

FIBER-REINFORCED CONCRETE AS AN ASPECT OF GREEN CONSTRUCTION TECHNOLOGY

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Abstract: This paper investigates the effects of the different types and percentages of fiber reinforcements in concrete on structures' design life. The primary parameter of the analysis is the tensile strength of concrete in correlation with compressive strength in dependence on the type and quantity of fibers. Using fiber reinforcement allows obtaining a pattern of evenly distributed micro-cracks instead of the usual system of localized individual relative wide cracks and increases the durability of structures. The durability of concrete is evaluated from the probability of the appearance of cracks through a comparative analysis of the results of experimental tests for mixtures with different types and amounts of fibers. The subject of the analysis is also a mixture of concrete made by increasing the coarse aggregate from recycled materials content and lower consumption of cementitious materials as a green concrete option with improved resistance to aggressive environmental influences. The main goal is to assess fiber-reinforced concrete (FRC) as cost-effective and green by increasing the recycled aggregate content and lowering the consumption of cementitious materials. A comparative analysis of results gained by statistical and machine learning methods is performed for the influential parameters' assessment of the FRC structures' design life.

Keywords: fiber-reinforced concrete; design life; durability; green technology

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1. INTRODUCTION

The paper's theme is investigating how different types and percentages of fiber reinforcements in concrete affect structures' design life. Fiber incorporation in up-to-date concrete mixtures began about 100 years ago. The ideas on improving the tensile strength of concrete using different fibers in the concrete mixture were intensively presented in the last decades. The experience of effects studied in the last three decades was presented through a few characteristic references (Li et al. 1992; Hussain et al. 2020; Ali et al. 2019). The impact of different types of fibers, such as steel fibers with straight or deformed shapes (twisted, hooked-end, and corrugated), was examined.

Besides steel fibers, the effects of the other types of fibers, such as glass, basalt, and synthetic fibers (polyvinyl, nylon, polypropylene, polyethylene), natural fibers (bamboo, palm, banana, coir), and a hybrid combination of fibers, were tested.

The ideas on improving the tensile strength of concrete using different fibers in the concrete mixture were presented. It reviewed the effects of steel and synthetic fibers as shear reinforcements in concrete beams without transverse but with longitudinal reinforcement. In this investigation, synthetic polymers (aramid, polyethylene, acrylic) were considered, and it showed that the ultimate shear strength of beams made by fiber-reinforced concrete has improved. While all beams without fibers failed by diagonal-tensioned shear, in some cases, this type of sudden failure was prevented by using fibers, and the ultimate failure was in flexure.

Later, more papers presented the effects of improved tensile properties of concrete on shear strength using fiber reinforcements. In recent years the particularly large influence of steel fibers on improving shear resistance has been highlighted (Tariq et al. 2021; Marcalikova et al. 2020; Sucharda et al. 2022). Some research has shown that the shear capacity of beams is affected by the steel fiber volume fraction, depending on the reinforcement ratio of longitudinal steel and transverse steel (Timothy et al. 2023). Some explanations related to the increase in shear strength for beams with fiber reinforcement have interpreted this phenomenon as developing stronger adhesion between the concrete matrix and steel fibers where it is used (Tariq et al. 2021).

Referring to the literature, it is concluded that further investigation into shear strength with steel fiber contributions is required, especially for straight steel fibers (Timothy et al. 2023). Besides that, various fiber types' physical and mechanical characteristics and their content in the mixture, as well as their shape, significantly affect

the properties of fresh concrete (rheology, workability), hardened concrete (microstructure, tensile and compressive strength), as well as on the structural properties of concrete structures.

Today, it is a particularly popular theme related to improving concrete structures' durability and duration of the life cycle. Relating to this, one more major advance in using fiber-reinforced concrete is limiting crack openings (Jiang et al. 2023). Research of fiber-reinforced concrete as an aspect of green concrete technology is based on advancing properties and durability.

2. MATERIALS AND METHODS

Several analyses based on the data from the literature, which are presented below, show the influence of fibers on concrete's mechanical and deformation characteristics. The adding analysis of those parameters directly related to the durability and cost-effectiveness of structures was done.

Different kinds of fibers are present in the market today, and the most analyzed are steel, glass, and polypropylene fiber. At the newer time, natural fibers from agricultural waste are in experimental use (Rajkohila et al. 2023). According to previous research, fibers' efficiency mainly depends on the nature of the material, geometry, and mechanical properties, but fiber combination effects shall be considered (Ravichandran et al. 2022). Two investigations of steel fiber effects on the mechanical properties of concrete were prepared using straight short fibers (with tensile strength of 2200 MPa (Marcalikova et al. 2020) and 2500 MPa (Kazemi et al. 2012) and fibers with hooked ends (tensile strength of 2300 MPa). Fibers were added in different dosages (0.6-1.5 % and 2-5 % per volume). Mechanical properties, compressive, flexural, and splitting strength of plain concrete and concretes with fibers are compared. Investigations comprised different mix designs for concretes with normal strength (NSC), high strength (HSC), and ultra-high performance concrete (UHPC). The properties of fibers are shown in

Table 1.



Figure 1 Different fibers types: 1,2-Steel; 3-Glass; 4,5-Polypropylene-PP; 6-Banana fiber

Table 1 The main properties of fibers presented through the research

ID	Type of fiber	l [mm]	d [mm]	Aspect ratio l/d	Tensile strength [N/mm ²]	Elastic modul [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 fiber GF	6-18	0.015	400-1200	>1700	72
4	Polypropylene PP-macro	30-65	0.5-1	60-65	400-750	5-12
5	Polypropylene PP-micro	6-19	0.018-0.3	63-333	300-450	3.5-7
6	Chopped banana fiber	40	1	40	-	9-16

Investigation of the fibers' effect on the concrete pavement structures' strength is represented through the design thickness of it. The thickness of plain concrete pavement is compared to the thickness of pavement made of concrete with fibers on the three concrete mixtures, every with a 1% volume fraction of hooked steel, polypropylene fiber, or glass fibers. These concretes have been exposed to different traffic loads in the concrete pavement to investigate the effects of fiber reinforcement on concrete's mechanical properties. The investigated mechanical properties were used to design the concrete pavement, where the thickness was evaluated under the same traffic-loading conditions (Hussain et al. 2020).

Two forms of fibers were tested for compressive strength and splitting tensile strength to determine the optimal ratio of the composition of fibers in the concrete reinforced by hybrid fibers (Blazy et al. 2021).

The further development of ordinary concrete (OC) structures is limited due to the high demand for natural aggregates, the exploitation of which seriously damages the natural environment. The reduction of aggregate content in concrete, as well as the size of the grain, leads to the use of too much cement in the concrete mixture, causing a higher carbon footprint. Cement concrete has bad performance in tension, and the appearance of cracks in concrete causes sensitivity to environmental attacks and shorter design life duration of concrete structures. The advancing solution to these issues can be to increase the resistance of concrete by incorporating fibers and reduce the use of natural aggregates using recycled aggregates in concrete.

Research comprises the fiber's influence on concrete's mechanical resistance with recycled aggregate (RA) and durability performance. The three types of concrete mixes with 0% recycled coarse aggregate (RCA), 50% RCA, and 100% RCA are used to investigate glass fiber effects in the concrete (Ali et al. 2019). The mechanical properties of recycled aggregate concrete (RAC) were evaluated based on compressive strength, splitting tensile strength, shear and flexural strength. The use of the artificial neural network (ANN) model to analyze the shear strength of 231 beams was done. The parameters include the recycled aggregate content besides the shear span-depth ratio, compressive strength of concrete, longitudinal reinforcement percent, and the width and depth of the beam (Ababneh et al. 2020). In the other research on the 252 concrete specimens made with recycled aggregate concrete, the stress-strain, initiation, and propagation of fiber-reinforced concrete cracks with sea sand and recycled aggregate were analyzed (Huang et al. 2022).

The findings in (Yu et al. 2020) indicate that the replacement recycled aggregate (RA) effect in concrete is significant. Consequently, the database of investigations of the shear strength for 264 beams with recycled aggregate, from which 206 comprise beams without shear reinforcement, is included in this analysis. The main statistical parameters are compared based on the derived values of nominal shear strength provided by concrete for tested beams and designed shear resistance of concrete section according to EN 1992-1-1.

Numerous tests in the literature showed that adding steel fibers increased the shear strength of reinforced concrete beams (Almasabha et al. 2023). The base of extensive experimental data about testing steel fiber reinforced concrete (SFRC) beams without the shear reinforcement is used to analyze the probability of cracks appearing in correlation to shear strength increasing as a design life parameter. The applied databases comprise 488 results of testing shear strength on SFRC beams without the shear reinforcement (SR) collected in (Tariq et al. 2021), against results for 209 beams of plain reinforced concrete (PRC) with the shear reinforcement (155 beams) and without SR (54 beams), collected in (Grebović 2009).

The analysis is 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 are expressed through the safety factor of the shear stress's peak measured load versus the designed values of shear stress and the shear strength to the compressive strength of concrete ratio. The Probability Distribution Functions (PDF) for the ratios mentioned are derived, and values are compared for concrete reinforced with steel fiber (SFRC), plain concrete with shear reinforcement and without it, and concrete with recycled aggregate. The effects of fiber reinforcement content in the concrete on the shear strength normalized by the design shear strength are illustrated in the diagrams, **Figure 4**.

3. RESULTS AND DISCUSSION

Most of the test results showed that the flexural strength of concretes is grown three to four times while splitting tensile strength is grown 2.5 times due to adding 1-1.5 % hooked ends steel fibers, **Figure 2**. At the same time, compressive strength stayed with a minor change of values, increasing between 3% and 8 %. However, Kazemi et al. 2012 found that adding up to 5% fiber could increase the compressive strength of concrete up to 25% measured on a cube 50 mm for ultra-high-performance fiber reinforced concrete (UHPC).

The straight, short steel fibers showed lesser effectiveness than hooked, especially at flexural strength increase. While adding short fibers with content 0.6-1.5 %, flexural strength increased by 46-74 %, and splitting tensile strength increased by 40-97 %, **Figure 2**. Besides, some research found increases in flexural tensile strength (up to 107%) and shear strength (up to 260%), with increases in fiber from 2 to 5%.

An analysis of the 488 results of the shear strength of beams with steel fiber reinforced concrete (SFRC) regarding the effects of steel fiber content is shown in **Figure 3**. The designed shear strength ($v_{Rdc,EC2}$), which includes all influential factors according to the EC2, normalizes the shear strength test results for the given specimen of beams without shear reinforcement ($\rho_v=0$). The factor of structure strength expressed through ratio nominal shear stress measure in testing to design shear strength increased approximately two times with the growth of content steel fiber from 0.25% to 1.5% per volume.

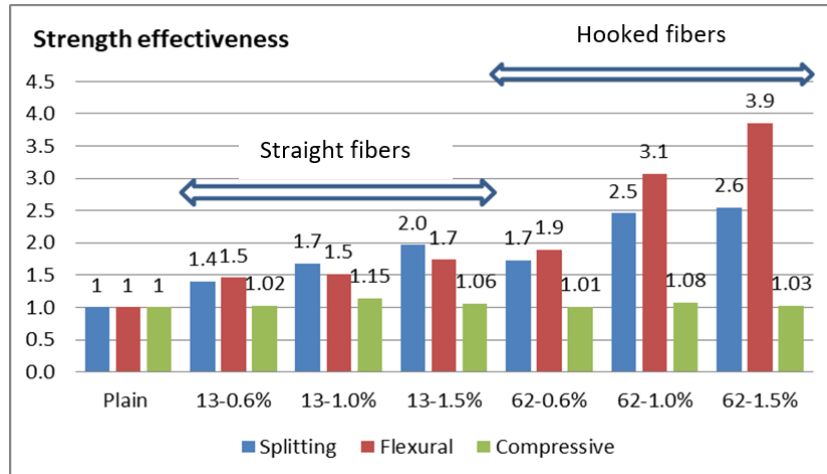


Figure 2 Effects of steel fibers (13 mm - straight and 62 mm - hooked)

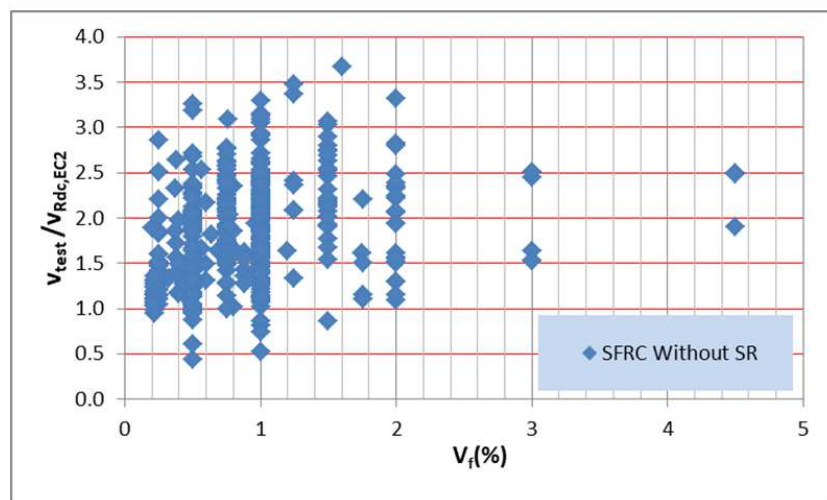


Figure 3 Effects of steel fiber content (V_f) on shear strength

The failure mode of beams composed of concrete with recycled aggregate (RACC) and the crack pattern of beams is similar to that of beams with natural coarse aggregate concrete (NCAC). It is indisputable that measures for reducing carbon print are on the side of RACC versus NCAC if considering the higher coarse aggregate content and lesser cementitious binder in RACC. The tensile strength to compressive strength ratio of concrete with recycled aggregate and polyethylene fiber (PFRACC) was increased with increased fiber content. It was an average of 0.091, slightly higher than those of RACC and steel fiber reinforced (SFRACC), which were 0.085 and 0.089, respectively. The fibers slightly change the initiation and distribution of cracks. The crack propagation and high-value strain of SSRAC greatly vary with the fiber type and their content variations.

Table 2 presents 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 steel fiber reinforced concrete (SFRC) without shear reinforcement ($\rho_s=0$) reach the level of shear resistance of NCAC beams with shear reinforcement. Considering the distribution of the transfer shear force between concrete and steel in both types of concrete, it is clear that bridging of cracking by the numerous fibers provides uniformity and lower stresses in steel than in the cross-section of the stirrups. It causes the new cracking patterns without localized individual relative wide cracks. Concrete with recycled coarse aggregates shows similar results related to shear strength as concrete with natural aggregates.

Table 2 Statistical analysis of test results of beam's shear strength

Type	SR	f_{ck} (MPa)	N	$X1 (\gamma = v_{test}/v_{Rdc})$			$X2 (v_{test}/f_{ck})$			$X_{char,5\%}$	
				AV	STD	COV	AV	STD	COV	X1	X2
SFRC	$\rho_v = 0$	>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	$\rho_v > 0$	>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
	$\rho_v = 0$	>50	54	1.165	0.430	37.0	0.036	0.019	53.3	0.476	0.005
RACC	$\rho_v = 0$	<50	206	1.242	0.578	46.5	0.047	0.024	50.8	0.317	0.009
	$\rho_v > 0$	<50	58	1.864	0.623	33.4	0.086	0.033	38.5	0.867	0.033

Figure 4 presents the empirical Cumulative Distribution Function (CDF) of the design shear strength safety factor, where nominal shear strength is calculated according to EN1992 for different concretes with and without fibers. The CDF value for the measured variable is the part of all results that are less than or equal to the observed value.

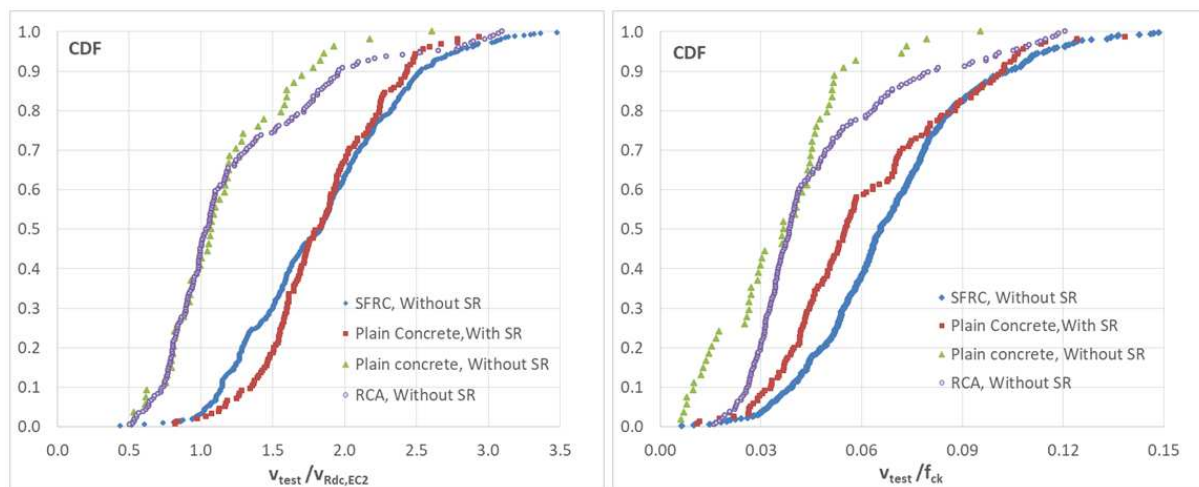


Figure 4 Probability of factor of test results versus design shear strength for SFRC and plain NCAC and RACC with and without shear reinforcement

It is shown that the fibers may increase the beams' shear strength, especially the correlation factor of nominal shear strength to compressive strength. The tension properties of concrete with recycled aggregates don't fall behind, or they even lead if compared to concrete with natural aggregates for the same compressive strength.

The effects of combining different fibers are the options for new advantages of the properties and durability of concrete. Combining two types of fibers was investigated to find the optimal composition of fibers in concrete and get better properties. Steel composition with any other fiber has better properties than other combinations without steel fiber. Using glass fibers with steel fibers will provide better tensile strength than combining steel fibers with polypropylene.

On the other hand, the polypropylene fibers effect is characterized by reducing plastic shrinkage and cracks in concrete surfaces. Results of several research studies showed a significant crack limitation in which the addition of 0.10% to 0.50% of fibers resulted in crack limitation up to 99% (Blazy et al. 2021).

The effects of polypropylene macro and microfibers composition are directed towards increasing tensile strength by the micro-fibers bridging micro-cracks and macro-fibers increasing ductility by the influence on macro-cracks. Shrinkage crack limitation as a significant instrumentality for corrosion and sulfate attack reduction is beneficial for sustainable development and extension of structure life. The production of PPF emits less CO₂ to 30% compared to steel fibers production and 9% less than glass fibers production.

The analysis influences of the incorporation of 1% steel, polypropylene, and glass fiber shows that the thickness of concrete pavement may be reduced by 35%, 18%, and 23%, respectively (Hussain et al. 2020).

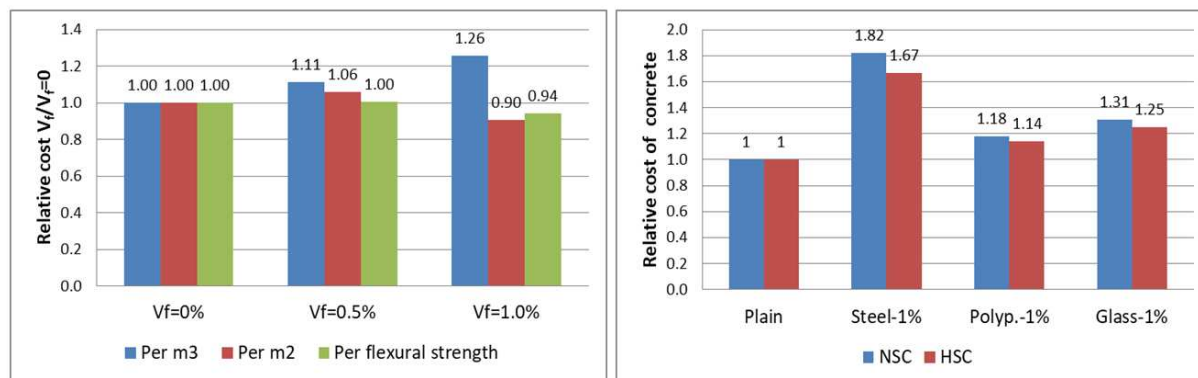


Figure 5 Effect of different PPF content and different kinds of fibers on the cost

The use of fiber reinforcement in concrete causes an increase in cost by adding fibers and superplasticizers because the presence of fibers reduces the workability of fresh concrete.

Different density of fiber materials causes different final cost per m³ of concrete. Polypropylene fibers have the lowest density, while the density of steel fibers is the highest. For 1% content of fibers in concrete, 9 kg of polypropylene fibers are required instead of 78 kilograms of steel or 26 kilograms of glass fibers.

4. CONCLUSION

The research aims to assess the effects of the different types and percentages of fiber reinforcements in concrete on structures' design life.

Based on many investigations, it is confirmed that fibers' efficiency mainly depends on their origin, type, mechanical properties, geometry, orientation, and combination. The fibers are an essential factor influencing concrete's rheological and mechanical characteristics but cost.

The researchers on the shear strength of concrete, a frequent theme caused by many influencing factors, observed that besides other factors, the presence of fiber reinforcement and its tensile strength increase the shear strength of beams. Adding shear reinforcement may be avoided in steel fiber-reinforced concrete beams with the simultaneous reduction of shear cracks.

The investigation confirms concrete's minor lower compressive strength but does not show a decrease in tensile and shear strength with a higher ratio of recycled aggregate content. The appropriates of concrete with recycled aggregate as green concrete is confirmed despite some results indicating its less shear strength than concrete with natural coarse aggregate (NCA).

The improvements in concrete design life are based on increasing tensile strength and avoiding cracks appearing in less loaded structures. It might be a crucial factor for characterizing fiber-reinforced concrete as green concrete.

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