*Turkish Journal of Civil Engineering, 2024 133-142, Paper 784, **Technical Note***

Flexural Experiments on B58 Type Railway Sleepers with Different Dosages of Steel Fibers

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ABSTRACT

The flexural strengths and toughnesses of 15 post-tensioned B58 type railway sleepers produced at the Turkish State Railroads Sivas Plant using C40 class concrete with addition of hooked steel fibers at dosages of 0, 20, 30, 40, 50 kg/m^3 were experimentally determined. Four-point flexural experiments were applied to them in one month after their production and proper curing. Three cylindrical samples of 15×30 cm dimensions taken from the first and the fourth batches apiece were subjected to standard compression tests with compressometer rings mounted on each sample after having been cured in 21 °C water tank for 28 days, resulting in their compressive strength and modulus of elasticity. Modeling a railway sleeper as a post-tensioned reinforced-concrete beam, the maximum load it can resist in the experimented configuration was calculated by the ultimate-strength method using its dimensions and material properties. The experimentally-measured maximum load carried by the reference sleeper without any steel fibers was found to be 1.34 times the theoretically-calculated value, and the same ratio was found to be 1.59 for the sleepers having steel fibers of 40 kg/m^3 dosage, accounting for an increase of 18%. And, the experimentally-measured toughness of the sleepers with 40 kg/m^3 dosage steel fibers was found to be 23% greater than that of the reference sleepers.

Keywords: Concrete railway sleepers, steel fibers, flexural strength, toughness.

1. INTRODUCTION

Addition of steel fibers to structural concrete with dosages of about 30 ~ 50 kg/m^3 improves its crack behavior and its tensile strength by making it less brittle at the expense of a small increase in its cost. There are standards, regulations and technical publications about steel-fiber-added concrete [e.g. 1, 2, 3]. Experimental studies were done at the Civil Engineering

Note:
- This paper was received on November 24, 2023 and accepted for publication by the Editorial Board on April 5, 2024.
- Discussions on this paper will be accepted by November 30, 2024.

- https://doi.org/10.18400/tjce.1394166

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Department of Erciyes University in 2000s about the effect of steel fibers on the flexural strength of reinforced-concrete (RC) beams, RC box beams [4, 5], and on the bearing strength of concrete sewer pipes [6]. Tangible improvements were observed in these elements using standard hooked steel fibers [7] having a tensile strength of 1050 N/mm^2, each having a length of 60 mm and a diameter of 0.75 mm. Having been influenced by these positive results, the same type of steel fibers were also tried in RC railway sleepers. They were produced as post-tensioned precast RC beams of 240 cm lengths by Sivas Plant of Directorate General of Turkish State Railroads (known by the acronym TCDD), as part of a M.Sc. thesis study [8]. Later, a few more experimental studies were done by other researchers about the effect of steel fibers on various mechanical properties of prestressed RC sleepers [e.g. 9, 10, 11, 12, 13, 14].

The report by Weisheit and Metzler [9] presents the results of a comprehensive experimental study which performed (1) compressive tests on 15 cm cubic samples, (2) four-point flexural tests on RC sleepers produced with a hybrid combination of fibers of steel, of plastic, and of glass as an admixture to high-strength concrete of C70 class, and (3) dynamic fatigue tests on these sleepers. Significant improvements in cracking behavior and in flexural and fatigue strengths were observed; however, no information about the cost of such modified sleepers was given [9].

Sadeghi et al [10] did detailed static and dynamic tests on prestressed RC sleepers with various amounts of a mixture of short and long steel fibers and different numbers of pre-stressing steel wires whose results indicated that the use of hybrid steel fibers in the sleepers led to tangible increases in their load-carrying capacity and flexural toughness while having almost the same natural dynamic frequency and damping ratios as the conventional ones. Sadeghi et al [10] concluded that such modified sleepers were more effective and cost efficient for high-speed tracks when compared with the conventional ones.

Parvez and Foster [11] did flexural and fatigue experiments on eight prestressed RC sleepers with steel fibers of dosages of 20 kg/m^3 and 40 kg/m^3 and concluded that the cracking behavior, the flexural and fatigue strengths of steel-fiber added sleepers improved; and, they recommended the dosage of 40 kg/m^3 as its performance was better than that of 20 kg/m^3.

Bae and Pyo [12] carried out flexural tests on post-tensioned RC sleepers produced by ultra-high performance concrete with steel fibers added at dosages of 0.5%, 1%, 1.5% by volume and recommended dosages of 1% and 1.5% for better flexural strength.

Wang et al [13] produced prestressed RC sleepers with four different combinations of steel fibers, which had volumetric dosages of 0.5% straight plus 1.5% hooked, 1.0% straight plus 1.0% hooked, 1.5% straight plus 1.0% hooked, the diameters and the lengths of straight and hooked fibers being 0.2, 13; 0.3, 22 mm. The tensile strength of these fibers were 2850 N/mm^2. The dimensions of these fibers are much smaller than 0.75 mm and 60 mm and the strength is much higher than 1050 N/mm^2 which are those of the hooked steel fibers used in our study [8]. Compressive and split tensile tests on 15 cm cubic samples and three-point flexural experiments yielded improved compressive, tensile and flexural strengths in all combinations; yet, 1.0% straight plus 1.0% hooked combination slightly outperformed the others, which revealed increases of 45% and 55% in compressive and flexural strengths as compared to the reference concrete mixes used in sleeper production [13].

In years 2021 and 2022, Çeçen and Aktaş published a few papers summarizing comprehensive experimental and theoretical studies on innovative concrete railway sleepers of the same dimensions as B70 type. Their developmental sleepers contained carbon-fiber-reinforced polyurethane laminates embedded in them instead of the post-tensioned steel bars. And, they asserted that these sleepers with no steel reinforcement bars had improved peculiarities over prestressed RC B70 type sleepers produced at Sivas Plant of TCDD. Those studies resulted in a novel patented non-prestressed product with a higher flexural strength, a highly improved fatigue behavior, much smaller probability of resonance with moving rail cars, smaller size crack formations, and much better damping ratios even after 50 cycles of 330 kN impact loadings than those of standard prestressed B70 type sleepers [15, 16, 17, 18, 19, 20, 21]. The post-tensioned steel tendons used in the conventional B70 sleepers are imported while the carbon-fiber-reinforced polyurethane (CFRP) laminates are produced in Türkiye. The cost of these new sleepers comprising CFRP laminates is just a little higher than that of the B70 types, but, the benefits such as no steel reinforcement and hence no post-tensioning, shorter manufacturing time, better fatigue strength, and longer service life will outweigh the B70 type sleepers. Although this newly put forth L-CFRP sleeper was shown to outperform the commonly used B70 type in many relevant peculiarities, it is yet to be verified in actual field applications.

Ahmed et al [14] applied static bending tests on B70 type of prestressed RC sleepers produced with C50 class of concrete in which steel fibers at volumetric dosages of 0%, 0.5%, 1%, and 1.5% were added, and they found that the first cracking load, failure load, failure mode, crack sizes, and load-deflection curve peculiarities of the steel-fiber added sleepers improved significantly.

Çankaya and Akan experimentally determined that addition of steel fibers to their concrete mixtures by a dosage of 1% in absolute volume increased the flexural strength of reinforced concrete beams by about 10% [22].

Türker et al, as a result of four-point flexural experiments on beams of 150×250×2500 mm dimensions, experimentally determined that addition of commonly used hooked steel fibers to ultra-high-performance concrete mixtures improved the flexural strength of reinforced-concrete beams by about 15% with appreciably improved crack formations [23].

The objective of this note is to summarize the findings of the flexural experiments done on a total of 15 post-tensioned B58 type of RC sleepers produced with addition of 0, 20, 30, 40, 50 kg/m^3 hooked steel fibers of diameters and lengths of 0.75 mm and 60 mm having a minimum tensile strength of 1050 N/mm^2 in their concrete batches [8] and to compare their results with those of similar studies. A total of 15 sleepers, three of which having the same steel fibers dosage, were tested and the average values were reported. According to the 2022 Annual Report by the General Directorate of Turkish State Railways, the total lengths of the conventional and the high speed railways under operation are 11688 km and 1460 km, respectively [24]. Up until ten years ago, mostly B58 type of sleepers were laid under the conventional railways. But, in recent years some of them have been replaced by higher-strength sleepers. Still, the experimental results obtained with B58 type of sleepers should be attributable to the B70 types because B70 are also prestressed RC units.

2. MATERIAL AND METHOD

2.1. Materials

The cement used in producing B58 type sleepers at TCDD's Sivas Plant is CEM I 42.5 R by EN 197-1. The 7-day and 28-day compressive strengths by the standard Rilem tests of EN 196 are about 40 and 50 N/mm^2. The mix recipe of the concrete used for B58 sleepers is given in Table 1.

Table 1 - Mix recipe of the C40 class of concrete used in B58 sleepers by Sivas Plant.

Ingredient	**Content** (kg)
CEM I 42.5 R	450
Tap water	135
River sand (Dmax=8 mm) (SSD)*	940
Fine crushed aggregate (Dmax=16 mm) (SSD)*	400
Coarse crushed aggregate (Dmax=32 mm) (SSD)*	500

*: SSD means "saturated surface-dry"

Two steel bars, each having a diameter of 9.4 mm, are used for post-tensioning. There are four circular tunnels throughout each sleeper of sufficient diameter so as to allow free passage of the post-tensioning bars. Both tips of each bar are grooved to be bolted after post-tensioning, and it is passed through two of the tunnels in diagonal position. A cross-shaped canal exists at one end of the sleeper, and a total of 320 kN tension force is uniformly applied to all four tip points of these two bars, and finally such stretched bars are firmly fixed in by an appropriate nuts-and-lock mechanism.

The average values of yield and ultimate strengths of three randomly taken samples of the post-tensioning steel bars used in the sleepers turned out to be 1264 N/mm^2 and 1619 N/mm^2 after having been subjected to standard tests in a certified Universal Testing Machine [8].

Five different batches of the mixture given in Table 1 were produced with dosages of 0, 20, 30, 40, 50 kg/m^3 of steel fibers. Three cylindrical samples of 15×30 cm dimensions were taken from the reference batch with no fibers and from the one with 40 kg/m^3 fibers and they were subjected to standard compression tests in a certified Compression Machine with a compressometer ring attached to each sample after having stayed for 28 days in curing tank. For each sample, the modulus of elasticity was computed as the slope of the line on the stress-strain curve passing through the points of 5% and 45% of the ultimate strength [8]. The average 28-day strength and modulus of elasticity for each sample of the two batches are given in Table 2.

The sleepers are treated in steam curing at 60 °C for about 10 hours in vapor room where they stay for 24 hours. A few days later, 15 sleepers manufactured with different dosages of steel fibers were transported from Sivas to the Structural Mechanics Laboratory of Erciyes University in Kayseri.

Table 2 - Average 28-day strength and elasticity modulus of concrete batches.

Batch	**Compressive strength** (N/mm^2)	**Elasticity modulus** (N/mm^2)
Mixture in Table 1 with no steel fibers	48.8	32,000
Mixture in Table 1 with 40 kg/m^3 steel fibers	57.1	29,000

2.2. Experiments

Because the objective of this experimental study was to observe the effects of addition of the hooked steel fibers of 80/60 dimensions having an ultimate strength of 1050 N/mm^2 in the mixture of C40 class of concrete used in production of B58 type of railway sleepers on their flexural strength and flexural toughness, each sleeper was treated as a simply-supported beam and hence was tested in a certified beam-testing setup by two-point loading as shown in Figure 1. In TS EN 13230-2 a similar configuration of flexural loading is specified [25] where the span length between the supports is 150 cm, which is the same as that in our tests. In TS EN 13230-2 a three-point flexural test is specified where the single load in mid-span of the sleeper is exerted by a resilient pad of 10×30 cm dimensions. Our loading rate was 10 tons/minute which was very close to 120 kN/minute given in TS EN 13230-2. Figure 2 shows the instant of placing a sleeper in the loading machine, and Figure 3 shows the beginning of the flexural experiment. The mid-span deflections were read from a strain gauge of 0.01 mm precision having a maximum range of 50 mm at every 0.5 tons of loading.

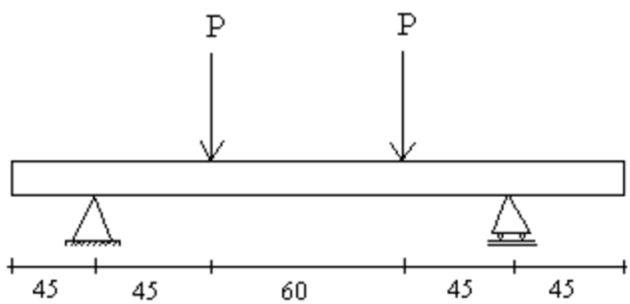

Figure 1 - Two-point loading configuration of a sleeper (dimensions are in cm).

These sleepers get slightly slender in height towards the mid-span, and the middle 30 cm part is approximately rectangular with a width of 185 mm and a height of 175 mm. The applied post-tensioning imposed a uniformly distributed compressive stress on the concrete part of each sleeper. The peculiarities and relevant quantities of the concrete and the reinforcing bars used in these sleepers were put in the appropriate steps of the analytical computations done in accordance with the ultimate-strength theory of prestressed RC section as articulated in Turkish Standard TS 3233 [26]. For example, the strain of the concrete (C40) at the outermost edge of the resisting cross-section was taken as 0.003, and the ultimate compressive strength of concrete was assumed to equal 85% of its characteristic strength. The details of these computations are given in [8]. The result of the theoretical analyses indicated an ultimate load of 2P = 85 kN for the loading configuration applied during the flexural experiments [8].

Figure 2 - A sleeper being carried to its position in the beam-loading machine (The other sleepers in stack waiting for their turns to be tested).

Figure 3 - A sleeper placed in the beam-loading machine in a two-point-loading position at the onset of the experiment.

3. RESULTS

The plots of 2P loads in metric tons against the mid-span deflections were drawn for each of the tested sleepers [8]. Here, Figure 4 shows the averaged such plots for all five combinations of sleepers. Table 3 presents: (1) the theoretical ultimate load computed by the ultimate-strength method treating a sleeper as a post-tensioned reinforced-concrete beam subjected to the two-point loading configuration in Figure 1, (2) the averaged observed loads to the first crack, (3) the averaged observed maximum resisted loads, and (4) the averaged flexural toughnesses. Flexural toughness of a reinforced concrete beam is a measure of its energy absorption capacity and is directly related to its ductility which characterizes its crack resistance. Experimentally, the flexural toughness is determined as the area under the load – midspan deflection curve. This area was computed numerically by the "trapezoidal integration".

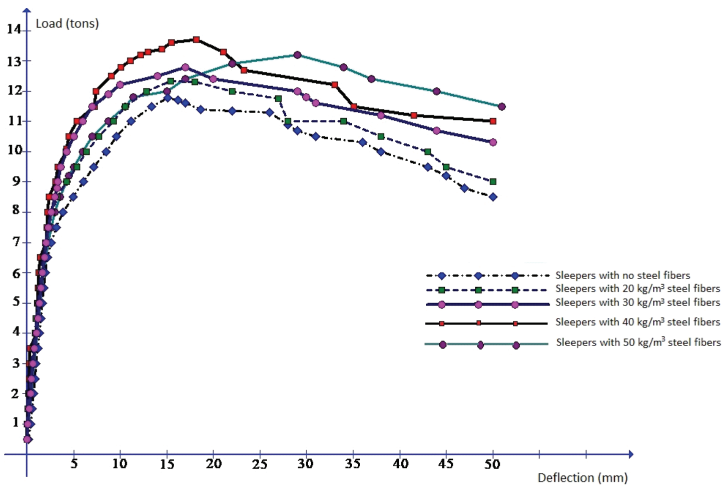

Figure 4 - The averaged plots of 2P loads against the mid-span deflections for all five combinations of sleepers.

Table 3 - Averages of the observed loads to the first crack, the maximum resisted loads, and the areas under the load-deflection curves of the experimented sleepers.

Sleeper Type	**Theoretical ultimate load** (kN)	**Load to first crack** (kN)	**Experimental ultimate load** (kN)	**Flexural toughness** (kN-mm)
Slprs with no SF*	85	80	114	4700
Slprs with 20 kg/m^3 SF	85	93	122	5200
Slprs with 30 kg/m^3 SF	85	94	123	5300
Slprs with 40 kg/m^3 SF	85	97	135	5800
Slprs with 50 kg/m^3 SF	85	95	131	5900

*: SF means "steel fibers"

We have contacted the responsible personnel both at the company producing the steel fibers and Sivas Plant of TCDD and we have obtained the information that recently the unit cost of the steel fibers is 1.5 Euro/kg and the cost of one standard sleeper is 55 Euro. Considering the fact that the concrete volume of a B58 sleeper is about 105 dm^3, 4.2 kg of steel fibers are used in a sleeper with a fiber dosage of 40 kg/m^3, bringing about an additional cost of 6.3 Euro per sleeper.

4. CONCLUSION AND DISCUSSION

Addition of steel fibers of 80/60 type which have an ultimate strength of 1050 N/mm^2 to the batch of C40 class of concrete used in production of B58 type RC railway sleepers with a dosage of 40 kg/m^3 (0.5% by volume) increased their flexural strength 18% and flexural toughness 23%. These positive increases in mechanical peculiarities will be realized at an additional cost of a 12% increase in the production of these sleepers.

Having done a detailed experimental study on the effects of various parameters of steel-fiber added concrete such as water/cement ratio, binder content, and fiber dosage on its electrical resistivity, Cleven et al [27] determined that the global electric resistivity of concrete with a steel fiber dosage of 40 kg/m^3 was about 30 Ωm while that of the reference concrete was around 60 Ωm in 185 days after pouring of concrete. Therefore, it is advisable to do in-situ tests to check whether any interference by such steel-fiber added sleepers laid down under railways will take place on signalization activities.

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