Numerical and experimental analysis of behaviour of steel fibre reinforced self-compacting concrete slabs under loading

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Abstract. The paper deals with testing of self-compacting concrete slabs with scattered steel reinforcement, which are designed for the production of garden furniture or benches. A self-compacting concrete was designed for the experiment and its composition was further modified by the addition of steel fibres. Plain self-compacting concrete was used to produce test specimens with nominal dimensions of 40×40×160 mm, which were used to determine the basic properties of concrete, and test slabs for experimental analysis of their behaviour under load. The self-compacting concrete with steel fibres was only used to produce test slabs. The slabs were loaded in three different ways, of which one was to simulate real loading of the horizontal part of a concrete bench. The results of the loading tests are compared to the results of a nonlinear numerical analysis conducted using the finite element method.

1 Introduction

For many years, concrete has been one of the most commonly used building materials. Its production offers many advantages in regard to both its physico-mechanical parameters and high variability of structural elements that can be manufactured from it. Today concrete is also popular in regard to the speed of construction. Production technologies of concrete are on a high level and are capable of influencing its rate of ageing, which is becoming shorter and therefore allows faster and more efficient construction. Massive use of concrete is, however, connected to considerable disadvantages, especially with regard to the environment. The cement industry produces a substantial amount of CO_2 emissions that are directly linked to the phenomenon of global warming. When designing a concrete formula it is therefore necessary to consider all the available aspects and choose an acceptable compromise from the point of view of both engineering and the environment [1].

If a concrete structural element is to be produced knowing it will be subjected to tensile forces, it is necessary to consider larger reinforced cross-sections in its design. However, this entails higher consumption of concrete and has adverse impacts on the environment. Recent decades have therefore witnessed increased use of special concrete such as high-strength concrete (HSC), high-performance concrete (HPC) or ultra-high-performance

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concrete (UHPC), which are less financially demanding. Such concrete can be used to create subtler structures which, in terms of concrete properties, compare to more robust structures from traditional vibrated concrete with reinforcement. An example of a modern concrete is self-compacting concrete SCC, which can be reinforced with steel fibres – as is then known as SFRSCC [2, 3].

Self-compacting concrete is a special type of concrete which does not require any external compaction during placing. This concrete is compacted solely by gravity. Its own weight allows it to flow and perfectly fill the formwork even in parts with increased reinforcement. In order to improve the tensile properties of concrete, its formula can include scattered reinforcement in the form of fibres from various materials (most common are metal, polymer and glass fibres). In this case, it is fibre-reinforced concrete, or fibre-concrete, where the fibres absorb the tensile forces generated by the stress between the grains of the coarse aggregate [3-5].

2 Experimental program

The main aim of the experiment was to assess the effect of scattered steel reinforcement on the properties of hardened SCC to be used for the production of concrete slabs designed for concrete benches. Two types of test specimens were produced, beams 40×40×160 mm for destructive and non-destructive testing of the properties of hardened SCC without fibres (reference concrete) and slabs from plain SCC as well as from SFRSCC with nominal dimensions of 300×50×900 mm. These were tested by bending loads. The aim of the experiment was to monitor the effect of scattered reinforcement on the behaviour of the slabs under load, which was conducted in three different ways. One of the loading scenarios simulated a real-life situation of loading a slab that is used in the structure of a bench.

2.1 Materials

Two SCC formulas were designed for the experiment - one without fibres and one with fibres. The materials for their production included CEM I 42.5 R cement, micronized limestone, coarse mined aggregate with grain size 4/8 mm, fine mined aggregate with grain size 0/4 mm, superplasticizer and water. The formulas were identical with one of them also containing scattered reinforcement in the form of 50 mm steel fibres (in the amount of 25 kg per 1 m^3 of fresh concrete). Due to the use of commercial products, their names and composition cannot be described in more detail in this paper. With the water/cement coefficient of 0.32, the fresh reference SCC achieved SF2 consistency and bulk density of 2340 kg/m^3.

The formula without scattered reinforcement was used to produce beams which were subjected to determination of basic physical and mechanical properties of concrete using non-destructive and destructive testing methods. In addition, 9 slabs with dimensions 300×50×900 mm were produced using the same formula and were used for testing of flexural strength at various types of loading. The formula containing scattered steel reinforcement was only used to produce 9 slabs, which were loaded in the same way as the slabs from plain SCC.

2.2 Testing methods

The determination of basic properties of the hardened reference concrete involved 24 specimens with dimensions 40×40×160 mm. After casting, these specimens were stored for 24 hours in plastic moulds covered with a PE foil. They were then removed from the moulds and stored in a water bath until the start of testing. The following properties of hardened SCC were determined at the age of 7, 28 and 90 days:

• bulk density D according to [6] (in saturated state, density was calculated from the actual measured dimensions),

• dynamic modulus of elasticity E_{cu} according to [7] using the ultrasonic pulse velocity method,

• dynamic modulus of elasticity E_{crL} according to [8] using the resonance method,

• static modulus of elasticity E_c according to [9],

• flexural strength f_{cf} according to [10],

• compressive strength f_c according to [10].

At the age of 28 days, values of tensile strength f_t according to [11] and fracture energy G_F were also determined, for the testing procedure see for example [12, 13]. Due to the non-destructive character of testing, bulk density and dynamic moduli of elasticity were determined on all specimens, the other properties were always determined on a set of three test beams. The flexural and compressive strength tests were conducted according to the cement standard EN 196-1 [10] and not according to the testing standard for concrete. Due to the grain size of the used aggregate $D_{\max}$ = 8 mm, smaller test specimens, which are typically used for cement testing, were produced. This is the reason why the strength tests followed [10] – however, the final results have not been significantly affected as the testing principle is similar to the procedure for concrete testing.

The main part of the experiment involved testing of concrete slabs using bending loading. The slabs were made from both plain (reference) SCC and scattered reinforced SCC (slabs designated "SFRSCC"). The slab-specimens were tested upside down to casting. Loading was applied onto the slabs in three different ways but the distance between the supports was always identical – 840 mm. In the first case, the slabs were point loaded (using a ball) in the centre of the slab (also in the centre of the span), see Fig. 1. The second case involved linear loading (a roller in the middle of the span), see Fig. 2.

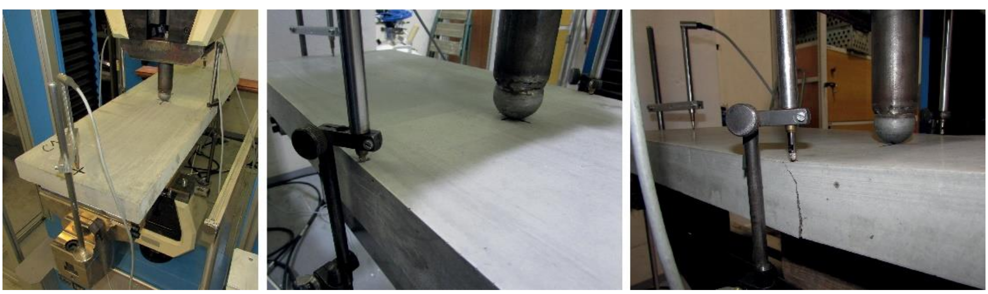

Fig. 1. The first method of test slab loading – a single point in the centre.

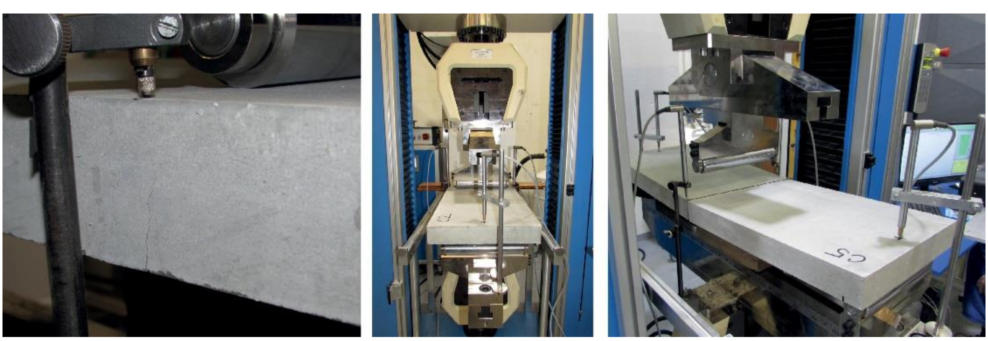

Fig. 2. The second method of test slab loading – a line in the centre.

In the third case, the slabs were subjected to loading by a circular steel plate with the diameter of 200 mm which was centrally placed on the slab. A 5 mm thick fibreboard (soundproof underlay) with the diameter 205 mm was placed between the loading steel plate and the tested concrete slab (Fig. 3). This method of loading was supposed to simulate real-life loading of the horizontal section of garden furniture or benches. At first, the circular plate (CP) acted uniformly, but the increasing bending of the tested slab eventually led to uneven loading of the slab, the use of the fibreboard plate was to ensure uniform loading for as long as possible [14].

Fig. 3. The third method of test slab loading – using a steel plate with inserted soundproof underlay.

3 Results and discussion

The resulting values of elastic, deformation and strength properties of hardened SCC without fibres (reference concrete) after 7, 28 and 90 days of ageing are presented in Table 1.

Table 1. Average values including sample standard deviations (s.s.d.) of basic properties of the SCC used in the experiment.

Age [days]	Statistical indicator	D [kg/m^3]	E_{cu} [GPa]	E_{crL} [GPa]	E_c [GPa]	f_c [MPa]	f_{cf} [MPa]	F_t [MPa]	G_f [N/m]
7	average	2400	47.6	42.5	32.3	69.4	8.0	-	-
	s.s.d.	7	0.55	0.39	0.27	2.80	0.17	-	-
28	average	2400	51.2	45.0	34.6	79.4	8.0	4.3	116
	s.s.d.	7	0.51	0.41	0.96	3.46	0.85	0.40	26
90	average	2400	53.0	47.0	36.3	86.5	9.1	-	-
	s.s.d.	4	0.29	0.55	0.57	1.11	0.43	-	-

Experimentally determined courses of loading tests of the slabs are presented in Fig. 4 to Fig. 6 based on the loading method. These are dependencies of the applied force on the slab deflection in the middle of the span between the supports. For all conducted loading tests applies that the resulting deflection in the middle of the span is equal to the value that was calculated as the average value from two sensors placed on the edges of the slabs in the middle of the span adjusted for the average value of sinking of the supports (the settlement of supports was measured by one sensor above each support) see Fig. 1 to Fig. 3.

Today, experimental tests are often modelled in Atena 2D software environment. ATENA software is an effective software tool for realistic deterministic simulation of failure of concrete and reinforced concrete structures. For analyses using the finite element method (FEM), the constitutive model plays a key role and determines how a given construction model captures reality. Given the fact that concrete is a multi-component material, special constitutive models are used for FEM analyses.

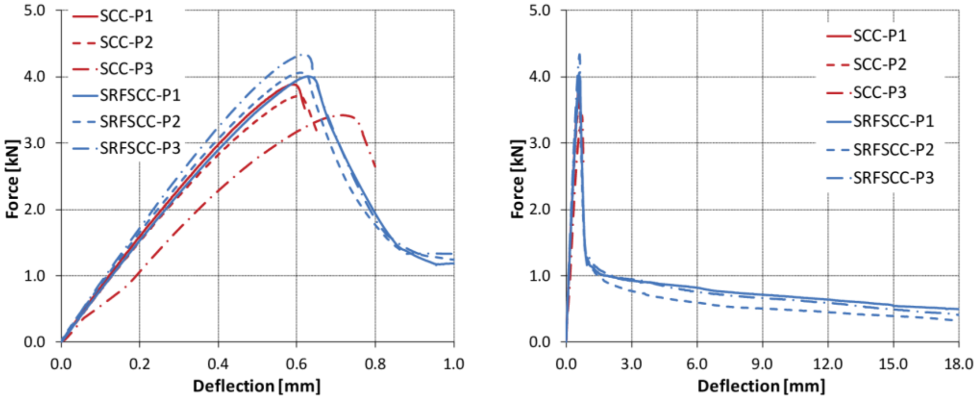

Fig. 4. The course of the loading tests of the slabs in the centre point (on the left detail of deflection up to 1 mm, on the right the entire test record up to 18 mm deflection).

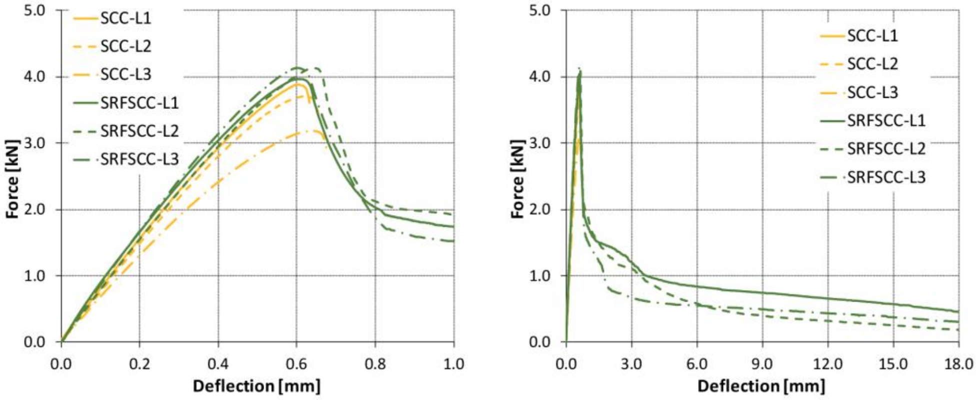

Fig. 5. The course of the loading tests of the slabs in the centre line (on the left detail of deflection up to 1 mm, on the right the entire test record up to 18 mm deflection).

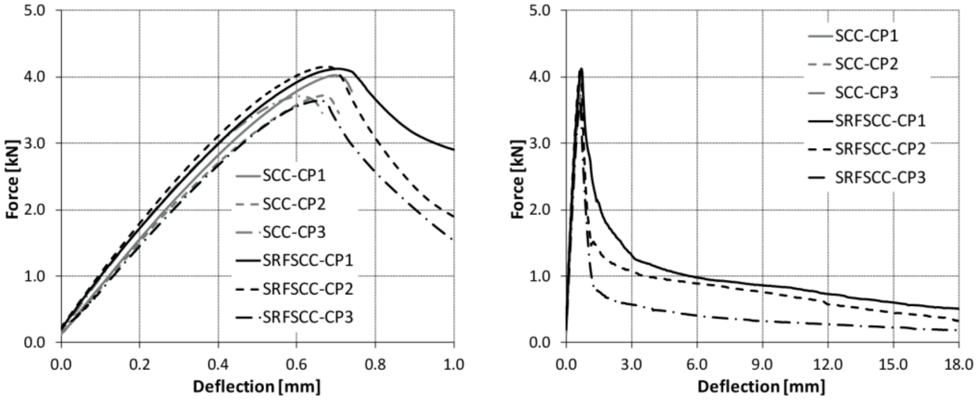

Fig. 6. The course of the loading tests of the slabs with the circular steel plate (on the left detail of deflection up to 1 mm, on the right the entire test record up to 18 mm deflection).

The analysis in the Atena 2D environment involved a material model of SBETA concrete with experimentally determined values of moduli of elasticity, compressive strength, tensile strength and fracture energy G_f. The SBETA material model is based on fracture mechanics of concrete in tension and smeared crack method. In the case of steel fibre reinforced concrete, the material of scattered reinforcement in the already used SBETA-concrete-model was modified according to the actual amount of steel fibres in concrete. Reinforcement direction angle was assumed to be 20°. A system of deformation increments with readings of reactions of monitored points was selected for loading. In addition, the deflection in the middle of the span of the element was monitored. The calculation itself was performed by non-linear analysis using the Newton-Raphson method. Numerical analysis was performed for loading using a line in the middle of the span and for the circular plate in the middle of the span – always for the first slab of the SCC and SFRSCC test set. Point loading in the centre of the slab (and of the span) was not analysed since this method of loading is very similar to the line method.

The analysis in the FEM environment of Atena 2D software corresponds to the procedure of the actual experiments of the given elements; see Fig. 7 and Fig. 8. The used model in the Atena 2D software can therefore be successfully used for numerical analysis of concrete behaviour with a larger amount of steel fibres (the amount of fibres for this experiment was selected at the lower limit of the recommended amount).

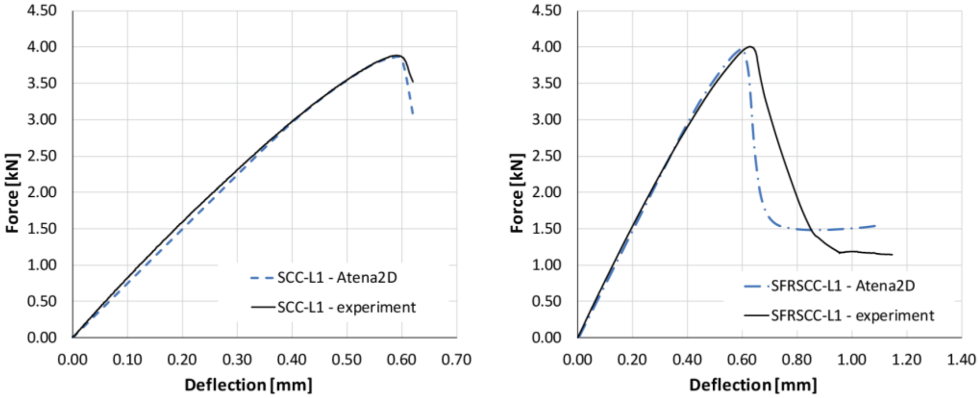

Fig. 7. Results of the numerical analysis in comparison to the performed loading tests (line loading in the middle of the span) for SCC (left) and SFRSCC (right).

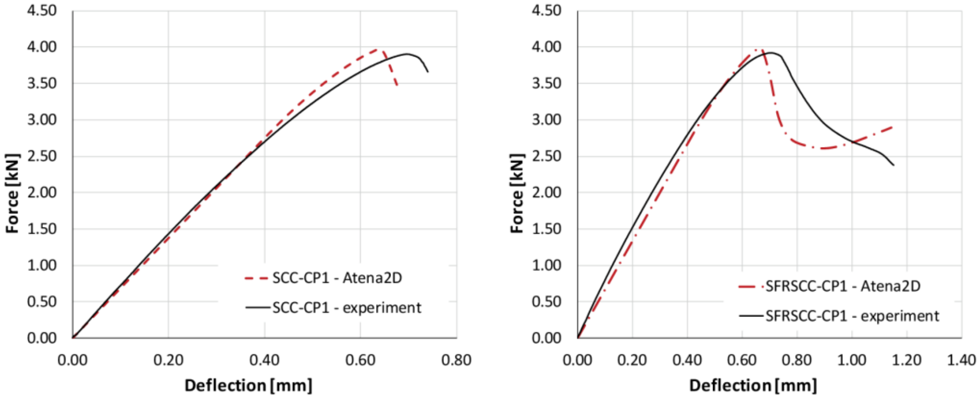

Fig. 8. Results of the numerical analysis in comparison to the performed loading tests (circular plate loading in the middle of the span) for SCC (left) and SFRSCC (right).

The maximum achieved strengths during loading of the slabs are presented in Table 2. It is evident that the concrete with scattered steel reinforcement achieved slightly higher average values of limit loads – exhibited higher load-bearing capacity. No differences in the results were observed with regard to the comparison of the individual loading methods.

Table 2. Maximum achieved loads in kN for individual slabs including average values and sample standard deviation (s.s.d.) for individual sets of test slabs.

Method of loading	**Force F_{max} [kN]**				
	1	**2**	**3**	**average**	**s.s.d.**
SCC - point	3.88	3.71	3.42	3.7	0.23
SFRSCC - point	4.01	4.06	4.34	4.1	0.18
SCC - line	3.88	3.70	3.19	3.6	0.36
SFRSCC - line	3.96	4.13	4.13	4.1	0.09
SCC - circular plate	4.02	3.72	3.71	3.8	0.18
SFRSCC - circular plate	4.12	4.15	3.64	4.0	0.29

The obtained results of the individual sets of test slabs were first used to verify data normality at the significance level of 0.05. The results of the individual sets were then statistically compared using a two-sample t-test. The statistical test was set up to allow assessment of the equivalence of the mean values of the test results. In the case of hypothesis rejection, the set results can be considered statistically significantly different. Based on the results of the statistical analysis it can be stated that the load-bearing capacity of the slabs of the individual test sets does not differ on the significance level of 0.05

4 Conclusions

On the basis of the conducted experiment, it can be said that the tested concrete slabs achieved a relatively high bending load-bearing capacity. Higher load-bearing capacity (relative to average values) was achieved in the case of SFRSCC slabs, however, the statistical analysis did not reveal any significant influence of scattered steel reinforcement on the increased load-bearing capacity – the test loading results did not differ at the significance level of 0.05. The fibres therefore positively affected only the way in which the slab failed after reaching its maximum strength, they therefore increased the residual strength. In order to achieve an increased bending load-bearing capacity of the concrete, in particular with regard to its possible use for the production of garden furniture, park benches, etc., it would be preferable to use a larger amount of steel fibres. This is the subject of further research.

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