Report

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Shear Capacity of Concrete Beams Reinforced with High Performance Composite Fibers (Minibars) from ReforceTech AS

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Shear Capacity of Concrete Beams Reinforced with High Performance Composite Macrofiber: MiniBars^{TM} from ReforcTech AS	**Report No.** **Date** 27. September 2024
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Summary

Shear tests have been carried out for two series of reinforced concrete beams: 9 regular beams (b·h=150·250mm) with 0, 10 and 20 kg/m^3 high performance composite macrofibers (3 beams each) and 6 shallow beams (b·h=360·180mm) with 0 and 10 kg/m^3 fibers (3 beams each). The applied high performance composite macrofiber is made from basalt fiber reinforced polymer wires. In this report they are denoted ReforceTech MiniBarsTM (RMB). The test results showed that the Minibars work well as shear reinforcement and that the shear capacity increases significantly compared to the reference beams without fibers. Considering the shear crack development, it was observed that when the 1st diagonal crack developed, the final shear failure occurred instantly for the reference beam. On the other hand, when the 1st diagonal crack developed in the fiber-reinforced beams, parallel cracks started to develop, and the load was significantly increased before the final failure occurred. The experimental shear capacities were compared to values calculated according to NB 38 (Norwegian Concrete Association Publication) and Annex L of the new Eurocode 2 (FprEC2:2022) assuming that the rules for steel fibers also hold for the high-performance composite fibers. Because all experimental values were significantly greater than the calculated ones using characteristic values for the material parameters, it is concluded that the formulas used for design of steel fiber concrete also can be used for the applied fibers (Minibars).

Indexing terms	**Stikkord**
Concrete	*Betong*
Shear	*Skjærkraft*
Composite fibers	*Komposittfiber*
Experimental results	*Forsøksresultater*

Summary

A series of laboratory full-scale tests were carried out to investigate the shear behavior of the beams with and without a high performance composite macrofiber made from basalt fiber reinforced polymer wires. In this report they are denoted ReforceTech MiniBarsTM (RMB). The main purpose of the project is to assess the performance of the RMB as shear reinforcement in concrete beams without traditional shear reinforcement. The main objective is to investigate the applicability of the calculation methods for shear capacity of fiber-reinforced concrete members according to NB 38 and Annex L of FprEC2:2022, which previously only are verified for steel fibre concrete.

In total 15 beams were cast at the laboratory at NTNU-Gjøvik and tested in the corresponding laboratory at NTNU-Trondheim. Nine regular beams (RB) with dimension bxhxL=150×250×2850 mm were made with 0, 10 and 20 kg/m^3 Minibars (3 beams of each), while 6 shallow beams (SB) with dimension 360×180×2850mm were made with 0 and 10 kg/m^3 RMB (three beams of each). The material properties, including compressive strength and the flexural tensile strength, were also measured. All the beams were tested under four-point bending tests until shear failure occurred. In addition, air content of the fresh concrete was measured, and the slump flow test was performed to characterize the fresh concrete consistency.

According to the test results, the addition of 10 kg/m^3 RMB in concrete beams significantly improve the structural behavior of the beams, and the shear capacity increased by 70% and 17% for the normal beams and the shallow beams, respectively. However, the further improvement in shear capacity is marginal by increasing RMB content from 10 to 20 kg/m^3. Regarding the development of cracks, the incorporation of RMB can not only delay the initiation of cracks, but also change the crack pattern: after the 1st diagonal crack develops, multiple parallel diagonal cracks occur in the shear zone, and this significantly slows down the development of the main diagonal crack, and at the same time leads to greater energy absorption capacity of the beams. From the results of the theoretical calculation based on the formulas given by NB 38 and the Annex L of FprEC2:2022 draft, using RMB as shear reinforcement instead of the traditional stirrups can meet the design safety requirements for the tested concrete beams, with an acceptable safety margin.

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1. Introduction

Fiber reinforced concrete has gained increased attention in recent years due to its potential for optimizing the use of concrete with regards to economy and environmental footprint. This increased focus has amongst others influenced the revision of Eurocode 2 [1], which will be published in the near future, to include Annex L focusing on design of steel fibre concrete structural members. In line with this revision, the Norwegian Concrete Association’s publication No. 38: Fiberarmert betong i bærende konstruksjoner (NB38) (In Norwegian) [2], has also been updated. While the rules in Eurocode 2 Annex L are strictly limited to steel fiber reinforced concrete, NB 38 is open to other types of fiber when the applicability for this type of fiber can be demonstrated.

In terms of environmental impact throughout the production and application processes, the applied high performance composite macrofiber made from basalt fiber reinforced polymer wires, is sustainable and regenerative. The applied macrofibers, in this report denoted ReforceTech MiniBarsTM (RMB), have shown potential to be a good alternative to conventional steel and synthetic fibers due to their durability, high temperature resistance, low cost and high tensile strength. But there is still a lack of documentation on the shear performance of structural members reinforced with such fibers. Therefore, the main purpose of this project is to assess the performance of RMB as a substitute for conventional shear reinforcement in beams and to investigate whether or not the shear formulas for steel fiber reinforced concrete according to NB 38 and Annex L of the new Eurocode 2 (FprEC2:2022) [1] may be used to design the shear resistance of concrete members reinforced with RMB.

The report presents the experimental and theoretical results achieved in the project: Shear Test of Beams Reinforced with Mineral Fibres, which was carried out by NTNU, Department of Manufacturing and Civil Engineering (NTNU, Gjøvik) and NTNU, Department of Structural Engineering (NTNU, Trondheim) for the client: ReforceTech AS (Org.nr: 957577067). The formal responsibilities related to the project are in accordance with standard NTNU-contract signed by the parties for “Oppdragsfinansiert aktivitet” dated 13.11.2023.

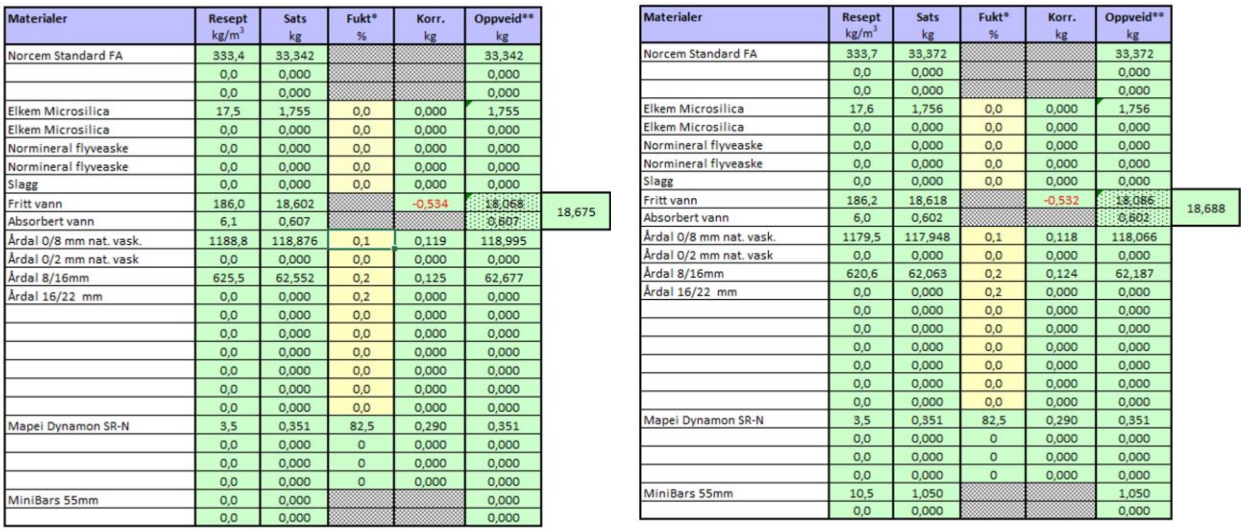
The experiments are also described and evaluated in the theses of the master students Fjeldstad and Lee [3] and Hammer [4] who joined the experimental program. Further details may be found and those references.

2. Experimental Program

2.1 Concrete mix design

The concrete mixtures were prepared with a water-to-binder ratio of 0.53 applying Standard FA cement (CEM II/B-M 42,5 R) and silica fume: Microsilica 920D. Natural sand was selected as fine aggregate with a particle size ranging from 0-8 mm, while the size of the coarse aggregate was between 8 and 16 mm. Tap water was used for both casting and curing.

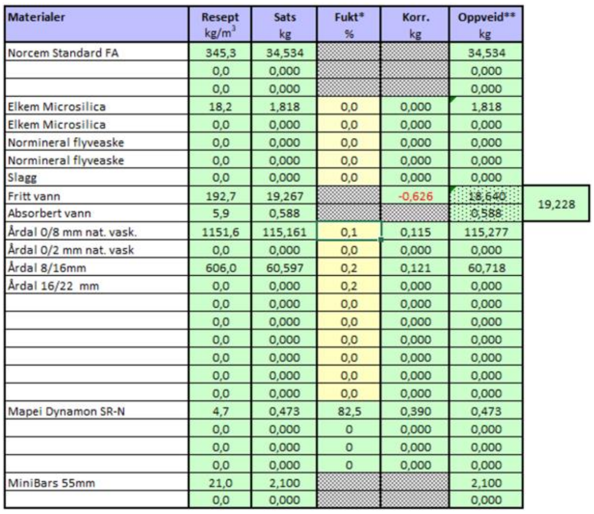
The planned concrete quality was B35, according to the standard EN206:2013. The applied high performance composite macrofiber, denoted ReforceTech MiniBarsTM (RMB), are made from basalt fiber reinforced polymer wires, and is type ‘3 43 32’, where 3 is the generation number, 43 is the length in mm, and 32 is the pitch length in mm. The mix designs for each 100 liters of concrete with different contents of basalt Minibar are shown Figure 1.



Materialer	Resept kg/m^3	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	333,4	33,342			33,342	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	17,5	1,755	0,0	0,000	1,755	
Elkem Microsilica	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000	0,0	0,000	0,000	
Slagg	0,0	0,000	0,0	0,000	0,000	
Fritt vann	186,0	18,602		-0,534	18,068	18,675
Absorbert vann	6,1	0,607			0,607	
Årdal 0/8 mm nat. vask.	1188,8	118,876	0,1	0,119	118,995	
Årdal 0/2 mm nat. vask	0,0	0,000	0,0	0,000	0,000	
Årdal 8/16mm	625,5	62,552	0,2	0,125	62,677	
Årdal 16/22 mm	0,0	0,000	0,2	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Mapei Dynamon SR-N	3,5	0,351	82,5	0,290	0,351	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
MiniBars 55mm	0,0	0,000			0,000	
	0,0	0,000			0,000	

Materialer	Resept kg/m^3	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	333,7	33,372			33,372	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	17,6	1,756	0,0	0,000	1,756	
Elkem Microsilica	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000	0,0	0,000	0,000	
Slagg	0,0	0,000	0,0	0,000	0,000	
Fritt vann	186,2	18,618		-0,532	18,086	18,688
Absorbert vann	6,0	0,602			0,602	
Årdal 0/8 mm nat. vask.	1179,5	117,948	0,1	0,118	118,066	
Årdal 0/2 mm nat. vask	0,0	0,000	0,0	0,000	0,000	
Årdal 8/16mm	620,6	62,063	0,2	0,124	62,187	
Årdal 16/22 mm	0,0	0,000	0,2	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Mapei Dynamon SR-N	3,5	0,351	82,5	0,290	0,351	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
MiniBars 55mm	10,5	1,050			1,050	
	0,0	0,000			0,000	

(a) Concrete with 0 kg/m^3 RMB (B-0) (b) Concrete with 10 kg/m^3 RMB (B-10)



Materialer	Resept kg/m^3	Sats kg	Fukt* %	Korr. kg	Oppveid** kg	
Norcem Standard FA	345,3	34,534			34,534	
	0,0	0,000			0,000	
	0,0	0,000			0,000	
Elkem Microsilica	18,2	1,818	0,0	0,000	1,818	
Elkem Microsilica	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000	0,0	0,000	0,000	
Normineral flyveaske	0,0	0,000	0,0	0,000	0,000	
Slagg	0,0	0,000	0,0	0,000	0,000	
Fritt vann	192,7	19,267		-0,626	18,640	19,228
Absorbert vann	5,9	0,588			0,588	
Årdal 0/8 mm nat. vask.	1151,6	115,161	0,1	0,115	115,277	
Årdal 0/2 mm nat. vask	0,0	0,000	0,0	0,000	0,000	
Årdal 8/16mm	606,0	60,597	0,2	0,121	60,718	
Årdal 16/22 mm	0,0	0,000	0,2	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
	0,0	0,000	0,0	0,000	0,000	
Mapei Dynamon SR-N	4,7	0,473	82,5	0,390	0,473	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
	0,0	0,000	0	0,000	0,000	
MiniBars 55mm	21,0	2,100			2,100	
	0,0	0,000			0,000	

(c) Concrete with 20 kg/m^3 RMB (B-20)

Figure 1 Concrete mix dsign. a) Without RMB; b) 10 kg/m^3 RMB; c) 20 kg/m^3 RMB

2.2 Concrete properties

The slump flow test was conducted to estimate the flowability of the fresh concrete mixture and the air contents of the fresh concrete mixes were measured. The pictures of the fresh concrete during the slump flow tests are presented in Figure 2. The results of the slump flow tests, and the air content of the fresh concrete are also given in Table 1.

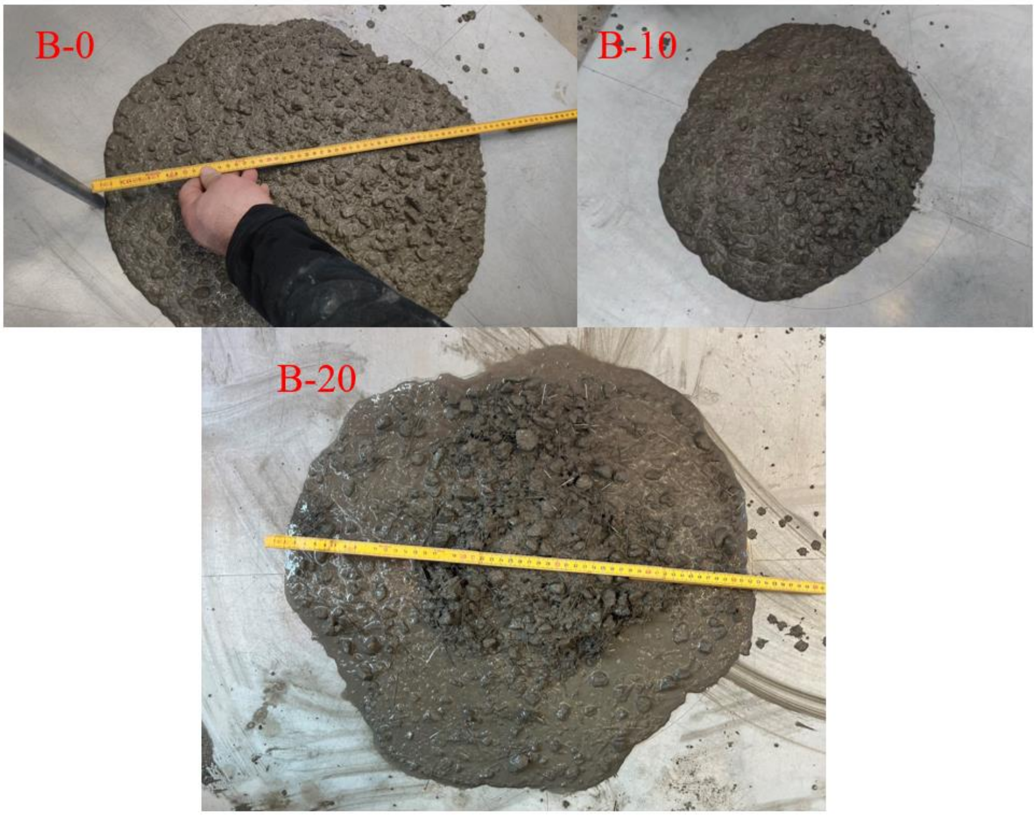


Figure 2 Pictures of slump test for the concrete with different contents RMB.

Table 1 Results of the slump flow test and air content of the three mixes

Fiber content (kg/m^3)	Spread		Density (kg/m3)	Air content (%)
	T500	cm		
0	2.62	53	2379	2.15
10	3.5	52	2343	1.0
20	2.29	52	2360	1.48

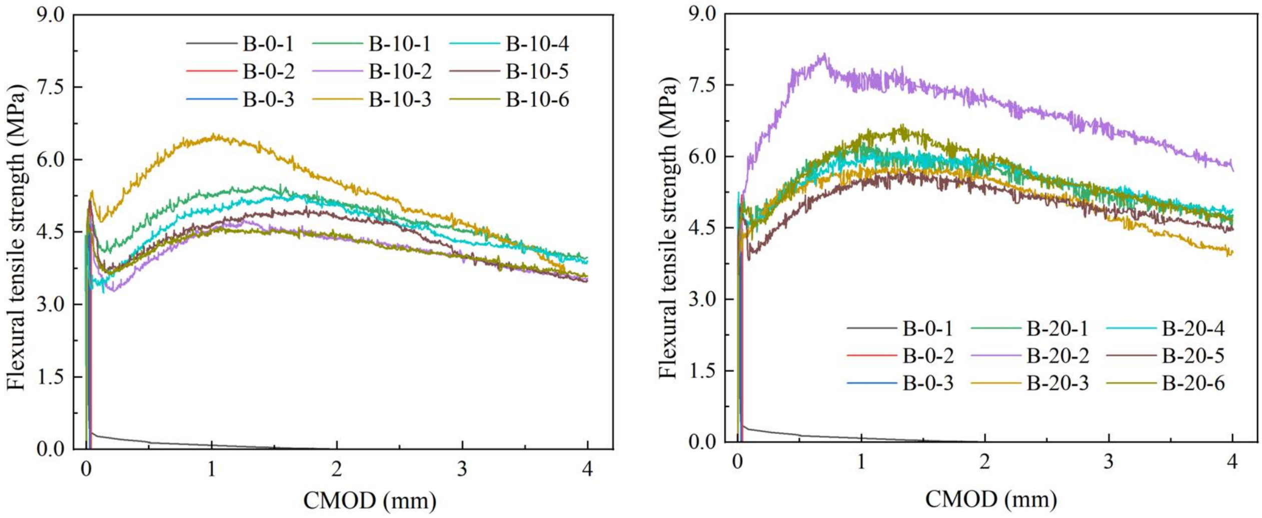
. Three 100 mm cubic specimens of each concrete mixture were produced in order to determine the cube compressive strength at 28 days. The results are summarized in Table 2.

Table 2 Compressive strength (results from 100 mm cubes reduced by 20% to achieve cylinder strength) of the three mixes.

Blanding	f_{cm}[MPa]	f_{ck} [MPa]	Cast date	Test date
0 kg/m^3	46.3	38.3	12.03.2024	09.04.2024
10 kg/m^3	49.4	41.4	20.03.2024	17.04.2024
20 kg/m^3	48.2	40.2	23.04.2024	21.05.2024

* $f_{ck} = f_{cm} - 8MPa$

The residual flexural tensile strengths of the concretes with different contents of RMB were measured according to the three-point bending test in NS-EN14651 [5]. For each concrete mix 6 center-notched beams with dimensions of 150 × 150 × 600 mm were cast. The flexural tensile strength- crack mouth opening displacement (CMOD) curves are shown in Figure 3 for the two concretes reinforced with RMB. The results for all three concretes are summarized Table 3.



(a) (b)

Figure 3 Stress-CMOD curves for the concrete with different contents of basalt Minibar.

Table 3 Residual flexural tensile strength (according to NS-EN 14651) of the three mixes.

Specimen	f_{ct} or $f_{ct,L}$		$f_{R,1}$		$f_{R,2}$		$f_{R,3}$		$f_{R,4}$	
	Mean	Char.	Mean	Char.	Mean	Char.	Mean	Char.	Mean	Char.
B-0	4.80	4.33	----		----		----		----	
B-10	4.50	3.63	4.48	3.45	5.12	4.21	4.58	4.06	3.97	3.61
B-20	4.82	4.30	5.78	4.26	6.19	5.20	5.56	4.52	5.02	4.08

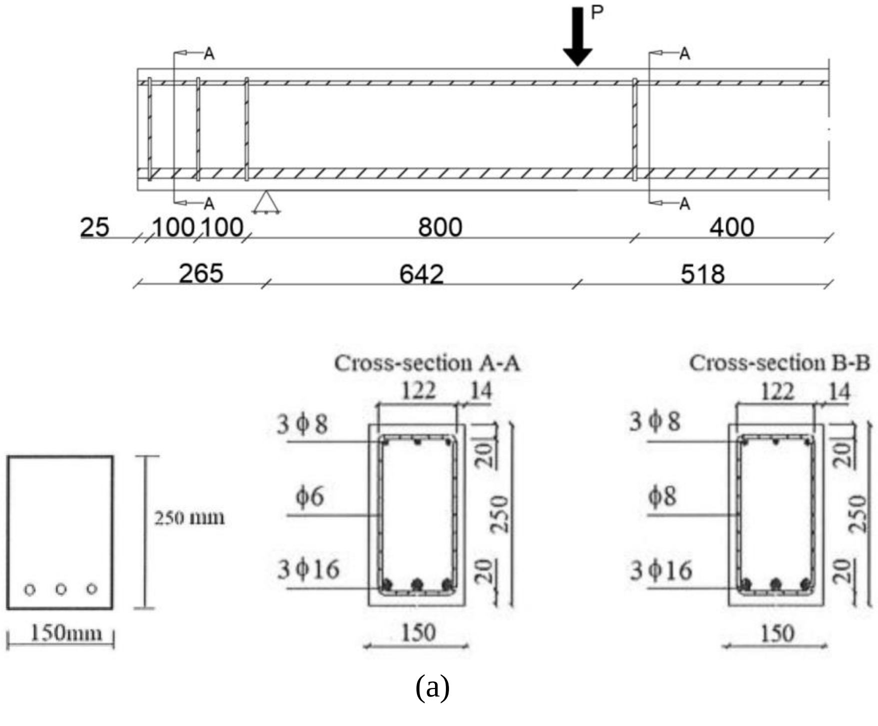
*Char. = Characteristic value; The unit in the table is MPa; f_{ct} is the tensile strength for plain concrete (B-0); $f_{ct,L}$ is the flexural tensile strength at limit of proportionality for concrete with BCF (B-10 and B-20).

Char. value=Mean value-1.64·standard deviation

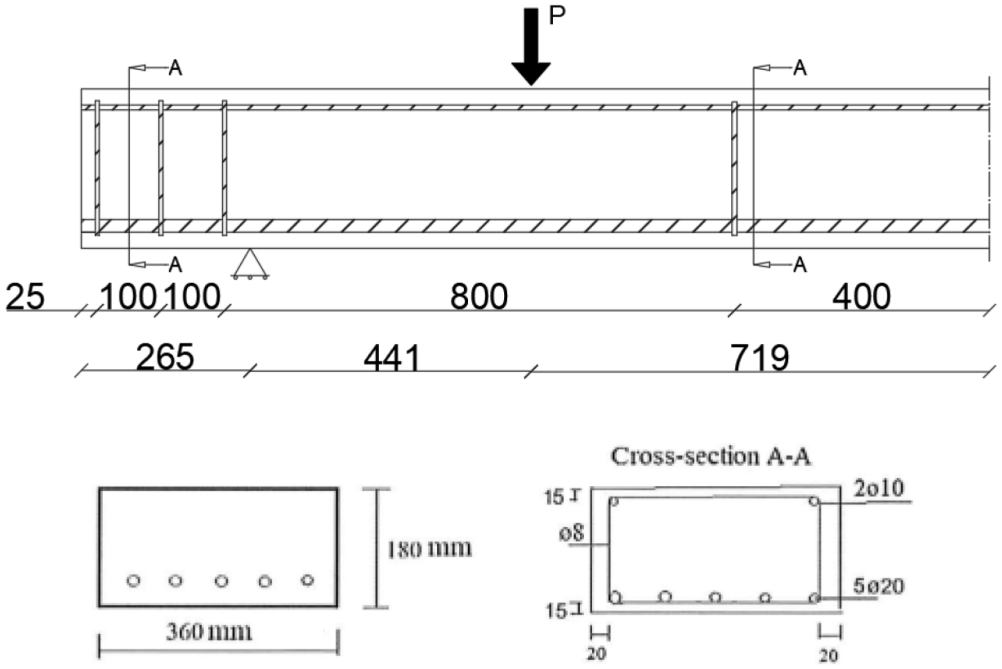
2.3 Shear test of beams

Two different beam geometries, and in total 15 beams designed for shear test were produced in the laboratory at NTNU-Gjøvik and tested in the corresponding laboratory at NTNU-Trondheim. The beams and the test set-up are presented in Figure 4.

Nine regular beams (RB), with cross section of 150 x 250 mm as shown in Figure 4 (a), were made with 0, 10 and 20 kg/m^3 RMB (3 beams of each mix), while 6 shallow beams (SB), with cross section of 360 x 180 mm as shown in Figure 4 (b), were made with 0 or 10 kg/m^3 RMB (also three beams of each mix). All the beams had a length of 2850 mm. The regular beams had a b_w/d value of 0.7, where b_w is the width of the beams and d is the effective depth of the beams, while the shallow beams had a b_w/d value of 2.45. The bar reinforcement used in this project was B500NC, according to the Norwegian standard NS 3576-3 [6] with characteristic yield strength of 500 MPa and a characteristic ultimate strength of 600 MPa. There are no shear reinforcements in the shear zone of the tested beams. The details are summarized in Table 4.



(a)



(b)

Figure 4 Beam layout and the test set-up. a) Regular beam (RB), b) Shallow beam (SB).

Table 4 Details of the tested beams

Beam	Dimensions (mm)			a/d	b_w/d	Reinforcement		Fiber content (kg/m^3)
	L	b_w	h			A_S	ρ_L %	
RB-0	2850	150	250	3	0.7	3Φ16	1.88	0
RB-10		150	250	3	0.7	3Φ16	1.88	10
RB-20		150	250	3	0.7	3Φ16	1.88	20
SB-0		360	180	3	2.45	5Φ20	2.7	0
SB-10		360	180	3	2.45	5Φ20	2.7	20

L: length of the beams; b_w: width of the beams; h: total heigh of the beams; a: horizontal distance from support to loading point; d: effective height of the beams.

3. Experimental results for the beams

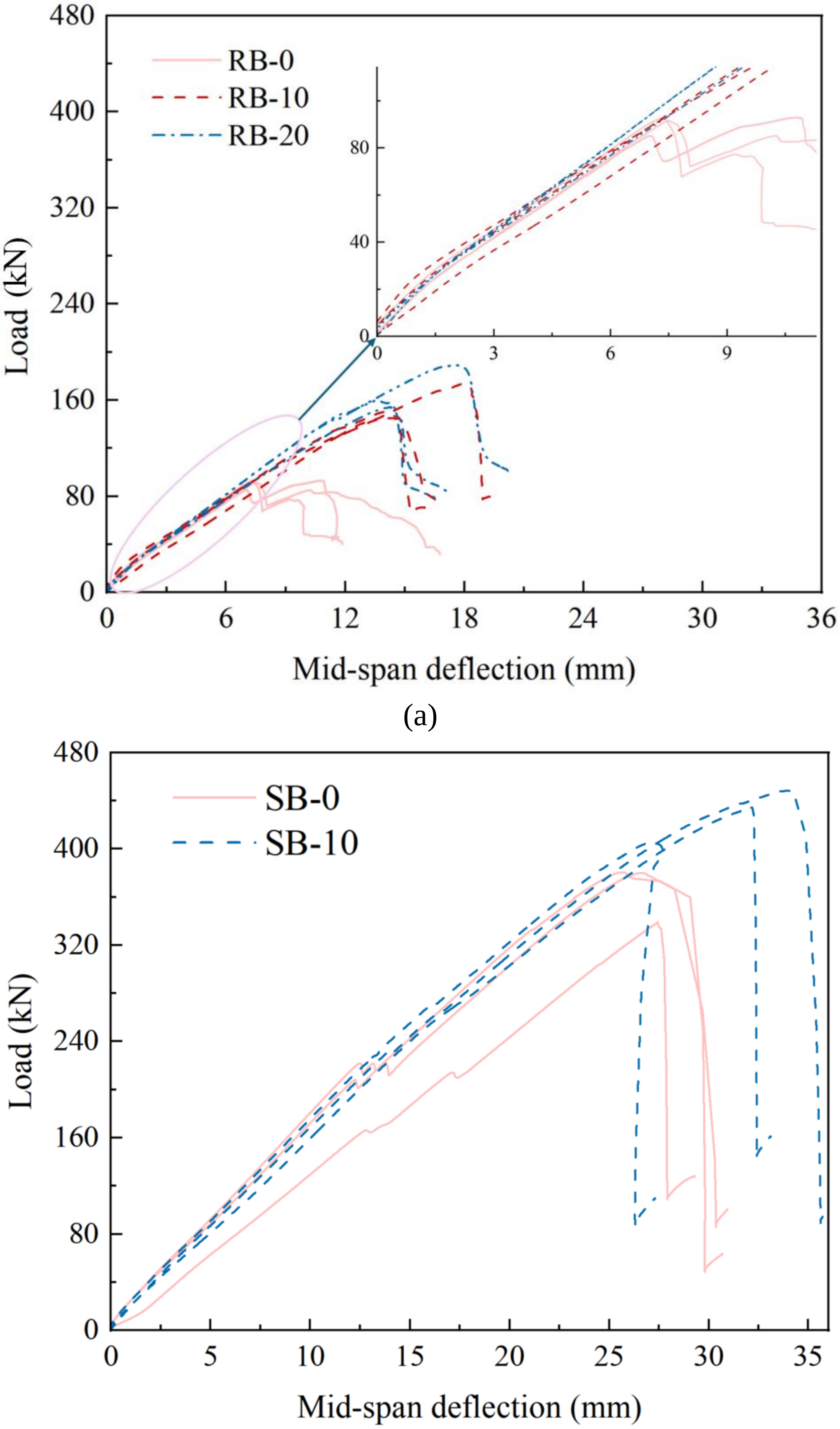
3.1. Load-deflection curves

The load-deflection curves from the shear test are shown in Figure 5 for the different beams. The deflections were measured by LVDT at the mid span. The RB-0 beams (without fibres) failed to carry increased load after the rapid shear crack development, and therefore shear failure occurred immediately afterwards. The average maximum load for the RB-0 beams was 92.4 kN and the average deformation at failure was 8.51 mm.

For the regular beams with 10 kg/m^3 RMB, a small drop in load was observed over a short period between 128 and 144 kN probably due to diagonal cracking, after which the load increased further until maximum load was reached. The average maximum load of the RB-10 beams increased to 156.3 kN, 70% higher than the RB-0 beams. The shear capacity of the regular beams was therefore greatly improved by adding 10 kg/m^3 basalt Minibar.

The RB-20 Beams (20 kg/m^3 RMB) showed a similar behavior as the RB-10 beams. The increased deformation of the beams with RMB implies that the energy absorption capacity of the beams was enhanced, and the beams exhibited considerably better ductility behavior than the beams without RMB. Although the increase in content of RMB is the same as from RB-0 to RB-10, the improvement of the shear capacity of RB-20 is not large. The average mid-span deflection of RB-10 and RB-20 beams were 15.4 mm and 15.2 mm, respectively and the average maximum load of RB-20 was only 7.3% larger than for the beams RB-10. For the mix with 20 kg/m^3 RMB it was observed during the casting that the fibers had a tendency to lump together and form balls during formwork filling (fiber balling). After the failure of beams, the congestion or balling of RMB in the beams could be seen for RB-20 as shown in Figure 6. This fiber balling will have a detrimental effect on the bonding between the RMB and the concrete matrix, lowering the post cracking strength and therefore also the shear performance of the beams. Since coarse aggregate occupies the dispersion space for fibers, it has been revealed that reducing the amount and the maximum size of coarse aggregate can alleviate the fiber balling behavior [7].

The performance of the fiber reinforcement in the shallow beams (SB) was different compared to the regular beams (RB). Only 17% increase in the average maximum load was observed after adding 10 kg/m^3 RMB in the shallow beams, which is considerably lower than for the regular beams. In general, the shallow beams even without stirrups are not so susceptible to shear failure [8, 9] as the rectangular beams. A second reason for the smaller improvement of shear capacity in the shallow beams by adding RMB is that the tensile reinforcement ratio in the shallow beams is higher, reaching 3.07%. This higher reinforcement ratio was adopted to ensure that the shear failure would occur in the test. The average mid-span deformation of SB-10 beams at ultimate load was increased by 16.9% compared to that of SB-0.



(a)

(b)

Figure 5 Load-deflection curves of the beams: (a) regular beams (RB); (b) shallow beams (SB)

Table 5 Results of the experimental shear capacity

Beam ID	Average maximum applied load for the three tests of each beam type (kN)
RB-0	92.4
RB-10	156.3
RB-20	167.7
SB-0	366.6
SB-10	429.2

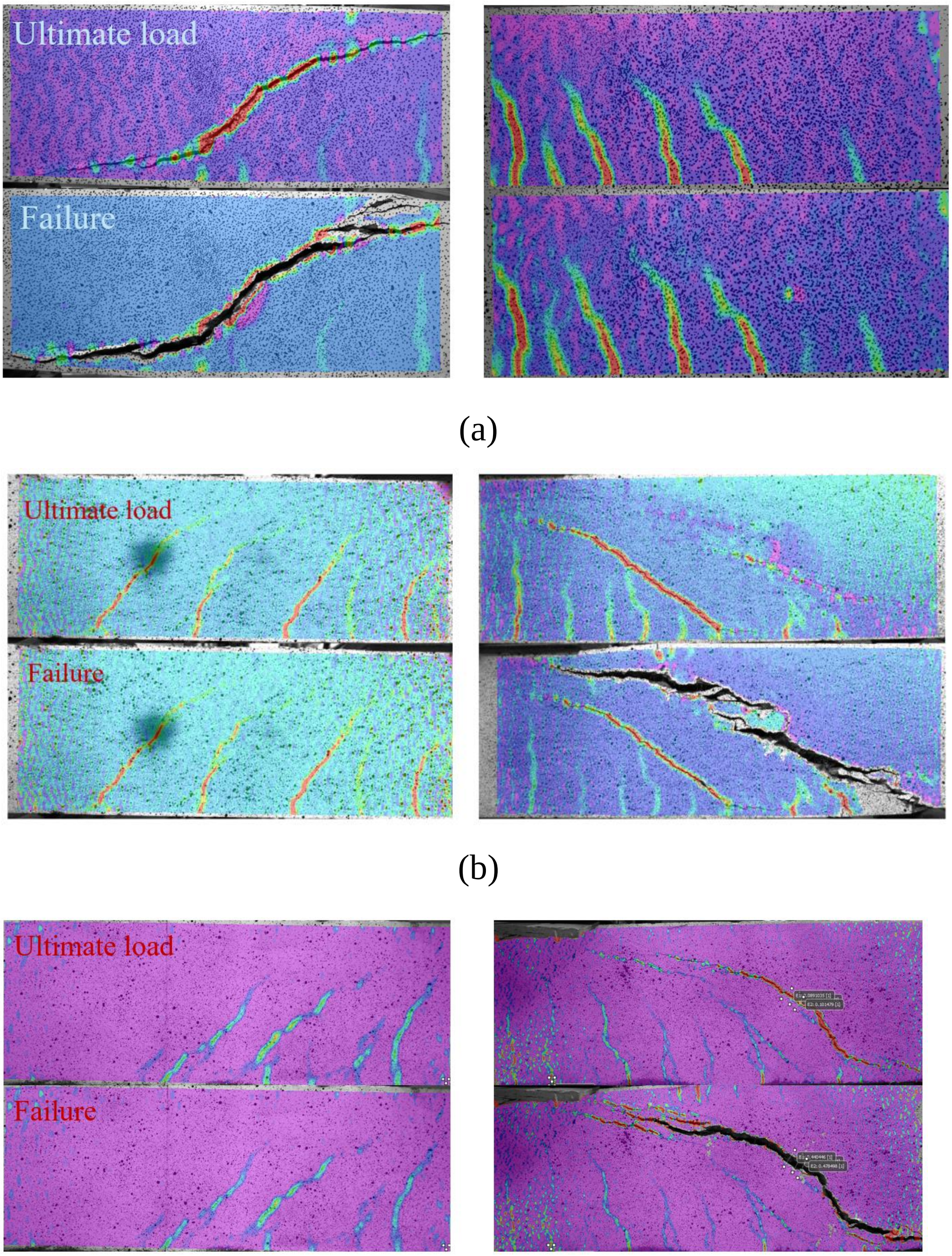
(a) (b)

Figure 6 Observation of balling of RMB during casting and after failure of beams when 20 kg/m^3 of RMB was adopted: (a) During casting and (b) after failure of beams RB-20

3.2. Crack development in beams during the shear test

Comparing the structural behavior of the reference beams without RMB and the beams with RMB, it was clearly seen that the RMB works well as shear reinforcement similarly as steel fibers do. Considering the shear crack development, it was observed that when the 1st diagonal crack develops, the final shear failure happens quite rapidly for the reference beams. On the other hand, when the 1st diagonal crack develops in the fiber reinforced beams, parallel cracks also start to develop, and the load is significantly increased before the final failure. In the beams RB-0, the shear cracks initiated at about 74.6 kN, while in the RB-10 and RB-20 beams, tiny shear cracks are observed when the load reached about 112.3 kN and 115.6 kN respectively. The incorporation of RMB therefore delay the shear crack initiation and slow down the further development of the main crack. Typical crack patterns illustrated by the pictures taken by the DIC-technique (Digital Image

Correlation) are shown in Figure 7. The failure patterns of all the tested beams are shown in Figure 8.

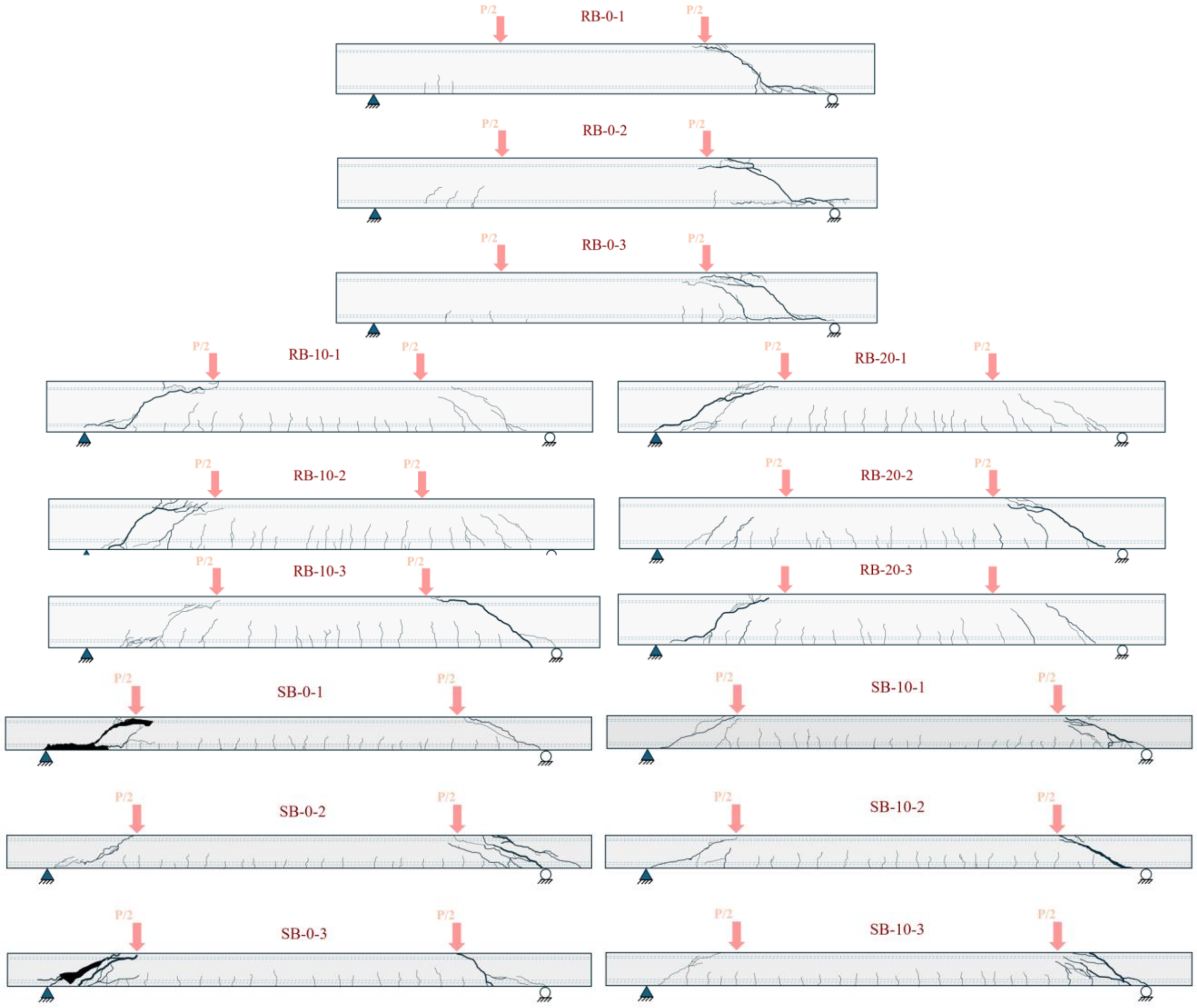


(a)

(b)

(c)

Figure 7 Crack pattens of different regular beams obtained from the DIC technology: (a) RB-0; (b) RB-10; (c) RB-20.



(b-1) (b-2)

Figure 8 Failure patterns of all the tested beams.

4. Verification of shear capacity according to FprEC2:2022 draft

Recently, Annex L was included in the future revision of Eurocode 2 (FprEC2:2022 draft) to guide the design of steel fiber reinforced concrete structures. All the related formulas to calculate the shear strength based on FprEC2:2022 are summarized in Table 6, while detailed calculations are shown in Appendix F for beam RB-10 and SB-10. Recently, the revised NB38 adopted the same formulas for the shear strength to achieve consistent Norwegian practice. The experimental and calculated shear capacities are summarized in Table 7 and compared in Figure 9. The calculations are carried out with characteristic values of the material parameters and material factors equal to 1,0.

The safety margin (SM) of the calculation models (V_{Exp}/V_{The}) was determined by dividing the experimental value by the theoretical value and shown in Figure 10. It is seen that all experimental values are larger than the theoretical ones, therefore it is concluded that the formulas predict results to the safe side. It is also seen that the safety margins are larger for the fiber reinforced beams than for the reference beams without RMB (RB-0). Generally, the shallow beams exhibit larger shear resistance than regular beam, being less susceptible to shear failure [10]. This may explain the large safety margins for the shallow beams in Table 7.

Table 6 Shear capacity formulations for FRC beams without stirrups (FprEC2:2022 draft and NB38)

Codes	Theoretical shear capacity formulas
FprEC2:2022 draft and NB 38	$\tau_{Rd,cF} = \eta_{cF} \cdot \tau_{Rd,c} + \eta_F \cdot f_{Ftud} \geq \eta_{cF} \cdot \tau_{Rdc,\min} + \eta_F \cdot f_{Ftud}$ $V_R = \tau_{Rd,cF} \cdot b_w \cdot z$; $\tau_{Rd,c} = \frac{0.66}{\gamma_V} \cdot (100\rho_l \cdot f_{ck} \cdot \frac{d_{dg}}{d})^{1/3} \geq \tau_{Rdc,\min}$ $z = 0.9d$; $\eta_{cF} = \max\{1.2 - 0.5 f_{Ftuk}; 0.4\} \leq 1.0$; $\eta_F = 1.0$ $\tau_{Rdc,\min} = \frac{11}{\gamma_V} \cdot \sqrt{\frac{f_{ck}}{f_{yd}} \cdot \frac{d_{dg}}{d}}$; $d_{dg} = 16 + D_{lower} \leq 40$ $\rho_l = A_{sl} / b_w \cdot d$; $f_{Ftud} = f_{Ftu,ef} / \gamma_{SF}$; $f_{Ftu,ef} = \kappa_0 \cdot \kappa_G \cdot 0.33 \cdot f_{R,3K}$ $k_G = 1.0 + A_{ct} \cdot 0.5 \leq 1.5$; $f_{R,3k*} = \min(f_{R,3k}; k_{K,\max} \cdot f_{R,3m})$; $k_{K,\max} = 0.6$

Table 7 Summarized results of experimental and calculated shear capacities.

Spesimen ID	Experimental shear capacity V_{Exp} (kN)	FprEC2:2022 draft	
		V_{The} (kN)	V_{Exp}/V_{The}
RB-0	46.2	42.2	1.09
RB-10	78.2	58.9	1.33
RB-20	83.9	60.1	1.40
SB-0	183.3	90.4	2.03
SB-10	214.6	111.1	1.93

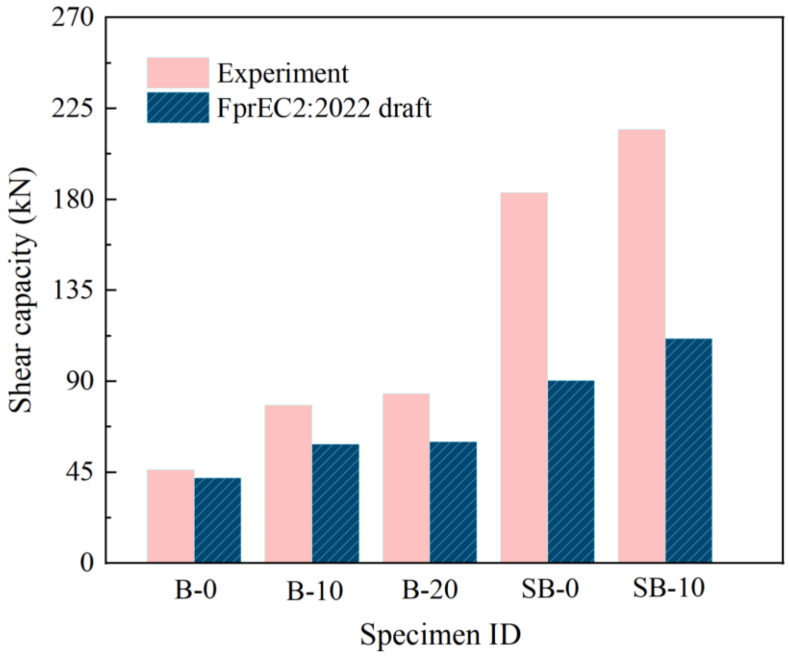


Figure 9 Comparison between the experimental shear capacity and theoretical shear capacity based on FprEC2:2022 draft and NB38.

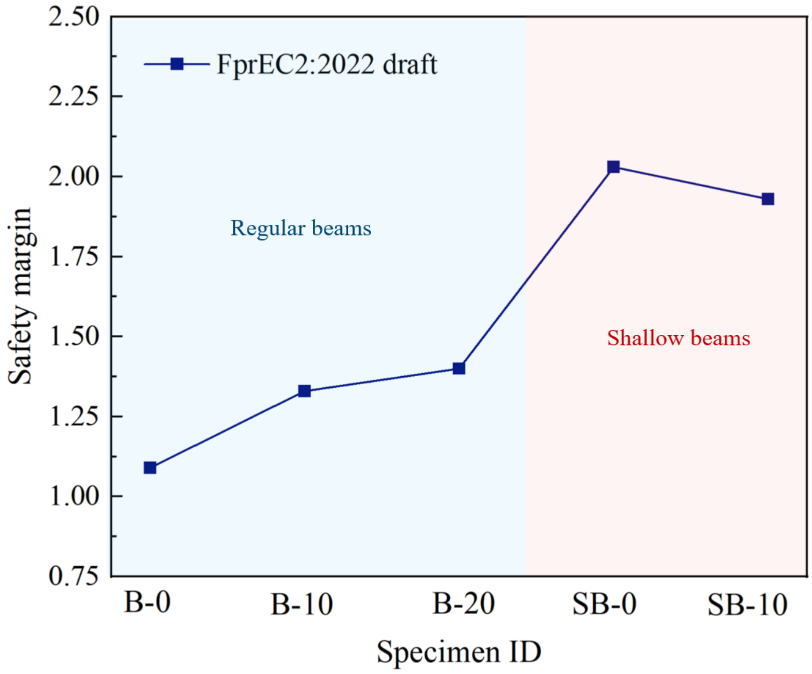


Figure 10 The safety margin of the theoretical shear capacity obtained from FprEC2:2022 draft and NB38.

5. Conclusions

In the project shear tests were carried out for concrete beams reinforced with high performance macrofibers from ReforceTech (RMB = ReforceTech Minibars) and the shear capacity was calculated according to NB 38 and Annex L of the draft of the new Eurocode 2 (FprEC2:2022). And, based on the results, the following conclusions can be drawn:

- By adding 10 kg/m^3 of RMB, the shear capacity of the regular beams (RB) was increased by 70% in comparison to the reference beams without fibers. The further improvement of the shear performance as a result of increasing the content of RMB from 10 to 20 kg/m^{3}was rather low.
- For the shallow beams (SB), the improvement of the shear capacity by adding 10 kg/m^3 RMB was about 17% which is lower than for the regular beams.
- The beams' deformation capacity was enhanced by adding RMB, which led to larger deflection at the point of maximum load. The beams with RMB therefore exhibited a higher capacity for energy absorption, resulting in a more ductile performance.
- The crack pattern is different between the reference beams and the fiber reinforced beams. It was observed that when the 1st diagonal crack develops, the final shear failure happens quite rapidly for the reference beams without RMB. On the other hand, when the 1st diagonal crack develops in the fiber reinforced beams, parallel cracks start to develop, and the load is significantly increased before the final failure occur. The incorporation of RMB does not only delay the shear crack initiation, but also slows down the development process of the main shear crack.
- The theoretical analysis showed that FprEC2:2022 draft provided conservative shear capacity results for the different beams with and without RMB when the characteristic values of the material properties and material factors of 1,0 were applied in calculations. All experimental values are larger than the theoretical results.
- The main conclusion is therefore that the RMB can be used as shear reinforcement instead of stirrups in concrete beams and slabs, and that the design method according to the FprEC2:2022 draft and NB38 provides conservative shear capacity for the tested beams.
- Shear force design according to NB 38 and FprEC2:2022 can be performed in the same way, same equations, with MiniBars that is used for steel fiber reinforcement.

References

[1] Eurocode 2: Design of concrete structures — Part 1-1: General rules and rules for buildings, bridges and civil engineering structures (DRAFT), 2022.
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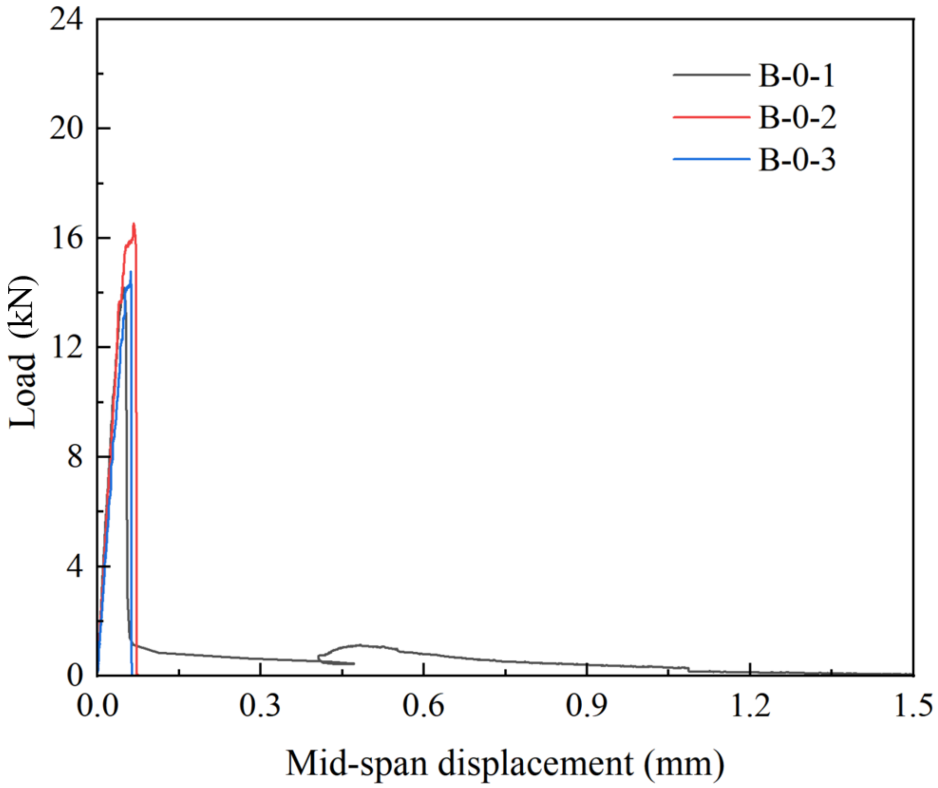
[3] Fjeldstad and Lee (2024), Evaluation of Calculation Methods for Composite Basalt Fiber Subjected to Shear Failure, Master thesis, Norwegian University of Science and Technology.
[4] Lars Hammer (2024), Evaluation of shear performance and calculation methodology for fiber-reinforced concrete beams with basalt Minibars, Master thesis, Norwegian University of Science and Technology.
[5] European Committee for Standardization. EN14651. Test Method for Metallic Fibered Concrete—Measuring the Flexural Tensile Strength (Limit or Proportionality (LOP), Residual). Brussels, Belgium: European Committee for Standardization; 2007.
[6] NS, EN 3576-3, Steel for the Reinforcement of Concrete - Dimensions and Properties - Part 3: Ribbed Steel B500NC, 2012.
[7] Shen, Chen, et al. "Investigating the influence of coarse aggregate characteristics and fiber dispersion on the flexural performance of ultra-high performance concrete (UHPC)." *Journal of Building Engineering* (2024): 110738.
[8] A. Conforti, F. Minelli, G.A. Plizzari, Wide-shallow beams with and without steel fibres: a peculiar behaviour in shear and flexure, Composites Part B: Engineering, 51 (2013) 282-290.
[9] A. Conforti, F. Minelli, A. Tinini, G.A. Plizzari, Influence of polypropylene fibre reinforcement and width-to-effective depth ratio in wide-shallow beams, Engineering Structures, 88 (2015) 12-21.
[10] A. Conforti, F. Minelli, G.A. Plizzari, Wide-shallow beams with and without steel fibres: a peculiar behaviour in shear and flexure, Composites Part B: Engineering, 51 (2013) 282-290.

Appendix A: Raw data of compressive strength test (Cubic samples)

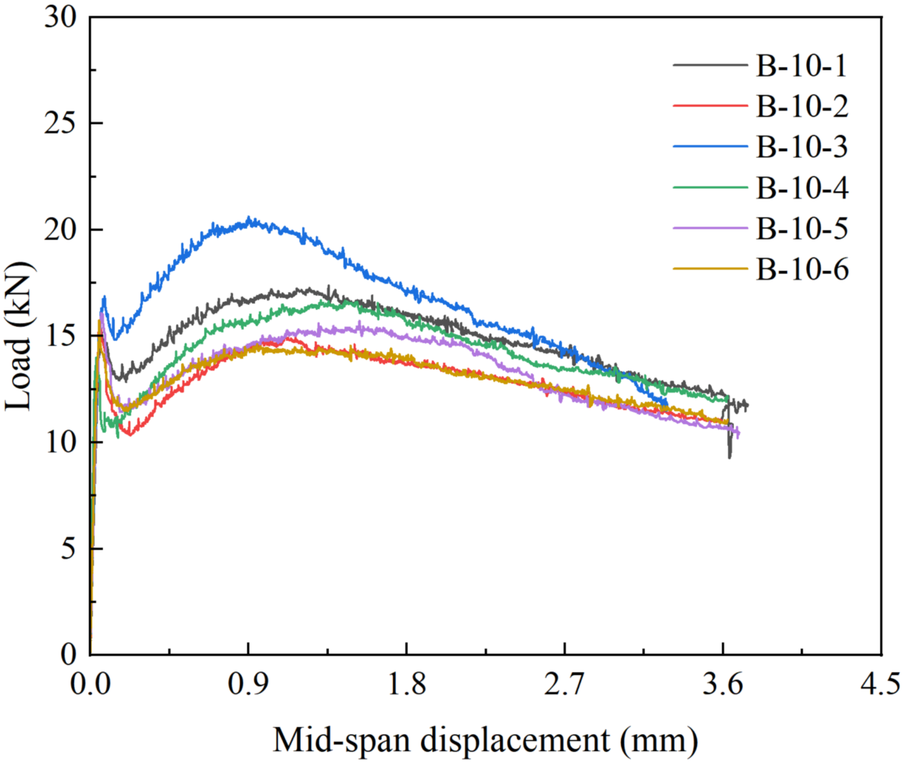
Concrete	Date of casting	Date of testing	Load (kN)	Size (mm)	Compressive strength (MPa)
B-0-1	2024/3/12	2024/4/09	586.2	100*100*100	58.62
B-0-2	2024/3/12	2024/4/09	587.6		58.76
B-0-3	2024/3/12	2024/4/09	563.6		56.36
B-10-1	2024/3/20	2024/4/17	611.8		61.18
B-10-2	2024/3/20	2024/4/17	624.1		62.41
B-10-3	2024/3/20	2024/4/17	614.3		61.43
B-20-1	2024/4/23	2024/5/21	587.4		58.74
B-20-2	2024/4/23	2024/5/21	612		61.20
B-20-3	2024/4/23	2024/5/21	609.6		60.96

Appendix B: Raw data of 3 point bending test of beams

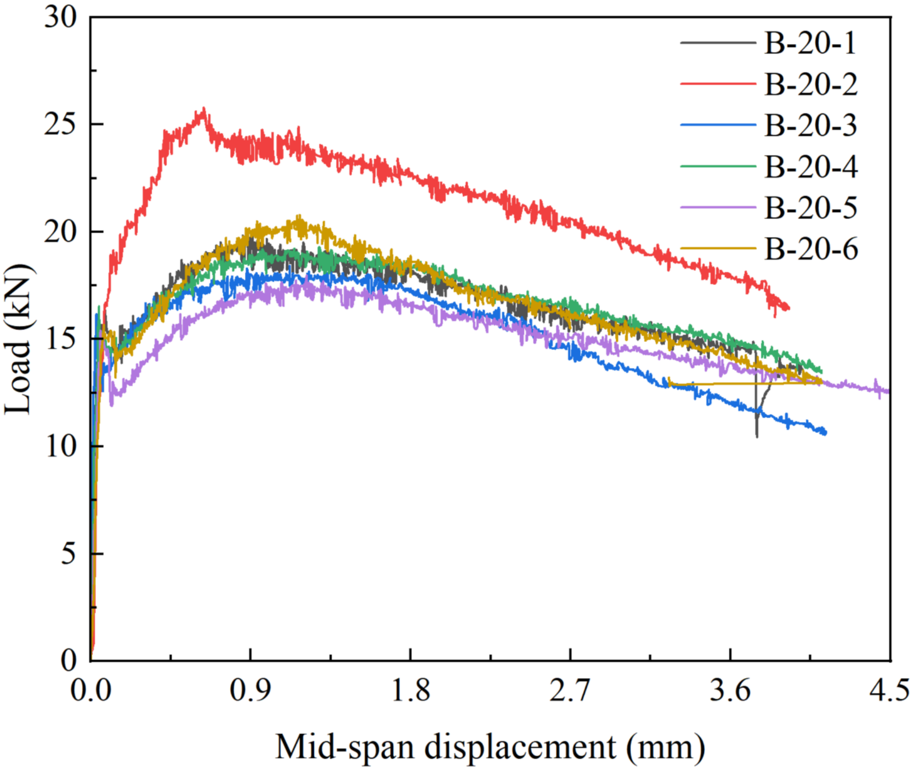
(1) Load-displacement curve for the concrete beams (160*160*600 mm) without basalt Minibar



(2) Load-displacement curve for the concrete beams (160*160*600 mm) with 10 kg/m^3 basalt Minibar

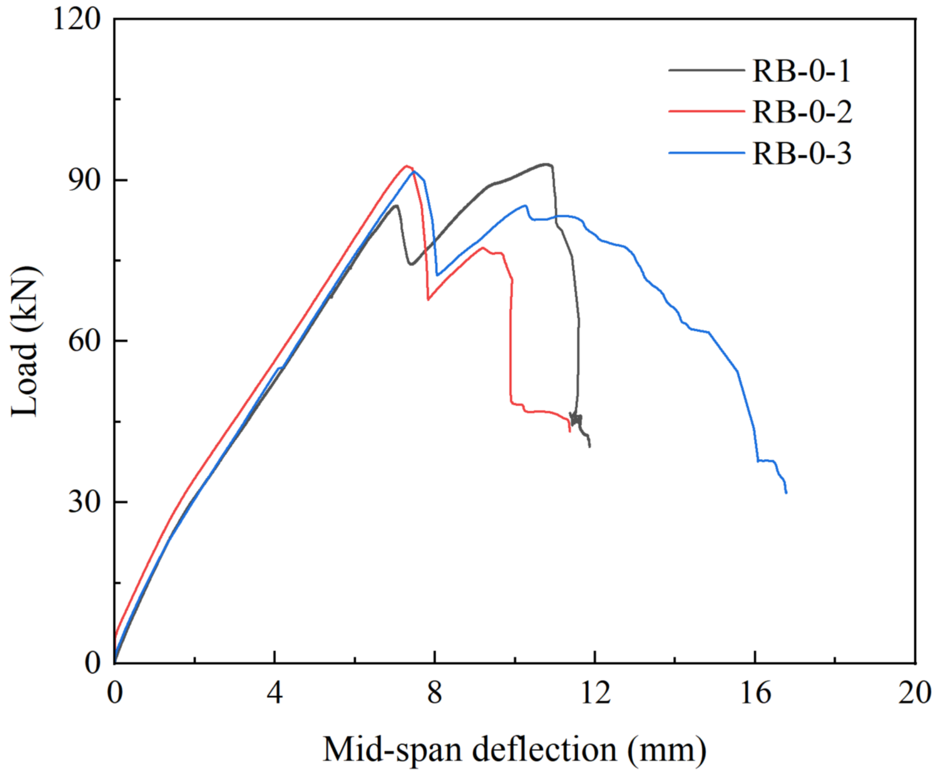


(3) Load-displacement curve of the concrete beams (160*160*600 mm) with 20 kg/m^3 basalt Minibar

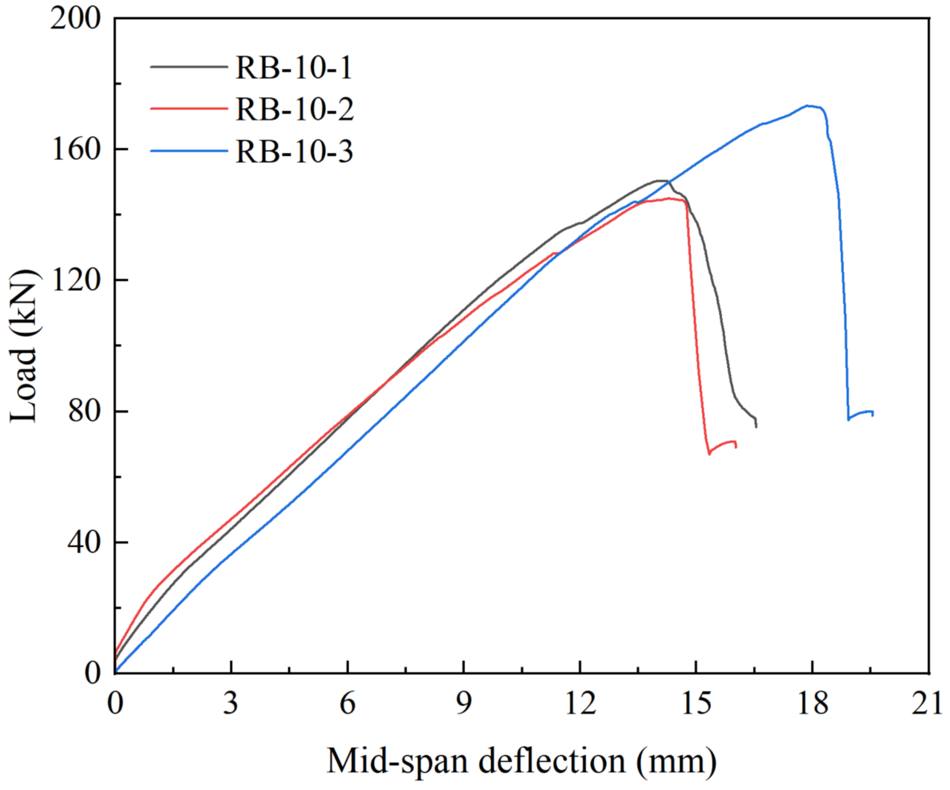


Appendix C: Raw data of shear test of beams

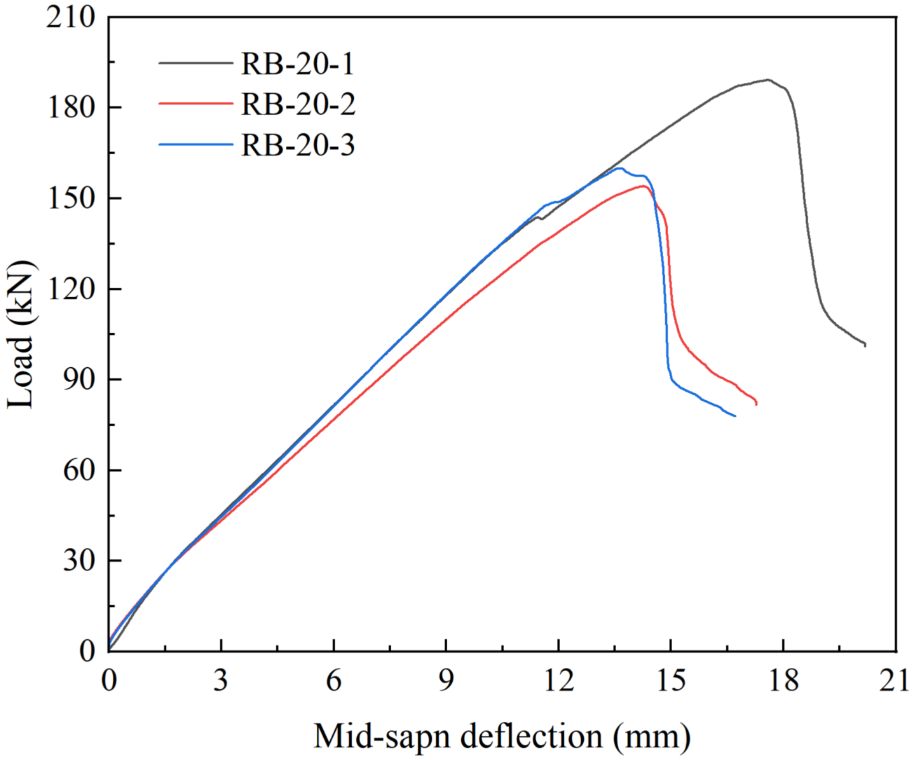
(1) Load-deflection curves for the regular beams (RB-0) without basalt Minibar



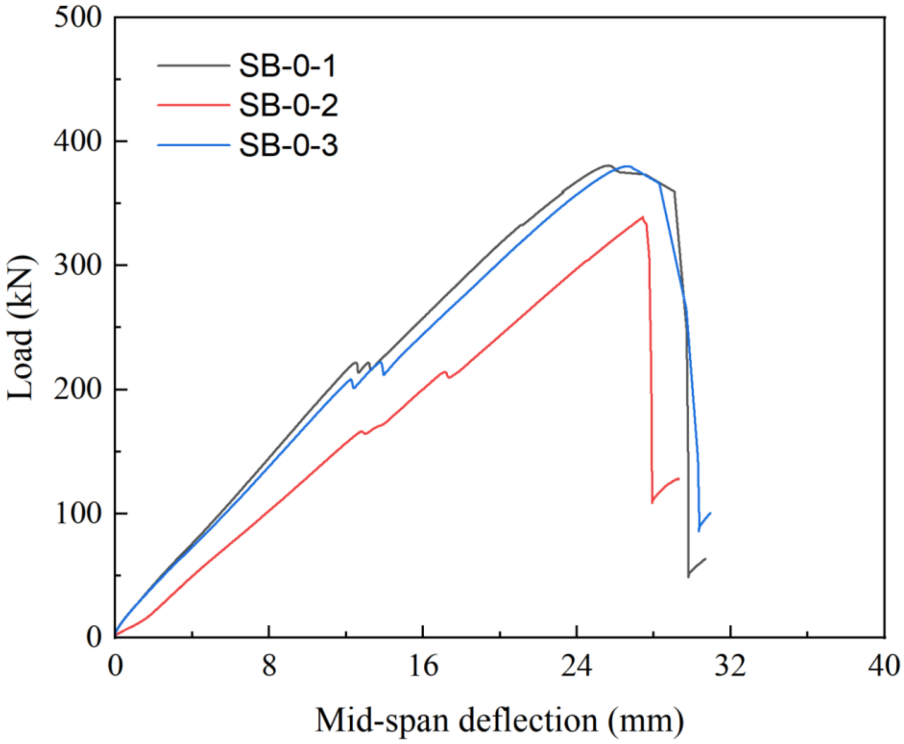
(2) Load-deflection curves for the regular beams (RB-10) with 10 kg/m^3 basalt Minibar.



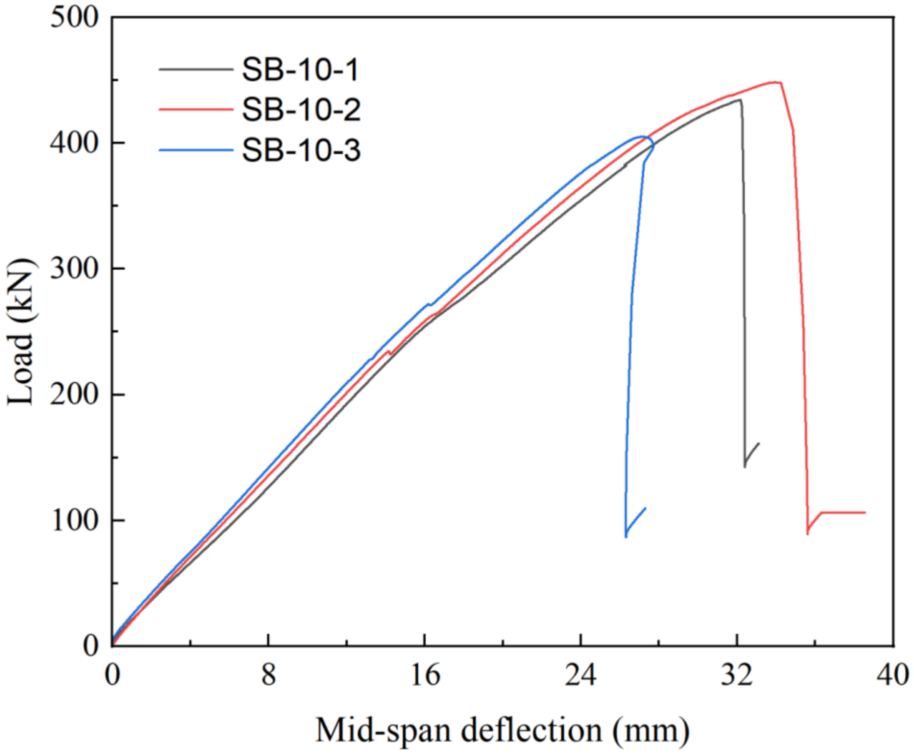
(3) Load-deflection curves for the regular beams (RB-20) with 20 kg/m^3 basalt Minibar.



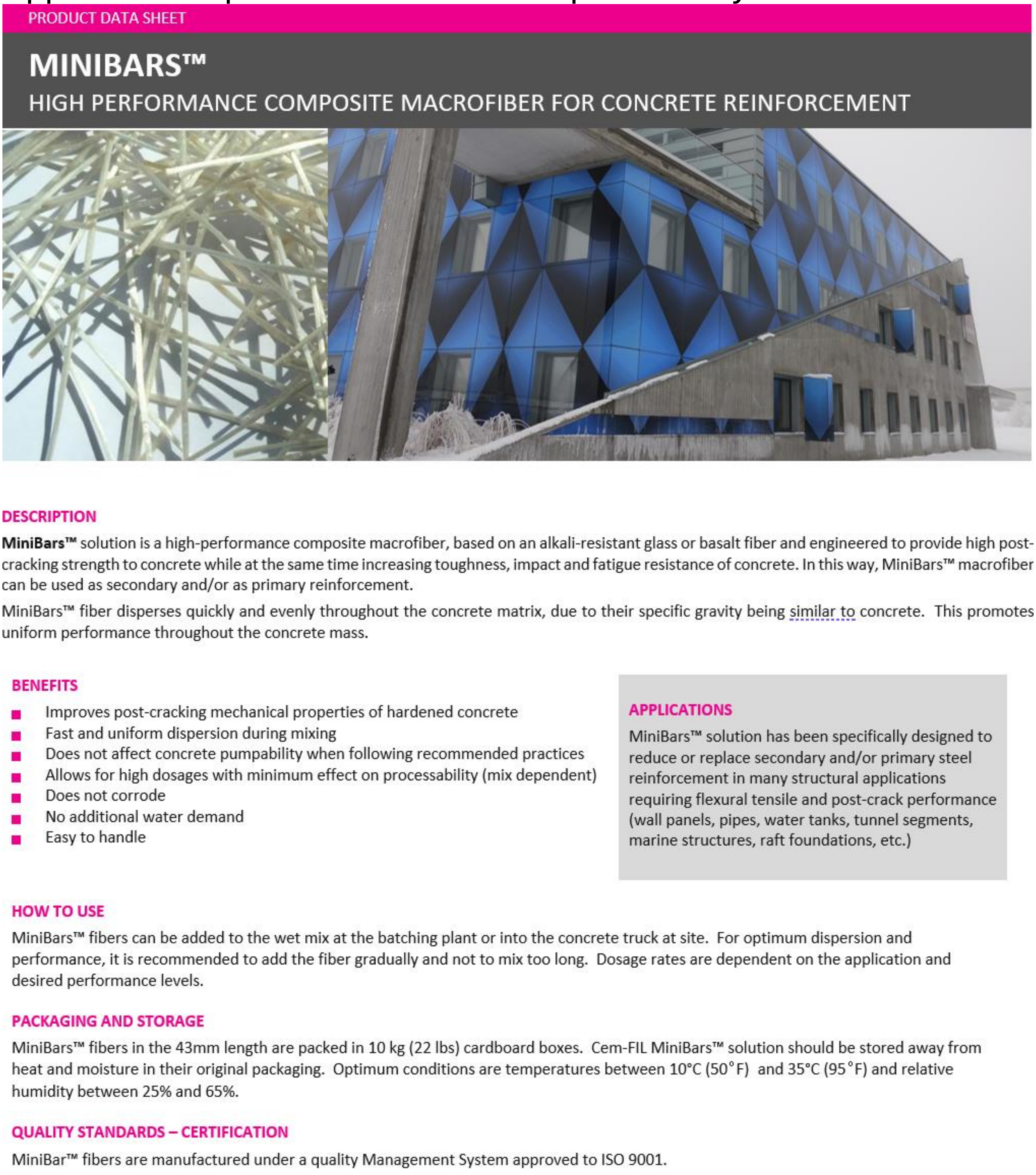
(4) Load-deflection curves for the shallow beams (SB-0) without basalt Minibar.



(5) Load-deflection curves for the shallow beams (SB-10) with 10kg/m^3 basalt Minibar.


SB-10-1
SB-10-2
SB-10-3
Load (kN)
0
100
200
300
400
500
0
8
16
24
32
40
Mid-span deflection (mm)

Appendix D: Specification of Minibar provided by ReforceTech



PRODUCT DATA SHEET

MINIBARS™

HIGH PERFORMANCE COMPOSITE MACROFIBER FOR CONCRETE REINFORCEMENT

DESCRIPTION

MiniBars™ solution is a high-performance composite macrofiber, based on an alkali-resistant glass or basalt fiber and engineered to provide high post-cracking strength to concrete while at the same time increasing toughness, impact and fatigue resistance of concrete. In this way, MiniBars™ macrofiber can be used as secondary and/or as primary reinforcement.

MiniBars™ fiber disperses quickly and evenly throughout the concrete matrix, due to their specific gravity being similar to concrete. This promotes uniform performance throughout the concrete mass.

BENEFITS

- Improves post-cracking mechanical properties of hardened concrete
- Fast and uniform dispersion during mixing
- Does not affect concrete pumpability when following recommended practices
- Allows for high dosages with minimum effect on processability (mix dependent)
- Does not corrode
- No additional water demand
- Easy to handle

APPLICATIONS

MiniBars™ solution has been specifically designed to reduce or replace secondary and/or primary steel reinforcement in many structural applications requiring flexural tensile and post-crack performance (wall panels, pipes, water tanks, tunnel segments, marine structures, raft foundations, etc.)

HOW TO USE

MiniBars™ fibers can be added to the wet mix at the batching plant or into the concrete truck at site. For optimum dispersion and performance, it is recommended to add the fiber gradually and not to mix too long. Dosage rates are dependent on the application and desired performance levels.

PACKAGING AND STORAGE

MiniBars™ fibers in the 43mm length are packed in 10 kg (22 lbs) cardboard boxes. Cem-FIL MiniBars™ solution should be stored away from heat and moisture in their original packaging. Optimum conditions are temperatures between 10°C (50°F) and 35°C (95°F) and relative humidity between 25% and 65%.

QUALITY STANDARDS – CERTIFICATION

MiniBar™ fibers are manufactured under a quality Management System approved to ISO 9001.

MINIBARS™

HIGH PERFORMANCE COMPOSITE MACROFIBER

TECHNICAL CHARACTERISTICS

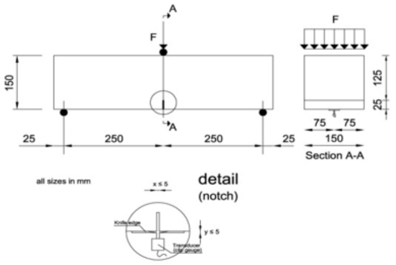
Material	Fiber Length	Fiber Diameter	Specific Gravity	Modulus of Elasticity	Tensile Strength
Basalt or Alkali-resistent glass fiber+ thermoset resin	43 +/-2 mm* 1.7 +/- 0.08 in.	0.70 mm 0.03 in.	2.1 ± 0.1	42 GPa 6,091,585 psi	> 1400 MPa / 200,000 psi

* Shorter or longer fibers are available on request

MECHANICAL PERFORMANCE

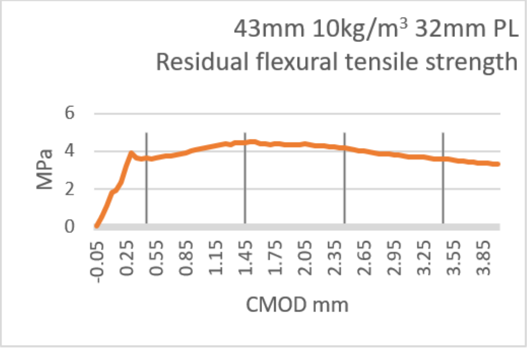
The fundamental mechanical performance of fibre reinforced concrete can be obtained from a three-point bending test performed on a prismatic beam of 150×150×550mm (6×6×22in.) including a notch at mid-span (EN 14651). The displacement-controlled testing system introduces a specific deflection or CMOD (Crack Mouth Opening Displacement) rate, and records load and displacement up to a CMOD limit of 3.5 mm (0.14 in). The fibre reinforced concrete performance is evaluated by means of residual flexural strength values at 0.5, 1.5, 2.5, and 3.5mm (0.02, 0.06, 0.10, and 0.14in.) of CMOD, namely f_{R1}, f_{R2}, f_{R3} and f_{R4}, respectively.

According to the fib Model Code 2010, the constitutive law of the material in tension is defined by means of the tensile stresses f_{Fts} and f_{Ftu}, calculated from f_{R1} and f_{R3} for service and ultimate limit state, respectively.



The sketch shows the basic configuration of the test.

The following curve shows a typical Load-CMOD response of a B35 concrete reinforced with 10 kg/m³ (17 lbs/yd³) of MiniBars™. The table presents the mean values of residual strength.

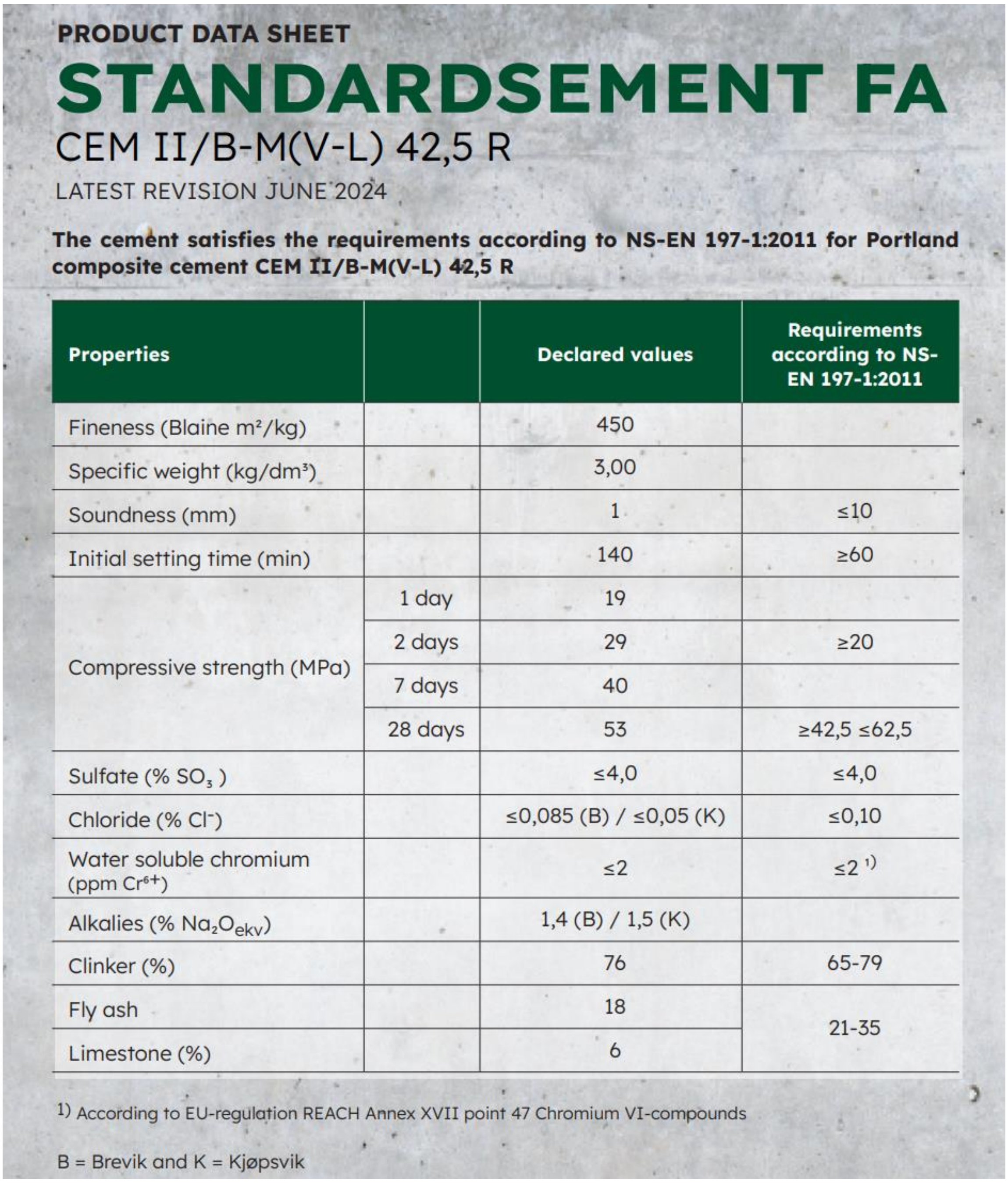


Mean flexural performance (prism 150x150x600mm)	MPa (mean)	psi (mean)
f_c (100 mm / 4 in cube)	56	8122
f_L	3,89	564
f_{R1}	3,61	523
f_{R2}	4,49	651
f_{R3}	4,13	599
f_{R4}	3.56	516
ARS= $(f_{R1}+ f_{R2}+f_{R3}+ f_{R4})/4$	3.95	572

Norway
ReforceTech AS
Luftveien 4
NO-3440 Røyken
Norway
+47 667680

reforcetech.com

Appendix E: Datasheet of standard FA cement



PRODUCT DATA SHEET

STANDARDSEMENT FA

CEM II/B-M(V-L) 42,5 R

LATEST REVISION JUNE 2024

The cement satisfies the requirements according to NS-EN 197-1:2011 for Portland composite cement CEM II/B-M(V-L) 42,5 R

Properties		Declared values	Requirements according to NS-EN 197-1:2011
Fineness (Blaine m^2/kg)		450	
Specific weight (kg/dm^3)		3,00	
Soundness (mm)		1	≤10
Initial setting time (min)		140	≥60
Compressive strength (MPa)	1 day	19	
	2 days	29	≥20
	7 days	40	
	28 days	53	≥42,5 ≤62,5
Sulfate (% SO_3)		≤4,0	≤4,0
Chloride (% Cl^-)		≤0,085 (B) / ≤0,05 (K)	≤0,10
Water soluble chromium (ppm Cr^{6+})		≤2	≤2 1)
Alkalies (% Na_2O_{ekv})		1,4 (B) / 1,5 (K)	
Clinker (%)		76	65-79
Fly ash		18	21-35
Limestone (%)		6	

1) According to EU-regulation REACH Annex XVII point 47 Chromium VI-compounds

B = Brevik and K = Kjøpsvik

*Download from: file:///C:/Users/chenli/OneDrive%20-%20NTNU/Desktop/Shear%20Test%20ReforceTech/Product%20data%20sheet%20_Standardsement%20FA_onesided_June2024.pdf

Appendix F: Calculation of shear capacity based on FprEC2: 2022

Beam RB-10

For concrete with 10 kg/m^3 RMB, $f_{R,3k}=4.06MPa$ $f_{R,3m}=4.58MPa$ $f_{ck}=41.4MPa$

$f_{yd}=500MPa$ (Design yield strength of reinforcement)

$f_{R,3k*}=\min(f_{R,3k};k_{K,\max}\cdot f_{R,3m})$ and $k_{K,\max}=0.6$ Therefore, $f_{R,3k*}=2.75MPa$

Width of cross-section: $b_w=150mm$; Effective depth of cross-section: $d=214mm$;

Reinforcement rate: $\rho_l=0.019$ $d_{dg}=16+D_{lower}=16+16=32\le 40$

The partial safety factors for materials were 1.0; $\gamma_{SF}=1.0$ $\gamma_v=1.0$

Therefore, $f_{Ftud}={f_{Ftu,ef}}/{\gamma_{SF}}=f_{Ftu,ef}=\kappa_0\cdot\kappa_G\cdot 0.33\cdot f_{R,3K*}$

Member size factor: $k_G=1.0+A_{ct}\cdot 0.5\le 1.5$ (A_{ct} is the area of tension zone in m^2)

For regular beam, $A_{ct}=\sqrt{h^2+(3d)^2}\cdot b_w$=0.103 m^2

Therefore, $k_G=1.0+A_{ct}\cdot 0.5=1+0.5\times 0.103=1.05\le 1.5$

Orientation factor: $\kappa_0=1.0$ $f_{Ftud}==\kappa_0\cdot\kappa_G\cdot 0.33\cdot f_{R,3K*}=1\times 1.05\times 0.33\times 2.75=0.95MPa$

For the RC beams with fibers, but no stirrups, the design value of shear strength can be taken as:

$$\tau_{Rd,cF}=\eta_{cF}\cdot\tau_{Rd,c}+\eta_F\cdot f_{Ftud}\ge\eta_{cF}\cdot\tau_{Rdc,\min}+\eta_F\cdot f_{Ftud}$$

$V_R=\tau_{Rd,cF}\cdot b_w\cdot z$ and $z=0.9d$

$$\tau_{Rd,c}=\frac{0.66}{\gamma_V}\cdot(100\rho_l\cdot f_{ck}\cdot\frac{d_{dg}}{d})^{1/3}=0.66\times(100\times 0.019\times 41.4\times\frac{32}{214})^{1/3}=1.5MPa\ge\tau_{Rdc,\min}$$

$$\tau_{Rdc,\min}=\frac{11}{\gamma_V}\cdot\sqrt{\frac{f_{ck}}{f_{yd}}\cdot\frac{d_{dg}}{d}}=1.22MPa$$

$\eta_{cF}=\max\{1.2-0.5f_{Ftuk};0.4\}\le 1.0=$ 0.725; $\eta_F=1.0$

$$\tau_{Rd,cF}=\eta_{cF}\cdot\tau_{Rd,c}+\eta_F\cdot f_{Ftud}=2.04MPa$$

$$V_R=\tau_{Rd,cF}\cdot b_w\cdot z=2.04\times 150\times 0.9\times 214=58.9kN$$

The theoretical shear capacity of beam RB-10 based on FprEC2: 2022 is 58.9 kN.

Beam SB-10

For concrete with 10 kg/m^3 RMB, $f_{R,3k} = 4.06MPa$ $f_{R,3m} = 4.58MPa$ $f_{ck} = 41.4MPa$

$f_{yd} = 500MPa$ (Design yield strength of reinforcement)

$f_{R,3k*} = \min(f_{R,3k}; k_{K,\max} \cdot f_{R,3m})$ and $k_{K,\max} = 0.6$ Therefore, $f_{R,3k*} = 2.75MPa$

Width of cross-section: $b_w = 360mm$; Effective depth of cross-section: $d = 142mm$;

Reinforcement rate: $\rho_l = 0.0307$ $d_{dg} = 16 + D_{lower} = 16 + 16 = 32 \leq 40$

The partial safety factors for materials were 1.0; $\gamma_{SF} = 1.0$ $\gamma_v = 1.0$

Therefore, $f_{Ftud} = {f_{Ftu,ef}}/{\gamma_{SF}} = f_{Ftu,ef} = \kappa_0 \cdot \kappa_G \cdot 0.33 \cdot f_{R,3K*}$

Member size factor: $k_G = 1.0 + A_{ct} \cdot 0.5 \leq 1.5$ (A_{ct} is the area of tension zone in m^2)

For shallow beam, $A_{ct} = \sqrt{h^2 + (3d)^2} \cdot b_w$ =0.167 m^2

Therefore, $k_G = 1.0 + A_{ct} \cdot 0.5 = 1 + 0.5 \times 0.167 = 1.08 \leq 1.5$

Orientation factor: $\kappa_0 = 1.0$ $f_{Ftud} == \kappa_0 \cdot \kappa_G \cdot 0.33 \cdot f_{R,3K*} = 1 \times 1.08 \times 0.33 \times 2.75 = 0.98MPa$

For the RC beams with fibers, but no stirrups, the design value of shear strength can be taken as:

$$\tau_{Rd,cF} = \eta_{cF} \cdot \tau_{Rd,c} + \eta_F \cdot f_{Ftud} \geq \eta_{cF} \cdot \tau_{Rdc,\min} + \eta_F \cdot f_{Ftud}$$

$V_R = \tau_{Rd,cF} \cdot b_w \cdot z$ and $z = 0.9d$

$$\tau_{Rd,c} = \frac{0.66}{\gamma_V} \cdot (100\rho_l \cdot f_{ck} \cdot \frac{d_{dg}}{d})^{1/3} = 0.66 \times (100 \times 0.0307 \times 41.4 \times \frac{32}{142})^{1/3} = 2.02MPa \geq \tau_{Rdc,\min}$$

$$\tau_{Rdc,\min} = \frac{11}{\gamma_V} \cdot \sqrt{\frac{f_{ck}}{f_{yd}} \cdot \frac{d_{dg}}{d}} = 1.5MPa$$

$\eta_{cF} = \max\{1.2 - 0.5 f_{Ftuk}; 0.4\} \leq 1.0 = 0.71$; $\eta_F = 1.0$

$$\tau_{Rd,cF} = \eta_{cF} \cdot \tau_{Rd,c} + \eta_F \cdot f_{Ftud} = 2.414MPa$$

$$V_R = \tau_{Rd,cF} \cdot b_w \cdot z = 2.414 \times 360 \times 0.9 \times 142 = 111.1kN$$

The theoretical shear capacity of beam SB-10 based on FprEC2: 2022 is 111.1 kN.