Bending Strength of Fiberconcrete with Nanoparticles, Having Polymer Fibers

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Abstract –*P*olymer fibers were used in structural applications as micro reinforcement in composite materials having concrete matrix. Comparing to steel, glass and carbon fibers, polymer fibers behave visco-elastically or visco-elasto-plastically. Such fibers having moderate elastic modulus are characterized by relatively large elastic deformations and pronounced Poisson's effect during stretching. Concrete prisms with dimensions 10x10x40 cm were fabricated, having different amounts of 3 cm long and 0.75 mm in diameter polymer fibers. All prisms were tested under four point bending conditions. Elaborated numerical model for crack opening in fiberconcrete was exploited for prism load –deflection mechanical behavior prediction under four point bending conditions. Experimental pull-out results were successfully used as an input data for the model.**

***Keywords* – polymer fibers, concrete prisms, pull-out, four point bending**

I. Introduction

Adding fibers to the concrete matrix causes a situation when the load bearing capacity of the material after cracking of the concrete matrix (appearances of magistral cracks) decreases within acceptable limits or does not decrease at all (Shao et al., 1993, Li et al., 1994 and Krasnikovs et al., 2010).

In this work, single polymer synthetic fiber pull-out of a concrete matrix is under investigation. A short synthetic polymer fiber is oriented under a certain angle to the direction of the pulling out force, is immersed by one end into the concrete matrix at a certain depth. Thereby - the fiber is oriented - has an angle between its direction and the direction of the force is pulling it out of the concrete matrix and has the embedment depth in concrete matrix. Experimental and theoretical data were obtained for the single fiber pull-out phenomena, as well as for the fiberconcrete prisms four point failure under bending.

II. Single polymer fiber pull-out experimental investigation

Single polymer synthetic fiber was placed in a concrete matrix (Fig. 1) and was oriented at an angle to the future tension direction [4]. Each fiber was embedded at a specific depth (less or equal to fibers half-length) corresponding to the accepted experimental program. Specimens were prepared in the following sequence: Step 1: Concrete mix was prepared. Step 2: Polymer synthetic fiber was placed into the concrete matrix. Specimen mould was filled in four steps.

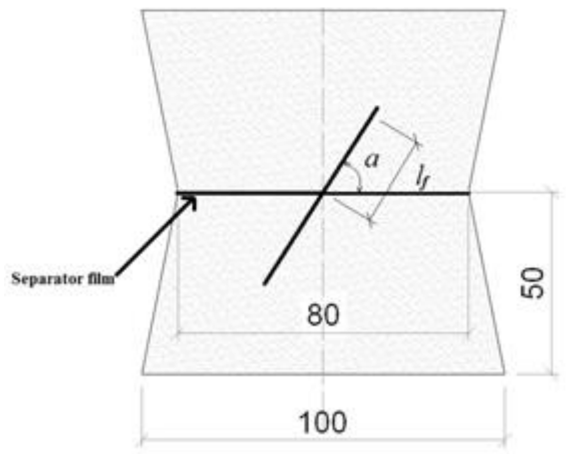

Fig.1. A) Configuration of a pull-out test specimen: lf - embedded length, α – inclination angle

The first and second layers were poured into the mould and were well compacted. Layers were rammed carefully with the goal to avoid air bubbles and voids in the concrete. The first and second layers were poured into the form, filling exactly half of the depth of the form, in order to facilitate future fiber emplacement (and orientation) in the mould. Both geometrically similar parts of the sample were separated by a

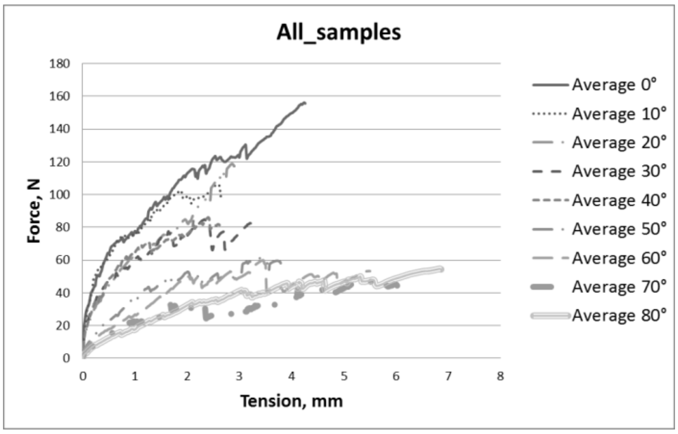

Fig.2. Pull-out curves for a polymer synthetic fiber embedded into concrete under different angles

plastic film. Then, after placing the oriented polymer fiber a third layer was poured into one half or the sample mould. The third layer was placed in such way that the concrete mix was taken and superimposed on the fiber, thereby fixing its position and orientation and then the concrete in the form was compacted. Ramming is important, otherwise after aging due to macro and micro cavities between fiber and concrete matrix, the polymer fiber without resistance will be pulled out of the concrete. Then the 4th layer was poured. Step 3: Aged specimens experimentally were tested using the tensile testing machine with an additional 1kN load sensor. Each specimen was placed into the grips and was carefully centered. Two stickers (each with a black horizontal line) were glued on both parts of the specimen in order to determine their mutual displacement increase, using the noncontact extensometer (camera) MESSPHYSIK. In Fig. 2 is possible to see pull-out curves were obtained testing polymer macro synthetic fibers which were embedded into the concrete at different angles to the direction of the pulling-out force. Each fiber was embedded symmetrically by its ends in concrete; each end was 15mm long. Each curve was obtained averaging results over eight to ten tested samples.

The pull-out process observation showed two different scenarios of the fiber pull-out, which depended on the angle between the fiber and the stretching direction:
a) if an angle is small (10° - 20°) fiber release in the crack zone happens by concrete matrix spalling and the fiber's middle part rotation according to the embedment points in both crack flanks. Such oriented fibers can easily break down the concrete matrix and the release of fiber due to the spalling of the concrete matrix adds to the length which is pulled out of the concrete. The fiber pull-out process starts when the distance between crack flanks reaches a few millimeters; b) for fibers oriented under angles from 30° to 90°, the fiber that is pulled out of the concrete breaks at a certain depth and the detached end is pulled out by friction which is possible to see in figure 3. For fibers that were oriented at an angle of 90°, it was about 4.5 mm (averaged value over tested fibers were oriented at such angle) and was longer than for the fibers oriented under the angles from 80° to 40°, that was probably caused by the fact that the fibers oriented at angles of 40° - 80° during pulling out are subjected to cutting shear stresses (spalling of the concrete in the output of the fiber out of concrete only shifts the cross section in which the fiber is subjected to shear).

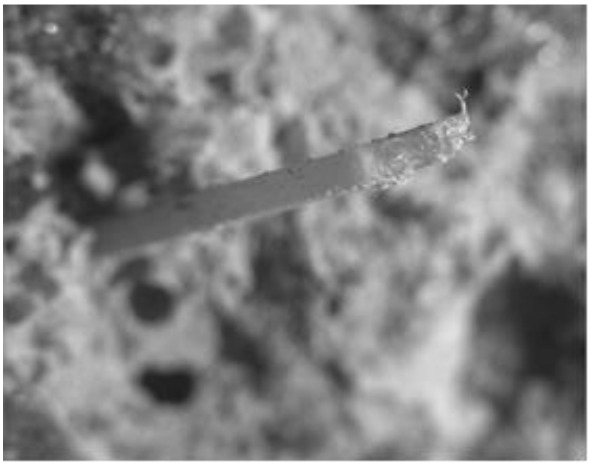

Fig.3. Macro synthetic fiber torn out from the concrete (under a microscope)

III. Elaboration of fiberconcrete samples with homogeneous polymer micro and macro synthetic fibers spatial distribution

Experimentally samples were elaborated (prisms having dimentions100x100x400 mm) with different fiber concentrations in the concrete matrix. Polymers macro synthetic fibers and micro synthetic fibers were homogeneously distributed in the material volume.

Samples were possible to subdivide into the following groups (Fig. 4):

1. fiberconcrete samples with micro synthetic fibers;
2. fiberconcrete samples with macro synthetic fibers;
3. fiberconcrete samples with micro and macro synthetic fibers.

Fig.4. Samples tested for four point bending

Fiberconcrete with micro synthetic fibers was created in the follow way:

1) all concrete ingredients, without micro synthetic fibers were mixed;

2) micro synthetic fibers were added to the concrete. Specimens were prepared with fiber concentrations: 1kg/1m3, 2kg/1m3 and 3kg/1m3.

Fiberconcrete with macro synthetic fibers was created in the following way:

1) all concrete ingredients, without macro synthetic fibers were mixed;

2) macro synthetic fibers were added to concrete. Specimens were created with concentrations of fibers: 1kg/1m^3, 2kg/1m^3, 3kg/1m^3, 5kg/1m^3, 6kg/1m^3 and 8kg/1m^3.

Fiberconcrete with micro and macro synthetic fibers was created in the following way:

1) all concrete ingredients, without micro and macro synthetic fibers were mixed;

2) in the second step, gradually micro synthetic fibers were added into the mix and then the macro synthetic fibers added. Specimens were created with fibers concentrations of: 1kg/1m^3 micro and 1kg/1m^3 macro; 2kg/1m^3 micro and 5kg/1m^3 macro; 2kg/1m^3 micro and 5kg/1m^3 macro; 4kg/1m^3 micro and 4kg/1m^3 macro; 5kg/1m^3 micro and 4kg/1m^3 macro; 8kg/1m^3 micro and 3kg/1m^3 macro synthetic fibers.

All the samples obtained after complete solidification (28 days) were subjected to experimental testing by four points bending using the tensile testing machine AUTOMAX Controls System V1.04.

IV. Experimentally obtained polymer macro synthetic fibers distributions (according to pull-out length and angle to the crack's plane)

Experimentally distribution of macro synthetic fibers on the crack surface was studied according to the location. During the bending test, each sample was separated into two pieces. Both of each sample's cracked halves surfaces were covered by graphic mesh (mesh cell size 1cm x1cm). On both surfaces of the crack location, all of the pulled out macro synthetic fibers were recognized (Fig. 5 and Fig. 6 a, b.).Tables 1 and 2 show every particular fiber crossing of the crack pulled out length and angle to the crack surface plane.

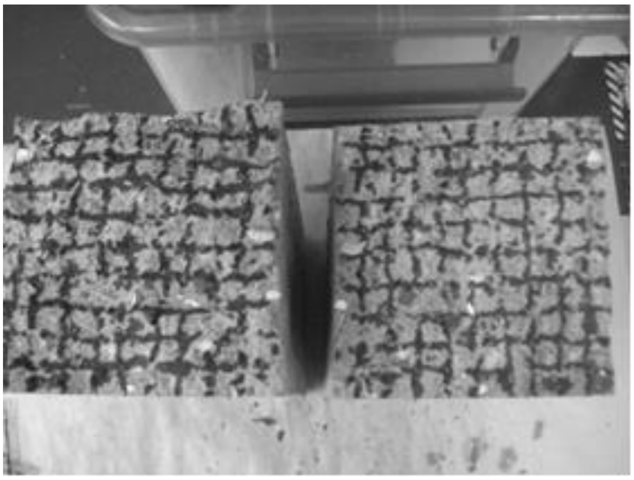

Fig. 5. View of the grid on one broken sample's both parts (concentration of macro synthetic fibers - 6kg/1m^3)

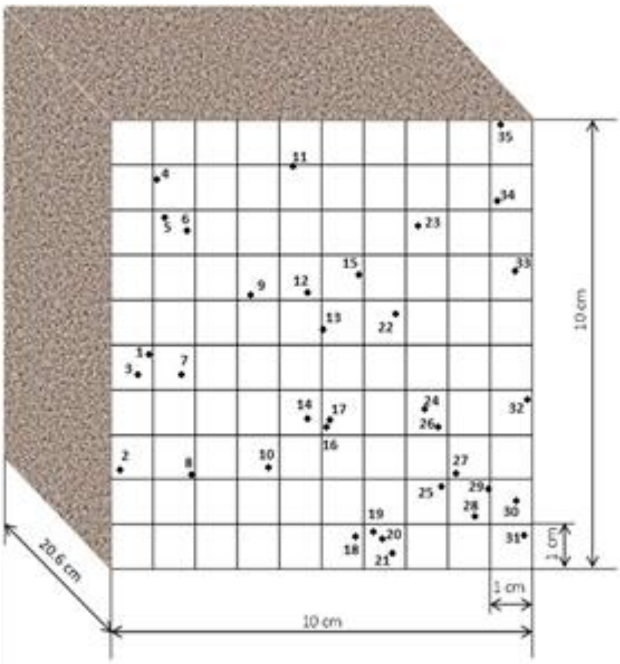

Fig. 6. a. Experimental macro synthetic fibers distributions (according to the pulled out length and fiber angle to the crack surface) counted on first (left side) crack's sides in sample N3. The concentration of fibers in the concrete matrix is 6kg/1m^3

TABLE I

Experimental macro synthetic fibers distributions (according to the pulled out length and fiber angle to the crack surface) counted on the first (left side) of the crack's sides in sample N3

Sample		**N3**
Number	**Angle,**	**Length,**
1	70	4
2	70	10
3	18	13
4	60	9
5	42	5
6	78	4
7	82	5
8	40	8
9	36	4
10	42	5
11	63	7
12	36	12
13	46	6
14	26	9
15	25	7
16	57	2
17	90	4
18	54	3
19	76	8
20	53	7
21	47	5
22	45	9
23	25	10
24	42	5
25	73	5
26	57	7
27	78	5
28	65	8
29	70	4
30	47	5
31	87	13
32	79	14
33	58	8
34	45	3
35	65	9

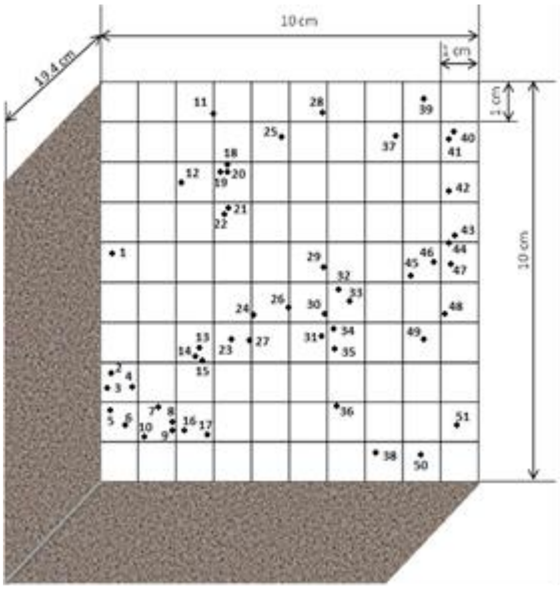

Fig. 6. b. Experimental macro synthetic fibers distributions (according to the pulled out length and fiber angle to the crack surface) counted on the second (right side) crack's side in sample N3. The concentration of fibers in the concrete matrix is 6kg/1m3

TABLE 2

EXPERIMENTAL MACRO SYNTHETIC FIBERS DISTRIBUTIONS (ACCORDING TO THE PULLED OUT LENGTH AND FIBER ANGLE TO THE CRACK SURFACE) COUNTED ON THE SECOND (RIGHT SIDE) OF THE CRACK'S SIDES IN SAMPLE N3

Sample		N3
Number	Angle, °	Length, mm
1	82	8
2	90	4
3	85	17
4	50	6
5	80	9
6	78	6
7	50	7
8	64	10
9	69	7
10	62	4
11	66	4
12	90	2
13	61	10
14	53	9
15	19	15
16	66	4
17	40	10
18	78	6
19	62	4
20	17	7
21	54	5
22	52	3
23	37	4
24	81	4
25	90	7
26	55	3
27	90	2
28	65	2
29	54	2
30	90	7
31	58	6
32	42	6
33	51	3
34	45	6
35	60	5
36	17	16
37	50	6
38	70	2
39	62	5
40	63	7
41	73	4
42	72	4
43	54	8
44	52	10
45	90	2
46	74	3
47	45	3
48	64	2
49	70	6
50	50	6
51	19	4

Following graphics were made:

a) The distribution of macro synthetic fibers (crossing the macro-crack) according to angles between the fiber and crack plane (Fig. 7);

b) The distribution of macro synthetic fibers on the crack surface according to the pulled out ends' lengths (Fig. 8).

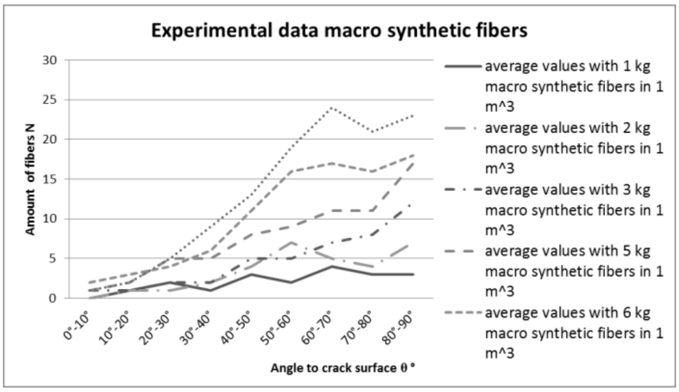

Fig.7. Angles to the crack surface distribution for pulled out macro synthetic fibers' ends

Looking at figure 7, it is possible to see that those fibers' orientation which are crossing the macro-crack to the crack's plane is non-uniform in all spatial directions. The main reasons for such phenomena may be two: a) fibers are located under an angle to the pulling out force are obtaining a "quazi" plastical deformation during pulling out;

b) fibers obtained orientation along each prism longitudinal direction when the mould is filled with fresh fiberconcrete. Figure 8 shows that among the pulled out fibers ends, the dominate length is less than 5 mm.

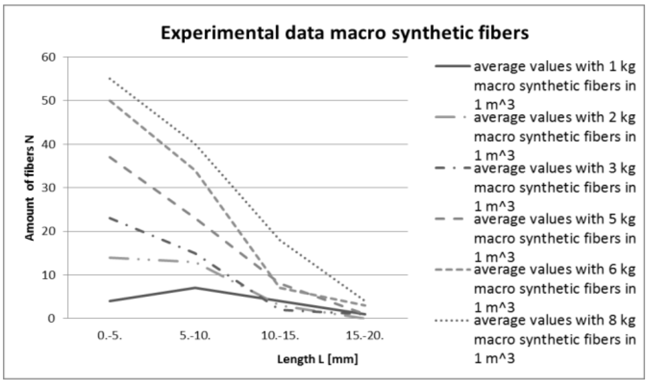

Fig.8. Macro synthetic fibers ends distribution according to pulled out lengths

V. FIBERCONCRETE SAMPLES LOAD BEARING CAPACITY

Reaching the highest deflection, each prism broke the “quazi” brittle way, separating in two parts. Since the micro synthetic fiber is relatively short and small in diameter, the number of such fibers in the material is much higher compared with the concrete containing the same concentration of macro synthetic fibers [5]. Applied force-deflection graphs of the middle

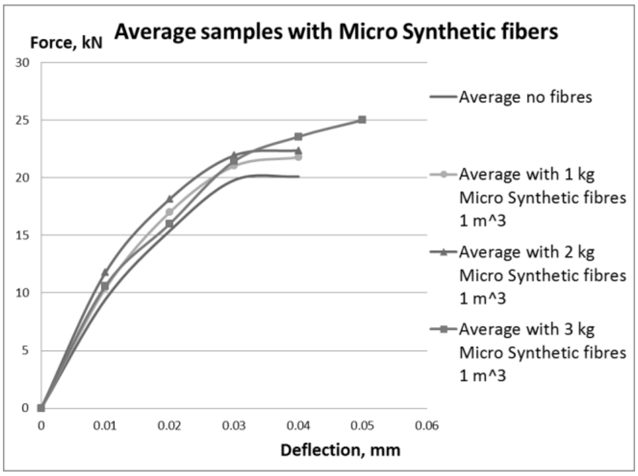

Fig.9. Force - the vertical deflection of the middle of a fiberconcrete prism. Curves correspond to fiberconcrete prisms with different amount of micro synthetic fibers which were tested by four point bending

of the prism (for material containing micro synthetic fibers) loaded under four point bending conditions, are shown in Figure 9. In the figure it is possible to see how the applied force and deflection are increasing, depending on the increasing amount of the micro synthetic fibers per 1 m3.

Samples contained micro synthetic fibers in a range from 1 kg to 3 kg per 1 m3. The highest bearing load and maximal deflection (≈ 0.052 mm) was obtained for the highest amount of fibers.

At the same time, the length of pulled out fibers ends of micro synthetic fibers is much shorter than for the macro synthetic fibers. Visual view (using a microscope) of the crack’s surface is shown in Figure 10.

Fig.10. Micro synthetic fibers on a macro-crack surface

In Figure 11, experimental data obtained in the four point bending tests of fiberconcrete samples with macro synthetic fibers are plotted. Graphs have two stages at the part corresponding to macro-crack opening (graph’s part at which the entire load is carried by stretching and pulling out fibers). Stage 1 – macro-crack cuts a major part of the sample prism

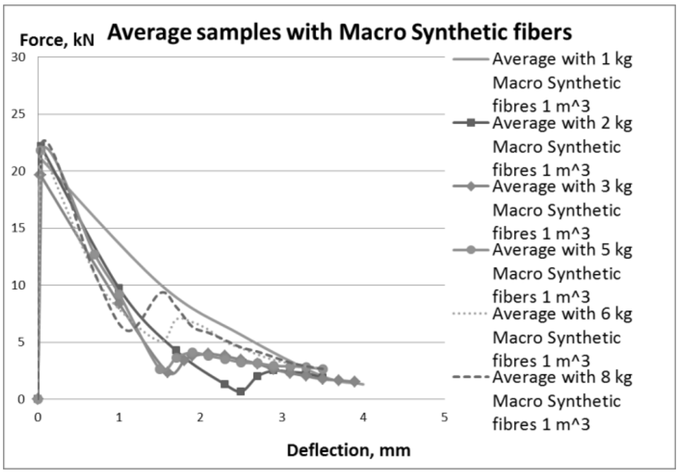

Fig.11. Force - the vertical deflection of the middle of a fiberconcrete prism. Curves correspond to fiberconcrete prisms with different amount of macro synthetic fibers which were tested by four point bending

crossection, the prism shows a sharp decrease of bearing capacity, this is explained by the fact that the macro synthetic fiber has a low modulus of elasticity and only fibers are carring the load. Stage 2 – Repeated increase of the load carrying capacity is explained by the fact that the macro synthetic fibers are stretched and after that break in the concrete, the elasto-plastic deformation of the fibers themselves, maintain the highest load.

In Figure 12 - graphs of the experimental data for fiberconcrete with micro and macro synthetic fibers that were tested under four point bending conditions are displayed. Adding micro and macro synthetic fibers in concrete leads to an increase in carrying capacity of the fiberconcrete, increase of strength, at the same time, two stages of destruction still remain, as was previously discussed for the graphs in Figure 11.

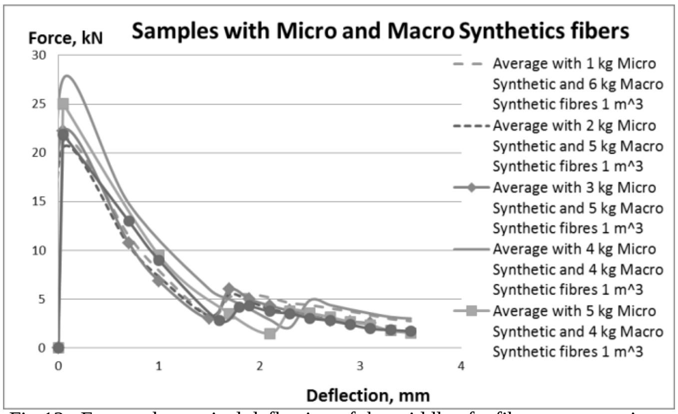

Fig.12. Force - the vertical deflection of the middle of a fiberconcrete prism. Curves correspond to fiberconcrete prisms with different amount of micro and macro synthetic fibers which were tested by four point bending

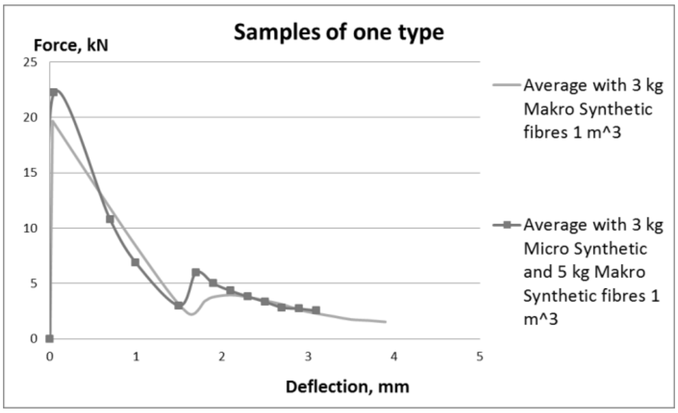

Fig.13. The average values of the same type fiberconcrete after testing by four point bending

Figure 13 shows the results of testing for one prism with micro synthetic fibers and one prism with macro- synthetic fibers. It is easy to see that the micro - synthetic fibers are working in fiber cocktails only at the starting stage of rupture. At the same time, increase of the material's integrity leads to a higher load bearing capacity of fiberconcrete with a fiber cocktail comparing with the material having the same amount of macro- synthetic fibers only.

VI. Theoretical model for polymer fiber concrete cracking under 4 point bending tests

Experimentally obtained pull-out observations were used as the main input data for the numerical model (Krasnikovs et al., 2010) with the goal to predict the linear and non-linear behavior of fiberconcrete beams under bending loads. Because the fibers during bending were pulled out of the concrete matrix, the ability of the FRC beam to carry applied load in the post-cracking state purely depends on the capacity of fibers in the broken cross section to carry pull-out loads. In the model the behavior of fiberconcrete beam was simulated by calculating internally existing load bearing value of each fiber crossing the crack (using this fiber experimentally measured pull-out curve), depending on the crack opening value i at the location of this particular fiber. The iteration procedure of beam behavior modeling in bending was performed according to step sequence. Further, number of fibers on one crack's surface unit was used as was obtained in experiment. Relation of externally applied load P as a function of crack opening displacement is thus obtained at each step. The force P represents total force applied to the beam that is divided in two symmetrical forces. To run the algorithms of the model, a computer software program was elaborated.

Since the local opening of crack b(y) is not constant and varies along the height of the crack the bridging force must be dependent on the local crack opening. In our model, we know all fibers coordinates on the macro-crack surface and every particular fiber orientation angle to the crack surface and each fiber shortest end embedded length, as well as how far it is pulled out if CMOD is equal δ.

VII. Conclusions

Detailed experimental and numerical fiberconcrete strength and post cracking behavior investigation was performed for material with macro and micro synthetic polymer fibers. A broad experimental program for macro-synthetic fibers pull-out of concrete was realized. Peculiarities of fracture for such materials were investigated. Beams with uniformly distributed macro-synthetic fibers, micro- synthetic fibers and simultaneously with macro and micro-synthetic fibers were tested and their mechanical behavior under bending loading conditions was numerically simulated. Numerical modeling results were compared with experiments and recommendations were made.

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Andrejs Krasņikovs, Artūrs Mačanovskis, Inese Teļnova, Irīna Boiko. Lieces stiprība fibrobetonam ar nanodaļiņām un polimēra šķiedrām
Mūsdienu polimēru šķiedras tiek izmantotas strukturālos pielikumos, kā mikroarmējums kompozītos materiālos ar betona matricu. Salīdzinot ar citām šķiedrām (tērauda, stikla, oglekļa un citiem), polimēra šķiedras uzvedas viskoelastīgi vai viskoelastoplastiski. Tika izgatavotas 10x10x40cm betona prizmas. Prizmu betons saturēja dažādu daudzumu polimēru šķiedru (makrošķiedras izmērs: 3 cm garumā un 0,75 mm diametrā). Visas prizmas tika pārbaudītas uz 4-punktu lieci. Tika izgatavotas un pētītas prizmas ar betonā haotiski sadalītām makrosintētiskām, mikrosintētiskām un kombinētām makro- un mikrosintētiskām šķiedrām. Paraugu nestspēja tika modelēta skaitliski, izmantojot izstrādāto maģistrālās plaisas augšanas un atvēršanās skaitlisko modeli. Modelis bāzēts uz vienas mikrošķiedras izvilkšanas mehānismu. Kā izejas dati modelī tika izmantoti eksperimentālie rezultāti par atsevišķas šķiedras izvilkšanu no betona matricas. Modelēšanas dati tika salīdzināti ar eksperimentiem, kas veikti uz fibrobetona prizmas 4-punktu liecē.

Андрей Красников, Артур Мачановский, Инесе Тельнова, Ирина Бойко. Прочность на изгиб фибробетона с наночастицами и полимерными волокнами.
Современные полимерные волокна используются в структурных приложениях, как микроармирование композиционных материалов с бетонной матрицей. Были изготовлены бетоные призмы размером 10x10x40см, содержавшие различное количество полимерных волокон (размер макроволокна - длина 3см, диаметр 0,75 мм). Все призмы были испытаны на 4-х точечный изгиб. Образцы, содержащие хаотически распределенные по объему макроволокна, микроволокна а также комбинацию макро- и микроволокон, были изготовлены и испытаны. Механическое поведение образцов моделировалось численно. Разработанная численная модель роста и раскрытия магистральной трещины в фибробетоне, основанная на механизме вытаскивания волокна из матрицы, была успешно применена при моделировании несущей способности образцов при изгибе. В процессе моделирования использовались экспериментально полученные данные по выдергиванию одиночных волокон из бетонной матрицы. Результаты моделирования сравнивались с данными экспериментов на 4-ёх точечный изгиб изготовленных призматических балок.