GALVANIZED STEEL FIBRES IN CONCRETE – INFLUENCE ON CONCRETE STRUCTURES AND BOND BEHAVIOUR DUE TO HYDROGEN FORMATION

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Abstract:

In concrete structures steel reinforcement normally is protected against corrosion by the special environment of the concrete with pH-values of about 12…13. Due to carbonation such a protection can not be ensured for steel fibres in areas next to the surface, with only small cover within a short period so that both a loss in load capacity, as well as an optical impairment of the surface can be caused by corrosion of the steel fibres. These problems can be avoided by the use of galvanized steel fibres. However, the zinc coating of the fibres can react with components of the cements when the chromate content of the cement used is low as it is required nowadays mostly in Europe. By such reactions hydrogen is released and accumulates preferably the fibre / matrix interface which can diminish in the bond strength between the fibre and the matrix.

In experimental studies the influence of the type and the content of fibres as well as the use of inhibitors on the temporal development of hydrogen and the pore size distribution were investigated in concrete samples. Furthermore, the bond behaviour of the fibres was determined in the pull-out- and flexural tension tests. By the formation of calcium hydroxide-zinc the roughness of the fibre surface was increased resulting in higher pull-out forces as well as in a more distinctive post-fracture behaviour.

Actual developments focus on the prevention of the zinc reaction by using an inhibitor. The effectiveness of such inhibitors could be confirmed in the experimental tests.

Keywords: galvanized steel fibres, flexural tension strengths, hydrogen formation

1 Introduction

In reinforced concrete structures the protection against corrosion of the steel reinforcement is usually ensured by the alkaline environment of concrete. The basis for such a durable corrosion protection is a sufficient concrete cover of the reinforcement. In steel fibre concrete structures a part of the bare steel fibres is located next to the concrete surface. Under these conditions the above-mentioned protection against corrosion can not be guaranteed for longer periods because of a fast carbonation into these sections. The result is the corrosion of steel fibres in this surface layers, primarily associated with an optical impairment.

To prevent such an impair steel fibres with an additional artificial corrosion protection by a zinc coating are on the market. This technique has already been tested in the past with rebars and prestressing steel to ensure a long-term protection against corrosion of the reinforcement at chloride exposure or in the case of very intricate structural elements.

However, by using galvanized steel fibres in concrete a reaction between the zinc and the alkaline pore solution is possible in fresh and young concrete. In this reaction hydrogen is separated off by the simultaneous formation of calcium hydroxide-zinc. Such adverse conditions especially are expected if the fresh concrete contains little chromate (VI), what's the present practice today by using chromate reduced cements. The gaseous hydrogen is preferably located in the interface zone between the zinc layer and the surrounding concrete. So the bond between these two constituents can be weakened more or less. Moreover, due to variations in the concrete structure caused by such gas bubbles and the adequate increased porosity, impairs in the concrete properties, especially in the peripheral zone, have to be expected, which also may affect the bond of the classic reinforcement bars with the concrete in the neighbourhood.

Based on a comparison of galvanized steel fibres and non galvanized steel fibres as well as galvanized steel fibres with inhibitors the effectivity of the fibres was evaluated. In this context the bond behaviour of steel fibres in concrete was investigated by determining the equivalent flexural strength. Furthermore in pull-out tests the bond behaviour of the used fibres was tested in mortars.

2 Chemical Reaction

2.1 Reaction process

In general sense alkaline solutions are aqueous solutions of alkali hydroxides. Due to the extremely corrosive nature of the highly alkaline solutions metals may be attacked.

Chemically zinc is one of the base metals and therefore reacts to its amphoteric property in accordance with strong alkaline mediums follows:

$$Zn(OH)_2 + OH^- \rightarrow Zn(OH)_3^-$$

Between pH-values of 7 and 12.5 zinc points its highest resistance against corrosion. In this pH-range also the carbonated concrete is situated. Only within a small exceeding of the pH-value 12.5 a strong dissolution of the zinc starts. Depending on the water-cement-ratio (w/c-ratio) and alkalinity of the cement the fresh concrete normally is in a pH-range between about 12 to 13.5. Therefore, in most cases zinc corrosion in fresh concrete can be assumed.

If zinc comes in contact with fresh concrete, they behave in the early stages very corrosive. The zinc coating will be attacked in a partial anodic reaction by the alkaline pore solution under preliminary development of hydrogen.

$$Zn \rightarrow Zn^{2+} + 2\ e^-$$

Due to the negative corrosion potential water decomposition under hydrogen formation will take place as a partial cathodic reaction.

$$2\ H_2O + 2\ e^- \rightarrow H_2 + 2\ OH^-$$

Subsequently zinc hydroxide develops which transforms into zinc oxide by a secession of water molecules:

$$Zn(OH)_2 \rightarrow ZnO + H_2O$$

2.2 Effect on the concrete structure and the concrete properties

During the formation of calcium hydroxide-zinc hydrogen gas bubbles develop at the surface of the steel fibres. Therefore it is important, how the concrete properties are impaired mainly in the bonding zone between the steel fibres and the concrete matrix.

With hydration progress these bubbles cause a porous concrete micro structure in the bonding zone and in their environment. Consequently, the concrete structure is weakened mainly next to the reinforcing steel or steel fibre resp..

If the concrete is casted with at least soft consistency (F3) the hydrogen bubbles can typically easy escape under the permission of small concrete overlaps. At stiffer concrete consistencies bubbles remain in the concrete and cause a porous structure. Duration and intensity of thus hydrogen formation mainly depend on the alkalinity of the used cements.

From some other investigations it is reported that the products of the zinc corrosion, including the calcium hydroxide-zinc, are installed in the hydration products. Cement clinker and calcium hydroxide-zinc react at the contact area and the hardening process slows in the initial stages. However, in later stages have this strength increasing effect.

3 Performed Tests

3.1 Used fibre types

Within the performed tests, three fibre types were investigated concerning their effect in concrete and mortar (Tab. 1). On the one hand galvanized steel fibres (Type A), which were loose and without inhibitor available were checked. On the other hand galvanized steel fibres, which were glued with an inhibitor charged adhesive to bundles (Type B) were tested. In addition, conventional non-galvanized steel fibres (Type C) were investigated.

Tab. 1 Characteristics of the tested steel fibres

Fibre type	Fibre surface	Form of delivery	Additive	Length / Thickness [mm]	l/t - ratio
Type A	galvanized	loose	without Inhibitor	60 / 0,75	80
Type B	galvanized	glued	with Inhibitor	60 / 0,75	80
Type C	non-galvanized	glued	without Inhibitor	60 / 0,75	80

3.2 Testing strategy

To evaluate the bond behaviour of the fibres flexural tests on beams of fibre-concrete (750 x 150 x 150 mm³) were performed to determine the equivalent flexural strength. The beams were prepared in accordance with DIN EN 12390-2. The steel fibre concrete beams were tested at the age of 28 days in accordance with the specifications of DIN EN 12390-5 in a 4-point flexural tension test. The two decisive post-cracking flexural strengths were determined from the load-deflexion curve at the deflections δ_{L1}=0.5 mm and δ_{L2}=3.5 mm.

To determine the bond strength between a steel fibre and a standardized mortar in accordance to DIN EN 196-1 pull-out tests were performed. Hence steel fibres were taken from the mortar mixer and embedded, including their anchorage, by hand 2.5 cm deep in a mortar prism (l/w/h = 5.0 cm / 5.0 cm / 2.5 cm). In each specimen only one fibre was inserted. This fibre must not be deformed by this procedure to prevent deflection forces during the tests. A plastic formwork was used for the production of these specimens. In this formwork the steel fibres were pre-fixed in the direction of the subsequent force application.

After testing the equivalent flexural strength the steel fibres were randomly extracted from the specimens and their surfaces were investigated by a stereomicroscope to check the variations on the fibre surface, probably raised by the calcium hydroxide-zinc reaction.

3.3 Concrete and Mortar mixes

For the steel-fibre-concrete beams for the flexural tests the following concrete mix was used:

Tab. 2 Concrete mix

- CEM I 32,5 R, Cr (VI) < 2 ppm		410 kg/m³
- Aggregates Rhine gravel / -sand Grading curve A/B16	Total	1740 kg/m³
	0 / 2	520 kg/m³
	2 / 8	610 kg/m³
	8 / 16	610 kg/m³
- Water content		205 l/m³
- w/c-ratio		0,50
- Steel fibres		40 kg/m³

To produce the test specimens for the pull-out tests a mortar mixture was used in accordance with DIN EN 196-1. The steel fibres were added to the mortar right from the beginning of mixing, so that in case of the fibre type RC-80/60-CN "Green" the glue with the inhibitor could be solved in the mortar mix during the mixing process.

4 Results

4.1 Results of the flexural tension tests

On the basis of the final draft of the DAfStb-guideline "Stahlfaserbeton" the provided performance classes were determined after evaluating the flexural strengths (Tab. 3).

Tab.3 Performance classes according to the final draft of the DAfStb-guideline „Stahlfaserbeton“

Fibre type	$f^{f}_{cflm,L1}$	$f^{f}_{cflm,L2}$	$f^{f}_{cflk,L1}$	$f^{f}_{cflk,L2}$	Performance class	
	[N/mm²]	[N/mm²]	[N/mm²]	[N/mm²]	L1	L2
Type A	3,53	3,09	1,80	1,58	1,8	1,5
Type B	4,18	3,59	2,13	1,83	2,1	1,8
Type C	4,53	3,87	2,31	1,97	2,1	1,8

The galvanized steel fibres with inhibitor achieved with L2,1/1,8 the same performance class as the non-galvanized steel fibres. In contrast to this the galvanized steel fibres without inhibitor could be related only to a lower performance class of L1,8/1,5. By a more intensive evaluation of the residual values for the deflections δ_1=0.5 mm and δ_2=3.5 mm, the galvanized steel fibres without inhibitor achieved only 16% lower flexural strengths compared to the same steel fibres with inhibitor.

The mean fracture loads F_u ranged at all determined fibre types from 27.9 kN to 29.3 kN. The standard deviations varied between 1.52 kN and 3.16 kN. Hence, the variances differed from 5.4 % to 10.8 %. From these low differences between the mean fracture loads, correlating with the low variances it can be concluded that hydrogen formation in concrete with galvanized steel fibres without inhibitor does not significantly affect the first cracking flexural strength, however the following behaviour in the stress-strain relation and thus in the ductility resp..

4.2 Results of the Pull-out Tests

The maximum pull-out forces and the force-pull-out-relationship were recorded by means of the experimental setup. The results of the measurements are summarized in Tab. 4.

Tab. 4 Results of the pull-out tests

Fibre Type	Average of the max. forces [N]	Bond stress [N/mm²]	Standard deviation [N]	Variation coefficient [%]	Minimum [N]	Maximum [N]
Type A	247	4,19	79	32,1	170	375
Type B	267	4,53	49	18,2	210	325
Type C	315	5,35	67	21,2	240	390

For the galvanized steel fibres without inhibitor (Type A) the lowest bond forces were recorded at a mean of about 247 N, i. e. a mean bond stress of about 4.19 N /mm². These values were 7.5% lower than those of the steel fibres type B and 21.7% lower than those of the non-galvanized steel fibres type C.

The mean displacement curves of the three investigated fibre types are illustrated in Fig. 1. It could be observed that the forces are nearly equal for all three fibre types at displacements up to 0.5 mm. In the further development the curves diverge enormously. The fibre types B and C exceed already at low displacements (1.5 mm - 3.0 mm) their maximum force, whereas for galvanized fibres without inhibitor an enlarged displacement (> 3.5 mm) is necessary to activate their maximum bond stress.

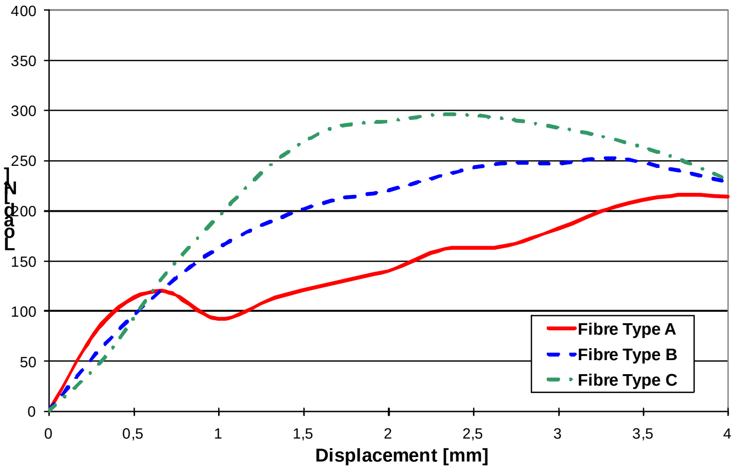

Fig. 1 Mean curves of the pull-out tests

4.3 Optical investigation of the specimens

The steel fibre surfaces were investigated under a stereomicroscope after a flexural tension test. Examples are illustrated in Fig. 2.

The surface of a galvanized steel fibre without inhibitor (Type A) is shown in Fig. 2, left. Hydroxide-zinc crystals have been formed as a result of the reaction between zinc and the fresh concrete. These crystals form a strong and solid structure around the steel fibres, so that cracks caused by a bending test have not been developed in the transition zone fibre/matrix, but rather in the surrounding hydroxide-zinc coating. The crater-like structure of the hydroxide-zinc coating results from the release of hydrogen during the reaction.

No hydroxide-zinc crystals were recognized on the steel fibre surface of Type B (galvanized, with inhibitor) (Fig. 2, middle). Here, only an unchanged smooth, galvanized surface was existent. This confirms the effectiveness of the used inhibitor because a reaction of zinc had apparently not taken place with the upcoming alkaline fresh concrete.

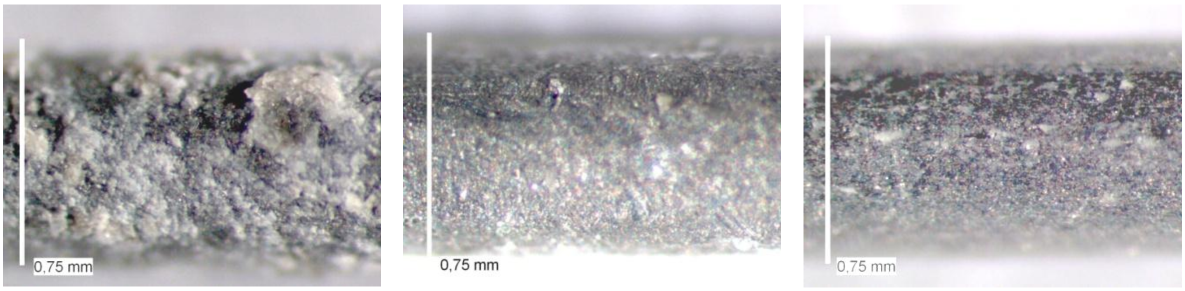

Fig. 2 Steel fibre surfaces at an extracted fibre (left: fibre Type A, middle: fibre Type B, right: fibre Type C)

In Fig. 3 significant gas pores in the matrix are observable which result in an incomplete embedding of the fibres (Fig. 3).

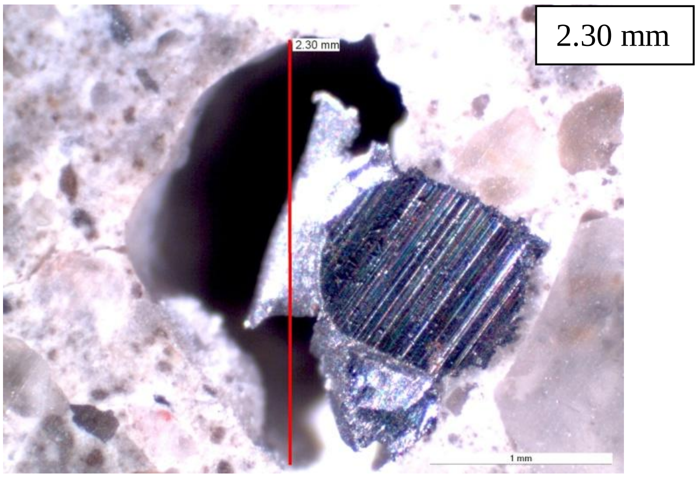

Fig. 3 Microscopic recording at a polished section on a concrete with galvanized steel fibres (Type A)

5 Conclusions

Within this investigation flexural tests on steel fibre reinforced beams were carried out with evaluation according the final draft of the DAfStb-guideline "Stahlfaserbeton". In these tests, the types of steel fibres were varied. In two series galvanized steel fibres and in one series non-galvanized steel fibres were used. The two types of galvanized steel fibres differed in an inhibitor that was used for one type.

In the bending tests the non-galvanized as well as the galvanized steel fibres with inhibitor reached almost the performance class for steel fibre reinforced concrete. In contrast, the beams with the galvanized steel fibres without inhibitor revealed significant lower flexural strengths for the ultimate limit state and the serviceability limit state which led to a classification of this type of steel fibre to a lower performance class. This evaluation methodology based on real values and allows therefore a good interpretation of the real influence.

In addition, the maximum pull-out forces of the different fibre types were determined on mortar samples. For this purpose the steel fibres were embedded in a standard mortar and were pulled out at the age of 2 weeks within a uniaxial tensile test. Both types of galvanized steel fibres showed lower bond strengths than the non-galvanized steel fibre type. The pull-out forces of the extracted galvanized steel fibres with inhibitor were around 10% higher compared to the galvanized steel fibres without inhibitor. The results of the pull-out test were subjected to a more or less high scattering of the measured values. Because of the relatively low number of tested specimens a trend of the steel fibre behaviour was observable only.

Finally, the steel fibre surfaces were investigated in more detail by means of a stereomicroscope. Neither the galvanized steel fibres with inhibitor nor the non-galvanized steel fibres showed reaction products in form of hydroxide-zinc on their surface. In contrast, the galvanized steel fibres without inhibitor were covered with an uneven layer of hydroxide-zinc.

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