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Tests on a two-layered ballast system

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ABSTRACT

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Considerable evidence suggests that ballast is the main cause of uniform and non-uniform settlement of railway track, provided the subgrade is adequately specified. Over a period of time uneven settlement of the ballast will cause voids to form under the sleepers, leading to unacceptable ride quality of the track. Regular maintenance is required to keep the track geometry within acceptable limits and to maintain ride quality. The proposed two-layered ballast system described in this paper would replace the crib ballast by stone of smaller size. The aim is to fill the voids beneath the sleepers as soon as they become unacceptably large and thus to maintain ride quality without the use of tamping or stone-blowing. Preliminary model tests carried out on the system indicate good potential for it. The results of the model tests have been validated by full-scale tests in the laboratory. The tests have shown that by replacing crib ballast by stone of smaller size a void beneath the sleeper will be filled up to less than the void size minus the average particle size of crib ballast. The next logical step is to go for full-scale live track trials, and it is anticipated that these will take place in the near future.

Keywords
materials technology, rail track design, strength & testing of materials

1. INTRODUCTION

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Ballast movement and/or deterioration have been identified as the main cause of average and differential settlement of railway track with passage of traffic. This is also influenced by the inherently variable nature of the formation, but if the formation is adequately specified, ballast remains the main cause of loss of geometry of track and subsequent loss in ride quality of the track.[1] For high-speed trains the passenger is more sensitive to ride quality deterioration, and thus more frequent track monitoring and maintenance are required.

1.1. Ballast

Ballast provides resilience to the track and distributes stresses from the sleepers to the subgrade. It provides lateral and longitudinal stability to the track and maintains track level. The ballast facilitates maintenance and provides immediate drainage of rainwater from the track. As specified by Cope,[2] the above functions are performed in a manner such that the position of the rail:

a. does not, in the loaded condition change, with time
b. returns to its original position after the passage of each train
c. moves elastically under vehicle loading within tolerable limits for the mechanical design and use of those vehicles.

Ballast was not given due consideration in the initial years of railway construction, and any cheaply and easily available material such as ashes, chalk or clay was used as ballast. It was not until the 1890s that engineers realised the importance of using good-quality stone as ballast, although the specification for the stone was not very clear about the size and quality. F. R. Conder, in his book *The Men Who Built the Railways,*[3] mentions an instance where the specification for ballast stated that no bit of broken stone be used as ballast larger than a man could put in his mouth. Even as late as 1922, 90% of the former North Eastern Railway was ballasted with ash.[2]

Over the years a wealth of experience has been accumulated on the requirements of depth, strength and durability of ballast. For the ballast to perform its functions satisfactorily different theoretical and empirical approaches are used for specifying the ballast, but the practice is generally similar in all countries, with some local variations.[2] The current practice is to use uniformly graded ballast, but the use of well-graded ballast has been suggested, with smaller sizes to reduce contact forces.[4] At present no universal agreement exists concerning the specifications for the ballast material index characteristics, and it is a subject still being researched.

1.2. Track geometry and maintenance

The traditional method of track maintenance was manual packing of ballast under the sleepers. A gang of maintenance workers would move along the track and strike the sleepers with a rod. The portion of track where the sleepers sounded hollow was lifted up, and stone chips were filled in the void under the sleepers. The traditional, manual track improvement measures have become economically obsolete. Railways with heavy traffic, welded rails and concrete sleepers require mechanisation of track maintenance to maintain minimum safety levels.

The most widely used machines for track maintenance are tampers and stone-blowers. Tamping machines squeeze the ballast up below the sleepers after they have been raised to the desired level, whereas stone-blowing machines add stone to the existing ballast surface after lifting the sleeper up to the required level (see Figs 1 and 2). Thus tampers disturb the compacted ballast beneath the sleepers, and the vertical track geometry deteriorates rapidly after tamping. The resultant track profile after tamping rapidly assumes its original pre-tamp condition, a phenomenon known as *ballast memory*. An explanation of this phenomenon is given by Selig and Waters.[1] It has been observed that, for low tamping lifts, the ballast below the sleepers is squeezed upwards and dilates into the void between the sleeper and the ballast surface. As the lift is small, on contacting the underside of the sleeper further deformation of ballast cannot take place, and thus the arrangement of the ballast particles within the ballast is unchanged. The passage of traffic re-compacts the ballast, the particles adopt their original position with respect to each other, and the track assumes it original pre-tamp shape.

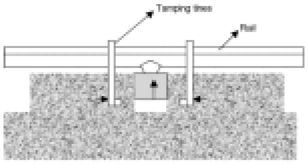

Fig. 1.
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Fig. 1.
Schematic diagram of tamping operation

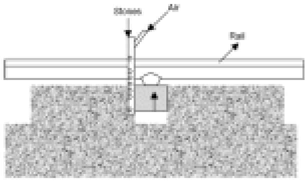

Fig. 2.
Click to view

Fig. 2.
Schematic diagram of stone-blowing operation

A solution to this problem as suggested by Selig and Waters is high-lift tamping. In high-lift tamping the ballast will have sufficient room for maximum ballast dilation, and rearrangement of particles will take place, with new particles being absorbed into the skeleton. Re-compaction of this new ballast skeleton by traffic will introduce a new geometry to the track. This method is also used for improving the inherent quality of track. Limited headroom and shortage of crib ballast may inhibit use of the high-lift tamping process. Another disadvantage of the tamping process is that it crushes ballast particles and generates stone dust, which increases ballast fouling.

Stone-blowing machines cause minimal disturbance of ballast below the sleeper, and thus result in far greater durability of the top ballast and generate less dirt. Stone-blowing machines use a stone size of 20 mm for their operations. Over a period of time stone-blowing operations create a layer of 20 mm stone on top of the 50 mm standard railway ballast. Research by Anderson *et al.*[5] on this two-layered ballast formation has not shown any deleterious effects on overall track response. The drawback of a stone-blower is that rectification of long-wavelength vertical defects with a stone-blower would require impractical quantities of stone chippings, and the maximum amount of track lift that can be achieved by a stone-blower is 40 mm.

After stone-blowing the track life before the next maintenance is on average four times longer than that of track maintained by traditional tamping methods. In addition, a tamper generates around 4 kg of fines per sleeper for one tamping insertion, whereas only 0·5 kg of fines per sleeper are produced by an equivalent stone-blowing cycle. Tamping is less effective on fouled ballast, whereas stone-blowing can work effectively on track with fouled ballast. A track with a stable compacted bed, even though it is fouled, can be maintained by the stone-blower.[1] Thus stone-blowing prolongs the track life and postpones replacement of ballast.

2. PROPOSED TWO-LAYER BALLAST SYSTEM

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Voids below sleepers are a common occurrence on the railways, and have to be dealt with by regular maintenance. It is generally accepted that voids below sleepers of sizes above 15–20 mm are encountered regularly on the railways. The preceding discussion shows that, for track vertical geometry to last longer after maintenance, it is important that the ballast below the sleeper is left undisturbed after it has been compacted by traffic. Thus to maintain the track vertical geometry a system is required that will fill up voids beneath the sleepers as soon as they become unacceptably large, without disturbing the compacted ballast below the sleepers. The proposed system (for which Coventry University holds a patent) consists of replacing the crib ballast (ballast between the sleepers) by stone of smaller size (Fig. 3(a)). When a void is formed under the sleeper larger than a certain size the smaller crib ballast rolls into the void (Fig. 3(b)), maintaining sleeper vertical alignment. It is proposed to use 20 mm stone-blowing stone as crib ballast, replacing the current practice of using 50 mm stone in the crib.

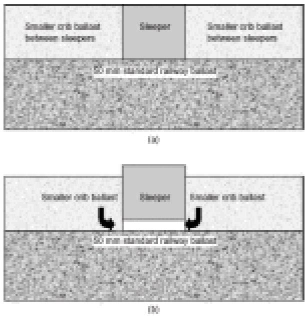

Fig. 3.
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Fig. 3.
Two-layered ballast system: (a) section through proposed two-layered ballast system; (b) the working of the system

This concept of using smaller stone as crib ballast was proposed by Dr Michael Keedwell of Coventry University and patented by him. He likened this idea to the potato masher principle. Consider a potato masher placed in a cylinder and the cylinder filled with sand (Fig. 4). If the potato masher is lifted, the void below the masher is readily filled up by the sand flowing in to the voids, and subsequently the masher cannot be pressed down to its original position.

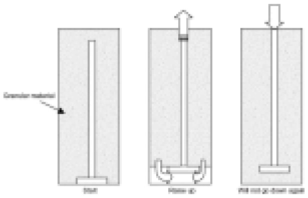

Fig. 4.
Click to view

Fig. 4.
The potato masher principle

3. MODEL TEST SET-UP

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A ten-sleeper assembly of tenth-scale model sleepers made of wood was used for the test. Two sleeper sizes were used: 28 mm (modelling a standard British railway sleeper at 280 mm) and 15 mm. Sleepers of 15 mm were used as an alternative size to the standard British railway sleeper. The two sleeper spacings used were 55 mm and 70 mm. The standard railway ballast was modelled as 5 mm stone (tenth scale of British railway ballast specification at 50 mm). The stone-blowing stone was modelled as stone of 2 mm size. The ballast below the sleepers was 5 mm stone, and both 5 mm and 2 mm stone were used for the crib ballast. A steel plate was used as a base for the model, and sandpaper was fixed onto the steel plate to simulate subgrade roughness. Fig. 5 shows the tenth-scale model sleeper assembly.

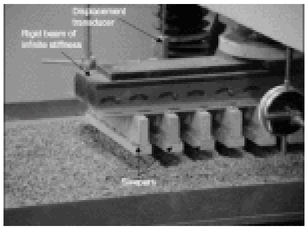

Fig. 5.
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Fig. 5.
Tench-scale model assembly of wooden sleepers

The sleeper assembly was attached to a cyclic loading machine with the help of a rigid beam assumed to have infinite stiffness (Fig. 5). Thus the effect of elastic deformation of the rails was eliminated from the model assembly. Each load cycle (Fig. 6) represented the passing of one axle on the model. Although the maximum load represents tenth scale of standard railway axle loading, including dynamic loads, transmitted to the sleeper, the rate of loading in the tests did not simulate live track loading. After running a few load cycles the occurrence of voids beneath the sleepers was simulated by lifting the sleepers between the cycles (uplift cycles). Thus for the simple cycles (without uplift) the subgrade is assumed as being rigid with no deformation under cyclic load. As it was not possible to create voids below the sleepers or simulate subgrade failure by moving the subgrade, the sleepers were lifted up to simulate subgrade failure or voidage below the sleepers.

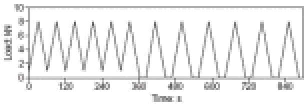

Fig. 6.
Click to view

Fig. 6.
Load cycle: schematic diagram of six simple loading cycles followed by six uplift cycles

The maximum displacement of the sleepers in the ballast was measured for each load cycle using a linear variable displacement transducer. The process was computer controlled (Labview-6 software), and thus complex cycles with different parameters could be run.

3.1. Initial tests

For initial tests on the system, short tests were run for 40 load cycles. The first 20 load cycles were simple load cycles without sleeper lift, with the load cycled between 1 kN and 8 kN. In the next 20 load cycles (uplift cycles) the sleepers were lifted by 2·5 mm (25 mm full scale) to simulate the formation of voids beneath the sleepers. The maximum displacement of sleepers into the ballast was measured for each cycle.

Figure 7 shows the maximum displacement of sleepers plotted against the number of cycles.

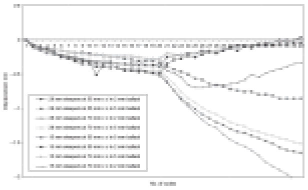

Fig. 7.
Click to view

Fig. 7.
Effect of sleeper size and spacing on sleeper height gain

It was observed that, for 5 mm stone as crib ballast, there was no correction in sleeper height for the uplift cycles, and the displacement of sleepers in ballast increased for the uplift cycles. This relates to the fact that, in a track with voided sleepers, the loss in track geometry is accelerated. For 2 mm stone as crib ballast the sleepers gained in height for the lift cycles. As the smaller crib ballast rolled into the void below the sleepers the sleeper vertical displacement was reduced.

3.2. Parametric study

From the initial tests carried out using the smaller crib ballast two key parameters were identified: the size of the crib ballast, and the uplift height of the sleepers between cycles (void size).

For the parametric study the sleepers were placed directly on the rigid base without any bottom ballast. Thus the effect of bottom ballast as a variable was eliminated. The sandpaper now represented the surface roughness of the bottom ballast (Fig. 8). Sleepers 28 mm in size at 55 mm spacing were used for the parametric study.

Fig. 8.
Click to view

Fig. 8.
Test set-up without 5 mm bottom ballast

For uplift height of sleepers as a parameter, the crib ballast was 2 mm stone (tenth scale of stone-blowing stone specification), which is stone passing a 2 mm sieve retained on a 1·2 mm sieve. Thus the average particle size of the crib ballast was 1·5 mm. The sleepers were lifted up 1·5 mm, 2·5 mm, 3·5 mm and 4·5 mm between cycles to simulate the formation of different void sizes under the sleeper, to study the effect of void size on the gain in sleeper height. The tests were continued until there was no further height gain for the sleepers.

A graph of maximum sleeper displacement against the number of cycles for various uplift heights is shown in Fig. 9. A graph of maximum sleeper height gain against sleeper uplift height is shown in Fig. 10.

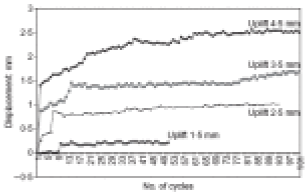

Fig. 9.
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Fig. 9.
Effect of uplift height on sleeper height gain

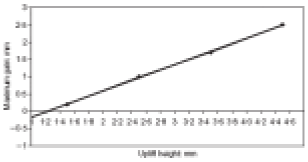

Fig. 10.
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Fig. 10.
Uplift height plotted against maximum gain

It was observed that the maximum height gain of sleepers was uplift height minus the average particle size of the crib ballast: for example, for sleeper uplift of 2·5 mm and average particle size of crib ballast 1·5 mm, the sleeper height correction was 1 mm. Fig. 10 indicates that, for all sleeper uplifts with an average particle size of 1·5 mm, there will remain a residual sleeper displacement of 1·2 mm. The effect of voids in the bottom ballast on the performance of the system was eliminated in this test, as the sleepers were placed directly on the rigid floor.

The effect of using different particle sizes was studied. The sleepers used were 28 mm sleepers at 55 mm centres placed on the rigid floor (Fig. 8) without bottom ballast. The uplift was 2·5 mm for each cycle. The different particle sizes used as crib ballast are shown in Table 1.

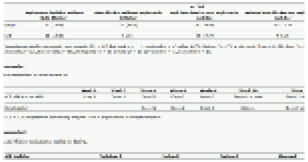

Table 1.
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Table 1.
Particle size of crib ballast

A graph of maximum sleeper displacement against number of cycles, for different particle sizes, is shown in Fig. 11. A graph of maximum height gain of sleepers against particle size is shown in Fig. 12.

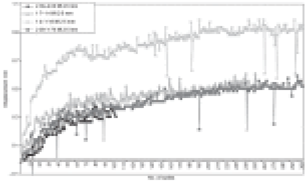

Fig. 11.
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Fig. 11.
Effect of particle size on sleeper height gain

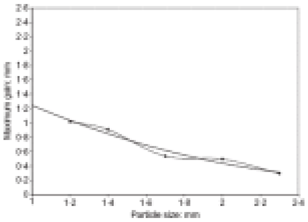

Fig. 12.
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Fig. 12.
Particle size plotted against maximum gain

It was observed that, for an uplift of 2·5 mm, the maximum height gain of the sleepers was equal to the uplift minus the particle size: for example, for a particle size passing a 2 mm sieve and retained on a 1·7 mm sieve the maximum correction is 0·5 mm for a 2·5 mm uplift. The best-fit line in Fig. 12 indicates that, for a particle size of 1·0 mm with 2·5 mm uplift of sleepers, the maximum correction in sleeper height would be 1·2 mm. Again, the effect of voids in the bottom ballast has been neglected in this test.

3.3. Uplift equal to displacement cycles

It has been observed that the sleepers sink into the ballast with each loading cycle: thus a test was designed with the uplift of sleepers after each cycle equal to the displacement of the sleeper in the ballast for that cycle. Thus after each load cycle the sleepers were brought to the initial zero level. This simulates ten loose sleepers in a length of track suspended from the rail and supported by adjacent sleepers. Tests were run with 5 mm and 2 mm stone as the crib ballast. A graph of maximum displacement of sleepers against number of cycles is shown in Fig. 13.

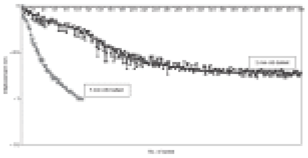

Fig. 13.
Click to view

Fig. 13.
Lift height equal to settlement

It was observed that for 5 mm stone as crib ballast there was no correction in sleeper height, and the rate of sinking of sleepers in the ballast was fast. For 2 mm stone as the crib ballast the displacement of sleepers into the ballast was slow, and was arrested at a displacement of 0·7 mm after approximately 350 cycles. The sleeper displacement was arrested at a maximum of 0·7 mm.

Thus there was a residual sleeper displacement of 0·7 mm (7 mm full size) with 2 mm stone as crib ballast. The earlier parametric study with sleepers on the rigid floor and crib ballast of particle size 2 mm (stone-blowing stone specification) had shown a residual sleeper displacement of 1·2 mm (12 mm full scale), whereas in the above test the maximum sleeper displacement is 7 mm (full scale). This is due to the presence of voids in the 5 mm ballast below the sleepers (Fig. 14), which helps the migration of the crib ballast into the voids under the sleeper so that the void is filled up to more than void size minus the average particle size of the crib ballast.

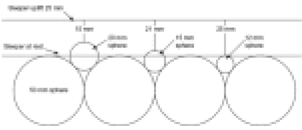

Fig. 14.
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Fig. 14.
Ballast particles idealised as spheres

4. FULL-SCALE TESTS

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To validate the results of the model tests full-scale laboratory tests were carried out with the proposed system of 20 mm crib ballast. The full-scale tests consisted of two different types of test:

a. box test
b. full-scale single sleeper test.

4.1. Box test

The box test was carried out by creating boundary conditions of a section of track in a box, as shown in Fig. 15. The length of the box was kept at 460 mm and the width of the box was kept at 550 mm, which is centre-to-centre distance between two sleepers. Thus the effect of loading in the transverse direction (along the sleeper length) was ignored. A rigid boundary was assumed at the centre of distance between two sleepers: thus it was assumed that load applied on one sleeper would not affect ballast beyond the centre of distance between two sleepers. The depth of the box was 500 mm, which is the total depth of ballast, including crib ballast and bottom ballast, in British railway practice. A concrete sleeper pad was used in the test, with dimensions of 450 mm long by 280 mm wide by 230 mm deep. The test was computer controlled, and load was applied directly to the sleeper. The maximum load was 40 kN (40% of standard wheel load on British railways). Standard 50 mm railway ballast was used as bottom ballast below the sleeper, and both 50 mm ballast and 20 mm stone-blowing stone were used as crib ballast. Load cycles similar to the model tests were run, with the first 20 cycles without uplift and then subsequent cycles with an uplift of 25 mm, to simulate a void of 25 mm under the sleeper. Displacement was measured at maximum load for each cycle. An inspection window was fitted into the side of the box to see the movement of the crib ballast in the uplift cycles (Fig. 15). After the 20 load cycles when the sleeper lifted up by 25 mm the crib ballast moving into the void was visible from the inspection window.

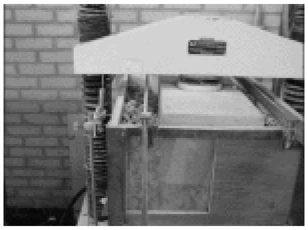

Fig. 15.
Click to view

Fig. 15.
Box test

The results for the 50 mm crib ballast are shown in Fig. 16, and the results for the 20 mm crib ballast are shown in Fig. 17. A graph comparing the results of the model tests and the full-scale tests for 20 mm crib ballast is shown in Fig. 18. It was observed that, for the box test with 20 mm crib ballast, the correction in sleeper height in uplift cycles was more rapid compared with the model tests.

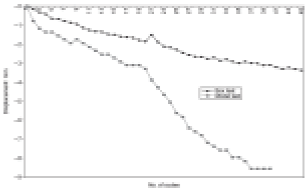

Fig. 16.
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Fig. 16.
Comparison of box test and model test with 50 mm crib ballast

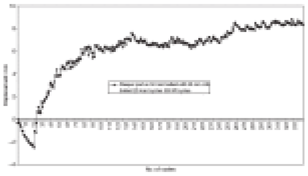

Fig. 17.
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Fig. 17.
Box test with 20 mm crib ballast

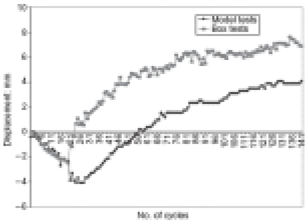

Fig. 18.
Click to view

Fig. 18.
Comparison of box test and model test with 20 mm crib ballast

4.2. Full-scale single-sleeper test

Again boundary conditions similar to those in the box test, for a small section of track around a single sleeper, were created in the laboratory by placing two concrete panels on each side of the sleeper 550 mm apart, as shown in Fig. 19. The concrete panels were assumed to provide a rigid boundary. The sleeper was placed in the centre with 230 mm depth of standard 50 mm ballast below it. Two lengths of rail were fixed to the sleeper, and the ends of the rails were supported by springs for the sleeper to lift up when the load was brought to zero. This replicates the uplift cycles of the model tests. Load was applied directly to the rails using rams driven by a hydraulic pump. The maximum load applied was 55 kN per rail. Twenty millimetre stone was used as crib ballast, and load cycles similar to the earlier model test and box test were run. Displacement was measured at maximum load for each cycle using linear voltage displacement transducers fixed to each rail. The results are shown in Fig. 20. A graph comparing the results of the model tests, box test and full-scale test is shown in Fig. 21. The result of the full-scale tests are similar to those of the box tests.

Fig. 19.
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Fig. 19.
Full-scale test set-up

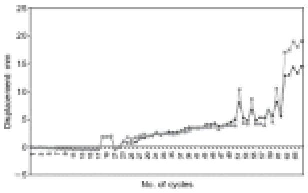

Fig. 20.

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Fig. 20.
Full-scale single-sleeper test with 20 mm crib ballast

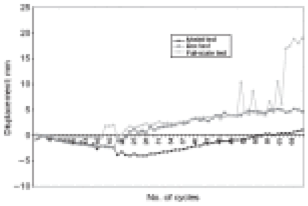

Fig. 21.

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Fig. 21.
Comparison of full-scale and model tests

5. CONCLUSION

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a. The system of using 20 mm stone as crib ballast is capable of partially filling voids occurring under sleepers and reducing sleeper displacement.
b. The system has shown better results for full-scale tests than for model tests.
c. For the tests run on a solid base to eliminate the effect of void size in bottom ballast on the system, it was observed that, for all uplift heights (void sizes) and particle sizes, the maximum correction in sleeper height was the uplift minus the average particle size of crib ballast—that is, void size minus the average particle size of the crib ballast.
d. For tests run with 5 mm stone (modelling standard railway ballast) as bottom ballast and 2 mm stone (modelling stone-blowing stone), the deterioration in vertical alignment of the track is arrested at a residual sleeper displacement of 0·7 mm (7 mm full scale).
e. For ‘standard’ 5 mm stone as crib ballast there is no correction in sleeper height for an uplift of 2·5 mm (void size 25 mm full scale). The sleeper displacement into the ballast is accelerated for the uplift cycles with the ‘standard’ system.

The tests have shown that the proposed system of replacing crib ballast by stone of smaller size is capable of filling up voids beneath the sleepers and maintaining sleeper vertical alignment within a certain tolerance. The system is self-maintaining, which indicates potential for the maintenance of railway track without the use of stone-blowing or tamping machines.

The initial results convinced Balfour Beatty Rail and RMC concrete products to provide financial backing to the project, and the authors are grateful to them for their support for the experimental work described in this paper. The aim was to carry out detailed model tests on the system, validate the results of the model tests with full-scale laboratory trials, and then try the system on live track. To date, model tests and full-scale laboratory tests have been carried out on the system. It is proposed to go out on live track trials of the system soon. Railtrack is supporting the project and it is anticipated that they will help in setting up the live track trials.

6. ACKNOWLEDGEMENTS

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