Cement and Concrete Research 40 (2010) 410–414

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Surface corrosion of steel fibre reinforced concrete☆,☆☆

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ARTICLE INFO

Article history:
Received 23 January 2009
Accepted 1 October 2009

Keywords:
Fibre reinforcement (E)
Concrete skin
Corrosion (C)
Durability (C)

ABSTRACT

Corrosion of SFRC (Steel Fibre Reinforced Concrete) in an adverse environment, less harmful as compared to corrosion of steel reinforced concrete, is often considered to be of minor importance, however it exists. It can affect the fibres bridging the cracks and then decrease the strength of the concerned structures. As well, it results in the appearance of corrosion spots at exposed surfaces. Then the damaging effect is no longer expressed in terms of resistance, it is only aesthetic. It is especially undesirable in prefabricated structures. The work developed in this paper focuses on this second point: surface corrosion. Fibre reinforced concrete prisms have been subjected to cycles of salt fog (1 week) and drying (1 week). The results obtained demonstrate that with high W/C ratio (0.78), all the fibres which are embedded in concrete less than 1 mm are susceptible to give corrosion spots at the surface. When W/C is reduced to about 0.5, the minimum necessary cover to prevent surface corrosion drops to 1/10 mm or 2/10 mm and further decrease of W/C does not bring extra significant benefit. This result is in agreement with the analysis, by mercury intrusion, of the skin concrete porosity. It confirms a sharp change in the pore diameters when W/C is decreased from 0.78 to 0.48 and a quasi stability when it is varied from 0.48 to 0.36.

Résumé

La corrosion des fibres dans les bétons renforcés de fibres métalliques (BFM), moins sévère que celle des armatures dans le béton armé, est souvent négligée. Cependant elle existe. Elle peut attaquer les fibres pontant les fissures et altérer la résistance des structures concernées. Elle se manifeste aussi par l'apparition de taches de rouille sur les surfaces exposées. Ceci n'affecte pas la résistance mais a une incidence esthétique certaine, particulièrement dans le cas d'éléments, souvent préfabriqués, restant visibles en parement.
Le travail présenté dans cet article est centré sur ce second point : la corrosion de surface. Des prismes de BFM ont été soumis à des cycles d'une semaine de brouillard salin alternant avec une semaine de séchage. Il en ressort que dans un béton de rapport E/C élevé (0,78), toutes les fibres enrobées de moins 1 mm sont susceptibles de donner naissance à des taches de rouille en surface. Lorsque E/C est réduit à environ 0,5, l'enrobage minimum nécessaire pour se prémunir de la corrosion de surface chute à 1/10 ou 2/10 mm et toute diminution supplémentaire de E/C n'apporte pas de bénéfice significatif. Ce résultat est en accord avec l'analyse porosimétrique du béton de peau. En effet, celle-ci confirme une chute importante du diamètre des pores lorsque E/C passe de 0,78 à 0,48 et une stabilités lorsqu'il est ensuite diminué jusqu'à 0,36.

1. Introduction

The use of SFRC (Steel Fibre Reinforced Concrete), firstly centred on pavements and sprayed concrete, is enlarging itself to numerous other domains of construction. The corrosion of SFRC is apparently less damageable than in the case of steel bars reinforced concrete. However it exists and we are going to see that its effect is not necessarily expressed in terms of resistance.

There is a fundamental difference between rebar reinforced concrete and fibre reinforced concrete. In the first case, the steel bars are perfectly located, with controlled cover depth usually equal to or exceeding 2 cm. In the case of SFRC, the fibres are dispersed in all the volume of the material and those, which are close to the surface, have very little concrete cover, saying zero. Thus corrosion can be viewed in two aspects. The fibres corrosion due to cracks can

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doi:10.1016/j.cemconres.2009.10.001

jeopardise structure strength and put their stability in danger. The corrosion at surface can be described as appearance of rust spots at the surface on the exposed concrete structures. The work presented here is focused on the second point, the surface corrosion.

This one was neglected for a long time; it however creates a crucial problem in the case of elements, generally prefabricated, which remain visible. The objective of this study is to measure the minimum concrete cover of fibres necessary to prevent the appearance of surface corrosion spots and to highlight its relation with the W/C ratio and the skin porosity of the concrete.

2. Literature survey

Literature is mainly focused on corrosion arising from cracks. The only casual results that we could find about surface corrosion are side results reported from studies of corrosion inside the cracks. Halvorsen et al. [1] prepared cracked concrete beams of 76*76*381 mm and a 5% solution of calcium chloride at the temperature of 145 °F (62.8 °C) was continuously blown onto each beam and through the cracks. They observed that corrosion both on the surface of cracked and un-cracked specimens. Mangat and Gurusamy [2] noticed corrosion spots at the surface of concrete specimens that were exposed to 150 cycles of marine water spray for 12 h and then followed by 12 h of drying.

3. Cover of fibres

It is a basic parameter in this study. Its measure, typical results and the possible influence of concrete vibration, are presented in details in Ref. [3].

To the measure cover of fibres, the methodology is to count the number of fibres available at a particular depth in the mass of concrete from the surface of a cast face. For each face studied, the fibres appearing on the surface are first counted, meaning those fibres whose cover depth is zero. Then, by grinding, a controlled thickness of the material (typically 0.02 mm or 0.1 mm) is removed. The counting of fibres encountered gives the number of fibres embedded at that grinded depth. The same procedure is repeated until 1 mm depth. The grinding machine available in the LMDC laboratory has the facility to grind up to the precision of 1/10 of mm. The prisms are first placed very precisely in the jaws of the machine by level plumb and tighten so that they are exactly at right angle to the blades of the machine. The measuring gauge available at the turning handle is then fixed at 0, so that initial fixed position of the prism cannot be disturbed. The second gauge, which controls the blades movement, is then fixed at 1/10 of mm. The machine will start grinding the surface of prism just up to one tenth of mm but will not go beyond this prescribed depth. The machine is stopped and after counting the number of fibres

Fig. 1. Prism before grinding.

Fig. 2. Prism after grinding.

encountered with highly illuminated lamp, the second position is given to gauge at 2/10 of mm and process of grinding is restarted. It is to note that during the whole campaign of grinding the prism is fixed in the jaws and the original position is not disturbed. The delicacy and effeteness of this method can be viewed in pictures shown in Figs. 1 and 2. Typically, a few fibres have a nil cover depth and a significant number of them are imbedded less than 2/10 mm inside the mass of the concrete. Increasing the mobility of the fibres in the concrete, by achieving a higher workability of the mix and by decreasing the proportion of coarse aggregates is beneficial. A better result is obtained when mould vibration is applied. Anyway, the benefit of an adequate grading and placement of the mix remains small. It clearly diminishes the number of fibres with nil cover but the number of fibres with a cover ≥1/10 mm remained unaltered. Industrial mightier formwork vibration means more visible results could probably be achieved but one should not expect to get a minimum cover of the fibres larger than 2/10 mm.

4. Surface corrosion

Two series of tests were carried out. One with high W/C ratio concrete reinforced with two different types of steel fibres, the other one with different W/C ratio concrete. The objective of this second series was to investigate the effect of skin porosity. The samples were 100*100*500 mm^3 prisms cast in two layers and table vibrated.

4.1. First series: high W/C ratio and two types of fibres

A high W/C ratio (W/C = 0.78) was chosen to test the extreme case of a low quality concrete. The composition of the mix is given in Table 1. Two types of fibre, at 40 kg/m^3, were investigated: macro fibres (hooked end, length = 30 mm, diameter = 0.5 mm) and micro fibres (straight end, length = 13 mm, diameter 0.17 mm). At the same dosage the micro fibres were found to be more in number in the mass of the concrete and at the proximity of the cast faces. After casting, the concrete prisms were cut into two halves of 100*100*250 mm^3 and were placed in an accelerated corrosion chamber at ambient

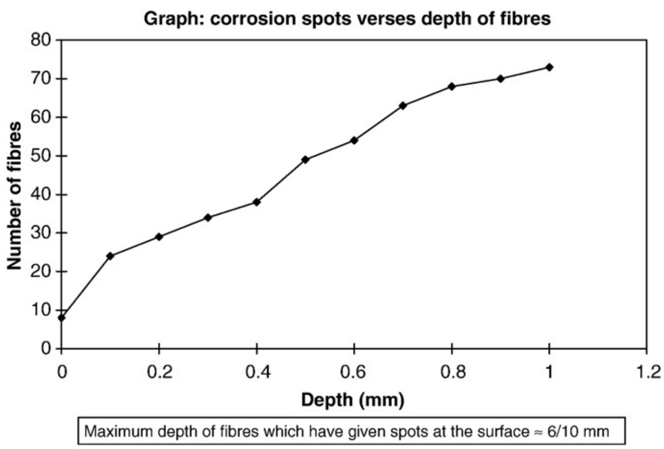
Table 1
Series 1: composition of the concrete mix.

Composition in kg/m^3	Concrete
Cement (CPJ CEM 52,5 R)	250
Sand 0–5 mm	655
Gravel 5–12 mm	1116
Water	170 to 195
W/C	0.70 to 0.78
Admixture	0 to 1.7% of weight of cement
Fibres	40

Table 2
Surface corrosion spots and depth of fibres (counting area = 100*250 mm^2).

Depth (mm)	0	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	1
Number of fibres	8	24	29	34	38	49	**54**	63	68	70	73

Sample type: W/C = 0.78, macro fibres type (30*0.5 mm), number of visible corrosion spots: 56.
Maximum depth of fibres which have given spots at the surface ≈6/10 mm.



temperature. There, they were subjected to weekly wet and dry cycles (one week of salted fog at 35 g/l of sodium chloride and then one week of dryness alternatively). At each cycle the prisms position was changed so that each face receive globally same conditions of fog and dryness.

The spots of corrosion started appearing after the first month and keep on increasing till the end of the 7th month when stabilisation of the number of spots of corrosion was reached. After that, each lateral face of each half prism (100*100*250 mm^3) was treated as follows: the corrosion spots were counted, with naked eye and with a loupe. Then the surface grinding procedure was carried out in steps of 0.1 mm depth and the fibres encountered were counted with respect to the depth. As one goes in the interior of the material, the grinding intercepts larger number of fibres. When this number is equal to the number of spots observed at the surface, the depth obtained is considered corresponding to the maximum cover of the fibres, which has produced these spots at the surface. This procedure is simple and efficient. It has the advantage of giving directly the average value on the whole surface of observation. Moreover, counting the number of spots with the passage of time, with a single final campaign of grinding reveals the ultimate concrete cover of the fibres affected by surface corrosion.

The sensitivity of the method can be judged by watching the results produced in Tables 2–4.

It follows that, with this high W/C ratio matrix (W/C = 0.78), all the fibres, which are embedded at inferior or equal to 1 mm depth are expected to be affected by surface corrosion. It is not possible to move away the fibres at this much depth from the surface to avoid the surface corrosion. Lower W/C ratio is expected to have beneficial effect and this was the objective of the second series testing.

4.2. Second series: effect of skin porosity on the surface corrosion

The skin porosity is closely linked to the W/C ratio of the concrete matrix. We have selected three types of concrete composition ranging from more porous to less, W/C = 0.78, W/C = 0.48, and W/C = 0.36 with macro fibres added in the proportion of 40 kg/m^3. As we already investigated (in the first series) 13 mm and 30 mm long fibres, to complete the domain, we chose for this series 60 mm long fibre

Table 3
Surface corrosion spots and depth of fibres (counting area = 100*250 mm^2).

Depth (mm)	0	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	1
Number of fibres	3	14	22	29	32	35	36	36	40	**46**	**46**

Sample type: W/C = 0.78, macro fibres type (30*0.5 mm), number of visible corrosion spots: 45.
Maximum depth of fibres which have given spots at the surface ≈1 mm.

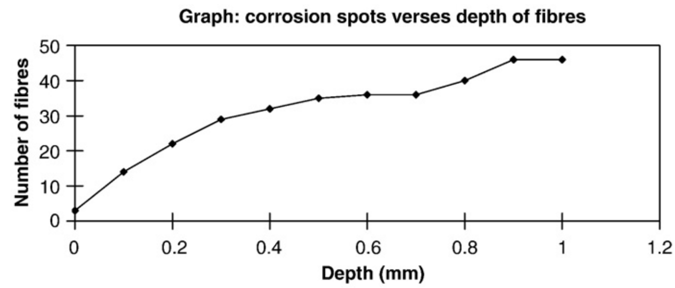
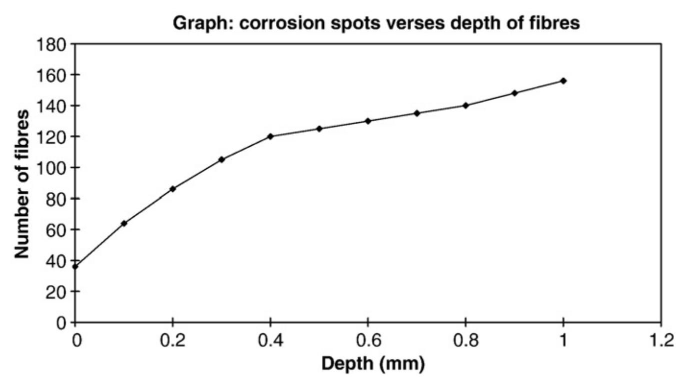


Table 4
Surface corrosion spots and depth of fibres (counting area = 100*250 mm^2).

Depth (mm)	0	1/10	2/10	3/10	4/10	5/10	6/10	7/10	8/10	9/10	1
Number of fibres	36	64	86	105	120	125	130	135	140	**148**	156

Sample type: W/C = 0.78 micro fibres type (13*0.17 mm), number of visible corrosion spots: 150.
Maximum depth of fibres which have given spots at the surface ≈9/10 mm.



(hooked end, length = 60 mm, diameter = 0.75 mm). The compositions of the mixes are given in Table 5.

According to Kreijger [4] the skin of the concrete can be defined as a surface layer of the concrete ranging from 0 to 5 mm thick. Its properties are different from those of the core of the concrete. It consists of paste of cement and fine aggregate. The aggregate/paste ratio is low and increases towards the core of concrete, the porosity is high and decreases towards the core of concrete. The more porous the skin, the more the fibres near to the surface are easily liable to aggressive environment, and the thicker should be the expected minimum cover of the fibres to prevent surface corrosion.

Table 5
Series 2: composition of concretes (kg/m^3).

Composition in kg/m^3	W/C = 0.78	W/C = 0.48	W/C = 0.36
Cement CPA CEM I 52,5 R	270	390	470
Sand 0–5 mm	950	915	901
Gravel 5–12 mm	950	915	901
Water	210	190	171
Fibres	40	40	40

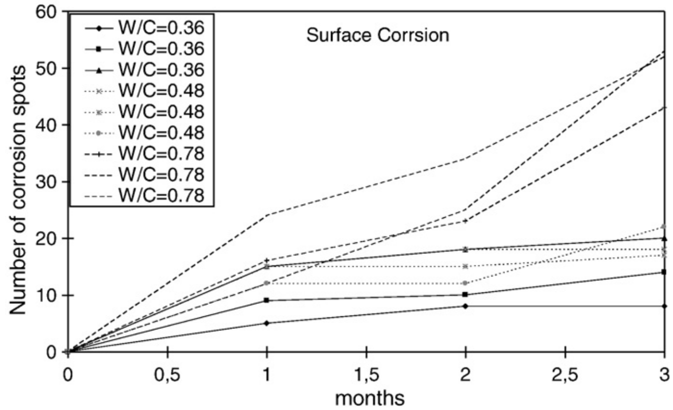


Fig. 3. Corrosion spots versus time as a function of W/C (counting area = 100*250 mm^2).

For each composition given in Table 5, four concrete prisms of 100*100*500 mm^3 were prepared. They were placed in the fog room for 28 days at 20 °C. One of the prisms was sawed into small pieces for porosity measurement. From these small pieces very precisely 2 mm skin slices were sawed to get samples for mercury porosimetry analysis.

The three remaining prisms were placed in the accelerated corrosion chamber for three months to receive the surface corrosion. The number of corrosion spots that appeared on surface was counted for each month. Just as for the samples of the first series, the counting was done on a 100*250 mm^2 area.

The results of corrosion spots counted are plotted in curve form in Fig. 3.

A grinding campaign was carried out to quantify the cover depth of the fibres affected by surface corrosion in the concrete with W/C = 0.48 and W/C = 0.36. The results are summarised in Tables 6 and 7. The W/C = 0.78 concrete already tested earlier (see Tables 2–4) was not tested again. The maximum depth of fibres affected by surface corrosion is in the vicinity of 1 mm.

Series 2 results gave the following outcomes:

- Using W/C ratios lower than 0.78 sharply decreases the intensity of surface corrosion.
- The results of corrosion spots counted have given a threshold value establishing a relation between W/C and surface corrosion. Indeed, no extra benefit was obtained by decreasing W/C lower than 0.48.
- The cover depth of the fibres affected by surface corrosion is coherent with the corrosion spots counted and reflects the same threshold.
- When W/C ≤ 0.48, the minimum cover of the fibres to prevent surface corrosion is dropped to less than 2/10 mm, a cover value which could be expected in an industrial process.

Table 6
Surface corrosion spots and depth of fibres (counting area = 100*250 mm^2).

Depth (mm)	0.02	0.04	0.06	0.08	**0.1**	0.12
Number of fibres	7	10	11	11	**13**	13

Sample type: W/C = 0.48, macro fibres (60*0.75 mm), number of visible corrosion spots: 13.
Maximum depth of fibres which have given spots at the surface ≈ 1/10 mm.

Table 7
Surface corrosion spots and depth of fibres (counting area = 100*250 mm^2).

Depth (mm)	0.02	0.04	0.06	**0.08**	0.1	0.12
Number of fibres	4	7	9	**9**	12	12

Sample type: W/C = 0.36, macro fibres (60*0.75 mm), number of visible corrosion spots: 9.
Maximum depth of fibres which have given spots at the surface ≈ 0.8/10 mm.

The threshold noted above is an important feature. The mercury porosimetry analysis included in this study confirms its actuality and specifies its characteristics. For each W/C considered, two skin samples were investigated. The drying technique may influence the measured values [5], note that the samples were prepared in the usual manner, they were dried for 24 h at 105 °C. The results, presented in Fig. 4 confirm that the critical pore diameter of the skin concrete does not decrease evenly with W/C. It exhibits a sharp drop, from ≈ 7000 nm to ≈ 200 nm when W/C is decreased from 0.78 to 0.48 and stands only at marginal variation with further decrease of W/C. The threshold value of the critical pore diameter is ≈ 200 nm.

Conjointly with corrosion observation, one infers that:

- The minimum cover of the fibres to prevent surface corrosion is dropped to less than 2/10 mm when the critical pore diameter of the skin concrete is as small as 200 nm
- With smooth, oiled and impermeable surface of the formwork, this result is achieved as long as W/C ≤ 0.5; changing the surface characteristics, for instance using wooden formwork, could change this result.

4.3. Chloride profiles

The % chloride content for the surface layer severely affected by corrosion was also evaluated for the second series and chloride profiles are drawn. For this purpose the same samples exposed to salted fog were used to evaluate the Cl contents at three different depths of 0–1 mm, 1–2 mm and 2–5 mm from the concrete surface. As the skin of concrete (0–5 mm) is very slim, surface evaporation

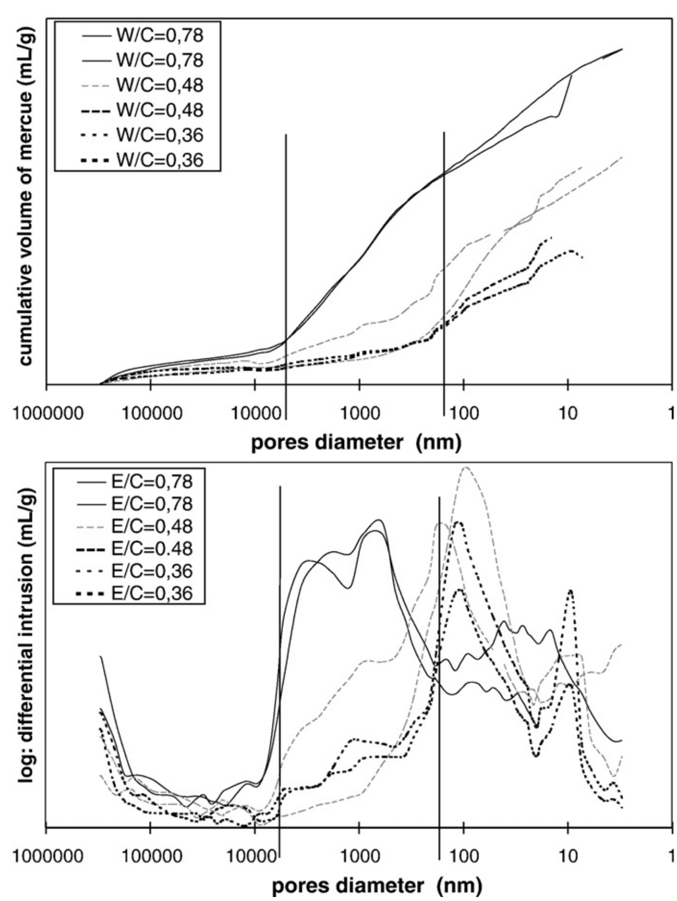


Fig. 4. Pore diameters in the concrete skin as a function of W/C ratio.

Table 8
Chloride profile for different W/C at different depths.

Depth (mm)	0–1	1–2	2–5
W/C = 0.78	0.0027	0.0029	0.0209
W/C = 0.48	0.0088	0.00720	0.0214
W/C = 0.36	0.04475	0.05085	0.0291

Table 9
Comparison between the number of fibres encountered and surface corrosion spots at different W/C and depths.

Depth (mm)	0.1	0.2	0.5	1
Number of fibres/corrosion spots (W/C = 0.78)	11/50	13/70	20/50	48/50
Number of fibres/corrosion spots (W/C = 0.48)	13/13	19/13	29/13	44/13
Number of fibres/corrosion spots (W/C = 0.36)	13/10	17/10	20/10	42/10

possibly may have an effect on the contents of the chloride. The results of average of three samples are produced in Table 8 below:

The results of Table 8 show that, almost all the three types of concrete with different W/C have been effected by the chlorides more than 2%, a threshold value recommended for corrosion. However for the W/C = 0.78 and W/C = 0.48 the surface evaporation has leached away the Cl contents from 0–2 mm (0.002) as compared to the 2–5 mm depth (0.02). Contrarily, for W/C = 0.36, the more dense the composition, the Cl contents were not effected by evaporation. Moreover the Cl is found more at 0–2 mm as compared to 2–5 mm depth in case of W/C = 0.36. This proves the fact that lower W/C ratio has resisted the penetration of chlorides and has finally controlled the corrosion process. Thus the concrete quality has the effect on the corrosion and they do not have any effect on the dispersion of fibres (3). Comparison has been made between the number of fibres encountered and the corrosion spots visible at surface for three different W/C ratios and depths, which is given in Table 9 below.

For different W/C ratio, Table 9 demonstrates that the number of fibres at different depths remains the same but there is a difference of visible corrosion spots. It is already demonstrated in Table 8 that chloride profile also remains the same for different W/C ratio.

Thus a study of concrete porosity and chloride contents reveal that:

- The porosity of concrete has a dominating effect on corrosion phenomena.

5. Conclusion

The procedure, which we have developed, permits to quantify the relation between the cover of the fibres and the appearance of rust spots at the surface of the concrete. In a second step, it allows to investigate the dependence of surface corrosion risk versus the W/C ratio of the concrete.

With W/C = 0.78 concrete matrix, all the fibres embedded less than 1 mm are expected to give corrosion spots at the surface. Using smooth, oiled and impermeable formwork the necessary minimum cover of the fibres to prevent surface corrosion is dropped to less than 2/10 mm when W/C is decreased to about 0.5. Further decrease of W/C does not give significant extra benefit. The critical pore diameter of the paste of the skin concrete is then stabilised in the vicinity of 200 nm.

An enhanced mobility of the fibres in the concrete matrix (higher workability and higher sand/gravel ratio) completed by an adequate vibration process, especially by formwork vibration, helps to push the fibres away from the cast surfaces. Nevertheless, it cannot be expected to achieve a minimum cover of the fibres larger than about 2/10 mm.

Consequently, to prevent surface corrosion, one must have conjointly: W/C ≤ 0.5 mm (which is common) and a design of the mix and a placement in the formwork which can, in all cases, provide a minimum cover of the fibres as large as 2/10 mm. If these two conditions are not fulfilled, rust resistant fibres, for instance galvanised fibres, must be used.

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