ISSN 2717-4638

Experimental Investigation of Particle Crushing Behavior of Melamchi Sand Using Compression Testing Machine

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Abstract

Understanding the particle crushing behavior of sand under high compressive stress is critical for accurate prediction of soil compressibility and strength characteristics. This study examines the particle breakage characteristics of Melamchi river sand under extreme vertical loads using a Compression Testing Machine (CTM). Dry sand specimens were placed in a CTM machine and loaded step-by-step upto 1000 kN (about 53 MPa). Particle size distribution analysis was done before and after each test to find $D_{10}, D_{30}, D_{50}, D_{60}$ and coefficient of uniformity (C_u). Breakage indices were calculated to quantify the degree of particle breakage. Results show upto 59% reduction in mean particle size with increasing stress levels at 1000 kN. The findings confirm that grain crushing must be considered in geotechnical infrastructure works like deep pile foundations, rockfill dams, embankments and hydropower tunnels, where high stresses occur. The findings are useful for the design of gravel drains and soil filters, where stress-induced particle crushing can change gradation and influence filtration performance.

Keywords: *Breakage Index, Compression Testing Machine, Granular Soils, Particle Crushing, Particle Size Distribution*

Introduction

In geotechnical engineering practice, granular materials such as sand and gravel are widely used as geomaterials in infrastructure including foundations, embankments, retaining structures and pavements (Lambe & Whitman, 1969). Due to change in stress the mechanical behavior of these soils undergoes changing. The mechanical behavior of these soils under loading are highly dependent on different parameters, including initial packing, grain size distribution (Lade et al., 1997). Another factor on which it depends is on the potential for particle breakage under applied stresses. Stress-strain and strength behavior, volumetric behavior and pore-pressure developments, including permeability are the important engineering properties that is altered by particle crushing (Hattamleh et al., 2013; Lade et al., 1997). The particle crushing mechanics or particle breakage is one of the complex area of study in geosciences (Einav, 2007). This field of study is of interest to many research discipline like minerals and mining, geology, powder technology, geophysics and geomechanics (Einav, 2007; Hattamleh et al., 2013). Several particle breakage factors have been proposed for quantification of amount of partical breakage, out of which the most widely used indices are those developed by Marsal, Lee and Farhoomand and Hardin (Lade et al., 1997).

Previous studies, such as those by (Ahadi et al., 2024; Coop et al., 2004; Hardin, 1985; Lade et al., 1997) have highlighted the following parameters as the influencing factor for particle breakage: initial grading of the material, grain morphology, stress level, the stress magnitude and the stress path, particle hardness and the presence or absence of water. As the particle angularity increases particle breakage increase. Uniform soils break down easily than well-graded soils. Since the average contact stress tends to decrease with more particles surrounding eachother particles, this tends to decrease the particle breakage. That as the relative density increases, the amount of particle breakage decreases (Lade et al., 1997). Commonly triaxial and conventional oedometer test have been used for the study of particle crushing. These equipments have capacity of applying moderate stresses. To overcome this limitation in our experimental investigation we have used CTM, which is capable of applying higher stress magnitudes. In this study, Melamchi river sand is treated as a granular geomaterial for geotechnical infrastructure, and its stress- and density-dependent particle crushing behaviour is investigated using one-dimensional high-stress compression tests in a compression testing machine, with particular emphasis on changes in particle size distribution and breakage indices. One-dimensional vertical compression load was applied using CTM at different load stages up to 1000 kN. Pre and post particle size distribution was performed before and after applying the loads, from where the different key gradation parameters, like $D_{10}, D_{30}, D_{50}, D_{60}$ and the coefficient of uniformity (C_u) were determined for further breakage evaluation. Results from this research provides essential data about the particle breakage of Melamchi Sand to the geotechnical researchers, in context of Nepalese Himalayas sourced sand.

This behaviour is particularly relevant in high earth and rockfill dams, deep piled and drainage or filter layers in dams and hydropower projects, where very high vertical stresses can cause particle crushing, alter the particle size distribution, and thereby influence compressibility, long-term settlement and filtration performance(Lade et al., 1997; Park & Santamarina, 2023). Soil particles may experience crushing under conditions of high effective stress, such as those induced beneath pile tips, by steel rollers, and within geological reservoirs during oil extraction (Park & Santamarina, 2023). Gravel drains and soil filters are located near the base of the dam, where the applied pressure is maximum which leads to particle crushing. Since filters are solely designed based on grain size, so after filter has been placed if alternation of grain size occurred due to particle crushing then the effectiveness of filter could be significantly altered (Farhoomand, 1925). Similarly, in highway base layers, particle crushing can reduce resilient modulus and contribute to permanent deformation and rutting, which ultimately lead to pavement distress (Zeghal, 2009). These outcomes highlight the need for careful evaluation of crushing behavior when selecting granular fill for engineering works.

Literature Review

Particle crushing is a critical phenomenon influencing the mechanical behavior of granular soils under high compressive stresses. Many researcher's studies show that particle breakage alters soil fabric, increases fines content, and significantly affects compressibility, strength and permeability characteristics. Under high stress, particle crushing is an important mechanism of granular soils. Marsal, Lee, Farhoomand and Hardin provided the frameworks for describing it. Among them Hardin's framework is mostly used framework, he explains that crushing occurs when the stresses transmitted at grain-to-grain contact points exceed the strength of individual particles, causing them to facture and produce smaller grains. Hardin introduced the concepts of breakage potential and relative breakage, which quantify how much the particle size distribution changes by comparing the areas between the initial and final gradation curves. Similarly his study shows that particle crushing leads to increased compressibility, decreased shear strength, and reduced permeability which can significantly influenced influence geotechnical performance in structures subjected to heavy stresses, such as embankments, rockfills and foundations (Lade et al., 1997). For precisely describing and to model the strength and stress-strain behavior of granular soils, it is necessary to find the extent of particle breakage that occurs under loading. Several factors influence the degree of crushing in a soil mass. These are initial grain size distribution, particle shape, level and path of effective stress, void ratio, mineral hardness and the presence or absence of water (Hardin, 1985). The term Breakage Mechanics introduced by (Einav, 2007) is a new way to describe particle crushing in sand. In his study a breakage index is the measures of how much the grain size distribution shifts as particle are crushed. Using laboratory data and testing on his model shows that as particles crush, the sand becomes denser, less dilative and more compressible. So, these study demonstrates that particle crushing strongly affects the mechanical behavior of sands and must be included when predicting settlement and strength at high stress levels. Furthermore from (Coop et al., 2004) study on carbonate sands , observed that particle breakage not only modifies particle size distribution but also influences the overall compressibility of granular soils. While studying filters used in earth dams (Farhoomand, 1925) introduced a method to evaluate particle crushing. This study was focused on whether grain breakage could reduce the effectiveness of filter after placing due to particle crushing or not leading to reduction of permeability by clogging the filter layers. Performing isotropic loading test on sand specimens, they proposed a breakage index based on the variation in the particle size corresponding to the D_{15} point (the size at which 15% of the sample is finer). This index allowed them to quantify the degree of crushing by comparing D_{15} values before and after loading.

Furthermore, the influence of relative density on crushing behavior has been studied in coral sands. (Wang et al., 2022) by performing the study on coral sand found that higher initial density conditions results in a greater probability of crushing. Additionally, their work shows that the relationship between breakage index and stress can be modeled using a stress-dependent power function. In addition to different type of sand, different gradation also shows different findings, breakage behavior differs on gap-graded soils. (Zhang & Baudet, 2013) found that crushing in such soils does not necessarily lead toward a fractal grading curve, indicating that initial gradation can govern the evolution of particle size distribution. This finding implies that predicting ultimate grading states must be guided by both mechanical behavior and initial grain structure.

Hence, the literature confirms that particle crushing is strongly stress-dependent, increases with increased loading cycles, and significantly impacts geotechnical behavior. However, many studies have relied on oedometer testing at relatively moderate stress levels. There remains a need for focused studies applying higher vertical stresses using compression testing machines to better simulate field-scale stress environments, which is the focus of the present study.

Significance of High-Stress Testing

Generally, typical vertical stresses encountered in geotechnical structures ranges between 200 kPa to 1500 kPa, in this study intentionally a higher compressive stress is applied up to 53 MPa using high capacity CTM machine. The objective was to investigate the particle crushing mechanisms due to higher stress. High-stress testing enables the observation of significant fines generation and substantial shifts in particle size distribution towards finer size fractions, which are not fully captured under moderate field stress conditions. Such extreme testing scenarios are critical for understanding soil behavior under exceptional loading events, including seismic surges, structural overloading, and localized stress concentrations beneath deep foundations. Similar high-stress compression approaches have been successfully adopted by (Wang et al., 2022; Xiao et al., 2017), reinforcing the scientific necessity and validity of the adopted methodology.

Methodology

Material Description

The material used for the study was sand samples collected from Melamchi River, Nepal. The sand is generally sub-angular to angular in shape, derived from crystalline Himalayan bedrock. Also these sediments travelled a short distance of steep mountain terrain. It is widely used both as a general construction material and, more importantly for this study, as a granular geomaterial. The specific gravity of the sand is 2.63. The collected sand was passed through 4.75 mm size sieve. Then the sample passed through 4.75 mm size sieve and retained on 75 µm size sieve was washed under a running water tap until a clean water flow through a 75 µm size sieve. It was then air dried under room temperature. Only this prepared sand sample was further used for tests.

Testing Equipment

CTM was used for providing a high stress compression load in this study. CTM available at Central Material Testing Laboratory (CMTL, Pulchowk Campus) was used throughout the experimental study. This CTM has capacity of 2000 kN, with least count 1 kN. Vertical compression load was applied to the sand specimen, sand specimen were inside a metallic mold. Here, the metallic mold is used of dimension diameter 15.4 cm and height 13 cm. The loading platen was flat and polished to ensure uniform distribution of compressive stress across the specimen surface. There was not any lateral deformation measured in this arrangement.

Sample Preparation

In our study sand was prepared in three different denseness state (loose, medium dense and dense state). These target relative densities was of 20%, 50% and 75%. At first the specific gravity was determined using the standard code (ASTM D 854, 2006). Also minimum and maximum density of the sand was determined following another standard code (IS:2720 (Part 1): 1983). For each target relative density (20%, 50%, and 75%), the mass of the sand specimen was calculated based on the mold volume and desired initial density. This mass was maintained constant throughout all incremental loading stages from 100 kN to 1000 kN i.e from stress 5.37 MPa to 53.67 MPa, ensuring that the initial packing condition remained consistent during the particle crushing study.

Loading Procedure

CTM was used for performing the crushing of sand particles. Strain-controlled condition of loading arrangement was provided. At first the pre-compression gradation analysis was done. After that the prepared sample was placed on CTM for crushing. First load was applied upto 100 kN, at constant strain rate of loading, after reaching 100 kN, the CTM machine was stopped, load was released. Then the sample was taken for post-compression sieve analysis. After post-compression sieve analysis for 100 kN, same sample was poured on the mold for 200 kN load compression. Similarly, the process was repeated for 400 kN, 600 kN, 800 kN, and 1000 kN compression load. This incremental loading and re-packing procedure allowed for a stepwise evaluation of particle crushing behavior under increasing compressive stresses.

Post-Compression Gradation Analysis

For post-compression gradation analysis, sand specimen after compression at each targeted load were removed carefully from the mold. After removing the sand specimen from the mold, sand specimen was poured to the sieve arranged in order so that the higher opening mesh size was on top, following the small opening size mesh for sieve analysis. Sieve Analysis was performed following the code (IS 2720-Part 4, 1985)to determine the post-compression particle size distribution (PSD). From the post-compression PSD, key parameters like D_{10} , D_{30} , D_{50} , D_{60} and the coefficient of uniformity (C_u) were calculated.

Particle Breakage Quantification

PSD analysis was done at different loadings to quantify the particle breakage. The effective particle size (D_{10}) was used as a prime indicator of crushing behavior. The effective particle size (D_{10}), is defined as the grain diameter at which 10% of the soil is finer. It is the fundamental parameter for the estimation of permeability, filter design and particle breakage. In addition to (D_{10}), the mean particle size (D_{50}) and the overall PSD curve was also used to understand changes in grain size characteristics. The mean particle size (D_{50}) is defined as the diameter at which 50% of the soil is finer. It is the primary indicator of grain size distribution in the soil classification system. The progression of particle breakage under compressive stresses was assessed through the obtained value of D_{10}, D_{50} reducing over the increased stress and shift of PSD curve towards finer grain size in PSD curve. The amount of particle breakage was evaluated from the grain size distribution curves using the method developed by (Hattamleh et al., 2013). Here, the parameter is based on the effective size (D_{10}) and can be obtained from

$$\boldsymbol{B_{10}} = \frac{\boldsymbol{D_{10i} - D_{10f}}}{\boldsymbol{D_{10i}}} \quad \text{.....................................(1)}$$

Where,

B_{10} = Particle breakage factor

D_{10f} = effective grain size of the final gradation

D_{10i} = effective grain size of the initial gradation

Results and Discussion

Initial Particle Size Distribution

Figure 1 shows the initial PSD of natural sand. Table 1 below gives the initial properties of the Melamchi sand. Since, C_u= 4.56 (less than 6 fails uniformity criteria) and C_C= 0.53 (less than 1 fails curvature criteria) so it does not meet USCS criteria for well-graded sand. Therefore, it is classified as poorly graded sand (SP).

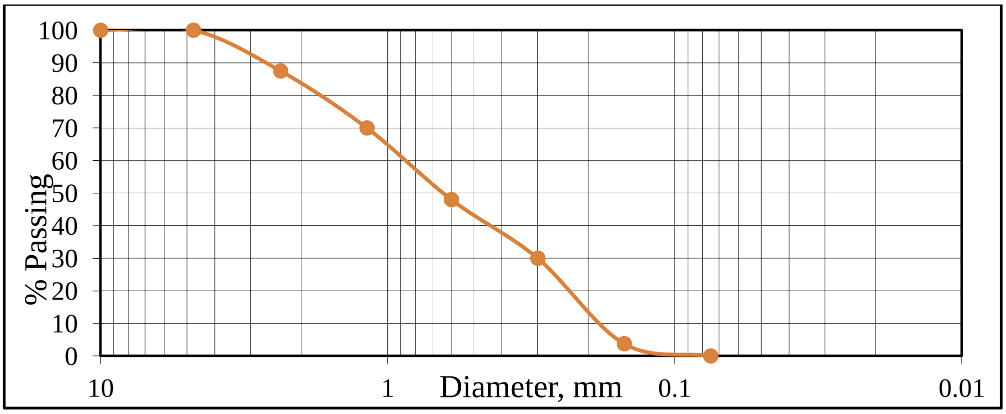

Figure 1: Initial Particle Size Distribution Curve

Table 1: Properties of Melamchi Sand

Sand	D_{10} (mm)	D_{30} (mm)	D_{50} (mm)	D_{60} (mm)	C_u	C_c
Melamchi	0.193	0.3	0.64	0.88	4.56	0.53

Changes in Gradation After Compression

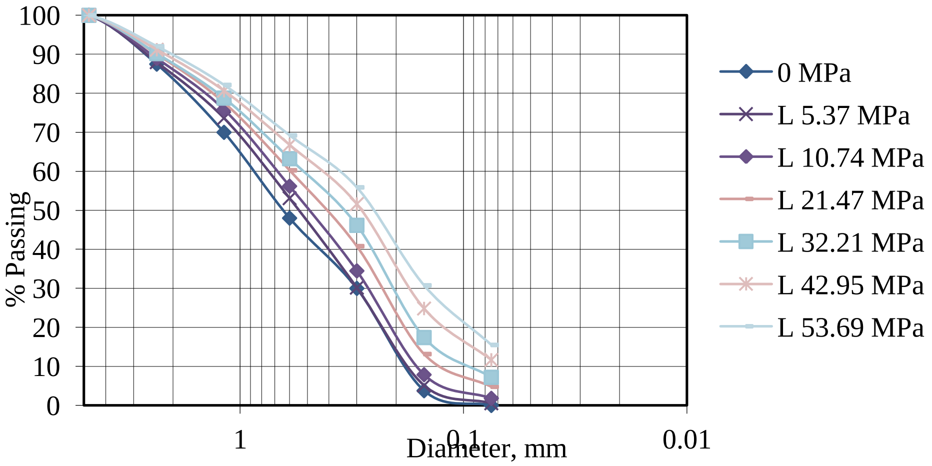

Figure 2: PSD (Loose State)

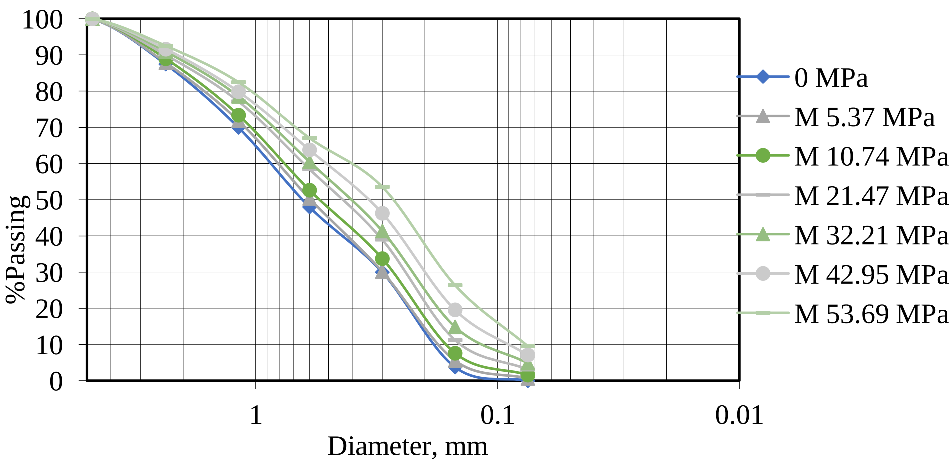

Figure 3: PSD (Medium Dense State)

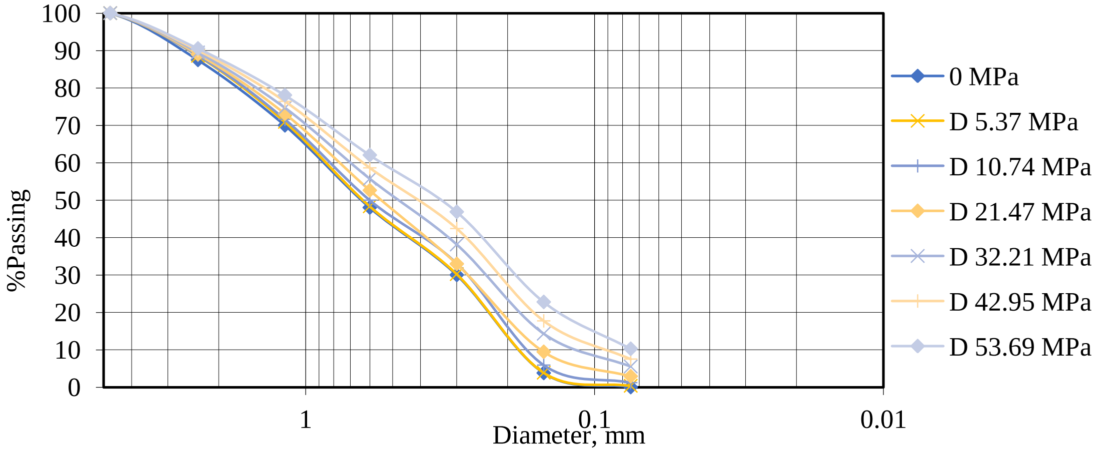

Figure 4: PSD (Dense State)

Figure 2 to Figure 4 shows PSD of sand at different relative density on varying loading. From these PSD we can observe that as the vertical load increases, the gradation curve shift towards finer size. The extent of shift varies with the initial density and applied load. This trend indicates increased particle breakage.

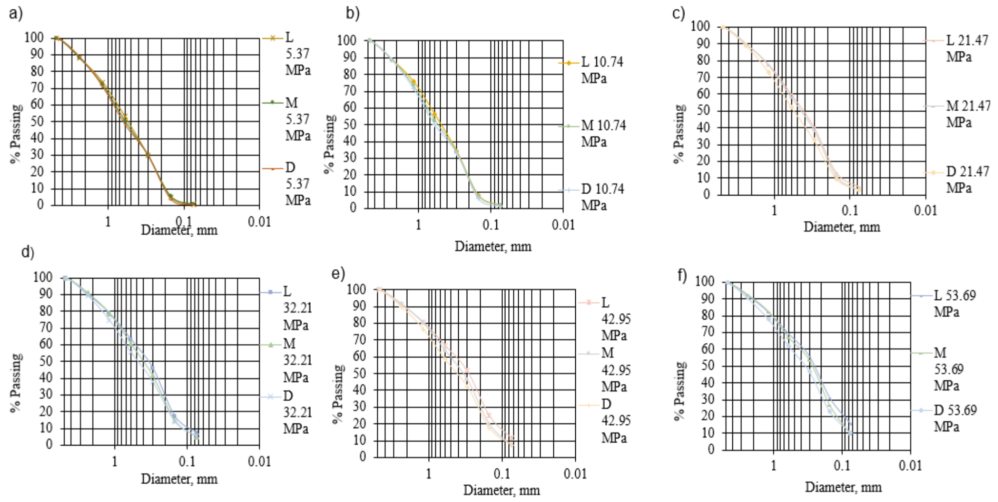

Figure 5: PSD of Melamchi sand at different vertical stress a) 5.37 MPa b) 10.74 MPa c) 21.47 MPa d) 32.21 MPa e) 42.95 MPa and f) 53.69 MPa

Figure 5 shows PSD at different stress 5.37 MPa to 53.69 MPa at different state of denseness. As per the PSD we can observe that crushing intensity increases from higher to lower from loose, medium dense to dense. The first three figures i.e up to stress 21.47 MPa, shows small shift of PSD curve in all state, but loose sand shows more notable shift. Dense sand shows the least change. Similarly, in stress from 32.21 MPa to 53.69 MPa all curves shift significantly to the finer size. Dense state begins to show visible breakage beyond 32.21 MPa.

Evolution of D50

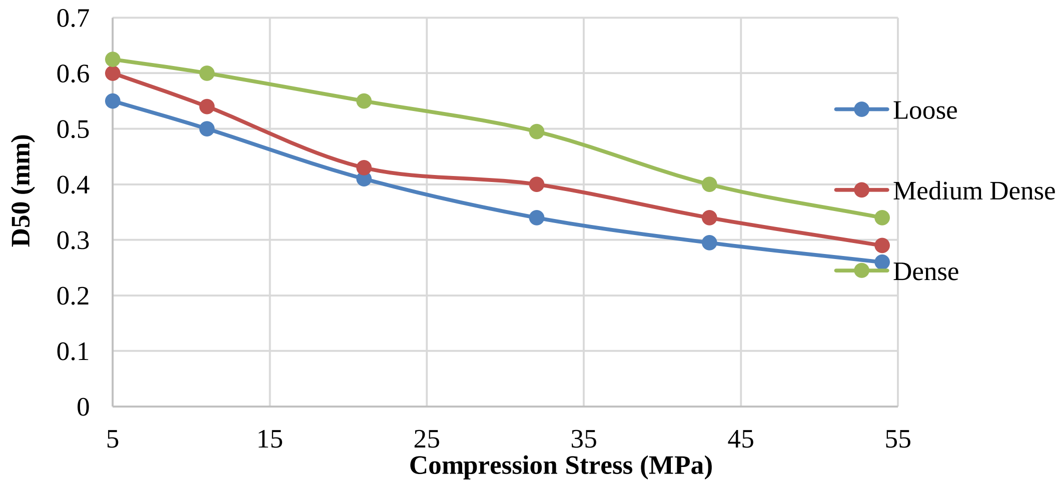

Figure 6 : D50 vs Vertical Stress

D50 decreases consistently with increasing vertical stress across all density states as shown in

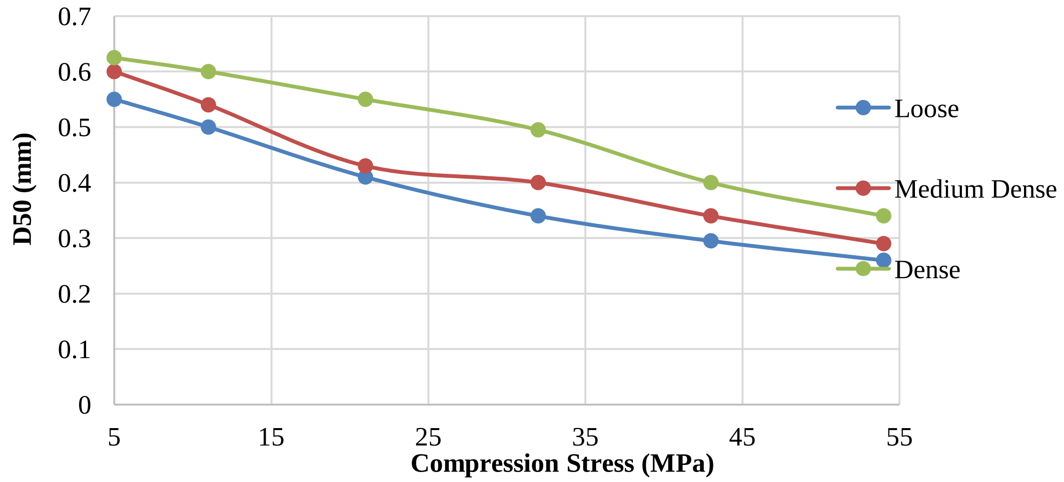

Figure 6. Dense state retains highest D50 at all stress, which shows greater resistance to particle breakage. Loose and medium dense sand show faster reduction in D50 (means weaker inter-particle structure).

Particle Breakage Quantification: Breakage Index

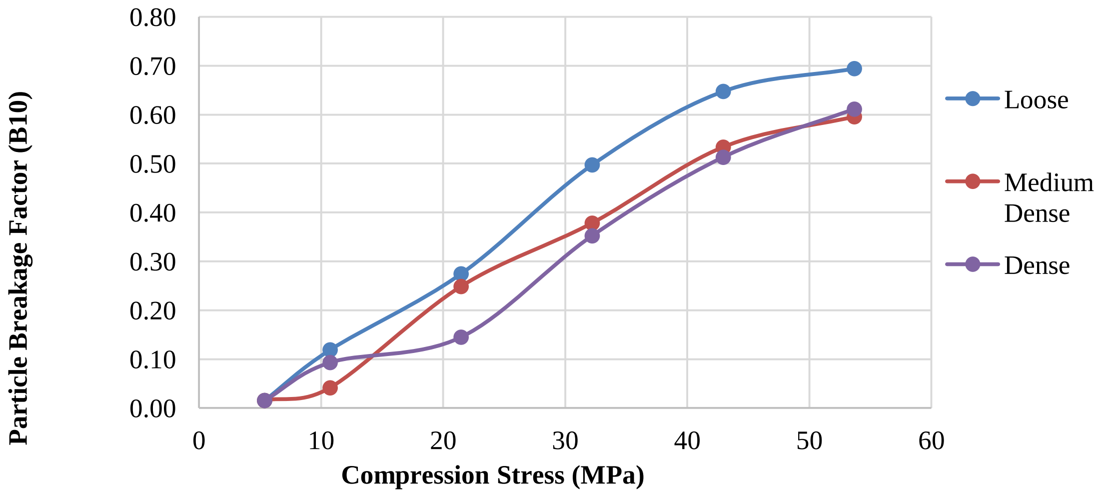

Figure 7: Progress of particle breakage due to compressive stress for three state

From Figure 7 we can find that B_{10} increases with applied compression stress for all density states (Loose, Medium, Dense). Below nearly 10 MPa, breakage is minimal due to primarily particle rearrangement. Loose sand shows highest B_{10} values, especially at moderate stresses due to high void ratio and weak inter-particle contact. Dense sand initially resists crushing due to better interlocking, beyond 45 MPa, curve start to converge indicating that initial density influence reduces as extensive crushing dominates. This finding aligns with the study by (Lade et al., 1997), with an increase in the number of surrounding particles per grain (higher coordination number), the average contact stress decreases, making well-graded soils more resistant to particle breakage than uniform soils. Similarly, as relative density increases, particle breakage decreases due to improved load distribution and reduced stress concentration at individual contacts.

Conclusion

This study experimentally examined the particle crushing behaviour of Melamchi sand under one-dimensional compression using a Compression Testing Machine. Gradation results before and after loading confirmed that particle breakage is strongly stress-dependent and influenced by the initial density of the sand. Increasing vertical stress caused a progressive shift of the PSD curves toward the finer fraction, accompanied by reductions in D_{10} and D_{50} and a steady rise in the breakage index up to around 21.47 MPa. A sharper increase in breakage occurred between approximately 32.21 MPa and 53.69 MPa, indicating that applied stresses surpassed grain strength. Loose samples exhibited the greatest crushing due to higher void spaces and lower interlocking, while dense samples resisted crushing at lower stresses; however, beyond the threshold stress, breakage trends converged irrespective of initial density.

Particle crushing has a significant impact on the long-term performance of engineering structures subjected to high stresses, and should therefore be considered in the design and evaluation of sand used in foundations, embankments, dams and similar earth structures. Future research should focus on crushing behaviour under cyclic or repeated loading, including micro-mechanical examination using SEM or X-ray micro-CT and numerical modelling using DEM to understand breakage mechanisms in greater detail.

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