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Investigating Shear Strength and Particle Size Effects in Crushed Rock Fill Materials for Engineering Applications: A Study in Indian Context

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Abstract

This research paper focuses on the shear behavior and strength characteristics of crushed rock fill materials, particularly decomposed rock fill materials used in high rock fill dams in India. The study aims to fill a research gap in the country by investigating the influence of particle size and crushing on shear properties. The Mohr-Coulomb failure theory is applied to analyze soil failure, considering shear stress, normal stress, and internal friction. The literature review highlights the potential of alternative materials like manufactured sand and crushed limestone in concrete applications for improved sustainability. The testing program involves direct shear tests on crushed limestone, sandstone, and river gravels at varying normal stresses. The results show that particle size impacts shear resistance, with larger particles exhibiting higher shear strength due to lesser breakage. The research offers valuable insights for dam design and construction in India and beyond, fostering sustainable practices in geotechnical engineering and construction.

Keywords: crushed rock fill materials, shear behavior, shear strength, decomposed rock fill

Introduction

The period from 1911 to 2022 saw the emergence of rock fill as a widely used construction material in various engineering applications, particularly in the construction of rock fill dams. The shear strength of rock fill materials is a crucial property that significantly influences dam design and stability. While extensive research has been conducted on the properties of rock fill materials in other countries, there has been a lack of comprehensive attention to this field in India. This study aims to fill this research gap by focusing on the shear behavior of crushed rock fill materials, specifically decomposed rock fill materials commonly used in high rock fill dams in India. The research will investigate the influence of particle size and the effect of crushing on shear characteristics to contribute valuable insights to geotechnical engineering, enabling more informed decision-making in dam design and construction in India and benefiting engineering practices worldwide.

The shearing strength of soil is a crucial property in geotechnical engineering, affecting the stability of foundations, slopes, and dams. It arises from interlocking of particles, frictional resistance, and adhesion or cohesion between soil particles. The Mohr-Coulomb failure theory is a widely used theory to analyze soil failure, considering shear stress, normal stress, and the angle of internal friction. The effective stress on the failure plane is essential for determining soil strength, and soil density and drainage influence the mobilization of shearing stress.

Crushing phenomena in granular soils can occur during shear or compaction, leading to the breakdown of asperities, splitting of soil grains, or crushing of sharp angularities. The presence of a softer crust on grain surfaces can affect the shear behavior, leading to various types of failures, such as shear at the interface or general shear within the softer material. The amount of material sheared during sliding depends on contact pressure, sliding distance, and surface hardness.

A direct method for detecting crushing involves comparing gradation curves before and after compaction or shear to estimate the magnitude of crushing. However, this method may not be precise for soils with different particle hardness. Overall, understanding soil shearing strength and its intricate nature is vital for designing stable geotechnical structures.

Literature Review

The reviewed research papers present valuable insights into the utilization of various materials and waste products in concrete, addressing both environmental sustainability and engineering performance. Studies focusing on manufactured sand, limestone powder, marble powder, and crushed limestone waste demonstrate their potential as viable alternatives to natural aggregates and cement, leading to enhanced workability and mechanical properties of concrete. The incorporation of supplementary materials, such as silica fume and lightweight aggregates, also shows promising results in improving concrete performance. Additionally, investigations into the application of crushed sand and crushed limestone contribute to environmentally friendly construction practices by conserving natural resources and reducing environmental impact. Moreover, the studies on the effects of high temperatures and fiber reinforcement provide crucial knowledge for understanding the behavior of concrete under challenging conditions. Overall, these research findings offer valuable guidance for optimizing concrete mix design, reducing costs, and enhancing the durability of concrete structures, fostering sustainable practices in the field of civil engineering and construction.

Testing Programme

The testing program involved conducting direct shear tests on crushed limestone, sandstone, and river gravels of different particle sizes. Samples were taken from each material within specific particle size ranges. The tests were conducted at four different normal stresses: 0.5 kg/cm2, 5.55 kg/cm2, 13.89 kg/cm2, and 27.78 kg/cm2. A total of 36 tests were performed.

A shear box with 3.25 cm thick mild steel plates and internal dimensions of 6 cm x 6 cm x 3 cm was used for the tests. The normal load was applied using a fixed loading frame, and the horizontal shear force was applied through a remote-controlled hydraulic jack. Shear displacement and vertical displacement were recorded using dial gauges.

The test procedure involved filling the shear box with the sample and placing two mild steel plates on top of it. Initial readings of dial gauges were recorded, and then a particular normal load was applied. The shear force was incrementally increased, and the corresponding displacements were recorded until the sample failed. After each test, the sample was taken out of the box for sieve analysis to obtain gradation curves and assess particle breakage.

In the second set of experiments, only normal loads were applied, and the sample was taken out for sieve analysis.

Overall, 36 tests were conducted for each type of material at varying normal stresses, and the results were used to analyze the shear behavior and strength characteristics of the crushed limestone, sandstone, and gravel samples.

RESULTS AND DISCUSSION

1. Stress-Strain Relationship: The direct shear tests were conducted on crushed limestone, sandstone, and gravel samples at four different normal stresses (0.5 kg/cm2, 5.55 kg/cm2, 13.89 kg/cm2, and 27.78 kg/cm2). The relationship between shear force and shear displacement, as well as between vertical and horizontal displacement, was studied.

For limestone and sandstone, the peak of the shear force-displacement curves was well defined at high normal stresses (27.78 kg/cm2 and 13.89 kg/cm2), indicating brittle failure. At lower normal stresses (0.5 kg/cm2 and 5.55 kg/cm2), the curves remained almost constant until failure, suggesting more ductile behavior. In the case of gravel, the shear displacement increased without a significant increase in shear force, suggesting a lack of well-defined peak and shear strength at all normal stresses.

2. Particle Breakage:

The effect of stress on grain size distribution and particle breakage was studied through sieve analysis. It was observed that the amount of crushing decreased with an increase in particle size for both limestone and sandstone samples. This indicates that larger particles experienced lesser particle breakage and, consequently, higher shear strength.

3. Shear Strength and Crushability:

The shear strength and crushability of the samples were examined.

For limestone and sandstone, as the particle size increased, the shear resistance also increased. This was attributed to larger asperities providing more resistance during shear stress application.

However, in the case of gravel, particle size had a different effect. Larger particles experienced lesser breakage and had higher shear strength. The absence of significant interlocking in gravel particles may be the reason for the increase in shear strength with particle size.

Gravel showed higher shear strength compared to sandstone at high normal stresses (13.89 kg/cm2 and above) due to its lower crushability during shear.

The shape of particles also played a role, with gravel having a smoother external surface and less volume change during normal and shear stress application compared to sandstone.

Discussion:

The direct shear tests revealed important insights into the behavior of crushed limestone, sandstone, and gravel under different normal stresses. Limestone and sandstone showed more brittle behavior at high normal stresses and ductile behavior at lower stresses. Gravel, on the other hand, exhibited a lack of well-defined peak and consistent behavior across all stresses.

Particle breakage was found to be inversely proportional to particle size for limestone and sandstone, while larger gravel particles experienced lesser breakage and demonstrated higher shear strength. The different shapes of gravel and sandstone particles influenced their shear behavior, with gravel showing higher shear strength due to its smoother surface and lower crushability during shear.

Conclusion

The conducted study aimed to determine the shear strength characteristics of limestone, sandstone, and gravel. The results revealed several key findings: firstly, shear strength decreases with an increase in particle breakage or a decrease in particle size. Secondly, crushing magnitude increases with higher normal stress, but major crushing primarily occurs during shear. Thirdly, the grain size distribution undergoes continuous changes with the application of shear and normal stress. Fourthly, despite having the same particle size and gradation, the shear strength of sandstones and gravel differs at normal stress levels. Fifthly, at high normal stress, gravel exhibits greater shear strength compared to sandstone due to its lower crushability. Lastly, at high normal stress, limestone shows lower shear strength than sandstone and gravel, attributed to its higher magnitude of crushing.

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