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## Article

# Investigation on Improvement in Shear Performance of Reinforced-Concrete Beams Produced with Recycled Steel Wires from Waste Tires

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**Abstract:** In parallel with the increase in vehicle sales worldwide, waste tires are becoming an increasing problem. The storage and disposal of these waste tires are critical environmental problems. Re-using these wastes in different areas instead of being disposed of is vital in preventing environmental pollution and creating new low-cost products. From this motivation, this paper investigates the properties of traditional reinforced-concrete beam with recycled steel wires (RSWT) obtained from the waste tires. RSWT were added to reinforced-concrete beam between 1% and 3% by weight with an increment of 1%. In total, 9 cubes, 12 cylinders and 12 reinforced-concrete beams were cast and tested to obtain the compressive, splitting tensile and flexural strengths, respectively. RSWT added to the concrete by 1%, 2% and 3% increased the compressive strength by 17.2%, 30.8% and 46.4%, respectively, compared to the reference concrete. In split tensile strength, 14.4%, 25.1% and 36.7% increases were observed, respectively. This showed that there was an effective increase in the compressive and tensile strength of concrete with the increase of fiber content. Although the effect of fiber content in samples with high stirrup spacing (27 cm) provides significant benefit in improving the beam behavior, the effect of fibers was more limited as the stirrup spacing decreased (20 cm and 16 cm). An approximation of over 91% was obtained between the analytical calculations and the experimental results. This shows that the analytical calculations given in the standards can be used for new experimental studies.

**Keywords:** recycled steel wires; reinforced-concrete beam; traditional concrete; waste tyres



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## 1. Introduction

Sustainability has become a major concern for humankind, especially in recent years. On the basis of this, the world's resources are constantly decreasing, and the human population continues to increase rapidly. The effective re-use of materials is extremely important in this respect [1–9]. There is a sustainability concern in concrete, which is the indispensable material of the construction and building industry. Concrete is the most widely used material in the construction industry; its production consumes a vast amount of natural resources and is responsible for 8–9% of the total global anthropogenic CO<sub>2</sub> emissions [10–13]. Concrete is inevitably affected by external conditions such as temperature and water in practical engineering [14]. Water can affect the mechanical properties of concrete beam, especially the compressive strength [15–17]. In this context, it is important to make the concrete mixture with recyclable materials as much as possible, without compromising the expected performance of the concrete (strength for hardened concrete/workability for fresh concrete), thus limiting the amounts of aggregate and cement used [18,19].

There have been efforts to use different waste materials in concrete. One of these is the wastes arising from tires that have expired. The chemical composition and storage problems of car tires pose a problem worldwide. Tires are not biodegradable. Especially in case of the stocking stage, they can cause viral and bacterial diseases to multiply. The environmental problems caused by around 300 million waste tires annually in the USA alone are significant [20]. Similarly, a significant portion (estimated 50%) of the one billion tires that complete their service life in the world every year is addressed through incineration [21]. However, the accumulation of worn-out tires creates health and fire hazards. Therefore, these wastes should be used in a more sustainable way. It is possible to use waste car tires as fuel in cement factories, to be used instead of aggregate in asphalt and concrete, and to use in industry by separating the steel fibers in tires. Steel wire recovered in this way in Europe amounts to over 500,000 tons per year [22].

Composite materials and various types of fibers (glass, steel, carbon, aramid, etc.) are used to improve the mechanical properties of concrete [23–27]. The most common of these is steel fibers (SF). Although the geometry of the fiber depends on the dosage and mechanical properties, SFs significantly improve the weak properties of concrete, which is a brittle material [28,29]. For example, fiber reinforcement improves the mechanical properties (i.e., tensile strain capacity and ductility) and controls crack propagation [30,31] by bridging the cracks and transmitting tensile force across them to enhance the post-cracking tensile behavior. Aiello et al. [32] stated that the main purpose of steel fibers is to prevent and control the crack propagation in concrete. Many studies have proven that using SFs in concrete improves the behavior of reinforced concrete in terms of shear, bending and tensile behaviors [33,34] rate of cracking [35] ductility and stiffness [36,37].

Unlike SF, recycled steel fiber from tire waste (RSWT) is an alternative building material to manufactured steel fibers (SF). In particular, many studies have been conducted to determine the compressive strength, tensile strength, workability and durability of SF-added concrete [38,39]. In these studies, there is no clear consensus on the compressive strength of concrete with RSWT additives. Some researchers say that RSWT decreases compressive strength [40,41]. However, some have mentioned the limited positive effect of RSWT on the compressive strength of concrete [32,42–44]. According to Caggiano et al. [45], increasing amounts of fibers (or higher aspect ratios) may enhance the compressive strength of concrete up to a certain threshold; however, a larger amount of steel fibers (beyond that threshold) could have an adverse effect on the resulting compressive strength, thus generating a loss in strength. The researchers found that there was no significant relationship between the increase in the RSWT ratio and the increase in compressive strength [42]. A significant problem is the inability to achieve homogeneity at high dosages of RSWT and the aggregation of RSWT in a certain region. There is a similar lack of information in the change of modulus of elasticity in RSWT-reinforced concrete, as pointed out by Bjegovic et al. [46] and Papakonstantinou and Tobolski [40].

From the above comparisons, it is understood that fiber-reinforced concrete has a positive effect on the mechanical performance of the concrete. However, when the issue is limited resources and sustainability, research on recycled materials such as steel wires from waste tires becomes more valuable.

In the literature, the contribution of RSWT to the mechanical properties of concrete in cube, cylindrical or prismatic (Caggiano et al.) [45] concrete elements has been investigated. Experiments on reinforced-concrete members such as beams, columns, slabs, etc., are very limited. To the authors' best knowledge, only few experimental studies have been carried out so far on reinforced-concrete members containing RSWTs. In particular, in reinforced-concrete elements, bending and tensile damage, which occurs due to the fact that the tensile strength of concrete is quite low and it has a brittle structure, can sometimes occur under service loads and under the influence of loads such as seismic loads. Apart from this, time-dependent creep deformation and shrinkage can cause significant damage to the concrete. After the formation of this damage, repair or strengthening may be required in the load-carrying members. Among this damage, shear damage is a type of damage

that is frequently seen and is relatively more difficult to repair than others. It is possible to prevent such damage with additional materials such as fiber to be used in the concrete.

In this study, the main motivation is to determine the shear behavior of small-scale reinforced-concrete beams manufactured with RSWT at various rates. Based on this motivation, an experimental study was planned. The experimental program consisting of 12 shear deficient reinforced-concrete beam specimens was conducted in Necmettin Erbakan University, Konya, Turkey. All rectangular specimens had cross sections of 100 mm  $\times$  150 mm and lengths of 1000 mm. The concrete used in the beams was produced with RSWTs in different volumetric ratios (0%, 1%, 2% and 3%). The shear reinforcement (stirrups) was kept very limited as the change in shear capacity of the beams was tested. Beams were manufactured with 6 mm diameter stirrups at 16, 20 and 27 cm spacings. In the beams, 2 $\phi$ 12 in the tension zone and 2 $\phi$ 6 in the compression zone was used as longitudinal reinforcement. In the four-point bending test, the change in shear capacity of shear beams was examined.

## 2. Materials and Methods

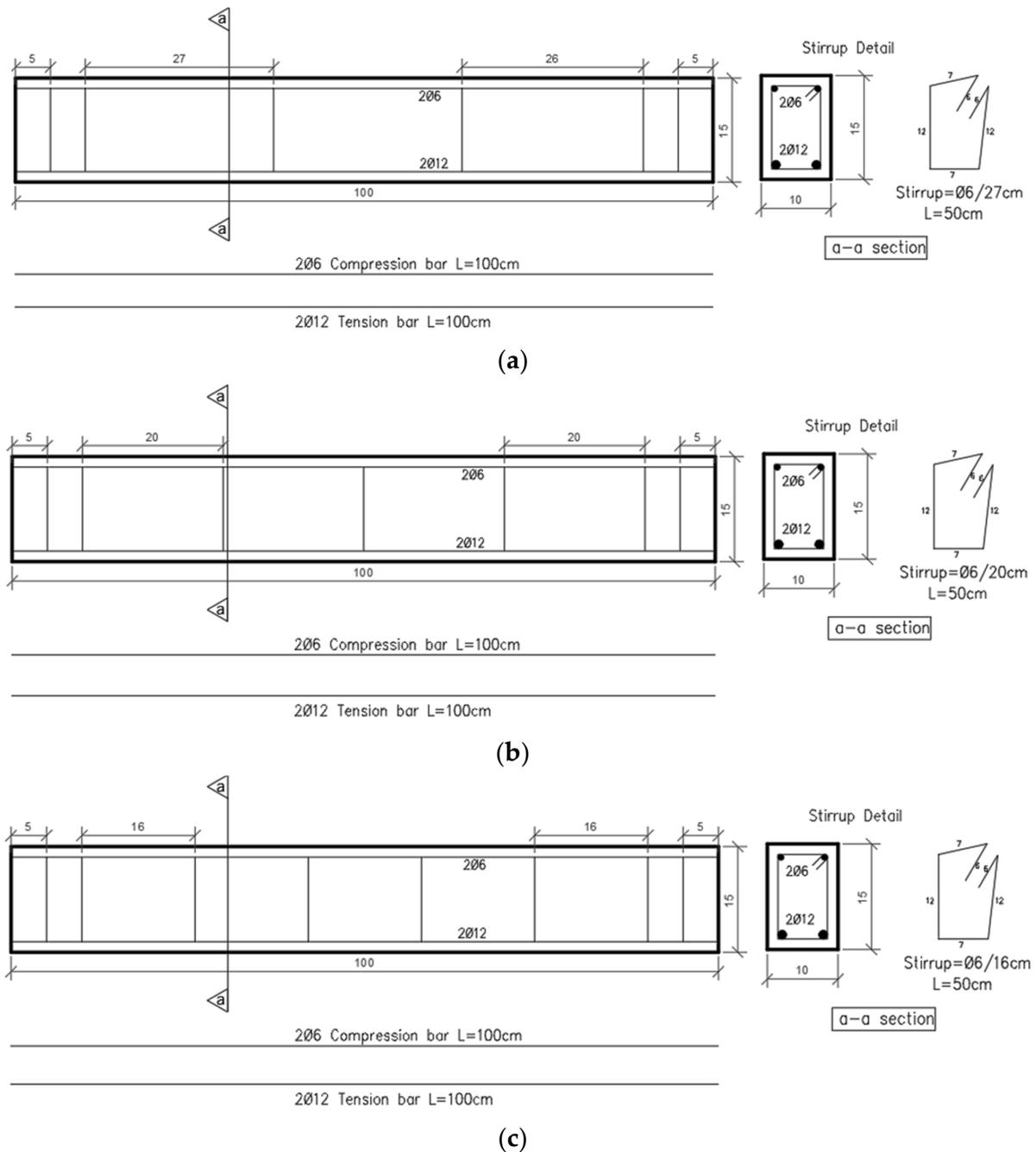
In this study, recycled steel wires obtained from waste tires were utilized. The used steel wires are shown in Figure 1. The geometry of steel wires was irregular but generally linear. Average length of the steel wires was approximately 30–50 mm. The use of steel wires is higher than 100 mm was avoided to prevent aggregation. For concrete production, CEM I 32.5 type of Portland cement was utilized. The water–cement ratio utilized was 0.6. The cement aggregate ratio was 0.22. Waste lathe scraps were utilized in order to increase the shear performance of the beams.



**Figure 1.** The recycled steel wires used in this study.

The experimental program consisting of 12 specimens was conducted in Necmettin Erbakan University. All specimens had cross sections of 100 mm  $\times$  150 mm and lengths of 1000 mm. Tensile longitudinal reinforcement of 2 $\phi$ 12 and compressive longitudinal reinforcement of 2 $\phi$ 6 was utilized for all specimens. The specimens were designed under a balanced reinforcement ratio of 0.0125. Stirrups of  $\phi$ 6 with three different spacings were considered. The spacings were 27 cm, 20 cm and 16 cm to obtain shear damage. Moreover, 1%, 2%, and 3% volumetric fiber ratios ( $V_f$ ) were studied. Using more than 3% volumetric fiber ratio ( $V_f$ ) was avoided, since it is difficult to work with a 3%  $V_f$  fiber ratio. Most probably, aggregation problems would occur if more than 3%  $V_f$  fiber ratio was utilized. Due to the possible aggregation problems, the compressive strength and tensile strength would be reduced if more than a 3% fiber ratio was used. Similar results were also reported,

with steel wires with more than 3% causing workability problems [36,47]. In order to eliminate the aggregation problem, small amounts of steel waste fibers were slowly and continuously added in the mixer. The details of the specimens, along with their names, are shown in Table 1. The reinforcement layout utilized in the specimens is demonstrated in Figure 2.



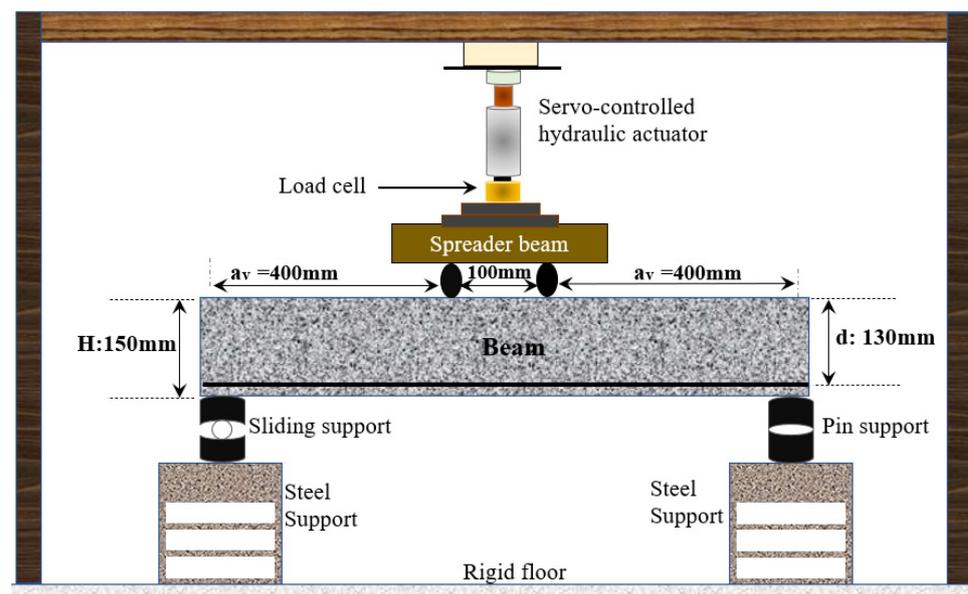
**Figure 2.** Reinforcement layout for specimens. (a) Stirrup spacing 27 cm. (b) Stirrup spacing 20 cm. (c) Stirrup spacing 16 cm.

**Table 1.** Properties of specimens.

#	Name	Stirrups Diameter/Spacing	Volumetric Ratio of Stirrups ( $\rho_w$ ) %	$V_f$ %
1	S-REF1	$\Phi 6/27$	2.1	0
2	S-REF2	$\Phi 6/20$	2.8	0
3	S-REF3	$\Phi 6/16$	3.53	0
4	S-TIRE1	$\Phi 6/27$	2.1	1
5	S-TIRE2	$\Phi 6/20$	2.8	1
6	S-TIRE3	$\Phi 6/16$	3.53	1
7	S-TIRE4	$\Phi 6/27$	2.1	2
8	S-TIRE5	$\Phi 6/20$	2.8	2
9	S-TIRE6	$\Phi 6/16$	3.53	2
10	S-TIRE7	$\Phi 6/27$	2.1	3
11	S-TIRE8	$\Phi 6/20$	2.8	3
12	S-TIRE9	$\Phi 6/16$	3.53	3

The specimens were loaded under four-point loading. The specimens were placed on two types of supports: pin and roller supports. A shear span to effective depth ( $a_v/d$ ) of 3.1 was seen to have shear failure [48,49]. During the experiments, the load and displacements were recorded. The test setup is shown in Figure 3. The volumetric ratio of stirrups ( $\rho_w$ ) was calculated using Equation (1). Here,  $n$ : number of stirrup arms;  $A_{sw}$ : stirrup cross-sectional area;  $b_w$ : beam width; and  $s$ : application range of stirrups.

$$\rho_w = \frac{n \times A_{sw}}{b_w \times s} \quad (1)$$

**Figure 3.** Test setup.

In order to produce the beams, the CEM I 32.5 type of Portland cement was utilized. The chemical properties of this cement are given in Table 1. The water–cement ratio utilized was 0.6. The cement aggregate ratio was 0.22. Recycled steel wires from waste tires (RSWT) were utilized to increase the beams' bending performance. The RSWT used in this study was helical. The recycled lathe scraps were divided into small pieces before being used. For each sample, 10 cm × 20 cm, 15 cm × 15 cm × 15 cm cylindrical and cube samples were used for compressive and splitting tensile tests.

In addition, a slight decrease in the workability of the concrete was observed with the addition of fibers. However, this did not cause a decrease in the compressive strength, as the compression processes were carried out appropriately in cylinder and cube preparation.

### 3. Experimental Results and Discussion

In the material tests, cylinder (10 cm × 20 cm) and cube (15 cm × 15 cm × 15 cm) compressive strengths were obtained as 25 MPa and 29.5 MPa, respectively, for concrete without any fibers. They were then calculated as 29 MPa and 34.6 MPa for 1% fiber content, 32 MPa and 38.6 MPa for 2% fiber content, and 37 MPa and 43.2 MPa for 3% fiber content. As a result of the cylinder (10 cm × 20 cm) tests used for splitting tensile strengths, 2.83 MPa in the reference sample, 3.24 MPa in the sample containing 1% fiber, 3.54 MPa in the sample containing 2% fiber and 3.87 MPa in the sample containing 3% fiber were obtained. When the conversion coefficients (0.8 and 1.05) are applied for the standard cube (15 cm × 15 cm × 15 cm) and standard cylinder (15 cm × 30 cm), the compressive strength for the reference sample is 23.6 MPa, for the 1% fiber content 27.68 MPa, for the 2% fiber content 30.88 MPa, and for the 3% fiber content 34.56. These were taken into account in the calculations as the MPa.

In the experimental study, vertical load midpoint displacement graphs of each sample were drawn. Three different reference samples (SREF-1, SREF-2 and SREF-3) that did not contain any RSWT were considered in the study as well as those with RSWT at different rates (STIRE-1, STIRE-2, STIRE-3, STIRE-4, STIRE-5, STIRE-6, STIRE-7, STIRE-8 and STIRE-9); by comparing a total of 12 different samples, information on the changes in the shear behavior of the beams was attained. The changes in load, displacement, stiffness, ductility and energy dissipation capacities obtained from experimental studies are given in Tables 2 and 3. Their production is shown in Figure 4.

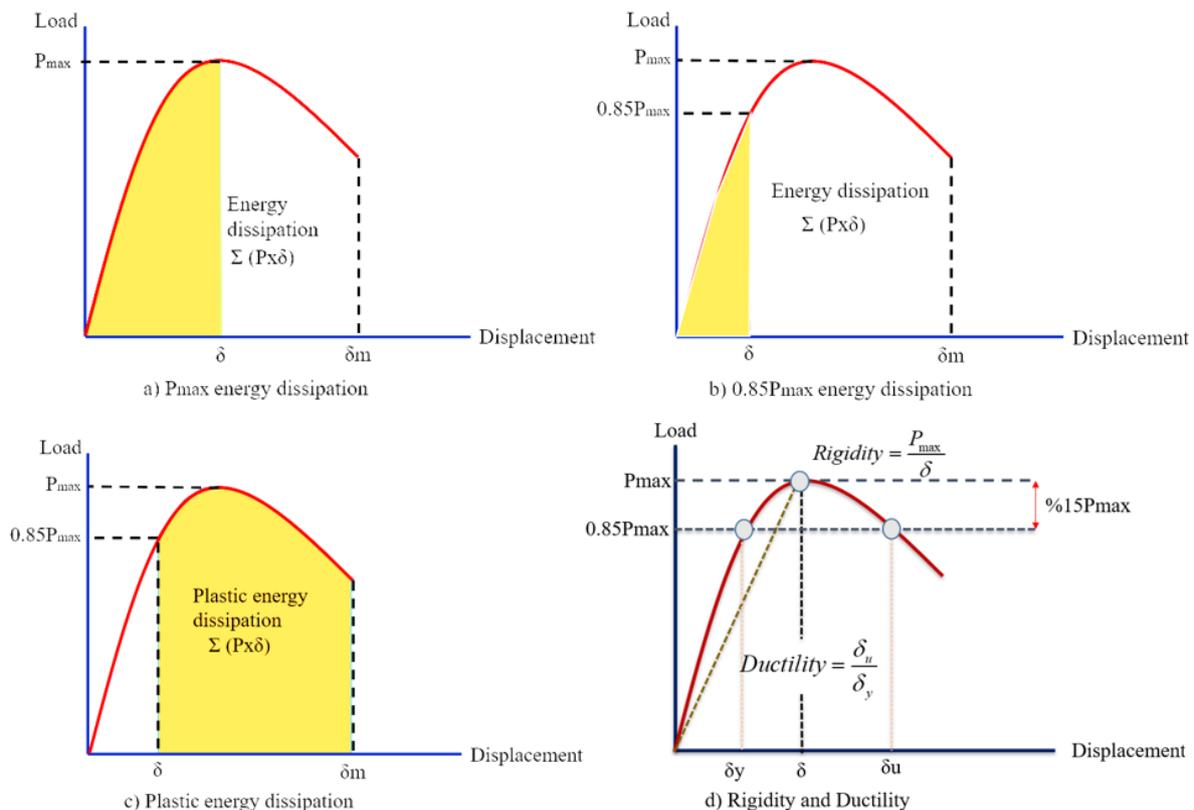


Figure 4. Energy dissipation capacity, ductility, and rigidity calculation of specimens.

**Table 2.** Experimental results for load and displacement values.

Test Specimens	$P_{max}$ (kN)	Displacement at $P_{max}$ (mm)	Stiffness at ( $P_{max}$ ) (kN/mm)	$P_u$ (0.85 $P_{max}$ ) (kN)	Displacement at Yield $\delta_y$ (mm)	Stiffness at Yield (0.85 $P_{max}$ ) (kN/mm)	$\delta_u$ (mm)	Ductility Ratio
SREF-1	39.90	4.55	8.75	33.91	3.39	10.00	6.53	1.92
SREF-2	45.16	7.23	6.24	39.39	4.92	7.79	8.27	1.68
SREF-3	51.40	6.41	8.01	43.69	5.04	8.66	14.44	2.86
STIRE-1	46.27	6.49	7.12	39.33	4.04	9.73	7.70	1.90
STIRE-2	51.04	7.07	7.21	43.39	5.30	8.17	8.97	1.69
STIRE-3	54.46	7.18	7.58	46.29	5.22	8.85	18.15	3.47
STIRE-4	51.21	7.97	6.41	43.53	4.04	10.77	8.19	2.02
STIRE-5	54.10	6.78	7.97	45.98	5.35	8.58	11.10	2.07
STIRE-6	57.07	8.32	6.85	48.51	5.80	8.36	16.73	2.88
STIRE-7	55.12	7.24	7.60	46.85	4.34	10.78	9.29	2.13
STIRE-8	56.68	7.30	7.75	48.18	5.69	8.46	12.70	2.23
STIRE-9	58.19	10.08	5.76	49.46	5.71	8.65	16.52	2.88

**Table 3.** Experimental test results for energy dissipation capacities.

Test Specimens	Maximum Displacement (mm)	Energy Dissipation at $P_{max}$ (kJ)	Energy Dissipation at 0.85 $P_{max}$ (kJ)	Plastic Energy Dissipation (kJ)	Total Energy Dissipation (kJ)	Failure Type	Ductility Level
SREF-1	12.52	0.103	0.059	0.249	0.308	Shear	Deficient
SREF-2	18.33	0.195	0.103	0.407	0.509	Shear	Deficient
SREF-3	22.12	0.178	0.113	0.685	0.798	Shear	Deficient
STIRE-1	19.44	0.195	0.094	0.444	0.538	Shear	Deficient
STIRE-2	21.67	0.204	0.115	0.548	0.664	Shear	Deficient
STIRE-3	27.77	0.230	0.126	0.983	1.109	Shear	Partially Sufficient
STIRE-4	15.00	0.282	0.088	0.394	0.482	Shear	Deficient
STIRE-5	19.84	0.191	0.117	0.663	0.779	Shear	Deficient
STIRE-6	27.51	0.286	0.147	1.059	1.207	Shear	Deficient
STIRE-7	17.45	0.262	0.108	0.510	0.618	Shear	Deficient
STIRE-8	21.40	0.398	0.138	0.749	0.887	Shear	Deficient
STIRE-9	27.45	0.400	0.157	1.037	1.194	Shear	Deficient

As seen in Table 3, the load carrying capacity of SREF-1, SREF-2 and SREF-3 reference samples without RSWT decreased with the increase in the transverse reinforcement spacing (SREF-1 < SREF-2 < SREF-3). When the transverse reinforcement spacing was reduced from 27 cm in SREF-1 to 20 cm in SREF-2, a 13% increase in load carrying capacity was observed. Similarly, when the transverse reinforcement spacing was reduced to 16 cm in SREF-3, the load carrying capacity increased by 29%. This situation remained valid for the samples in the range of STIRE-1 to STIRE-9 with different ratios of RSWT content, and an increase in load carrying capacity was observed as the transverse reinforcement spacing decreased (Figures 5–7). According to SREF-1, with transverse reinforcement spacing of 27 cm and no RSWT, load carrying capacity and displacement value against maximum load are 16–42.6% in STIRE-1 containing 1% RSWT, 28–75.1% in STIRE-4 containing 2% RSWT, and a 38–59.1% increase in STIRE-7 containing 3% RSWT (Figure 5). Compared to the SREF-2 with a stirrup spacing of 20 cm, the STIRE-2 with 1% RSWT had a 13% increase in load carrying capacity and a 2.2% decrease in the maximum load versus displacement value, while the STIRE-5 with 2% RSWT had a 13% increase in load carrying capacity. 19.7% increase in maximum load was detected in STIRE-8 with 3% RSWT (Figure 5). Finally, compared to SREF-3 with a stirrup spacing of 16 cm, STIRE-3 with 1% RSWT increased the load carrying capacity and displacement value against maximum load by 5.9–10.45%, and for STIRE-3 with 2% RSWT 11.03%. There was a 29.79% increase and a 13.2% increase in STIRE-9 containing 3% RSWT. In other words, while an increase was observed in the displacement values under maximum load for the samples with 1%, 2% and 3% RSWT content with a stirrup spacing of 27 cm and 16 cm, a decrease was observed in the samples

with a stirrup spacing of 20 cm and a RSWT ratio of 1% and 2%. This naturally led to an increase and decrease in the stiffness values under maximum load. In other words, the highest stiffness value under maximum load occurred in SREF-1 (8.75 kN/mm) with no RSWT and 27 cm transverse reinforcement spacing, while the lowest stiffness value was seen in STIRE-9 with 16 cm transverse reinforcement spacing and 3% RSWT (5.76 kN/mm). Considering the 0.85  $P_{max}$  value, where the linear elastic capacity is represented, the yield load carrying capacity increases with the decrease of the transverse reinforcement spacing, as in  $P_{max}$ , and this value increases as the RSWT ratio increases. In addition, when the displacement values corresponding to 0.85  $P_{max}$  were examined, an increase was observed as the RSWT ratio and transverse reinforcement spacing increased. The highest stiffness value corresponding to the yield moment was 10.78 kN/mm for STIRE-7, while the lowest value was 8.36 kN/mm for STIRE-6. The yield ( $\delta_y$ ) and rupture ( $\delta_u$ ) displacement values are two important parameters for ductility. According to the literature [50], a sufficient ductility ratio (ductility coefficient) for a sub-balanced ductile design is around 4~5. Although partial ductility was observed in the STIRE-3 sample, sufficient ductility was not observed the other samples. However, as the transverse reinforcement spacing and RSWT ratio increased,  $\delta_u$  reached higher values. This is an indication of improvement in ductility. While the ductility rate was highest in STIRE-6 and STIRE-9 samples, the lowest ductility rate was obtained for the sample with 20 cm transverse reinforcement spacing and no waste steel wire.

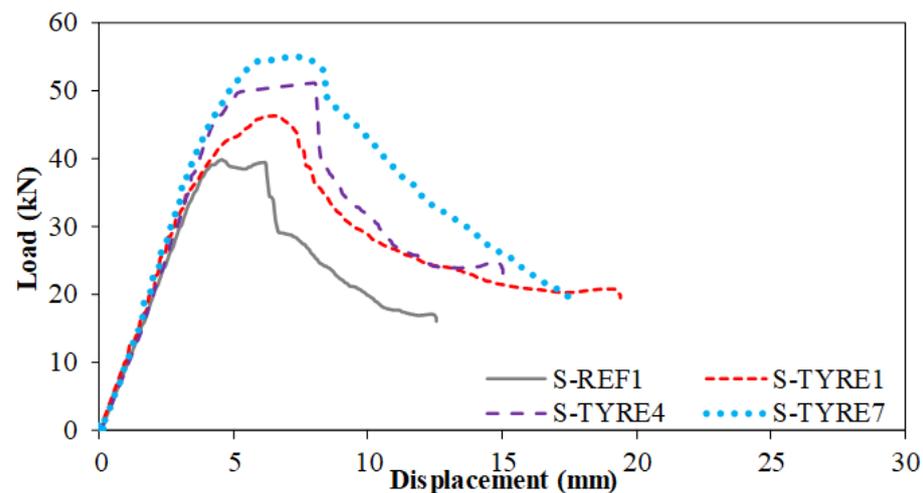


Figure 5. Comparison of the samples with 27 cm transverse reinforcement spacing.

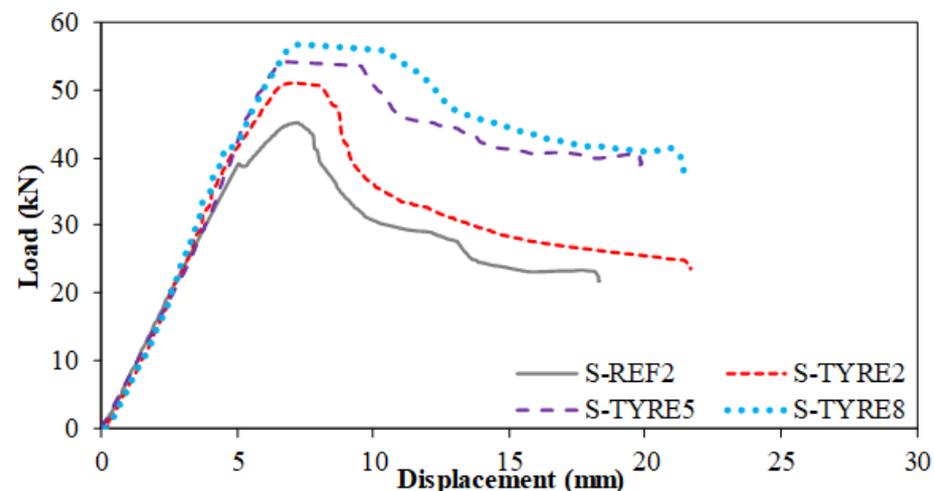
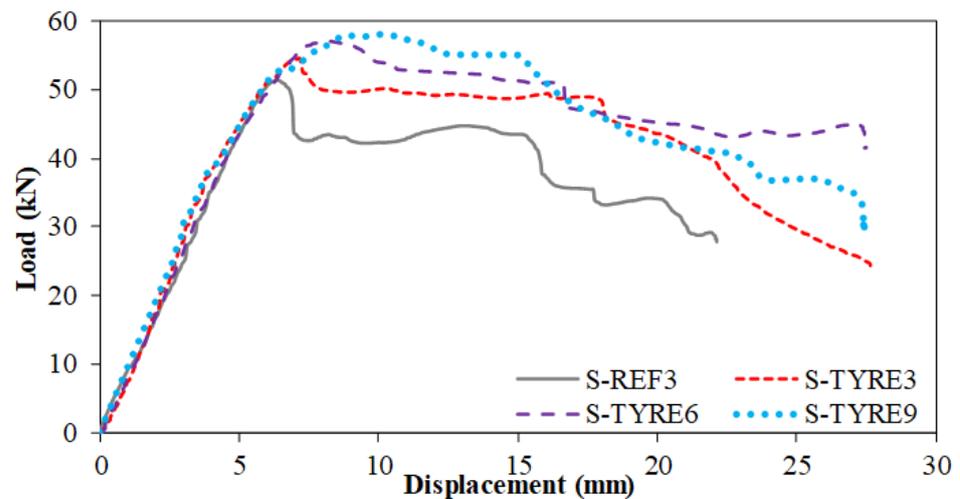
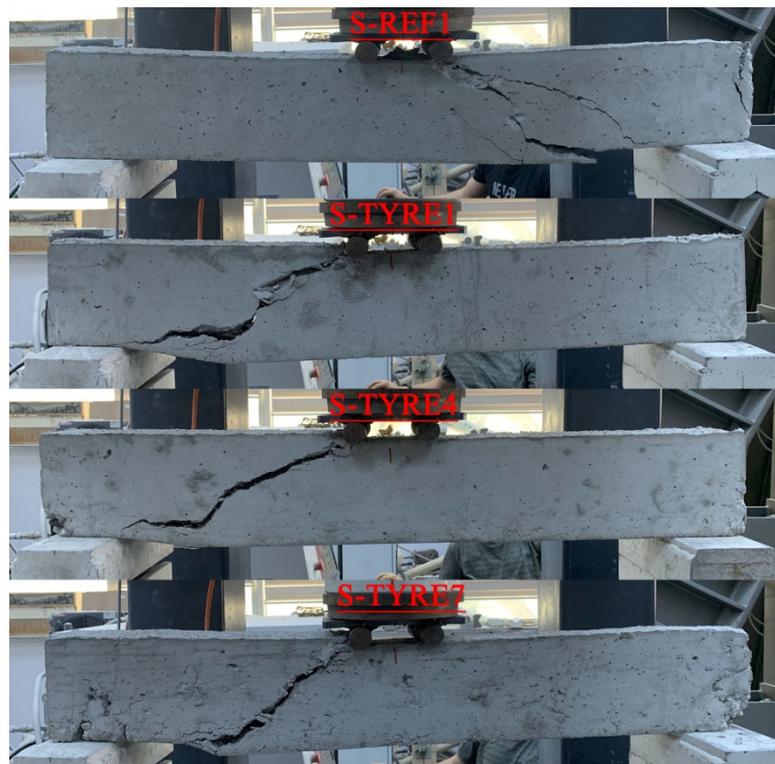


Figure 6. Comparison of the samples with 20 cm transverse reinforcement spacing.



**Figure 7.** Comparison of the samples with 16 cm transverse reinforcement spacing.

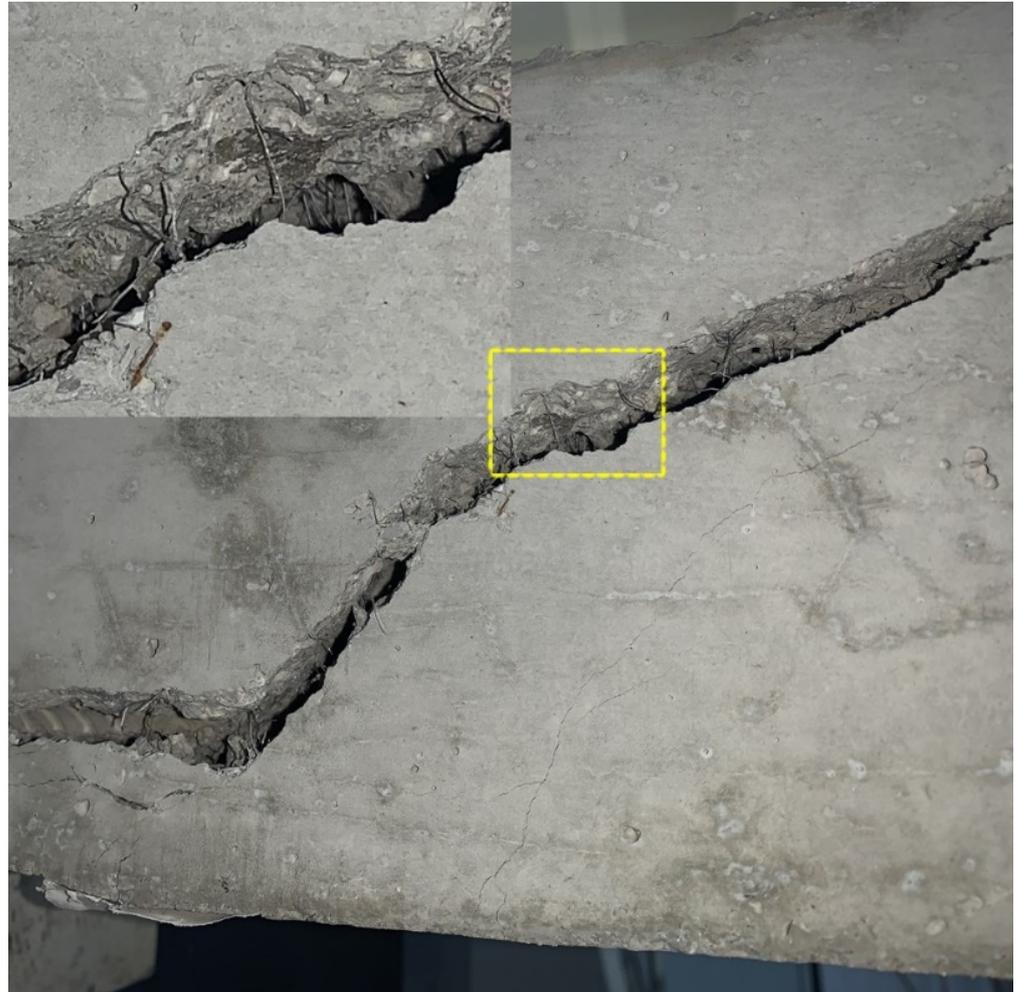
When Figures 5–7 are examined, it is understood that the use of RSWT in concrete makes a significant contribution to both displacement and load carrying capacity. For the samples (SREF-1, STIRE-1, STIRE-4 and STIRE-7) with the same transverse reinforcement spacing (27 cm) as shown in Figure 5, the end-of-test damage views are shown in Figure 8.



**Figure 8.** Damage views of the reference sample and samples with 27 cm transverse reinforcement spacing and RSWT ratios of 1%, 2% and 3%.

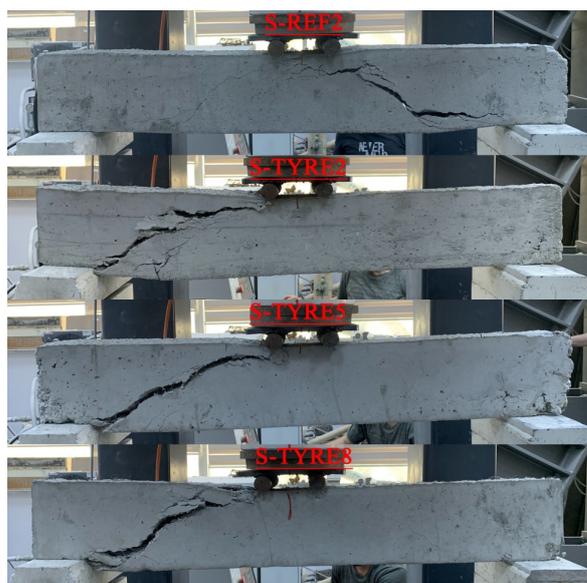
As seen in Figure 8, typical shear damage was observed in all samples. However, when the fracture patterns are examined, it is understood that the fracture direction changes with the increase in the fiber ratio. Especially in STIRE-7, where the fiber ratio is 3%, damage close to  $45^\circ$  occurred, while cracks were observed between  $45\text{--}60^\circ$  in other samples. As the stirrup spacing was high and the fiber ratio was the highest, adherence cracks were

observed in the samples, except for STIRE-7. The relatively high fiber content in STIRE-7 limited the occurrence of this damage. RSWT appearance after fracture in the STIRE-4 specimen, as shown in Figure 9. In Figure 9, it can be seen that RSWT act as bridges between concrete parts. However, since they have a certain length, they break with the increase of the load in the shear zone. This situation indicates that more load can be carried and fibers can work together with concrete by increasing the fiber ratio to optimum levels.



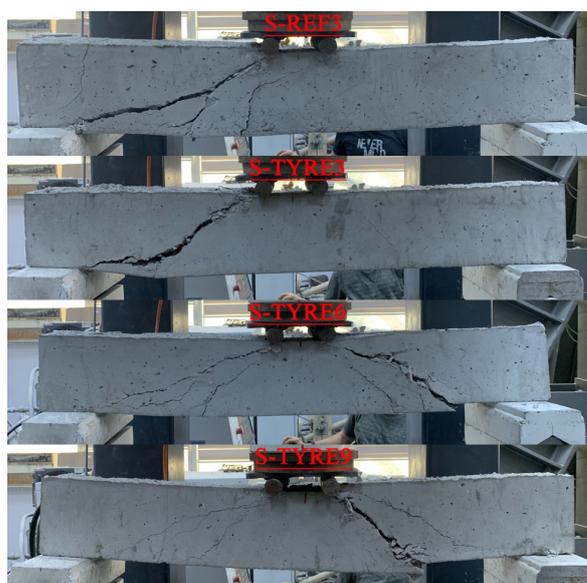
**Figure 9.** Close view of specimen STIRE-4.

The damage views at the end of the test are shown in Figure 10, with the transverse reinforcement spacing reduced to 20 cm (SREF-2, STIRE-2, STIRE-5, STIRE-8). Here, too, typical shear damage occurred, but the shear fracture caused by the reduction of the stirrup spacing extended from the support face to the lower point of the spreader beam to form an angle of 45–60°. Here, while adherence damage was observed towards the support in the SREF-2 sample, this situation was not observed in the other samples. Decreased stirrup spacing and fiber additives limited the occurrence of this damage. In other words, a change was observed in the damage behavior. Thus, the greatest contribution to the change was provided by reducing the stirrup spacing to 20 cm.



**Figure 10.** Damage views of the reference sample and samples with 20 cm transverse reinforcement spacing and RSWT ratios of 1%, 2% and 3%.

In the experimental study, SREF-3 was obtained by adding different fiber ratios to the samples with the most frequent stirrup spacing (16 cm): STIRE-3 and STIRE-6. At the end of the experiment, STIRE-9 specimens suffered shear damage and collapsed, as shown in Figure 11. Here, the fracture behavior observed in the samples with a fiber ratio of 2% (STIRE-6) and 3% (STIRE-9) was different from all other samples. The bending capacity of the beam is forced, but the bending capacity of the beam is higher than the shear capacity, so the cracks in the bending region are limited. Therefore, shear cracks in both shear openings of the beam became evident. Finally, shear fracture occurred in the right shear opening in both samples. Notice that in STIRE-6, the fracture ended after approximately  $h$  in the support flat, and in STIRE-9, after about  $2h$  due to the support. This indicates that the fibers increase the shear capacity and contribute to the orientation of the damage towards the bending zone.



**Figure 11.** Damage views of the reference sample and samples with 16 cm transverse reinforcement spacing and RSWT ratios of 1%, 2% and 3%.

The vertical load values obtained experimentally as a result of the study were supported by analytical work. The analytical study was carried out using the shear capacity formulas given in TS500-2000 [51]. The corresponding formulas are given in Equations (2)–(6):

$$V_c = 0.65 \times f_{ct} \times b_w \times d \quad (2)$$

$$V_w = n \times \frac{A_{sw}}{s} \times f_{yw} \times d \quad (3)$$

$$V_r = V_c + V_w \quad (4)$$

$$f'_{ct} = \frac{2P}{\pi DL} \quad (5)$$

where  $V_c$  is the contribution of concrete to shear capacity,  $f_{ct}$  is the axial tensile strength,  $f'_{ct}$  is the split tensile strength,  $b_w$  is the width of the beam,  $d$  is the useful height value,  $V_w$  is the contribution of stirrup shear,  $n$  is the number of stirrup legs,  $A_{sw}$  is the reinforcement area of the stirrup,  $s$  is the stirrup spacing,  $f_{yw}$  is the stirrup yield strength,  $P$  is the vertical breaking load,  $D$  is the diameter of the cylinder sample,  $L$  is the length of the cylinder sample and  $V_r$  is the sum of the contribution of concrete and stirrup to the shear capacity. Analytical calculations were made using the data obtained according to the experimental cylinder and cube sample results. The analytical calculation results obtained to be compared with each test sample are given in Table 4. In Table 4, it is seen that the experimental and analytical calculations are in harmony. This shows that calculations can be made if different fiber ratios are taken into account.

**Table 4.** Experimentally and analytically obtained maximum load carrying capacities of the samples.

Test Specimens	Experimental	Analytical	Ratio *
	$P_{max}$ (kN)	$P_{max}$ (kN)	
SREF-1	39.90	40.34	1.01
SREF-2	45.16	45.47	1.00
SREF-3	51.40	50.42	0.98
STIRE-1	46.27	44.15	0.95
STIRE-2	51.04	49.26	0.96
STIRE-3	54.46	54.23	0.99
STIRE-4	51.21	46.87	0.91
STIRE-5	54.10	52.00	0.96
STIRE-6	57.07	56.95	0.99
STIRE-7	55.12	49.82	0.90
STIRE-8	56.68	54.95	0.97
STIRE-9	58.19	59.90	1.03

\* Analytically and experimentally obtained  $P_{max}$  ratios.

Three different transverse reinforcement spacings (27 cm, 20 cm and 16 cm) were considered in the study. This study makes an important contribution to the results obtained for samples with different spacing and different sizes. In the study, 6 mm was considered as the transverse reinforcement diameter. The effect of transverse reinforcement diameter change can be taken into account in future studies.

#### 4. Conclusions

At the end of a series of experimental studies, the effect of using a certain ratio (0, 1%, 2% and 3%) of RSWT on reinforced-concrete beam behavior in reinforced-concrete beams produced with different stirrup spacings (27 cm, 20 cm and 16 cm) was observed, and the results are summarized below:

1. RSWT added to the concrete by 1%, 2% and 3% increased the compressive strength by 17.2%, 30.8% and 46.4%, respectively, compared to the reference concrete. In split

tensile strength, 14.4%, 25.1% and 36.7% increases were observed, respectively. This showed that there was an effective increase in the compressive and tensile strength of concrete with the increase of fiber content. Similar results were obtained in the experiments performed in the literature. For instance, Sahrei et al. [52] used RSWT to improve the mechanical properties of concrete, and it has been observed that fiber's effect on improving tensile and flexural strengths was much more significant (with 1% RSF enhancement of 11, 90, and 122%, for compressive strength, splitting tensile strength, and flexural strength, respectively, in comparison with the plain mixture. In the literature, similar results have been found by other researchers [53–60].

2. With the increase of the RSWT ratio, both the  $0.85 P_{\max}$  value and the  $P_{\max}$  value of the samples increased. Thus, it was concluded that the beam behavior improved with the increase of the fiber ratio.
3. All beams reached failure mode with shear damage. Dominant cracks started at the shear opening and extended to the spreader beam. In addition, no ductile behavior was observed, even at the rate of 3% RSWT. This is due to the high beam bending capacity. The load carrying capacity obtained from STIRE-7 and STIRE-9 with a 3% RSWT ratio increased by 38.14% and 13.2%, respectively, compared to SREF-1 and SREF-3. Since the analytically calculated bending capacity of the reference SREF-1, SREF-2 and SREF-3 was 74.66 kN, the contribution of the fibers to the load bearing capacity was not sufficient to observe the ductile behavior.
4. Total energy consumption increased as the transverse reinforcement spacing decreased. In addition, it is understood that there is a linear relationship between the increase in the fiber content and the increase in the total energy consumption capacity.
5. Although the effect of fiber content in samples with high stirrup spacing (27 cm) provides significant benefit in improving the beam behavior, the effect of fibers was more limited as the stirrup spacing decreased (20 cm and 16 cm).
6. An approximation of over 91% was obtained between the analytical calculations and the experimental results. This shows that the analytical calculations given in the standards can be used for new experimental studies.
7. Because as fiber is added the workability of concrete may decrease, it is necessary to increase the water/cement ratio, and a decrease in mechanical properties can be expected as the water–cement ratio increases. In this study, compaction of concrete was carried out fairly regularly under laboratory conditions. However, in real practice, it is difficult to achieve this level of production quality in large-scale manufacturing.

Although there are some studies in the literature on the behavior of concrete produced by using RSWT, it is extremely important for the continuation of these studies in terms of the results obtained, examining the behavior change with the shear beam tests used in this study. In addition, the fact that RSWT mixed into concrete in certain proportions in the study can be produced by recycling methods is also extremely important in terms of the use of alternative waste materials in reinforced-concrete structures.

The competition in the market is ever-increasing; companies are trying to improve their current situation with new products. Especially in the traditional and prefabricated reinforced-concrete construction sector, companies are looking for new materials and approaches that will improve building behaviors in response to earthquakes. With this study, the waste RSWT was recovered in the construction sector. The behavior change of the structure can be examined by adding RSWT at the appropriate rate into the concrete in conventional or prefabricated reinforced-concrete structures, with tests of RSWT at different rates to be carried out in the future.

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