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EVALUATION OF MATERIAL PROPERTIES OF STEEL FIBRE-REINFORCED CONCRETE FULL-SCALE ELEVATED SLABS

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Abstract
The paper examines the methods used to determine the mechanical properties of steel fibre-reinforced concrete (SFRC) slabs. The proper design of SFRC properties is fundamental to ensuring safe and sustainable building structures. Along with compressive strength, tensile strength and residual tensile strength of SFRC are essential in structural analysis. In this study, the mechanical properties of two full-scale cast-in-situ SFRC and two steel fibre-reinforced self-stressing concrete (SFRSSC) slabs are investigated. To assess the compressive strength of the concrete, both cubes and cylinders were cast and tested. Modified conversion factors for non-standard specimens were proposed to adjust the strength of standard specimen's size and shape. The moulded specimens were compared with the results of the specimens extracted from the slabs. To determine concrete tensile strength, prism specimens were cast and tested according to the three-point bending test method described in EN 14651. The tensile strength of notched prism specimens derived from three-point bending tests shows results similar to those of four-point bending tests; therefore, it can be used to evaluate the uniaxial tensile strength of steel fibre reinforced concrete. The findings of this research offer a better understanding of how to evaluate concrete mechanical properties for safe fibre concrete structural design.
Keywords: steel fibre reinforced concrete (SFRC), residual tensile strength, three-point bending test, compressive strength.

Introduction

Steel fibre-reinforced concrete (SFRC) is increasingly used in various load-bearing structures. Recent improvements in the material composition have led to improved behaviour of the structures under loading conditions (He et al., 2008; Oslejs & Kravalis, 2014; Cepuritis et al., 2023). Several full-scale tests of floors on piles and elevated slabs demonstrate the capacity of the material if designed and built properly (Aidarov, 2021; Suta et al., 2024). SFRC reduces construction timelines and facilitates the cost-effective production of prefabricated components by integrating fibres during manufacturing, thereby eliminating the need for costly reinforcement (Look et al., 2021). With the increase of structural application of SFRC, it is very important to understand how basic material properties are affected and can be determined for use in numerical analysis of the structures.

Concrete mechanical properties such as compressive strength, tensile strength, and modulus of elasticity are much studied and well-known among scientists and material engineers and are well described in the design standards. Compressive strength can be obtained by different methods, including direct and indirect ones. Each method gives slightly different results that can be converted to the standard cylinder compressive strength necessary for the evaluation of the safety of building structures. One way to do this is to use conversion factors to adjust the strength obtained from non-standard specimens to match the strength of the standard specimen (*fib* Special Activity Group, 2013; European Committee for Standardization, 2022). The coefficient depends on the size and shape of the test specimen as well as the concrete strength (Sinaie et al., 2015). With the increase in variations in concrete technology and the use of additives and fibres of different sizes, these coefficients need to be re-evaluated.

Another important mechanical property used in structural design is uniaxial tensile strength. The most appropriate method is to load the specimens under direct tension (Look et al., 2021; De Smedt et al., 2022). However, it comes with several experimental difficulties; therefore, it is not practically used (*fib* Special Activity Group, 2013).

More popular are the methods where tensile strength can be determined indirectly from e.g. flexural tensile strength or splitting tensile strength. The flexural strength tensile strength of concrete is obtained mainly from 3-point and 4-point bending tests. It is noted that the 3-point bending test method gives about 13% higher values for flexural strength than the 4-point bending test method (European Committee for Standardization, 2019b).

Another method is to calculate tensile strength from the compressive strength of concrete specimens; however, this method neglects the influence of fibre orientation and formwork geometry on tensile strength (Fraile et al., 2024). Round panel tests according to ASTM C1550–02 may also be conducted to evaluate the properties of fibre-reinforced concrete. However, due to the larger specimen size (800mm in diameter), the tests are complex and time-consuming; therefore, it is not widely used, although it is known to provide more consistent results (Tan et al., 2021).

If SFRC is used in the design without the conventional reinforcement, it is important to use the appropriate tensile strength because it is one of the governing properties determining the sizes and, eventually, the costs of the structure.

The aims of the current study are to compare the experimental results of both compressive and tensile strength of SFRC obtained using various approaches and methods, as well as to evaluate how the flexural strength of unnotched beams correlates with the flexural tensile strength of notched beams, and whether it can be used to derive uniaxial tensile strength.

Materials and Methods

All the test specimens discussed in this paper are part of two full-scale tests of steel fibre-reinforced concrete (SFRC) and self-stressing steel fibre-reinforced concrete (SFRSSC) slabs conducted in Jelgava. During these experiments, four slabs (two in 2023 and two in 2024) were produced and tested. Materials SFRC-1 and SFRSSC-1 refer to the tests in 2023, while materials PC-2 (plain concrete), SFRC-2 and SFRSSC-2 refer to tests in 2024. In addition to the full-scale slabs, a battery of laboratory tests was performed to determine the various mechanical properties of the materials. All the samples were tested in the LBTU Structures Laboratory. Only samples tested at 28 days are covered in the present study. Six specimens were used in each sample. The concrete mix design was the same for all specimens of the same year except for the chemical components of self-stressing concrete. Hooked-end steel fibres (L=60 mm, d=0.9 mm) were added to the concrete mixture. The composition of materials is shown in Table 1.

Compressive strength f_c was determined according to the standard EN 12390-3 (European Committee for Standardization, 2019a) using three different types of moulded specimens: 100 mm cubes (C100), 150 mm cubes (C150), and cylinders with a diameter of 150 mm and a height of 300 mm (CY150). These specimens were cured in laboratory conditions fully emerged in water.

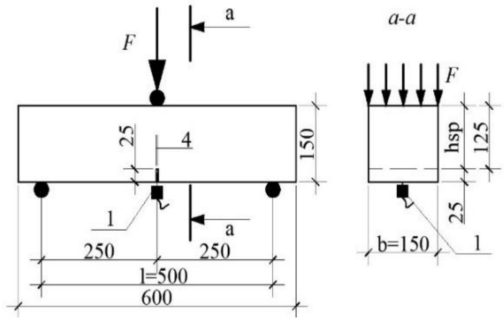
In addition, cores were drilled from the full-scale slabs with a diameter of 70 mm and a height of 150 mm (CO70) and cured under the same outdoor conditions as the full-scale slabs. The CO70 specimens were tested according to standard EN 12504-1 (European Committee for Standardization, 2021).

Uniaxial tensile strength f_{ctm} was derived using three methods: 1) from the characteristic compressive strength obtained from the cylinders (CY150), 2) from the strength at the limit of proportionality $f_{R,LOP}$ according to the standard EN 14651 (European Committee for Standardization, 2007) determined using 150×150×600 mm prisms in three- point bending tests, and 3) from the flexural tensile strength determined according to the standard EN 12390-5 using 150×150×600 mm prisms in four – point bending tests (both with and without fibres).

Figure 1 illustrates the three-point bending loading scheme of the prism. A Class 1 bending testing machine, Type Delta 5-300 (Form+Test), was used. The test was controlled by crack mouth opening displacement (CMOD). A PI-shape displacement transducer (PI-5-50, Tokyo Measuring Instrument Lab) with a gauge length of 50 mm was used to register CMOD.

Figure 1

Three-point bending scheme for prism specimens with a notch (1 – PI-shape displacement transducer)



The flexural strength in three-point bending $f_{ct,fl3}$ can be calculated by equation (1).

$$f_{ct.fl3} = \frac{3}{2} \cdot \frac{F_{LOP} \cdot l}{b \cdot h_{sp}^2}, \quad (1)$$

where F_{LOP} – maximum load in the range of CMOD up to 0.05 mm, as shown in Figure 3, l – the distance between supports, b – specimen width, h_{sp} – the distance between the tip of the notch and the top of the specimen.

Table 1

Concrete mix design

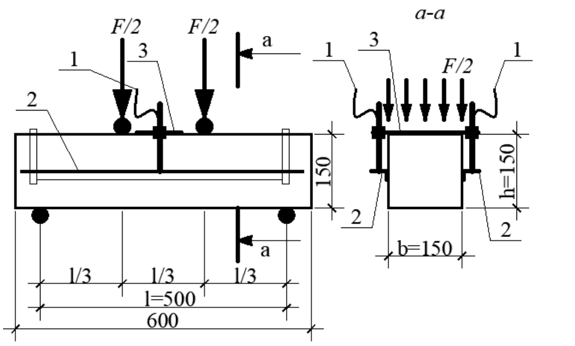
Material	***Amount, kg m^{-3}***				
	2023		***2024***		
	SFRC-1	***SFRSSC-1***	***PC-2***	***SFRC-2***	***SFRSSC-2***
CEM II/A-LL 52,5N	360		360		
Water	162		165		
Water/cement ratio (w/c)	0.45		0.47		
Sand	952*		783**		
Gravel	914***		300/791****		
Admixture (PrīmX Flow HRWRA)	3.60		3.24		
Steel fibres (L=60 mm, d=0.9 mm)	50			50	
Admixture (PrīmX DC)	-	40	-	-	40

*- grain size 0-8 mm, ** - grain size 0-4 mm; ***- grain size 5-16 mm; ****- grain size 2-8/8-16 mm.

The loading scheme in the four-point bending test is shown in Figure 2. deflections were measured using two LVDTs, which recorded the distance from the top surface of the prisms to the horizontal rod affixed to the specimens at the supports, positioned halfway up the specimen's height.

Figure 2

Four-point bending scheme for unnotched prism specimens (1 – linear variable differential transformer (LVDT), 2 – reference rod, 3 – plate attached to the specimen for fixing LVDTs)



The tensile strength in four-point bending $f_{ct,fl4}$ can be calculated by equation (2).

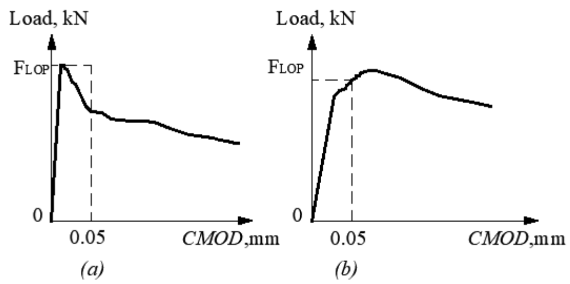
$$f_{ct,fl4} = \frac{F \cdot l}{b \cdot h^2}, \qquad (2)$$

where F – maximum load, l – distance between supports, h – specimen's height.

In the case, where this formula was applied to the results of unnotched SFRC or SFRSSC prisms, the maximum load F was determined according to the method shown in Figure 3, in the range of deflections up to 0.1 mm. In this range, the first crack had appeared and the first local peak was passed.

Figure 3

Load- CMOD diagram and FLOP for the prism (a) with a local peak and (b) without a local peak in the range of CMOD up to 0.05mm



Uniaxial tensile strength f_{ctm} is derived from the experimental results using three different approaches:
1) based on the characteristic value of compressive strength obtained from CY150 according to equation (3);
2) using the conversion factor α_f given in Model Code 2010 according to equations (4) and (5);
3) according to the equation (6) given in Eurocode 2 (European Committee for Standardization, 2023).

$$f_{ctm} = 0.3 \cdot f_{ck}^{2/3} \qquad (3)$$

In equation (3), f_{ck} – characteristic concrete compressive strength, which in this study is calculated by subtracting 8 MPa from the mean compressive strength f_{cm} obtained experimentally from CY150.

$$f_{ctm} = \alpha_f \cdot f_{ctm.fl} \qquad (4)$$

$$\alpha_f = \frac{0.06 \cdot h^{0.7}}{1 + 0.06 \cdot h^{0.7}} \qquad (5)$$

$$f_{ctm} = \frac{f_{ctm.fl}}{1.6 - \frac{h}{1000}} \qquad (6)$$

In the equations (4) to (6), $f_{ctm.fl}$ is flexural tensile strength $f_{ct,fl3}$ and $f_{ct,fl4}$ determined according to the equations (1) and (2), h – the height of the beam, which should be taken as h_{sp} for notched prisms.

Results and Discussion

Compressive strength

The results of the compression tests are given in Table 2.

Table 2

Concrete compressive strength f_{cm}

Sample	***SFRC-1***		***SFRSSC-1***	
	f_{cm}, MPa	***CoV, %***	***f_{cm}, MPa***	***CoV, %***
C100	44.88	3.39	54.96	4.00
C150	44.24	3.71	54.53	3.20
CO70	29.83	6.34	44.71	5.02
CY150	41.03	4.29	49.29	1.58
	SFRC-2		SFRSSC-2	
C150	56.55	2.91	60.32	2.60
CY150	50.49	3.91	53.61	3.65
	PC-2			
C100	62.57	3.18		

The compressive strength varies from 41.03 to 44.88 MPa for SFRC-1 and from 49.29 to 54.96 MPa for SFRSSC-1 if moulded specimens cured in laboratory conditions are tested. The strength of the corresponding extracted specimens is 29.83 MPa for SFRC-1 and 44.71 MPa for SFRSSC-1. The lower values of the extracted specimens can be justified by the lower air temperatures and fluctuating moisture content during the curing process. The compressive strength ranges from 50.49 to 56.55 MPa for SFRC-2 and from 53.61 to 60.32 MPa for SFRSSC-2. The compressive strength of plain concrete specimen PC-2 is 62.57 MPa, which is the highest result among all tested samples.
The relationships between the strength values obtained from the different specimen shapes and sizes are

represented in a matrix form in Table 3. The coefficients in Table 3 represent the mean values for each specimen shape and dimension.

Table 3
Conversation factors for different specimen sizes and shapes

	C100	C150	CO70	CY150
C100	1.00	0.99	0.74	0.91
C150	1.01	1.00	0.75	0.90
CO70	1.37	1.35	1.00	1.24
CY150	1.10	1.11	0.82	1.00

Latvian national standard LVS 156-1 suggests using a conversion factor of 0.95 to obtain standard 150 mm cube strength from smaller 100 mm cubes' strength. The main reason is that the smaller cubes have fewer initial imperfections. Therefore, their strength is higher than that obtained from larger specimens. In the present study, this coefficient is 0.99, which shows that the actual difference is negligible. This can be justified by the presence of long (60 mm) fibres that reduce the level of compaction in smaller specimens during the casting process.
The coefficient that converts the compressive strength from 150 mm cubes into standard cylinders (diameter of 150 mm) is 0.90, which is higher than ~0.8 used in the design standards EC2. In this case, the conversion factor accounts for different stress flow in the specimen. Shorter specimens, like cubes, are both compressed and confined at the loading surfaces, which increases the compressive strength. Due to the height (300 mm) being twice as the diameter, the confining effect at the middle of the specimen's height is not present. Therefore, the obtained strength is smaller and more realistic. Obtaining a coefficient of 0.9 instead of 0.8 shows that the coefficient suggested by the standards is on the safe side. To increase the value of the coefficient and eventually the efficiency of the use of concrete, more experimental investigations are needed to cover the main influencing aspects. The conversation factor from CO70 to CY150, which was 1.24, is opposite to 0.85 suggested by LVS 156-1. It should be noted that the cores extracted from the slab structure were subjected to lower air temperatures and fluctuating moisture content during the curing process. This must be taken into account when one is trying to predict the compressive strength of an outdoor structure using the laboratory test results of specimens cured in different conditions.
The effect of the values of the conversion coefficients can be evaluated by taking the current experimental test slab as an example. The mean value of the concrete strength used in the verification of the SFRC slab should be calculated as follows if 100 mm cubes were available:

$$f_{cm} = (0.95 \cdot 0.8) f_{cm,c100} \quad (7)$$

where 0.95 and 0.8 are the conversion factors suggested by standards resulting in 0.76, which is 83% of the one given in Table 3 (0.91).
Tensile strength
Load versus CMOD diagrams are plotted in Figure 4. The corresponding flexural tensile strength values are presented in Table 4. Three-point bending test results show a flexural strength of 4.93 MPa for SFRC-1 specimens and 6.65 MPa for SFSSC-1. Flexural strength for SFRC-2 is 5.46 MPa, and for SFRSSC-2 specimens is 6.06 MPa. For SFRC-1 specimens, the four-point bending test results show a flexural strength of 5.71 MPa, which is 13.7% higher than flexural strength from three-point bending test. The flexural strength of SFRSSC-1 in a four-point bending test is 6.19 MPa, which is 0.46 MPa lower than in a three-point bending test. While the results for SFRSSC-1 material support the assertion that three-point bending tests demonstrate greater flexural strength (Committee for Standardization, 2019b), albeit only for 7.4%, the results from SRFC-1 specimens display entirely opposite tendencies.

Figure 4
Load–CMOD diagrams

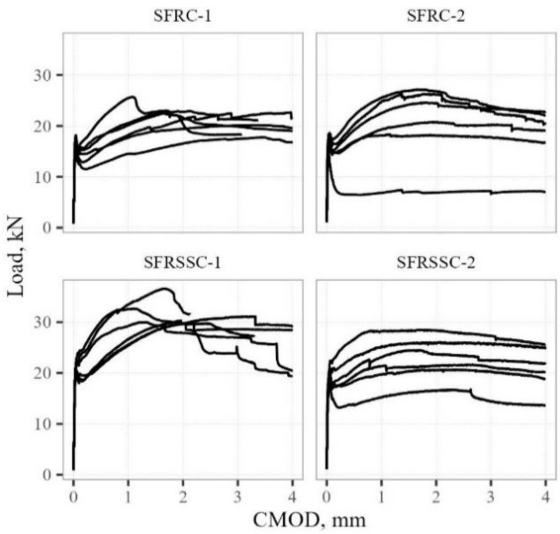


Table 4
Flexural strength f_{ctm}, MPa

Samples	3-point bending		4-point bending	
	$f_{ct,fl3}$	CoV,%	$f_{ct,fl4}$	CoV,%
SFRC-1	4.93	7.78	5.71	5.98
SFRSSC-1	6.65	4.36	6.19	5.49
SFRC-2	5.46	6.01		
SFRSSC-2	6.06	7.45		
PC-2			6.20	5.20

The uniaxial tensile strength f_{ctm} is calculated from the flexural strength $f_{ct,fl}$ using the Eurocode 2 (EC) method and the Model Code 2010 (MC) method, as presented in formulas (4) to (6) in this article. The results are compared with the uniaxial tensile strength calculated from the compressive strength of concrete cylinders f_{cm} and are presented in Table 5.

Table 5

Uniaxial tensile strength f_{ctm}, MPa

Samples	from $f_{ct,fl3}$		from $f_{ct,fl4}$		from f_{cm}
	EC2	MC	EC2	MC	EC2
SFRC-1	3.35	3.16	3.94	3.49	3.09
SFRSSC-1	4.51	4.25	4.27	3.87	3.58
SFRC-2	3.70	3.49			3.65
SFRSSC-2	4.11	3.87			3.83
PC-2			4.28	4.14	

Uniaxial tensile strength for SFRC-1 specimens varies from 3.09 to 3.94 MPa, obtaining the highest values from four-point bending test results. For SFRSSC-1 specimen, tensile strength varies from 3.58 to 4.51 MPa. For these specimens, the three-point bending test provides the highest results. The tensile strength of SFFC-2 and SFRSSC-2 specimens are 3.70 MPa and 4.11 MPa, respectively. The tensile strength derived from the compressive strength of concrete cylinders exhibits the lowest values and, as such, can be regarded conservative.

Conclusions

1. The effect of the size and shape of the specimens on the compressive strength is significantly smaller than suggested by the conversion factors given in standards.
2. Strength ratio between cubes of 100 mm and 150 mm was 0.99 being higher than suggested coefficient 0.95 that can be justified by the presence of long steel fibres.
3. Concrete compressive strength in real structures can be underestimated if standard conversion coefficients are used (in the current study it is up to 83% of the measured cylindrical strength) and overestimated if curing conditions are ignored.
4. All the standard methods discussed in this paper used to obtain uniaxial tensile strength resulted in similar values if the specimens from test of the year 2024 are used (difference varies in a range of 0.28 MPa). The difference is in the range of 0.85 MPa for the specimens of the other test and the lowest values are obtained using the compressive strength.
5. The tensile strength of notched prism specimens derived from three-point bending tests shows results similar to those of four-point bending tests; therefore, it can be used to evaluate the uniaxial tensile strength of steel fibre reinforced concrete.

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