Closure to **"The Influence of Rubber Inclusion on the Dynamic Response of Rail Track"** **by** Yujie Qi, Ph.D., A.M.ASCE; Buddhima Indraratna, PhD., F.ASCE; DOI: **https://doi.org/10.1061/(ASCE)MT.1943-5533.0004069**

Yujie Qi, Ph.D., A.M.ASCE[1]; Buddhima Indraratna, Ph.D., F.ASCE[2];

[1]Lecturer, and Program Co-leader of Transport Research Centre, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney NSW 2007, Australia. Email: yujie.qi@uts.edu.au

[2]Distinguished Professor of Civil Engineering, Founding Director of Australian Research Council's Industrial Transformation Training Centre for Advanced Technologies in Rail Track Infrastructure (ITTC-Rail), Director of Transport Research Centre, School of Civil and Environmental Engineering, University of Technology Sydney, Sydney, NSW 2007, Australia. Email: buddhima.indraratna@uts.edu.au

†Author for correspondence:
Yujie Qi
Lecturer & Program Co-leader of Transport Research Centre,
Faculty of Engineering and Information Technology,
University of Technology Sydney,
Email: Yujie.qi@uts.edu.au

Response to Discussion:

The authors appreciate the comments made by the Discusser, and for providing an opportunity to further clarify the findings related to "deformation behavior" and "Energy absorption property and ballast degradation", while elaborating on the application of these research findings to real-life track structures in frozen regions.

Please note all the figure numbers mentioned in this Closure are from the original paper (Qi and Indraratna 2022).

Deformation Behavior

(a) The authors agree that when describing the plastic collapse of SEAL40 mix, the Figs. 3a and 3b in the original paper (Qi and Indraratna 2022) should be the correct figures to be referred to rather than Fig. 4d.

(b) The changing sign of the accumulating rate indicates that the mixtures having rubber content $R_b \geq 20\%$ have shown unstable behavior (in the horizontal direction) with alternating lateral compression and extension (dilation). This behavior is more appropriately depicted in Figs. 4c and 4d, rather than in Fig. 4c or Fig.4d, noting that Fig. 4c is for $R_b \leq 30\%$ and Fig. 4d is for $R_b = 40\%$.

(c) In the original paper, to evaluate the feasibility of using SEAL as the subballast, the deformation behavior of SEAL was compared with traditional subballast (compacted sandy gravel). In the field, material used for subballast comes from a variety of granular media, e.g., broadly-graded natural aggregates or blended mixtures of sand, gravel and slag etc. (Indraratna et al. 2011). In this regard, instead of only using the subballast (well-graded aggregates) tested in the current study as the baseline, the authors have also referred to the behavior of traditional subballast materials (e.g., well-graded crushed basalt) tested under the same test apparatus and loading conditions (Navaratnarajah et al. 2018), in a way that is more beneficial to industry practices.

(d) The elastic displacement shown in Fig. 5b is only for the subballast tested in the current study, as the elastic behavior from Navaratnarajah et al. (2018) was not available.

(e) The authors appreciate the discusser for the query on lateral deformation trends. In Fig. 4a, it will be more accurate to describe the lateral deformation as follows. As R_b increases from 0 to 20%, it is observed that the lateral dilation is reduced, and when $R_b \geq 20\%,$ the lateral displacement fluctuates with the loading cycles. This trend in fluctuating displacement becomes more apparent for SEAL30 whose lateral dilation is even greater than SEAL0 for $2 \times 10^3 < N < 2 \times 10^4$, and then diminishing to values lower than SEAL20 when N exceeds 2×10^5.

(f) The authors would like to reiterate the fact that SEAL is a mixture of coal wash, steel furnace slag and rubber crumbs, rather than a mixture of traditional subballast mixed with rubber crumbs. Indeed, the authors agree that the loading condition and the shape of rubber particles can influence the deformation behavior of the blended mix. For instance, rubber crumbs which are prismoidal/cuboidal in shape create a stronger interlocking granular assembly than elongated rubber chips or shreds which offer a substantially different interspersed fabric (Fu et al. 2017, Qi et al. 2019). It has been observed that rubber chips may keep migrating internally and changing shape during the entire loading period (Mashiri et al. 2015, Badarayani et al. 2021). However, in the current study, all the experiments were conducted with the same loading condition and the same batch of rubber crumbs (i.e. same shape), hence, the deformation of SEAL mix was controlled initially by the original compacted density or void ratio, while over time, the behavior became more a function of the rubber content (Qi et al. 2019).

Energy Absorption Property and Ballast Degradation

Fig. 8 shows the BBI (ballast breakage index) of the ballast track specimens with different SEAL mixtures, where a sharp drop in BBI can be observed for SEAL10 (BBI=0.0312) compared to SEAL0 (BBI=0.0746) and traditional ballast (BBI=0.0735). Subsequently, relatively marginal changes from 0.0403 to 0.0259 are noted as R_b increases from 20 to 40%. These results indicate that in terms of reducing ballast degradation, all SEAL specimens with 10-40% rubber could offer benefits if adopted as a subballast material. However, selecting an optimal SEAL mix should consider the behavior in relation to the overall stress-deformation response and shear strength, and not solely on the extent of BBI. As indicated in the original paper, both SEAL30 and SEAL40 are unsuitable, because, SEAL40 could induce the failure of a ballast specimen while SEAL30 showed significant fluctuation in the lateral deformation reflecting a key tell-tale symptom of track instability. In contrast, SEAL20 is also not recommended by the authors, as its vertical displacement was 2-3 times that of traditional subballast, implying the potential of not meeting the stringent track settlement standards for freight trains set by Australian rail authorities.

Application of Current Research in Real-life Track Structures in Frozen Zones

The authors admit that one of the limitations of the current study is that the findings are only suitable for tracks that are not subjected to sub-zero temperatures as frozen conditions prevailing in North America, Europe and East Asia have not been tested within the scope of this study. In such sub-zero temperatures, the track substructure is subjected to freeze and thaw cycles which have not been studied for this SEAL material. It is anticipated that a frozen track bed would result in higher track modulus (greater stiffness), which might induce greater vibration and ballast degradation as discussed elsewhere (Ling et al. 2009, Tian et al. 2020, Zhang et al. 2022). According to the test conditions described in the current study, the addition of rubber inclusions in the track substructure reduces the track modulus, i.e. slight increase in overall compressibility (Qi et al. 2018, Qi and Indraratna 2022). Using rubber materials in frozen track substructure may still reduce track vibration and ballast degradation, but the authors would not like to speculate without testing SEAL under frozen conditions.

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