Influence of different PVA fibres on the crack behaviour of foamed cement paste

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ABSTRACT: Foamed cementitious materials are highly porous materials with low density, low compressive and bending strengths, caused by their high porosity. Due to the small strength and the scatter of the properties the material is not commonly considered as a load bearing material.
The aim of this work is to improve the mechanical properties and to reduce the variability of the properties of foamed concrete while keeping its favourable physical properties. To achieve the main goal of this research fibres are added to the foamed cement paste to improve the mechanical properties, specifically the compressive and bending strengths at the macroscopic level.
The crack patterns are analyzed by sectioning after impregnation with fluorescent epoxy resin. Emphasis is on fracture mechanisms in various foamed concretes. The varied parameters are the material density of the foamed concrete (with various amounts of foam), the w/c-ratio, fibre content and fibre size. The main result is that, in particular the flexural strength and ductility of foamed concrete can be improved significantly by adding fibres, achieving a bending strength a factor 5 higher than commonly observed values for plain mixtures without fibres.

1 INTRODUCTION

The idea of adding fibres to a cementitious matrix, to improve the mechanical properties, is well known from different applications in steel fibre concretes.

In the field of lightweight concretes, especially not autoclaved foamed materials, fibres are not common, as not autoclaved foamed cementitious materials are not common as load bearing materials.

In this preliminary test series, we are interested to see whether mechanical properties of foamed concrete can be improved by adding fibres. Moreover, do fibres affect the foam structure, also in the hardened cement, and to what extend are the mechanical properties affected? Do fibres cause different fracture mechanisms of the foamed concrete; if yes, is the influence favourable or not.

The foamed cementitious materials that are investigated are produced with protein-based pre-formed foam that is mixed with cement paste. Density, pore structure and the final water-cement ratio are related to the amount of foam that is mixed with the cement paste. At present no aggregates are added. The amount of foam that can be added is between 0 and 80% of the volume of the final mixture. The used fibres are made of PVA (poly vinyl alcohol). For these test series three different lengths were used (3, 6 and 12 mm). All fibres have the same diameter of 0.2 mm and a density of 1300 kg/m^3 with a Young's modulus of 30 GPa and a tensile strength of 1000 MPa.

PVA was chosen, because steel fibres are much heavier and according to the matrix density (in-between 600 and 1600 kg/m^3) they lead to sagging and segregation. A further consideration is the fact that durability of steel in cementitious materials with air void contents of more than 40% is rather low. Another reason for choosing PVA was the fact that it is well known in our group from earlier projects see Bäumel (2002) and Meyer and van Mier (2004).

The effect of foam behaviour and the amount of foam on the reproducibility was investigated before, and published in Meyer et al (2005) and Meyer & van Mier (2006).

2 TEST PROGRAM

The test program contains ten different mixtures containing fibres of varying length, amount of fibres and different amounts of foam. Additionally, four reference mixtures without fibres, but variable amounts of foam, were made. The details of the mixtures are given in Table 1.

The fibre contents were defined after preliminary tests where the mix-ability of mixtures with different fibres and various foam ratios had been investigated. In Table 1 the upper value of the fibre content corresponds to the maximum amount that can be added to a given mixture, without sagging, segregation or balling to occur. Results from these preliminary mixing experiments are gathered in Section 4.1. The lower fibre ratio in Table 1 represents 20% of the maximum value. With this, a first-order approximation of the effect of the fibre addition on the mechanical parameters and the crack behaviour is obtained.

Table 1. Mixture overview.

Mixture [-]	Amount of foam [V%]	Fibre length [mm]	Amount of fibres [V%]
Ref 1	0	No fibres	
Ref 2	20		
Ref 3	40		
Ref 4	60		
M 1.1	40	3	7
M 1.2	40		1.4
M 2.1	40	6	4.2
M 2.2	40		0.84
M 3.1	20	12	2.5
M 3.2	20		0.5
M 4.1	40	12	2
M 4.2	40		0.4
M 5.1	60	12	1
M 5.2	60		0.2

With this test program two effects are to be separated mainly (see also Figure 1), one is the influence of the fibre length and the fibre content on mixing, rheology, pore structure and mechanical properties (A) and the second the influence of the amount of foam on the allowable fibre content and the ensuing mechanical properties (B) in comparison to the reference mixtures without fibres (C).

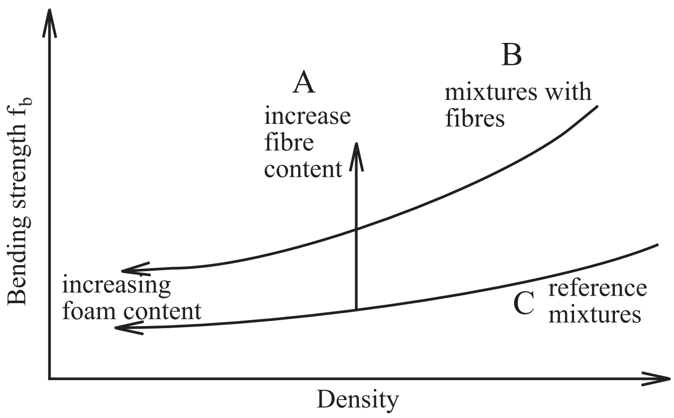

Figure 1. Idea behind the mixture composition.

3 SAMPLE PREPARATION AND TEST SETUP

All samples were manufactured following the same procedure, which was defined during the preliminary tests. The following list shows the chronological order of the steps during the mixing and production of the samples.

– Preparation of test instruments, moulds and materials for plain cement paste
– Mixing of plain cement paste
– Rheology test on plain cement paste
– Weighing out plain cement paste and preparation of tests for cement paste with fibres
– Mixing fibres and cement paste
– Rheology tests on cement paste with fibres
– Weighing out cement paste with fibres, preparation of tests for foamed cement paste with fibres (new mixer)
– Production of foam
– Mixing of foam and cement paste with fibres
– Rheology tests on foamed cement paste with fibres
– Filling of moulds (surfaces of moulds are treated with silicon spray)
– Cleaning

After casting the samples were stored in controlled climate (20 °C and 95% RH). After one day the samples were de-moulded. About one week prior to testing, the top and bottom surfaces were ground plan-parallel. The top surface during casting was also ground in order to obtain samples of regular size and shape. Before the samples were tested, geometry and the weight were measured. The mechanical tests carried out are summarized in Tables 2 and 3.

Table 2. Test program mechanical tests.

	Test type	Sample size [mm]	Nr. of samples
f_b	3-point bending*	150 x 50 x 50	5
$f_{c,cube}$	ID-compression	50 x 50 x 50 (1/2 Prism)	5
$f_{c,prism}$	ID- compression	150 x 50 x 50	5

* Span = 120mm

Table 3. Test parameters for mechanical tests.

Test	Starting load	Loading velocity	Deformation measurement
3 point bending	50 N	0.005 mm/s	Yes
Compression ½ prisms	2000 N	0.5 kN/s	No
Compression standing prisms	2000 N	0.5 kN/s	Yes

4 RESULTS

4.1 *Preliminary test (mixing)*

With the preliminary experiments on mixing, the main interest was to evaluate the maximum amount of fibres that can be added to a cement paste containing a pre-defined amount of foam, without sagging, segregation or balling of the added fibres.

During the preliminary test it was found that a certain amount of foam was destroyed during mixing and placing, see Figure 2. Short fibres (3-6 mm) lead to a higher loss of foam than the long fibres (12 mm) causing an increase of the fresh density in comparison to the reference mixtures without fibres but containing the same amount of foam. A possible explanation therefore could be the number of fibre-tips, that is much higher in the case of short fibres at constant fibre volume, and so the probability that fibre tips are piercing foam bubbles.

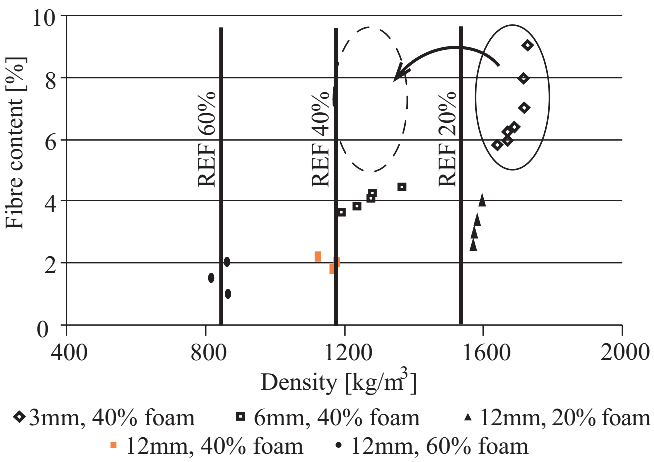

Figure 2. Context of fibre type, fibre amount and fresh density.

4.2 *Pore structure and fibre distribution*

The pore structure of foamed cement paste can be influenced by the foam properties (amount of protein concentrate and the production method) and by the total amount of foam that is added to the cement paste. For these tests on fibre reinforced foamed cement paste we focused on the comparison of the macroscopic material (bubble) structure of samples with the same amount of foam, with and without fibres.

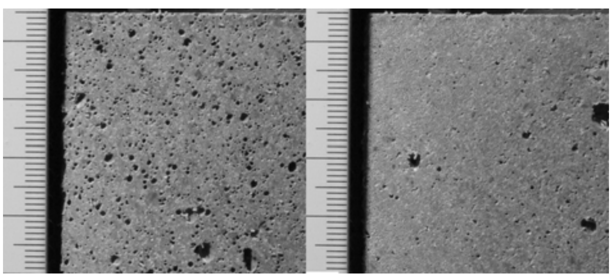

Figure 3. Comparison of pore structure of M 1.2 (left) with 1.4% 3mm fibres and M1.1 (right) with 7% 3mm fibres, both produced with 40% foam.

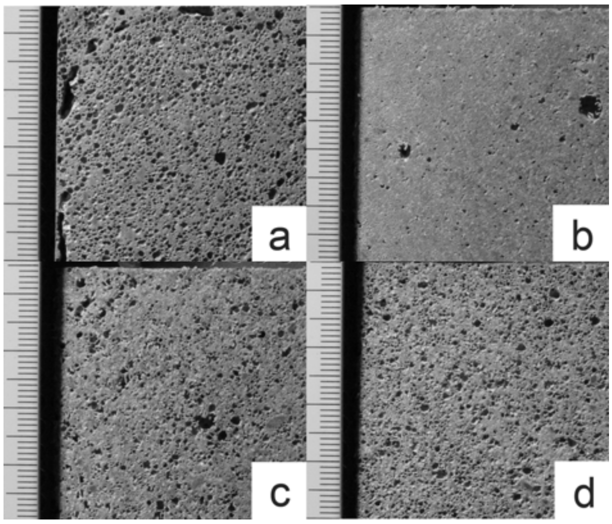

Figure 4. Comparison of pore structure of mixtures produced with an amount of 40% foam by volume. a) Reference mixture without fibres, b) M1.1 7% 3mm fibres, c) M2.1 4.2% 6mm fibres and d) M4.1 2% 12mm fibres.

The effects of fibres of different sizes on the material/pore structure can be seen in Figures 3 and 4. The different fibre types (different length) lead to different loss of foam volume during mixing (see Figure 4), filling of moulds and hardening and as a result they have different effects on the pore structure. Smaller fibre ratios, more exactly smaller numbers of fibres, lead to a smaller loss of foam. The more foam is added, the greater this effect is, based on the probability of contact between foam bubbles and fibres. This perception leads us to the model, that greater numbers of fibres, and so great numbers of fibre tips, destroy increasingly more foam bubbles. We think the foam bubbles are pierced by the fibres. The fact that no fibres were found reaching an air void in hardened material confirms this assumption.

One of the main interests of the preliminary experiments was to know if the fibres are distributed regularly over the whole cross section of the samples, or if there are effects such as balling and segregation, which have not been recognised in the preliminary tests or the rheology tests.

We benefit from the fact that the PVA fibres are sensitive to UV light. Figure 5 shows images, where the fibres were made visible with UV light. The images then were optimised by using an image editing software. As can be seen, the fibre distribution is quite regular over the whole cross sections.

4.3 *Mechanical tests*

As mentioned before, compression tests and bending tests were done to determine the mechanical properties. The main results are shown in Table 4 and 5. PVA fibres showed no appreciable increase of the ultimate compressive strength (Figure 6). The only improved parameters were the post peak behaviour.

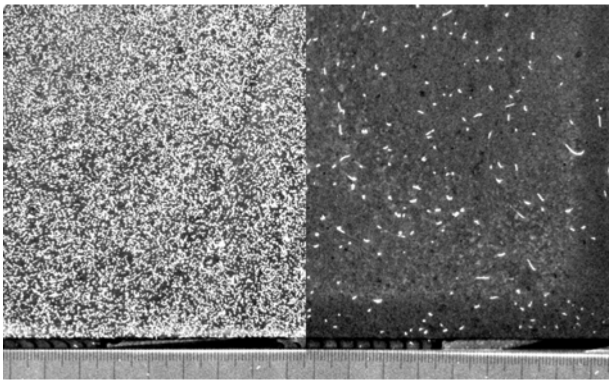

Figure 5. Fibre distributions in foamed cement paste.
Left: M 1.1 7% 3mm and right: M 5.2 1% 12mm White spots represent the fibres, black and grey shades are matrix material.

Table 4. Results compression tests.

Mix [Nr.]	Density [kg/m^3]	f_c [MPa]	COV [%]	E-Modul [GPa]
Ref 1	1912.6	47.8	0.89	11.54
Ref 2	1595.8	27.6	2.49	7.14
Ref 3	1215.5	13.2	2.85	4.55
Ref 4	868.4	7.1	2.76	2.96
M 1.1	1770.2	42.4	0.64	9.51
M 1.2	1653.1	32.2	5.60	8.29
M 2.1	1279.3	14.0	7.17	4.47
M 2.2	1304.4	14.8	4.18	5.45
M 3.1	1602.1	30.1	4.76	7.41
M 3.2	1652.6	31.0	3.11	7.95
M 4.1	1232.6	13.2	3.26	4.79
M 4.2	1251.4	12.2	7.64	4.76
M 5.1	871.3	5.6	3.77	5.33
M 5.2	922.7	6.4	8.78	4.34

COV ….Coefficient of variation

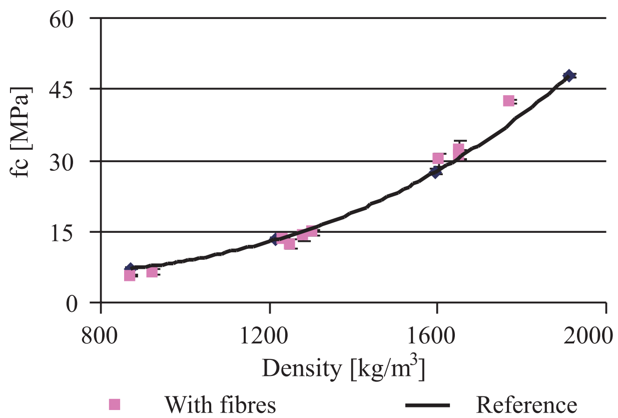

Figure 6. Relation of density and compressive strength.

The bending strength was significantly affected by the addition of fibres, see Figures 7-10. The increase of the bending strength and ductility is surprising. With the 12 mm fibres the difference in density between the reference mixture and mixtures containing fibres is small. The fact, that the scatter of all parameters is smaller than the reference mixtures, besides the mixture with 60% foam and the low fibre content (M 5.1), confirms the idea that adding fibres

Table 5. Results bending tests.

Mix [Nr.]	Density [kg/m^3]	f_b [MPa]	COV [%]	Increase [factor]
Ref 1	1912.6	2.70	7.81	-
Ref 2	1595.8	1.76	1054	-
Ref 3	1215.5	1.03	12.65	-
Ref 4	868.4	0.74	21.88	-
M 1.1	1770.2	8.70	6.79	3.22
M 1.2	1653.1	4.43	4.24	2.52
M 2.1	1279.3	5.52	10.56	5.37
M 2.2	1304.4	2.23	7.18	2.17
M 3.1	1602.1	9.50	10.87	5.41
M 3.2	1652.6	3.74	11.30	2.13
M 4.1	1232.6	5.00	16.04	4.86
M 4.2	1251.4	2.10	5.89	2.05
M 5.1	871.3	1.92	38.14	2.61
M 5.2	922.7	1.03	6.41	1.40

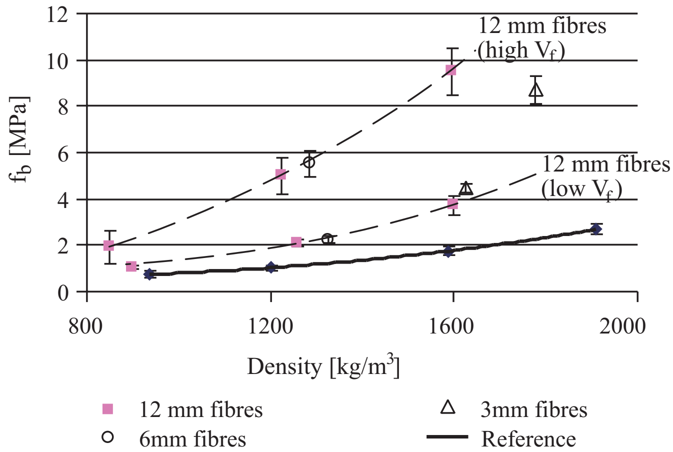

Figure 7. Influence of fibre addition to the bending strength.

to foamed cement paste improves the mechanical parameters, in particular the behaviour in bending significantly.

As can be seen in Figure 9 all mixtures with high fibre content lead to a very high bending strength compared to the references (Figure 8) and the mixtures with the low fibre content. Moreover the mixtures with 12 mm fibres and high foam amount show strain hardening and a high ductility. When only 20% foam is added to the mixture strains up to 4.0% are observed before peak-stress is reached. In the mixtures with only 20% foam fibres appear to be anchored better in the matrix, so the strength and the ductility are more favourable compared to samples with smaller amounts of foam.

The mixtures with the lower fibre content (20% of maximum mixable amount of fibres) show no strain hardening. After the peak the applicable load drops immediately to a level between 40 to 75% of the peak load (depending on the fibre length). After that drop all mixtures show a light secondary strain hardening and a long trail in the softening diagram except the mixture with the short 3mm fibres (see Figure 10).

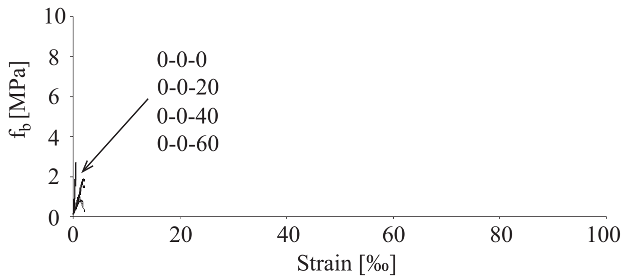

Figure 8. Stress-strain diagrams for the reference mixtures from bending tests. In the caption of the lines the first number means the fibre content [%], the second the fibre length [mm] and the last number represents the percentage of foam that is added to the total foam volume.

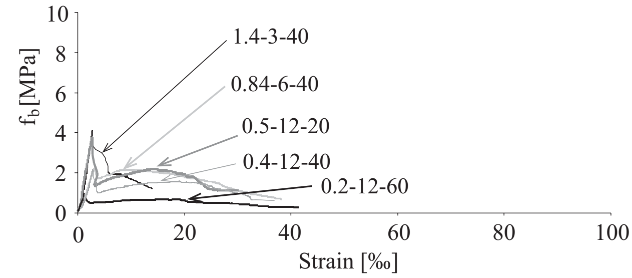

Figure 9. Flexural stress-strain diagrams for mixtures with high fibre content. Explanation of the captions 1.4-3-40 stand for 1.4% of 3mm fibres in a mixture where 40% foam is added.

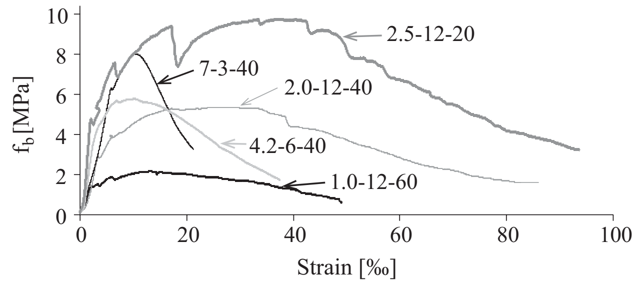

Figure 10. Flexural stress-strain diagrams for mixtures with low fibre content.

The diagrams kept on the same scale in order to show the differences between plain foamed cement paste and fibre reinforced foamed cement paste as clearly as possible.

4.4 *Crack patterns*

As described in Section 4.3 the PVA fibres had a cause effect on the strength and the ductility. Also cracking behaviour is changing by adding fibres to foamed cement paste. Depending on the fibre type and the amount of fibres that is added to the mixture, but also influenced by the amount of air voids that a sample contains, the crack behaviour leads to multiple cracking or not. Multiple cracking was recognized in the mixtures M 3.1 and M 4.1; all the other mixtures lead to a single crack or had only in some samples more than one crack, as it was recognized on series M 1.1, M 2.1 and M 5.1. Some selected photographs of crack patterns are shown in Figures 11-13 to illustrate the crack behaviour.

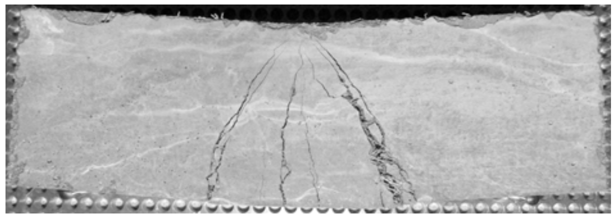

Figure 11. Crack pattern for mixture M3.1 (20% foam, 2.5% 12mm PVA fibres), showing multiple cracking.

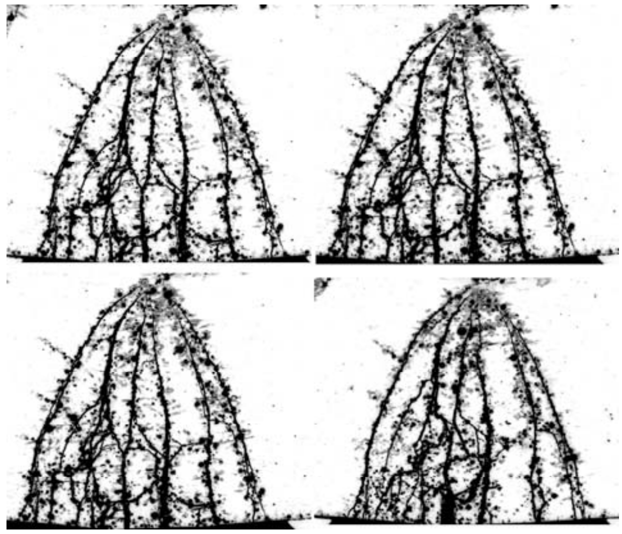

Figure 12. Crack pattern of longitudinal cuts of the same sample as shown in Figure 12. The sample was impregnated with epoxy resin and photos were taken under UV light. The contrast of the crack was optimized with image editing software.

Figure 12 shows the devolution of the crack from the sample from Figure 11 in four longitudinal sections. It can bee seen that over the whole section multiple cracking takes place; all major cracks grow through the entire depth of the beam.

In Figure 13 typical crack patterns from different mixtures are shown, indicating the various crack modes from a single localized macro crack (Figure 13a) to multiple cracking (Figure 13c) and apparent shear fracture (Figure 13d).

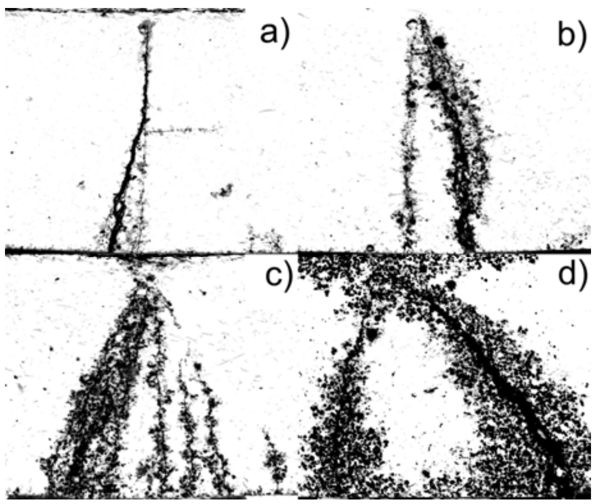

Figure 13. Crack patterns from different mixtures. a) M 1.1 7% 3mm fibres, 40% foam; b) M 2.1 4.2% 6mm fibres, 40 % foam; c) M 4.1 2% 12mm fibres, 40 % foam & d) M 5.1 1% 12mm fibres, 60% foam.

5 DISCUSSION AND CONCLUSIONS

The main interest of the presented test series was to evaluate the influence of PVA fibres on the mechanical properties, pore structure and fracture mechanisms of foamed cement paste, in comparison to the behaviour of plain reference mixtures without fibres. Of additional interest was the reproducibility of the results.

The tests showed that it is important that plain cement paste and fibres are mixed properly before the pre-formed foam is added. The amount of foam that is destroyed during mixing, placing and hardening differs strongly, depending on the size of the fibres used and the amount of fibres added to the mixture. The short 3 mm fibres, where a high volume can be added to foamed cement paste, lead to the largest loss of the added foam. Even if only a low amount of such short fibres is added the volume of foam that is destroyed is considerable, so the difference between planned and final density is considerable. With longer fibres this difference is smaller. With the longest used fibres (12mm) the difference was irrelevant. The fact that high volume of short fibres, and thus a large number of fibres and fibre tips, lead to a larger volume of foam loss during mixing and placing, guided us to a possible explanation that the foam bubbles are pierced when the mixture is in motion. So a greater number of fibres, and thus a greater number of fibre tips, lead to a higher loss of foam volume.

In all mixtures, independent of fibre type, the fibres were distributed homogeneously over the whole cross section in the observed samples. The fibre orientation, however, differed in the observed samples, influenced by the way the mould was filled. If the material could flow, fibres tended to align in the flow direction. Note that this is a qualitative observation only since the effect was not studied systematically, and was not quantified.

The compressive and flexural properties are influenced differently by the added PVA fibres. The compressive strength is not affected by the addition of fibres. The post peak behaviour, however, was improved and became more ductile. After reaching the peak, the carrying capacity dropped to 30-50% of maximum load. Subsequently the sample was deformed at nearly constant stress until the fibres bridging the cracks were pulled out.

The bending strength f_b can increase up to a factor of five compared to plain foamed cement, depending on the fibre volume, fibre type and amount of foam. The ductility also is improved by adding PVA fibres to foamed cement paste mixtures and a high amount of fibres lead to multiple cracking. Mixtures with the long 12 mm fibres reach remarkable strains. Some mixtures with longer fibres and a high fibre volume lead to multiple cracking. Other mixtures, as mentioned in the text before, only show multiple cracking in individual samples and not over the whole test series.

PVA fibres are a good and easy way to improve the bending strength and the ductility of foamed cement paste while keeping density and reproducibility under control. The effects of fibres to the foam structure during mixing, placing and hardening have to be taken in consideration. Based on the experiments that have been done PVA fibres can be added easily to foamed cement pastes to reach a homogeneous mixture and a relatively small scatter of the parameters.

From a practical point of view, the addition of PVA fibres brings us one step closer to foamed cement paste as a load-carrying material. The low weight of the material, in combination with a high bending strength seems to defy common response observed in porous media.

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