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Influence of particle gradation and moisture content on the repose angle of railway subballast

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Abstract. The repose angle serves as an important parameter for evaluating the interaction and flowability of granular material. In this study, a series of repose angle test using the plate lifting method was conducted to measure the repose angle of subballast with 17 different gradations and 7 varying moisture contents. The effects of the maximum particle size D_{100}, the median particle size D_{50}, and the content of fine particles below 1.7 mm on the repose angle were investigated. Test results shown that the repose angle increases with an increase in D_{100} or D_{50}, and decreases with an increase in the content of particles smaller than 1.7 mm. The Span parameter is commonly used to describe the distribution width of particle gradation and reflects the uniformity across different size ranges. The upper and lower spans of the gradation were defined. The effect of upper span and lower span shows that the combination of lower span (1.6–1.8) and upper span (1.0–1.2) enhances internal friction between ballast particles. Based on the repose angle performance of subballast, the optimized gradation interval within the standard was identified. Furthermore, the effect of water content on the repose angle of subballast was also investigated, and the results revealed that the repose angle could be roughly divided into four typical stages with the increase of the water content: sudden change stage, horizontal stage, rapid increase stage, and slow decrease stage. The optimized gradation curve can provide a reference for the design of subballast grading in practice.

Keywords: ballast gradation; fine particle; median particle size; moisture content; repose angle

1. Introduction

Subballast consists of well-graded gravel or a mixture of sand and gravel, positioned between the ballast layer and the subgrade. It is considered a loose medium in which particles do not adhere to one another. The overall strength of subballast primarily depends on interlocking forces and frictional resistance. As a transitional component of the ballasted track structure, the subballast layer must provide sufficient strength to support the train load. Furthermore, it plays a crucial role in preventing the migration of ballast aggregates into the subgrade and mitigating the upward movement of fine particles from the subgrade (Ding *et al.* 2023). In addition to these functions, the subballast layer serves as a drainage medium, dissipating pore water pressure in the subgrade soil under cyclic loading conditions (Koohmishi and Azarhoosh, 2020). Therefore, in addition to ensuring adequate strength to support the train load, the subballast layer must also account for the optimal gradation to maintain its drainage, filtering, and segregation functions.

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The particle size distribution of subballast is one of the crucial parameters of ballasted track beds, directly influencing track stability, safety, and drainage. Numerous studies have shown that a well-graded combination of particles, significantly affects the interaction modes between ballast particles, the void ratio of the ballast, as well as the shear strength and permanent deformation of the ballast under loading (Hussain and Hussaini 2023, Mittal and Meyase 2012). Trani and Indraratna (2010) found that the compressive characteristics of subballast under cyclic loading and unloading are closely related to the particle size distribution, or the range of particle sizes within the composition. Touqan *et al.* (2020) highlighted that particle size influences the dynamic response and damping characteristics of subballast. In general, larger subballast particles can improve both permeability and shear strength. However, under cyclic loading, the degradation of aggregates and the intrusion of fine particles often lead to excessive deformation and failure of the ballasted track.

The drainage capacity of ballasted track is crucial. During rainfall or flooding, water may infiltrate various parts of the roadbed structure. The high hydraulic gradient generated by cyclic loading drives fine particles from the subgrade to migrate upward into the subballast layer (Indraratna *et al.* 2020), and under the influence of water, these fine particles tend to adhere to coarse aggregates, causing ballast fouling (Kumara and Hayano 2016). The fouling of fine particles adversely impacts the load distribution from the subballast to the underlying subgrade,

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significantly affecting track performance and its service life. Heyns (2000) investigated water movement within the trackbed and discovered that water passes through the subballast layer significantly slower than through the ballast layer. Consequently, the moisture content has a more pronounced impact on the subballast. Water adhering to the ballast surface reduces the friction coefficient, causing lubrication and significantly impacting the friction and interlocking performance of the ballast, thus decreasing the friction angle (Faghihi *et al*. 2018). Studies have shown that an increase in moisture content significantly decreased the peak shear strength of the coarse aggregate (Huang *et al*. 2024; Ishikawa *et al*. 2016). Additionally, when the moisture content of the ballast approaches the liquid-limit moisture content of intruded fine soil or fluctuates, it exacerbates the plastic deformation of the roadbed under cyclic loading, affecting the stability of the railroad track (Yang *et al*. 2021, Nguyen *et al*. 2023). Previous studies have investigated ballast performance through triaxial tests; however, due to the complexity of particle gradation combinations, conducting triaxial tests for all potential gradations is time-consuming and costly. Furthermore, research on the repose angle behaviour of ballast under varying moisture contents is also limited. Therefore, conducting repose angle tests is a feasible and rapid approach for determining the influence of gradation.

The repose angle is the stable slope angle formed by the free accumulation of granular material in a loose state, which is an important macro-mechanical parameter reflecting the internal friction characteristics and stability (Beakawi *et al*. 2018, Wang *et al*. 2024). Influenced by various factors including gradation, the repose angle is also associated with the internal friction angle at its loosest condition, with higher friction angles indicating stronger interparticle interactions and less relative motion. Well-graded ballast tends to be denser, resulting in higher shear strength and resistance to deformation (Koohmishi and Palassi 2017, Biabani and Indraratna 2015). Sun *et al*. (2017) observed that well-graded ballast beds settle less than those consisting of single-grain-size ballast, with a larger angle of internal friction present in well-graded ballast beds. Aela *et al*. (2022) examined the impact of homogeneity parameters on the repose angle of ballast, finding a significant correlation between coefficient of uniformity (C_u) and ballast particle size, with an increase in C_u leading to higher overall porosity of the ballast and decreased stability, resulting in a lower repose angle.

While extensive research has been conducted on the repose angle of granular materials, such as sand and fine powders, limited studies have focused on coarse materials like subballast (particle sizes ranging from 0.075 mm to 43 mm). Moreover, there is currently no standardized and universally applicable method for measuring the repose angle of such coarse aggregates. The choice of testing method should be tailored to the specific material properties and intended engineering application. Common methods for measuring the repose angle include the fixed funnel method (FFM), tilting box method (TBM), hollow cylinder method (HCM), and revolving cylinder method (RCM) (Beakawi *et al*. 2018). Similar to the HCM, the plate lifting method (PLM) involves placing the test material in a box and then carefully pulling off the plate on one side of the box (Kavinkumar *et al*. 2021). PLM is frequently employed for determining the repose angle of coarse-grained materials. In railway applications, subballast layers are subjected to long-term service conditions that inevitably lead to gradation degradation and fouling, primarily due to the infiltration of fine particles and moisture. These changes significantly alter the particle packing structure and interactions. Therefore, it is essential to investigate the effect of varying moisture content on the repose angle of subballast to better understand its stacking behavior in practice.

This study focuses on the influence of gradation on the repose angle of subballast. This provides insights into the physical and mechanical properties of the subballast from a macroscopic perspective. For this study, the PLM is employed as the optimal method, and the test gradation is determined according to the Chinese ballast standard. The investigation aims to assess the influence of grading parameters, including maximum particle size (D_{100}), median particle size (D_{50}), and the percentage of particles below 1.7 mm, on the repose angle (φ). Additionally, the study examined the impact of moisture content (w) on the repose angle of subballast aggregate, and analysed the underlying influence mechanism.

Fig. 1 Subballast with varying particle sizes

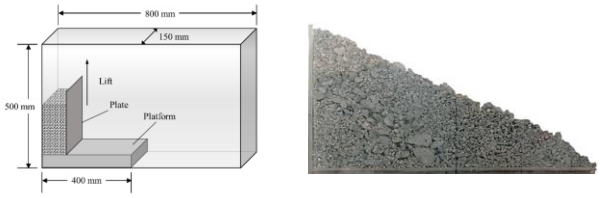
Table 1 Particle size distribution of subballast in standard

Sieve size (mm)	0.075	0.1	0.5	1.7	7.1	16	25	45
Mass passing (%)	0~7	0~11	7~32	13~46	41~75	67~91	82~100	100

2. Experimental repose angle test of subballast

2.1 Test materials

Subballast utilized for track construction could not only be the natural sand or gravel, but could also originate from the rock, gravel and pebble which have been crushed and sieved according to the ballast standard. The subballast material used in the test was crushed stone sourced from Ezhou Changlong Quarry, certificated as premium granite by China Railway Corporation. The particle density of the ballast aggregates was 2560 kg/m³. For the fine particles (< 1.7mm), the bulk density was 1620 kg/m³ and the specific gravity was 2.6. The required gradation for subballast according to the standard is listed in Table 1 and the subballast in this paper were selected following the requirements of the standard. Specifically, particles in sizes ranging from 0.075 mm to 1.7 mm are available natural gravel, while those of sizes in range between 1.7 mm and 45.0 mm were retrieved from the railway subballast. The sieved subballast in different sizes are shown in Fig. 1.



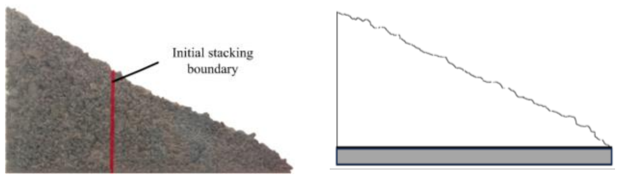
(a) Plate lifting method (b) Subballast slope profile

Fig. 2 Repose angle test of subballast using the PLM

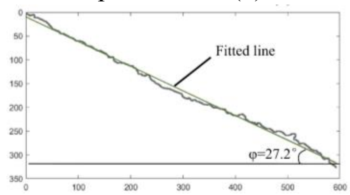
2.2 Measurement of repose angle

Numerous experimental tests have been conducted to determine the repose angle of granular materials in previous literature (Just *et al*. 2022, Xie *et al*. 2024). However, these studies often focus on only a few influencing factors and use a limited number of test samples, with the effects of particle gradation and moisture content on the construction of the repose angle being seldom explored. In this study, a series of PLM test were conducted to measure the repose angle of coarse aggregate. The photograph and the schematic diagram of the apparatus were shown in Fig. 2. The apparatus consists primarily of an upper opening box, a bottom platform, and a side plate. The dimensions of the opening box are 800 mm (length) x150 mm (width) x 500 mm (height), and the side plate also has a width of 150 mm, allowing it to retain the subballast particles before the formal tests. In previous researches on repose angle measurement, coarse particles tended to spread outward from the anticipated position after the falling or flowing process and the discrete particles may significantly influence the shape of the particle pile and consequently the accuracy of repose angles. To address this issue, a 400-mm-long metal platform was introduced and placed at the bottom of the box to allow the formation of the complete slope of particles.

Currently, no specific standard exists for measuring the angle of repose of graded railway subballast within the 0.075–45 mm particle size range. Therefore, this study adopted the apparatus specifications and procedures outlined in the Chinese standard (GB/T 16913-2008). The test procedure involved first preparing subballast samples with the designated particle size distribution by weighing and thoroughly mixing the required proportions. The well-mixed sample was then poured into the containment space formed by a custom-designed box and a vertical side plate; the internal dimensions of the apparatus were verified against the standard's specifications prior to testing. The top surface was carefully leveled to prevent overflow or unevenness. Based on preliminary tests which determined that a sample mass of 13 kg provided stable and reproducible results within the apparatus, this mass was standardized for all subsequent tests. Following sample preparation, the vertical side plate was carefully lifted vertically to minimize disturbance and avoid applying horizontal forces, allowing the subballast particles to slide under gravity and form a stable slope. Upon stabilization, the repose angle profile was photographed using a fixed-position camera. To ensure the validity and reproducibility of the results, each test condition was repeated three times, and the average angle was calculated.



(a) Subballast slope (b) Contour of slope



(c) Fitted line and repose angle

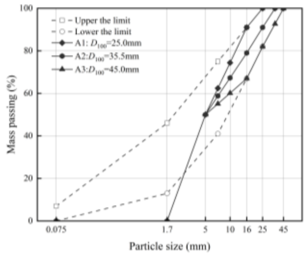
Fig. 3 Measurement of the repose angle of subballast slope

Although direct measurement using a ruler or goniometer has been previously employed to determine repose angles (Ileleji and Zhou, 2008), the accuracy of these methods is highly dependent on the operator, which increases the likelihood of measurement errors. In this study, digital image analysis techniques were employed for measuring the repose angle. The side view of the stable subballast slope was captured from a fixed position using a levelled, fixed-focus camera. Specifically, the subballast pile images were processed using ImageJ software to extract the pile contour. The processed images were then imported into MATLAB, where the original images were converted into binary images for contour extraction. Each point on the extracted contour corresponds to specific x and y coordinates. Using the least squares method, a linear fit was performed on these contour points to obtain the slope line, whose angle represents the repose angle of the pile (Chen *et al*. 2025). This method reduces errors associated with traditional direct measurements and enhances the accuracy of repose angle determination.

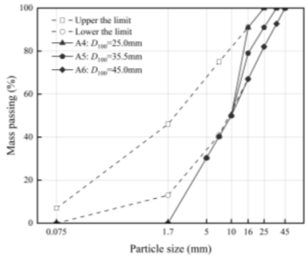
Apart from the repose angle, the diffusion degree (D) of the slope is also an important parameter for the description of the morphological characteristics of the slope. It facilitates the accurate characterization of the participation of particles in the slope formation process. The diffusion degree is defined as the ratio of the mass of particles falling outside the bottom platform to the total mass of all particles. This measure not only aids in the preliminary evaluation of the reliability of experimental results but also supports the systematic analysis of the underlying mechanisms of particle slope formation in conjunction with the repose angle.

2.3 Test programs

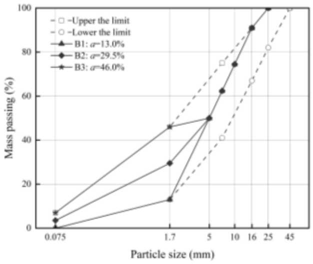
The design of this program was guided by the particle gradation specified in the subballast standard, with a particular focus on evaluating the influence of gradation on the repose angle of subballast. More specifically, five series of tests were carried out to systematically investigate the influence of different particle gradation parameters on the repose angle including D_{50}, D_{100} and percentage of the fine particles a (d < 1.7 mm).



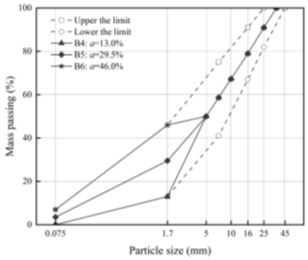
(a) Series I



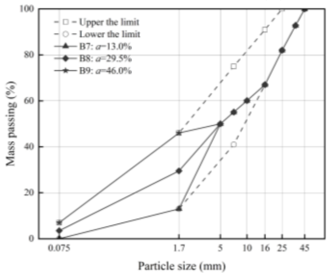
(b) Series II



(c) Series III



(d) Series IV



(e) Series V

Fig. 4 Subballast gradation curves

The designed gradation curves for the five series of tests are shown in Fig. 4, with the upper and lower limits based on the subballast standard. Series I (Group A1-A3): D_{50} = 5.0 mm, a = 0%, D_{100} = 25.0 mm, 35.5 mm and 45.0 mm. Series II (Group A4-A6): D_{50} = 10.0 mm, a = 0%, D_{100} = 25.0 mm, 35.5 mm and 45.0 mm. Additionally, 9 gradation designs were developed to study the effect of fine particle content. Series III (Group B1-B3): D_{50} = 5.0 mm, D_{100} = 25.0 mm, a = 13%, 29.5% and 46.0%. Series IV (Group B4-B6): D_{50} = 5.0 mm, D_{100} = 35.50 mm, a = 13%, 29.5% and 46.0%. Series V (Group B7-B9): D_{50} = 5.0 mm, D_{100} = 45.0 mm, a = 13%, 29.5% and 46.0%.

3. Results and discussion

3.1 Repose angle of subballast slope

A total of 17 particle gradation groups were tested, comprising 15 distinct gradations (see Fig. 4) along with standard upper and lower limit gradation curves. The repose angle was compared across these gradations. The subballast slopes from different test groups (A1-A6), showing the final morphology and their corresponding repose angles, are presented in Fig. 5. In these images, the red lines indicate the initial position of the side plate that provided support during the tests. Overall, the outline of each slope approximates a straight line, even though some large

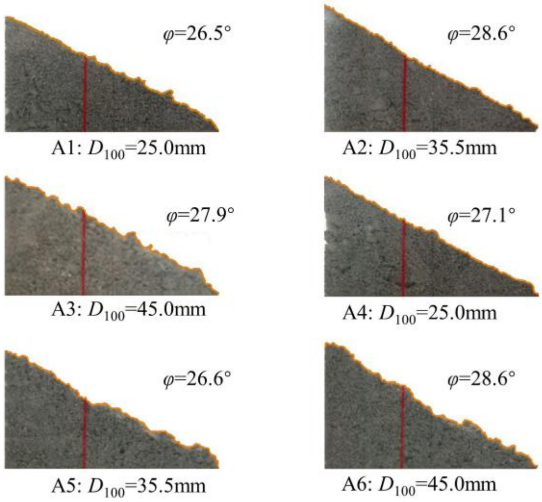


Fig. 5 Comparison of subballast slopes

particles appear upon the outline occasionally. These particles have a relatively slight impact on the overall continuity of the slope. It is noteworthy that the slopes formed in this study were completely triangular in shape, which differs slightly from some previous studies where plateaus were sometimes observed at the top of the slope (Duverger *et al*. 2024). The triangular morphology of the subballast slopes in this study is advantageous as it allows for the clear identification of the peak point of the slope. Additionally, the slope surface extends further, enabling the subballast particles to slide down more extensively. This extended formation allows for a more detailed observation of the interaction between particles and the granular material characteristics.

3.2 Influence of particle gradation parameters

3.2.1 Influence of D_{50} and D_{100}

According to the test program, both series I and II (Group A1-A6) are set to investigate the influence of the D_{100}. In addition, the results from these two series with different D_{50} could also be parallelly compared. The variation of repose angle φ and diffusion degree D with different D_{100} of the subballast are shown in Fig. 6. Generally, the repose angle presented an increasing tendency with increasing D_{100}. Specifically, the value of φ increased from 26.5° to 28.5° in the case of D_{50} = 5.0 mm, and it increased from 27.1° to 29.0° when D_{50} equals to 10.0 mm. It was found that the repose angles of the groups of D_{50} = 10.0 mm are larger than those of the groups of D_{50} = 5.0 mm. Regarding the diffusion degree, for the two different D_{50}, the value of D was essentially halved with D_{100} increasing from 25.0 mm to 40.0 mm, indicating that approximately 5% more subballast particles participated in the formation of the stable particle slope as D_{100} increased. The D ranges from 5% to 10%, indicating that most ballast particles contribute to the slope formation, making the measured repose angle reliable.

According to the gradation curves of Groups A1-A6 in Figs. 4(a) and 4(b), with the same D_{50} and the maximum diameter D_{100} increasing constantly, the proportion of large-

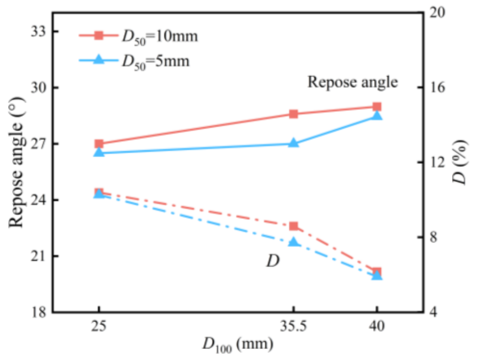


Fig. 6 Influence of D_{100} and D_{50} on repose angle and diffusion degree

sized particles increases, and the gradation curves become progressively more uneven. Due to that the PLM test was based on the sliding and the piling of the subballast particles, the formation of the particle slopes was not only dependent on the inter-particle friction forces, but also the interlocking among particles. Typically, larger particles tend to be more angular, which enhances the interlocking within the particle slopes.

Furthermore, subballast is a granular material with a wide range of particle sizes, including fine particles ($d < 1.7$ mm) as well as larger particles with diameters less than 45.0 mm. During the PLM test, as particles slide and pile up, the finer and medium-sized particles tend to fill the voids between larger particles. The presence of these large particles reduces the sliding tendency of smaller particles, which leads to an increase in the repose angle. This is partly because the PLM test for repose angle is minimally affected by side friction resistance between the side walls and particles, which is sufficiently small to be neglected. Overall, large-sized particles contribute to the structural stability of the particle slope by significantly enhancing the interlocking effect.

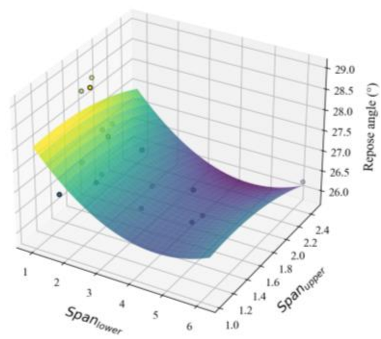
3.2.2 Influence of $Span_{lower}$ and $Span_{upper}$

The gradation curves of subballast are often discontinuous to enhance performance. By using the mass passing rate of 50% as the boundary, the gradation curve is divided into an upper segment (>50%) and a lower segment (<50%). These segments are then defined as $Span_{upper}$ and $Span_{lower}$, respectively, to more accurately characterize the gradation curve. The definitions are as follows

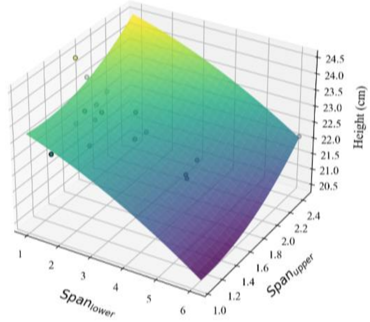
$$Span_{upper} = \frac{D_{100}\text{-}D_{50}}{D_{80}} \quad (1)$$

$$Span_{lower} = \frac{D_{50}\text{-}D_{0}}{D_{30}} \quad (2)$$

Fig. 7(a) illustrates the coupling effect of $Span_{upper}$ and $Span_{lower}$ on the repose angle of ballast. It is evident that the larger particle size span in the lower portion of the ballast significantly influences the overall trend of the repose angle. As the $Span_{lower}$ increases, the repose angle of the ballast generally decreases, with a slight increase observed near $Span_{lower} = 6$. Although the effect of the $Span_{upper}$ is relatively weak, it is noteworthy that in the range of



(a) Repose angle



(b) Slope height

Fig. 7 Influence of $Span_{lower}$ and $Span_{upper}$ on repose angle and slope height

$Span_{upper}$:1.6-1.8, this region tends to exhibit higher repose angles compared to other areas. The concentrated distribution of higher repose angles in the region where the $Span_{lower}$ is approximately 1.6 to 1.8 and $Span_{upper}$ is 1.0 to 1.2 suggests that this specific PSD combination can be considered a favourable arrangement for enhancing the internal friction between ballast particles.

It is worth noting that the height of the stabilized particle slope was also recorded after each PLM test, as shown in Fig. 7(b). The height of the ballast slope significantly decreases as $Span_{lower}$ increases. Obviously, the variations in slope heights and repose angles generally follow a consistent trend, which partially suggests that the height of the particle slope could also reflect the stacking characteristics of the granular materials. However, the measurement errors in the slope heights are relatively high compared to those in the repose angles, making the use of height to characterize the internal friction properties of ballast inappropriate.

3.2.3 Distribution of the repose angle within the limits

The distribution of the repose angles for the 15 designed particle gradation groups (including Group A1-A6 and B1-B9) is shown in Fig. 8. Generally, the measured repose angles were all found to be larger than 25.7°. Accordingly, the repose angle distribution within the range of upper and lower limits of the standard gradation could be basically divided into three specific ranges, including $\varphi \leq 26.5°$, $26.5° < \varphi < 27.5°$ and $\varphi \geq 27.5°$ (see Fig. 11). Note that, the value of φ reaches the maximum, when $a = 0.0\%$ and $D_{100} = 45.0$ mm (i.e., Group A6), while the second-largest repose angle occurred at $a = 0.0\%$ and $D_{100} = 35.5$ mm. This

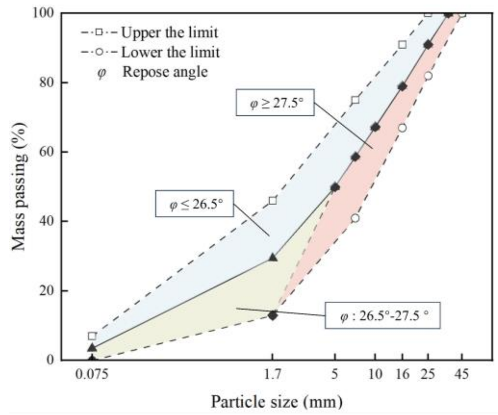


Fig. 8 Distribution of repose angle intervals for subballast

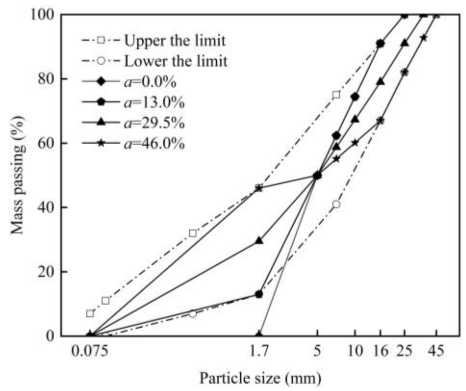


Fig. 9 Gradation with different fine particle contents

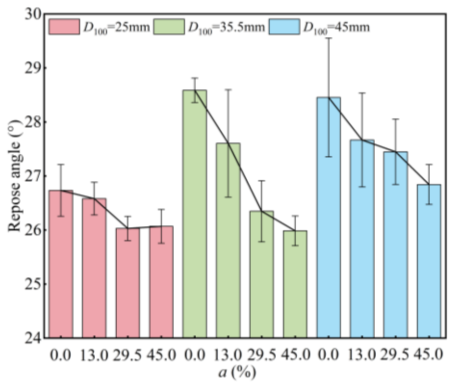


Fig. 10 Influence of fine particle content on repose angle

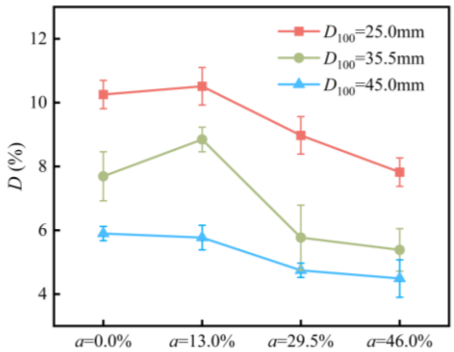


Fig. 11 Influence of fine particle content on diffusion degree

indicates that the absence of fine particles contributes to higher repose angles in subballast particle slopes. However, particle gradations without any fine particles smaller than 1.7 mm are not appropriate according to the subballast standard. Also, upwelling of the subsoil particles are more likely to occur without the block of the fine particles of subballast, therefore the gradation groups with a = 0.0% were not considered in Fig. 8 for the range division. Overall, the divided range for particle size distribution based on the standard gradation limits could not only provide valuable references for the design and construction of the ballast track, but also the guidance for the pavement procedure of subballast particles.

3.3 Influence of fine particles

Fine particles play a crucial role in subballast gradations, as they can help mitigate the fouling of track ballast caused by subsoil particles to some extent. However, some studies have suggested that fine particles tend to have lower angularity compared to larger granular materials, which may act as lubricants and reduce the shear resistance of the particle aggregation (Zhang *et al*. 2024, Kian *et al*. 2018). To investigate the effect of fine particles (with sizes smaller than 1.7 mm) on the repose angle of the piling, three different percentages (a = 13.0%, 29.5%, and 46.0%) were used, corresponding to Groups B1-B9. In addition, the Group A1-A3 containing no fine particles (a = 0.0%, D_{50} = 5.0 mm) are set as reference groups for comparison. For this purpose, the predesigned 4 gradation with the same D_{50} but different values of parameter a are presented in Fig. 9.

The diffusion degree and the repose angle of each gradation group were determined after three repeated measurements of the captured photos of the particle slope, which are shown in Figs. 10 and 11, respectively. According to the Fig. 10, for a specific maximum diameter (D_{100}), the repose angle of the particle slope decreases as the fine particle content increases. Specifically, the decrement degree of the repose angle became the most significant (from 28.4° to 25.7°) when D_{100} = 35.5 mm. However, the amount of the particles participating into the piling increases with the value of a. In the case of a = 0.0% (i.e., the particle sizes are all larger than 1.7 mm), the repose angles come to their maximal value, with the lowest content of particles contributing to the slopes. This phenomenon could be explained by the fact that the fine particles are more rounded and less angular comparing with large-sized particles, and thus the lubrication effect could become increasingly evident with higher content of fine particles.

In addition, since the particles in diameters ranging from 1.7 mm to 5.0 mm, which are relatively angular, are gradually substituted by fine particles, the interlocking effect was therefore alleviated, which could also be the reason for the decreasing of the repose angle with increasing a. When D_{100} = 25.0 mm, the variation in fine particle content has a relatively minor effect on both the repose angle. However, this influence becomes more pronounced as D_{100} increases, further emphasizing the effect of D_{100} on the piling behavior of the subballast.

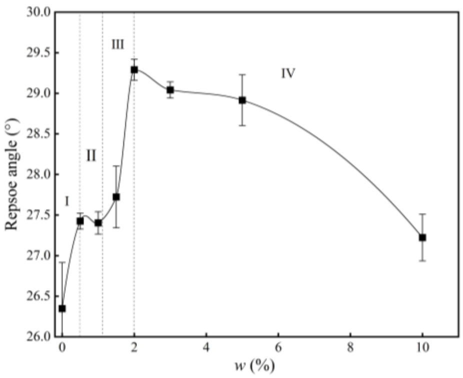


Fig. 12 Effect of moisture content on repose angle

3.4 Influence of moisture content on the repose angle

Ballasted tracks are exposed to external environmental conditions, particularly rainfall, which significantly influences the subballast moisture content-a key factor affecting the repose angle. To investigate the moisture content effects, a series of PLM tests were conducted on Group B5, which was identified as the optimal gradation achieving maximum φ, across moisture contents ranging from 0.5% to 10.0%. The moisture content, w was calculated as the mass ratio between the water (m_w) and subballast (m_s). Each moisture level was tested at least three times, with average values recorded.

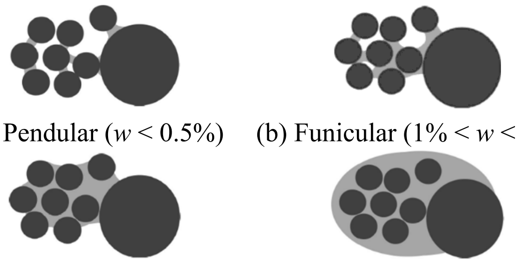
As established by Baker and Frydman (2009) and Likos (2014), unsaturated particles experience adsorbed suction due to water tension and particle interactions. This generates quasi-cohesion forces via interfacial tension, restricting particle movement. During saturation, adsorbed suction decreases with rising moisture, eventually providing lubrication that reduces inter-particle friction. Fig. 12 illustrates the relationship between repose angle and moisture content, including the best-fitting regression line. The observed trend can be characterized by four distinct stages:

(I) Abrupt change (w < 0.5%): The φ increased sharply from 26.4° at dry conditions to 27.4°, driven by initial liquid bridge formation at contact points (Fig. 13(a)). Wide gradation promoted fine particle adhesion to larger grains, amplifying this effect.

(II) Plateau (0.5% < w < 1%): The φ stabilized between 27.4° and 27.5°as liquid bridge forces between fine particles reached saturation, maintaining consistent fine-large particle contacts and minimal cohesion variation.

(III) Rapid growth (1% < w < 2%): The repose angle (φ) increased significantly from 27.5° to a peak of 29.3°, as more fine particles adhered to the surfaces of larger particles. This is attributed to enhanced matric suction, which promotes consolidation among particles. During this phase, liquid bridges transitioned from the linear state to funicular and capillary states (Figs. 13(b) and 13(c)). The concave liquid surface, driven by pressure differences, strengthens cohesion between fine and large particles.

(IV) Slow decline (w > 2%): φ decreased constantly to about 27.2° at w =10%. Increasing free moisture progressively collapsed liquid bridges and reduced cohesion forces as shown in Fig. 13(d). Nevertheless, the repose angle at 10% moisture remained higher than the dry state, indicating persistent residual suction effects.



(a) Pendular (w < 0.5%) (b) Funicular (1% < w < 2%)

(c) Capillary (1% < w < 2%) (d) Slurry (w > 2%)

Fig. 13 Model of inter-particle capillary suction

(a) w = 0.0% (b) w = 5.0%

Fig. 14 Subballast particles at varying moisture contents

(a) w = 0.5% (b) w = 5.0%

Fig. 15 Subballast piles at varying moisture contents

The photos of the individual subballast particle (d > 25 mm) with and without the addition of 5% moisture content were compared in Fig. 14. It is evident that, with a 5% moisture content, numerous fine particles adhere to the surface of the large subballast particles, a stark contrast to the dry subballast material. This observation highlights the significant impact of moisture content on particle stacking behaviour. In particular, typical photographs of particle piling under two different moisture contents (Fig. 15) illustrate distinct behaviors. At a low moisture content (w = 0.5%), the particles exhibit high discreteness, with larger particles (especially those larger than 25.0 mm) primarily attached to fine particles, but the adhesion strength remains relatively weak. In contrast, at 5% moisture content, the particles become more aggregated, with fine particles adhering more strongly to the large particles due to increased adhesion forces, and water overflow can be observed from the inter-particle spaces.

5. Conclusions

The influences of gradation and moisture contents on the repose angle of subballast pile were investigated through the PLM. Moreover, the optimization scheme of subballast gradation was put forward in consideration of various influencing factors. The main conclusions are as follows:

• The repose angle increases with an increase in D_{100} or D_{50}. The maximum repose angle is obtained when the gradation does not contain particles smaller than 1.7 mm, and D_{50} is 10.0 mm with D_{100} of 45.0 mm. The effect of $Span_{upper}$ and $Span_{lower}$ shows that a larger $Span_{lower}$ decreases the repose angle. $Span_{upper}$ has a weaker influence. The combination of $Span_{lower}$:1.6–1.8 and $Span_{upper}$: 1.0–1.2 enhances internal friction between ballast particles.

• Based on the repose angles of 17 subballast gradations, the standard grading curves were classified by repose angle. The optimized gradation curve serves as a reference for subballast design in engineering practice.

• The increase in fine particle content in the subballast will result in a lower angle of repose for the ballast pile, although the mass of particles contributing to the pile formation increases. This indicates that the inclusion of fine particles gradually acts as a lubricant, undermining the interlocking effect between larger particles.

• The repose angle evolves through four stages with increasing moisture content: abrupt change, plateau, rapid growth, and slow decline. At 2% moisture content, liquid bridge forces increase, raising the repose angle. Beyond this point, increased moisture content enhances lubrication, reducing particle friction and lowering the repose angle.

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