Strength, Deflection and Watertightness of Steel Fiber Reinforced Concrete Modified by Silica Fume

J. Katzer

This research concerns concrete composites based on fine aggregate modified by up to 25% of silica fume and reinforced by up to 2% (by volume) of steel fiber. Concrete was modified by replacing cement by silica fume and adding steel fibers. All examinations were carried out after 120 days of curing. The received results of the research on ultimate compressive strength, flexural strength and watertightness are presented on charts. The author noted a considerable improvement in compression strength and watertightness of the examined concrete mixes. The subject of the analysis of the research results was to define the relation between flexural strength of the examined concrete composites and effective spacing.

Key words: Concrete, fine aggregate, silica fume, steel fiber, watertightness

1. Introduction

Concrete is one of the main civil engineering materials because of the versatility of its applications, the popularity of occurrence and also because of the easy production technology. There is a growing need for materials of high resistance to weather conditions and high strength. This need causes an intensive development of different concrete composites. SFRC belongs to a group of composites characterized by high flexural strength, dynamic strength, and fatigue strength [1, 5].

2. The Research Programme

Keeping the above facts in mind, the author had worked out a research programme of fine aggregate concrete modified by silica fume, steel fiber, and a plasticizer. Fine aggregate concrete was created on the basis of waste sand. Waste sand is a by-product of hydrograding natural all-in aggregate. During the process of hydrograding, all-in aggregate is divided into gravel and sand which, due to its excessive amount, is called waste sand. This sand has lower grain-size distribution**,** a smaller amount of stone dust and a higher content of minerals and crystal rocks than the pit sand obtained from the same mine [3]. The fiber reinforced concrete matrix of water/cement ratio W/C = 0.5 was made on the basis of the waste sand whose chosen physical features were set up in table 1.

The examinations were carried out with the help of an experimental design. All the simplex two-level designs were taken into account. Finally the author employed the so-called "central composite experimental design" presented on fig.1 and in table 2. The subject of the research was defined as complex material whose interior structure was unknown and unavailable for an observer [7]. The observer knew the input parameters which were the addition of steel fiber - V_f, and silica fume – SF. The output parameters were strength and other properties of concrete. The examination results were statistically processed and values bearing the gross error were assessed on the basis of Smirnow-Grabbs criterion. The objectivity of the experiments was assured by the choice of the sequence of the realization of specific experiments from a table of random numbers. All calculations connected with specifying an

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equation regress factor and graphic interpretation of the received model was carried out with the help of "Statistica 5.0" computer programme.

TABLE 1: Physical features of waste sand

Feature	Symbol	Size
Loose bulk density	ρ_n^l	1631 kg/m^3
Compacted bulk density	ρ_n^z	1805 kg/m^3
Fineness modulus by Kuczyński	U_K	3.279
Fineness modulus by Humml	U_H	66.4
Fineness modulus by Abrams	U_A	2.206
Cavity of loose aggregate	j_l	38 %
Cavity of compacted aggregate	j_z	32 %
Porosity	P	3.39 %

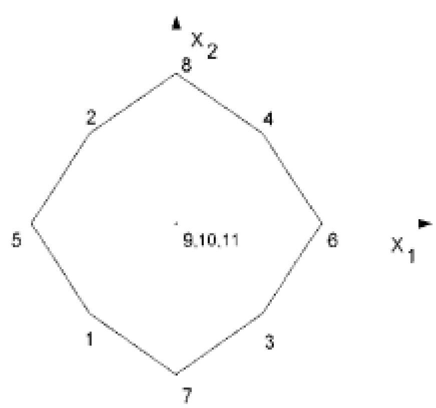

FIGURE 1: The scheme of the arrangement of measuring points

TABLE 2: Experimental design values of input factor

Number of experiment	Number of realization	Input factor			
		in code values		in natural values	
		x_1	x_2	SF %	V_f %
1	2	-1,00000	-1,00000	5,0	0,4
2	5	-1,00000	1,00000	5,0	1,6
3	10	1,00000	-1,00000	20,0	0,4
4	9	1,00000	1,00000	20,0	1,6
5	1	-1,68179	0,00000	0,0	1,0
6	8	1,68179	0,00000	25,0	1,0
7	3	0,00000	-1,68179	12,5	0,0
8	4	0,00000	1,68179	12,5	2,0
9,10,11	7,6,11	0,00000	0,00000	12,5	1,0

11 concrete mixes were modified by the addition of silica fume (from 0% to 25%), addition of steel fibre (from 0% to 2%) and by admixture of plasticizer (1.8%). The geometry of the employed steel fiber is shown on fig.2. From each concrete mix 24 specimens were made - 6 specimens 15*15*15 cm, 12 specimens 10*10*50 cm and 6 specimens 15*15*15 cm. The research program covered the examinations of features after 120 days of curing because of a high silica fume reactivity in time. This reactivity has a significant influence on concrete parameters examined after 28 days of curing.

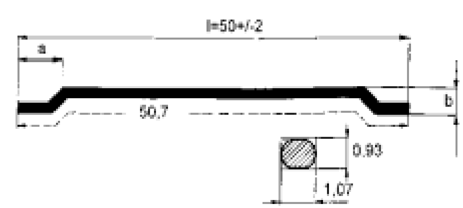

FIGURE 2: The geometry of the employed steel fiber in mm (a = 5 mm, b = 3 mm)

3. Results of the research

The results of the ultimate compressive strength examination are shown on fig. 3. The ultimate compressive strength examination was carried out on specimens 15*15*15 cm. Both, silica fume and steel fiber cause the growth in ultimate compressive strength, and both of their influences accumulate. The growth of ultimate compressive strength appears mainly because of the addition of steel fiber. Above a certain optimum value of the steel fiber addition (about 1.5%), ultimate compressive strength of the examined composites slightly decreases.

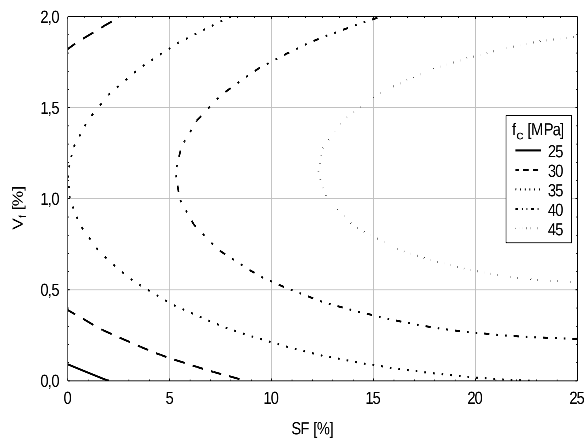

FIGURE 3: Ultimate compressive strength f_c

To realize the flexural strength examination under four point loading, two concentrated loads were applied on the samples in spacing 1/3 of the span. The scheme of four point loading of the concrete beam is presented on fig.4. The results of flexural strength examinations carried out on specimens 10*10*50 cm are presented on fig.5. The shape of the presented surface shows a big influence of the steel fiber addition on acquiring quasi-plastic features by the composite. Concrete mix without any silica fume addmixture has the biggest flexural strength. During the flexural strength examination deflection was measured at the imposed force F=2*2.5 kN. The results of the deflection examination are shown on fig.6. Fig.7 shows the interdependence σ–ε for chosen SFRC composites. The examination was carried out on specimens ϕ15*50 cm with axial compression. The examination was finished after having achieved about 0.9 failure load.

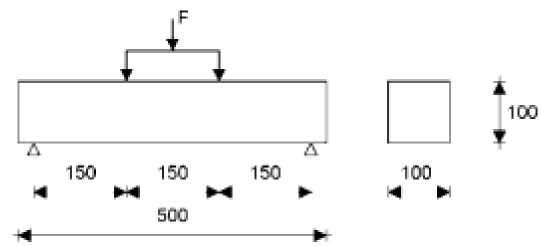

FIGURE 4: Scheme of four point loading of a concrete beam. All dimensions in mm.

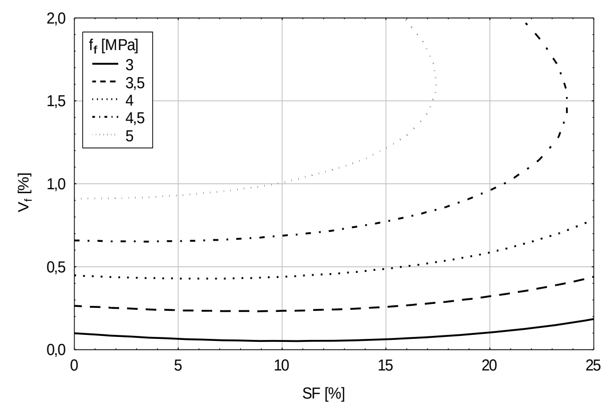

FIGURE 5: Flexural strength f_f

The examination of watertightness of concrete samples does not reflect watertightness of concrete composite in an actual construction. Each, even the simplest construction works within constantly changing conditions, where loads appear and disappear in time. The influence of the changeability of static loads in time on concrete parameters has already been well known, especially as far as ultimate compressive strength is concerned [4]. Keeping the above facts in mind, the author has worked out watertightness after a cycle of loads. The cycle consisted of loading a sample eight times. When the 45% of breaking stress was achieved the sample was unloaded. The samples were loaded with an increasing force at a uniform rate (the speed of growing of stress 0.5 +/- 0.1 MPa/s). In these conditions the achieved pulse frequency was 1/35 Hz. Comparative samples were not subjected to load. These samples were treated as control ones. After the cycle of load, samples were dried in temperature +60°C. Drying the samples was to eliminate the influence of absorbtion of vapour from air while curing. Watertightness of fine aggregate concrete was tested using an instrument which supplies water from below and can test simultaneously six samples under a constant pressure of 0.2 MPa to 1.2 MPa. The test was carried out under constant pressure of 1.2 MPa within 72 hours. After this period of time samples were split and the depth of water penetration was measured. The results were presented with the use of a "speed of leaking water parameter" k_v [2] calculated according to the equation (1):

$$k_V = x_{max} /(2 \cdot \Sigma\, h_i\, t_i), \qquad (1)$$

Where:
x_{max} – maximum depth of water penetration in meters
h – pressure of water in meters H_2O
t_i – time of lasting of pressure in seconds.

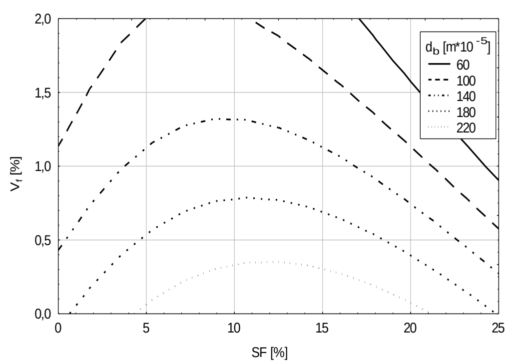

FIGURE 6: Deflection d_b of a beam 10*10*50 cm

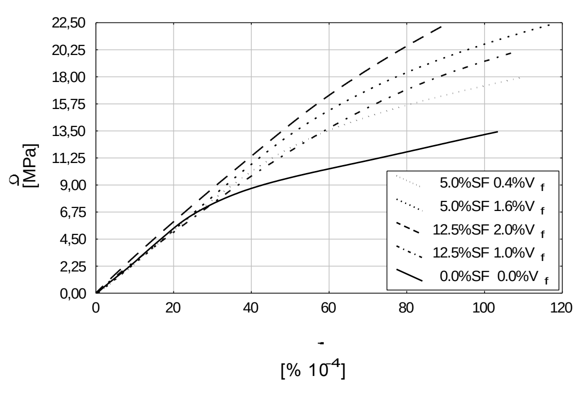

FIGURE 7: Stress-strain σ−ε axial compression curves

The expression of watertightness with the use of parameter k_v allows to compare watertightness of both samples which were thoroughly or partially penetrated by water during the experiment. One may also compare the watertightness of samples examined with varied methods.

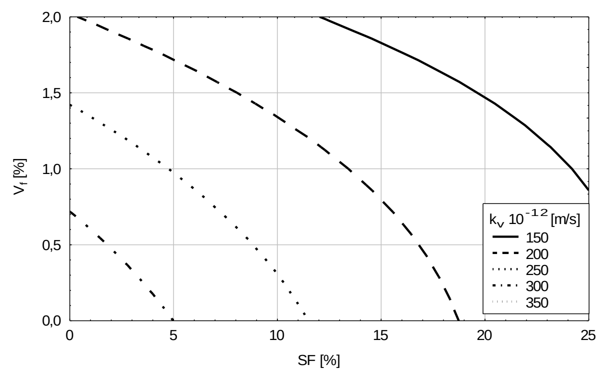

FIGURE 8: Watertightness of fine aggregate concrete composite after a cycle of loads in relation to the addition of silica fume SF and fiber reinforcements V_f

Watertightness of fine aggregate concrete composites subjected to a cycle of loads is shown in fig. 8. Watertightness of the described composites increases both in relation to the addition of SF as well as of V_f. The increases of watertightness are at a uniform rate in both directions and they are close to a linear relation. A comparative concrete mix has $k_V = 340 \cdot 10^{-12}$ m/s and the most tight of the maximum additions SF and V_f $k_V = 120 \cdot 10^{-12}$ m/s. Watertightness of fine aggregate concrete composites which were not subjected to any pre-load is shown in fig.9. Watertightness of concrete without any additions expressed with the use of parameter equals $230 \cdot 10^{-12}$ m/s. Modifying the concrete mix solely with steel fiber reinforcement allowed to achieve watertightness of $103 \cdot 10^{-12}$ m/s. Modifying the concrete mix solely with silica fume allowed to achieve $39 \cdot 10^{-12}$ m/s. It is visible in fig.10 that the addition of reinforcement worsens the tightness attained with silica fume when its quantity exceeds 10%. With the increase of the amount of silica fume the tightness of the fine aggregate concrete composite grows, especially in concrete mixes of a high content of reinforcement. With the addition of more than

15% of silica fume all concrete mixes are characterized by considerable tightness, which stabilizes at a level of $25\text{-}23\cdot10^{-12}$ m/s.

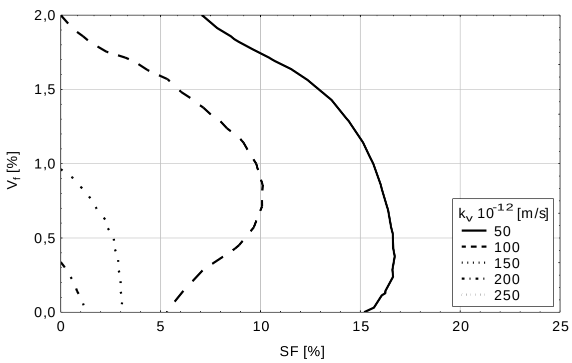

FIGURE 9: Watertightness of fine aggregate concrete composites not subjected to load in relation to the addition of silica fume SF reinforcement V_f

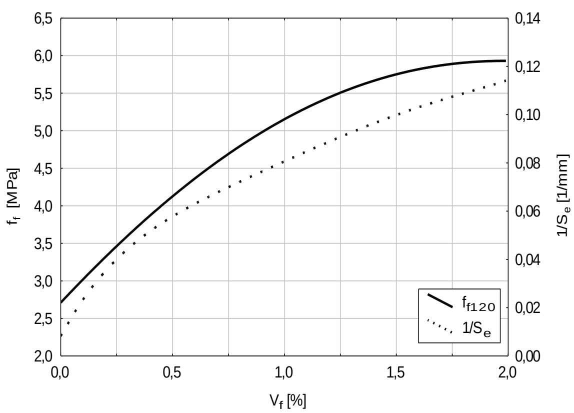

FIGURE 10: The parameter $\frac{1}{S_e}$ and flexural strength f_{f120} of the analysed fiber reinforced concrete

4. The analysis of the results

Ultimate compressive strength (which was 24 MPa for plain concrete) grew by over 100% (to 50 MPa) for the most optimum concrete mixes. All concretes were made of Portland Cement 32.5 (400 kg/m^3) without admixtures. It proves that there are yet other possibilities of achieving significantly bigger strengths. For this feature the combination of the two additives in the cured composite is very effective.

The results of flexural strength examinations disclose the effectiveness of steel fiber addition behaviour with this kind of loading. Plain concrete mix obtains the strength 2.75 MPa, and concrete reinforced by 2% of steel fiber equals 6 MPa. Despite of the passing 120 days of curing, silica fume additive worsens significantly flexural strength obtained thanks to the steel fiber itself. Despite this negative tendency concrete mixes of maximum 15% of silica fume and from 1.5% to 2% of steel fiber additive are characterised by much higher strength than plain mixture.

The deflection measurement, similar to the flexural strength described above, shows the acquirement of quaziplastic features by SFRC composite. The deflection of composite modified by 25% of silica fume and 2% of steel fiber is five times smaller than the deflection of composites modified by silica fume alone. Watertightness of fine aggregate fiber reinforced composites without any load reaches the level from $k_V=23$ to $230\cdot10^{-12}$ m/s. Composites which were subjected to a cycle of loads are characterised by watertightness from $k_V=120$ to $340\cdot10^{-12}$ m/s. If one assumes the watertightness of composites without load as a point of reference then the relation of watertightness of not modified fine aggregate concrete, loaded with the cycle of loads is 1:5. A similar relation for a composite modified with a maximum addition of SF and V_f is 1:1.5. It is observable in the above proportions how significant is the influence of the addition of steel fiber and load onto watertightness of fine aggregate concrete composites. Concrete ”working” in a construction carries most frequently loads causing about half of the breaking stress changing in time. Bearing this in mind the most important mechanical property of the fine concrete composites for the application in engineering is watertightness under a cycle of loads. In such a case watertightness of fine aggregate concrete composite modified only by silica fume examined in a traditional way is very high. The same concrete subjected to the cycle of loads loses about 80% of its primary watertightness and it fails to meet the primary requirements as far as watertightness is concerned.

One of the main problems connected with fiber reinforced concretes is their precise designing as far as their flexural strength is concerned, which has a great significance in their appropriate and effective application. The use of the parameter specifying spacing of fibers in concrete matrix creates a potential possibility of designing flexural strength of fiber reinforced concrete.

The relation between the number of fibers and their general volume in concrete matrix influences the distance between single fibers. There is a noticeable influence of fibers on elongation of concrete matrix when the average distance between axis of fibers is smaller than 12 mm. In order to achieve a precise description of the phenomenon Mangat [6] defined a parameter describing apparent fiber spacing in concrete matrix marked with a symbol S_e. Calculating S_e involves, apart from the geometry of a fiber, such features as fiber-matrix bond strength and fiber ultimate strength. The parameter describing apparent fiber spacing in concrete matrix was called ‘effective fiber spacing’. The relation between S_e and diameter (d), length (l) and contents of fibers (V_f) of a circular cross-section characterized by fiber-matrix bond strength τ = 1 MPa is presented below.

$$S_e = 87{,}4\sqrt{\frac{d}{V_f l}} \qquad (2)$$

For V_f =1.016% the parameter S_e of the examined fiber reinforced concrete samples equals 12 mm. Together with the increase of the quantity of fibers, S_e decreases and finally reaches 8.74 mm for V_f = 2%. Assuming S_e = 12 mm as a binding border of effectiveness of the steel fiber addition one may say that in the described composites the effective addition of steel fiber equals V_f = 1%. The course of the curve describing flexural strength f_{f120} of fiber reinforced concretes after 120 days of curing and the relation1/S_e characterizing the same composites are shown in fig.2.

Both of the presented curves have similar shapes and after scaling the relation 1/S_e for the analysed concrete matrix reflects well flexural strength f_{f120}. Assuming that k_1 is a nondimention factor determined empirically one can write:

$$f_f = k_1 \cdot \frac{1}{S_e} \qquad (3)$$

In case of considered fiber reinforced concrete composites k_1 equals about 524. The employment of the parameter S_e for expressing flexural strength of reinforced concrete composites requires vast experiments of fiber reinforced concretes based on different matrixes and modified by different types of fibers. The analysis of flexural strength in reinforced concrete composites presented above is an encouraging beginning to the introduction of relations more universal and possible for wider applications in engineering practice.

5. Conclusions

The presented research on concretes based on waste sand modified by steel fiber and silica fume lead to the following conclusions:

1. The addition of both silica fume and steel fiber improves ultimate compressive strength.
2. Steel fiber improves flexural strength of the examined concretes and it decreases deflection and linear strain.
3. Despite 120 days of curing silica fume does not improve flexural strength and it does not decrease strain under axial load.
4. The relatively high watertightness of the described composites after the cycle of loads is achieved due to the addition of steel fibers.
5. It is possible to obtain composites, on the basis of waste sand, which are characterized by very high chosen features.
6. “Central composite design” may be effectively employed for examinations of fine aggregate concretes modified by steel fiber and silica fume.

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