RHEOLOGICAL PROPERTIES OF SELF-COMPACTING CONCRETE WITH CHOSEN STEEL FIBRES

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Abstract

In the paper the methodology and test results of the investigation are presented and discussed of the influence of steel fibres on rheological properties of Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC). The rheological parameters of SFRSCC - behaves as Bingham body, their rheological parameters yield value g and plastic viscosity h were determined to using new kind of rheometer BT2 to mortar and concrete mix research. In the research, an experimental verification of and significance of an influence: volume fraction of fibres, fibres factor, lengths and shape of fibres on rheological properties of SFRSCC was investigated. In the paper the results obtained for mixes with 3 kind of steel fibres shapes are presented. Concrete mixtures are proportioned to provide the workability needed during construction and the required properties in the hardened concrete. The length of fibres does not have the significant influence on yield value g and plastic viscosity h of SFRSCC. The significant influence of the length of fibres on plastic viscosity h of tested hooked steel SFRSCC was observed only. The rheological properties of SFRSCC from workability point of view are better than for SCC with other types of fibres.

Keywords: steel fibres; self-compacting concrete; rheology; Bingham model; Hershell-Bulkey model

1. Introduction

Technology of self-compacting concrete allows shaping structure of engineering objects in the quicker and safer way than in case of concrete with traditional properties. Technological operations of concrete elements forming are in case of self-compacting concrete considerably simplified and end results allow to expose hardened concrete structures in more extended way [12][14]. One modification of considered concrete is to add to its volume various kinds of fibres as diffused reinforcement [5][6][8]. This is not a new issue in the technology of concrete, however in case of concrete with self-compacting properties it provides current area of research. Problems resulting from using modified in such way concrete mixes were determined based on carried out tests of workability of fresh self-compacting concrete mix modified with steel fibres in rheological context [10].

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Technological problems in applying self-compacting concrete modified with steel fibres as diffused reinforcement is the subject of the present article.

Analysing of influence of fibres on workability and durability parameters of concrete is one of new tendencies in research of self-compacting concrete [3][7][12][15][17][18][19]. Research of steel fibres of various geometric parameters influence were presented to determine the impact of its volume fraction, the length and the shape on rheological and mechanical properties of self-compacting concrete.

Essence of applying steel, polypropylene and other fibres to cement mix has been already discussed in earlier publications [17]. General tendency of the improvement of hardened self-compacting concrete characteristics with the increase of contents of fibres in its volume, makes workability of these concrete mixes worse during forming [5][8]. The current problem, also in case of self-compacting concrete modified with steel fibres, is technological difficulty of its production and carrying out of technological processes in concrete works [20]. It compels to recognise the real nature of workability and to determine an impact of added fibres on phenomena taking place in fresh and hardened self-compacting concrete.

2. Rheological model and measurements of rheological parameters of fresh concrete

It is well documented that fresh mortar and fresh concrete behaves as Bingham material, whose properties can be expressed by two rheological parameters, the yield stress and the plastic viscosity according the formula:

$$\tau = \tau_o + \dot{\gamma}\, \eta_{pl} \tag{1}$$

where τ (Pa) is the shear stress at shear rate $\dot{\gamma}$ (1/s), τ_o (Pa) is the yield value and η_{pl} (Pa·s) is the plastic viscosity [4][9][11][13][16][21]. The physical interpretation of yield value is that of the stress needed to be applied to a material in order to start flowing. When the shear stress is higher then yield value the mix flows and its flow resistance depends on plastic viscosity.

Rheological parameters of fresh mortar, like those of fresh concrete, can be measured using Two Point Workability Test (TPWT), by applying a given shear rate and measuring the resulting shear stress. Because of the nature of rheological behaviour of cement mixtures, the measurements should be taken at no less than two considerably different shear rates. The rheological parameters are determined by regression analysis according to the relation:

$$T = g + N\,h \tag{2}$$

where T is the shear resistance of a sample measured at rotation rate N and *g* (Nmm) and *h* (Nmms) are constants corresponding respectively to yield value τ_o and plastic viscosity η_{pl}. By suitable calibration of the rheometer, it is possible to express *g* and *h* in fundamental units. According to Banfill [2], in the apparatus like used in this work, $\tau_o = 7.9\ g$ and $\eta_{pl} = 0.78\ h$, but all results are given below in terms of parameters *g* and *h*. The principles of TPWT and rheological properties of fresh cement mortars and concretes are presented in existing literature [22].

It should be noted that rheological properties of cement pastes and cement binder mixtures (mortars and concretes) differ from each other. During the flow test cement paste reveals plastic characteristics with high degree of nonlinearity and with high ticsotropic effects [21]. As far as Bingham model is adequate to characterize rheological properties of fresh mortar and concrete, characterization of rheological properties of cement paste demands more complex models. It was demonstrated in [1] that rheological properties of cement paste are best described by the following models: Herschel-Bulkley, Robertson-Stiff and Ellis model. In the same time it was stated that Bingham model may be used for characterization of properties of cement paste only in narrow range.

3. Assumptions and methodology of research

Results of workability tests of self-compacting cement mixes modified with steel fibres in rheological context are presented in this paper. Testing carried out with method of rheometrical of workability test (RWT) were conducted with rheometer for mortars and concrete mixes - BT2. (Fig. 1). RWT method was discussed detailed in literature [21].

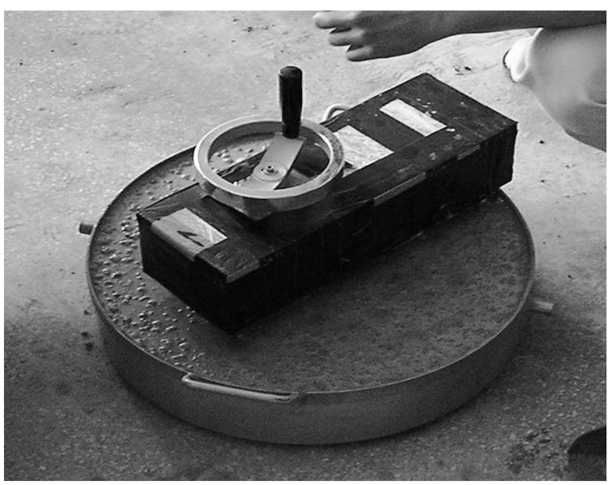
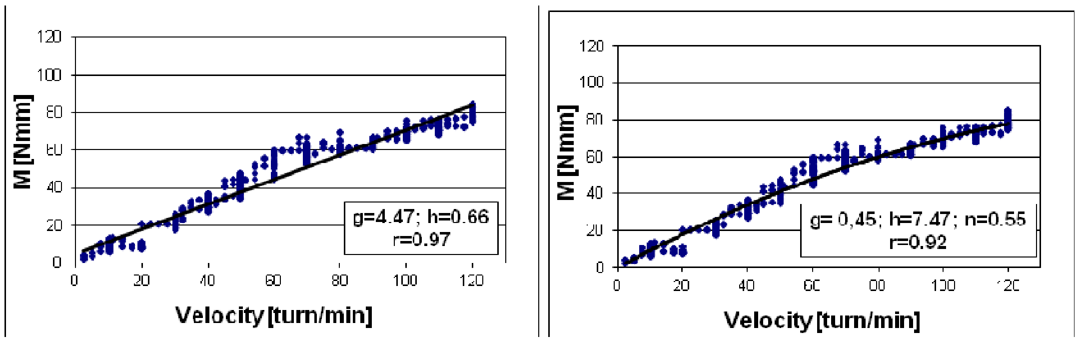


Fig. 1: Rheometer BT2 to determine rheological parameters of concrete mixes - general view of the apparatus during the measuring procedure.

Approximation of measurement results conducted by two-parameter Bingham rheological model and three-parameter Hershell-Bulkey model was done (figure 2). It allowed determining two basic rheological parameters - yield value *g* and plastic viscosity *h*. The values were determined by two-parameter model.



a) b)

Fig. 2: The rheological behaviour of the fresh concrete; typical example of flow curve and determined rheological parameters as: a) Bingham model; b) Hershell-Bulkey model

Composition of the tested self-compacting mixture is presented in table 1. The concrete mix was modified - variable kinds and volume fraction of steel fibres were used. Steel fibres were selected out of a large number of fibres available on the market. Despite of their availability and the variety it is however difficult to purchase fibres of similar geometric parameters and shape. Results of testing of self-compacting mixtures modified with eleven kinds of steel fibres are presented in the article. Tests were carried out in two blocks for four levels of variability. In the first block tests were carried out for variable volume fraction of fibres in the matrix. In the second block a variable level of the fibre reinforcement was examined (fibre factor - F_F), taking geometric parameters of fibres into consideration (length L and diameter d) as well as fibre volume fraction V_f in the mixture, according to the following pattern.

$$F_F = V_f \cdot \frac{L}{d} \tag{1}$$

Taking the level of the fibre reinforcement into consideration in testing (F_F) allows to determine the influence of each parameter that characterise the used diffused reinforcement on workability of self-compacting mixtures in rheological context in more reliable way.

Tab. 1: Composition of the self-compacting mixture

Component		For batch of concrete	For m^3
CEM II B-S 42.5	[kg]	12.3	344
Fly ash	[kg]	4.9	138
Water	[kg]	5.9	164
SP Viscocrete 3	[1,5%]	0.19	5
Aggregate 2-8	[kg]	29.0	810
Sand 0-2	[kg]	27.8	776
Steel fibres	[%]	0.5 – 1.0 – 1.5 – 2.0	
W/(C+SP)		0.34	0.34

In block I, tested fibre volume fraction in the concrete mixture was 0.5-1.0-1.5-2.0 % what corresponds to 39.25-78.50-117.75-157.00 kg/m^3 contents. In block II a level of variability (F_F) was considered 0.2-0.4-0.6-0.8, what corresponds to fibre mass that is subject to slenderness of fibres, as presented in table 2.

Tab. 2: Geometric characteristics of tested steel fibres and variability of fibres volume fraction level of fibres reinforcement (FF) in self-compacting concrete mixture.

Characteristics of fibres [mm]			Mass of fibres for variable (F_F) [kg]			
Shape	L	d	0.2	0.4	0.6	0.8
Straight	13	0.16	20.93	41.87	62.80	83.73
Straight	25	0.40	25.12	50.24	75.36	100.48
Straight	6	0.16	41.87	83.73	125.60	167.47
Wavy	50	1.00	31.40	62.80	94.20	125.60
Wavy	35	0.80	35.89	71.77	107.66	143.54
Wavy	30	0.70	36.63	73.27	109.90	146.53
Hooked	50	0.45	14.13	28.26	42.39	56.52
Hooked	60	0.65	17.01	34.02	51.03	68.03
Hooked	64	0.80	19.63	39.25	58.88	78.50
Hooked	60	0.80	20.93	41.87	62.80	83.73
Hooked	30	0.50	26.17	52.33	78.50	104.67

Geometric characteristics of tested fibres and fibre volume fraction in concrete mixture according to level of fibre reinforcement were presented in table 2. The shape of fibres due to variability of their geometry is an additional factor influencing test results but overlapping with considered remaining variable parameters of fibres.

4. Results of tests and discussion

Properties of self-compacting mixtures modified with steel fibres were tested to determine rheological parameters measured with RTU method. On the basis of pre-examinations, determining relationship between the time and the flow diameter measured with Abram's cone method, an estimated self-compacting limit was deter-mined for tested mixtures with steel fibres, according to the assumption: flow time T_{50} = max 9 seconds and the flow diameter R = min. 600 [mm]. The above mentioned assumptions of the self-compacting limit were obtained for maximal yield value *g* on the level 600 [Nmm]. Any plastic viscosity h value as a limit one for self-compacting mixtures with steel fibres was unambiguously determined. Figures 3 and 4 present influence of kind and volume fraction of straight steel fibres on rheological parameters of self-compacting mixtures - yield value *g* and plastic viscosity *h* value.

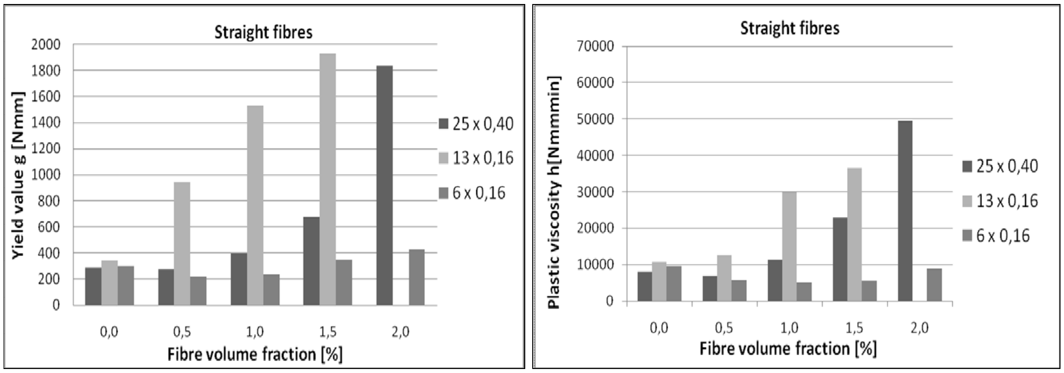


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Fig. 3: Influence of kind and volume fraction of straight steel fibres on:
a) yield value *g*; b) plastic viscosity *h* value

The increase of yield value *g* and plastic viscosity *h* value along with the increase of straight fibres volume fraction in the considered research area of modified self-compacting mixtures was shown. In this research group (straight fibres), addition of 13x0.16 fibres to the mixture resulted in the biggest increase of g parameter and, what follows, workability becomes wrong. Addition of 6x0.16 fibres to the mixture resulted however in the smallest increase in the g parameter. Thus the smallest worsening of the considered mixture workability was obtained. In case of plastic viscosity h, the biggest value of this parameter was also obtained for the self-compacting modified mixture with 13x0.16 fibres, what also makes workability of considered mixture worse.

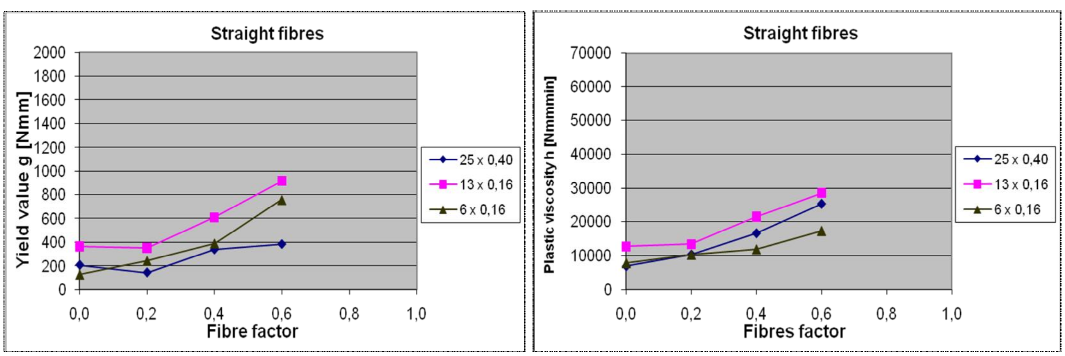

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Fig. 4: Influence of kind and fibre factor of straight steel fibres on:
yield value *g*, b) plastic viscosity *h* value

Addition of 6x0.16 fibres to the mixture resulted in the smallest increase of the *h* parameter. Thus the smallest worsening of the considered mixture workability was obtained. Similar results of examinations of self-compacting mixtures modified with straight fibres were obtained research blocks I and II. Mixtures with the addition of 13x0.16 fibres started not to fulfil conditions for self-compacting mixtures sooner.

Figures 5 and 6 present influence of kind and volume fraction of wavy steel fibres on yield value *g* and plastic viscosity *h* value. The increase of yield value *g* and plastic viscosity *h* value along with the increase of wavy fibres volume fraction in self-compacting mixtures was shown. In this research group (wavy fibres), addition of 50x1.0 fibres to the mixture resulted in the biggest increase of *g* parameter in both research blocks and, what follows, the biggest worsening of workability of modified self-compacting mixtures. Condition of self-compacting was obtained for all considered wavy fibres in the whole range of variability of volume fraction. In case of the factor (F_F), self-compacting limit for all wavy fibres was level 0.6.

All tested hooked fibres except of the discussed above 64x0.80 fibres fulfilled self-compacting condition within the whole range of fibre reinforcement.

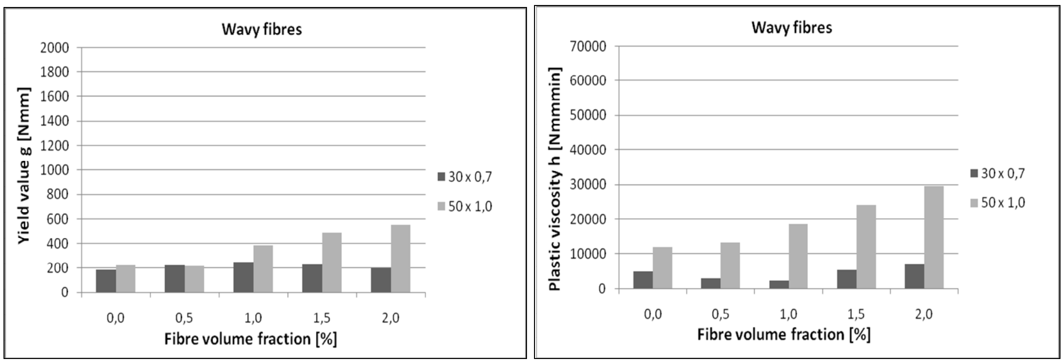

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Fig. 5: Influence of kind and volume fraction of wavy steel fibres on:
a) yield value *g;* b) plastic viscosity *h* value

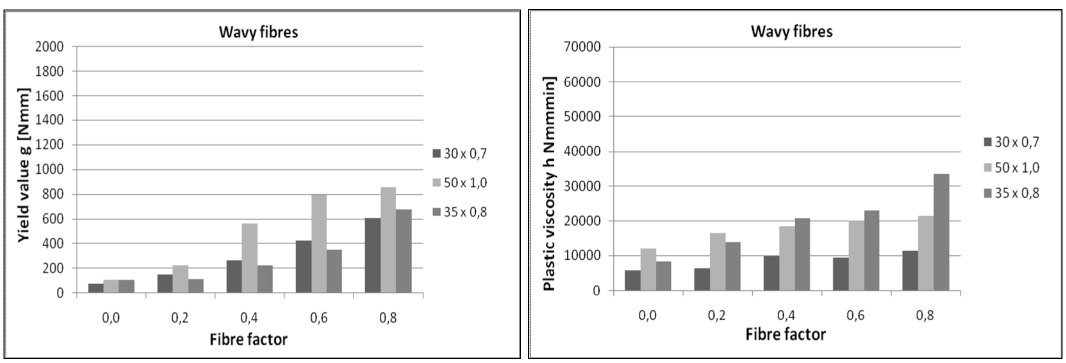

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Fig. 6: Influence of kind and fibre factor of wavy steel fibres on:
yield value *g;* b) plastic viscosity *h* value

On the basis of carried out tests it is possible to feature estimated brackets of properties of self-compacting mixtures with steel fibres of various geometrical parameters and volume fraction. Hooked steel fibres were the next considered fibres. Influence of these fibres on rheological parameters of self-compacting mixtures was presented on figures 7 and 8. The increase of yield value *g* and plastic viscosity *h* value along with the increase of hooked fibres volume fraction in self-compacting mixtures was shown. In this research group addition of 64x0.80 fibres to the mixture resulted in the biggest increase of *g* and *h* parameters and limitative fulfilling of self-compacting condition for volume fraction 0.5. Similar parameters were obtained for fibres 30x0.5. Addition of 60x0.65 fibres to the mixture resulted in the smallest increase in the g parameter. Condition of self-compacting was obtained for volume fraction close to 1.0%

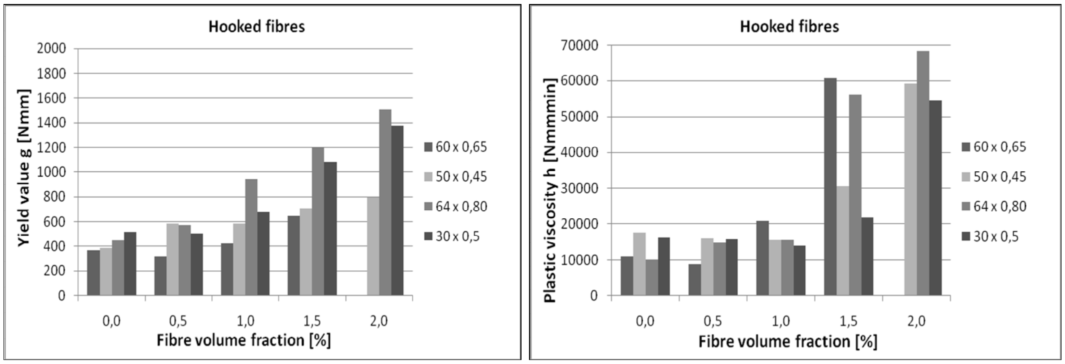

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Figure 7. Influence of kind and volume fraction of hooked steel fibres on:
a) yield value *g*; b) plastic viscosity *h* value

Table 3 presents brackets of properties of self-compacting for variable volume fraction together with fibres weight quantity. Table 4 presents brackets of properties of self-compacting for variable level of fibre reinforcement (F_F), together with fibres weight quantity. Lack of self-compacting effect of mixtures in the whole considered block I of added straight fibres 13x0.16 was shown. Total – in block I - self compacting effect of mixtures modified with steel fibres was stated in case of two types of wavy fibres 30x0.7 - 50x1.0 and straight fibres 6x0.16. For two types of fibres the tests were not carried out in block II.

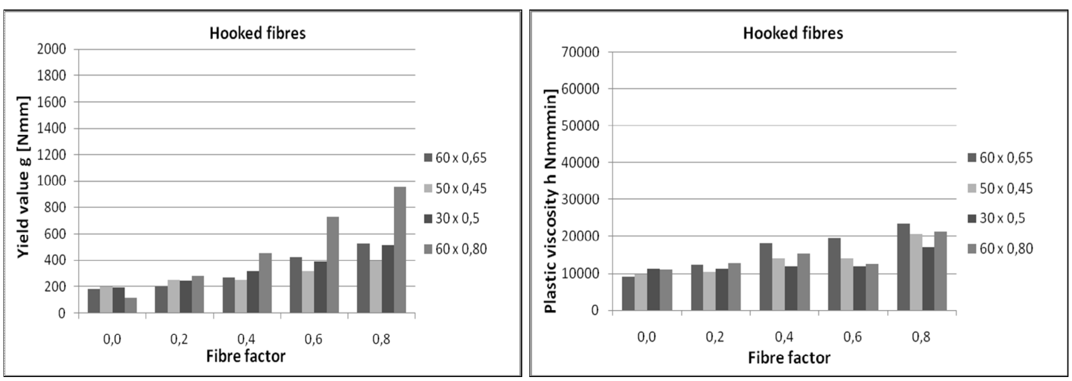

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Fig. 8: Influence of kind and fibre factor of hooked steel fibres on:
a) yield value *g*; b) plastic viscosity *h* value

There is a lack - insignificant though - of consequence in results of tests. Straight 13x0.16 fibres in research block I have not indicated any self-compacting effect within the total research area, however in block II these properties were kept up to F_F value 0.4 i.e. for 42 kg/m^3. Wavy fibres 50x1.0 fibres in research block I have indicated self-compacting effect within the total research area i.e. maximum 157 kg/m^3, however in block II these properties were not kept for F_F value 0,4 i.e. for 125.6 kg/ m^3.

Tab. 3: Brackets of properties of self-compacting for variable volume fraction (V_f) together with fibres weight quantity.

Characteristics of fibres [mm]	Mass of fibres for variable V_f [kg]

Shape	L	d	0.5	1.0	1.5	2.0
Straight	13	0.16	-	-	-	-
Straight	25	0.40	39.2	78.5	-	-
Straight	6	0.16	39.2	78.5	117.7	157.0
Wavy	50	1.00	39.2	78.5	117.7	157.0
Wavy	35	0.80	nd	nd	nd	nd
Wavy	30	0.70	39.2	78.5	117.7	157.0
Hooked	50	0.45	39.2	78.5	-	-
Hooked	60	0.65	39.2	78.5	-	-
Hooked	64	0.80	39.2	-	-	-
Hooked	60	0.80	nd	nd	nd	nd
Hooked	30	0.50	39.2	-	-	-

Description to tables 3; (nd)-no data available, (-)-condition of self-compacting not fulfilled

Tab. 4: Brackets of properties of self-compacting for variable level of fibre reinforcement (FF), together with fibres weight quantity.

Characteristics of fibres [mm]		Mass of fibres for variable V_f [kg]			
Shape	L/d	0.2	0.4	0.6	0.8
Straight	75,0	20.9	41.8	-	-
Straight	62,5	25.1	50.2	75.4	100.5
Straight	37,5	41.8	83.7	-	-
Wavy	50,0	31.4	62.8	94.2	-
Wavy	43,8	35.8	71.8	107.6	-
Wavy	42,9	36.6	73.3	109.9	-
Hooked	111,1	14.1	28.3	42.4	56.5
Hooked	92,3	17.0	34.0	51.0	68.0
Hooked	80,0	nd	nd	nd	nd
Hooked	75,0	20.9	41.8	-	-
Hooked	60,0	26.2	52.3	78.5	104.7

Description to tables 4; (nd)-no data available, (-)-condition of self-compacting not fulfilled

Hooked fibres 30x0.5 were the last incorrect case. In block I they indicated self-compacting properties for $V_f = 1.0\%$ i.e. at most for 78.5 kg/m^3, however in block II self-compacting properties were indicated within whole considered research area i.e. even for 104.7 kg/m^3. Any impact of the length of fibres on changes of rheological parameters of the considered modified mixtures was unambiguously determined.

5. The summary and final conclusions

Analysis of mutually exclusive factors taking place as a result of adding steel fibres to self-compacting concrete: workability worsening or even loss of self-compacting properties and improvement of self-compacting concrete mechanical properties was the subject of the present article. Presented results of testing self-compacting concrete modified with steel fibres show influence of fibre addiction to worsen workability of fresh mixture and increase in compressive strength of hardened fibre concretes made out of self-compacting mixtures.

To keep self-compacting effect of mixtures modified with steel fibres, the volume fraction of 2.0% seems to be recommended to ensure its maintenance. This in not however the case with all fibres taken under consideration. The number of possible to apply steel fibres to ensure self-compacting effects increases along with the decrease of fibres volume fraction but simultaneously probability to improve mechanical properties drops down.

Problems occur with homogenous filling of concrete volume with the added fibres and the required technological processes for this type of concrete make keeping homogenous structure even more difficult. Pumped self-compacting fibre concrete should be delivered directly to forming place, with limiting of horizontal relocation of mixtures within formed concrete structure. The slenderness and volume fraction of steel fibres in the mixture worsens its workability but improves strength parameters though not for all fibres. Keeping the homogeneity of steel fibres during the process of self-compacting concrete forming is the current research problem.

It seems recommendable to carry out broader re-search to determine influence of steel fibres on properties of fresh and hardened self-compacting concrete based on variability of so called fibre factor. Taking workability under consideration it seems to be proper to add shorter fibres with higher volume fraction into concrete mixture. This should ensure homogeneity of formed concrete structure.

Influence of added fibres shape, important from fibres anchorage energy in self-compacting concrete matrix, has not been unambiguously determined in the research. Currently the author conducts research of relationship between energy to draw fibres out of the concrete matrix and fibres geometric parameters as well as research of the influence of real distribution of diffused reinforcement on concrete compressive strength parameters. It is necessary to remember about the diversified shape of tested fibres together with their diversified slenderness. It is recommendable to carry out additional re-search to eliminate overlapping of variable factors. The broad commercial offer of fibres imposes however some limitations.

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