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ORIGINAL ARTICLE

Reinforcing the brittle resistance of high-strength concrete using agricultural waste fiber

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Abstract: The utilization of natural fiber wastes could be an ideal way to tackle two problems. Firstly, this may be a solution to the issue of environmental challenges related to agricultural wastes. Secondly, it can potentially fix high-strength concrete's (HSC) issue of unexpected (sudden) collapse. This study looked at the results of using two different kinds of natural fiber waste in HSC. Seven HSC mixtures were manufactured; three included rice straw fibers (RSF), three contained palm leaf sheath fibers (PLSF), and one was a control mix (without fibers). In this research, the volume fractions of RSF and PLSF ranged from 1% to 3% and had an aspect ratio equal to 100. Different tests, including slump test, compressive strength, modulus of elasticity, flexural strength and tensile strength were conducted to determine their various properties. There were no significant improvements on compressive strength due to use of natural fiber while its tensile and flexural strengths increased particularly when including 1% RSF. RSF improved the properties of HSC more significantly than PLSF.

Keywords: High-strength concrete; physical and mechanical properties; rice straw fibers; palm leaf sheath fibers

1 Introduction

Concrete is an exceptional building material as it has great compressive strength (CS) [1]. High-strength concrete (HSC) is a specialized form of concrete that depends on the mix design and often includes other types of materials like silica fume and/or fly ash besides normal concrete ingredients [2,3]. Unlike normal strength concrete (NSC), HSC is typically characterized by a reduced stress. This abrupt decline in CS after peak load zone results to a brittle failure pattern that is unique to such materials [4,5]. There is a need to look into other options to improve the brittleness of concrete, for example fiber reinforced concrete [5–7]. Brittle cracking may be alleviated by the incorporation of dispersed fibers. The role of such fibers is to link cracked regions thus ensuring that stress is uniformly distributed in cement structure [8–10]. Natural fibers can be used in concrete where there are few resources and people need cheap construction [11,12]. The incorporation of natural fibers into concrete invariably gives room for greater mitigation against cracking, toughness, and showing a better performance in post-cracking phase [13,14]. Little research has focused on the use of date palm fiber in concrete. Date palms are mostly found in arid and dry regions around the

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world, mainly including areas such as Southern United States, India, and Middle East countries [15–17]. Date palm plants cover a region of almost 1.3 million hectares in around 30 nations, with an estimated 140 million trees which is expected to be the case in Egypt [18–20]. Djoudi et al. [21] found that that incorporating date palm fibers in concrete improves its properties such as flexibility, tensile bending strength, compressive strength and crack resistance [22,23]. On the other hand, an increased amount of fiber resulted in a decrease in both compression as well as flexural strength. The length of the fibers did not cause any significant changes in the concrete's characteristics [24–26]. Research studies which aimed at integrating agricultural fiber in concrete have produced encouraging results [27,28]. Newly conducted researches have pursued the option of using natural fiber as reinforcement in building [29–34]. These studies have shown hopeful outcomes, mainly in regard to mechanical response. For instance, Amin et al [27] carried out an investigation in which palm leaf sheath fibers (PLSF) were utilized in strengthening concrete beams that led to improve their mechanical properties [35,36]. However, the traditional technique of crop straw treatment by in-situ burning is associated with several problems [37,38]. Modern technology has made extensive use of crop straw for environmentally friendly purposes, such as enhancing soil properties for better water retention and overall health, creating electricity, and recycling it for biogas [39]. For example, [38,40,41], in their investigation of concrete, they observed that the more fibrous materials increased, the weaker it got as compared to control concrete. On the other hand, while compressive strength reduced due to increasing amounts of fibrous materials, flexural strength improved [38,40,41]. Awoyera and Akinrinade [42] after a certain level of addition has been reached, they have concluded that increasing fibrous materials compromised flexural strength. This implies that the ability to resist bending is improved [43–45].

Furthermore, Khelifa et al. [46] studied the mechanical properties of mortar that included chemically treated date palm mesh fibers. They have used fibers in three different proportions (1%, 3%, and 5%) and lengths (5, 10, and 15 mm). The study found that the flexural and compression stresses increased by 46.6% and 50%, respectively, compared to the control mortar. Awad et al. [29] discovered the impact of utilizing ground granulated blast furnace slag (GGBS) in place of cement and PLSF addition in weight ratios of 1, 2, and 3% in mortar. They examined the properties of water absorption and mechanical strength. It was found that PLSF percentages of 1% and lengths of 20 mm worked best. The flexural strength was enhanced by 30.97% and the compressive strength by 57.12%.

Additionally, Shang et al. [47] explored the characteristics of a cementitious composite created using rice straw fibers (RSF) treated with sodium hydroxide solution. The fibers were used in proportions of 0%, 1%, and 2%. They recorded that the compressive strength was enhanced by 12.5% to 22.3% and an enhancement in flexural strength by 4.7% to 14.6%. Liu et al. [48] performed a study on the influence of RSF grafted with nano-silica (NS) on concrete properties. They used RSF and NS at varying percentages: 1%, 2%, 3%, and 4% for RSF and 1%, 3%, 5%, and 7% for NS. The results revealed that at 28 days, the combination of 2% RSF and 3% NS increased compressive and flexural strength by 28.6% and 27.9%, respectively. Additionally, at 90 days, the addition of 1%, 2%, and 3% RSF combined with NS resulted in increased compressive strength by 8.3%, 20.7%, and 40.1%, respectively.

Based on the information provided, previous studies have primarily focused on studying RSF and palm leaf sheath fibers (PLSF) separately, without comparing their results or studying them together. Additionally, there are variations in how these natural fibers affect the properties of cementations composite materials, which could be attributed to differences in fiber content, aspect ratio, and surface treatment methods used in the literature. Furthermore, only a few studies have explored the impact of these fibers on the properties of HSC, particularly in terms of brittleness properties. Therefore, this study is intended to enrich the resistance of HSC against brittleness by employing two natural fibers: PLSF and RSF. In this study, three different ratio of fibers (1%, 2% and 3%) were used in order to analyse their influence on the behavior of HSC. This work aims to increase the material's brittle resistance by incorporating PLSF and RSF into HSC mixes. It also intends to investigate how these additives influence the mechanical behavior of HSC, see **Fig. 1**.

2 Significance of research

This research was conducted with the aim at producing HSC by using two global available natural waste products, PLSF and RSF. These waste materials are present in large amounts in different regions of Egypt. The two fibers were cut into the aspect ratio stated by ACI to ensure they are suitable for inclusion into HSC [49]. Prior to their addition into HSC mixtures, the fibers underwent alkaline treatment as per proposed method by [50]. This study sought to find out how these natural fibers can be incorporated into HSC. Egypt could significantly benefit from this model in HSC improvements and sustainable waste management.

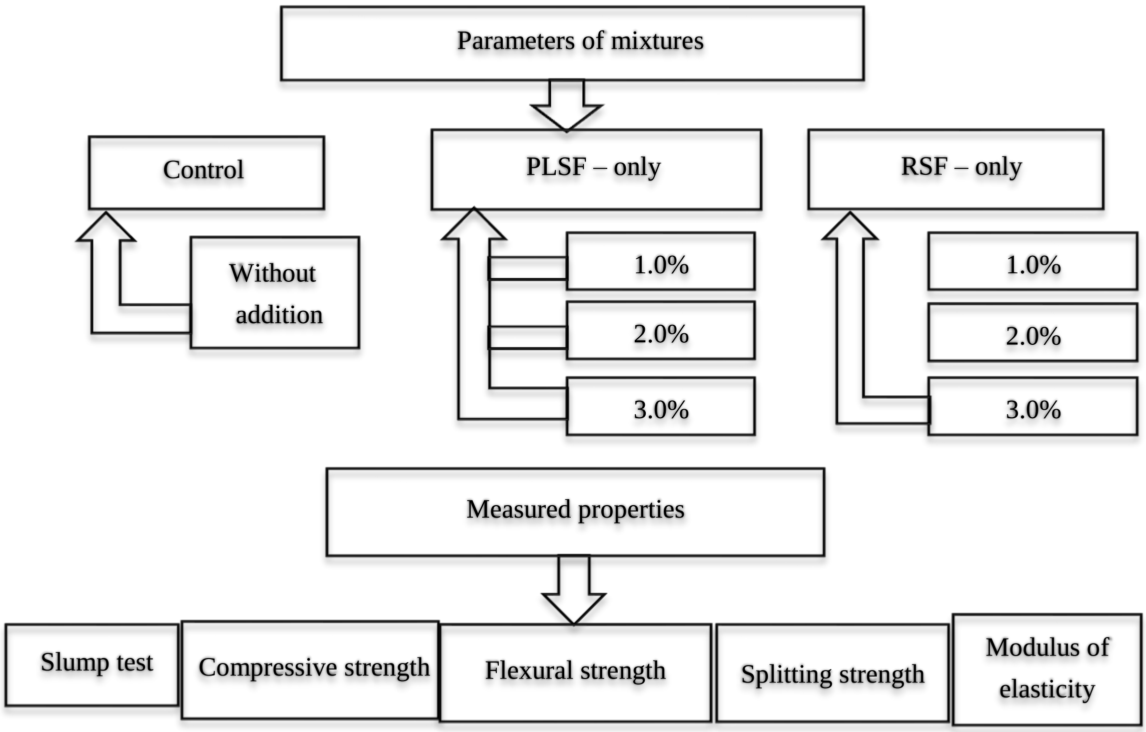

Fig. 1. The experimental program of the research plan.

3 Experimental Procedures

3.1 Materials

3.1.1 Ordinary Portland Cement (OPC)

This paper obtained OPC type (CEM I 42.5N) from Egypt's Helwan Company. According to ASTM C150 [51], the substances employed in this study was ordinary Portland cement (OPC). The specific gravity and surface area of OPC are 3.15 and 3250 cm^2/g, respectively.

3.1.2 Silica Fume (SF)

Silica fume (SF) is a pozzolanic substance typically employed in conjunction with cement and often utilized as a replacement for cement in a proportion of 15%. It has specific properties that are advantageous for concrete uses. The specific surface area and specific gravity of SF are 22270 cm^2/g and 2.15, respectively. The major cause for using it in making concrete is because it contains very high amounts of SiO_2 (silicon dioxide). During the cement hydration process at higher temperatures, SiO_2 reacts with the available calcium hydroxide releasing free water or steam. This reactivity allows reactions which lead to closing internal pores and ultimately developing compressive strength in cementations pastes. Adding silica fume to concrete makes it denser and more durable by reducing internal porosity, thus densifying the matrix.

3.1.3 Aggregates

To analyses this, the ratio of sand to stone was 1:1.5. Consequently, fine aggregate (FA) was obtained from the river for use in this research and it has been used in a clean state with rounded particles, thus being termed clean river sand. The specific gravity of the fine aggregate has been measured as 2.63. Also, FA had an absorption capacity of 1.7%. The concrete mixture uses broken rocks as the coarse aggregate (CA), which runs up to 12.5 mm in size. The water absorption percentage of CA is 1.1% and the specific gravity equals to 2.67 [52]. The results of particle grading analysis displayed that particle size distribution for both coarse aggregate and fine aggregate satisfied the respective specified criteria. By using clean rounded shaped FA and well graded CA, better workability, strength and general performance are achieved in concrete mixture.

3.1.4 Super-plasticizer (SP)

In this research, the HSC mixtures' water content was minimized by using Viscocrete-3425 which is a super plasticizer that has high performance properties. It is made up of a modified polycarboxylate and is put in water to create Viscocrete-3425 having distinct traits useful for amending diverse elements of concrete. It also can be used to produce concretes with excellent workability and those with high initial strength requirement. These qualities are designed to achieve different performance objectives in the concrete. The ASTM C494 complies with the super-plasticizer admixture [53]. Viscocrete-3425 has a specific gravity of 1.08. The addition rate of Viscocrete-3425 for all mixtures was fixed at 2% of the cement weight. This amount was selected to counterbalance the reduced water to cement (W/C) content. Thus, when applied as an admixture in making concrete, great advantages can be seen both in terms of workability, bulk density reduction and fluidity for these concretes as well as enhancing their functional properties thus guaranteeing superior performance.

3.1.5 Fibers

In this research, two types of agricultural waste; RSF and PLSF were used. RSF was collected from rice crops in Sohag City, Egypt, while PLSF was obtained from date palm trees in the same area. They were sliced to aspect ratio of about 100. **Table 1** shows mechanical, physical and chemical properties of RSF and PLSF [16,50,54]. Fibers' properties are essential information which are vital during assessing their probable performance as well as contribution to HSC mixtures while considering improvement in crack patterns or other mechanical properties. **Fig. 2** shows shapes and details of both fibers.

Fig. 2. Shape and dimensions for fibers.

3.2 Mixing procedure

Seven mixtures were executed for this study. One reference mixture (free of fibers), while three mixtures included RSF and three mixtures contained PLSF. An absolute volume approach was employed in making the mixtures. The concrete samples used in this research had a constant cement content of 500kg/m3 and SF that replaces 15% of the cement by mass. The FA/CA ratio was 1:1.5. SP was used with the range of 2.0 to 2.7% by weight of cement. Different volume fractions (1%, 2% and 3%) of RSF and/or PLSF fibers were put into concrete. The water to binder ratio was maintained at 0.25 while aspect ratio of fibers was kept at 100. FA and CA were initially mixed together in a saturated surface dry condition for three minutes as part of the mixing process. Following that, cement and silica fume were fed into the mixer, and the mixture was stirred for a further three minutes. After that, the SP and water were added to the other ingredients, and they mixed for five minutes. The fibers were appended afterward, and the mixture was operated for an additional two minutes. Details regarding HSC mix design are given in **Table 2.**

Table 1. The characteristics of (PLSF & RSF).

Properties	RSF	PLSF
Water absorption (%)	52	72
Density (g/cm^3)	1.37	1.17
Tensile strength (MPa)	50	340
Specific gravity	0.72	0.94
Elongation at break (%)	0.90	3.63

Table 2. Mixtures design (kg/m^3).

No	Mix	Cement	SF	Sand	Coarse aggregate	Water	SP	PLSF	RSF
1	C -0.0%	500	75	534.3	1068.7	125	10	0	0
2	PLSF -1%	500	75	534.3	1068.7	125	10.5	21.8	0
3	PLSF -2%	500	75	534.3	1068.7	125	12.5	43.6	0
4	PLSF -3%	500	75	534.3	1068.7	125	13.5	65.4	0
5	RSF -1%	500	75	534.3	1068.7	125	11	0	21.8
6	RSF -2%	500	75	534.3	1068.7	125	12	0	43.6
7	RSF -3%	500	75	534.3	1068.7	125	12.5	0	65.4

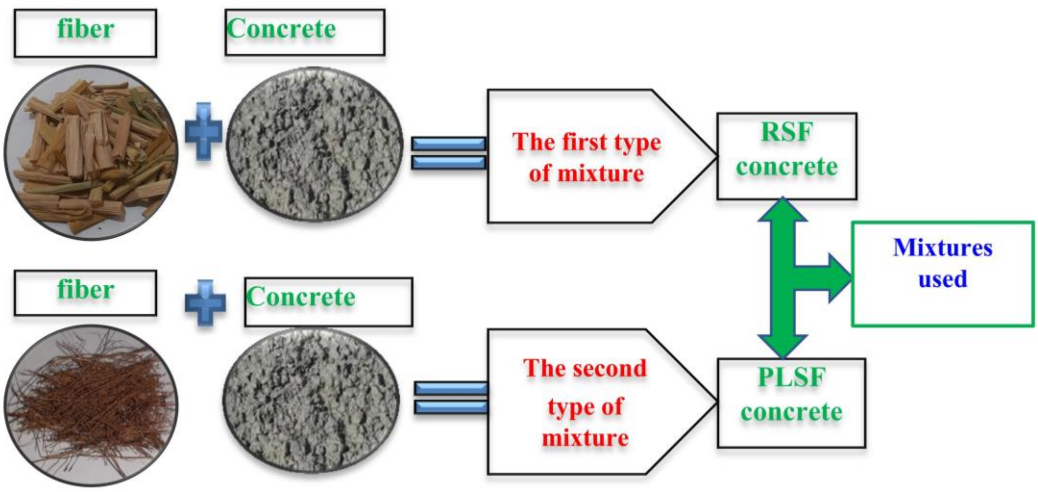

Fig. 3. Combining HSC mixes using PLSF and RSF**.**

3.3 Tests Conducted

Evaluating different features of both fresh and hard HSC was the aim of this experiment. The study included the following tests:

Slump Test (ST): This examination was performed following the ASTM C143/C143M [55] to assess the fresh properties (workability) of HSC mixtures.

Mechanical properties:

Compressive Strength: Cubic specimens of 150 × 150 × 150 mm in dimensions were used to assess compressive strength (CS) at 7, 28, and 56 days as per BS 1881-116 [57].

Flexural Strength (FS): In accordance with the instructions of C293/C293M, FS was conducted on beam specimens measuring (100 × 100 × 500) mm at 28 days [58].

Splitting Tensile Strength (STS): Cylindrical specimens (d=300mm and L= 150mm) were subjected to STS. This examination was carried out at the 28-day following the process outlined in ASTM C496/C496M [59].

Modulus of Elasticity (ME): This examination was measured following ASTM C469/C469M [56]. The test used cylinder specimens of 150mm diameter and 300mm length. Measurements were taken after 28 days.

4 Results of the Tests

4.1 Fresh Characteristic

The slump test (ST) is one of the ways to measure the workability of concrete. The resultant ST data can be seen in **Fig. 4**. As compared to the C -0.0%, Compared to the reference specimen (C - 0.0%), the workability percentages increased by 5.3%, 6.7%, and 8% for PLSF mixes containing 1%, 2%, and 3%, respectively. Conversely, RSF mixes showed a decrease in workability of approximately 5.3% when compared to the C - 0.0% mix for 1% RSF. For mixtures with RSF fractions of about 2% and those of about 3%, the decrease was almost equal to 9.3%. Similar observation were reported in previous studies [60–62]. In relation to PLSF based mixes, HSC mixes had reduced workability's mainly because they contained PLSFs compared with RSFs.

Moreover, RSF is characterized by its high hydrophilicity, which increases its water absorption and thus decreases the mixing water and workability [63]. Similar findings were also found in previous works [40,64].

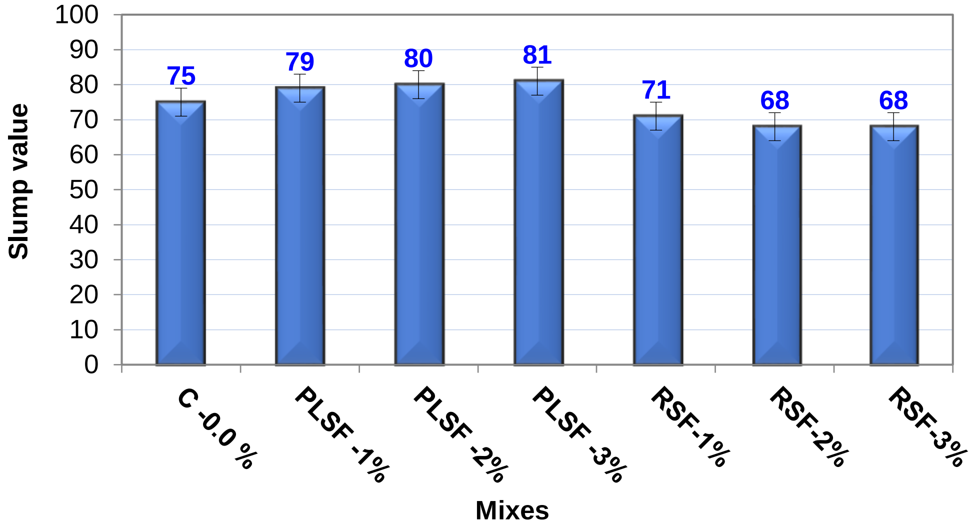

Fig. 4. Slump test results of the HSC mixtures.

4.2 Hardened Properties

4.2.1 Behavior of compressive strength (CS)

Fig. 5 illustrates the correlation between the compressive strength of high-strength concrete and the volumes of RSF and PLSF at various curing ages. It was found that increasing curing duration increases the CS of the HSC. Conversely, CS decreased with the addition of PLSF to the HSC mixtures at all ages. These findings are compatible with the literature [65]. This reduction was proportionate to the quantity of added PLSF, similar findings were reported by other researches [66,67].

It is worth noting that CS for RSF mixture was higher than that for PLSF mixture. At 28 days, reductions in CS were found to be 13.00%, 31.90%, and 35.45% for the PLSF mixtures with fiber volume fraction (FVF) equal to 1%, 2%, and 3%, see **Fig. 5**. **Fig. 5** also shown that the mixture with 3% RSF fibers had a 7.20% lower CS compared to the control mixture. The presence of fibers within HSC which formed zones of failure within its rigid matrix resulted in this reduction in CS as has been reported by [68,69]. The results at 56 days showed that for most fiber addition ratios, the decrease in compressive strength of the mixes containing fibers was lower compared to the reference mix at earlier ages. This was because of the improved bond strength between the matrix and fibers due to cement hydration. The mixes with RSF fibers had compressive strengths very close to the reference mix, with a reduction in strength ranging from 3.65 to 4.58%, indicating the effectiveness of using these fibers in high-strength concrete. Shang et al. found comparable results [47].

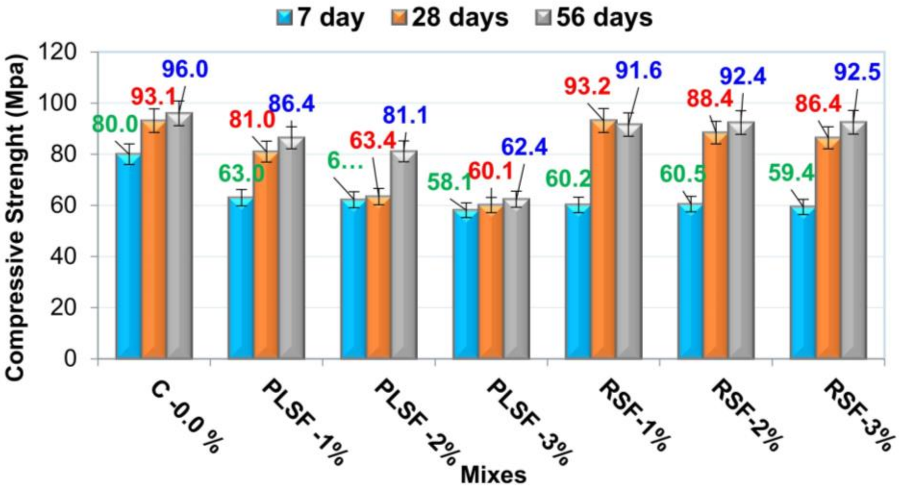

Fig. 5. CS results of the HSC.

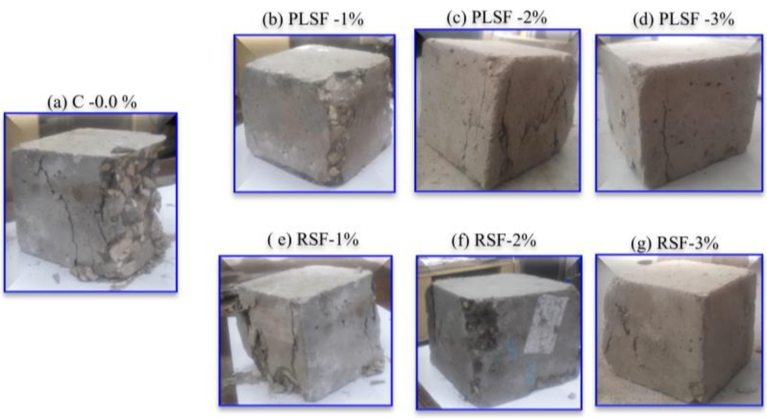

Fig. 6. Concrete cubes' failure form across all mixes.

On the other hand, the mode of failure in compression tests of HSC depended on specific shape for RSF and PLSF. This study also showed that brittle failure pattern of the mixtures could be transformed into a more ductile type by addition of RSF and PLSF as depicted in **Fig. 6** [70,71].

4.2.2 Behavior of splitting tensile strength (STS)

Fig. 7 displays STS findings for all HSC mixes. The mixes with 1, 2 and 3% RLSF contents showed reduced STS relative to the C0-0 % ranged between 22.88% and 44.92%. this could be due to the development of a less strong boned between the HSC component and RSF that resulted in decreased STS with increasing the RLSF content [72,73]. Furthermore, the mixture with 1% RSF had higher STS than C0-0 %. For this mixture, the increase percentage was approximately 0.85%. Nevertheless, 2% and 3% RSF addition reduced the STS by about 11.44% and 9.75%, respectively. These findings imply that FVF of 1% RSF were very effective in enhancing STS; this might have resulted from a stronger bond formed within the concrete matrix. The ratios of STS-to-CS (T/C) were comparable between PLSF mixes and HSC without fiber (C0-0%), but T/C ratios for RSF mixtures were higher than both the control and PLSF mixtures. It is evident that RSF was better in improving STS behavior of HSC than PLSF [74,75].

Fig. 8 shows how the addition of two types of fibers affected the failure performance of HSC cylinders. When no fiber was added, the control HSC sample split in two upon reaching its maximum tensile strength. Nevertheless, this splitting was not observed when it came to fibers-containing cylinders. With regard to the mixtures with 1% and 2% RSF, specimens developed bigger cracks within their sections than that with 3%. Furthermore, for samples containing 1%, 2%, and 3% PLSF, there was a stronger link between the two halves of the specimen when it is stretched and some cracks in its middle region both longitudinally and transversely.

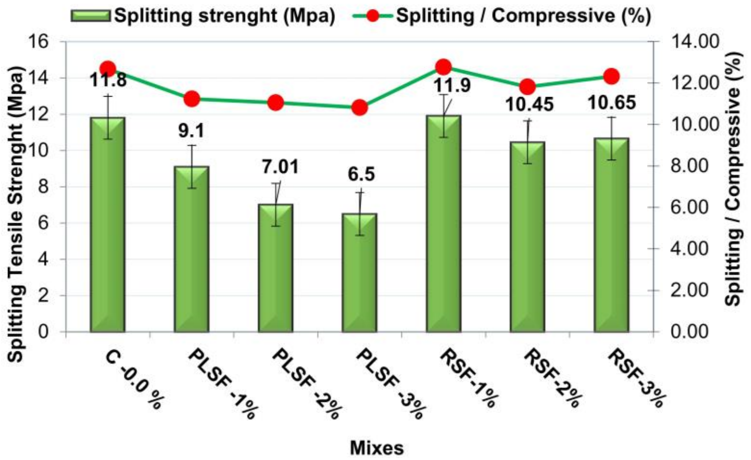

Fig. 7. Splitting tensile strength of the HSC.

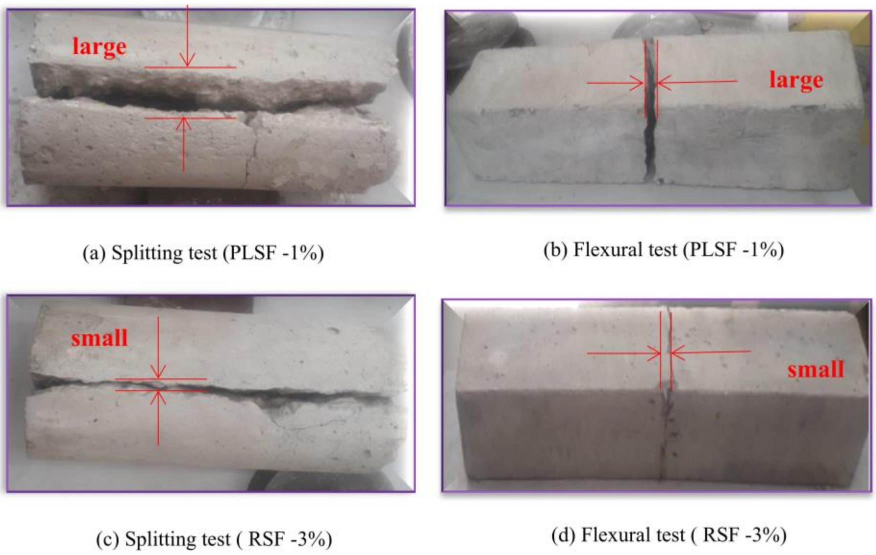

Fig. 8. Splitting tensile flexural strength specimens contained 1% and 3% of PLSF and RSF fibers.

4.2.3 Behavior of flexural strength (FS)

Fig. 9 present the FS results of the HSC mixtures. As indicated by **Fig. 9**, the FS of mixtures with 1%, 2% and 3% PLSF were as follows: 10.1, 7.8 and 7.03 MPa, respectively. The FS decreased considerably with increased PLSF percentages, reaching about 46.74% for a HSC mix containing 3% PLSF. This decline resulted from a lower bonding strength between HSC matrix and PLSF and an agglomeration of PLSF within the blend [76,77]. Contrastingly, there was a small decrease in FS of only 12.88% and 9.85%, respectively in mixes containing 2% and 3% RSF compared to the control mixture. Astonishingly, mixtures with 1% RSF increased FS by around 0.76% above the control. The ratio FS-to-CS (F/C) are also shown in **Figs. 9 and 10**. It is noted that F/C ratios for PLSF mixtures at a level of 1%, 2%, 3% were about 10.1%, 7.8%, and 7.03%, respectively. For the mixtures with RSF levels of 1%, 2% and 3%%, their F/C ratio rate were reported as 13.3%, 11.5% and 11.9%, respectively. Without fibers, the F/C ratio for the mixtures was 13.2%. These ratios show that RSF and PLSF fibers added to HSC have enhanced its flexural behavior, although RSF has higher F/C ratios than PLSF [78,79].

Furthermore, natural fibers had a greater impact on tensile and flexural strength compared to compressive strength. This finding aligns with Younis' research [80], which suggests that adding fibers can increase air voids within the matrix, leading to a decrease in compressive strength. Moreover, in the presence of fibers, concrete's compressive strength deteriorates when it cracks, while tensile and flexural strengths bear more load due to the bridging influence of the fibers between the two sides of the cracks, contributing to their increase [81,82].

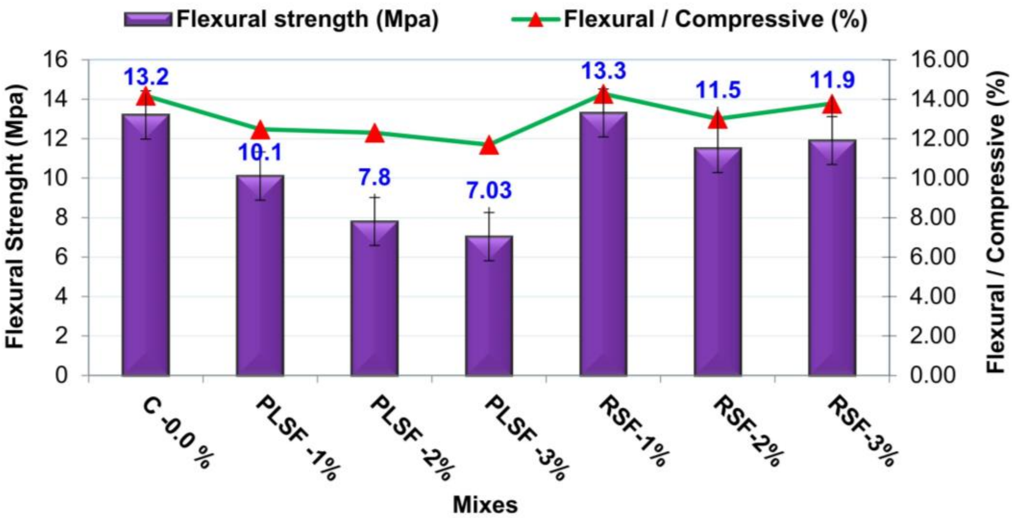

Fig. 9. Flexural strength of the HSC.

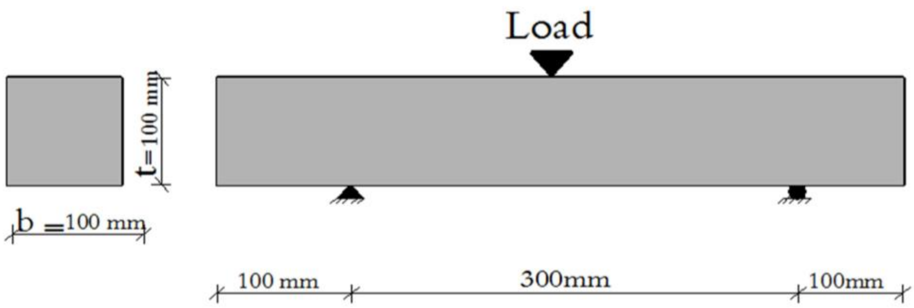

Fig. 10. Flexural strength specimen on machine test.

4.2.4 Behaviour of modulus of elasticity (ME)

The behavior of mixtures under deformation was evaluated by using ME test through which comparisons were made between mixes without natural fibers and those with fibers. The ME findings of the HSC mixes are displayed in **Fig. 11**. Relative with the control mix's, the mixes containing PLSF experienced a drop in ME as PLSF content increased. The decrease came at about 8.46%, 12.69% and 13.81% for the combinations having 1%, 2%, and 3% PLSF, respectively. This is due to the fact that its CS value, at the same low strain level, was lesser than that of the reference HSC, See **Fig.12**. It can be explained by the existence of interior hairline cracks within the HSC structure around this fiber resulting in poor adhesive properties between HSC matrix and the PLSF [63,83].

Furthermore, all other RSF mixes had a comparable ME in comparison with the control mixture with a decline of 8.24% and 10.24% for 2% and 3%, respectively. In relation to the control mixture, ME increased marginally by about 0.67% in the blend with 1% RSF. The HSC mixtures using RSF had more ME than those made from PLSF because RSF has relatively higher CS compared to PLSF.

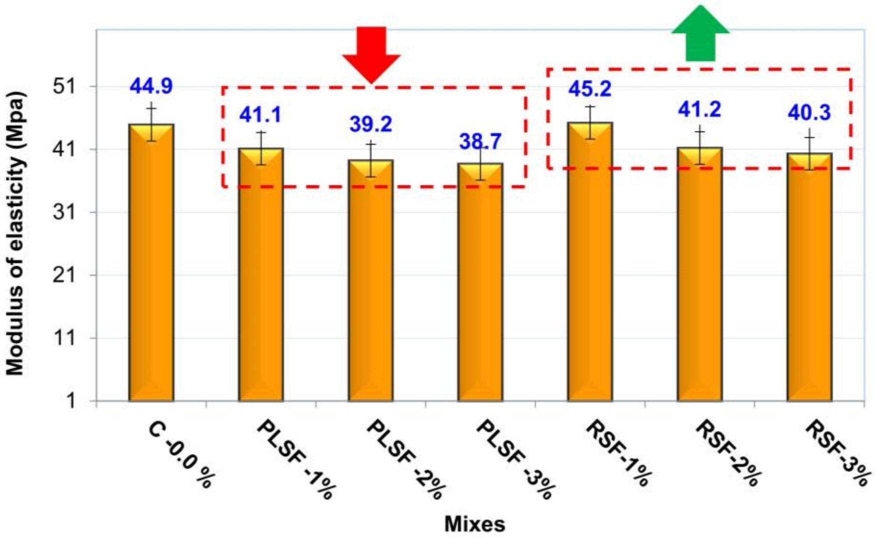

Fig. 11. Modulus of elasticity of the HSC.

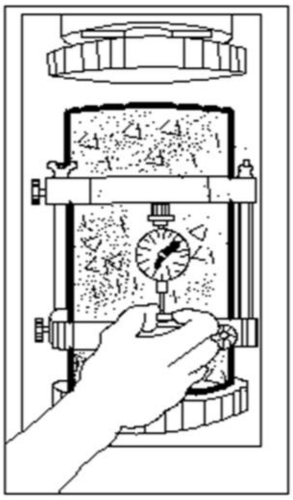

Fig. 12. Modulus of elasticity specimen on machine test.

5 Discussions and conclusions

The primary purpose of this study was to examine the influence of varies formulations of RSF and PLSF on the characteristics of high strength concrete. Consequently, the findings resulting from this research work would be summarized as stated below:

The use of RSF fibers in HSC mixtures caused a drop in the slump (workability) reached to about 5.3% for mixture with 1% RSF compared to the fiber-free mixture. The reduction rate in workability of 2 and 3% RSF reached to about 9.3%.

The outcomes demonstrated that the higher the curing duration, the higher the compressive strength (CS) of HSC.

The brittleness failure mode of HSC could be changed to a more plastic one through the inclusion of RSF and PLSF additives.

Some of the mixes with 1, 2 and 3% RLSF contents reduced STS compared to the C0-0% mixture by 22.88% and 44.92%.

The FS of HSC decreased considerably with increased PLSF percentages, reaching 46.74% for 3% PLSF content.

In comparison with the control mix's elastic modulus, the mixtures containing RSF showed comparable ME values.

6 Future studies

On the other hand, this study has some limitations. Among them, some durability characteristics, such as rate of water absorption and chloride penetration, as well as the effect of using these fibers when HSC exposed to high temperatures, were not conducted. Moreover, the long-term behavior of the mechanical properties of concrete containing these natural fibers was not studied. Accordingly, among the works that the authors recommend for future work are:

Conducting a comprehensive investigation to explore the properties of concrete containing natural fibers in the long and short term, focusing on durability properties.

Using other types of natural fibers, such as hemp and flax fibers, and comparing their performance with the fibers utilized in the current study.

Using more than one type of cement, such as pozzolanic and sulphate-resistant cement, in conjunction with natural fibers since these fibers are affected by the environment's basicity and properties.

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CRediT authorship contribution statement

All authors contributed equally to this research.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

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