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Fibre-reinforced concrete as an aspect of green construction technology

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Abstract:
This study investigates the effects of the different types and percentages of fibre reinforcements in concrete on structures' design life to advance the phase of the products' use. Clearly, relatively wide cracks in the concrete during the structure's exploitation, using fibre reinforcement, will be transformed into a pattern of fine microcracks. Restricting the width of cracks using fibres in concrete advances the structure's design life, increasing its durability. Moreover, the investigation of the correlation between compressive and tensile strength indicates a significant increase in the tensile strength of fibre-reinforced concrete. The safety factor against failure of fibre-reinforced beams on the shear strength for mixtures with different amounts of fibres increased approximately two times with the growth of content steel fibre from 0,25 to 1,50 %. Concrete with recycled coarse aggregates and fibre reinforcement shows similar strength and ductility properties as concrete with natural aggregates. Using the synergy of positive effects of increased recycled coarse aggregate content, reduced participation of cementitious materials, and improved tensile behaviour by incorporating fibres in the concrete mixture is believed to be an option for green concrete with improved resistance to aggressive environmental influences. Cost-effective and environmentally friendly methods to advance fibre-reinforced concrete sustainability imply increasing the recycled aggregate content and lowering the consumption of cementitious materials with improved behaviour in exploitation.

Keywords:
fibre-reinforced concrete; design life; green technology

1 Introduction

The objective of this study is to investigate how different types and percentages of fibre reinforcements in concrete affect the design life of structures. Fibre incorporation into concrete mixtures began approximately a century ago. Concepts for improving the tensile strength of concrete using different fibres in concrete mixtures have been intensively proposed in recent decades. The effects studied over the last three decades have been presented in a few characteristic references [1-3]. The effects of different types of fibres, such as steel fibres with straight or deformed shapes (twisted, hooked-end, or corrugated), have been examined [4].

In addition to steel fibres, the effects of other types of fibres such as glass, basalt, synthetic fibres (polyvinyl, nylon, polypropylene, and polyethylene), natural fibres (bamboo, palm, banana, and coir), and hybrid combinations of fibres have been tested [2, 3, 5-7]. The physical and mechanical characteristics and content of various fibre types in the mixture, as well as their shape, significantly affect the properties of fresh concrete (rheology and workability) and hardened concrete (microstructure, tensile strength, and compressive strength), as well as the structural properties of concrete structures. [2-5, 8].

Concepts for improving the tensile strength of concrete using different fibres in concrete mixtures are proposed. The effects of steel and synthetic fibres as shear reinforcements in concrete beams without transverse reinforcement but with longitudinal reinforcement are reviewed. In this study, synthetic polymers (aramid, polyethylene, and acrylic) were considered, and it was shown that the ultimate shear strength of beams made of fibre-reinforced concrete improved. While all beams without fibres failed by diagonally tensioned shear, in some cases, this type of sudden failure was prevented using fibres, and the ultimate failure was in flexure.

Over the last few years, a large amount of experimental research has included tests on beams under shear action. Additional studies have proposed the effects of the improved tensile properties of concrete on the shear strength using fibre reinforcements. In recent years, the considerable influence of steel fibres in improving shear resistance has been highlighted [8-13]. Some studies have shown that the shear capacity of beams is affected by the steel fibre volume fraction, based on the reinforcement ratio of the longitudinal and transverse steels [11]. Some explanations related to the increase in shear strength for beams with fibre reinforcement have interpreted this phenomenon as the development of stronger adhesion between the concrete matrix and the steel fibres [9]. The literature concludes that further investigation of shear strength with steel fibre contributions is required, particularly for straight steel fibres [11].

In life cycle assessment (LCA), concrete structures have several typical stages: raw material acquisition, production of concrete and structural components, design and construction, operation and maintenance, repair, refurbishment, demolition, recycling, and waste disposal. The impact of using fibres on the life cycle of each phase can be appreciated from the cost aspect of the individual phase. The goal is to reduce the life cycle cost per unit of construction life and the overall impact on the environment, which is often quantified through the total CO_2 emissions. According to the literature, there are clear indications that using fibres in a mixture can contribute to the extended phase of use of concrete structures. Several authors have highlighted that construction with fibres is characterised by a better ductile behaviour of the tensioned areas after forming the pattern of cracks, lower stresses in the reinforcement at the location of the cracks, and a significantly smaller characteristic width of the cracks [14-16]. This indicated an increase in the design life of the structure.

The use of fibres in concrete production significantly extends the use phase of construction and significantly reduces the costs associated with maintenance, repairs, and renovations. This is a crucial aspect to consider when evaluating the life cycle cost per unit duration of a structure. By enhancing the initial durability and ductility of a structure, fibres can help minimise the requirement for frequent repairs and renovations, thereby reducing the overall cost of the construction life cycle.

The increased cost of the high-performance concrete (HPC) production phase can be compensated for multiple times during the use phase.

The effects of recycled aggregate (RA) on the LCA include several parameters. Life cycle studies are typically adapted to the environmental impact assessment of concrete with natural aggregate (NA) and RA. However, the problem of LCA requires a broader analysis, which includes additional factors. A complete LCA includes mix design, functional requirements, inventory allocation, RA transport distances, and CO_2 uptake. Life cycle analysis refers to a precisely defined construction [16, 17].

Currently, improving the durability and duration of the life cycle of concrete structures is a popular theme. One major advancement in the use of fibre-reinforced concrete is limiting crack openings [4]. Research on fibre-reinforced concrete (FRC) as a green concrete technology is based on its advanced properties and durability.

This study does not intend to cover the entire life cycle of a structure made of RA in the context of sustainability impact analysis. Rather, it discusses options that can lead to progress in sustainability, making concrete greener.

2 Materials and methods

Several analyses based on data from the literature, which are presented below, show the influence of fibres on the mechanical and deformation characteristics of concrete. An additional analysis of these parameters, which are directly related to the durability and cost-effectiveness of the structures, was performed.

Currently, different types of fibres are available on the market, and the most widely analysed are steel, glass, and polypropylene fibres. Recently, natural fibres from agricultural waste have been used experimentally [6]. According to previous research, fibre efficiency is mainly based on the nature of the material, geometry, and mechanical properties; however, fibre combination effects should be considered [7]. Two investigations on the effects of steel fibres on the mechanical properties of concrete were conducted using straight short fibres (with tensile strengths of 2200 [5] and 2500 MPa [18]) and fibres with hooked ends (tensile strength of 2300 MPa). Fibres were added at different dosages (0,6-1,5 % and 2-5 % by volume). The mechanical properties and compressive, flexural, and splitting strengths of plain concrete and concrete with fibres were compared. The investigations comprised different mix designs for concrete with normal strength (NSC), high strength (HSC), and ultra-high-performance concrete (UHPC). The properties of frequently used fibre samples are listed in Table 1.

Table 1. The main properties of fibres presented through the research

ID	Type of fibre	l (mm)	d (mm)	Aspect ratio l/d	Tensile strength (N/mm^2)	Elastic modulus (GPa)
1	Steel SF - straight short	13	0,2	65	2200-2500	200
2	Steel SF - hooked ends	35-62	0,9	39-68	1200-2300	200
3	Glass fibre GF	6-18	0,015	400-1200	> 1700	72
4	Polypropylene PP-macro	30-65	0,5-1,0	60-65	400-750	5-12
5	Polypropylene PP-micro	6-19	0,018–0,300	63-333	300-450	3,5-7,0
6	Chopped banana fiber	40	1	40	-	9-16

The effect of fibres on the strength of concrete pavement structures is represented by their design thickness. The thickness of plain concrete pavement was compared to the thickness of pavement made of concrete with fibres in the three concrete mixtures, each with a 1 % volume fraction of hooked-end steel, polypropylene fibre, or glass fibres. These concretes were exposed to different traffic loads in the concrete pavement to investigate the effects of fibre reinforcement on their mechanical properties. The investigated mechanical properties were used to design a concrete pavement, and its thickness was evaluated under the same traffic loading conditions [2]. Two types of fibres were tested for compressive strength and splitting tensile strength to determine the optimal ratio of fibre composition in concrete reinforced with hybrid fibres [19].

The further development of ordinary concrete (OC) structures is limited owing to the high demand for NAs, the exploitation of which seriously damages the natural environment. The reduction in the aggregate content in concrete, as well as the size of the grains, leads to the use of excessive cement in the concrete mixture, resulting in a higher carbon footprint. Cement concrete exhibits poor performance under tension, and the appearance of cracks in concrete causes sensitivity to environmental attacks and shortens the design life of concrete structures. An advanced solution to these issues is to increase the resistance of concrete by incorporating fibres and reducing the use of NAs and RAs in concrete.

Research has shown the influence of fibres on the mechanical resistance of concrete with RA and durability performance. The three types of concrete mixes with 0 % recycled coarse aggregate (RCA), 50 % RCA, and 100 % RCA were used to investigate glass fibre effects in the concrete [3]. The mechanical properties of RA concrete (RAC) were evaluated based on compressive strength, splitting tensile strength, shear strength, and flexural strength. An artificial neural network (ANN) model was used to analyse the shear strength of 231 beams. The parameters include the RA content, shear span-depth ratio, compressive strength of the concrete, longitudinal reinforcement percentage, and width and depth of the beam [20]. In another study of 252 concrete specimens made with RAC, the stress-strain, initiation, and propagation of fibre-reinforced concrete cracks with sea sand and RA were analysed [21].

The results in [22] indicated that the replacement RA effect in concrete was significant. Consequently, a database of investigations of the shear strength of 264 beams with RA, of which 206 comprised beams without shear reinforcement, was included in this analysis. The main statistical parameters were compared based on the derived values of the nominal shear strength provided by the concrete for the tested beams and the designed shear resistance of the concrete sections based on EN 1992-1-1.

Numerous studies have demonstrated that the addition of steel fibres increases the shear strength of reinforced concrete beams [23].

This study used extensive experimental data for testing steel-fibre-reinforced concrete (SFRC) beams without shear reinforcement to analyse the probability of cracks appearing in correlation with the increase in shear strength as a design life parameter. The applied database comprised 487 results of testing the shear strength of SFRC beams without shear reinforcement (SR) collected in [9] against the results for 209 beams of plain reinforced concrete (PRC) with SR (155 beams) and without SR (54 beams), collected in [24]. Details of the collected data can be found in the literature.

The analysis was based on the ratio between the ultimate shear force in the test and the design shear strength according to EN 1992-1-1. The results were expressed as the safety factor of the shear stress peak measured load versus the designed values of shear stress and shear strength to the compressive strength ratio of the concrete. Probability distribution functions (PDF) for the aforementioned ratios were derived, and the values were compared for concrete reinforced with steel fibre (SFRC), plain concrete with and without shear reinforcement, and concrete with RA. The effects of the fibre reinforcement content of the concrete on the shear strength normalised by the design shear strength are illustrated in the diagrams.

3 Results

Most of the test results showed that the flexural strength of concrete increased three-to four-fold, whereas splitting tensile strength increased 2,5 fold owing to adding 1,0-1,5 % hooked-end steel fibres, Figure 1. Simultaneously, compressive strength has a moderate change in value, increasing between 3 % and 8 % [5]. However, in [18], researchers discovered that adding up to 5% fibre could increase the compressive strength of concrete up to 25 % measured on a cube 50 mm for ultra-high-performance fibre-reinforced concrete (UHPFRC).

A previous study [25] investigated the effects of polypropylene fibre volume fraction in concrete on the flexural bearing capacity, failure mode, crack development, and ductility of polypropylene FRC beams. The results showed an increase in the cracking moment of beams by 7,6 % when the volume fraction of fibres increased from 0,0-0,4 %, the flexural bearing capacity increased by 6,9 %, and the ductility index increased by 21,4 %. It was also shown that the addition of polypropylene fibres significantly reduced the crack width and spacing.

In [12], research showed that the presence of fibres in a concrete mix in the range of 0,5-2,0 % by volume clearly increased the shear capacity of the beams. The trend is clearly expressed for slender beams with a relatively high shear-to-span ratio ≥ 3. The correlation matrix formed in [12] between various influencing parameters also showed that, after the section height (correlation factor of 0.53) and section width (correlation factor of 0,43), the percentage of fibres had the strongest influence on the beam shear capacity (correlation factor of 0,37). The concrete compressive strength was the weakest influencing parameter, with a correlation coefficient of 0,00029. It should be noted that the model was applied to UHPC with a compressive strength in the range of 100-205 N/mm^2.

The results in [13, 26] showed that a 1,27 % fibre volume fraction could replace the transverse reinforcement. They also showed that combining steel fibres with longitudinal reinforcement was an option for achieving better resistance under bending.

Straight, short steel fibres were less effective than hooked-end fibres, particularly at increasing flexural strength. By adding short fibres with a content of 0,6-1,5 %, flexural strength increased by 46-74 %, and splitting tensile strength increased by 40-97 %, as shown in Figure 1. In addition, some research has discovered increases in flexural tensile strength (up to 107 %) and shear strength (up to 260 %) with increases in fibre from 2-5 % [18].

Regarding investigations of the effects of RA, the failure mode of beams of concrete with RA (RACC) and the crack pattern of the beams were similar to those of beams with natural coarse aggregate concrete (NCAC) [3]. The tensile strength-to-compressive strength ratio of concrete with RA and polyethylene fibre (PFRCAC) increased with increasing fibre content. It had an average of 0,091, which was slightly higher than those of RACC and steel fibre reinforced (SFRACC), which were 0,085 and 0,089, respectively. The fibres slightly changed the initiation and distribution of cracks. The crack propagation and high-value strain of sea-sand RAC (SSRAC) greatly vary with the fibre type and their content variations [21]. The addition of steel fibres to RAC improves its structural properties. In [27], a cost-effectiveness analysis of the optimum combination of fibres and RA was performed and compared with the fibre and NA combination. The optimum combination was determined using an experimental study of beams, while a cost-benefit analysis revealed the direct and indirect costs and benefits of the RA.

Experimental research on the nine beams with combinations of 0; 30; and 100 % RA and with 0 %; 0,3%; and 0,6 % steel fibres (SF) showed that the optimum combination was 30 % RA with 0,6 % steel fibre [27]. All the tested beams without fibres produced the most propagated and widespread cracks, regardless of the NA or RA. Beams with 30 % RA and 0,6 % SF exhibited significantly less cracking and less cracking propagation. It was shown that 30 % replacement NA with RA in combination with 0,6 % SF was the best replacement ratio in the studied sample.

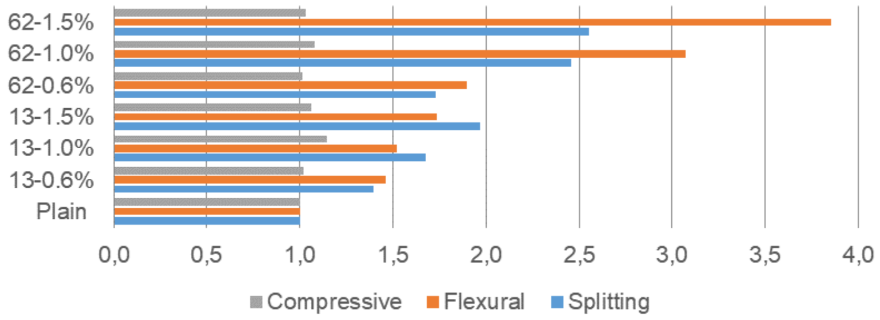


Figure 1. Effects of steel fibres (13 mm - straight and 62 mm - hooked)

In this study, based on the collected shear test data provided in [9], a database of the test results of 487 fibre-reinforced beams without stirrups was established. The safety factor was analysed based on the relationship between the nominal test strength and the designed shear strength of the beams. Figure 2 shows the relationship between the shear strength of SFRC beams and the steel fibre content of beams without shear reinforcement.

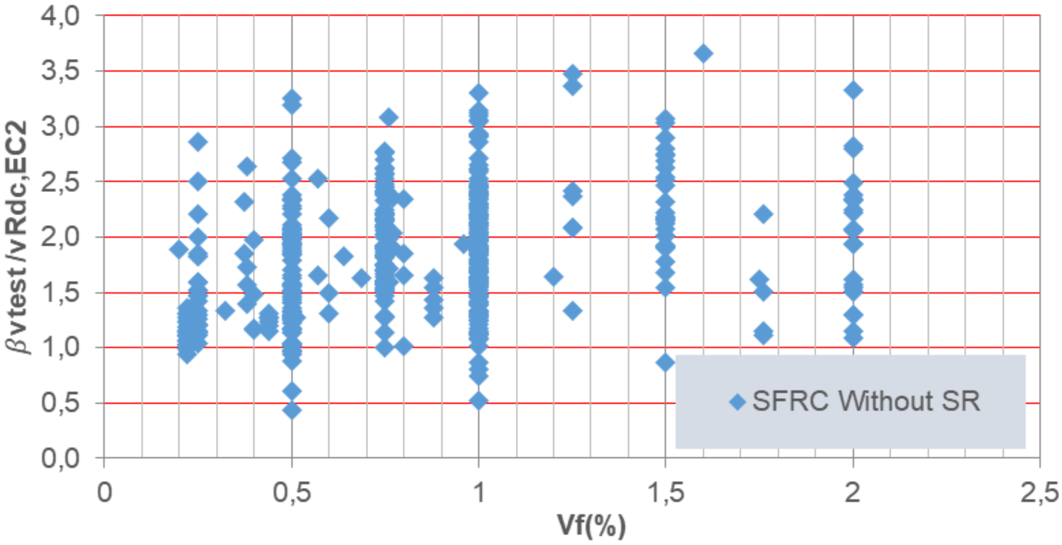


Figure 2. Effects of steel fiber content (Vf) on the shear strength

The normalised test results of the shear strength for the provided specimen of beams without shear reinforcement (ρ_v=0) were compared with the designed shear strength ($v_{Rdc,EC2}$), which included all influential factors based on the EC2 (longitudinal reinforcement ratio, shear-span-to-depth ratio, compressive strength of concrete, and depth of the beam). A correction factor $\beta = a_v/2d$ if $a_v/d \ngtr 2$ to calculate the influence of the proximity of the support in accordance with EC2 was included by reducing the shear test capacity. An increase in the safety factor was observed with increasing fibre content. The mean value of the beam shear strength safety factor, expressed through a ratio of nominal shear stress measured in testing to design shear strength, increased approximately two times with the growth of content steel fibre from 0,25 to 1,50 % per volume.

Figure 3 shows the nominal shear strength from the test versus the design shear strength for SFRC and plain concrete beams, which is defined as the safety ratio. The mean safety ratio of the SFRC beams was significantly higher than that of the safety ratio for ordinary concrete beams. The prediction of the shear strength of plain concrete beams based on the EC2 rules indicates lower safety for beams with lower shear strength values. This is primarily related to beams with high shear-to-span ratios and slenderness. The increase in the compressive strength of plain concrete has no significant effect on the shear strength of slender beams because the tensile strength has a key effect. However, it remains relatively low, although the compressive strength increases. By adding steel fibres to concrete, the tensile and shear strengths of the concrete increase, although the increase in compressive strength may be moderate.

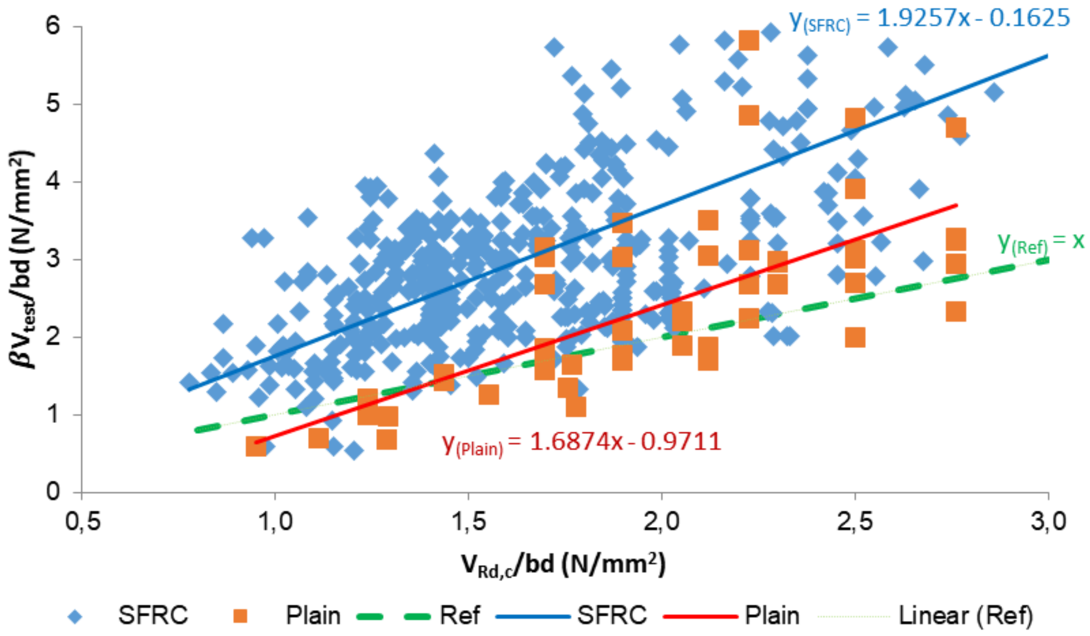


Figure 3. The nominal shear strength versus the design shear strength for SFRC and plain concrete beams

Table 2 lists the values of the average safety factor, unbiased estimation of standard deviation, variance, and characteristic value, with 5 % of expected values below this value for the nominal shear strength of concrete beams. The beams of SFRC without shear reinforcement (ρ_v = 0) reach the level of shear resistance of NCAC beams with shear reinforcement (ρ_v > 0). This was confirmed by comparing the average safety factors for all 487 tested beams with SFRC without shear reinforcement (X1 = 1,832), NCAC beams with shear reinforcement (X1 = 1,880), and RACC beams with shear reinforcement (X1 = 1,864). In addition, a comparison of the average safety factors for the NCAC and RACC beams, all without shear reinforcement, amounted to X1 = 1,165 for NCAC and X1 = 1,242 for RACC, which confirmed the equality of natural and RAs in the shear strength of concrete.

Table 2. The probability analysis of test results of the beam's shear strength

Type	SR	f_{ck} (MPa)	N	X1 ($\gamma=\beta v_{test}/v_{Rdc}$)			X2($\beta v_{test}/f_{ck}$)			$X_{char,5\%}$	
				AV	STD	COV	AV	STD	COV	X1	X2
SFRC	ρ_v=0	> 50	169	1,892	0,590	31,2	0,054	0,021	38,9	0,948	0,020
		< 50	318	1,791	0,532	29,7	0,077	0,024	31,3	0,939	0,038
		All	487	1,832	0,553	30,2	0,069	0,025	36,6	0,947	0,029
NCAC	ρ_v>0	> 50	102	1,841	0,452	24,5	0,052	0,020	39,0	1,118	0,020
		< 50	53	1,954	0,684	35,0	0,085	0,042	49,7	0,860	0,017
		All	155	1,880	0,543	28,9	0,064	0,034	52,8	1,011	0,010
	ρ_v=0	> 50	54	1,165	0,430	37,0	0,036	0,019	53,3	0,476	0,005
RACC	ρ_v=0	< 50	206	1,242	0,578	46,5	0,047	0,024	50,8	0,317	0,009
	ρ_v>0	< 50	58	1,864	0,623	33,4	0,086	0,033	38,5	0,867	0,033

Further value analysis was performed using PDF. The safety factor is the ratio of the test and design calculated values, marked X1, whereas the nominal value of the tensile strength from the shear test results is shown in correlation with the compressive strength of concrete, marked X2. Using this method, it is possible to define the characteristic values of variables X1 and X2 with a certain probability of the occurrence of a result with a value lower than the characteristic value.

Figure 4 shows the empirical cumulative distribution function (CDF) of the design shear strength safety factor, where the nominal shear strength was calculated based on EN1992 for different concrete types. The CDF value for the measured variable is the part of all results that are less than or equal to the observed value. Consequently, the values in the diagram indicate the probability that the shear-strength design safety factor will be less than a certain value. This factor for the SFRC beams without shear reinforcement was nearly equal to that for the plain concrete beams with shear reinforcement.

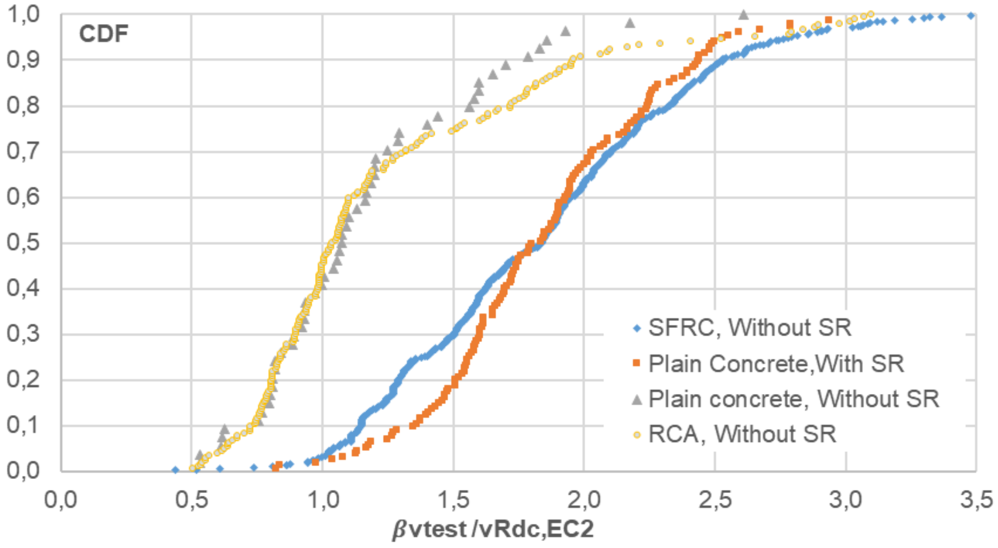


Figure 4. CDF of test results versus design shear strength of concrete for SFRC and plain NCAC and RACC with and without SR

Figure 5 shows the CDF for the test results of the shear strength versus compressive strength of concrete for SFRC beams and plain NCAC and RACC beams with and without shear reinforcement. This ratio represents a measure of the shear tension behaviour in correlation with the compressive strength. The results show significantly better values of this ratio for SFRC beams than others, and even better than plain concrete beams with shear reinforcement. It is characteristic that RCAC beams have better results than NCAC beams without shear reinforcement.

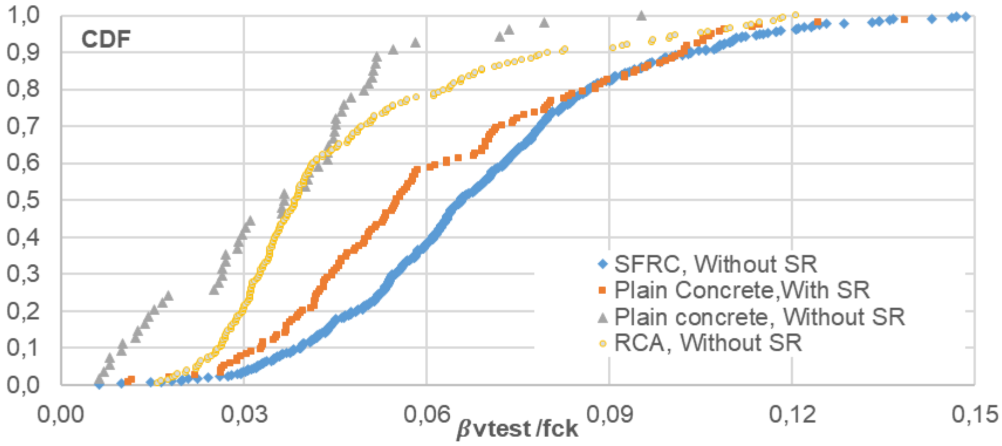


Figure 5. CDF of test results versus compressive strength of concrete for SFRC and plain NCAC and RACC with and without SR

4 Discussion

This study provides an overview of the various aspects of using fibres in concrete and their synergy with the beneficial effects of RA on the economic, ecological, and constructive indicators of reinforced concrete structures. The use of fibres in concrete in combination with RA can provide multiple benefits that overcome the individual disadvantages. Numerous tests have confirmed the advantages of concrete with fibres in terms of basic durability parameters, such as limited cracks owing to increased flexural and splitting tensile strengths and ductility.

The fibres may increase the shear strength of the beams, particularly the correlation factor between the nominal shear and compressive strengths. The tension properties of concrete with RAs do not fall behind, or even lead, those of concrete with NAs of the same compressive strength.

Considering the distribution of the transfer shear force between the concrete and steel in both types of concrete, it is clear that the bridging of cracking by the numerous fibres provides uniformity and lower stresses in the steel than in the cross-section of the stirrups. This caused new cracking patterns without localised, individual, or relatively wide cracks. The concrete with recycled coarse aggregates exhibited similar results with respect to the shear strength of the concrete with NAs.

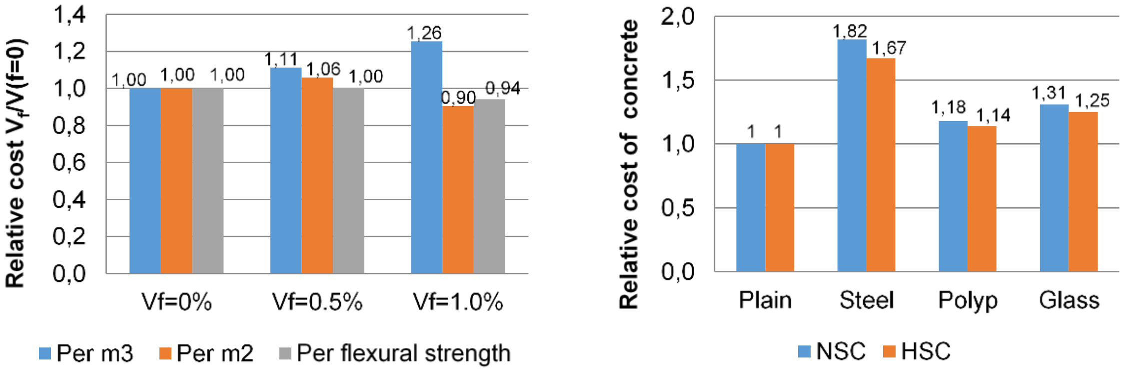
The effects of combining different fibres are options for new advantages in the properties and durability of concrete. The combination of the two types of fibres was investigated to determine the optimal composition of fibres in concrete and obtain better properties. Steel compositions with any other fibres have better properties than other combinations without steel fibres. The use of glass fibres with steel fibres provided better tensile strength than the combination of steel fibres with polypropylene.

However, the polypropylene fibre effect was characterised by reduced plastic shrinkage and cracks on concrete surfaces. Results of several studies showed a significant crack limitation, with the addition of 0,10-0,50% of fibres limiting cracks up to 99 % [19].

The results showed that the effects of polypropylene macro- and microfiber composition were directed towards increasing tensile strength by the microfibres bridging microcracks and macrofibres, increasing ductility by the influence on macrocracks. Shrinkage crack limitation was a significant instrumentality for corrosion and sulphate attack reduction, which is beneficial for the sustainable development and extension of structural life.

The production of PPF emitted 30 % less CO_2 than the production of steel fibres and 9% less than the production of glass fibres.

An analysis of the influence of the incorporation of 1 % steel, polypropylene, and glass fibres showed that the thickness of concrete pavement may be reduced by 35 %, 18 %, and 23 %, respectively [2].



a) b)

Figure 6. Effect of different PPF content and different types of fibres on the cost

Fibre reinforcement in concrete increases the cost per m^3 by adding fibres and superplasticisers. However, the beneficial effects of fibres on the load-bearing capacity, as well as the reduced dimensions of the structural elements, led to a decrease in the cost measured by the surface of the structure and bending capacity, as shown in Figure 6.

Different densities of fibre materials result in different final costs per cubic meter of concrete. Polypropylene fibres had the lowest density, whereas steel fibres had the highest density. For a 1 % content of fibres in concrete, 9 kg of polypropylene fibres were required instead of 78 kg of steel or 26 kg of glass fibres, as shown in Figure 6b.

It can be observed that by increasing the fibre content in concrete, despite the increase in the price per m^3 of concrete, the relative cost per m^2 of the structure and flexural strength decreased. It is essential to note that high-performance concrete showed better initial cost price parameters compared to normal-strength concrete. A higher initial cost of concrete with fibres was more acceptable for high-performance concrete. The significant benefits of the durability of HPC structures, combined with the potential reduction in the use of natural raw materials for aggregates, fillers, and active pozzolanic materials, compensate for the initial cost of fibres in concrete. In addition, the significant use of recycled materials, mainly from demolition concrete made with a low water-to-cement ratio, reduced the use of pure Portland cement in ultra-high-performance concrete mixes. In particular, RAs from UHPC with a low water-to-cement ratio, which had a significant amount of dehydrated cement particles, exhibited supplementary pozzolanic activity in the presence of materials for activation [30].

The results from [27] illustrate the importance of steel fibres in improving the strength, ductility, and stiffness of RA concrete. The cost-benefit analysis showed that the savings from replacing NA with recycled were nearly 2,5 times higher than the cost increase owing to steel fibre addition. These results confirmed that the additional cost increase of using steel fibres could be offset by the significant cost reduction and benefits of replacing NA with RA.

5 Conclusions

This study aims to assess the effects of different types and contents of fibre reinforcements in concrete on the design life of structures as a potential parameter for life cycle efficiency.

Based on numerous investigations, fibres have been confirmed as an essential factor influencing the rheological and mechanical characteristics of concrete.

The shear strength of beams is frequently examined owing to several influencing factors. Fibre reinforcement may increase the shear strength of concrete and reduce the requirement for additional shear reinforcement while reducing shear cracks.

Research has shown that fibres in concrete improve the shear resistance of concrete sections. The safety factor expressed through a ratio of nominal shear stress measured in testing to design shear strength increased approximately twofold with an increase in the steel fibre content from 0,25-1,50 % per volume.

Improvements in the concrete design life are based on increasing the tensile strength and avoiding the appearance of cracks in less-loaded structures.

However, investigations showed that concrete with a higher ratio of RA content did not decrease the tensile and shear strengths.

There are clear indications that measures to reduce the carbon footprint are more favourable for RA concrete than for natural coarse aggregate concrete if a higher coarse aggregate content and less cementitious binder are considered in recycled coarse aggregate concrete.

Concrete made with recycled coarse aggregates and with a reduced participation of cementitious materials is an option for green concrete with improved resistance to aggressive environmental influences. This resistance can be improved by delaying the occurrence and reducing the width of cracks by using fibres in the concrete mixture.

These may be crucial factors for characterising fibre-reinforced concrete as green concrete. Cost-effective and environmentally friendly methods to advance the sustainability of fibre-reinforced concrete involve increasing the RA content and lowering the consumption of cementitious materials, with improvements in the tensile behaviour using fibres.

Abbreviations

ANN – Artificial Neural Network
CDF – Cumulative Distribution Function
HSC – High Strength Concrete
NCA – Natural Coarse Aggregate
NCAC – Natural Coarse Aggregate Concrete
NSC – Normal Strength Concrete
OC – Ordinary Concrete
PFRCAC – Polyethylene Fibre Recycled Coarse Aggregate Concrete
PPF – Polypropylene Fibre
PRC – Plain Reinforced Concrete
RA – Recycled Aggregate
RAC – Recycled Aggregate Concrete
RCA – Recycled Coarse Aggregate
SFRC – Steel Fibre Reinforced Concrete
SR – Shear Reinforcement
UHPC – Ultra High-Performance Concrete
UHPFRC – Ultra High-Performance Fibre Reinforced Concrete

References

[1] Li, V. C.; Ward, R.; Hamza, A. M. Steel and Synthetic Fibers as Shear Reinforcement. *ACI Materials Journal*, 1992, 89 (5), pp. 499-508.

[2] Hussain, I. et al. Comparison of mechanical properties of concrete and design thickness of pavement with different types of fiber-reinforcements (steel, glass, and polypropylene). *Case Studies in Construction Materials*, 2020, 13, e00429. https://doi.org/10.1016/j.cscm.2020.e00429

[3] Ali, B.; Qureshi L. A. Influence of glass fibers on mechanical and durability performance of concrete with recycled aggregates. *Construction and Building Materials*, 2019, 228, 116783. https://doi.org/10.1016/j.conbuildmat.2019.116783

[4] Jiang, Y. et al. Comparison of the Mechanical Properties and Crack Expansion Mechanism of Different Content and Shapes of Brass-Coated Steel Fiber-Reinforced Ultra-High-Performance Concrete. *Materials*, 2023, 16 (6), 2257. https://doi.org/10.3390/ma16062257

[5] Marcalikova, Z.; Racek, M.; Mateckova, P.; Cajka, R. Comparison of tensile strength fiber reinforced concrete with different types of fibers. *Procedia Structural Integrity*, 2020, 28, pp. 950-956. https://doi.org/10.1016/j.prostr.2020.11.068

[6] Rajkohila, A.; Prakash Chandar, S.; Ravichandran, P. T. Influence of Natural Fiber Derived from Agricultural Waste on Durability and Micro-Morphological Analysis of High-Strength Concrete. *Buildings*, 2023, 13 (7), 1667. https://doi.org/10.3390/buildings13071667

[7] Ravichandran, D. et al. Influence of fibers on fresh and hardened properties of Ultra High Performance Concrete (UHPC) – A review. *Journal of Building Engineering*, 2022, 57, 104922. https://doi.org/10.1016/j.jobe.2022.104922

[8] Sucharda, O.; Marcalikova, Z.; Gandel, R. Microstructure, Shrinkage, and Mechanical Properties of Concrete with Fibers and Experiments of Reinforced Concrete Beams without Shear Reinforcement. *Materials*, 2022, 15 (16), 5707. https://doi.org/10.3390/ma15165707

[9] Tariq, M. et al. Improved Shear Strength Prediction Model of Steel Fiber Reinforced Concrete Beams by Adopting Gene Expression Programming. *Materials*, 2022, 15 (11), 3758. https://doi.org/10.3390/ma15113758

[10] Marcalikova, Z.; Mateckova, P.; Racek, M.; Bujdos, D. Study on Shear Behavior of Steel Fiber Reinforced Concrete Small Beams. *Procedia Structural Integrity*, 2020, 28, 957-963. https://doi.org/10.1016/j.prostr.2020.11.069

[11] Frank, T. et al. Comparison of Steel Fibers and Transverse Steel Reinforcement for Shear Capacity in Reinforced Ultra High Performance Concrete Beams, In: *Third International Interactive Symposium on Ultra-High Performance Concrete*. June 4-7, 2023, Delaware, USA, Iowa State University Digital Press; 2023, 3 (1), 47. https://doi.org/10.21838/uhpc.16670

[12] Huang, Y.; Yao, G. Shear Strength of Ultra-High-Performance Concrete Beams without Stirrups – A Review Based on a Database. *Buildings*, 2024, 14 (5), 1212. https://doi.org/10.3390/buildings14051212

[13] Shende, A. M. et al. Global performance indicator (GPI) approach to predict the steel fiber reinforced concrete strength with error analysis. *HBRC Journal*, 2024, 20 (1), pp. 123-137. https://doi.org/10.1080/16874048.2024.2305067

[14] Hájek, P.; Fiala, C.; Kynčlová, M. Life cycle assessments of concrete structures - A step towards environmental savings. *Structural Concrete*, 2011, 12 (1), pp. 13-22. https://doi.org/10.1002/suco.201000026

[15] Valente, R.; Pimentel, M. Fibre reinforced concrete under in-plane shear stresses. *Engineering Structures*, 2024, 307, 117890. https://doi.org/10.1016/j.engstruct.2024.117890

[16] Mishra, O.; Singh, S. P. An overview of microstructural and material properties of ultra-high-performance concrete. *Journal of Sustainable Cement-Based Materials*, 2019, 8 (2), pp. 97-143. https://doi.org/10.1080/21650373.2018.1564398

[17] Zhang, Y. et al. A review of life cycle assessment of recycled aggregate concrete. *Construction and Building Materials*, 2019, 209, pp. 115-125. https://doi.org/10.1016/j.conbuildmat.2019.03.078

[18] Kazemi S.; Lubell A. S. Influence of Specimen Size and Fiber Content on Mechanical Properties of Ultra-High-Performance Fiber-Reinforced Concrete. *ACI Materials Journal*, 2012, 109 (6), pp. 675-684.

[19] Blazy, J.; Blazy, R. Polypropylene fiber reinforced concrete and its application in creating architectural forms of public spaces. *Case Studies in Construction Materials*, 2021, 14, e00549. https://doi.org/10.1016/j.cscm.2021.e00549

[20] Ababneh, A.; Alhassan, M.; Abu-Haifa, M. Predicting the contribution of recycled aggregate concrete to the shear capacity of beams without transverse reinforcement using artificial neural networks. *Case Studies in Construction Materials*, 2020, 13, e00414. https://doi.org/10.1016/j.cscm.2020.e00414

[21] Huang, Y. et al. Mechanical properties of fibre reinforced seawater sea-sand recycled aggregate concrete under axial compression. *Construction Building Materials*, 2022, 331, 127338. https://doi.org/10.1016/j.conbuildmat.2022.127338

[22] Yu, Y. et al. Machine Learning-Based Evaluation of Shear Capacity of Recycled Aggregate Concrete Beams. *Materials*, 2020, 13 (20), 4552. https://doi.org/10.3390/ma13204552

[23] Almasabha, G. et al. Sustainability of Using Steel Fibers in Reinforced Concrete Deep Beams without Stirrups. *Sustainability*, 2023, 15 (6), 4721. https://doi.org/10.3390/su15064721

[24] Sinđić Grebović, R. The effects of high strength of concrete to shear resistance of reinforced concrete beams. [doctoral thesis], University of Montenegro, Faculty of Civil Engineering, Podgorica, Montenegro, 2009. Accessed: September 30, 2024. Available at: http://eteze.ucg.ac.me

[25] Wei, B., et al. Research on the flexural behavior of polypropylene fiber reinforced concrete beams with hybrid reinforcement of GFRP and steel bars. *Materials and Structures*, 2024, 57 (66). https://doi.org/10.1617/s11527-024-02343-9

[26] Bui, T. T. et al. Shear Performance of Steel Fiber Reinforced Concrete Beams Without Stirrups: Experimental Investigation. *International Journal of Civil Engineering*, 2020, 18, pp. 865-881. https://doi.org/10.1007/s40999-020-00505-8

[27] Senaratne, S. et al. The costs and benefits of combining recycled aggregate with steel fibres as a sustainable, structural material. *Journal of Cleaner Production*, 2016, 112 (4), pp. 2318-2327. http://dx.doi.org/10.1016/j.jclepro.2015.10.041

[28] Kwon, S. et al. Strain Softening of High-Performance Fiber-Reinforced Cementitious Composites in Uniaxial Compression. *International Journal of Concrete Structures and Materials*, 2024, 18 (17), pp. 1-15. https://doi.org/10.1186/s40069-023-00658-5

[29] Zheng, Y.; Zhang, Y.; Zhang, P. Methods for improving the durability of recycled aggregate concrete: A review. *Journal of Materials Research and Technology*, 2021, 15, pp. 6367-6386. https://doi.org/10.1016/j.jmrt.2021.11.085

[30] Hosseinzadehfard, E.; Mobaraki, B. Investigating concrete durability: The impact of natural pozzolan as a partial substitute for microsilica in concrete mixtures. *Construction and Building Materials*, 2024, 419, 135491. https://doi.org/10.1016/j.conbuildmat.2024.135491