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Benefits of blast furnace slag and steel fibers on the static and fatigue performance of prestressed concrete sleepers

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ABSTRACT

This study investigates the influence of the use of steel fibers and ground granulated blast furnace slag (GGBFS) on the static and fatigue performance of prestressed concrete sleepers. Two series of sleepers with a partial replacement of type III cement by GGBFS (56% by weight of the binder) were tested and the performances of these sleepers were compared to conventional railway sleepers. One series of sleepers were reinforced with the same number of prestressing strands (sixteen strands) as conventional railway sleepers, while the other series of sleepers had a reduced number of strands (fourteen strands). Each series consisted of two types of sleepers with ($v_f = 0.75\%$) and without steel fibers. Static and fatigue tests causing positive moments at the rail seat section and additional static tests causing negative bending moments at the center section of the sleepers were carried out. The sleepers produced with GGBFS showed improved static flexural and fatigue performance at the rail seat section compared to conventional sleepers with Type III cement. The addition of steel fibers instead of conventional stirrups resulted in increased flexural and fatigue capacity at the rail seat section by controlling crack propagation and by preventing brittle shear failure. The performances of all sleepers at the center section were quite similar. The combination of the reduced number of strands together with steel fibers improves the performance and achieves greater economy.

1. Introduction

Prestressed concrete sleepers are widely used for application in railway construction [1–3]. However, increasing concerns about CO_2 emissions have led to efforts to use alternative materials for the manufacture of prestressed concrete sleepers [4]. Furthermore, premature failures of prestressed concrete sleepers caused by various types of loading and concrete deterioration have been reported [5–8]. The use of ground granulated blast furnace slag (GGBFS) as a concrete binder and the addition of steel fibers in concrete mixes can be used to address these issues. Previous studies [9–11] have shown that the use of GGBFS results in higher long-term strength, improved durability, as well as reduced CO_2 emissions and energy consumption. The benefits of steel fibers, including reduced and delayed spalling of concrete, control of initiation and growth of cracks, impact resistance and durability, have also been reported [12]. While the benefits of GGBFS and steel fibers may provide solutions to the problems encountered in current prestressed concrete sleepers, their performance needs to be evaluated in order to satisfy code requirements for their intended applications.

The major role of railway sleepers is to transfer and distribute rail loads to the substructure [13,14]. The flexural capacity of sleepers at the rail seat section is a predominant issue because a single sleeper typically carries 45–65% of the wheel load directly above it [5]. Furthermore, cracking at the top center location of sleepers, which is called “center binding”, has been reported and this is known as one of the three primary failure mechanisms of prestressed concrete sleepers [5,6]. It is noted that this crack occurs when large negative moments at the sleeper center section, caused by ballast deteriorations, exceed the cracking moment of the sleepers. These facts demonstrate critical sections for positive and negative moments, corresponding to the rail seat and center sections, respectively. It should be noted that the magnitude and distribution of the moments vary depending on the wheel loading conditions, ballast and sub-grade conditions, as well as sleeper spacing [5,15–17].

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Nomenclature

d_p	diameter of prestressing wire
A_p	nominal area of three wire strand
d_b	diameter of reinforcing bar
A_s	nominal area of reinforcing bar
f_{pi}	initial stress in prestressing strand
f_{pe}	effective stress in prestressing strand after allowance for all prestress losses
l	length of steel fiber
d	diameter of steel fiber
l/d	aspect-ratio of steel fiber
Mdr	positive design bending moment at rail seat
Mdc_{n}	negative design bending moment at center section
L_r	clear span length of static and fatigue tests at the rail seat section
L_c	clear span length of negative bending moment tests at the center section

Fr_0	positive initial reference test load for the rail seat section
Fr_{r}	positive test load produced the first crack formation at the rail seat section
Fr_{B}	maximum positive test load at the rail seat section
Fr_{u}	lower test load for the dynamic test of the rail seat section
w_{Fr0}	crack width at a load Fr_0 after fatigue loading
w_{res}	residual crack width after fatigue loading
$Fc_{0\mathrm{n}}$	negative initial reference test load for the center section
Fc_{rn}	negative test load produced the first crack formation at the rail seat section
Fc_{Bn}	maximum negative test load at the center section
$T_{P,max}$	toughness up to the maximum load (Fr_{B})
$T_{P,fail}$	toughness up to the load of the sleeper failure (Fr_{B})
$T_{D,20mm}$	toughness up to a deflection of 20 mm
k_{2s}	static coefficient to be used for the calculation of Fr_{B}

Previous studies [18,19] have shown that the rail loads can be considered to be static and quasi-static under low to moderate train speeds, while a dynamic impact pulse is in general due to increased speeds of the continual moving ride over track irregularities. Previous studies [8,13] have also indicated that the failure of a railway sleeper is more likely due to the damage from cumulative impact conditions rather than due to a single impact event, which might occur due to derailment. Although the dynamic effects are evident in failures of the prestressed concrete sleepers, most of the design concepts are based on the static capacity of the sleepers. Numerical modeling of the sleepers also requires the properties obtained from static tests [18,19]. Therefore, the static performances at the rail seat and center sections of the sleepers were investigated in this study. Furthermore, fatigue tests at the rail seat section were performed. One of the objectives for the fatigue tests was the simulation of an exceptionally high load to create an initial crack, followed by fatigue loading, to study the effect of trains running continuously on cracked sleepers.

2. Experimental program

2.1. Test specimens and variables

Eight prepressed concrete sleepers were produced for each of the five variables under the same manufacturing process as conventional railway sleepers, resulting in a total of 40 sleepers (see Fig. 1). Sleepers were designed by the allowable stress design method based on the Korean Railway Standard (KRS TR 0008) [20,21], that are classified as 'Prestressed concrete sleepers for 60 kg K rail'. It is noted that KRS TR 0008 is equivalent to BS EN 13230-1 (general requirements) [22] and 13230-2 (prestressed monoblock sleepers) [23]. However, the material requirements of KRS TR 0008, which are based on the Korean Standard (KS) for construction materials, are marginally different from BS EN Standard to accommodate availability of materials.

Fig. 1. Prototype prestressed concrete sleepers.

All sleepers had the same geometry, a total length of 2400 mm, but were constructed with three different concrete mixes (CC, BS, and BSF) and reinforced with two different numbers of strands (sixteen and fourteen strands) as shown in Fig. 2. The specimen names indicate the mix type, including the type of binder and the steel fiber content, and the number of strands. For example, BS16 is the sleeper constructed with a mix BS without steel fibers and containing sixteen strands. While, BSF14 is the sleeper constructed with mix BS with 0.75% steel fibers and pretensioned with fourteen strands. It is noted that sleepers with steel fibers (BSF16 and BSF14) were constructed without any stirrups, whereas sleepers without steel fibers contained seven stirrups in each rail seat region which is a typical sleeper design currently used in Korea (see Fig. 2).

Sleepers CC16 represent conventional prestressed concrete sleepers which are currently used in the Korean railway system. These sleepers are produced with Type III Portland cement (high-early strength) to acquire sufficient early-age strength for the release of the strands. These sleepers are reinforced with sixteen strands along the length and seven stirrups at each rail seat, resulting in a total of fourteen stirrups per specimen. Sleepers BS16 had the same geometry as well as reinforcement details as sleepers CC16, but eco-friendly concrete mix (56% replacement by GGBFS) was used to fabricate these sleepers. Sleepers BSF16 also represent sleepers with an eco-friendly concrete mix, and these sleepers contained 0.75% of steel fibers in the mix instead of stirrups. A comparison of the behavior of sleepers in series BS16 and BSF16 demonstrates the beneficial effects of steel fibers in terms of crack control as well as replacement for the stirrups. It is noted that the mix design for the concrete with GGBFS and the volume fraction of steel fibers were determined from numerous trial batches [2,24]. The flexural capacity of the prestressed concrete sleepers were calculated in accordance with the International Union of Railways (UIC) Code 713R [17], and the results indicated that the current railway sleeper design is conservative [24]. In order to provide an understanding of the beneficial effects of steel fibers and GGBFS for the performance of sleepers, a reduced number of prestressing strands were considered as a variable of the testing. As a result, sleepers BS14 and BSF14 were designed to have a reduced number of prestressing strands (fourteen of three-wire strands) compared to sleepers BS16 and BSF16. It is noted that removing the 2nd