

The problem of durability of concrete shields exposed to radiation seems to be more complicated. Several authors, e.g. [2]and [3] published test data showing that there is certain limit for radiation input on concrete when critical degradations were observed. There are, however, published opinions also that the degradations were due to thermal effects. Basic question that should be answered is whether these degradations are expected before or after the exploitation period of time scheduled for the nuclear plant. The requirements for demolitions should be taken into considerations also.

Kaplan [4] presented a review of the actual state of technique in designing slabs and walls as protection shields against gamma and neutron radiation without considering dispersed fibres; these indications are not very much modified up to present time.

Main role in the composition of concrete in the shields is played by the aggregate that covers over 70% of its volume. As heavy aggregate against gamma radiation often barite (barium sulphate $BaSO_4$) is used, but also magnetite, hematite and other kinds of iron ores and steel scrap are used, [5], [6]. Moreover, secondary components even in small quantities, like sulphates may create additional and negative effects.

In the shields against neutron flux the boron aggregates or with high content of bound water are necessary. These are colemanite and ulexite. The tests published by [7] confirmed excellent efficiency of the shields, also against secondary gamma radiation. Concrete with colemanite is difficult for execution and only up to 20-30% of natural aggregate may be replaced. The difficulties in executing concretes of high quality with these kinds of special aggregates result in relative low tensile strength and sensibility to cracking under variation of temperature and cycles of mechanical loading. That is why cracking and spalling in concrete shields and containment domes are reported by [8] and other authors. Multiple incidences of that kind are caused by environmental agents like freezing and thawing cycles and by corrosion of containment liners. The situations are degrading with the age of structures, particularly when microcracks are already open and external humidity may cause rusting of steel reinforcement.

From all viewpoints it seems reasonable to apply dispersed reinforcement in the form of metal, glass, carbon and polypropylene fibres in order to increase the local concrete tensile strength or to distribute local thermal stress to control cracking and spalling of concrete. However, in published papers and books on concrete protections against ionizing radiation the fibre reinforcement is only infrequently considered and applied. Or, dispersed fibres may have two basic functions in concrete walls, ducts and other structural elements:

- metal fibres as reinforcement against local tensile stresses and microcracking,
- polypropylene (PP) fibres for protection against local thermal stress concentrations.

3. CRACKS AND CRACK-RESISTANCE OF CONCRETE IN THE SHIELDS

Degradation of concrete shields can be caused by inadequate performance of cement based matrix or aggregate due to ageing and various internal phenomena like efflorescence or leaching, influence of sulfates, acids, bases, salt crystallization or AAR. Damages may be the effects of various actions like freeze-thaw cycles, thermal cycles, abrasion, erosion and cavitation, fatigue or excessive vibrations that are observed on the shields. Degradation may occur also as an effect of long term irradiation, which is not completely understood neither determined as to the extent and reasons. The results of research in that very field are still under discussion, [9].

It seems incontestable that adequate reinforcement of concrete shields with dispersed fibres would increase considerably their durability. In Fig. 1 cracks in a concrete wall of a radioactive waste storage are shown with characteristic efflorescences. The wall was reinforced traditionally with rebars and this kind of damages may be avoided when dispersed fibres would be applied.

Visible manifestation of various kinds of distress are cracking and local delaminations; in some serious cases decrease of strength and stiffness may be observed in a form of excessive deformations. Initial cracks that are exposed on external agents create open gates to the progress of degradation.

Observation and appropriate recording of cracks and their development in time should be a part of the overall evaluation process. In-situ permeability tests can also be conducted on concrete shields to situate particular areas that are more susceptible to degradation. In concrete shields but also in containments, ducts, channels, cooling pipes, etc. there are many 'hot' points where concentrations of stresses are possible, particularly when the intensity of the functioning of a nuclear reactor is modified, e.g. when it is temporally disconnected for instrumentation and control purposes and connected again. These 'hot' points where stresses may produce some permanent degradation are slots and gaps for control and observation, streaming paths and other physical irregularities in the radiation shields. All these points may be strengthened by dispersed reinforcement.

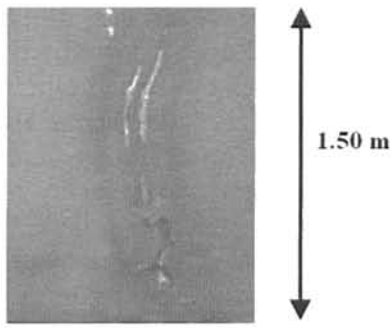

Figure 1: Crack and salt efflorescence at the lower part of a concrete wall in the underground storage for nuclear waste

For these kinds of cracking the dispersed fibre reinforcement seems to be an appropriate remedy. There are few published results of such application of FRC and perhaps this is an effect of professional policy to keep good solutions for restricted use.

4. EXAMPLES OF APPLICATION OF DISPERSED FIBRES IN CONCRETE STRUCTURES IN NPP's

Since 1970s it is known that dispersed steel fibres can improve mechanical properties of concrete, including crack control, tensile strength and post-peak ductility; compressive strength may be increased also. However, only in few studies the application of fibre reinforced concrete in construction of NPPs was investigated.

Special steel fibres (Fibraflex) made with molten alloy and produced by Saint-Gobain in France were proposed as reinforcement of precast concrete casks and boxes for storage of low and medium radioactive wastes. These fibres are resistant against corrosion and are recommended with durability of 300 years (SEVA, Technical Documentation).

The effect of radiation on PP fibres reinforced concrete was discovered as the influence of γ radiation on the mechanical properties of composites, [10]. The specimens were exposed to γ radiation with various doses from 5 to 150 kGy with a rate of 3.5 kGy/h. The FRC specimens were kept in air at room temperature and strength and stiffness before testing were determined. The results indicated that at certain doses of gamma rays the mechanical properties were improved, perhaps by increasing the fibre-matrix bond. Irradiation γ up to 50 kGy can increase compressive strength and modulus of elasticity of concrete with PP fibres, Fig. 2. When concrete was reinforced with fibres < 1.5%vol. the mechanical properties were improved proportionally to the fibre volume. This effect is probably due to the ionizing energy generating more surface contacts between fibres and hydrated cement phase. However, at radiation with higher doses of 100 and 150 kGy the mechanical properties decreased.

Ordinary straight steel fibres 30 mm long and 0.6 mm diameter were used as dispersed reinforcement with amount of 85 kgs/m^3 for construction of boxes for a nuclear waste storage as a part of research studies for PhD Thesis, [11]. The selection of fibres was based on two complementary criteria: durability and homogeneity of reinforced concrete. Because the nuclear waste packages are designed at least for a few hundred years, stainless steel fibres were chosen in order to avoid corrosion risks. These fibres were selected to reduce the risk of balling at relatively high fibre content, as is often observed with other types of fibres, e.g. hook-handed fibres.

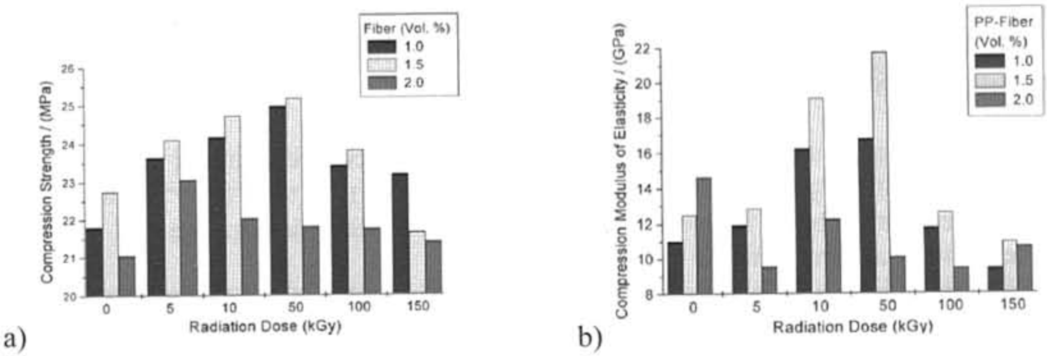

Figure 2: (a) Compressive strength with various radiation doses and (b) modulus of elasticity test with various radiation doses,[10]

The influence of polypropylene and steel fibres on the behaviour of concrete subjected to high temperature was studied in [12]. Tests were carried out on concrete elements subjected to four levels of temperature: 150, 300, 450 and 600 °C with the heating rate 1° C/min. The specimens without fibres, with polypropylene fibres (1, 1.5 and 2 kgs/m^3) and with steel fibres (20, 30 and 40 kgs/m^3) were tested and the behaviour under compression and tension was observed as well as modulus of elasticity and porosity as functions of temperature. The polypropylene fibres did not improve the residual mechanical properties of the concrete exposed to high temperature. The addition of steel fibres in the concrete limited the strength loss, but 20 kgs/m^3 was minimum reinforcement to increase mechanical properties of the composite material.

Ferraris et al. [13] suggested that dispersed fibres may be incorporated in two kinds of advanced cement based composites, namely Ultra-High Performance Concretes (UHPC) and reactive powder concrete (RPC), in order to obtain a very ductile and durable material. Short, randomly oriented steel fibres provide not only increased ductility, but improve dynamic strength, toughness, tensile strength, and resistance to spalling. The application of SFRC may allow to reduce rebar congestion in certain locations of the structures and to better arrange the traditional reinforcement.

In the later issue of this Recommendations, [14], dispersed carbon fibres were indicated as useful strengthening of existing structure or repair, applied in order to add or replace structural strength performance. Furthermore, it is indicated that fibre reinforcedpolymer (FRP) systems used as strengthening may replace other traditional solutions. General information on the use of FRP is provided and ACI 440.3R-04 Guide is suggested as an auxiliary document.

The Recommendations edited by [8] contain basic information on the behaviour of FRC in elevated temperature in which concrete shields and other structural elements of NPPs are exposed. Though the reported tests were not directly addressed to construction of NPPs, the results obtained may be useful for that field of application. The Recommendations are based on extensive review of available published paper and covers application of discrete fibres (mainly steel, polypropylene, alkali resistant glass and aramid) dispersed in cement based matrix.

There are not enough experimental data to formulate any definite conclusions concerning the influence of dispersed fibre reinforcement on the resistance of concrete at elevated temperature. Steel fibres increase strength and crack resistance of concrete, however their influence is different in exploitation temperature that is usually below 65 – 95°C and at higher temperature. In the report prepared by [8] several studies are mentioned and discussed in relation with the application of fibre reinforcement in concrete shields in NPPs where elevated temperature is accepted during exploitation or may appear in some kinds of emergency situations.

In order to avoid potential degradations of high strength concretes under thermal loadings, fibres are incorporated into the mixes. Steel fibre additions (0.5 to 2%, by volume) enhance the mechanical behavior of high-strength concrete at elevated temperature and improve the concrete ductility according to the study by [15].

Addition of relatively small amounts (e.g., 0.3%, by volume) of polypropylene fibres to the concrete mix improves the resistance to spalling as the polypropylene fibres melt at around 165°C to relieve the vapor pressure.

A comparison of stress strain curves for specimens containing polypropylene fibres with several concretes tested at room temperature (reference) and after exposure for 7 days at 200°C (residual) has been performed. Aggregate type had an effect on ultimate strain under high temperature conditions (i.e., carbonate aggregate concrete strain at peak strength was up to 40% greater than that for siliceous aggregate concrete) and addition of steel fibres increased ductility at elevated temperature of both concretes.

In the paper[16] the results of computations are presented and discussed and the proposed conclusions are:

- application of PP fibres in concrete of a shield allows to reduce neutron radiation, however the influence on gamma radiation is less effective;
- use of dispersed steel fibres is not recommended in the shields.

It should be observed, however, that these results of calculations were not confirmed by any test results.

Ikraiam et al. [17] tested concrete cylinders ø 0.10x0.20 m reinforced with steel fibres from 0 up to 4 % by mass. Slices of 20 mm depth were subjected radiation from γ-sources. The values of the attenuation coefficient were determined from the equation $I = I_0\, e^{-\mu x}$, here I is the gamma radiation intensity after the shield,$I_0$is the intensity before the shield, μ is the attenuation coefficient that characterizes the material of the shield and x is the shield depth. The μ coefficient as a function of the percentage of steel fibres was determined for various intensity of radiation in Fig. 3. It appeared that fibre volume of 3% by mass (appr. 0.9 by vol.) corresponded to the most effective attenuation of radiation. Low values ofμcoefficient for 4% of fibres may be explained by difficulties in obtaining good concrete for relatively high fibre content.

The effect of fibre type and volume on the splitting-tensile strength of specimens tested hot is shown in Fig. 4. The tensile strength at splitting of the fibre reinforced concrete was higher than that of the plain concrete for all values of temperature and that the strength of the glass fibre concrete was lower than that of the steel fibre concrete. At temperature higher than 350°C, the effect of fibre content was not significant, that was probably due to the loss of bonds of fibres to the matrix, [18].

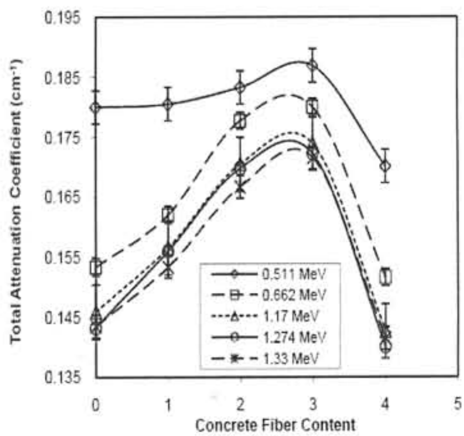

Figure 3: Attenuation coefficient as a function of fibre content (mass), [17]

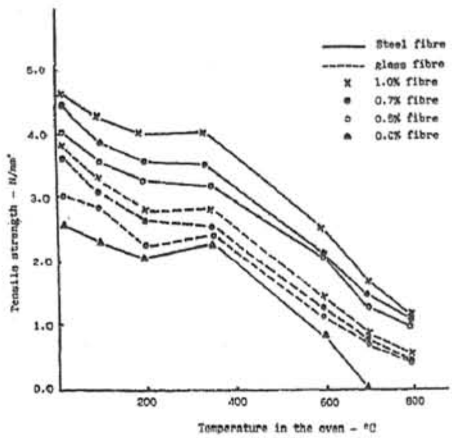

Figure 4: Effect of temperature and fibre reinforcement type and quantity on splitting-tensile strength of specimens tested at temperature, [18]

Sharma et al. [19] tested the influence of steel (1%) and lead fibres (up to 3%) on the shielding effectiveness of such composites; mechanical properties of FRC were also verified using traditional procedures. The results have shown that steel fibres had no influence on the shielding properties, and lead fibres did not improve mechanical properties. However, the lead and steel-lead hybrid fibre reinforcement increased the attenuation of gamma radiation by 50% with respect to plain concrete.

Tests on notched beams executed as part of study by [20] indicated that the application of hybrid fibre (steel and polypropylene) reinforcement of concrete elements resulted in appreciable improvement in fracture energy at room temperature and after elevated temperature exposure compared to companion plain concrete beams.

5. CONCLUSIONS

There are only few applications of dispersed fibres in concrete barriers intended to resist release of radioactive rays in nuclear facilities and storages. It seems that for both effects: increased resistance to cracking and better distribution of excessive heating, appropriate fibre reinforcement may be considered together with their potential ability to attenuate radiation.

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