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Design and Performance of Pre-Stressed Concrete Railway Sleepers Containing Fibres

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ABSTRACT

The design of railway sleepers must account for irregularities of the train or the rails that generate dynamic loads. The sleepers could develop cracks during a train passage although not influential enough to disturb immediately the global track system. However, these cracks can pose a threat to the overall stiffness properties as they can propagate further under repeated loads induced by the train. Consequently they can cause fatigue, which is a structural failure at service condition. This will later constitute a major maintenance item if the problem is not properly addressed. It is intended that the application of high-strength concrete (HSC) with the inclusion of fibres in railway sleepers could reduce, delay or in certain conditions arrest the rate of crack growth. The design of sleeper was proven to comply in partial of the referenced Standards requirements. The fabrication works undertaken also proved that all procedures were followed satisfactorily and that the laboratory of the Faculty of Civil Engineering was able to handle the production. Structural tests carried out where loads were applied at rail seat showed that behaviour of HSFC sleepers had high flexural strength capacities due to the presence of fibres.

***Keywords**: Railway sleepers, fibres, compliance, flexural behaviour*

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Introduction

Over the years, when traffic congestions arise, the Malaysian Government found necessary to adopt policies for new developments of light rail transits and expansions of existing rail networks (of which the latter is through *Keretapi Tanah Melayu Berhad*, KTMB, a government-linked company) so as to provide alternatives to land transportation. Now the rail industry is becoming more progressive with infrastructure rehabilitation and enhancement programs which include electrification, resignalling and doubling the tracks of the rail network [1]. As such, local expertise must meet to an acceptable standard in order to address all pertaining issues of the rail industries, including rail components such as railway sleepers.

The design of railway sleepers must account for irregularities of the train or the rails that generate dynamic loads. The sleepers could develop cracks during a train passage although not influential enough to disturb immediately the global track system [2]. However, cracks are still a threat to the overall stiffness properties as they can propagate further under repeated loads induced by the train. These cracks can cause fatigue, which is a structural failure at service condition of the sleeper and consequently this can constitute a major maintenance item if the problem is not properly addressed.

Existing prestressed concrete sleepers utilised normal concrete strength of grade 40 and more that can fall in the category of ‘high strength’ but do not include special admixtures. This study focussed on a proposal of a new design mix using fibre-reinforced high strength concrete (HSFC) that is tough to prevent fracture of sleepers. The main objectives were to design and fabricate prestressed concrete railway sleepers with the new HSFC material and that they complied to design standards. The flexural behaviour of the sleeper under four-point bending at rail seat was also compared to that of a high strength concrete (HSC) sleeper without fibres.

Experimental Study

The experimental investigation was carried out in the Faculty of Civil Engineering laboratories. In the preliminary study, cube and prism samples were prepared from the established design mix of Abu-Bakar *et al.* [1] and tested for compression, flexural and fracture bending strengths respectively. Results had been presented earlier [3]. Design calculations were made for a sleeper based on guidelines given by Australian Standards, AS 1085: 14 [4]. The study limits to *meter-gauge monoblock* sleeper that is similar to those laid on the KTMB rail tracks and able to undertake a 20-tonne axle load rolling at a maximum speed of 200 km/h. A trial sleeper was firstly fabricated to understand all the procedures pertaining to prestressing works. Table 1 shows the type of tests undertaken.

Table 1: Sleeper Identification and Test Type

Sleeper 'C' Compliance type tests	Sleeper 'S' and 'PS' Structural test
1. Rail seat positive moment test 2. Rail seat repeated load test	Flexural 4-point bending test

Notes: 1. 'PS' is prestressed HSC sleepers without fibres
2. 'C' and 'S' are prestressed HSFC sleepers with fibres

Materials

The mix design of HSFC material was of Grade 60 with silica fume (SF) of 10 % replacement of ordinary Portland cement (OPC) with 0.5 % total volume of polypropylene (PP) fibre additives. OPC, fine and coarse aggregates constituted the main ingredients of the mix design. For the strength of the structural member, indented tendon wires of 5 mm diameter having a characteristic strength of 1800 MPa were stressed to not more than 70 % of its ultimate strength. The prestressing force was applied from a hydraulic jack and transferred to a total of 16 numbers of wires.

Design and Fabrication of Prestressed HSFC Railway Sleepers

The sleepers were fabricated using an existing prestressing bed that was maintained and only being used for the first time for this study. Thus no record history is available in terms of its performance and reliability. The preparation of the bed involved getting the sleeper moulds and end plates ready. These end plates of each mould have to be prepared in accordance to the designed tendon profile. Necessary improvements had to be taken to consider group tensioning of the wires simultaneously by using a designed stress plate to take up all the prestressing loads. Using the bed, a total of three (3) sleepers, each measuring 2 m long, can be fabricated at any one time of prestressing (see Figure 1).

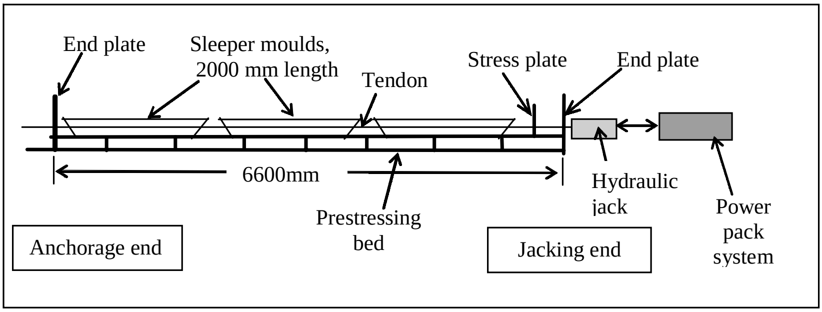


Figure 1: Schematic Layout of Sleeper Fabrication

There were a few initial challenges that required immediate attention [5]. The prestressing techniques depended a lot on the performance of the individual components such as welding strength of the hydraulic jack support, the lock ring device that maintain wire positions and the stress transfer to the wires. Fabrication of the sleepers also depended on the suitability of the stress bench itself to accommodate easy placement of the concrete. These include providing temporary steps to enter the working area and plywood panels placed between the stress benches. The technique to transfer concrete from the mixer to the mould should also consider time taken so as not to cause delay as high strength concrete can set faster than normal concrete. Plates 1 to 3 show some of the fabrication processes undertaken.

Experimental Tests

Hardened Concrete Test

For each batching, enough cube samples were prepared to determine their compression strength. Minimum of three cubes were tested prior to releasing the jacking force and another set of three for their 28-day strength. The test method was in accordance to BS 1881: Part 116 [6].

Compliance Type Tests

A critical test method that is Rail Seat Positive Moment test [4] was conducted on a sleeper identified as ‘C’ at not more than 35 days at both rail seats (see Plate 4). The specimen was assembled on the Universal Testing System (UTS) available in the laboratory. The UTS mainly consists of a servo-hydraulic control loading with Computer Data Acquisition

Plate 1: Arrangement of Sleeper Moulds on Stress Bench

Plate 2: Concrete Placement in Moulds

System (CDAS) and linked to a personal computer (PC). The machine supports a suite of UTS software applications and application of load is totally controlled via a virtual pendant in the computer programme. A static load was applied at the stipulated rate of not more than 0.4 kN/s

Plate 3: Curing of Sleepers

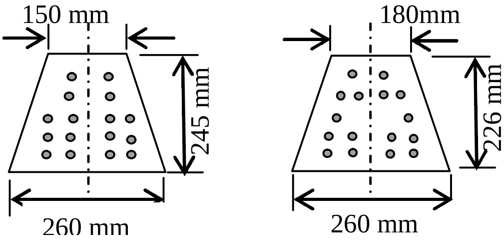
Plate 4: Rail Seat Positive Moment Test Set-up

until the load actuator reached a test load (P_2) equalled to 130 kN; which is determined in accordance to the Standard. This load is considered to produce rail seat positive cracking moment. Inspections were made for any structural cracks during a three-minute rest period and test was repeated at the other rail seat.

A repeated (cyclic) load test was then conducted on one seat (marked 'A') in accordance to AS 1085. Firstly, a pre-crack was introduced by applying static load at the rail seat until the crack line reached the lowest tendon level. Repeated load was then applied sinusoidally at a minimum of 15kN and maximum of $1.15P_2$ at loading frequency of 5Hz up to three (3) million cycles. Soon after the test, static load was applied up to $1.15P_2$ and observation for cracks was made during a three-minute rest period. Further load was applied until $1.5P_2$ and if no cracks occurred, loading was continued until failure of the sleeper and the ultimate strength was then determined.

Flexural Static Test

Upon conformance to the referenced Standards, the sleeper (marked 'S') was examined and compared to a HSC sleeper without fibres under static flexural load. The latter sleeper ('PS'), obtained from a local supplier, was designed with similar numbers and size of tendons, and having similar concrete strength. The geometries differ slightly with section modulus ratio of 0.98 to that of the HSFC type (see Figure 2). Test set-up followed the same Positive Moment Rail Seat condition and LVDT and strain gauges were mounted on the sleeper specimen to measure deflection and strain readings respectively. Using displacement control, each sleeper was loaded until failure and readings could be accessed from the CDAS. The test data file created in the programme were exported to a text file and then transferred easily in EXCEL format.



a) HSFC b) HSC

Figure 2: Tendon Profile and Sleeper Geometries at Rail Seat

Results and Discussions

Compressive Concrete Strength

Typical results of compression cube strengths are represented in Figure 3. High early strengths were achieved and this allowed the removal of sleeper moulds within three days after casting. Although PP fibres were known not to gain strength with age, the slight increases until they reached the 28th day were probably due to good bonding of the composites. Nonetheless, the mix design was found to be consistent with the earlier work and generally the 28th day strength was attained after 18 days of casting.

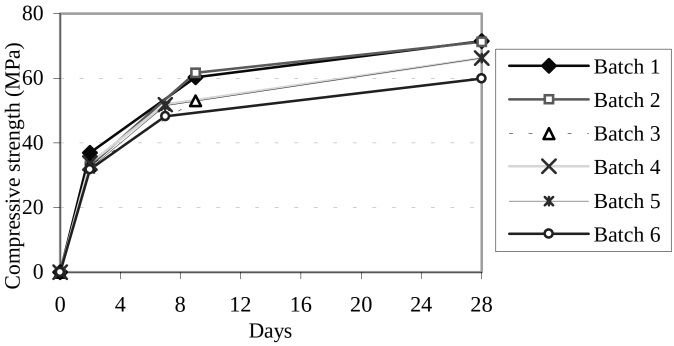


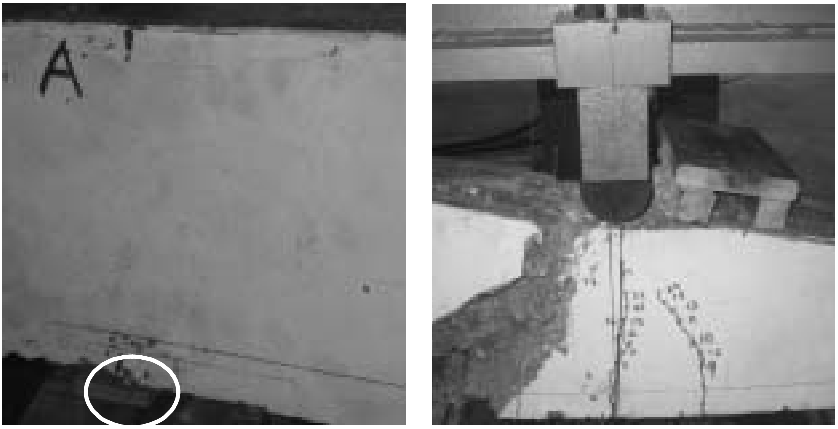
Figure 3: Development of HSFC Cube Strength

Design Compliance of HSFC Railway Sleepers

Compliance test results are summarised in Table 2 showing that the sleeper did not show any structural cracks. Plate 5(a) shows the introduced pre-crack did not propagate further and there were also no other cracks seen. In general the sleeper was able to resist the 3 million cyclic loads. When the ultimate strength test was later conducted, the sleeper crushed badly along the diagonal crack line with as can be seen in Plate 5(b). The presence of SF in the concrete coupled with the cause after subjected to fatigue load, might have contributed to the significant concrete crushing.

Table 2: Compliance Performance Test Results on Sleeper ‘C’

Compliance Test Type (to AS 1085: 14: 2003)	Seat A	Seat B
Rail seat positive moment ~ at load P_2	*No structural cracks*	*No structural cracks*
Rail seat repeated load ~ at $1.15P_2$ and $1.5P_2$ static loads after 3 million cycles	*Able to support the 3 minute static loads*	-
Ultimate load (kN)	534.5	-



(a) (b)

Plate 5: Condition of HSFC Sleeper: (a) No Extension of the Pre-crack just after Undergoing Cyclic Loads, and (b) After Complying to Ultimate Strength Test

Flexural Behaviour of HSFC Railway Sleepers

Under the ordinary static test, the HSFC sleeper behaved quite differently where cracks were more distributed and the widths were small; not exceeding 0.2 mm. In fact, under a corresponding design wheel load of 127.5 kN, there were no cracks observed. Due to high loading rate selected at 2.3 mm/s for seat A, the first cracking load was unable to be detected as failure was quite abrupt as seen in Figure 4. There were significant yieldings of the sleeper before it reached maximum ultimate strength. This behaviour is in agreement with the earlier work on the

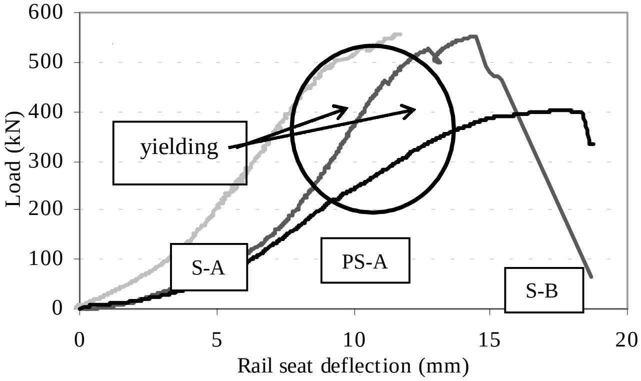


Figure 4: Comparative Flexural Behaviour of Railway Sleepers

unreinforced prism [4] where there was a drop in the load capacity after the first crack. This phenomenon is also described by Balaguru and Shah [8] for concrete containing polymeric fibres such as the PP type.

For seat B, a lower loading rate of 0.008 mm/s was used and thus able to detect the first crack appearing at 285 kN. In general, the sleeper strength at the rail seats was high with an average of 554 kN, which is about four times higher than the design wheel load. By analysing the elastic paths for both seats, yield strength was taken as the tangent modulus at the corresponding 0.2 % strain and found to be at an average of 242 kN. Table 3 shows summary of results obtained from the static tests. At design wheel load of 127.5 kN, the average rail seat deflection is found to be 5.3 mm which is just below the limiting value of 6 mm suggested by Banks [9] for railway sleepers. Meanwhile Plate 6 shows

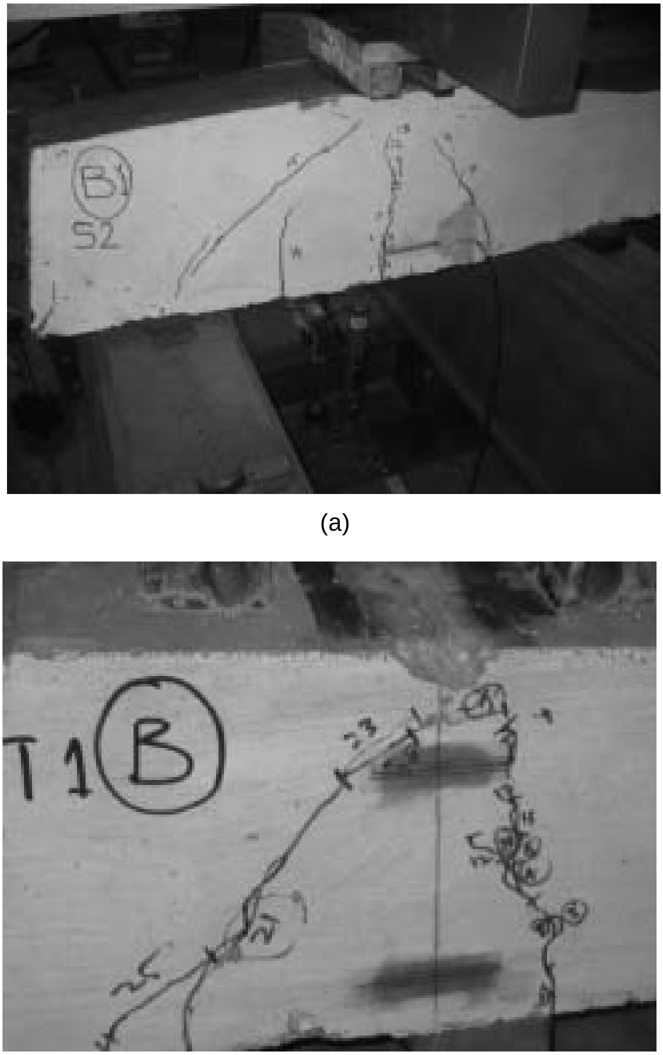
Table 3: Static Test Results

Specimen identification	Rail seat deflection (mm) at equivalent 127.5 kN	Ultimate Strength (kN)	Yield load (kN)	Observed first crack load (kN)
S-A	4.04	556.99	259.56	*
S-B	6.52	551.48	223.83	285.0
PS-A	6.97	404.31	180.78	193.0

Note: 1. * Crack not detectable

2. 'A' or 'B' indicates seat position

the sleeper failed in shear, as it was apparent that shear resistance was not provided in most of the railway sleeper design standards.



(a)

(b)

Plate 6: Ultimate Condition of (a) HSFC and (b) HSC Railway Sleepers

Comparative Behaviour of Prestressed HSFC and HSC Railway Sleepers

The HSFC material was suitable for railway sleeper and in general, the behaviour indicates normal performance of prestressed concrete structures. In the earlier works of Abu-Bakar *et al*. [7], fibres were found to enhance structural performance of non-prestressed HSFC prisms. Apparently, this remains true for the HSFC sleepers as the results indicated that they were able to resist more than 37 % static strength compared to the HSC sleeper although the later was also pre-tensioned with the same force magnitude. In Figure 4 it can also be seen that large deformations occurred earlier in HSC sleeper whereas presence of fibres in HSFC sleeper seemed to delay crack occurrence and thus prolong the life of the sleeper. The bending crack lines observed were fine and more distributed with lesser deformation at the rail seat compared to the HSC sleeper with wider crack opening as shown in Plate 6(b).

Challenges in Fabrication and Testing of Prestressed HSFC Railway Sleeper

There were a few factors that were found to be influential from the beginning of the design stage through the fabrication works and finally during testing of the sleeper members.

- Design and fabrication
  There were no proper local design codes on the design of sleepers except for KTMB's Technical Specification Notes. The AS 1085: 14: 2003 does have some guidelines for application of new materials in sleeper design. A lot of literature covers on standard techniques of pretensioning works only and information on practical procedures are still lacking.

- Experimental investigations
  There were not much data available on flexural behaviour of railway sleeper incorporated with fibres except for Mindess *et al*. [2] who had tested railway sleepers using steel and also PP fibres under impact load. Lack of understanding of degradation mechanisms of sleepers can only be overcome by testing more specimens and this would implicate cost.

Conclusions

The design of HSFC sleeper met partial requirements of design standards. It should be noted that the two type tests were considered critical, yet the sleepers complied the criteria. The HSFC sleeper reached average ultimate load of 554 kN at the rail seat while the HSC type without fibres achieved only 404 kN. This proves that fibres are efficient in delaying or arresting crack growths. The HSFC sleeper also endured the three million load cycles without any crack propagation or formation of new crack growths. The procedures undertaken during fabrication process were also a testimony that the laboratory was able to handle tensioning and fabricating of sleepers in line with industrial methods and has also adequate testing machine for testing purposes.

Acknowledgements

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References

[1] Abu-Bakar, A. and Din, K. 2004. Design and development of concrete sleepers on Malaysian rail networks. *22nd Conference of ASEAN Federation of Engineering Organizations* [CAFEO 22], vol. 2, Energy and Infrastructure Development, Myammar, pp. 402-01 to 402-10.

[2] Mindess, S., Yan, C. and Venuti, W. J. 1991. Impact and fatigue of prestressed concrete railroad sleepers. *International Symposium on Fatigue and Fracture in Steel and Concrete Structures*, India, pp. 537-557.

[3] Abu-Bakar, A., Din, K. and Ibrahim, N. 2004. Influence of silica fume on flexural strength of fibre-reinforced concrete. *7th International conference on Concrete technology in developing countries* (7th ICCT): Sustainable Development in Concrete Technology, Malaysia, pp. 299-308.

[4] Australian Standards, AS 1085: Part 14. 2003. *Design specification for concrete sleepers.*

[5] Din, K., Abu-Bakar, A. and Marwi, M. S. 2006. *Performance and fatigue behaviour of concrete railway sleepers containing fibres*. Report to IRDC, Universiti Teknologi MARA, Malaysia, unpublished.

[6] British Standard Institute, BS 1881: Part 116. 1983. *Method for determination of compressive strength of concrete cubes.*

[7] Abu-Bakar, A., Din, K. and Hamzah S. H. 2003. Mechanical properties of high strength concrete containing polymeric fibres. *3rd Asia-Pacific Conference on Fibre Reinforced Materials,* China, pp. 75-81.

[8] Balaguru, P. N. and Shah, S. P. 1992. *Fiber-reinforced cement composites*. Mc Graw-Hill Inc., USA.

[9] Banks, J. H. 2002. *Introduction to transportation engineering.* 2nd Ed., McGraw Hill Int. Edition, New York.

[10] Din, K., Abu-Bakar, A. and Yong, C. B. 2004. *Fatigue performance on polypropylene fibre high strength concrete*. 7th ICCT, Vol. on Repair and Enhancement of Concrete Structures, Malaysia, pp. 269-278.

[11] Gustavson, R. 2002. *Structural behaviour of concrete railway sleepers*. PhD. Thesis, Chalmers University of Technology, Sweden.