

Article

Experimental Study and Modelling on the Structural Response of Fiber Reinforced Concrete Beams

Vitalijs Lusis ^{1,2} , Krishna Kiran Annamaneni ¹, Olga Kononova ², Aleksandrs Korjajins ³ , Inga Lasenko ² , Rengasamy Kannathasan Karunamoorthy ²  and Andrejs Krasnikovs ^{2,*}

¹ Research Center for Ecological Construction, Riga Technical University, 1 Paula Valdena Street, LV-1048 Riga, Latvia

² Department of Theoretical Mechanics and Strength of Material, Institute of Mechanics and Mechanical Engineering, Riga Technical University, LV-1048 Riga, Latvia

³ Department of Building Materials and Products, Institute of Materials and Structures, Riga Technical University, LV-1658 Riga, Latvia

* Correspondence: andrejs.krasnikovs@rtu.lv

Abstract: In many structural applications, concretes reinforced with short metal or synthetic fibers (fiber-reinforced concrete (FRC)) have a number of advantages over traditional concretes reinforced with steel rebars reinforcement, such as easier and more economical production, wear resistance, impact resistance, integrity, etc. In the present study, several concrete mixes were developed and prismatic FRC specimens were fabricated. Their structural behaviors were studied using bending tests until prisms were fractured. Two types of fibers, namely, steel and polypropylene (PP) and three different concrete matrixes were investigated, testing in total 12 FRC prismatic specimens. Every group of FRC had the same concrete matrix, but different internal fiber architecture. All specimens were tested by Four-Point Bending (4PBT). The analysis was carried out with a goal to determine the workability and flexural tensile strength of all FRC groups, comparing these parameters with fracture modelling results. Single crack formation and opening model were established. Crack is crossing whole stretched part of the prism's orthogonal cross-section. Crack is opening, fibers are bridging the crack and are pulling out. Load bearing curves in the model were compared with experimentally obtained.

Keywords: reinforced concrete; mechanical properties; steel fiber; polypropylene fiber; bending strength



Citation: Lusis, V.; Annamaneni, K.K.; Kononova, O.; Korjajins, A.; Lasenko, I.; Karunamoorthy, R.K.; Krasnikovs, A. Experimental Study and Modelling on the Structural Response of Fiber Reinforced Concrete Beams. *Appl. Sci.* **2022**, *12*, 9492. <https://doi.org/10.3390/app12199492>

Academic Editors: Alexey Beskopylny, Evgenii Shcherban and Sergei Stel'makh

Received: 24 August 2022

Accepted: 20 September 2022

Published: 22 September 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



Copyright: © 2022 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Nowadays, development and introduction of more efficient mass-produced materials are among the main engineering challenges which can be encountered in all industrial areas. Today, concrete is the second most consumed material after water, with three tonnes of concrete being produced for every person living on the globe per year. Twice as much concrete is used in construction as the total of all other building materials [1,2]. Reinforcement of various scale is increasingly used in modern materials and concretes, ranging from reinforcement at the nanoscale [3–7] to the macro-scale reinforcement that has already become classic [8–10]. Bars and fibres made of steel and other materials are used as the main or the secondary reinforcement bearing the tensile and shear stresses [11–16]. If fibres are randomly uniformly dispersed in the concrete volume, the resulting material is supposed to be homogeneous Fibre Reinforced Concrete (FRC). One important property of FRC is its superior resistance to cracking and crack propagation [17–21]. Concrete matrix can be successfully reinforced with the fibres of various geometry [22–26] and made from various materials [27–33]. The properties of the concretes with non-metallic fibers are slightly less recognized, especially concretes with new types of the polymer fibers. Additionally, the lack of standardized methods of testing concrete with polymer fibers

make their application much more difficult. Designing elements or structures made of fiber-reinforced concrete requires knowledge of its basic mechanical parameters. Unfortunately, the currently available data describing this type structures are insufficient and research in this area is fragmentary. FRC and its modelling are interesting for future practical application. Every investigation in this field is important. Industrial use of the fibers, comparing with steel rebars is only in the starting point. Polypropylene fibre is used in concrete mix design mainly for shrinkage crack arrest, or, in combination with additional reinforcement [34–36], also for improvement of the non-linear deformation of FRC ensuring resistance to cracking of the concrete structures [37–39]. The bridging effect of the fibres across the cracks inside concrete volume improves the toughness of the concrete after cracking [40–43]. It is also important to take into consideration that even when the concrete is called “homogeneous”, it does not means it is really homogeneous, because during filling the construction formwork (mix flowing process), fibres added to the concrete mix obtain their slightly non-homogeneous distribution and non-random orientation in the fresh concrete volume mix, which inevitably affects the mechanical properties of FRC [44–48].

The current research presents several concrete mixes were developed and prismatic FRC specimens were fabricated, reinforced with three different fibre types: hooked steel 35 mm, polypropylene PP 40 mm, and PP 45 mm. Their structural behaviours were studied using bending tests until prisms were fractured. Every group of FRC had the same concrete matrix, but different internal fiber architecture. All specimens were tested by 4PBT. The analysis was carried out with a goal to determine the workability and flexural tensile strength of all FRC groups, comparing these parameters with fracture modelling results. Load bearing curves in the model were compared with experimentally obtained.

2. Materials and Methods

2.1. Concrete Mix Materials

Mix design of FRC matrix implies combining Portland cement with multi-fractional aggregates and reactive pozzolanic admixtures, such as fly ash, silica fume and nano-silica. When selecting raw materials for production of a concrete matrix, preference was given to the locally available mineral materials and cement. The composition of the developed concrete mixture and the exact concentration of the ingredients. In the current research, the following components were used as FRC mix materials:

1. Portland cement CEM I 42.5N.
2. Sikament[®] 56, a third generation (polycarboxylate based) superplasticizer admixture. It was used to provide flowability of the mix and dispersion of microparticles. Basic properties: light yellow and highly flowable liquid, density— $1.08 \pm 0.02 \text{ kg/dm}^3$, pH— 4.5 ± 1 , solid content— $37 \pm 1\%$. Recommended dosage: in the range of 0.1–2.0 % by weight of cement.
3. Stabilizer AkzoNobel Cembinder 50. A commercial colloidal nano-silica product Cembinder 50 was used. Nano-silica is a new generation of reactive silicon dioxide admixtures. Its high reactivity is explained with chemical purity and extremely high specific surface ($>30,000 \text{ m}^2/\text{kg}$) and particle size $<100 \text{ nm}$. The size of the silica fume particle corresponds up to 1000 nano-silica particles and, comparing with the size of cement particles, one cement particle corresponds to approximately one billion of nano-silica particles. This determines high chemical reactivity of the admixture and its accelerated effect on the cement hydration.
4. Coarse aggregates. Crushed limestone (fractions 2/6 mm) was used as a coarse aggregate. The shape of the rough aggregate has a significant influence on the workability of a concrete mix, because water quantity depends on the type of aggregate, particle size distribution, the shape and texture of grains and the quantity of fines.
5. Fine aggregate Saulkalne. Fine aggregate of three grades was used: washed quartz-based sand, fractions 0/0.4 (fine), 0/1 (medium), and 0.4/1.2 mm (coarse).
6. Silica fume or Micro-silica, a very fine pozzolanic material composed of amorphous silica produced by electric arc furnaces as a by-product of production of elemental sili-

con or ferro silicon alloy. Addition of micro silica to cementitious systems can improve the strength by controlling the structure of C-S-H. Silica fume is high-purity amorphous silicon dioxide with >92% SiO₂ content. Silica fume particles are characterized by spherical shape and diameter in the range of 0.05–0.5 µm or 50–500 nm.

7. Fly ash. This pozzolanic admixture is produced as a by-product of coal combustion in the power plants, it is usually collected with electrostatic filters. Good quality conventional fly ash offers such advantages as improvement of concrete workability properties, improvement of structural tightness, reduction of hydration heat, increase of resistance to chemical aggression, participation of ash in cement binding reactions, higher resistance of concrete over long period and reduction of production costs of the concrete mixture. Commercially used fly ash with the cumulative content of oxides SiO₂ + Al₂O₃ + Fe₂O₃ was equal to 84.7% thereof. It was classified as class F fly ash in accordance with ASTM C618 [49].

2.2. Fibers

Short 12 mm long polypropylene fibers (PB Eurofiber MF 1217) have been added in small amount to reduce FRC shrinkage. Additionally, three main types of fibers were used in the research:

1. Steel fibers: Krampe Harex hooked end steel fibers of 35 mm in length were chosen for the first FRC group. Figure 1a shows the fibers and Table 1 summarizes the properties of the fibers;
2. PP fibers: Strux PP 40 mm long fibers were used in the second FRC group to compare the structural properties of two different fiber groups. Figure 1b shows the fibers, their properties are given in Table 1;
3. PP fibers: Durus PP 45 mm long fibers were used in the third FRC group, employing the opportunity to compare the results of the samples with the same type of fiber, but of different fiber length, produced by a different company, and ultimately compare them with the samples made using different types of fiber. Figure 1c and Table 1 provide the illustration and the properties of this fiber, respectively.

Table 1. Fiber's specification, by supplier's data.

Fibres	Steel Fibres DE 35/0.55-E446 (Krampe Harex GmbH & Co. KG, Germany)	PP Fibres Strux (GCP Applied Technologies, USA)	PP Fibres Durus (ADFIL, Belgium)	PP Fibres PB Eurofiber MF 1217 (Baumhueter Extrusion GmbH, Germany)
Shape	Hooked ends	Straight	Straight	Straight
Cross Section	Round	Rectangular	Non-regular	Round
Length, mm	35.00	40.00	45.00	12.00
Volume fraction, %	1	1	1	0.1
Diameter	0.55 mm	0.43 mm	0.90 mm	15.4 µm
Aspect ratio	63	90	50	—
Density, kg/m ³	7900	2100	905	910
Tensile strength, N/mm ²	1700	620	465	282.1
Modulus of elasticity, N/mm ²	2 × 10 ⁵	1389	3350	1000
Quantity of fibers (ref. 1 kg)	15.319	187.000	38.600	~500 × 10 ⁶

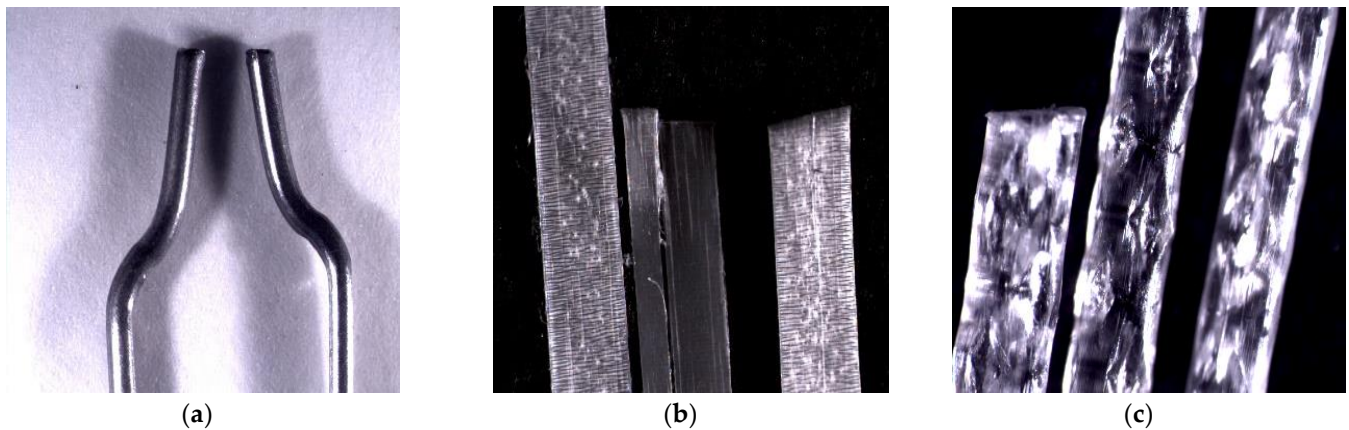


Figure 1. (a) DE 35/0.55 steel fibers; (b) Strux PP fibers; (c) Durus PP fibers.

As regards the concrete mix design, water-to-cement ratio was $W/C = 0.3$ in each group. Other ingredient amounts are given in Table 2. Volumetric concentration of fibres in the mixes was 1.0% and 0.1% from the total volume of a concrete, according to the Table 3.

Table 2. Designed concrete mix composition and used components.

Composition	Weight, kg/m ³
Portland cement CEM I 42.5N (SCHWENK Latvia Ltd., Latvia)	551.4
Crushed limestone 2/6 mm (Latvia)	700.0
Quartz Sand 0.4–1.2 mm (Saulkalne, Latvia)	450.0
Quartz Sand 0–1.0 mm (Saulkalne, Latvia)	300.0
Quartz Sand 0–0.4 mm (Saulkalne, Latvia)	100.0
Silica Fume, grade 920D (Elkem, Norway)	53.2
Fly Ash (SCHWENK Ltd., Kozienice, Poland)	90.0
Tap water	200.5
“Cembinder 50” (AkzoNobel, Netherlands)	10.0
Superplasticizer “Sikament [®] 56” (Sika Baltic SIA, Latvia)	9.1
Total	2464

Table 3. Name of groups and fibers quantity, kg/m³ ^a.

Fiber Quantity Required, kg	Group CSf	Group CPPfS	Group CPPfD	PB Eurofiber MF 1217 (12 mm), for all Three Groups
	3120.00	364.00	364.00	18.20

^a C—Cement composite; Sf—Steel fibre, DE 35/0.55-E446 (Krampe Harex GmbH & Co. KG, Germany); CPPfS—PP fibres Strux (GCP Applied Technologies, USA); CPPfD—PP fibres Durus (ADFIL, Belgium).

2.3. Sample Preparation

2.3.1. Concrete Mixing

The concrete mix was prepared according to EN-206 [50]. The mix should have a uniform dispersion of the fibres in order to prevent segregation or balling of the fibres during mixing. Most balling occurs in the process of adding fibres. Increase of the aspect ratio, percentage of fibre in the concrete volume, and the size and quantity of coarse aggregate will intensify the balling tendencies and decrease workability [51]. Fibres were added uniformly into the open end of the concrete mixer, just before taking the concrete out to pour it into the beam mould, so that not to damage the fibres (this remark applies to the non-metallic fibres).

2.3.2. Fiber Quantity

It is very important to know the quantity of each fibre required for each individual group while forming the prisms for testing all three FRC groups. Their values are indicated in Table 3.

2.3.3. Specimen Sizes

The FRC was placed into the prism moulds of the size $100 \times 100 \times 400$ mm, all groups contained small polypropylene fibres and were casted in compliance with code provisions. The prisms were placed in water for curing [52]. The tests for 4PBT flexural strength were done after 28 days.

2.4. Testing Technological Properties

Slump Cone Test Slump cone test is one of the tests done to check the workability of a concrete [53]. The workability of the FRC mix was evaluated by means of Abram's cone slump test in accordance with EN 12350-2. Additionally, time to final cone spread was determined as an additional flowability parameter. Measurements were done for all three FRC groups.

Sieve Segregation Test

The test aims to investigate the resistance of high performance concrete (HPC) to segregation [54] by measuring a portion of a prepared high performance concrete specimen passing through a 5 mm sieve. If the HPC has a weak resistance to segregation, the paste passes easily through the sieve. Thus, the sieved portion indicates whether the HPC is stable or not. This test was also performed for all concrete groups.

The equipment required for this test includes: (1) a sieve with a perforated plate with 5 mm square holes, (2) a frame with a $\varnothing = 300 \pm 1$ mm, a height is 40 ± 0.5 mm or $\varnothing = 315 \pm 1$ mm, a height is 75 ± 0.5 mm, (3) a tray of a shape, with volume suitable to hold the materials passing through the sieve and easily removed by the operator without forcing the passage of excess materials, (4) a digital type scale with a capacity ≈ 10 kg, which can be zeroed, (5) a hard plastic or metal bucket with a maximum inside diameter of 300 ± 10 mm and a capacity of $10 \div 12$ L and a top suitable to cover the bucket to protect fresh concrete from intensive drying.

The scale was placed in a stable and aligned position. 10 ± 0.5 L of representative fresh FRC was poured into the beaker and covered with a top. It was left to stand for 15 ± 0.5 min. During the waiting period, only the pot was weighed; the weight was noted as W_p . The sieve was placed on the pot without removing it from the scale. The bucket was filled after 15 ± 0.5 min. The surface of the concrete in the bucket was inspected for clear water leaking out, and the result was recorded. The scale was zeroed, and concrete in the amount of 4.8 ± 0.2 kg was poured onto the central part of the sieve from a height of 50 ± 5 cm. The weight of the concrete poured (on the sieve) was noted as W_c . Two minutes later the concrete was poured, the sieve was carefully removed from the pan without any shaking that could force excess material through the sieve. The pan with the sifted materials was weighed and the weight was noted as W_{ps} .

The sifted part, the mass fraction of the sample that passed through the sieve, was calculated according to the equation $\Pi = ((W_{ps} - W_p)/W_c) \times 100$, expressing the result in percent.

2.5. Testing Structural Properties

2.5.1. Compressive Testing Procedure and Strength of Concrete Cube

Adhesive bonds between the parts of the sintered and cemented materials are the properties defining the strength of these materials, they can be detected both by non-destructive methods [55–57] and by the classical destructive method in accordance with EN 12390-3 using a Controls Automax 5 testing machine.

Standard cube samples ($100 \times 100 \times 100$ mm, 6 samples in the experimental series) were prepared. Fresh samples were covered with the plastic film, after two days the samples were demoulded and cured in water for 28 days at the temperature of 20 ± 2 °C until testing.

2.5.2. Four Point Bending Testing Procedure

This test is commonly used to determine the bending strength and bearing capacity with a cracked beam. The bending test is the most often used test to measure the mechanical and fracture properties of the FRC in the regime of crack propagation. The 4PBT was used as a constant bending moment test on the portion of the specimen located between the two upper supports, as shown in the Figure 2. The provisions of several standards, such as EN 14651, ASTM C1018-97 and RILEM TC 162-TDF were taken into consideration. The tests were carried out in accordance with these standards and the results were recorded and considered.



Figure 2. Four Point Bending Test scheme.

The samples of all three groups of FRC with dimensions of $100 \times 100 \times 400$ mm was experimentally tested.

The prisms were mounted exactly as shown in Figure 2, according to the marking per load points. A frame with two HBM WA20 LVDTs sensors on each side, was used to record the deformation in the prisms during the test, was then installed at the same marks. The mechanical properties were tested using the 4PBT method applying a Controls Automax 5 loading machine. The load was applied with increments 0.25 kN in the period of 60 s.

The load was applied monotonically in small increments, and load, strain and stress were recorded at each increment. Resistance strain gauges were installed on the prisms, and the mid-span deflection and support settlements were measured with LVDT. The load versus vertical deflection (mid-span) curve was obtained in every download. The

measurement data of the strength obtained on the HBM Spider-8 data acquisition system were processed, synchronized, and stored in MS Excel files, which were later used to construct the necessary graphs. The deflection of the prism was received by counting and summing the values from both sensors and obtaining the average value. The graphs showing the processes in FRC, namely the behavior of the fibers under the influence of bending, were created from these files, using the MS Excel program. The test procedure was performed for all three FRC groups in the same way, as shown in Figure 2, and the graphs were plotted using deflection and load values. The load was applied until the specimens failed completely.

3. Experimental Results and Discussion

The resultant segregation value for all three groups of fibre concrete mixtures was zero.

The slump cone test results for the concrete matrix Group CSf are as follows: slump height equal to 24 cm with a settling time of 8 s (see Figure 3a). Based on these results, it can be concluded that this concrete matrix has very low workability. For Group CPPfS, slump height was 4 cm with a settling time of 5 s (Figure 3b). It indicates that the workability of concrete in this group is very good. For Group CPPfD, the slump height was 23 cm with a settling time of 7 s (see Figure 3c). These indicators imply that this group is characterised by very poor workability.

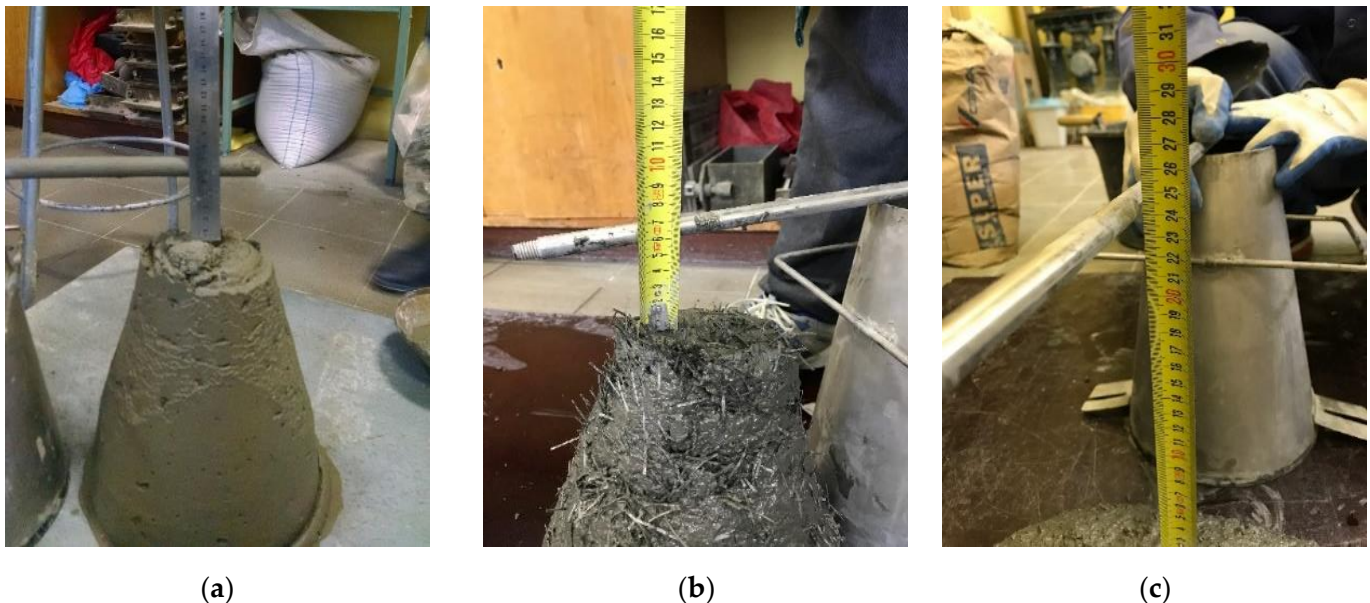


Figure 3. Slump cone test: (a) Group CSf; (b) Group CPPfS; (c) Group CPPfD.

Compressive strength of 6 specimens were found out, materials compressive test (concrete cube test) was used in accordance with EN 12390-3 [58]. According to standard LVS 156-1 [59], the correction factor 0.95 was implemented, thus, the obtained concrete corresponds to class C70/85.

The results of tests under the impact of bending forces were presented in the form of Excel values. All values were taken for all three groups, strength-deflection average values were plotted using MATLAB software for 4PBT test and the average graphs were drawn based on the results thereof. During the experiment, a large amount of data was obtained, and the values along the deflection axis often did not coincide with each other.

Therefore, using the code in MATLAB software, a selection of experimental data values with the given deflection step was obtained. The resulting database was used to obtain the average strength-deflection values. The graphs in Figure 4 represent the three groups

respectively, and all three groups are drawn in a single frame to plot the differences in their behaviour.

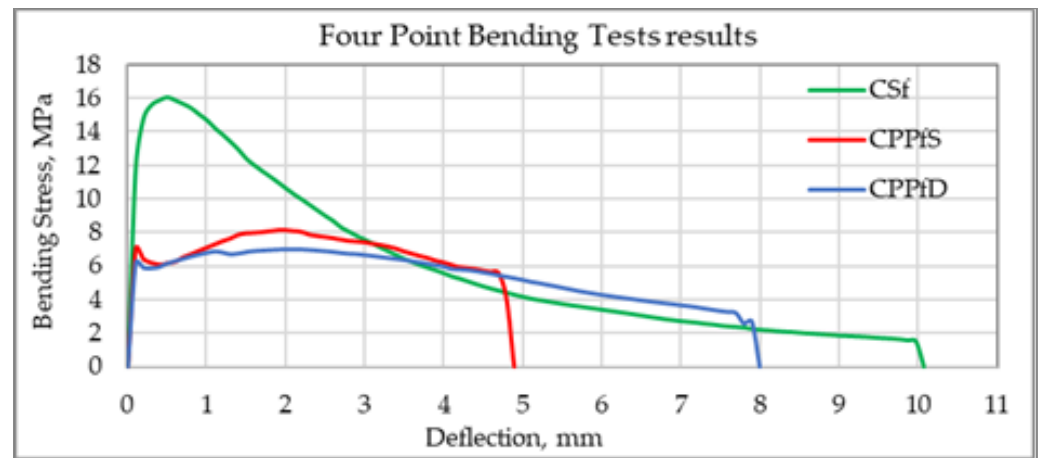


Figure 4. Average graphs: Stress—middle of a span Deflection, for all groups.

The above plotted curves consist of the following phases:

Group CSf:

1. The phase of linearly elastic deformation of concrete matrix, indicating the linear deformation from 0.02 mm to 0.25 mm with no formation of visible cracks and without significant load in the fibres.
2. The phase of critical load, showing the linear deformation of concrete matrix from 0.25 mm to 0.5 mm.
3. The phase of fibre pull-out, indicating the formation of macro-cracks with the opening width from 0.1 mm to 0.35 mm. The tension force transfer resulted in the resistance to crack propagation, imparting the strength, i.e., the fibres were bridging the cracks, collecting tension forces at the edges of the cracks. The results obtained correlate with the data from the related research [60,61]. The comparison of experimental data of the steel fibre pull-out test and numerical simulation results was carried out. The third phase corresponds to the growth of delamination along the fibre and matrix interface until full debonding of the fibres (crossing micro-cracks), followed by fibre sliding out of the matrix with friction, and partial plastic deformation of the fibres [62,63].

Group CPPfS and Group CPPfD:

1. The phase of linearly elastic deformation indicating the linear deformation from 0.01 mm to 0.15 mm with no formation of visible cracks and without significant load in the fibres.
2. The phase of critical load showing the linear deformation from 0.15 mm to 0.2 mm.
3. The phase of elastic deformation provided by the PP fibres, increasing the load bearing capacity of the members and resisting the loads. The change in the deformation from 0.2 mm to 2 mm during the fibre pull-out or change indicating the formation of cracks with the opening width from 0.1 mm to 0.35 mm was recorded. The tension force transfer resulted in the increased resistance to crack propagation, imparting the strength to the prism members.

Steel fibres demonstrate good performance in the elastic deformation, as it is demonstrated in Figure 4. Mechanical (not chemical) adhesion between steel fibres and concrete is higher compared to the adhesion between PP and concrete. As soon as the concrete absorbs the initial load, fibres carry most of the subsequently applied load until macro-cracks are formed and stretched fibres become visually observable at the fractured walls of the macro-cracks. The concrete–steel combination ensures higher material integrity, fibre sliding starts at higher values of the bending load or deformation in the sample. Although steel fibres demonstrate good load bearing capacity, PP fibres play a major role in resisting

the loads due to their elastic nature. The number of micro-cracks increases, and a network of micro-cracks is formed. The formation of macro-cracks occurs in the perpendicular direction to the longitudinal axis, which indicates a good way for load application. Density of the network of micro-cracks depends on the distribution of the particles in the concrete matrix, as well as the sizes and concentration of the fibres. The complete pull-out of the fibres occurs during the last stages of application of the critical load. The intensity of load in each fibre depends on the material of the fibre, its shape, length and orientation in relation to the plane of the crack, direction of the applied force of pull-out and the depth of fibre inside the matrix of the concrete member. During the last stage of loading (deflection higher than 3–3.5 mm), fibres bridging the macro-crack with one tail are pulled out of the concrete. The process when the polymer fibres are pulled out needs more constant load, in the case with steel fibres, the necessary load is decreasing more rapidly. The pull-out process finishes with the partial or complete removal of the fibres from the concrete matrix in the areas, where friction caused by slipping occurs between the fibre and concrete matrix.

Once the fibres are fully stretched (fully utilised), the crack width increases. The specimen breaks, indicating the maximum loading capacity and the maximum tensile force absorption by the FRC member.

The differences between steel and PP fibres are worth further discussion. Figure 4 allows considering the major differences between these two types of fibre, which are observed during the breaking (failure) mechanism of the concrete members. At the initial stage of loading, each steel fibre interacts with the surrounding concrete as a common material. Mainly thanks to the hooks on its ends, the steel fibre does not slip out of the concrete when micro-crack split the concrete. The hooked ends of the steel fibre in combination with high value of plastic stress necessary to deform steel fibre and the value of friction force between the fibre and concrete are the factors that determine higher resistance of this material. Compared to PP fibres, a higher load is necessary to start the pull-out process (15 MPa for steel fibres as compared with 7.2 MPa for Strux PP fibres and 6.4 MPa for Durus PP fibres). After the first peak on the curves, all samples have macro-cracks. During this pull-out process, steel fibre ends form clouds of micro-cracks. The concrete matrix is rapidly losing elastic modulus and toughness, which results in rapidly decreasing load bearing capacity. Polymeric fibres are softer, the pull-out process of each fibre happens along with the deformation of fibre surface and fibre body. Fibres are not hooked, and the pull-out force is more stable along the entire pulling length.

Several observations can be made considering the results of the research:

1. It is necessary to take care about the concrete mix during addition of the fibres to make the mix homogeneous, for example, by adding the fibres in layers. Proper finishing of the top layer is necessary, making sure no marks of fibres are left on the sidewalks.
2. Fibre pull-out is a process dependant on how far each fibre is pulled out. Some fibres are more effective in the beginning, when deflection of structural elements is small (deformation of the structural member with a more sophisticated geometry), some—at the final stage, when many cracks in the material are formed. Since the PP fibres are smooth and do not have a proper grip to the surfaces in the concrete mix, they propagate all over the mix, which might cause problems due to accumulation of several fibres in some places. This may result in value change. Homogeneous fibre distribution in the material volume is important for the decrease of the scatter of load bearing results.
3. The non-corrosive nature is another important benefit of the PP fibres. It is rarely observed in the steel fibres if they are not properly coated with resins. Therefore, care must be taken in this regard if it is planned to create longer spans for any construction.

4. Modelling

Based on experimental observations, we accept on the middle span of each beam, subjected to four-point bending (see Figure 4) only one single macro-crack finally opens. This crack grows reaching the neutral axis, opens and finally divides the sample into

two pieces. It is possible to suggest that at initial stage micro-cracks are few. Only one of them is forming the macro-crack that is reaching the neutral axis of the beam. Macro-crack growth (increase the length) is characterized by small its opening (at initial stage non-visible by eye). After reaching the neutral axis, its growth stops (further increase in the crack length is small) and the crack begins to open with an increase in the applied external load. Macro-crack opening is happening by fibers pull-out process. At this stage length of the macro-crack is “in general” stable, in our experiments it was 80–85 mm. Each fiber crossing the surface of a macro-crack pulls out the shortest end in the process of its opening. Polymer (polypropylene) fiber breaks inside the concrete when pulled. Only part of the end length is pulled out.

Crack opening numerical structural model based on the similar suggestions as in [64,65] was accepted and used. Basic model's assumptions were: (a) crack's length is stable, it opens, fibers, crossing its plane under different angles, are pulling out; (b) fibers distribution in the volume is random (according to orientation angles and each fiber geometrical centre spatial location); (c) each fiber is pulling out as a single fiber—is possible to use experimental data set with pull-out curves for fibers oriented under different angles and embedded at different depth in the concrete (single curves and average data) [64]. Number of fibers in every prism with dimensions $100 \times 100 \times 400$ mm is known (in average) from the experiment. Single prism volume was divided into elementary volumes. N-elementary volumes are on the one side of the crack and the same number on opposite. Number of fibers crossing one particular element grain (which is on the surface of the crack) is easy to calculate.

For every particular grain is possible to evaluate each fiber tail length and orientation. Using experimental data obtained in pull-out experiments and performing averaging procedure, is possible to calculate force applied to particular grain depending on “local opening value”. “Local opening value” is distance between two grains-neighbours (when macro-crack is closed distance between grains-neighbours is zero. In the model crack mouth opening displacement (CMOD) were numerically changed by steps. At every step, forces applied to every pair of grains-neighbours were calculated, such way all forces on the surface of macro-crack were calculated. From equilibrium conditions applied to the prism external forces were calculated [64]. In the modelling was used commercial software MATLAB. Modelling results were compared with the experimental curves for beams. Predictions generated by the model were validated by 4PBT of $100 \times 100 \times 400$ mm prisms.

Modelling Results

Modelling results for FRC of the group CSf is shown in Figure 5. Model is approximating experimental data quite good. Difference between modelling and experimental data at the first peak is easy to explain—model is describing only macro-crack opening stage.

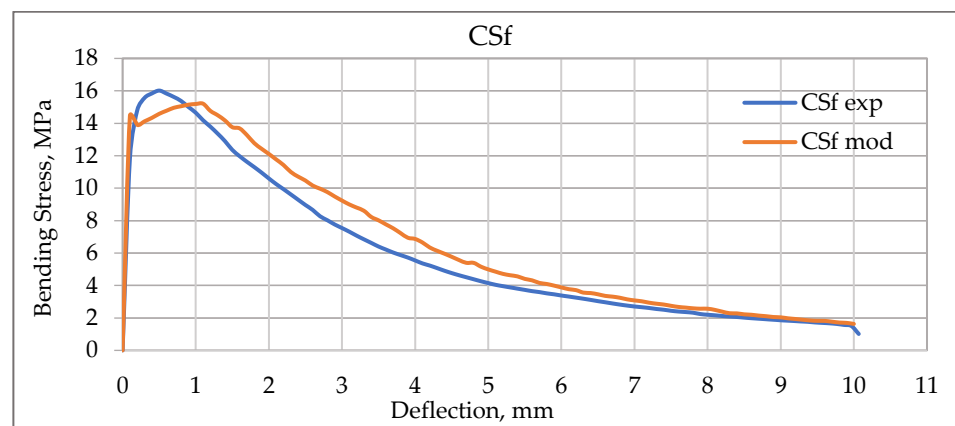


Figure 5. Experimental and modelling data comparison for materials in the group CSf.

Macro-crack growth and stage of concrete aggregates working as “cohesive” elements are absent in the model. Modelling results for FRC of the group CPPfS and the group CPPfD are shown in Figures 6 and 7. Model is “in general” approximating experimental data. At the same time, pull-out data for fibers oriented close to 90° are characterized by short length of pulled out tail. Fibers are not currying load and are breaking, see in Figure 8. After that only part of fibers is currying load.

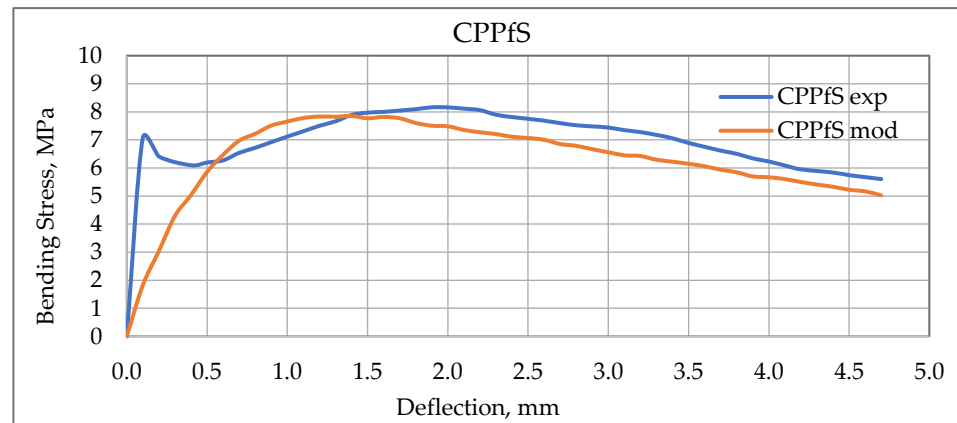


Figure 6. Experimental and modelling data comparison for the group CPPfS.

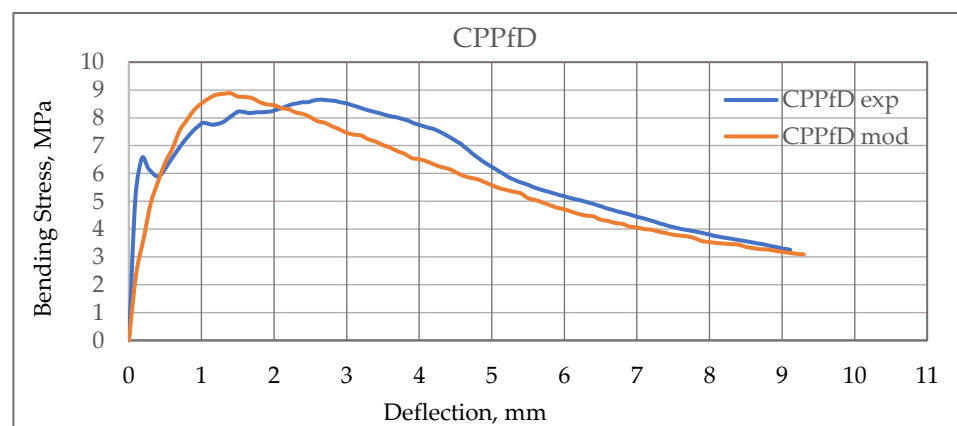


Figure 7. Experimental and modelling data comparison for the group CPPfD.



Figure 8. Crack surface in broken sample CPPfD with Durus PP fibers. Long fiber tails are not pulled out of the concrete, but mainly lifted up. Such fibers were oriented under small angles to the crack surface.

Load bearing mechanisms at initial stage of the curve is different. For the group CPPfD we obtained necessary pull-out curve by back—analysis approach (by minimization difference between modelling and experimental data). Obtained pull-out curves are different from experimentally obtained, see in Figure 9. Here we can conclude—load bearing mechanisms in FRC with PP fibers is more complicated than simple pulling out fibers are bridging the crack. Bigger role is playing fibers oriented under smaller angles than 90° .

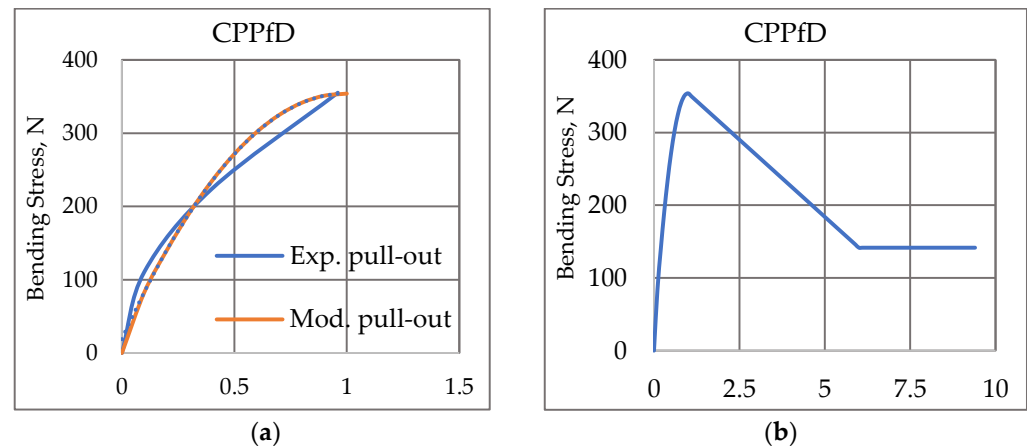


Figure 9. Back analysis. Pull-out curve for single Durus PP fiber: (a) pull-out curve at the stage till the first peak; (b) whole curve.

5. Conclusions

Based on the results presented and discussed in the paper, the following conclusions have been drawn:

1. Macro-crack opening in the concrete with steel fibers is possible to describe by fibers pull-out process. Macro-crack opening in the concrete with polymer (PP) fibers is happening with partial fibers breaking, pulling out of fibers oriented under smaller angles and partial rotation of pulled out fiber part. This not-obvious crack opening mechanism needs additional investigation.
2. The four-point bending tests of FRC prisms allow to analyze and predict load bearing potential of the FRC mix at different stages of damage accumulation in the material. Load bearing capacity of FRC is changing during cracking, along with the increase of the value of deflection of the damaged beam. Cracked beams with opened cracks, with polymer fibers start carrying higher load compared to the samples with the steel fibers.
3. Hooks (or geometry change) on the ends of steel fibers play an important role in ensuring the bending strength.
4. Failure mechanism in FRC with metal and polymer fibres may be different. Comparing them is possible to recognize the micromechanics of processes happening on the stage of crack opening. Steel FRC load bearing on this stage is characterized by intensive fibers, that are bridging the macro-crack, pulling out process. In the situation with FRC having PP fibres Duru's micromechanics of load bearing is different.

Author Contributions: Conceptualization, V.L. and K.K.A.; methodology, V.L. and K.K.A.; validation, K.K.A., V.L., O.K., A.K. (Aleksandrs Korjaks) and A.K. (Andrejs Krasnikovs); formal analysis, K.K.A., V.L., I.L., O.K., A.K. (Aleksandrs Korjaks) and A.K. (Andrejs Krasnikovs); investigation, K.K.A., R.K.K. and V.L.; resources, V.L. and A.K. (Andrejs Krasnikovs); original draft preparation, K.K.A. and V.L.; review and editing, V.L., O.K., I.L., A.K. (Aleksandrs Korjaks) and A.K. (Andrejs Krasnikovs); supervision, V.L. and A.K. (Andrejs Krasnikovs); funding acquisition, R.K.K., V.L. and A.K. (Andrejs Krasnikovs). All authors have read and agreed to the published version of the manuscript.

Funding: This work has been supported by the project Innovation in concrete design for hazardous waste management applications (ICONDE), EEA-RESEARCH-165, financially supported by the European Economic Area (EEA) Grants of Iceland, Liechtenstein and Norway, as well the funder Riga Technical University's (Riga, Latvia) Doctoral Grant program, funding No. DOK.TMMPK/21.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

- Gagg, C.R. Cement and concrete as an engineering material: An historic appraisal and case study analysis. *Eng. Fail. Anal.* **2014**. [\[CrossRef\]](#)
- Jacobs, J.P. (Ed.) *Sustainable Benefits of Concrete Structures*; European Concrete Platform ASBL: Brussels, Belgium, 2009; pp. 2–40.
- Lasenko, I.; Grauda, D.; Butkauskas, D.; Sanchaniya, J.V.; Viluma-Gudmona, A.; Lusiš, V. Testing the Physical and Mechanical Properties of Polyacrylonitrile Nanofibers Reinforced with Succinite and Silicon Dioxide Nanoparticles. *Textiles* **2022**, *2*, 9. [\[CrossRef\]](#)
- Viluma-Gudmona, A.; Lasenko, I.; Vrajlal Sanchaniya, J.; Abdelhadi, B. The amber nano fibers development prospects to expand the capabilities of textile 3D printing in the general process of fabrication methods. In Proceedings of the International Scientific Conference (Latvia), Engineering for Rural Development, Jelgava, Latvia, 26–28 May 2021; pp. 248–257. [\[CrossRef\]](#)
- Grauda, D.; Bumbure, L.; Lyashenko, I.; Katashev, A.; Dekhtyar, Y.; Rashal, I. Amber Particles as Living Plant Cell Markers in Flow Cytometry / Dzintara Daļiņas Kā Dzīvu Augu Šūnu Marķieri Plūsmas Citometrijā. *Proc. Latv. Acad. Sci. Sect. B Nat. Exact. Appl. Sci.* **2015**, *69*, 77–81. [\[CrossRef\]](#)
- Viluma-Gudmona, A.; Lasenko, I.; Sanchaniya, J.V.; Podgornovs, A. Electro-resistant biotextile development based on fiber reinforcement with nano particles. In Proceedings of the International Scientific Conference (Latvia), Engineering for Rural Development, Jelgava, Latvia, 26–28 May 2021; pp. 804–812. [\[CrossRef\]](#)
- Lasenko, I.; Gaidukovs, S.; Rombovska, J. Manufacturing of amber particles suitable for composite fibre melt spinning. *Proc. Latv. Acad. Sci. Sect. B Nat. Exact. Appl. Sci.* **2016**, *70*, 51–57. [\[CrossRef\]](#)
- Corradi, M. Concrete for the construction industry of tomorrow. In *Measuring, Monitoring and Modeling Concrete Properties*; Springer: Dordrecht, The Netherlands, 2007. [\[CrossRef\]](#)
- Sahmenko, G.; Rucevskis, S.; Lusiš, V.; Dembovska, L.; Korjakins, A.; Annamaneni, K.K.; Bajare, D. The study of the combined effect of fly ash, silica fume, colloidal silica and superplasticizer on high performance cement composite applying mix optimization method. *Mech. Compos. Mater.* **2022**, unpublished manuscript.
- Birzniece, I.M.; Cizevska, A.; Goljandin, D.; Lusiš, V. Comparison of Electrical Conductivity of Cement Composite Materials. In Proceedings of the 7th World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium—WMCAUS, Prague, Czech Republic, 5–9 September 2022; pp. 1–10, unpublished work.
- Duy, N.P.; Anh, V.N.; Hiep, D.V.; Anh, N.M.T. Strength of concrete columns reinforced with Glass fiber reinforced polymer. *Mag. Civ. Eng.* **2021**, *101*, 10108. [\[CrossRef\]](#)
- Kulakov, V.L.; Terrasi, G.P.; Arnautov, A.K.; Portnov, G.G.; Kovalov, A.O. Fastening of a High-Strength Composite Rod with a Splitted and Wedged End in a Potted Anchor 2. Finite-Element Analysis. *Mech. Compos. Mater.* **2014**, *50*, 39–50. [\[CrossRef\]](#)
- Kovalovs, A.; Akishin, P.; Chate, A. Detection Prestress Loss in Prestressed Concrete Slab using Modal Analysis. *IOP Conf. Ser. Mater. Sci. Eng.* **2019**, *471*, 102015. [\[CrossRef\]](#)
- Ramanathan, S.; Benzecry, V.; Suraneni, P.; Nanni, A. Condition assessment of concrete and glass fiber reinforced polymer (GFRP) rebar after 18 years of service life. *Case Stud. Constr. Mater.* **2021**, *14*, e00494. [\[CrossRef\]](#)
- Gluhih, S.; Kovalov, A.; Tishkunov, A.; Akishin, P.; Chate, A.; Auzins, E.; Kalnins, M. Identification of the elastic modulus of polymeric materials by using thin-walled cylindrical specimens. *Mech. Compos. Mater.* **2012**, *48*, 57–64. [\[CrossRef\]](#)
- Lusiš, V.; Annamaneni, K.K.; Krasnikovs, A. Concrete Reinforced by Hybrid Mix of Short Fibers under Bending. *Fibers* **2022**, *10*, 11. [\[CrossRef\]](#)
- Ng, T.S.; Nyan, T.S.H. Structural Application of Steel Fibres Reinforced Concrete with and Without Conventional Reinforcement. *New Zeal. Concr. Ind.* **2017**, 3101.
- Abolmaali, A.; Mikhaylova, A.; Wilson, A.; Lundy, J. Performance of steel fiber-reinforced concrete pipes. *Transp. Res. Rec.* **2012**, *1*, 168–177. [\[CrossRef\]](#)
- Lusiš, V.; Harjkova, G.; Macanovskis, A.; Kononova, O.; Krasnikovs, A. Fracture of layered fiberconcrete with non-homogeneous fiber distribution. In Proceedings of the 12th International Scientific Conference on Engineering for Rural Development 2013, Jelgava, Latvia, 23–24 May 2013; pp. 273–277.
- Sikarskas, D.; Antonovič, V.; Malaiškieņē, J.; Boris, R.; Stonys, R.; Šahmenko, G. Modification of the Structure and Properties of Lightweight Cement Composite with PVA Fibers. *Materials* **2021**, *14*, 5983. [\[CrossRef\]](#)

21. Khabaz, A. Analysis of sliding mechanism of straight steel fibers in concrete and determine the effect of friction. *Arch. Civ. Mech. Eng.* **2017**, *17*, 599–608. [\[CrossRef\]](#)
22. Hussain, I.; Ali, B.; Akhtar, T.; Jameel, M.S.; Raza, S.S. Comparison of mechanical properties of concrete and design thickness of pavement with different types of fiber-reinforcements (steel, glass, and polypropylene). *Case Stud. Constr. Mater.* **2020**, *13*, e00429. [\[CrossRef\]](#)
23. Singhal, K.; Mishra, S.; Kumar, B. A study of curling in rib-knit constructions. *J. Text. Inst.* **2021**, *112*, 666–675. [\[CrossRef\]](#)
24. Macanovskis, A.; Lukasenoks, A.; Krasnikovs, A.; Stonys, R.; Lusiš, V. Composite Fibers in Concretes with Various Strengths. *ACI Mater. J.* **2018**, *115*, 647–652. [\[CrossRef\]](#)
25. Sarkar, A.; Hajihosseini, M. The effect of basalt fibre on the mechanical performance of concrete pavement. *Road Mater. Pavement Des.* **2020**, *21*, 1726–1737. [\[CrossRef\]](#)
26. Shanbara, H.K.; Ruddock, F.; Atherton, W. A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibres. *Constr. Build. Mater.* **2018**, *172*, 166–175. [\[CrossRef\]](#)
27. Ali, B.; Qureshi, L.A.; Kurda, R. Environmental and economic benefits of steel, glass, and polypropylene fiber reinforced cement composite application in jointed plain concrete pavement. *Compos. Commun.* **2020**, *22*, 100437. [\[CrossRef\]](#)
28. Benaoum, F.; Khelil, F.; Benhamena, A. Numerical analysis of reinforced concrete beams pre-cracked reinforced by composite materials. *Frat. Integr. Strutt.* **2020**, *14*, 282–296. [\[CrossRef\]](#)
29. Elbehiry, A.; Elnawawy, O.; Kassem, M.; Zaher, A.; Mostafa, M. FEM evaluation of reinforced concrete beams by hybrid and banana fiber bars (BFB). *Case Stud. Constr. Mater.* **2021**, *14*, e00479. [\[CrossRef\]](#)
30. Bleive, L.L.; Lusiš, V. Experimental study and numerical modelling for flexural capacity of FRC structural elements. *Environ. Technol. Resour. Proc. Int. Sci. Pract. Conf.* **2021**, *3*, 30–35. [\[CrossRef\]](#)
31. Krasnikovs, A.; Kononova, O.; Machanovskis, A.; Zaharevskis, V.; Akishins, P.; Rucevskis, S. Characterization of mechanical properties by inverse technique for composite reinforced by knitted fabric. Part 2. Experimental evaluation of mechanical properties by frequency eigenvalues method. *J. Vibroeng.* **2012**, *14*, 691–698.
32. Blazy, J.; Blazy, R.; Drobiec, Ł. Glass Fiber Reinforced Concrete as a Durable and Enhanced Material for Structural and Architectural Elements in Smart City—A Review. *Materials* **2022**, *15*, 2754. [\[CrossRef\]](#)
33. Lasenko, I. Mechanical properties of nanocomposite reinforced with the PA6 electro spun nanofiber. *Multidiscip. Digit. Publ. Inst.* **2022**, unpublished work.
34. Monazami, M.; Gupta, R. Influence of Polypropylene, Carbon and Hybrid Coated Fiber on the Interfacial Microstructure Development of Cementitious Composites. *Fibers* **2021**, *9*, 65. [\[CrossRef\]](#)
35. Blazy, J. Case Studies in Construction Materials Polypropylene fiber reinforced concrete and its application in creating architectural forms of public spaces. *Case Stud. Constr. Mater.* **2021**, *14*. [\[CrossRef\]](#)
36. Acosta-Calderon, S.; Gordillo-Silva, P.; García-Troncoso, N.; Bompá, D.V.; Flores-Rada, J. Comparative Evaluation of Sisal and Polypropylene Fiber Reinforced Concrete Properties. *Fibers* **2022**, *10*, 31. [\[CrossRef\]](#)
37. Lesovik, V.; Fediuk, R.; Amran, M.; Alaskhanov, A.; Volodchenko, A.; Murali, G.; Uvarov, V.; Elistratkin, M. 3D-Printed Mortars with Combined Steel and Polypropylene Fibers. *Fibers* **2021**, *9*, 79. [\[CrossRef\]](#)
38. Tawfik, M.; El-said, A.; Deifalla, A.; Awad, A. Mechanical Properties of Hybrid Steel-Polypropylene Fiber Reinforced High Strength Concrete Exposed to Various Temperatures. *Fibers* **2022**, *10*, 53. [\[CrossRef\]](#)
39. Feng, X.; Gong, B.; Tang, C.; Zhao, T. Study on the non-linear deformation and failure characteristics of EPS concrete based on CT-scanned structure modelling and cloud computing. *Eng. Fract. Mech.* **2022**, *261*, 108214. [\[CrossRef\]](#)
40. Watts, M.J.; Amin, A.; Gilbert, R.I. Time-dependent deformation and cracking behaviour of FRC beams. *Eng. Struct.* **2022**, *268*, 114741. [\[CrossRef\]](#)
41. Zhang, P.; Han, S.; Ng, S.; Wang, X.H. Fiber-Reinforced Concrete with Application in Civil Engineering. *Adv. Civ. Eng.* **2018**, *2018*. [\[CrossRef\]](#)
42. Kasu, S.R.; Mitra, N.; Muppireddy, A.R. Influence of polyester microfiber reinforcement on flexural fatigue characteristics of concrete. *Road Mater. Pavement Des.* **2020**, *22*, 2866–2882. [\[CrossRef\]](#)
43. Annamaneni, K.K.; Dobariya, B.V.; Krasnikovs, A. Concrete, reinforced by carbon fibre composite structure, load bearing capacity during cracking. *Environ. Technol. Resour. Proc. Int. Sci. Pract. Conf.* **2021**, *2*, 232–237. [\[CrossRef\]](#)
44. Herrmann, H.; Goidyk, O.; Braunbrück, A. Influence of the Flow of Self-Compacting Steel Fiber Reinforced Concrete on the Fiber Orientations, a Report on Work in Progress. In *Part of the Advanced Structured Materials Book Series (STRUCTMAT, Volume 95)*; Springer: Cham, Switzerland, 2019; pp. 97–110. [\[CrossRef\]](#)
45. Herrmann, H.; Goidyk, O.; Naar, H.; Tuisk, T.; Braunbrück, A. The influence of fibre orientation in self-compacting concrete on 4-point bending strength. *Proc. Est. Acad. Sci.* **2019**, *68*, 337–346. [\[CrossRef\]](#)
46. Krasnikovs, A.; Zaharevskis, V.; Kononova, O.; Lusiš, V.; Galushchak, A.; Zaleskis, E. Fiber concrete properties control by fibers motion investigation in fresh concrete during casting. In *Proceedings of the 8th International DAAAM Baltic Conference “Industrial engineering”*, Tallinn, Estonia, 19–21 April 2012; pp. 657–662.
47. Bao, C.; Bi, J.H.; Xu, D.; Guan, J.; Cheng, W.X. Numerical simulation of the distribution and orientation of steel fibres in SCC. *Mag. Concr. Res.* **2020**, *72*, 1102–1111. [\[CrossRef\]](#)
48. Herrmann, H.; Braunbrück, A.; Tuisk, T.; Goidyk, O.; Naar, H. An Initial Report on the Effect of the Fiber Orientation on the Fracture Behavior of Steel Fiber Reinforced Self-Compacting Concrete. *Adv. Struct. Mater.* **2019**, *95*, 33–50. [\[CrossRef\]](#)

49. ASTM C618; Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete. American Society of Testing and Materials: West Conshohocken, PA, USA, 2005. [\[CrossRef\]](#)
50. EN 206-1; Concrete-Part 1: Specification, Performance, Production and Conformity. European Committee for Standardization (CEN): Brussel, Belgium, 2000.
51. Properties and Applications of Fiber Reinforced Concrete. *JKAU Eng. Sci* **1410**, 2, 49–63.
52. Criado, M.; Palomo, A.; Fernández-Jiménez, A. Alkali activation of fly ashes. Part 1: Effect of curing conditions on the carbonation of the reaction products. *Fuel* **2005**, *84*, 2048–2054. [\[CrossRef\]](#)
53. Sahmaran, M.; Yurtseven, A.; Ozgur Yaman, I. Workability of hybrid fiber reinforced self-compacting concrete. *Build. Environ.* **2005**, *40*, 1672–1677. [\[CrossRef\]](#)
54. Sonebi, M. Evaluation of the Segregation Resistance of Fresh Self-Compacting Concrete using different test methods. In Proceedings of the SCC'2005-China—1st International Symposium on Design, Performance and Use of Self-Consolidating Concrete, Changsha, China, 26–28 May 2005; RILEM Publications SARL: Marne la Vallée, France, 2005; pp. 301–308. [\[CrossRef\]](#)
55. Ogunbayo, B.; Aigbavboa, C. Experimental Investigation of Concrete Block Walls Compressive Strength Using a Non-destructive Test. In *Collaboration and Integration in Construction, Engineering, Management and Technology*; Springer: Cham, Switzerland, 2021; pp. 393–397. [\[CrossRef\]](#)
56. Kruschwitz, S.; Oesch, T.; Mielentz, F.; Meinel, D.; Spyridis, P. Non-Destructive Multi-Method Assessment of Steel Fiber Orientation in Concrete. *Appl. Sci.* **2022**, *12*, 697. [\[CrossRef\]](#)
57. Mellios, N.; Oesch, T.; Spyridis, P. Finite element modelling of UHPC under pulsating load using X-ray computed tomography based fiber distributions. *Mater. Struct.* **2022**, *55*, 1. [\[CrossRef\]](#)
58. EN 12390-3:2019; Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. European Committee for Standardization: Brussels, Belgium, 2019.
59. LVS 156-1:2017; Concrete. Latvian National Annex to the European Standard EN 206:2013 Concrete. Technical Regulations, Execution of Works, Production and Conformity; Cabinet Regulation No 156 “Procedures for the Market Surveillance of Construction Products”. Latvian Standard: Riga, Latvia, 2017.
60. Zhang, J.; Stang, H.; Li, V.C. Experimental Study on Crack Bridging in FRC under Uniaxial Fatigue Tension. *J. Mater. Civ. Eng.* **2000**, *12*, 66–73. [\[CrossRef\]](#)
61. Sabuncuoglu, B.; Lomov, S.V. Micro-scale numerical study of fiber/matrix debonding in steel fiber composites. *J. Eng. Fibers Fabr.* **2020**, *15*, 1–15. [\[CrossRef\]](#)
62. Mihai, I.C.; Jefferson, A.D.; Lyons, P. Micromechanics based modelling of fibre reinforced cementitious composites. In *Computational Modelling of Concrete Structures*; CRC Press: Boca Raton, FL, USA, 2018; pp. 895–901. [\[CrossRef\]](#)
63. Dehghani, A.; Aslani, F. Effect of 3D, 4D, and 5D hooked-end type and loading rate on the pull-out performance of shape memory alloy fibres embedded in cementitious composites. *Constr. Build. Mater.* **2021**, *273*, 121742. [\[CrossRef\]](#)
64. Kononova, O.; Lusi, V.; Galushchak, A.; Krasnikovs, A.; Macanovskis, A. Numerical modeling of fiber pull-out micromechanics in concrete matrix composites. *J. Vibroeng.* **2012**, *14*, 1852–1861.
65. Lusi, V.; Kononova, O.; Macanovskis, A.; Stonys, R.; Lasenko, I.; Krasnikovs, A. Experimental Investigation and Modelling of the Layered Concrete with Different Concentration of Short Fibers in the Layers. *Fibers Spec. Issue Mech. Fiber Reinf. Cem. Compos.* **2021**, *9*, 76. [\[CrossRef\]](#)