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An innovative ballasted track utilizing stabilized clayey subgrade

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ABSTRACT

The traditional ballasted tracks have been used widely in railway transportation infrastructure. Construction of ballasted tracks on the clayey soft subgrade causes high settlement and low bearing capacity. Significant maintenance cost and time-consuming operation have been encountered due to presence of clay. Different methods of soil stabilization have been presented in literature. Using road construction experience with Royal Road Product ($RRP_{235\ Special}$), as an innovative method for the first time, the layers underneath the sleeper have been replaced with the clayey subgrade stabilized with $RRP_{235\ special}$. A series of static and dynamic lab experiments such as Maximum Compaction test, California Bearing Ratio, Unconfined Compressive Strength, Brazilian Indirect Tensile test, Direct Shear Strength, and Uniaxial Cyclic tests were carried out. Samples with different dosages of additive were made, and an optimal percentage was found. As the result, the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ was determined as the suitable dosage in terms of mechanical and physical tests, while only in the Maximum Compaction test, by increasing the additive, the optimum water content decreased.

Introduction

Ballasted tracks have been considered due to benefits such as low construction cost, proper drainage, and simple technology. Despite the mentioned benefits though, some challenges such as maintenance costs, vertical settlement, horizontal displacement, and low lateral resistance have led to extensive investigation in order to manage these drawbacks.

It will be a caught-in-crossfire situation when structures fail due to the presence of clayey soils and the need for their microstructural, mechanical, and strengthening properties to be improved before construction.

Challenges occur in the construction of railway tracks in presence of clay that causes settlement, pumping and slippage. Encounting of clayey soils in the subgrade of railway tracks reduces the bearing capacity, increases water absorption and as a result creates horizontal and vertical deformations that are transmitted through the ballast layer to the railway pavement.

Transportation projects require large amount of suitable soil as subgrade and filling materials. However, suitable soils have to be acquired with enormous costs. Thus, stabilizing of weak subgrade has been considered by scientists [1]. Soft clay is widely found all over the world and its low strength, high compressibility and huge volumetric changes cause damage to transportation infrastructure, generate expensive maintenance costs and cause difficulties in subgrade construction [2,3]. The roadbed is the most deformable part of railway track which produces increasing maintenance costs [4]. The design of railway track is challenging in the face of soft subgrade. Long-term behavior of soft clayey subgrade materials under repeated loading applied by trains is an important point of track design [5].Volumetric changes of clay during wet-dry conditions cause damage to the structure and extensive costs [6]. Weak cohesive subgrade soils that are stabilized with cement or lime are considered environmentally unfriendly. Thus, Sodium Alginate biopolymer is used under repeated traffic loads for pavement construction with 2–4 % of additive as optimum content. The advantages revealed that resilient modulus was generally increased up to 300 % with increases in Sodium Alginate content and caused increases in stiffness up to 400 % and strength between 115 and 160 % depending on soil type, Alginate concentration, curing time and treatment method [7]. Silty soil has been stabilized with Lime-Microsilica as railway subgrade to improve CBR. Advantages show more than 470 % increase by adding 5 % lime and 12 % micrisilica [8]. Fly ash-stabilized soil has been used as Railway subgrade and evaluations show significant increases in shear strength and CBR. Results illustrate up to 170 % and in the range of 75–230 % increase in cohesiveness and CBR, respectively [9].

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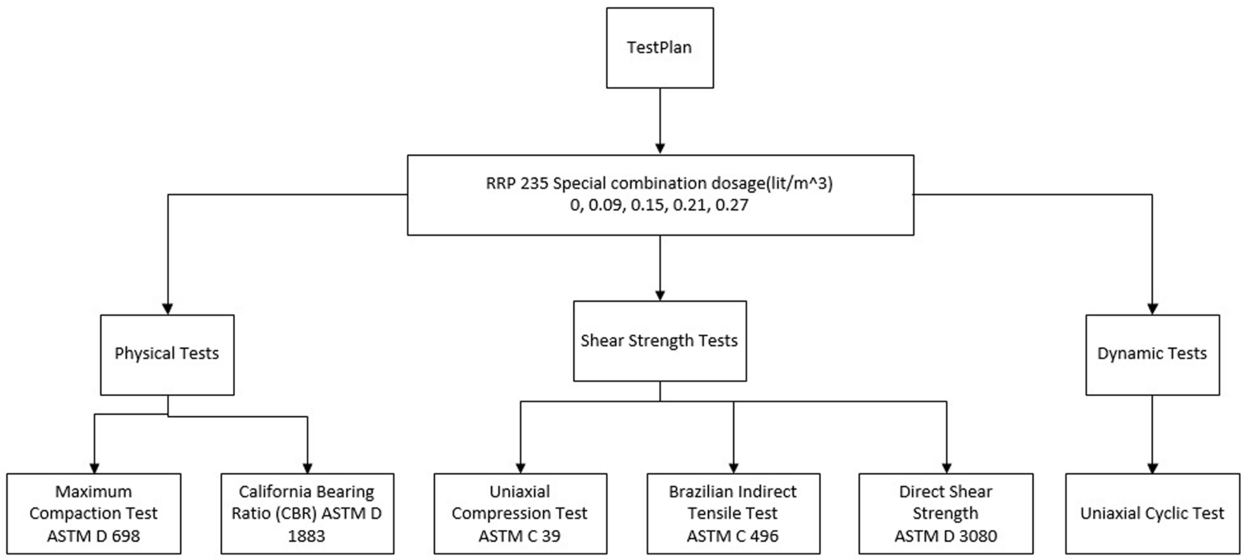

Fig. 1. Test plan.

Replacing the soft soil with suitable material, stabilizing with additives and using mechanical technics are common methods in subgrade enhancement. Various solutions have been proposed for stabilizing soft subgrades. Reliable research has been conducted on the application of chemical additives as well as mechanical methods, some of which are listed below:

To minimize the impact of lime treatment, advanced techniques were successfully used to improve subgrade bearing capacity [10]. Lime alone doesn't give sufficient specified properties and the cement had environmental affects more than lime so, optimum suitable combination of them is an important influential factor. Optimum percentage was investigated by compressive strength test and the results revealed highest amount with 5 % lime and 5 % cement, which caused up to 300 % increase [11].

Lime-stabilized weathered red Mudstone was investigated using cyclic loading experiments as high-speed railway (HSR) subgrade. Appropriate thickness of subgrade was determined that meets the requirements of HSR specifications [12]. To construct pavements in economical manner and increase strength to satisfactory level, there is a need to stabilize soil with an appropriate substance. As the cement and lime are more common additives to enhance the soil, an experimental program was directed and evaluated. Cement improves the strength and plasticity of stabilized soil [13]. Greenhouse gas emission and raw material usage are problems of cement-stabilized soils. In order to reduce negative effects, partial replacement with zeolite was investigated. Thus, the advantages show increases in maximum dry density and unconfined compressive strength (UCS) [6].

Nano silica is another additive that is used in combination with cement to stabilize soils. Results demonstrate indispensable role of the combination in improving mechanical properties of the stabilized soil. The CBR and resilient modulus are increased to satisfied criteria of subbase codal provisions [14]. Contamination of soil by crude oil is another problem that affects mechanical strength of soil. Incorporation of lime and cement has been used to stabilize kaolin clay. Results show increase in the compressibility, UCS and shear strength [15]. Volcanic ash and ordinary cement have been used in combination to stabilize clayey soil in terms of mechanical properties. The specimen was tested in dry and wet situations. Higher energy absorption, improved compressive strength and superior ductility are the advantages of stabilization [16]. Despite the advantages of cement for treating expansive soils, more use of it substantially increases environmental issues such as greenhouse gas emission and considerable raw material usage [6]. The cement-stabilized soil has been employed as heavy-haul railway subgrade in test section of the Inner Mongolia. The cement-improved soil can meet requirements. The UCS has been increased up to 56 % by different cement dosages [17]. Increases in compressive strength, CBR, density, performance, engineering properties and loading capacity are realized in stabilized soils.

Fly ash is another common additive and has been widely used in soft soil stabilization. Results reveal that CBR has increased up to 320 % by fly ash [1]. Soft and expansive soils meet high compressibility, differential settlement and poor shear strength. Usefulness of fly ash was investigated and revealed that the load bearing capacity, compaction behavior, shear strength and settlement were improved [18].

Nowadays, researchers are interested in the use of by-product and waste materials for soil stabilization. Some new chemical additives give strength parameters more than ordinary materials. Epoxy resin increases soft clayey soil strength by 100 to 1000 times [19]. Lingnosulfonate is an additive that gives more strength to the clayey soil [20]. Granulated blast furnace ash increases UCS, CBR and strength parameters 35 %, 260 % and 28 %, respectively [21]. Poly vinyl alcohol, tetra carboxylic butyric acid, recycled Bassanite, epoxy resin and Hydrophilic polymers are used for soil stabilization. Results imply improvement in durability, compressive strength, stiffness, tensile strength, and performance.

$RRP_{235\ Special}$ has been used to stabilize cohesive clayey soils. $RRP_{235\ Special}$-stabilized clayey soils exhibit higher strength parameters than those stabilized with cement and lime. It can carry even the heaviest loads with no limitation if the optimum compaction have been implemented [22]. The advantages show less water withhold, less deformation and improvement in mechanical properties [23]. Due to ion exchange between colloids and $RRP_{235\ Special}$, the stabilized soil renders hydrophobic properties and breaks capillarity [24]. Despite the mentioned cases, diesel fuel can negatively affect the performance of the additive. If an increase in additive has been negligible in the soil strength properties [25].

$RRP_{235\ special}$ was made in Germany since 1960 s. This additive improves clayey soil quality using chemical–mechanical process. After diluting the additive in water, in the first stage by mixing the additive to the soil, RRP acts chemically and replaces the double water layer, and the excess water is released and gives hydrophobic properties to the soil using ion exchange. Depending on the soil type and gradation, this process takes between 8 and 24 h [26]. Then using suitable compaction energy and optimum water content the soil is compacted. Use of RRP in road layers inhibits water infiltration and consequently keeps the

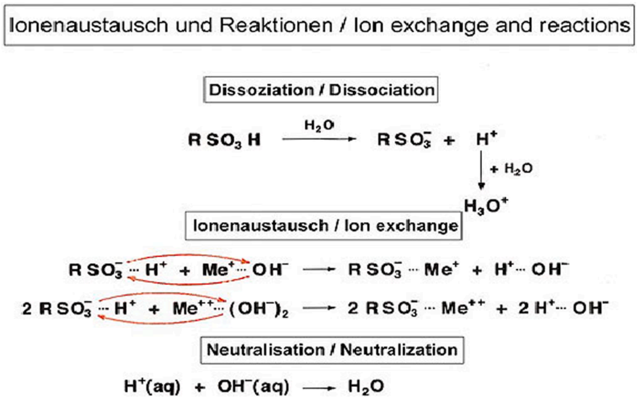

Fig. 2. Chemical reaction of $RRP_{235\ Special}$ [26].

mechanical properties of road. The principle of RRP is to make the soil hydrophobic and with adequate compaction keeps the mechanical properties of the layer. Due to these advantages, it has been used in road infrastructure all over the world for many years and enables the application of clayey soils in transportation infrastructure. The RRP-stabilized soil has not been employed in the railway subgrade or layers underneath the sleeper and, no projects have been done with this method. Therefore, using road literature, the possibility of replacing materials underneath the sleeper with $RRP_{235\ Special}$-stabilized clayey soil has been investigated as the main theme of this research.

The present research deals with the use of RRP-stabilized soil to partially replace the constructed layers underneath the sleeper. Mechanical and physical properties of the stabilized soil with different dosages of the additive have been investigated using the Maximum Compaction, California Bearing Ratio (CBR), Uniaxial Compressive Strength (UCS), Brazilian Indirect Tensile, Direct shear and Uniaxial Cyclic tests. Fig. 1 depicts necessary tests and standards. The specimens for all the tests were made with same compaction energy with five different additive dosages of 0, 0.09, 0.15, 0.21 and 0.27 L/m^3soil.

Materials and methods

RRP235 Special

$RRP_{235\ Special}$ is an acidic brown liquid that improves the properties of clayey soils using chemical-physical process. Fig. 2 shows the $RRP_{235\ Special}$ with the R symbol and its chemical reaction. This product has been made in Germany since 1960 s in RRP Gmbh International Company.

The colloids and the space in between are bounded and free ions of different elements located. As shown in Fig. 2, reaction progress contains three stages of Dissociation, Ion exchange and Neutralization. The

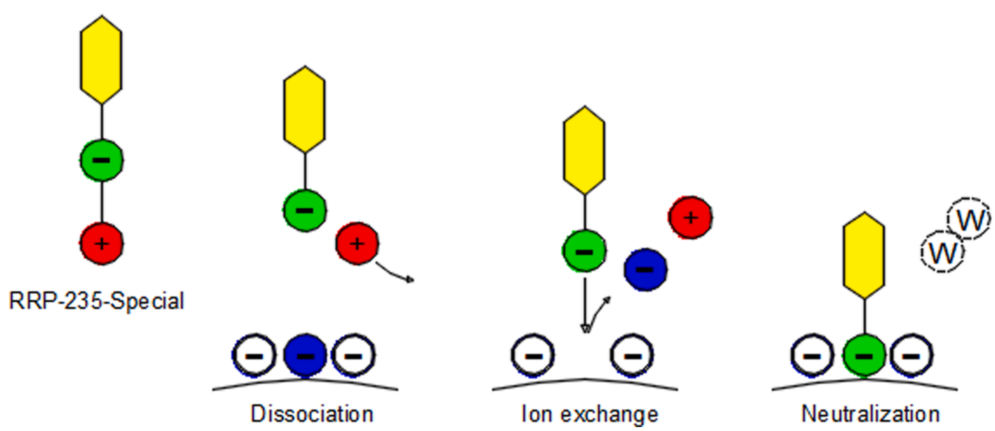

Fig. 3. Description of the ion exchange at the colloids [26].

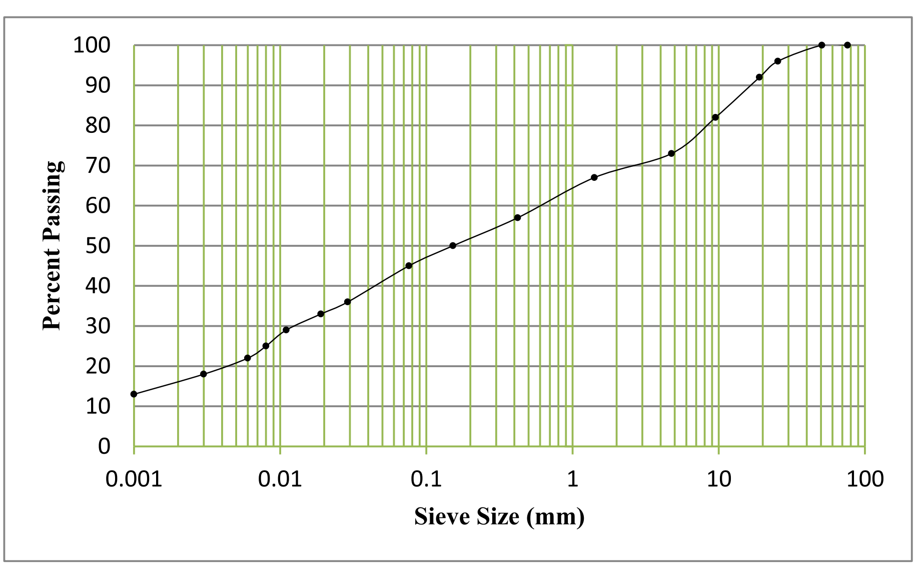

Fig. 4. Particle size distribution of the soil.

Table 1
Physical tests.

Test name	Standard
Maximum Compaction Test	ASTM D 698 [27]
California Bearing Ratio (CBR)	ASTM D 1883 [28]
Uniaxial Compaction Test	ASTM C 39 [29]
Indirect Brazilian Tensile Test	ASTM C 496 [30]
Direct Shear Test	ASTM D 3080 [31]

additive is diluted with water to achieve dissociation. After procurement of the mixture of RRP, the ion exchange can start (Fig. 3). The reaction time depends on the type of soil and thereby, on the percentage of the fine grain fraction and the chemical elements of the soil. The neutralization is done by exodus of water.

The soil must be able to cohere with water or other elements to perform the chemical reaction or a connection. Sand and gravel can be wet on the outside surfaces, but they are not able to produce a chemical connection with the water. Only cohesive soils with a fine grain fraction less than 0.06 mm are able to perform a chemical reaction or an adsorption with water and other elements.

Clayey sand subgrade

According to manufacturer’s statement, the dosage of the RRP$_{235\ Special}$ is determined by the particles smaller than 0.06 mm. In this research, SC soil was used to evaluate the effects of RRP$_{235Special}$ on fine particles of soil. The particle size distribution was drawn and as shown in

Fig. 5. a) Sample with 0.15 lit/m^3 additive tested in 7 days of age and b) sample with 0.21 lit/m^3 additive tested in 28 days of age.

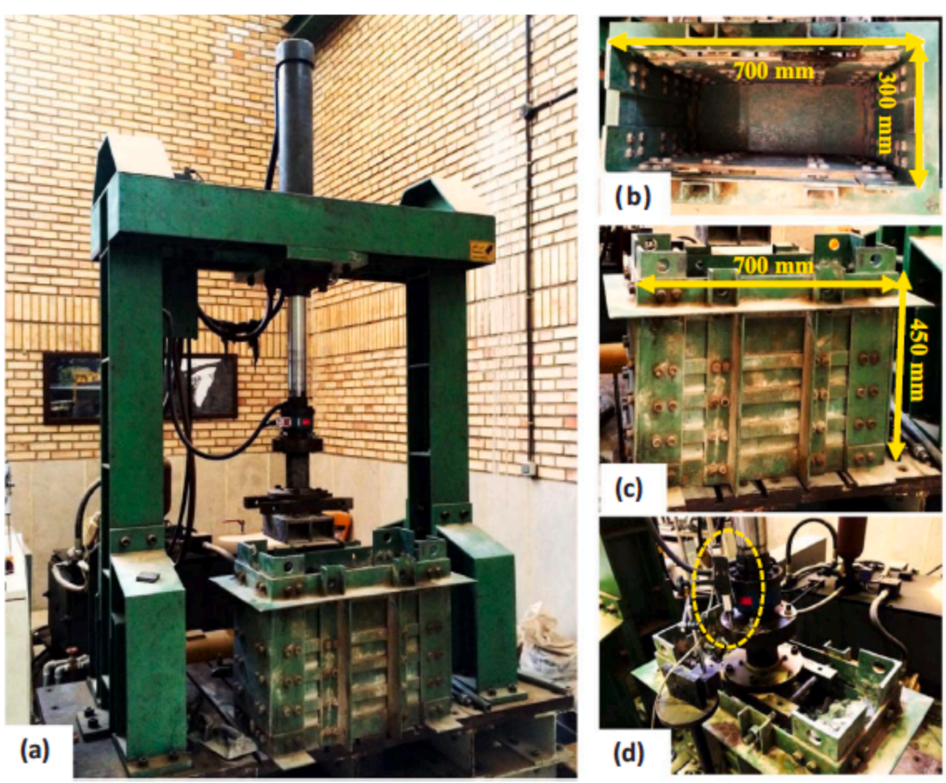

Fig. 6. a) Ballast box test apparatus; b and c) Ballast box dimensions; d) LVDT location [33].

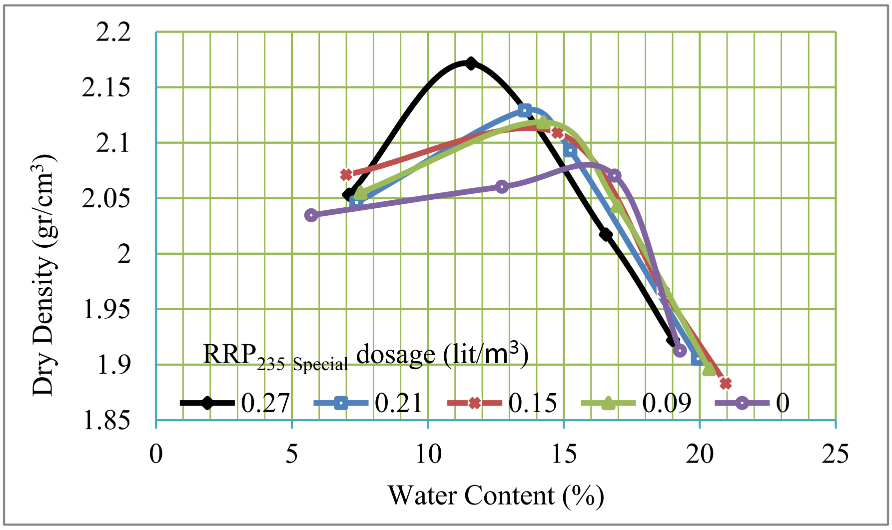

Fig. 7. Maximum dry density curves.

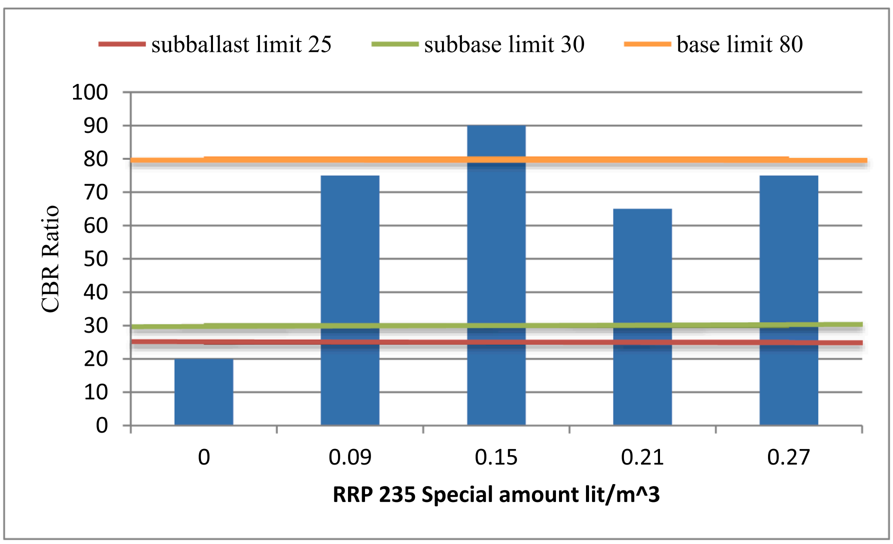

Fig. 8. The effect of RRP235 Special on CBR value.

Fig. 4, the soil has between 40 and 50 percent fine particles smaller than 0.06 mm.

According to other experiments, the plastic limit, liquid limit, plastic index was obtained 25, 44, 19, respectively and maximum dry density was obtained 2.17 gr/ cm^3.

Laboratory tests plan

$RRP_{235\ Special}$-stabilized subgrade and partial replacement with ballast layer is the goal of this research. Therefore, in order to investigate the stabilized soil properties as the novel solution, static and dynamic lab experiments that represent loads derived from rolling stock was designed. It was necessary to determine appropriate additive usage. As shown in Fig. 1, static experiments with five different additive dosages of 0, 0.09, 0.15, 0.21 and 0.27 lit/m^3 were conducted. Then, uniaxial cyclic dynamic test using ballast box device with the same additive dosage was carried out to evaluate settlement, stiffness and damping ratio. Meanwhile, to ensure repeatability, the tests were repeated three times and the average results were presented, and in some cases inappropriate answers were removed.

Physical Tests

As depicted in Table 1, physical experimental schedule included basic engineering tests. All the specimens in these tests were made by the same compaction energy derived from equation (1) and tested in different ages to evaluate the effect of additive over time. Each test includes different dosages of additive according to Fig. 1. Findings have been used to determine optimum dosage of RRP to the selected soil and also behavior of specimens and process of strengthening over time and different dosages of additive.

The Compressive strength samples were made in dimensions of 15 by 15 by 15 cm and loaded with speed of 0.3 MPa per second. Six samples were made for each dosage of additives and tested in six different ages. Fig. 5 depicted some of the prepared samples. Last series of specimens was tested in age 46 because of complete drying.

Based on the manufacturer's statements about the possibility of loading the route and releasing traffic immediately after construction, the shear test age was conducted one the day after sample preparation [32].

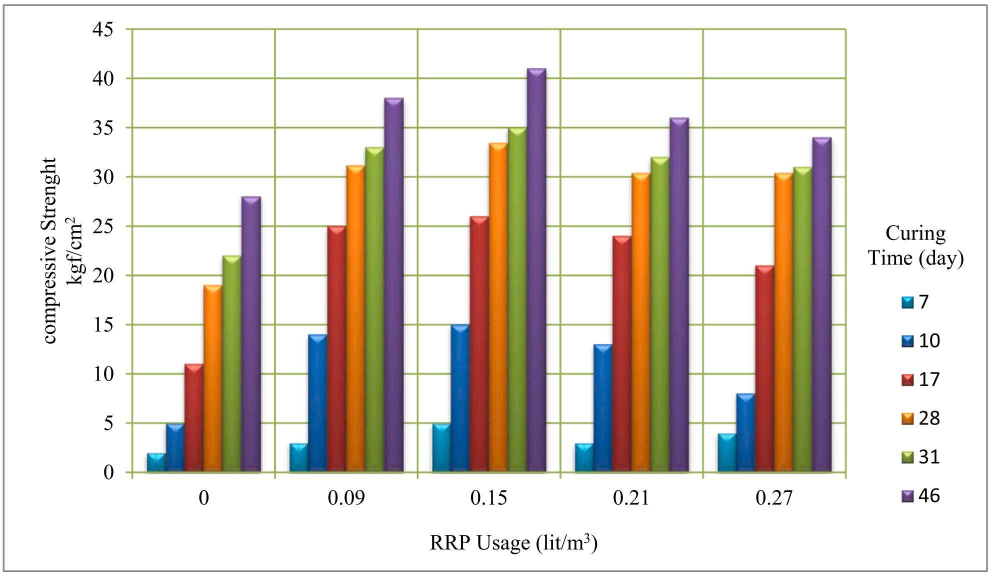

Fig. 9. RRP-stabilized soil compressive strength with different amounts over time.

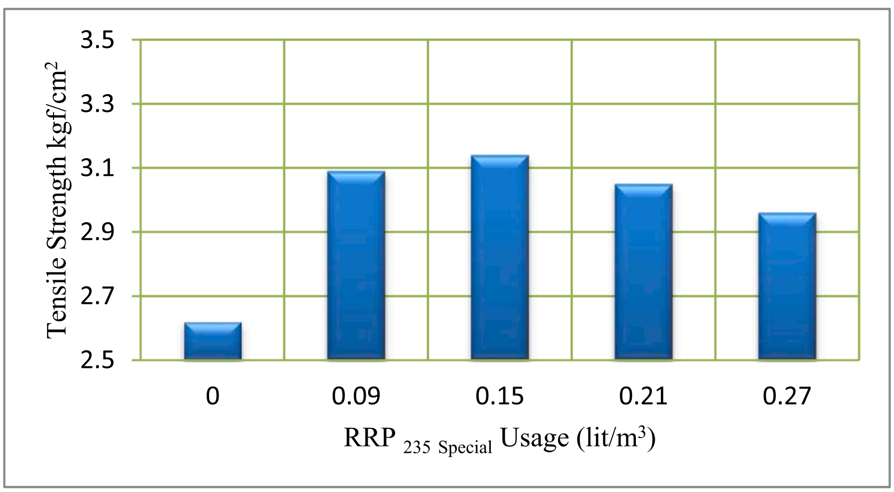

Fig. 10. Tensile strength of samples with different RRP235 Special at 46 days of age.

Uniaxial cyclic test

To investigate the properties of RRP-stabilized soil, the dynamic test is required. Changing the material used in the track, causes change in the properties and different behavior in terms of damping, hardness and settlement. Ballast box test was conducted to investigate the dynamic responses and possibility of the partial replacement of the ballast layer with the stabilized soil. The ballast box apparatus simulates the dynamic forces transmitted in the ballasted layer.

Cyclic test set up

As depicted in Fig. 6, the device is constructed and used at the laboratory of the School of Railway Engineering (SRE) in Iran University of Science and Technology (IUST). The ballast box is the device that includes a power supplier, computer, sensors, pump, piston and box with the dimensions of 0.7 m (l) × 0.3 m (w) × 0.45 m (h). The vertical force is applied by the piston that is powered by the hydraulic pump with a horn by the dimension of 0.22 × 0.22 m. The device was connected to a computer and controlled by software that was able to measure the applied force by the TMR-7200 data logger and displacements by a 0.1 m Linear Variable Displacement Transducer (LVDT). Applied force, frequency, and number of cycles can be changed by the user. Hence, in this research, the vertical force of 27 kN and frequency of 3 Hz in 100,000 cycles were applied to the specimens.

Sample preparation

The specimens with different dosages of RRP were compacted with the same energy derived from maximum compaction test according to ASTM D 698 with 3 layers by the 4.54 kg hammer. The required compaction energy has been determined from the equation (1);

$$E = \frac{N^{*}L^{*}W^{*}h}{V} \tag{1}$$

where E is compaction energy (kJ/m^3), N number of blows, L number of layers; W hammer weight (N), h height of falling (m) and V is the mold volume (m^3). E for the standard mold by 943.3 cm^{3}volume with 56 blows per layer and 5 layers by 4.54 kg hammer with 45.7 cm falling height is equal to 6037 kJ/ m^3. The numbers of blows obtained for box by inner dimension of 0.65 by 0.25 by 0.40 m is 6400. RRP was diluted and mixed with the 0, 0.09, 0.15, 0.21 and 0.27 lit/m^3 dosages. At least

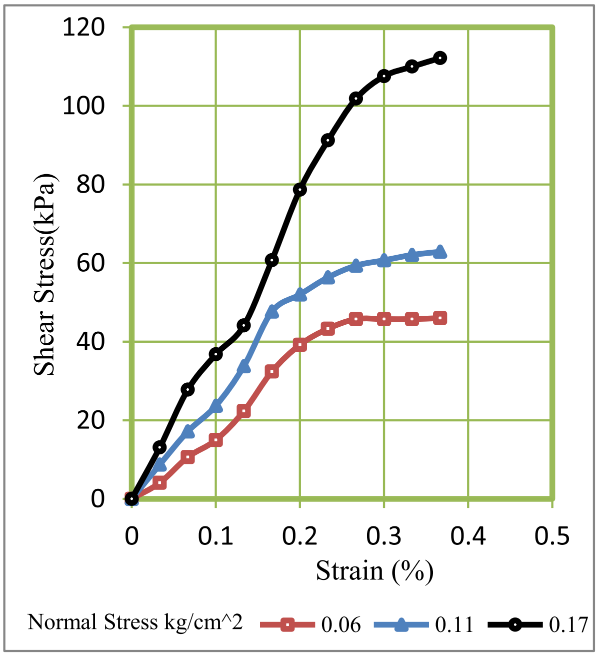

Fig. 11. Shear stress–strain diagram (the sample with 0.15 lit/m^3 additive).

8 h were needed for ion exchange as rest time [26]. Then, the samples were compacted at the mentioned compaction energy. The ballast box tests were carried out in 28 days of age.

Results and discussion

Physical tests results

Maximum compaction test

The results show that further use of RRP increases the maximum dry density and reduces the optimum water content. Fig. 7 illustrates that maximum dry density increases and optimum water content decreases 4, and 38 percent, respectively.

According to the chemical reaction in Fig. 3, the water between double layers will be released during ion exchange. This reduces the water needed for maximum compaction and leads to more congestion of colloids. The more use of RRP, the more release of interlayer water. The water required for compaction is supplied by releasing water between the clay colloids.

CBR

The CBR value generally increases due to the use of the additive, strengthening from 0 to 0.15 lit/m^3 additive dosage and then being reduced and then by further use of the additive, is increased in strength again. Fig. 8 illustrates CBR values versus RRP dosages and the sub ballast, sub-base and base limitations [34,35]. The sample with 0.15 lit/m^3 additive has the best results. The CBR increased more than 400 % compared to the sample with no additive.

Clay colloids absorb a certain amount of additives, and the excess remains between the colloids. It seems that a large amount of excess material reduces the physical properties of the soil and makes situation to glide colloids. Due to concentration of the ions, the zeta potential decreases and cations and anions are liberated from diffuse double layer, thereupon, swelling properties of soil reduces.

Shear strength tests results

Compressive test results

One of the effective tests in determining the possibility of placing the

Fig. 13. Ballast box samples after testing (specimens from left to right correspond to 0, 0.09, 0.15, 0.21 and 0.27 lit/m^3 of RRP235 Special).

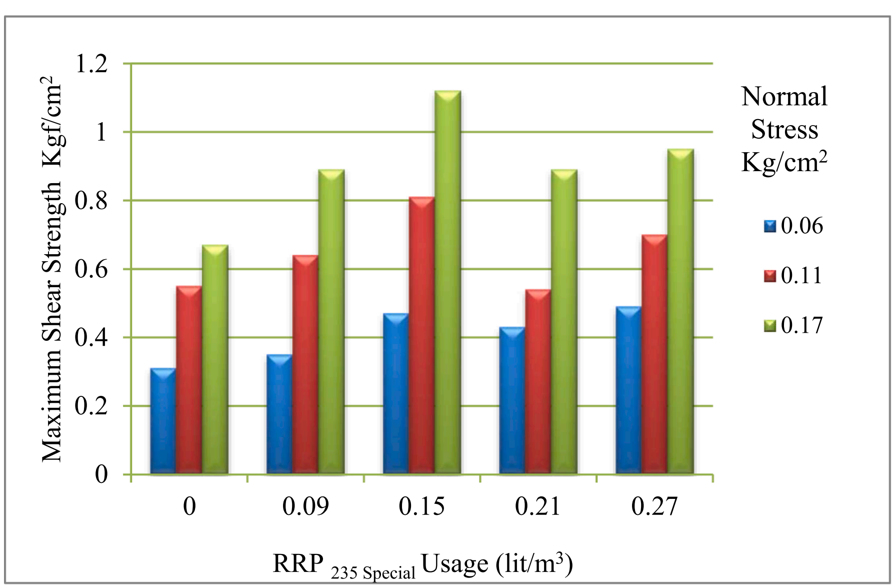

Fig. 12. Maximum shear stress diagram.

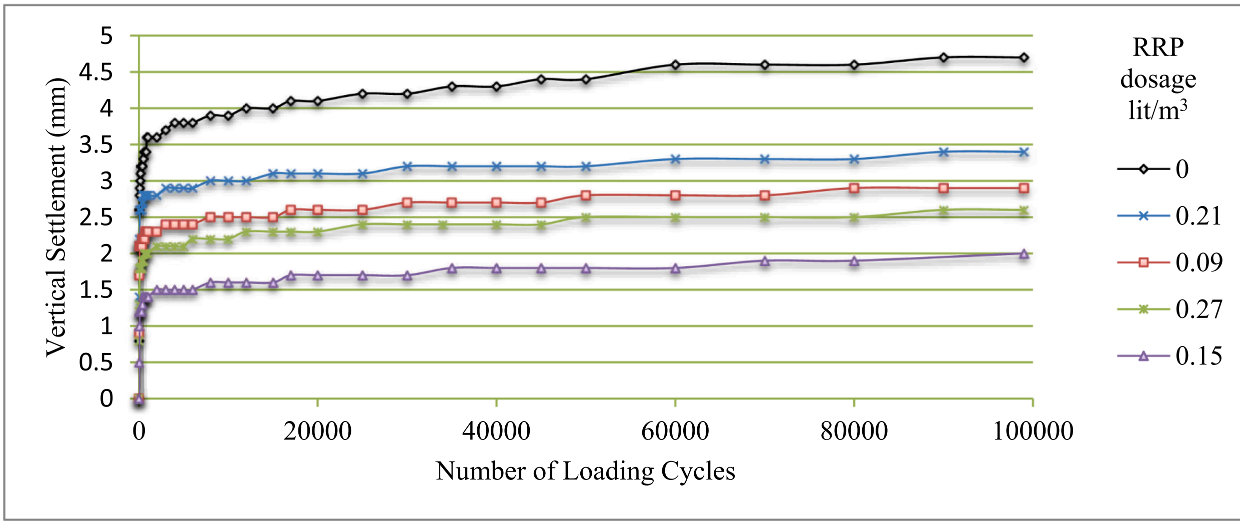

Fig. 14. Settlement diagram.

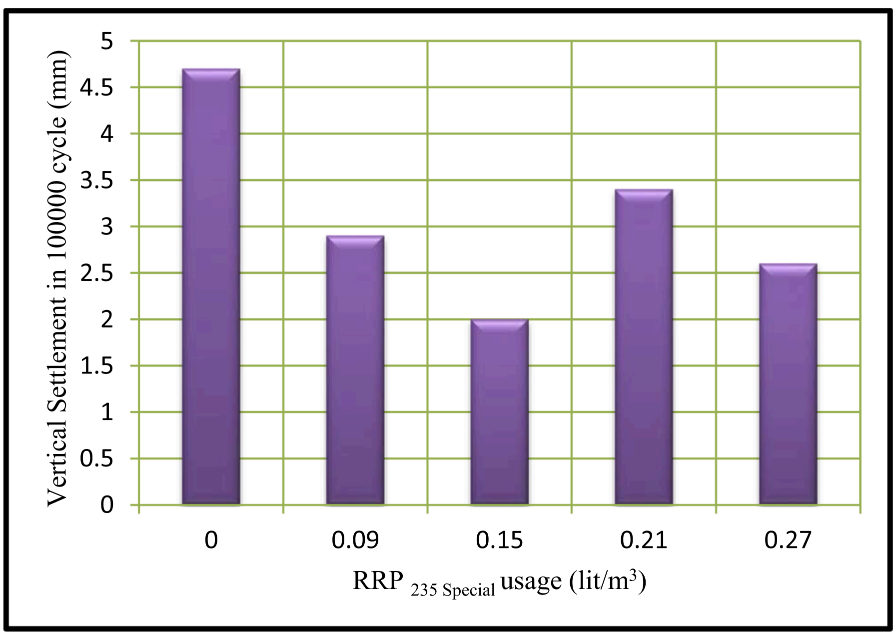

Fig. 15. Settlement of samples in cycle 100,000.

sleepers on the stabilized soil is the compressive strength. As indicated in Fig. 9, compressive strength increases by adding $RRP_{235\ Special}$ until 0.15lit/m^3 and then decreases by further use. Strengthening of samples is not proportional to additive usage. This pattern is the same for different ages of specimen. Use of RRP had caused 46 and 300 percent increase in the compressive strength compared to the sample with no additive. It seems excess free RRP existing between soil colloids, negatively affects the mechanical properties.

According to the pattern of the samples in Fig. 9, the optimal required amount of additive for the compressive strength was determined as 0.15lit/m^3.

Indirect Brazilian tensile test results

As indicated in Fig. 10, use of $RRP_{235\ Special}$ improves the tensile strength. Increasing additive to 0.15lit/m^3 increases the tensile strength, and then decreases with further use. The pattern of strengthening of tensile test is the same as compressive strength.

The highest strength is related to the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ with an increase of about 20 % compared to those without additive. The more compressive strength mirrors the more tensile strength.

Direct shear test results

Shear stress–strain diagram was shown in Fig. 11. Since the cohesive coefficient and internal friction angle are not suitable criteria to understand the shear stress, using the Mohr–Coulomb diagrams, maximum shear stress was obtained.

Fig. 12 shows maximum shear stress for different $RRP_{235\ Special}$ dosages. The pattern of shear stress acquisition is similar to those of compressive and tensile tests. Use of additive results in increases in maximum shear stress up to 0.15 lit/m^3 and then decreases and further use causes increases again. A value of 0.15 lit/m^3 additive is selected as the optimal value for direct shear test. Good compaction and high density of soil increases the shear strength. When the reaction has occurred, less water can accumulate in the soil than was originally possible. As a result, the swelling capacity is reduced, and the internal moisture of the soil is also reduced, and complete compaction to zero

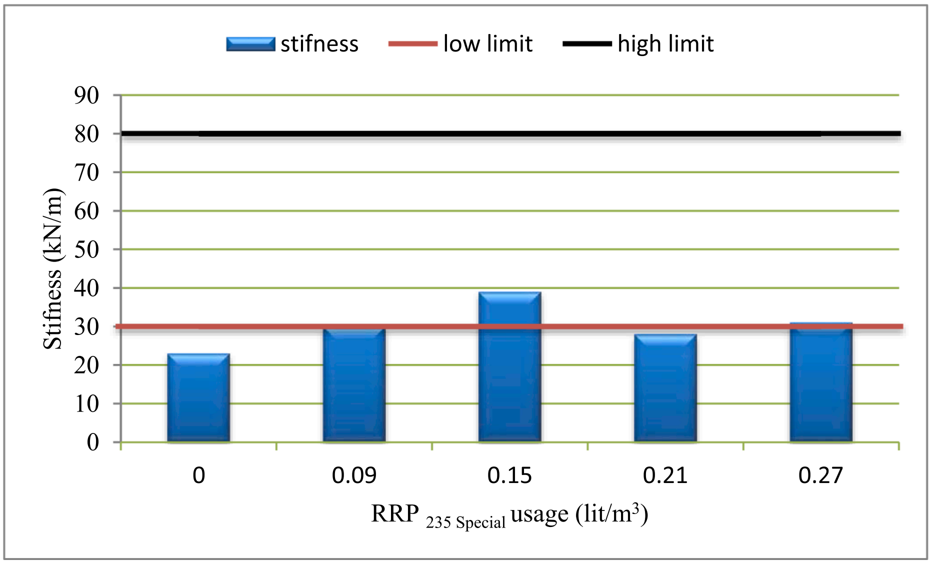

Fig. 16. stiffness of samples with different dosage of $RRP_{235\ Special}$.

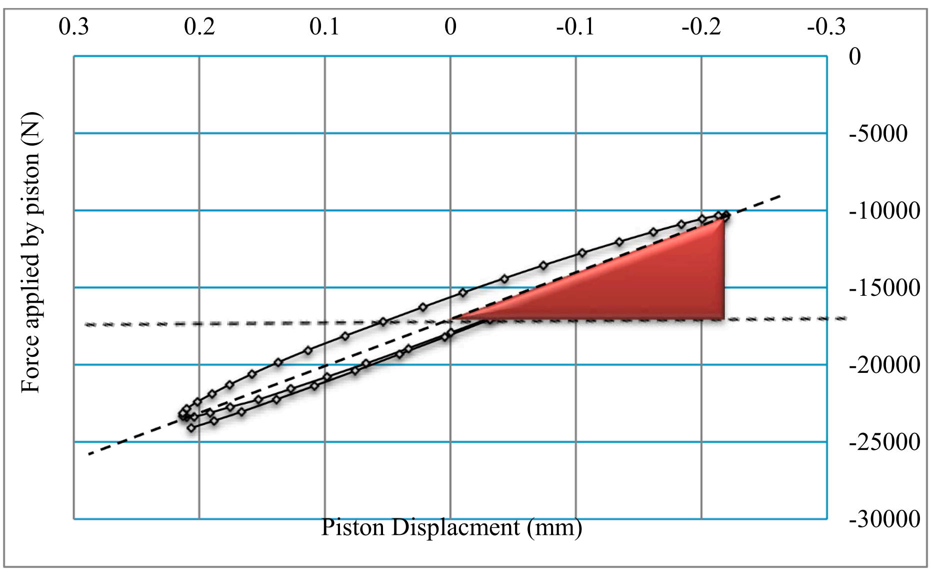

Fig. 17. Calculation of damping ratio by means of the force–displacement.

content of air-tilled voids becomes possible because of the space that has become available from the expelled pore water. Subsequent additions of water cannot reverse this process, once the latter has been accomplished (the swelling capacity is destroyed and the shearing strength increased) [36].

Uniaxial cyclic test results

Settlement

Large and asymmetrical displacement is an important problem that causes noticeable change in track geometry that reduces maintenance intervals and consequently increases the maintenance costs. Partially replacing the ballast layer with $RRP_{235\ Special}$-stabilized soil can significantly reduce the settlement. Fig. 13 shows the specimens after testing.

Ballast box test was carried out on specimens and results indicated that $RRP_{235\ Special}$ reduce settlement. Fig. 14 and Fig. 15 illustrate the vertical settlement in terms of the number of cycles with different additive dosages. As indicated in Fig. 14, the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the least and sample with no additive has the largest amount of settlement with 2 and 4.7 mm, respectively. Results show more than 57 % reduction in settlement. The pattern of strengthening is similar to static tests. Adding $RRP_{235\ Special}$ up to 0.15 lit/m^3 decreases vertical settlement and then increases it and with further use, decreases it.

Exodus of interlayer water due to ion exchange gives improved compaction to the stabilized soil and is the main factor of strengthening, but increased additive results in an excess of free ions around the colloids, which renders negative properties. Any grading of soils requires proportional additive to make chemical reaction and excess dosages help to make increase the Zeta potential and negatively affect the mechanical properties [36].

Stiffness

A change in the type of material in the railway tracks will cause a change in the stiffness. Examination of the stiffness of the samples showed that with increasing the additive, at first, the stiffness increases and then with increasing the $RRP_{235\ Special}$, the stiffness decreases. As shown in Fig. 16, the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the

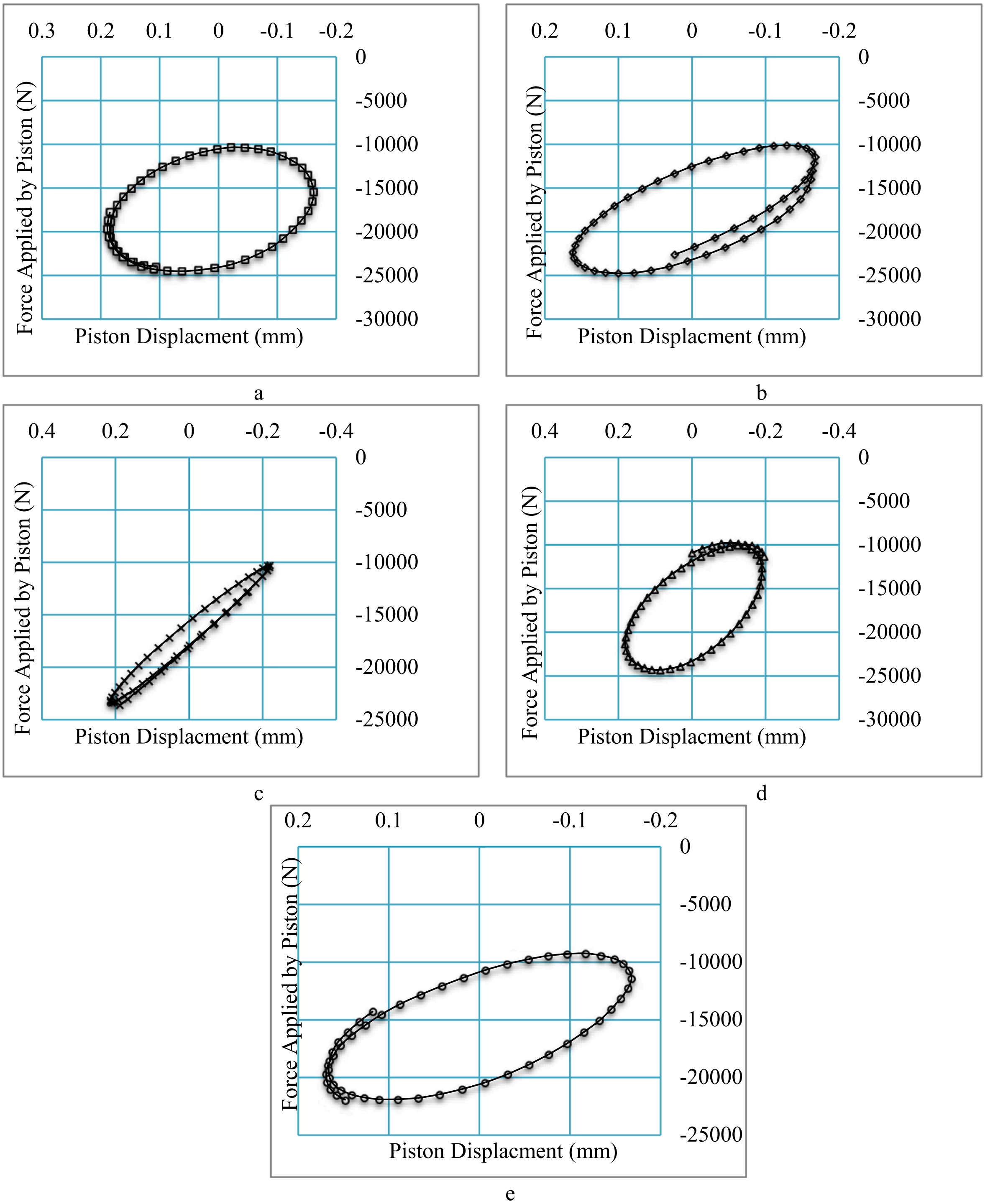

Fig. 18. Piston force-displacement graphs for 5different samples (a, b, c, d and e are the sample with 0, 0.09, 0.15, 0.21 and 0.27 lit/m^3 additive Respectively).

highest stiffness and the sample with no $RRP_{235\ Special}$ has the lowest. Low and high limits of stiffness has been shown in Fig. 16 by 30 and 80 kN/m, respectively [34]. As mentioned in previous section, excess or less dosage of additive cannot reach maximum strength, so the optimal value of $RRP_{235\ Special}$ is important to realize the optimal mechanical results.

Damping ratio

Comparing different amounts of $RRP_{235\ Special}$, the damping ratio of each sample, which is representative of the lost energy, divided by the energy input in a cycle, has been determined using equation (2), proposed by Jacobsen [37];

$$\xi = \frac{\Delta E}{2\pi K x^2} \tag{2}$$

where ΔE is the dissipated energy, and k and x refer to the stiffness and deflection of samples, respectively.

Fig. 17 illustrates the force–displacement relationship of the sample with 0.15lit/m^3 $RRP_{235\ Special}$ at the final cycle (100,000th). The red zone on this graph indicates the dissipated energy. In order to calculate the damping ratio of the samples, the area of this zone should be divided by that of the loop.

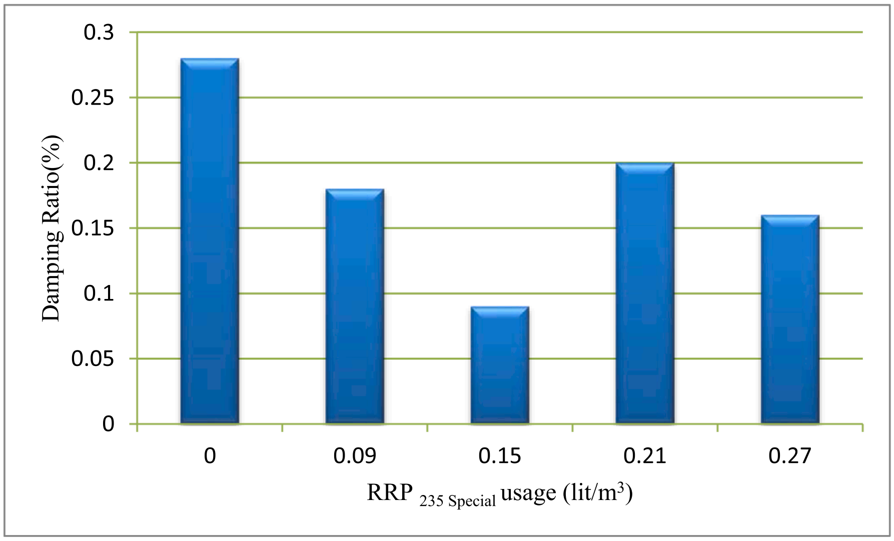

Fig. 19. Damping ratio of samples with different percentages of $RRP_{235\ Special}$.

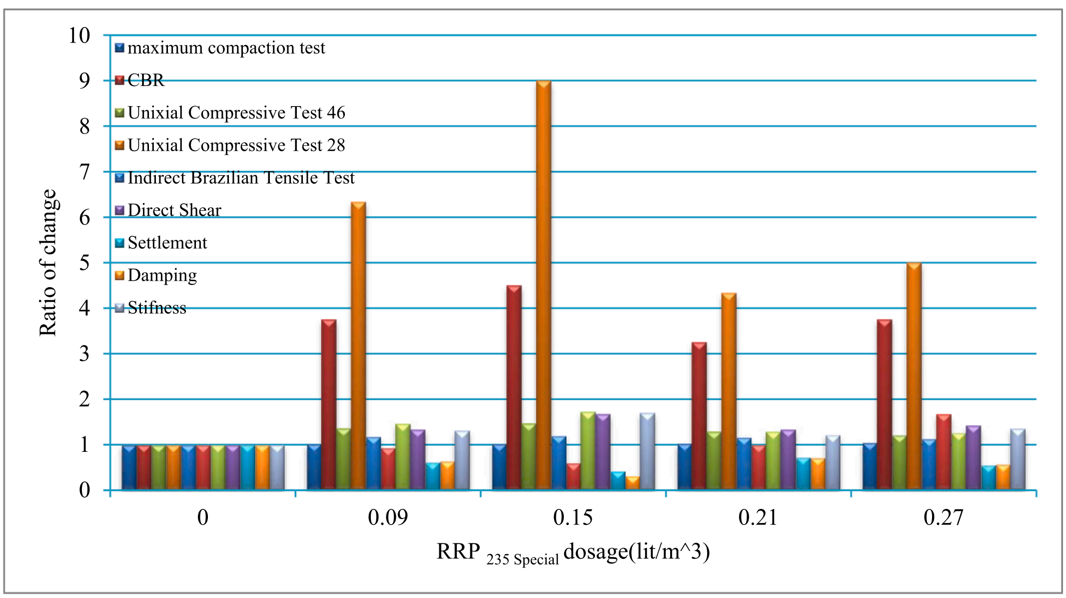

Fig. 20. Maximum compaction test, CBR, uniaxial compaction test, indirect Brazilian tensile test, direct shear, settlement, damping, stiffness.

Fig. 17 and Fig. 18 show the force–displacement loops of all samples and their damping ratio values, respectively.

The results of examination of the damping in the ballast box test show that the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the lowest and the sample with no additive has the highest damping ratio and behaves better than others facing dynamic effects and reduces transmitted energy. The sample with high damping ratio renders high settlement and vice versa. Although the sample with no additive has the best damping ratio, preference for stiffness and settlement cause the challenge of optimal dosage selection. Though the use of 0.15 additive causes a significant decrease in damping ratio, this issue seems reasonable against a significant increase in hardness and decrease in settlement. Greater concentration of colloids with the use of additive and ion exchange causes vibration transmission and low damping ratio.

Suitable percentage of $RRP_{235\ Special}$

Experiments were carried out in static and dynamic series with different dosage of additive. As depicted in Fig. 20, in term of maximum compaction test, the 0.27 lit/m^3 has the best result if by increasing additive dosage, maximum dry density increases. In term of CBR, Uniaxial Compressive test, Indirect Brazilian test and Direct Shear test, the specimens with 0.15 lit/m^3 render the best results. Among the results obtained from static experiments, according to the most repetition of appropriate dosage of additive, the sample with 0.15 lit/m^3 $RRP_{235Special}$ was selected as static experiments optimum RRP dosage (see Fig. 19).

Dynamic cyclic load test was conducted using the ballast box apparatus. In terms of settlement and stiffness the sample with 0.15lit/m^3 RRP had the best performance. Regarding damping, the sample with 0.15lit/m^3 $RRP_{235\ Special}$ had the lowest rate. However, considering the importance of settlement and stiffness, the sample with 0.15lit/m^3 $RRP_{235\ Special}$ was selected as the optimal dosage, in view of dynamic behavior.

Fig. 20 demonstrates that all of the properties have improved due to the use of $RRP_{235\ Special}$. Engineering properties of stabilized soil do not improve in accordance with the amount of additive use. Based on static and dynamic results, the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ is selected as the optimal value.

Summary and conclusion

$RRP_{235\ Special}$ has not been used to stabilize the railway track clayey sub-grades. The innovation of this study is to partially replace ballast layer and all structural layers underneath the sleeper with RRP-stabilized clayey soil as a novel railway track. A set of mechanical-physical laboratory tests have been done in static and dynamic modes. The tests were carried out on SC soil with different RRP dosages. The main results are mentioned below:

1- Use of $RRP_{235\ Special}$ causes reduction of optimum water content and increase in maximum dry density 38 and 4 percent, respectively. The amount of additive consumption was inversely proportional to the optimum water content.
2- Compressive strength improves significantly due to the use of $RRP_{235\ Special}$. Various factors such as additive dosage and age of samples affect the results. The increase in strength is not proportional to the consumption of the additive and the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the highest strength. After some 46 days, it increases by 47 %, and after 28 days, by some 76 %.
3- Tensile strength of $RRP_{235\ Special}$-stabilized soil has been enhanced. Similar to compressive strength, the sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the highest strength with a 20 % increase.
4- Shear properties of the soil improved due to the use of $RRP_{235\ Special}$. Stabilized soil shows a 67 % increase in maximum shear stress. The sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the best improvement.
5- Stabilized soil shows enhanced properties in the CBR test. The sample with 0.15 lit/m^3 $RRP_{235\ Special}$ meets the highest amount of increase by 400 %.
6- Dynamic tests imply that the use of $RRP_{235\ Special}$ causes a decrease in the settlement. The sample with 0.15 lit/m^3 $RRP_{235\ Special}$ has the lowest settlement with 57 % reduction.
7- Use of $RRP_{235\ Special}$ causes increases in stiffness and a decrease in damping ratio. The sample with 0.15 lit/m^3 additive has the highest stiffness and lowest damping ratio percent of changes by 61 % and 81 %, respectively.
8- Mechanical properties of stabilized soil were improved. The sample with 0.15 lit/m^3 additive has the maximum influence in the dynamic and static tests and was selected as optimum amount of $RRP_{235\ Special}$ for the soil with 40 to 50 % particles finer than 0.06 mm.
9- Generally, positive influence of additive was proved, but more use of $RRP_{235\ Special}$ leads to increase in the free ions additive between colloids and this can negatively affect soil mechanical properties.
10- Stabilizing clayey soil with RRP completely differs from ordinary materials such as cement and lime. RRP changes the properties of colloids and gives permanent changes to the soil, whereas, cement and lime give their own properties to soil. RRP-stabilized soil properties depend on chemical-physical process, so that there is no limitation to compaction energy. According to manufacturer's statement, the additive makes colloids hydrophobic and creates a waterproof layer and consequently prevents capillarity action.

In general, by comparing the common methods of soil stabilization with RRP $_{235\ special}$, it was found that on average the maximum density, compressive strength and shear strength increased by 5.15 %, 120 %, 170 %, 305 % and 242 for other methods and 4 %, 300 %, 67 % 400 % and 70 for RRP, respectively.

Recommendation

In order to use this method in ballasted railway tracks, it is necessary to carry out more tests including STPT and PLT and evaluate long term durability. The vertical stiffness is being investigated by the research team, the results of which will be published soon.

CRediT authorship contribution statement

Hossein Ghorbani Dolama: Investigation, Data curation, Validation. **Jabbar Ali Zakeri:** Supervision, Funding acquisition, Project administration, Conceptualization, Methodology. **Morteza Esmaeili:** Conceptualization, Methodology, Formal analysis, Writing – original draft. **Parham Hayati:** Project administration, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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