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Rafael Kamalov completed his Ph.D. in Civil Engineering in 2021 at the University of Birmingham, focusing on railway subgrade stability within the Birmingham Centre for Railway Research and Education.

His research addressed foundational challenges in subgrade resilience, significantly enhancing the understanding of railway infrastructure performance. Rafael also holds an MSc in Geotechnical Engineering and has worked as an Engineer at Atkins, where he worked on major infrastructure projects, including HS2. His interdisciplinary expertise combines rigorous academic research with practical engineering applications, making him well-equipped to contribute to advancing the field of civil engineering.

Gurmel Ghataora (PhD, MIMMM) has over 50 years of experience in Civil and Geotechnical engineering. He worked with a ground investigation contractor and Arup for eight years before joining the University of Birmingham in 1990.

He retired in 2021 as Associate Professor and started his own company (Geo G Ltd) providing research project and research student support. His research interests included geotechnics of railway track, ground improvement and use of waste/marginal materials in construction, particularly in rural roads in developing countries. He has worked on numerous research projects and supervised 60 PhD students and has published 175 papers and co-authored 5 books.

EFFECT OF UNDER SLEEPER PADS ON RAILWAY TRACK SUBGRADE

INTRODUCTION

Under sleeper pads (USPs) have been used under concrete sleepers since the 1980s. Their main function is to increase the contact area between the sleeper and ballast (Getzner, 2014, Ghataora, and Burrow, 2016) thereby mitigating the pressure between the ballast and the concrete sleepers at the interface. Other benefits include a reduction in inter-particle abrasion and sleeper–ballast attrition (Müller-Boruttau et al., 2001, Schneider et al., 2011), improved stability (Lakušić et al., 2010), reduced vibration (Müller-Boruttau et al., 2004) and Piaxao et al., 2015) and they help to reduce the impact of change in stiffness at transition zones (UIC, 2019).

There are, however, few, if any, studies that investigated the effect of USPs on the subgrade soil. The study reported herein, based on laboratory experimental work, considers the effect of USP on the deformation of the track in both wet and dry conditions for four types of clayey subgrade. In particular, the study focused on the erodibility of the subgrade, which can lead to the development of wet beds (also known as ballast fouling). It was found that the benefits achieved depended on the consistency of the subgrade soil.

BACKGROUND

Clayey subgrade soil erosion of clay and its migration into the overlying layers can take place under certain conditions, particularly poor drainage (Selig and Waters, 1994; Alobaidi and Hoare, 1996; Ghataora, 2006; Duong et al. 2014). Instances of fines migration into the ballast have been observed at locations with imperfections in the rail running surface and at rail joints, where dynamic load from train wheel impacts can be substantial (Ghataora, 2005; Ghataora et al., 2006; Rushton & Ghataora, 2009; Nguyen et al., 2019). The presence of clayey fines in the ballast leads to its inability of the ballast to provide adequate support to the track (Takatoshi, 1997, Ghataora and Burrow, 2010, Liu et al. 2013; Hudson et al., 2016; Nguen and Indraratna, 2019). Numerous solutions for this problem include the use of geotextiles/geotextile composites Alobaidi (1994, 1996, and 1998); Indraratna et al. (2010); Chawla and Shahu (2016); Ghataora and Burrow (2014, 2016 and 2018), sand blanket (Selig and Waters, 1994), asphalt overlay (on subgrade) Ito (1984), cement stabilization of subgrade amongst others.

The use of sand blankets and sub-ballast in addition to its action as a filter layer helps to reduce dynamic stress at the subgrade level and hence reduce the development of erosion (Selig & Waters, 1994). The asphalt layer serves as a separation barrier, further diminishing dynamic loading at the subgrade level to some extent, while also potentially sealing the subgrade surface from rainwater (Ito, 1984). However, this impermeable seal may pose challenges if it results in the accumulation of porewater pressure in the underlying subgrade (Ghataora & Burrow, 2010). The utilization of USP, is engineered to alleviate stress in the uppermost layer of ballast at the ballast/concrete interface and to dampen vibrations, consequently reducing dynamic stress at the subgrade level (Müller-Boruttau et al., 2001). Using USP results in reduction in the ballast sleeper contact stresses which reduces the deterioration of both the ballast and sleepers. (Lundqvist et al., 2006; Johansson et al., 2008; Dahlberg, 2010; Schneider, 2011). Abadi et. al. (2019) show the use of USPs may reduce the requirement for track maintenance and hence improve whole life costs.

Although the benefits of USPs have been reported over the last 20 years and are used in railways, there is limited, if any, information about the effect of USPs on the subgrade. There is no available information on the effect of USPs on the development of pore water pressure, which is the main factor in the creation of the mud-pumping phenomenon (Alobaidi and Hoare 1994; Selig and Waters, 1994; Ghataora, 2006, Duong et al., 2014). The study reported herein considered the behaviour of the subgrade-subbase system with and without USP through a laboratory-based experimental investigation. In particular, the focus of the study was on investigating the behaviour in terms of permanent deformation, stiffness, subgrade erosion, and the development of pore water pressure.

METHODOLOGY

Materials - Subgrade soil

Some types of fine-grained, clayey subgrade soils in a railway track, under certain conditions, can liquefy and erode. Four medium to high plasticity soils, namely, London clay (LC), Etruria marl (EM), and two manufactured soils: English China clay (CC) and a mixture of English China clay and Bentonite (CCB) were tested at a range of moisture contents, namely 80%, 100% and 120%, of optimum moisture content (OMC). Berkbent 163 Bentonite was used to modify the China clay to form the CCB. Atterberg limits, particle size analysis, specific gravity, compressibility and permeability were determined in accordance with BS 1377-2:1990 and results are listed in **Table 1**.

Soil	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	Maximum dry density (Mg/m^3)	Optimum moisture content (%)	Specific gravity	c^v (mm^2/min)	m^v (m^2/MN)	K (m/s)
Etruria marl	48	18	30	1.89	17	2.54	19.4	0.71	$2.2*10^{-9}$
London clay	60	25	35	1.68	21	2.41	13.2	0.79	$1.55*10^{-9}$
China clay	55	27	28	1.53	30	2.35	27.2	1.13	$7.65*10^{-9}$
China clay plus 5% bentonite	63	30	33	1.51	32	2.32	24.6	1.04	$5.71*10^{-9}$

Table 1: Summary of properties of subgrade soils

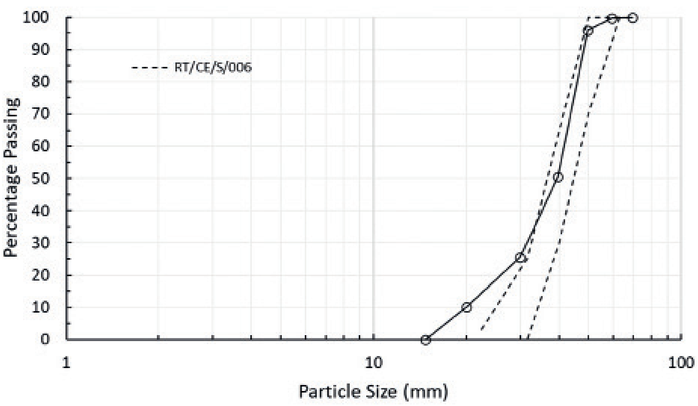


Figure 1: Particle Size Distribution of ballast.

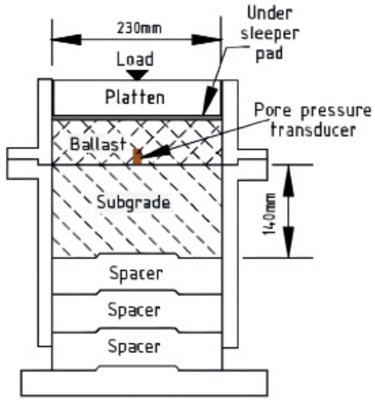


Figure 2: Cross-section of the Terram cell layout with USP.

Figure 3: Set up of the Terram cell in the load frame.

MATERIALS - BALLAST

The selected ballast material used in this research was in the range of the industry requirements provided by Network Rail Standard (RT/CE/S/006, 2019), with approximately 70% falling within the 32-50mm size range. **(See Figure 1)**.

MATERIALS - UNDER SLEEPER PAD (USP)

The USPs used in this study were provided by Getzner Werkstoffe, GmbH and identified as SLB 3007. The static bedding modulus of the USP was 0.36 N/mm^3 and the static spring stiffness was 70 MN/m when applied to half the bottom surface area of the sleeper.

TEST APPARATUS AND PROCEDURE

The apparatus used for this study was the Terram cell, described by Ghataora (2006). Its development was based on previous studies on the erosion of subgrade soils in roads and railway tracks at the University of Birmingham, UK (Hoare, 1982; Alobaidi and Hoare 1994; 1996, Hoare, Alobaidi and Ghataora, 1995). The Terram cell was built and supplied by Terram Ltd. UK.

The test cell comprises two 230mm (id) steel tubes with flanges such that the two parts can be clamped together. The lower cylinder had a base plate and spacers. The latter were used to adjust the thickness of the subgrade soil. The Terram cell was developed to assess the migration of fines through a geocomposite placed on the subgrade. A 75mm thick layer of ballast was placed directly on the subgrade. The load platen was either directly on the ballast or on the USP which was placed on the ballast as shown in the cross-section of the apparatus in **Figure 2**. In some tests pore water pressure developed under the ballast was measured by installing a fluid-filled tube in a ballast rock and connecting it to a transducer. The position of the pore water pressure measurement is also shown in **Figure 2**.

The test cell was placed in a 50 kN load frame and the cyclic load was applied at 3 Hz to give minimum and maximum pressures of 0.6 kPa and 128 kPa respectively at the top of the subgrade. The arrangement of the cell setup is shown in **Figure 3**.

Subgrade soils at 80% Optimum Moisture Content (OMC), 100% OMC, and 120% OMC were compacted at Maximum Dry Density (MDD) to a depth of 140mm on the spacers (see cross-section layout, Figure 2). Four test types were conducted: ballast/subgrade; ballast/subgrade/water; ballast/subgrade/USP; and ballast/subgrade/water/USP. Water was added in two tests to simulate lack of drainage. In such tests, 500ml water was added before the application of cyclic load in accordance with the procedure developed by Ghataora (2006). The setup procedure is shown in **Figure 4 (a)** to **(d)**.

Load was applied in steps of 50,000 cycles up to a total of approximately 200,000 cycles. Upon completion of the test, the ballast and the USP (where used) were removed, and all the slurry was collected and oven-dried to quantify the amount of subgrade material eroded (i.e., slurried). The strength of the subgrade soil immediately under the slurry was measured using a hand vane in accordance with BS 1377-2:1990. Additionally, the moisture content of the upper layer of the subgrade was determined.

Test designations follow a specific format: dry tests on each clay type have a suffix "bs" (e.g., CC-bs for China clay/ballast/subgrade),

(a) Compacted subgrade. **(b)** Ballast inundated with water. **(c)** Under sleeper pad. **(d)** Terram cell – completed assembly.

Figure 4: Key stages of the test setup.

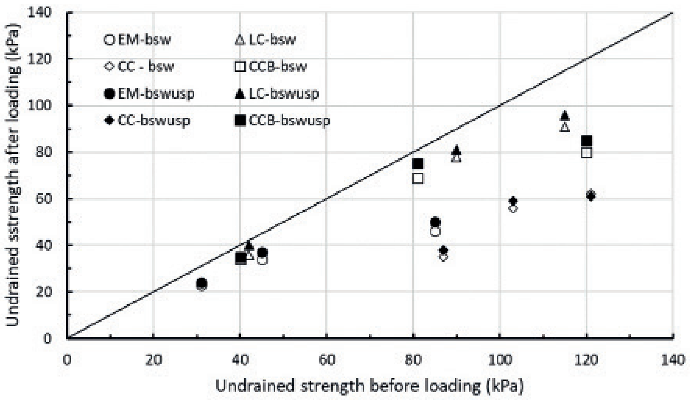


Figure 5: Comparison of strength of subgrade with water added, both with and without USP before and after application of 200,000 load cycles.

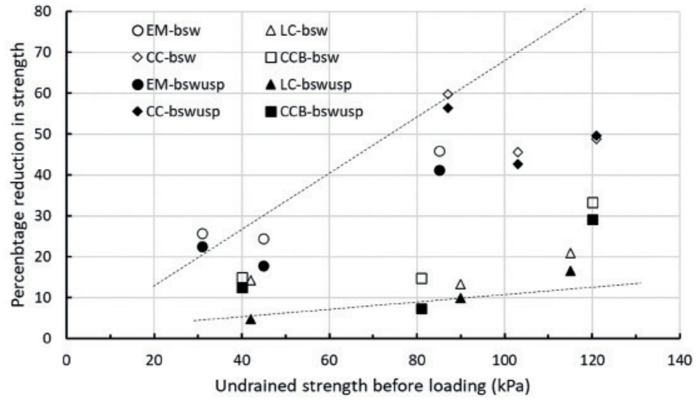


Figure 6: Percentage reduction in strength after loading relative to initial strength with and without USP.

while wet tests have a suffix "bsw" (e.g., CC-bsw for China clay/ballast/subgrade/wet test). For tests conducted with USP, "usp" is added to the suffix (e.g., CC-bswusp for China clay/USP/ballast/subgrade/wet test).

RESULTS

Ballast/sleeper contact area

Prior to investigating the effect of USP on the subgrade, the contact area between ballast and sleeper with and without USP was studied using the Terram cell described in the 'Test Apparatus and Procedure' section above. To study the contact between the sleeper and the ballast a sheet of paper was attached to the bottom of the steel load platen and the top of the ballast particles were coated with ink. The cell was assembled, and 250,000 load cycles were applied, as suggested by Ghataora and Burrow, (2016). The paper was removed, and impressions of ballast on the paper measured as the contact area. The procedure was repeated with USP instead of paper. At the end of the tests, the areas of impressions of ballast in USP were measured.

The contact area between the sleeper and ballast was found to be about 1.8% (expressed as a proportion of load plate area), which aligned closely with the findings of Ghataora and Burrow, (2016), who reported values ranging from 1 to 1.5%. Potocan and Dorfner, (2013) noted that the contact area between ballast and sleeper may be 3 to 5%, whereas Abadi et al. (2015) demonstrated ballast/sleeper contact area of less than 1%. Thus, although the ballast used in this study was slightly finer than the Network Rail specifications, the results were considered reasonable. Based on the small areas contact stresses may increase by up to 100 times (up to 10MPa) greater than that based on uniform contact. Using the USP, contact area increased to about 29%. Sol-Sanchez et al., (2014) stated that the contact area may increase by up to 35% depending on the stiffness of the under-sleeper pad. Ghataora and Burrow (2016) and Getzner (2021) have shown that the contact area may be increased to between 20 to 30%.

Bearing in mind that the stiffness of the USPs used by the various researchers may differ, the contact area results of this work were in line with other researchers' findings. Therefore, it was deemed that the test results of this study would give a reasonable indication of the of clay subgrade behaviour of the effect of using USP at the sleeper/ballast interface.

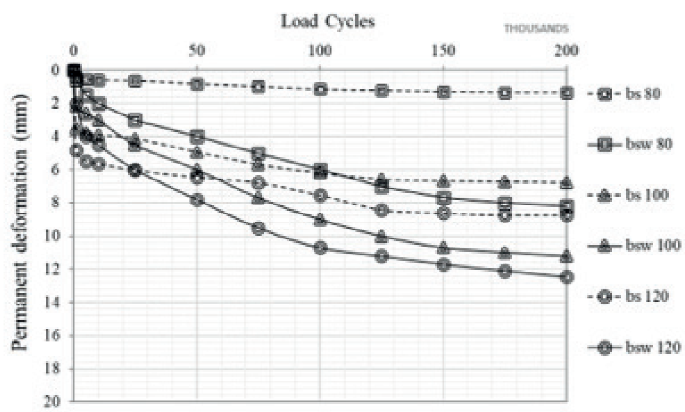
SUBGRADE STRENGTH

The strength of the upper 10 mm of the subgrade was measured using a hand penetrometer before and after applying 200,000 load cycles, for all the wet tests. A comparison of strengths of subgrade (with water added) both with and without USP before and after application of 200,000 load cycles are shown in **Figure 5** and percentages of reduction in strength after loading relative to initial strengths are shown in **Figure 6**. Results show (**Figures 5** and **6**) that reduction in strength is greater for stiffer clays. Although there may be a trend line expressing the behaviour of each clay type, the available data do not allow for the establishment of a general relationship for all clay types. Nevertheless, the data suggest that, in general, there is a slightly lesser reduction in strength with the use of USP.

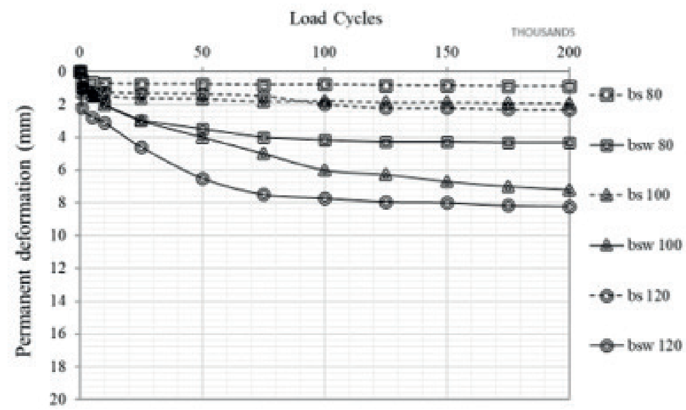
DEFORMATION - EFFECT OF WATER ON SUBGRADE

The focus of the study was primarily on investigating the long-term impact of USP on subgrade, and hence, only permanent deformation is discussed herein. Cyclic deformation was used to assess the stability of the tests. In all cases, this was not an issue.

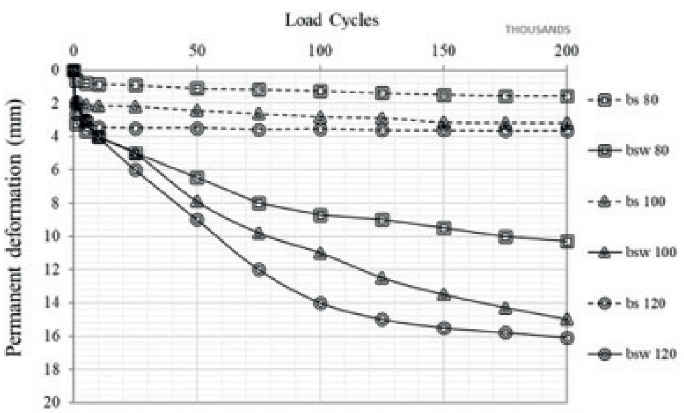
The deformation trends observed were consistent across all soil types, demonstrating initial high deformation levels during the early loading stages, up to approximately 50,000 cycles.



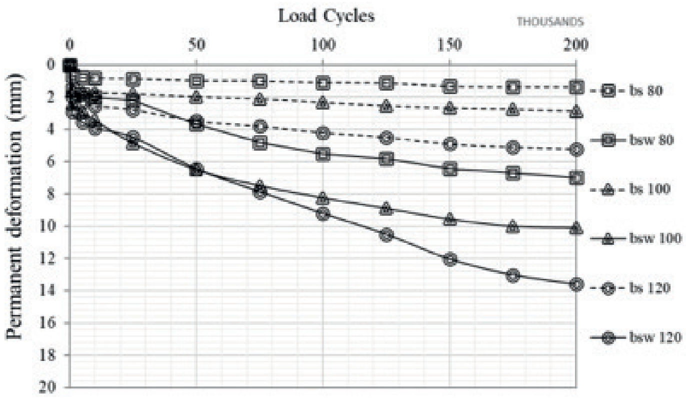
(a) Etruria marl (EM).



(b) London clay (LC).

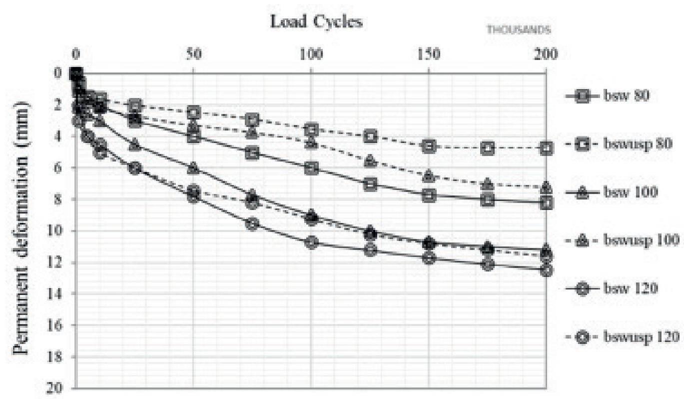


(c) China clay (CC).

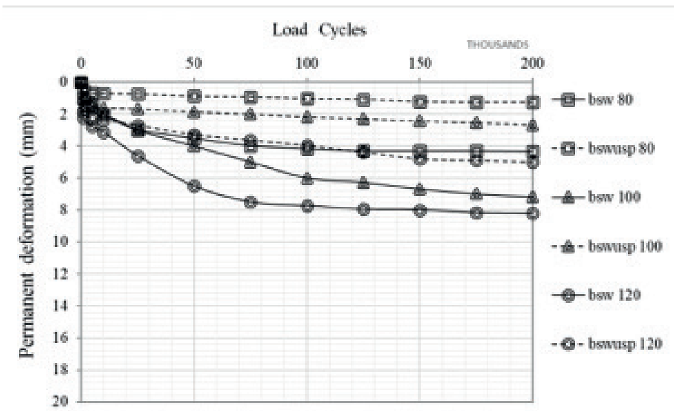


(d) China clay with bentonite (CCB).

Figure 7: Effect of free-standing water on permanent deformation subgrades with and without standing water.



(a) Etruria marl (EM).



(b) London clay (LC).

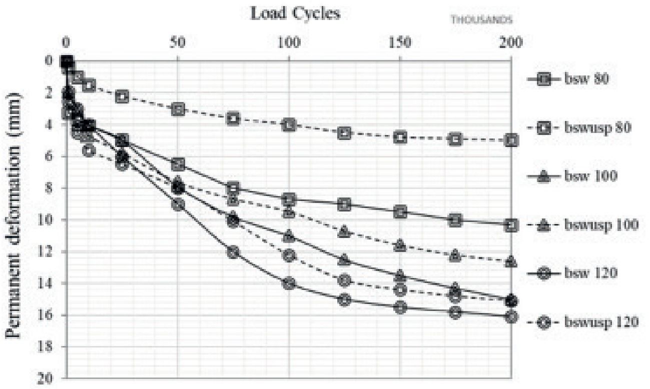
Figure 8: Relationship of permanent deformation and compaction moisture content for subgrade with standing water and both with and without USP.

As the number of load cycles increases, the rate of deformation generally decreases. Across all soil types, the subgrade subjected to water infiltration consistently displayed up to approximately four times greater deformation compared to the dry subgrade, regardless of their initial moisture content. This trend persisted over the entire loading range examined, encompassing 200,000 cycles, as depicted in **Figure 7**. In addition to this change in settlement generally continues for a much greater period of loading for inundated subgrade. This behaviour is expected as soils become softer with time when inundated with water and the rate of softening depends on their plasticity. The findings are in general agreement with those of Alobaidi and Hoare (1994) and Li and Selig (1995).

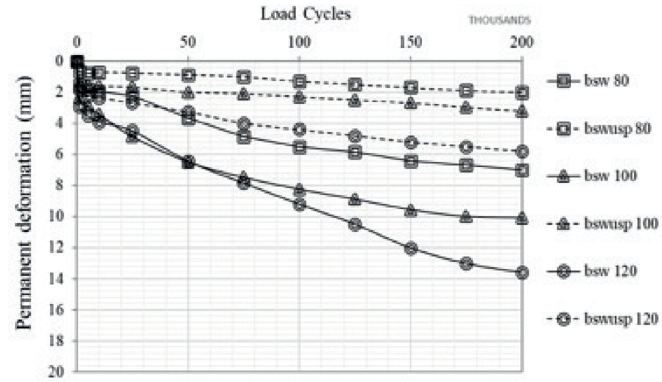
This trend was as expected, and the tendency was the same with and without USPs. All subgrades without USP and with initial moisture content of OMC 120% showed a large permanent deformation with both CC-bsw120 and CCB-bsw120 exhibiting the largest deformation of 16 mm and 14 mm respectively. All four soils tested with USP deformed less and did not exceed values observed without USP, see **Figure 8**. The most significant reduction in permanent deformation was observed with the CCB-bsw which showed a change from 14mm to 6mm (with USP). However, EM and CC showed the least reduction at high moisture contents of 120%. This reduction is considered to be due to the reduction of stress due to dynamic loading at the subgrade level as the USP reduces the impact from repeated loading.

DEFORMATION OF SUBGRADE AND SUBGRADE SOIL TYPE

Figures 9, **10**, and **11** show the permanent deformation of subgrade soils for each compaction moisture content (80, 100, and 120% OMC). Across all moisture contents, China clay consistently displayed the



(c) China clay (CC).



(d) China clay with bentonite (CCB).

Figure 8: Relationship of permanent deformation and compaction moisture content for subgrade with standing water and both with and without USP.

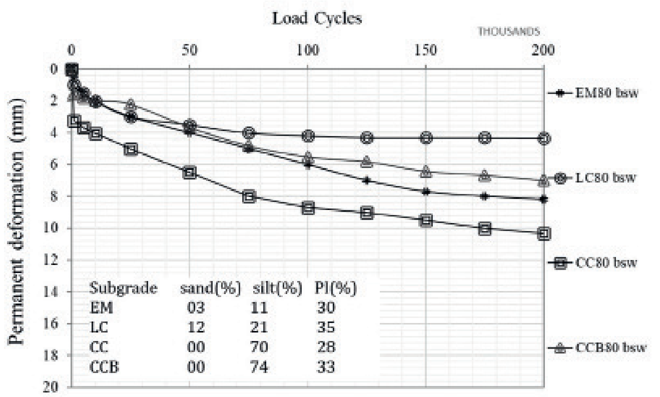


Figure 9: Comparison of permanent deformation and the effect of soil type, OMC 80%.

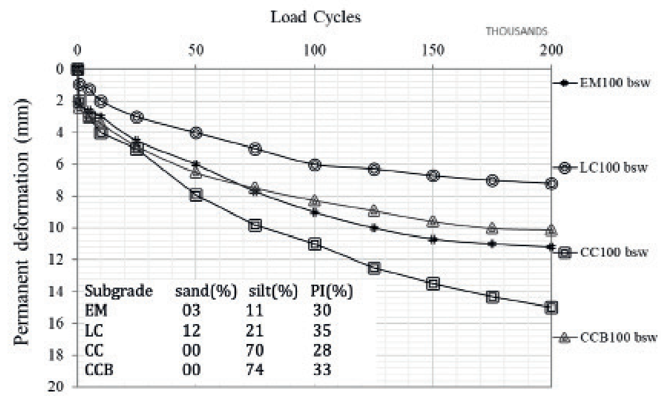


Figure 10: Comparison of permanent deformation and the effect of soil type, OMC 100%.

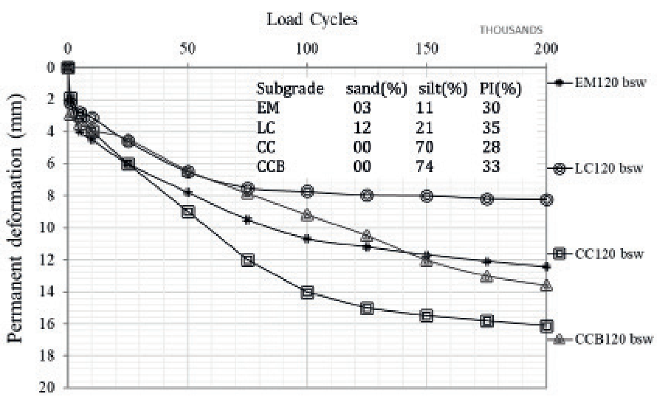


Figure 11: Comparison of permanent deformation and the effect of soil type, OMC 120%.

highest permanent deformation, while London clay exhibited the least susceptibility to deformation. Etruria marl (EM) exhibited intermediate settlement patterns, showing trends similar to those of China clay but with lesser magnitude.

London clay at 80% OMC, with an initial shear strength of 115 kPa, showed the least deformation, and China clay (initial strength (120kPa) exhibited the highest permanent deformation. These results were expected, as the undrained shear strength before and after the test reduced by about 21% and 50% respectively. The results also showed that with an increase in initial moisture content (100% OMC to 120% OMC) the permanent deformation increased by approximately 15-20%. These findings are in general agreement with Alobaidi and Hoare (1996) and Duong et al., (2014).

PORE WATER PRESSURE

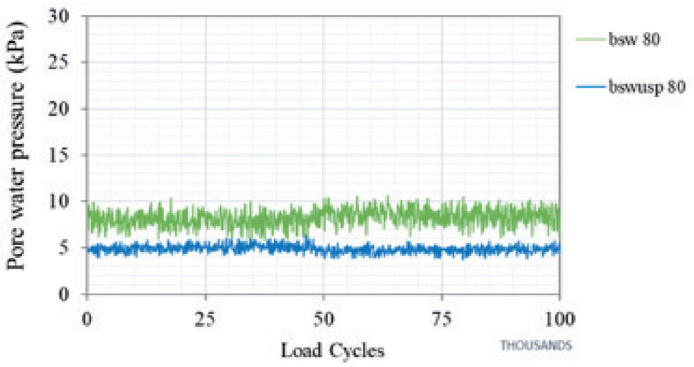
Development of pore water pressure due to repeated loading is one of the main reasons of the migration of fine particles and mud pumping phenomenon (Alobaidi and Hoare 1996, 1998; Ghataora et al. 2006; Trinh et al. 2012; Duong et al. 2014, Chawla 2016). Therefore, it was deemed important to measure the dynamic pore water pressure to assess the effect of USPs.

Results of pore water pressure in the subgrade immediately under the ballast for the four soils, with and without USP, compacted at three moisture contents are shown in **Figures 12**, **13**, and **14**. Generally, for all the soils at 80%OMC and 100%OMC, pore water pressure tended to remain steady throughout the test without USP, but for 120% OMC it tended to increase with number of load cycles. Also, lower pore water pressures, were observed (by as much as 50% with some soils) where USPs were used. Lowest pore water pressures were noted in all the soils compacted at 80% OMC. The pore water pressure attenuating effect of the USP was largest for subgrade soils compacted at a moisture content of 120% OMC for both CC and CCB.

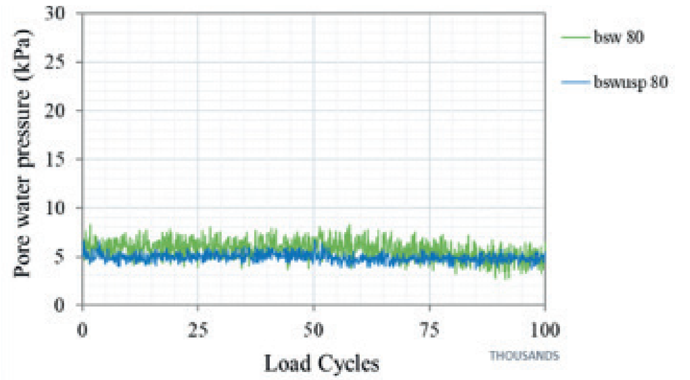
In terms of erosion, it is important to note that although the pore water pressure generated was less than about 18 kPa (maximum) it was enough to reduce the effective shear strength of subgrade at or near the surface to cause particle detachment and form slurry i.e., result in erosion. Since the use of USP reduced pore water pressure developed, it may help to reduce erosion of soil due to cyclic loading.

RELATIONSHIP BETWEEN LIQUIDITY INDEX AND DEFORMATION UNDER CYCLIC LOADING

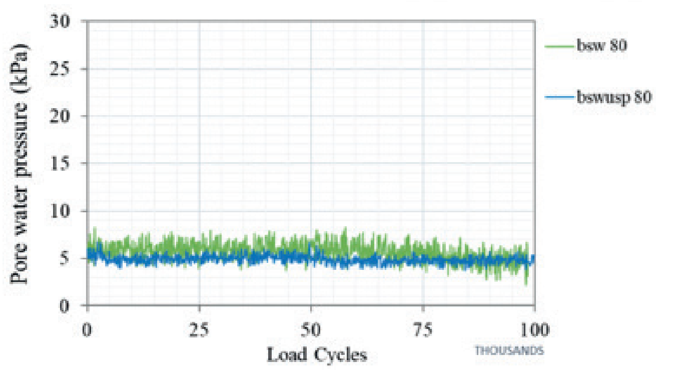
The undrained strength of clays is related to the Liquidity index (Vardanega and Haigh, 2014). Generally, as the soil Liquidity index is reduced to 1, its strength tends to be in the region of 1 to 1.7 kPa and



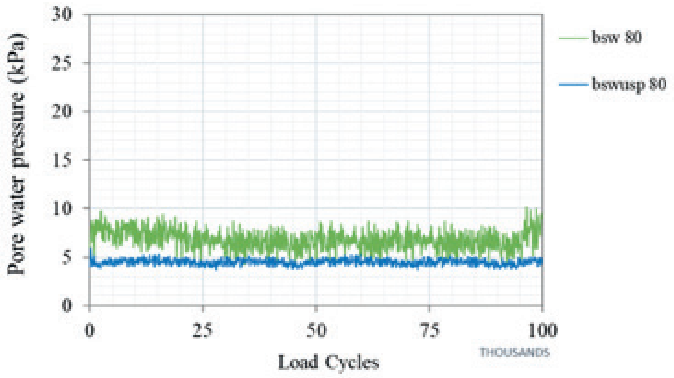
(a) Etruria marl (EM).



(b) London clay (LC).

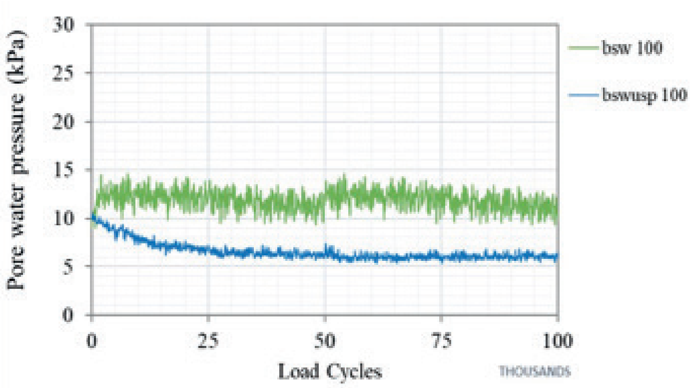


(c) China clay (CC).

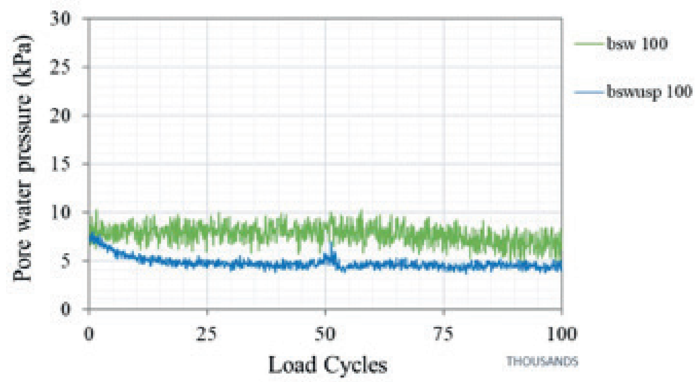


(d) China clay with bentonite (CCB).

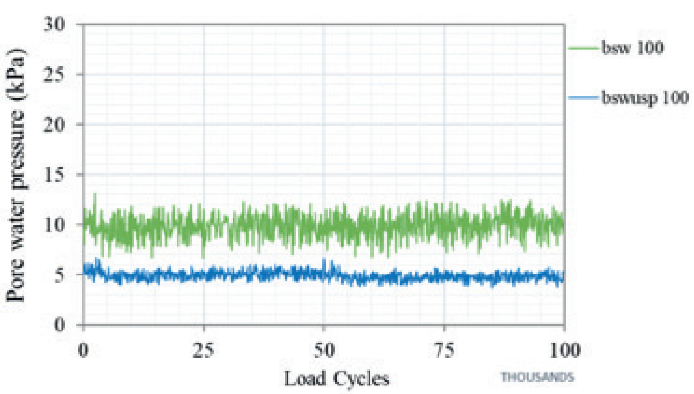
Figure 12: Development of pore water pressure – subgrade at 80% OMC.



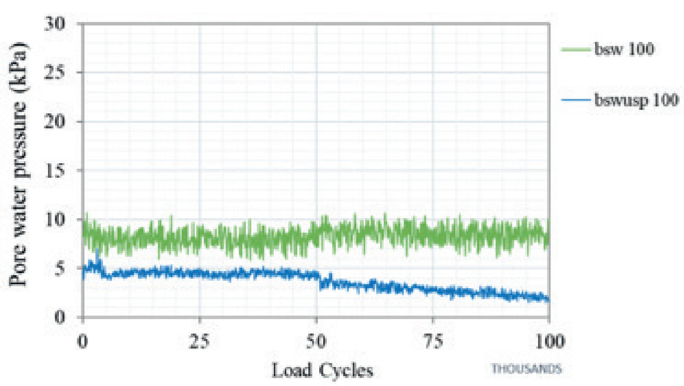
(a) Etruria marl (EM).



(b) London clay (LC).

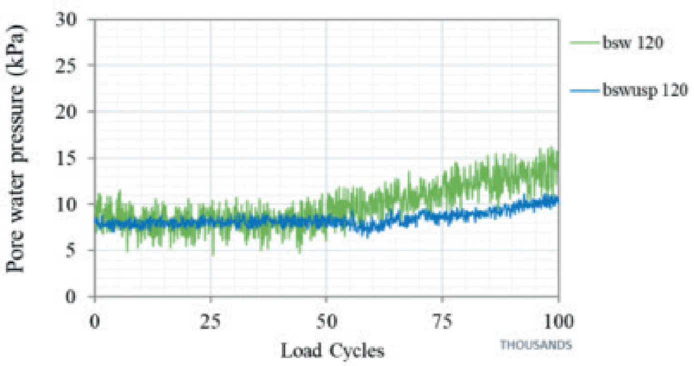


(c) China clay (CC).

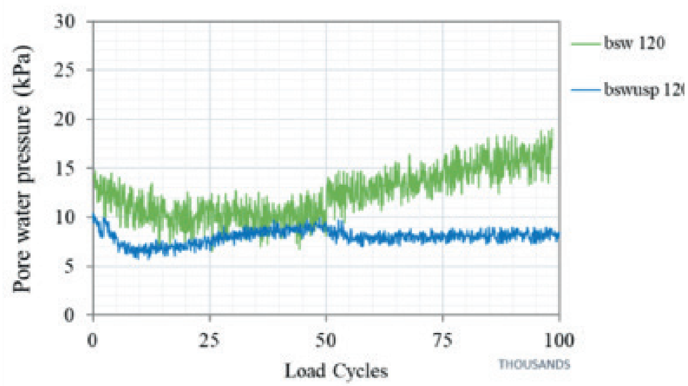


(d) China clay with bentonite (CCB).

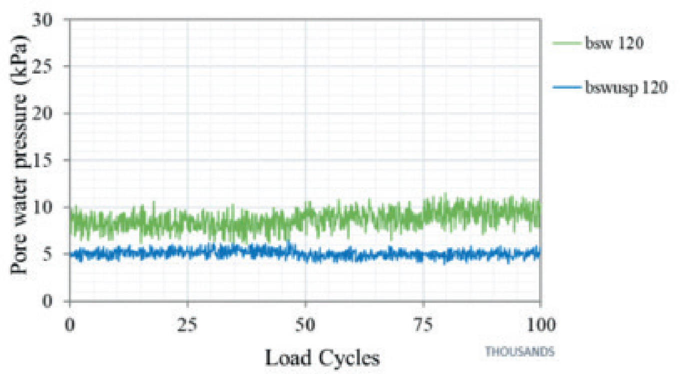
Figure 13: Development of pore water pressure, 100% OMC.



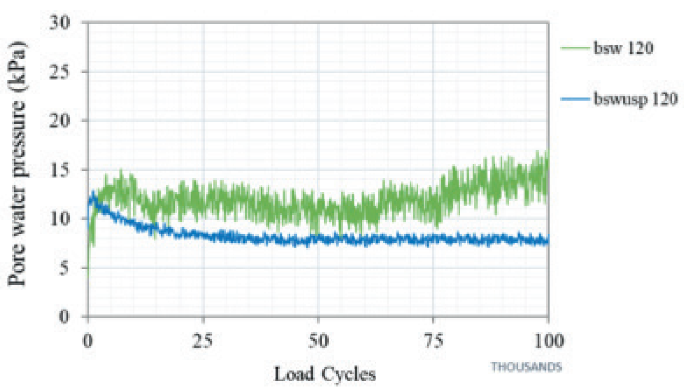
(a) EM.



(b) LC.



(c) CC.



(d) CCB.

Figure 14: Development of pore water pressure, 120% OMC.

when Liquidity index is zero strength is about 100 kPa. This general trend of change in strength was observed for all the soils as can be seen in **Figure 15**. In order to identify strengths beyond which USP is more effective permanent deformation/Liquidity index relationship for all the soils was examined as shown in **Figure 16**. Results suggest that although USP has some benefit in terms of reduction in deformation for all moisture contents, a more significant effect seems to occur for Liquidity index values less than 0.1 equivalent to a strength of about 60 kPa. Liquidity index of about 0.1 also corresponds with a point beyond which (i.e., Liquidity index >0.1) significant increase in erosion as can be seen in **Figure 17**.

RELATIONSHIP OF LIQUIDITY INDEX AND ERODED SOIL

Alobaidi and Hoare (1996) suggested that the quantity of eroded subgrade soil rises with an increase in its moisture content, a notion also supported by Selig and Waters (1994). The findings from this investigation align with this pattern. As depicted in **Figure 17**, the amount of eroded soil increases proportionally with the rise in the Liquidity index determined at the as-placed moisture content. This trend indicates that the rate of increase in eroded soil is higher in the case of subgrade soil without USP. Under similar conditions, USP demonstrates a reduction in the erodibility of the subgrade soil as the moisture content of the subgrade increases beyond the Plastic Limit. The increase becomes very significant with moisture content increases with Liquidity index for values greater than about 0.1.

The increase in erosion of soil between the stronger and weaker subgrades corresponds with the findings of Ghataora (2006); Duong (2014); and Chawla (2016).

EFFECT OF USP ON SOILS STIFFNESS

The effect of USP is depicted in terms of stiffness and Liquidity index in **Figure 18**. It confirms that USPs reduce the stiffness of the track only when the subgrade soils are firm or stronger, with a strength greater than about 60 kPa (Liquidity index>about 0.1). At lower strengths, subgrade soils deform more readily compared to USP, and the use of the latter in the track does not exhibit any significant effect.

CONCLUSIONS

The effect of USP (SLB 3007 supplied by Getzner Werkstoffe) on the four clay subgrade soils (Etruria marl, London clay, China clay (Kaolin) and China clay with 5% Bentonite) was investigated through a laboratory experimental study simulating railway ballast and subgrade system, subjected to 200,000 load cycles, in a test cell. The key aim was to assess the effect of USP on erosion of subgrade placed at 80% OMC, OMC and 120% OMC when the subgrade was inundated with water.

THUS, THE OVERALL CONCLUSION FOR THE FOUR SUBGRADE SOILS AT THE COMPACTED DENSITIES EXAMINED IS THAT USP CAN HELP TO REDUCE EROSION OF SUBGRADE SOILS AND MAY HAVE OTHER BENEFITS SUCH AS POSSIBLE REDUCTION IS LONG-TERM DEFORMATION

The key findings of the study are as follows:

- the small-scale laboratory tests showed that the use of USP resulted in an increase in ballast/subgrade area from approximately 1.8% to about 29% which is similar to other researchers' findings;
- the use of USP resulted in a lesser reduction in strength with the number of load cycles in all cases compared to scenarios without USP;
- permanent deformation of the soil/ballast system was reduced across all soil types and moisture contents with the use of USP;

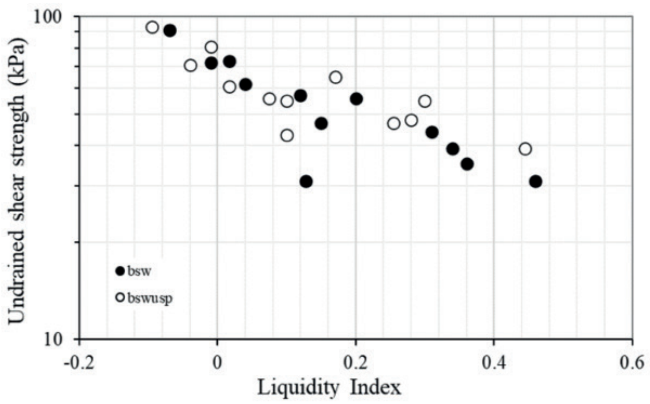


Figure 15: Relationship of shear strength and Liquidity index.

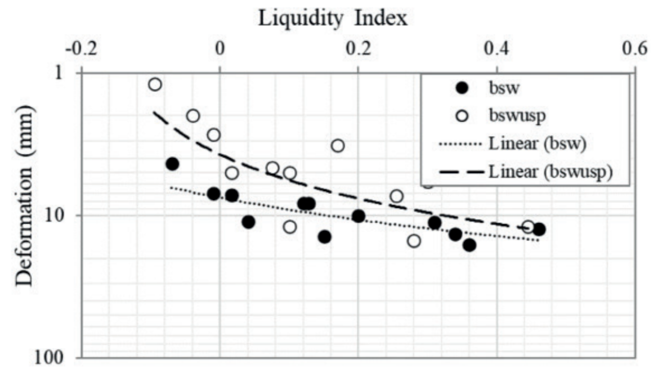


Figure 16: Relationship of Liquidity index and subgrade permanent deformation.

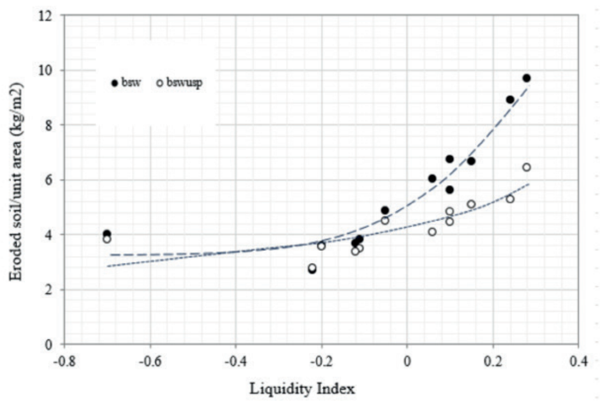


Figure 17: Relationship of Liquidity index (at the as-placed moisture content) and eroded soil at the end of the test.

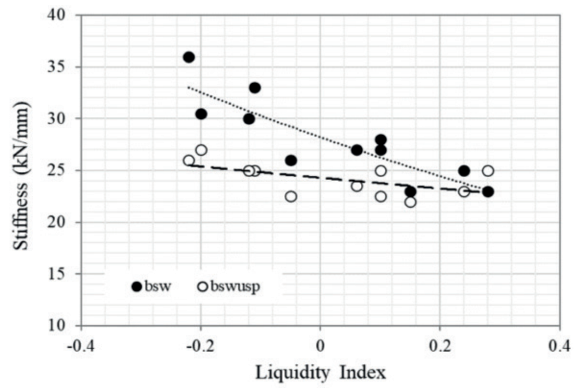


Figure 18: Relationship of Liquidity index (at the as-placed moisture content) and stiffness of subgrade.

- USP led to a decrease in pore water pressure development across all test cases;
- a general trend of increase in soil erosion with an increase in the initial moisture content of the soils examined was observed. USP reduced erosion at all moisture contents greater than the plastic limit as the moisture increased, the benefit increased.
- there was a reduction in stiffness with USB only when the subgrade soils had strengths greater than about 60 kPa.

Thus, the overall conclusion for the four subgrade soils at the compacted densities examined is that USP can help to reduce erosion of subgrade soils and may have other benefits such as possible reduction is long-term deformation, provided the strength of the soils is greater than about 60 kPa.

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