Construction and Building Materials 166 (2018) 356–372

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Enhancing the resistance of prestressed concrete sleepers to multiple impacts using steel fibers

Hyun-Oh Shin [a], Doo-Yeol Yoo [b,*], Young-Soo Yoon [c,*]

[a] New Transportation Systems Research Center, Korea Railroad Research Institute, 176 Cheoldobangmul gwan-ro, Uiwang-si, Gyeonggi-do 16105, Republic of Korea
[b] Department of Architectural Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 04763, Republic of Korea
[c] School of Civil, Environmental and Architectural Engineering, Korea University, 145 Anam-ro, Seongbuk-gu, Seoul 02841, Republic of Korea

HIGHLIGHTS

- Hammer weight and loading protocol strongly affect the impact resistance of PSC sleepers.
- Multiple impact resistance of PSC sleepers is improved by including GGBFS, steel fibers, and more strands.
- Dropping lighter hammer at higher height causes more severe damage of PSC sleepers than counterpart.
- Steel fibers effectively inhibit crack propagation and decrease width and number of cracks.
- Flexural strength of pre-damaged PSC sleepers is efficiently improved by adding steel fibers and more strands.

ARTICLE INFO

Article history:
Received 7 October 2017
Received in revised form 30 December 2017
Accepted 18 January 2018

Keywords:
PSC sleeper
Steel fiber
GGBFS
Number of strands
Multiple impacts
Progressive failure
Damage classification

ABSTRACT

This paper investigates the effects of replacing cement with ground granulated blast furnace slag (GGBFS), adding hooked steel fibers, and reducing the number of prestressing strands on the behavior of prestressed concrete (PSC) sleepers subjected to multiple impacts. Five PSC sleepers with and without GGBFS and steel fibers were fabricated and tested using a drop-weight impact test machine. Test results indicate that the hammer weight and loading protocol strongly influenced the multiple impact resistance of PSC sleepers. In terms of peak reaction load, maximum deflection, and residual deflection, the multiple impact resistance of PSC sleepers was enhanced by including GGBFS and 0.75 vol% steel fibers and increasing the number of strands. The maximum crack width was reduced by increasing the number of strands and including steel fibers, and the steel fibers also effectively limited crack propagation, the number of cracks formed, and concrete spalling. Lastly, the flexural strength of PSC sleepers damaged by multiple impacts was improved by including steel fibers and more strands. Consequently, the overall performance of PSC sleepers subjected to multiple flexural impacts was improved by adding 0.75 vol% steel fibers and increasing the number of strands.

1. Introduction

Railway track systems consist of 1) substructures, including ground formation, subgrade, sub-ballast, and ballast, and 2) superstructures, including rail, rail pads, fastening system, and sleepers or ties [1]. Among those components, railway sleepers play a major role in both track performance and safety, with actions such as transferring and distributing the axle loads from rails to substructures, maintaining the track gauge, and withstanding the vertical and longitudinal movement of the rails [1–3]. Previous studies [1–4] showed that concrete sleepers, especially prestressed concrete (PSC) sleepers, are most widely used in many countries because of their advantages, including improved durability, better structural performance, longer life cycle, and lower maintenance costs, over sleepers made of other materials. However, there are increasing concerns about the environmental effects of PSC sleepers: CO_2 emissions and energy consumption during fabrication, mainly in the raw-material phase through incorporation of cement and the concrete production phase through the oil used in the boiler for steam curing [5]. In particular, the CO_2 emission from the cement production occupies approximately 7% of the total global emissions of CO_2 [6]. Demand for enhanced structural performance and durability in PSC sleepers is also increasing with the increasing construction of high-speed railway systems. Premature failures

* Corresponding authors.
E-mail addresses: dyyoo@hanyang.ac.kr (D.-Y. Yoo), ysyoon@korea.ac.kr (Y.-S. Yoon).

https://doi.org/10.1016/j.conbuildmat.2018.01.095

mean that 2–5% of sleepers must be replaced within their expected lifetimes [4,5].

In order to address those issues, previous research has investigated the use of supplementary cementitious materials [5,7–10], including ground granulated blast furnace slag (GGBFS), fly ash, and silica fume. The use of GGBFS as a partial replacement binder instead of cement is a well-established research area, and it is well known that using GGBFS increases long-term strength and durability of concrete [5,11]. Those studies demonstrated the beneficial effects of using the GGBFS to fabricate PSC sleepers: reduced CO_2 emissions and life cycle costs and improved durability and flexural performance under static and fatigue loadings. The concerns regarding the environmental effect of CO_2 emission on the PSC sleepers, which have been raised worldwide, can also be overcome by partially using the GGBFS, leading to a preservation of limited resource, i.e., limestone. Kho et al. [10] conducted dynamic loading tests and found that sleepers made with new materials showed improved dynamic performance compared with those made of ordinary concrete. However, the dynamic load effects applied to the PSC sleepers in the previous study [10] and current design provisions [12–15] use a quasi-static load with a dynamic impact factor, which does not adequately model real impact-induced loadings.

To improve durability of concrete material and sleeper, several researchers have examined the use of steel fibers [5,7,8,16–21]. El-Dieb [16] reported that the durability of ultra-high-strength concrete against chloride attack and chloride induced corrosion of reinforcement is improved by including steel fibers due to the enhanced total charge passing and densified microstructures. In the same vein, Bernal et al. [17] and Afroughsabet and Ozbakkaloglu [18] experimentally verified that the durability performance of concrete in terms of water absorption and permeable porous quantity is substantially improved by adding steel fibers, and the effectiveness is enhanced with increase of their volume fraction. Carbonation resistance of high-strength concrete was also increased by including steel fibers, as was reported by Shin et al. [5] and Wang et al. [19]. Based on the test results of Shin et al. [5], the addition of 0.75% (by volume) hooked steel fibers decreased approximately 18% the carbonation coefficient of GGBFS concrete without fibers. Likewise, not only can adding steel fibers improve the mechanical properties, especially post-cracking tensile and flexural behavior, of concrete [20,21], but also enhance the durability of concrete.

Previous studies [4,14,15,22–25] have successfully addressed the fact that the principal causes of cracking in PSC railway sleepers are infrequent but high-magnitude impact loads of very short durations, underlining the importance of considering real impact loads in the design of PSC sleepers. For example, Kaewunruen and Remennikov [14,15,22–24] reported that 200–750 kN dynamic impact loads per rail seat could be generated in 1–10 ms, whereas the designed static wheel load per rail seat for a 40-ton axle load would be as low as 110 kN. Ahlbeck [25] reported that the radial profile error of a railroad wheel results in high dynamic loads at the interface between wheel and rail, often exceeding 400 kN in peak amplitude. Those dynamic impact loads can be caused by abnormalities in either a wheel or a rail, such as wheel flats, out-of-round wheels, wheel corrugation, short and long wavelength rail corrugation, dipped welds and joints, pitting, and shelling [23]. In general, such phenomena are inevitable during the service life of sleepers; therefore, sleeper failures caused by impact-induced loadings should be fully addressed in the design phase by considering real loading cases. In particular, such an impact on railway sleepers occurs repeatedly during their service life, and therefore, the impact performance of PSC sleepers needs to be examined under multiple impact loading conditions in order to accurately consider its implication.

The impact resistance of railway sleepers was initially studied by a research group at the University of British Columbia, Canada, in the mid-1990s. Xe et al. [26] carried out static and impact load tests to investigate the cracking mode of PSC sleepers dependent on the support conditions and loading rate. For the impact tests, they used a drop-weight impact machine that could drop a 345–504 kg mass from heights of up to 2.3 m. Two different Pandrol pads and two different rubber supports were used to provide four different loading conditions, and the supports had a clear span length of 750 mm. It is noted that repeated impact loads were applied in this test program, and the applied load was measured using only a load cell attached to the bottom of the striking tup, which includes inertia load effects. They found that approximately the same magnitude of impact and static loads were applied before the first cracking occurred in the sleepers. However, the type of first crack depended on the magnitude of the impulsive force and the loading rate: flexural cracks occurred under low-level impulsive loads, whereas flexural-shear cracks and shear cracks occurred under high-level impulsive loads. They also demonstrated that the stiffness of the sleeper systems under impact loads depended on the stiffness of the supports and rail pads. Wang [27], also a researcher at the University of British Columbia, performed two different series of impact tests on PSC sleepers to study 1) the effects of the support conditions and rail pads in minimizing sleeper damage caused by rail abnormalities; 2) the effects of loading rate on crack mode and fracture energy of the sleepers; and 3) strategies for improving the dynamic properties of PSC sleepers to reduce cracking caused by wheel-flats and rail abnormalities in service. From the first series of tests, they found how the maximum load, loading rate, fracture energy, and fracture mode depended on the stiffness of the supports. From the second series of tests, they learned the effects of concrete strength, steel fiber addition, changes in prestressing force, and the presence of stirrups on the impact resistance of railway sleepers, demonstrating the beneficial effects of steel fibers and stirrups, especially steel fibers.

In the mid-2000s, a research group at the University of Wollongong, Australia, provided comprehensive research results from a significant number of impact tests on PSC sleepers currently used in Australia and from an analytical study [14,15,22,23,28–34]. Specifically, they identified the cumulative impact damage and crack propagation in PSC sleepers using a series of incremental impact loading tests. They also presented the effects of track environment and the relationship between the bending moment and the applied impact force. They compared the responses of the PSC sleepers under a single impact and repeated impact loads associated with different probabilities of occurrence and evaluated the residual capacity of the damaged PSC sleepers, eventually presenting new limit-state design concepts and procedures for PSC sleepers.

Although comprehensive research on impact resistance of PSC sleepers has been carried out during the past two decades, as just described [14,15,22,23,26–34], a lack of research on the impact resistance of PSC sleepers constructed of alternative materials continues, particularly study of environmental effects and strategic reinforcement details that promote both economical construction and improved performance. Especially, to the best of author's knowledge, there is no published study examining the effect of partial replacement of cement with GGBFS for environmental benefits on impact resistance of PSC sleepers. Furthermore, previous research used limited data acquisition systems. For example, the impact test results from the University of Wollongong could not provide complete impact load-deflection curves because the tests were carried out on a strong floor or ballast bed. The impact test setup at the University of British Columbia could measure mid-span deflection, but they measured applied impact load using a load cell attached to the striking tup, which includes inertia effects.