Part 1 – General aspects and action of fibres

Optimising concrete mixes for greater safety in case of fire

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Civil and industrial engineering building structures are subjected to various loading conditions during their service life. Besides permanent or frequently recurring actions, extraordinary stresses can occur. These can also include fire, for example. The behaviour of concrete in case of fire is principally characterised by the temperature-dependent change in the physical, chemical and mechanical behaviour of its constitutive materials. This behaviour can cause impairment in load-bearing capacity right up to failure of the construction material and structure. This article is based on the results of current research into the action of polymer fibres in reducing concrete spalling. It summarises important new knowledge as to how measures and optimisations in concrete technology can be employed to improve the fire resistance of concrete. This first part of the report at hand is concerned with the general aspects and action of fibres. The influence of cement type and aggregates will be dealt with in the second part of this article in CPI 1/2019.

Concretes of common compositions are classified as non-inflammable construction materials. This means that they do not contribute to an increase in fire load. Concrete limits any damage that might occur as a result of the action of fire, for example as thermal protection of steel reinforcing if there is sufficiently resistant concrete cover. In cases where the concrete mix is not resistant to the action of fire, it is possible that physical-chemical conversion processes take place within the concrete's microstructure that will be accompanied with a loss of strength and rigidity at a macroscopic level. Thermo-mechanical and thermo-hydraulically induced deformations can be added to this and in certain cases concrete spalling as a consequence. The latter can lead to substantial limitations in the load-bearing capacity of structures made from both non-reinforced and reinforced concrete. These limitations can be primarily traced back to insufficient permeability for water vapour in the concrete and be considerably reduced with the aid of polymer fibres, for example.

If the specific high temperature behaviour of individual concrete constituents is known, it then becomes possible to adjust the properties of the concrete as a whole in a targeted manner and thereby significantly improve fire and spalling behaviour.

Performance of concrete under short-term fire exposure

Definition of a short-term fire exposure from a material science perspective

It may be assumed that a fire action is short-term when the duration of the fire exposure amounts to a maximum of 240 minutes and does not exceed a maximum temperature of approximately 1,400°C. These limiting values are founded on material science grounds, i.e. they are presumed in relation to describing the behaviour of concrete constituent materials as a consequence of fire exposure. However, they do not reflect any normative or safety-related consideration of the action of fire – as in the case of a standardised temperature-time scenario.

Fires occurring in real life can, depending on fire load and other conditions relevant to geometrics and ventilation, deviate substantially from the length of fire action and maximum temperature mentioned above. Nonetheless, taking the marginal conditions formulated above into account, the performance of concrete in the case of a brief fire action is essentially influenced by the thermal and temporal behaviour of its individual source substances as well as their interaction with each other. In comparison with other construction materials, greater thermal stability, lack of smoke formation and absence of toxic gases can be named as other performance features of concrete under the action of fire.

Behaviour of different types of concrete under short-term fire exposure

Considerable differences in the thermo-mechanical and thermo-hydraulic behaviour of various types of concrete do exist in a fire action. There are very distinct differences between normal and high-performance concretes. High-strength, self-compacting and ultra-high-strength concretes display a tendency to premature spalling on surfaces exposed to fire stress in experimental investigations in a laboratory, as also in fire testing. The reason for this is that significantly fewer diffusive means of transport for water vapour are generated in the cement matrix on account of its denser microstructure

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and associated lower permeability in comparison with normal concrete. Permeability of ultra-high-strength concrete is still lower when compared with that of self-compacting and high-strength concrete. The greater density does indeed have a positive effect on durability characteristics in a cold state but is rather disadvantageous in case of fire. If concrete is heated as a result of fire, free and physically bound water evaporates above a temperature of approximately 105°C. One part of the resulting water vapour diffuses into the concrete in line with the heat front's progression and condenses in areas that have not as yet been heated. This procedure is then concluded when a temperature-related condensation zone is almost completely filled with liquid water. Further diffusion of the water vapour into the concrete's cooler zones is inhibited by the liquid water's incompressibility in the condensation zone. As a consequence, vapour pressure increases disproportionately, especially inside of the cement matrix's capillary pores. With normal concretes, with their relatively good porosity and micro-crack formation ensuing from an earlier heating stage, vapour pressure can either be released into the larger pores or be reduced by escaping through micro-cracks. Contrary to this, an increase in vapour pressure occurs with a very dense concrete microstructure. If this pressure attains the concrete's tensile strength, then spalling – like explosions – takes place. This can lead to construction material failure if it continues to progress.

Increasing fire resistance by optimising concrete composition

A thermal action inside concrete basically causes specific chemical reactions, mineralogical phase transformations and physical processes (e.g. thermal expansion, alterations in the state of the aggregates etc.), as a result of which its mechanical properties are also influenced [1, 2].

A differentiation can be made according to heating rate, maximum temperature and duration of action as regards the thermal action in differing application cases (e.g. refractories or fire). No matter how the increase in temperature comes about, the crucial issue is what processes are initiated as a consequence of the action of temperature in concrete and the effect they have on its suitability for a selected purpose.

The continually changing and mutually interdependent mechanisms of concrete plus its great heterogeneity as a multiphase construction material are decisive factors in why an optimisation of concrete technology must take place on the basis of fundamental scientific investigations into its behaviour at high temperatures. Every component of this composite construction material has its own weighting with regard to high temperature behaviour and must initially be taken into consideration on its own on account of its chemical-mineralogical composition, microstructure characteristics and importantly in respect of its substance fraction in the composite system. Optimising individual components is meaningful for the overall system.

Measures (see e.g. [3-13]) can be taken to optimise the mix composition and improve the fire resistance of concrete based on current research results concerning the high temperature behaviour of cementitious binders, temperature-related damage mechanisms within aggregates and the mode of action of polymer fibres in reducing concrete spalling. This article will restrict itself to mix optimisation using polymer fibres.

Polymer fibres

Micro-polymer fibres made from polypropylene (so-called PP fibres) are usually added to concrete with the aim of increasing permeability during the action of fire. This effect of PP fibres is attributed to their melting and decomposing which creates micro-channels in the concrete that contribute to a lessening of (saturation) vapour pressure in the concrete's pore microstructure. In addition, PP fibres decompose as a result of the progressive action of temperature, which leads to a volume expansion of the molten PP fibres and thus to enhanced micro-crack formation in the concrete. This, in turn, facilitates a reduction in temperature-related residual and restraint stresses [14].

Normative fundamentals and special properties

In Germany, polypropylene fibres (PP fibres) are classified according to DIN EN 206-1 [15] in conjunction with DIN 1045-2 [16] under the group of concrete additives. DIN EN 14889-2 [17] is of valid application in characterising the product properties of PP fibres. Further specific properties, such as improvement in fire and spalling behaviour, were furnished until recently within the framework of a building authority certificate of usability. The building authority approvals granted up to date will run out latest in the year 2020. This will then require an adaptation of national regulations for infrastructure projects (ZTV-ING [18] and DB guideline 853.1001A01 [19]) with regard to the stipulations placed on PP fibres for improving fire and spalling behaviour.

Polymer fibres can be manufactured using a spinning process (wet spinning, dry spinning or melt spinning) or by punching them out of a foil sheet. Mono-filament PP fibres (single fibres) are spun, surface treated and finally cut to length. Their modulus of elasticity and strength can be substantially enhanced by special mechanical and/or thermal processes, e.g. stretching and/or heat treatment. On top of this, polymer fibres can be exposed to electromagnetic radiation in order to attain better flow behaviour at temperatures under the melting point. This can be described by means of the MFI value (MFI – Melt Flow Index). PP fibres treated in this way should be utilised for structural fire protection because their proven effectiveness in relation to fire protection can be exploited at a relatively early stage of stress due to temperature. When their interaction with other concrete source substances is also taken into consideration, PP fibre content can be reduced thereby improving fresh concrete consistency.

New findings concerning polymer fibre durability

Generally speaking, polypropylene possesses very good resistance to chemicals and is highly resistant to alcohols, organic acids, esters and alkalis or bases. This means that PP fibres can be viewed as basically resistant to all the usual conditions prevailing in concrete. However, intensified thermal-oxidative ageing can occur in polypropylenes due to increased ambient temperatures, which can influence PP fibre properties. This has to be taken into account in assessing the long-term stability of PP fibres in concrete (Fig.1). Oxidation stability can be employed using differential scanning

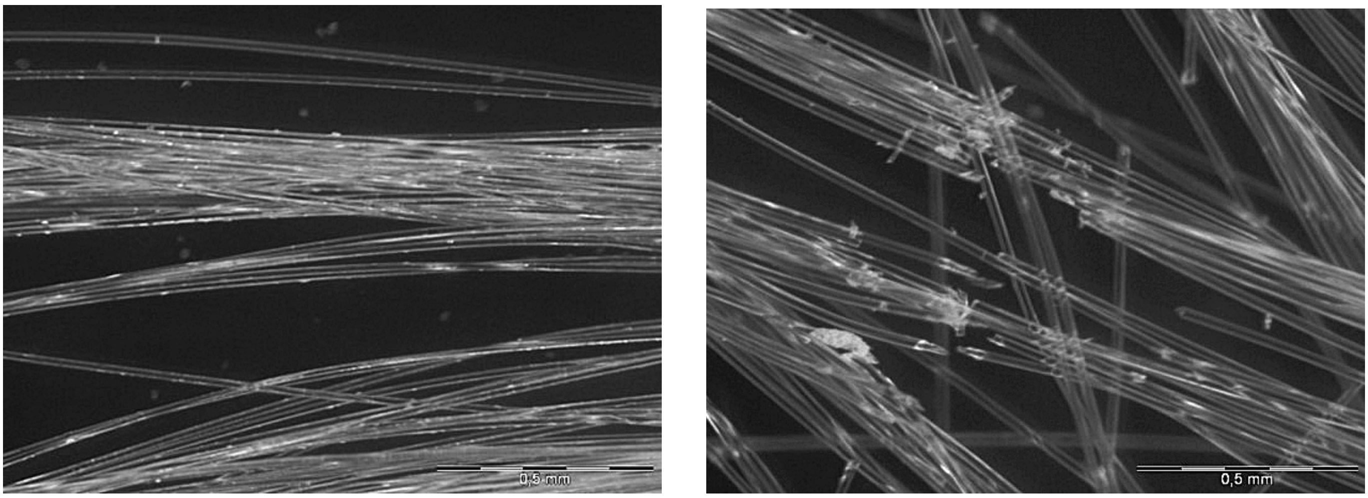

Fig. 1: Change in PP fibres as a result of ageing

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Fig. 2: Scanning electron microscope images of PP fibres

calorimetry with a view to qualitatively estimating the ageing resistance of polymer fibres (see DIN EN ISO 11357-6:2013-04 [20]). It enables a rough estimate to be made of the degree to which PP fibres in a surface – and thus possibly fire-stressed area – are still effective at all if such ageing might have taken place.

Functioning of PP fibres in case of fire

An effective reduction in explosive spalling in concretes can be achieved by means of a pore system, which leads to a sufficient decrease in (saturation) vapour pressure. This is possible by adding polymer fibres, which, on the one hand, melt with the action of fire, open up uninterrupted micro-pores and in addition form micro-cracks in the cement matrix and, on the other hand, form - between cement matrix and PP fibres - a porous transition zone, through which any (saturation) vapour pressure can be released at an early stage. As a consequence, there is a need for pores, cracks and PP fibres with specific diameters, lengths and layers in order to conduct water vapour away and thus restrict tensile stresses. Optimal pore cross sections can be given by two counteracting factors depending on the concrete source substances and its microstructure: firstly by the diffusion path and large surface, and secondly by the inhibited substance transportation within the pores. Large capillaries create too long a path and make too small a surface available for water vapour transport.

However, small pores are not capable of letting the water vapour escape rapidly enough. Based on these considerations, the upper limit for effective pore diameters must presumably be less than a tenth of a millimetre. The lower limit will have been reached when the pores' substance transportation is reduced to the degree of diffusion speed (smaller than 3 µm). The testing carried out suggests that a major part of the free and physically bound water has already vaporised before the PP fibres begin to decompose. However, PP fibres are still to be found locally in the cement matrix. As a consequence, possible escape channels for water vapour pressure will be generated in particular through the filtered transition zones between cement matrix and aggregates as well as between cement matrix and PP fibres. The positive action of polymer fibres on the resistance of concrete to fire can be mainly attributed to the following factors listed below, however it has not yet become clear which of these factors is dominant [21]:

- Improved permeability in concrete through the formation of capillary pores, which are formed when PP fibres melt and burn (Fig.2).
- Improved permeability through the creation of transition zones open to diffusion (Interfacial Transition Zone, ITZ). It is clear, when looking at the structure in the transition area between aggregates and cement matrix, that additional pores and soft hydration products, such as portlandite and ettringite, are formed at these border areas. The thickness of these transition zones is primarily dependent on the equivalent w/c ratio, on the type of cement and the utilisation of reactive fines as concrete additives (silica fume, fly ash, metakaolin, etc.). In principal, the transition zones facilitate greater substance transportation (moisture diffusion) but they are only sometimes connected to each other. The addition of PP fibres generates supplementary transition zones around the PP fibres, which create a connection between the various transition zones and thus make the concrete more permeable. In addition to this exists early formation of micro-cracks, which are formed as a result of the expansion of the molten PP fibre mass and make an additional contribution to the reduction of internal pressure and stresses in the concrete microstructure (Fig.2).
- Improved permeability through additional micro-pores, which are formed as a result of the structure loosening up when mixing PP fibres into conctete. That such an action does indeed occur is shown by the fact that the compressive strength of concrete is lowered by adding greater proportions of polymer fibres.

Conclusions

Protection against fire is an essential basic requirement for civil and industrial engineering structures. Building structures made from concrete as a construction material also have to satisfy this basic requirement and the protection objectives implied therein. Structural measures are conceivable in order

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*Figures provided are based on an actual case from the precast concrete element factory fdu Betonwerke, Germany to attain these objectives, for example as described in relevant design standards (e.g. DIN EN 1992-1-2 [9] etc.). Optimisation is possible involving purely the material composition of concrete so that any damage as a result of the action of fire will be minimised and so that the protection of both humans and property can be assured on a permanent basis. Growing complexity, e.g. through the diverse combination possibilities of constituent materials, manufacturing conditions and post-treatment, are tending to cause concrete to develop increasingly into a high-tech material and tailor-made construction material, which can and must be harmonised with specific project requirements. As a consequence of these developments, it must be said that, up to the present time, knowledge has not been available for all concrete properties under differing actions. Amongst these is its specific behaviour when subjected to the action of fire. It has nevertheless been shown that it is possible to substantially enhance the resistance of concrete to fire through concrete technology measures. A more thorough understanding of the high temperature behaviour of concrete source substances can be exploited to this end. Further possibilities for concrete optimisation will be offered by taking this new understanding into account as well as by future developments in concrete technology with regards to cementitious binders, aggregates and concrete additives. These new possibilities will permit concretes to be produced that exhibit great resistance to fire, yet entirely without any additional structural protection measures.

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