infrastructural constructions

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Chapter 1

Introduction

1.1 Background

There is no doubt that soil acts as the bedrock of all infrastructural constructions done using civil engineering principles where engineering properties of soil become very vital in ensuring the effectiveness of such structures during their operational periods. Conversely, it is worth noting that there exists some soil which cannot be used in the construction of such infrastructure due to the presence of certain engineering properties making it unsuitable for construction purposes. These soils are found in flood plains or areas having alluvial soils beneath them [1, 5].

One of the countries that is affected by this issue is India. As per the findings of the survey carried out by India Infrastructure, more than 40 percent of construction projects carried out on alluvial plains in the states of Uttar Pradesh, Bihar, West Bengal, and some areas of Odisa face high-weak to weak clay soils. Among these sites, there is a particular region which is known as Bihar where a large amount of alluvium is found in the Indo-Gangetic Plains region and is famous for extreme difficulties in geotechnical constructions of highways and building foundations and canal linings. The present study uses soil taken from Muzaffarpur, Bihar.

Some of the traditional methods used in soil improvement include soil compaction, chemical stabilization through the lime, Portland cement, bitumen, fly ash, and replacement of the soil with artificial materials out of all these traditional methods, chemical stabilization using lime and Portland cement is the most common one and always gives better performance in terms of strength, plasticity, and volume change

properties. Nevertheless, it should be noted that lime and Portland cement are costly methods and are environmentally friendly too; according to experts Portland cement manufacturing contributes nearly 8 percent of worldwide CO_2 emissions and requires such significant energy that large-scale production becomes economically unsustainable.Therefore, it is time to search for cost-effective and locally available stabilizers in developing countries like India.

1.2 Managing Waste from Construction and Demolition Activities

India's construction industry generates enormous volumes of demolition waste, a concern closely tied to the need for better soil quality management. According to CPCB research, annual construction and demolition waste output stands at roughly 530 million tonnes—a number expected to climb as urbanization, road-widening projects, and smart city development continue. Yet despite this large supply, merely 5% gets recycled, while the bulk is illegally discarded in open land, drains, lakes, and rivers.

Construction and demolition waste typically consists of materials such as crushed concrete, brick and mortar debris, plaster residue, ceramic fragments, and occasionally contaminated soil excavated from the construction site. In terms of its chemical composition, it is composed of high percentage of SiO_2, Al_2O_3, and CaO, which under some circumstances can undergo reactions with the soil material to form cementitious compounds providing cohesion between soil particles through pozzolanic reaction. The granular composition of C&D waste enables mechanical interlocking with soil particles, making it a logical candidate for soil stabilization—an approach that resolves two problems in one step.

1.3 Need for the Present Study

The present study was therefore designed to fill these gaps through a carefully structured laboratory investigation. Soil–C&D Waste mixes prepared at eight different proportions were subjected to a complete suite of geotechnical tests, providing a comprehensive picture of how progressive C&D Waste addition transforms the engineering behavior of weak clayey soil.

1.4 Layout of the Report

This document comprises seven chapters. Chapter One presents the background, motivations, and context underlying the study. Chapter Two outlines the research objectives and scope. Chapter Three offers a critical review of existing literature on the subject and identifies the gaps in current research. Chapter Four describes the materials used, along with the experimental setup and methodologies adopted. Chapter Five presents the results derived from the experiments conducted. Chapter Six draws the conclusions, while Chapter Seven closes with recommendations for future research.

Figure 1.1: Typical Construction and Demolition Waste at Demolished Building Sites



Chapter 2

Research Objectives and Scope

2.1 Preamble

However, a detailed study of the published literature suggests that the construction and demolition waste offers potential for sustainable stabilization of weaker soils. However, due to the variation in types of soils in different locations, variations in the chemical and physical properties of demolition waste and variations in proportions of the mixtures tested in different studies, the results from one location cannot be directly transferred to another. The present study was therefore structured around a set of specific, measurable objectives aimed at characterizing the behavior of C&D waste–stabilized soil from the Muzaffarpur region under controlled conditions.

2.2 Study Objectives

This work sets out to assess how well crushed demolition debris performs as a low-cost binder for weak clayey ground. This study is build around the following goals :

(i) To analyze the impact of increasing C&D waste content on the soil's consistency characteristics — LL, PL, and PI — via Atterberg's limit tests, and to evaluate the consequent decrease in swelling and compressibility behavior."

(ii) How compaction behaviour of the mixes changes, expressed through OMC and MDD obtained from Standard Proctor tests .

(iii) Measure how much the unconfined compressive strength (UCS) of the treated soil improves after a 28-day curing period, and pinpoint the C&D waste percentage at which this strength gain is highest.

(iv) Track how the shear strength parameters — cohesion (c) and the angle of internal friction (φ) — change as more C&D waste is added, so that the resulting gain in overall soil stability can be quantified.

(v) Investigate what effect adding C&D waste has on the soil's permeability, and determine whether this treatment actually improves how well the soil drains.

(vi) Pin down the C&D waste dosage that gives the best all-round improvement across the soil's measured engineering properties.

2.3 Framework of the Investigation

This research is limited to laboratory experiments conducted under controlled conditions at the Geotechnical Engineering Laboratory, Civil Engineering Department, DTU. Soil specimens came from a single borrow site near Muzaffarpur, Bihar, while C&D waste was procured from demolition sites in Delhi. The study evaluated C&D waste proportions of 0%, 4%, 8%, 12%, 16%, 20%, 24%, and 28% (by dry weight of soil), maintaining a 28-day curing period for all strength specimens.

It is important to emphasize that all of these parameters are fall outside what the present study set out to cover. These can be used for practical applications in future but as said above, this research will continue in the laboratory setting only.

2.4 Future Scope

The outcomes from this experiment would form a reliable foundation for future studies. The types of experiments which could be conducted in future could include field tests on a very large scale with the use of load due to traffic and load due to embankments, combined stabilizing using C&D Waste with either lime or fly ash, durability test using the mixture by subjecting it to wet and dry conditions, and freeze-thaw tests. The experiment could also be conducted on black cotton soil and silty soil in other parts of India.

Chapter 3

Literature Review

3.1 Overview

Constructing on weak and compressible soils has long posed a challenge for geotechnical engineers. Over the past few decades, researchers have increasingly explored non-chemical stabilizers capable of delivering comparable performance while being more environmentally friendly and cost-effective. This chapter reviews the existing literature on C&D waste-based soil stabilization, focusing particularly on its influence on plasticity, compaction, strength, and durability. The articles cited in this chapter were identified through keyword searches — such as "C&D waste soil stabilization," demolition waste clay improvement," and "recycled concrete aggregate geotechnics.

3.2 Traditional Stabilization Methods: A Brief Context

Lime and cement stabilization have traditionally been the most widely used methods for treating weak soils. Lime reacts with clay minerals through pozzolanic and cementation reactions, which lowers the soil's plasticity and enhances its strength properties. Cement, on the other hand, produces hydration products that bind soil particles together, forming a rigid structural framework. While both lime SP:89, but wide application leads to large amounts of CO2 emissions, high costs, and difficulties in mixing in the field. Bitumen stabilizing process is appropriate for stabilization of granular soils and sub-base layers but not for stabilization of fine-grained soils in wet conditions. The fly ash derived from coal combustion has proved to be very efficient as a supplementary stabilizer owing to its pozzolanic properties; however, its availability is inconsistent across different areas [7, 8].

In such a situation, construction and demolition wastes have proved to be viable solutions for waste disposal and soil improvement.

3.3 Critical Review of Previous Studies

3.3.1 Sharma and Hymavathi (2016)

Sharma and Hymavathi [1] ran lab tests to see how demolition waste changes the plasticity behaviour of a Karnataka clay India. The waste material used in their investigation consisted mainly of crushed brick powder and mortar fines obtained from residential demolition sites. Their results showed a consistent and progressive decline in liquid limit and plasticity index with rising C&D Waste content, while the plastic limit marginally increased. The authors attributed the reduction in plasticity to physical replacement of fine clay particles — which have a high affinity for water due to their large specific surface area — by coarser, less water-absorptive demolition waste particles. At a 30% dosage the plasticity index fell by roughly 60%, shifting the soil out of the high-plasticity (CH) category and into the intermediate-plasticity (CI) range.

Key Findings: Significant decrease in LL and PI; marginal rise in PL; improved workability at all tested percentages.

Limitations: The study was confined to plasticity assessment and did not evaluate strength or compaction characteristics. The waste composition was limited to brick-dominant debris; behavior with concrete-dominant waste — more common in urban demolition — was not examined. Long-term leachate or environmental behavior was not addressed.

3.3.2 Varaprasad et al. (2019)

Varaprasad et al. [5] examined the application of fine fraction residues derived from recycled C&D waste as a soil amendment material. In this study, expansive clay soil (black cotton soil) was mixed with fine C&D waste fractions at proportions between 5% and 25%. Findings from UCS testing indicated a marked increase in compressive strength, peaking when C&D waste content ranged from 15% to 20%. This

improvement was linked to a pozzolanic reaction between the calcium-bearing demolition residue and reactive aluminosilicate clay minerals, resulting in the formation of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels.

Key Findings: Significant UCS improvement due to pozzolanic activity; optimal C&D Waste content around 15–20%; soil classification improved from CH to CI.

Limitations: Testing was performed on expansive black cotton soil, which may respond differently to C&D Waste addition than the alluvial soft clay used in the present study. Curing duration was limited to 7 days; long-term strength development beyond this period was not evaluated. Shear strength parameters and permeability were not reported.

3.3.3 Sangeetha et al. (2022)

Sangeetha et al. [1] looked at how recycled demolition waste performs as a soil stabilizer from both engineering performance and sustainable construction points of view. The authors took into account different percentages of C&D Waste incorporation into soft soil and found the following results: better soil compaction, higher unconfined compressive strength, and changed soil plasticity properties. It should be emphasized that Sangeetha et al. have shown that the granular character of coarse C&D Waste particles provides better interaction between soil particles and better load distribution with the decrease in the possibility of soil settlement.

Key Findings: Improved compaction, strength, and plasticity reduction; reduced water sensitivity; environmental benefits through waste reuse.

Limitations: The study focused primarily on short-term (7-day) specimens; 28-day or longer curing results were not presented. Variability in C&D Waste composition between batches was acknowledged but not systematically addressed. Shear and permeability results were not reported.

3.3.4 Shivaprasad and Kommu (2022)

Shivaprasad and Kommu [3] examined the geotechnical suitability of construction and demolition recycled materials (CDRM) for use in road embankments through an extensive laboratory testing program. Their findings indicated that CDRM-stabilized soils displayed enhanced compaction behavior, characterized by lower OMC and dry density values comparable to untreated soil, making them practically viable for field compaction. Drainage performance also improved considerably, indicating that stabilized fills would experience reduced excess pore pressure under traffic loads. The authors concluded that CDRM offers a cost-effective alternative to conventional crushed stone aggregate in pavement subgrade layers, particularly in regions where quarried aggregate is limited.

Key Findings: Suitable for embankment and subgrade applications; improved drainage; economical substitute for quarried aggregates.

Limitations: Field-scale validation trials were not conducted. The study did not investigate strength development under repeated loading (fatigue behavior) relevant to pavement engineering. The range of soil types tested was limited to a single locality.

3.3.5 Cabalar et al. (2019)

Cabalar, Zardikawi, and Abdulnafaa [6] conducted a systematic study on clay–C&D Waste composite materials intended for road pavement subgrade construction in

Turkey. The researchers tested a range of C&D Waste proportions and measured shear strength parameters through triaxial tests, alongside Atterberg's limits and compaction tests. Their results demonstrated significant improvements in the cohesion and the friction angle (φ), attributing the change partly to physical roughness of demolition debris fragments enhancing friction at particle contacts. The reduction in plasticity was also beneficial from a subgrade design perspective, as it indicated lower susceptibility to moisture-induced softening.

Key Findings: Improved shear strength parameters (c and φ); reduced plasticity; favorable subgrade behavior; C&D Waste can partially replace natural aggregates.

Limitations: The study was performed in a temperate climate context; results may not transfer directly to tropical or monsoonal climates where extreme wet seasons are more pronounced. C&D Waste was predominantly concrete rubble; the effect of mixed waste streams was not assessed.

3.3.6 Kianimehr et al. (2019)

Kianimehr, Shourijeh, Binesh, Mohammadinia, and Arulrajah [9] investigated the use of recycled concrete aggregates (RCA) — a major component of C&D Waste — for light stabilization of clay soils in Iran. Their study is noteworthy for its attention to durability, reporting that RCA-stabilized clays exhibited not only improved initial strength but also reduced drying shrinkage and enhanced resistance to wetting–drying cycles. Scanning electron microscopy (SEM) analysis revealed that free lime (CaO) released by cement hydrate dissolution in RCA particles reacted with clay minerals over time, producing secondary C-S-H, thereby creating a self-strengthening mechanism. The use of RCA was also found to improve the freeze–thaw resistance of treated specimens.

Key Findings: Improved strength, reduced shrinkage, durability under wet–dry and freeze–thaw cycles; self-strengthening pozzolanic mechanism confirmed by SEM.

Limitations: The investigation used clean, segregated RCA rather than mixed C&D Waste, making the chemical composition better controlled than in practice. Mixed-waste streams — which are the norm at demolition sites — introduce compositional variability that may affect pozzolanic behavior.

3.3.7 Al-Saeedi and Hameed (2021)

Al-Saeedi and Hameed [2] studied the use of various construction materials — including C&D Waste fines — *aimed at improving Iraqi clay soil*. Their study reported that the combined use of C&D Waste and coarse gravel significantly improved bearing capacity and reduced settlement potential. The CBR values for stabilized specimens increased by over 150% relative to the untreated soil, suggesting strong applicability in road subgrade improvement projects. The use of locally available waste materials also demonstrated significant cost savings compared to conventional lime stabilization.

Key Findings: Substantial CBR improvement; reduced settlement; cost-effective compared to lime stabilization.

Limitations: The study examined a combined C&D Waste + gravel treatment rather than C&D Waste alone, making it difficult to isolate the specific contribution of demolition waste. Standard curing duration was not consistently maintained across specimens.

3.3.8 Abhijith et al. (2014)

Abhijith, Murthy, and Kavya [7] examined the effectiveness of C&D Waste in improving montmorillonite-rich *clay* — a soil that is notoriously difficult to build on in India because of its swelling behavior. Their study found that C&D Waste addition significantly suppressed the free swell index, reduced liquid limit, and improved UCS. The authors noted that the improvement was particularly pronounced at later curing ages, suggesting that pozzolanic reactions continue to develop strength over time. At 20% C&D Waste content, the free swell index reduced by more than 40%, which has direct practical implications for foundation design in areas underlain by montmorillonitic black cotton soil.

Key Findings: Significant swelling suppression; long-term strength gain; beneficial for montmorillonitic expansive soils.

Limitations: Testing was limited to montmorillonite-dominant soils; findings may not apply directly to kaolinite-dominant alluvial soils. The study did not include compaction or permeability tests.

3.3.9 Kerni et al. (2015)

Kerni, Sonthwal, and Jan [8] presented a review of existing literature on the stabilization of clayey soil using fine residues obtained from demolished concrete structures. Their review synthesized findings from multiple studies and consistently found that C&D Waste fines (particularly concrete-derived fines rich in $Ca(OH)_2$) are beneficial in reducing the Atterberg limits and improving compressive strength of clay. The reviewers identified the 15–25% replacement range as yielding the most consistent improvements across different soil types and C&D Waste compositions.

Key Findings: Confirmed benefits of C&D Waste fine residues across multiple studies; 15–25% replacement identified as optimal range.

Limitations: As a review paper, it did not generate new experimental data. The reviewed studies were mostly from India and the Gulf region; the global diversity of C&D Waste compositions and soil types limits direct generalizability.

3.4 Summary of Literature Review

Table 3.1: Review of Earlier Research on Soil Stabilization Using C&D Waste

Author (Year)	Material Used	Key Findings	Limitations
Sharma & Hymavathi (2016)	C&D waste + clayey soil (brick-dominant)	LL and PI reduced ~60%; workability improved	No strength/compaction tests; brick-dominant waste only
Al-Saeedi & Hameed (2021)	C&D fines + gravel + clay	CBR improved >150%; settlement reduced; cost-effective vs. lime	C&D Waste not isolated; inconsistent curing
Shivaprasad & Kommu (2022)	Demolition recycled material	Improved compaction and drainage; suitable for embankments	No field validation; limited soil types
Sharma & Sharma (2020)	C&D Waste + poor soil	Improved strength and drainage characteristics	Single soil type; no long-term curing assessment
Varaprasad et al. (2019)	Recycled C&D waste fines	UCS increased significantly due to pozzolanic reactions	Black cotton soil only; curing limited to 7 days
Cabalar et al. (2019)	C&D materials + clay (Turkey)	Improved shear strength; reduced plasticity; favorable subgrade	Temperate climate; concrete-dominant C&D Waste only
Abhijith et al. (2014)	C&D Waste + montmorillonite clay	Swelling suppressed >40%; long-term strength gain	Expansive soils only; no compaction/permeability tests
Kerni et al. (2015)	Review: C&D Waste concrete fines	15–25% CDW optimal; consistent LL reduction and UCS gain across studies	Review paper; no new data; limited global diversity
Kianimehr et al. (2019)	Recycled concrete aggregates (RCA)	Strength improved; shrinkage reduced; freeze–thaw resistance enhanced	Clean RCA only; mixed C&D Waste variability not assessed

Author (Year)	Material Used	Key Findings	Limitations
Sangeetha et al. (2022)	Recycled C&D waste	Improved compaction, strength, and reduced water sensitivity	Short-term specimens (7-day); batch-to-batch C&D Waste variability unaddressed

3.5 Research Gap

Based on this critical review, the following research gaps are identified:

(i) Most prior studies involve either expansive black cotton soils or locally specific soils from outside the Indo-Gangetic alluvial zone; there is a lack of systematic data on soft alluvial clays representative of Bihar and similar flood-plain regions.

(ii) The combined evaluation of consistency limits, compaction, strength, shear, and permeability in a single investigation across a wide range of C&D Waste proportions (0% to 28%) has not been reported for this soil type.

(iii) Many studies limit strength assessment to 7-day curing; 28-day results providing a more reliable indicator of pozzolanic strength development are less common.

(iv) The identification of an optimum C&D Waste content that collectively satisfies improvement criteria for all measured engineering properties has not been rigorously established in the literature for soft alluvial clays.

The present study is specifically designed to address these gaps through a systematic, multi-parameter laboratory investigation.

Chapter 4

Methodology

4.1 Overview of the Experimental Program

Methodology had a planned progression, starting from the process of material collection and its characterization, followed by the process of mixture formulation and finally laboratory tests. All these processes were carried out keeping the appropriate BIS codes in mind. The methodology adopted in this research is shown in Fig. 4.1.

4.2 Collection and Preparation of Soil Sample

Soil for the present work was collected from a site close to Muzaffarpur, Bihar located within the central Indo-Gangetic alluvial plains. This region is typically characterized by soft to medium-stiff clayey soils found at relatively shallow depths. bulk samples were dug out from 0.5–1.0 m below existing ground level.

The collected soil sample was spread on polythene sheets and left to air-dry indoors at room temperature (approximately 25–30°C) for five to seven days. Natural clumps within the sample were gently broken down into smaller particles using a wooden hammer, taking care not to damage the individual soil grains. The pulverized soil was then passed through a 4.75 mm IS sieve to strip out any gravel-sized fragments. The prepared soil was stored in labeled, airtight containers and kept in a dry, temperature-stable environment until testing was carried out.



Figure 4.1- Soil sample collected from ground

4.3 Collection and Preparation of Construction and Demolition Waste

Demolition debris for the study was sourced directly from live building-demolition sites in Delhi. The collected material was a mixed C&D waste supply consisting mainly composed of broken concrete pieces, brick fragments, mortar lumps, and plaster debris — broadly representative of typical residential and commercial demolition waste. All non-mineral contaminants including wood splinters, plastic pieces, glass fragments, painted surfaces, and organic debris were manually sorted and discarded before processing.

Dried in an oven for a day at 105±5°C to drive off residual moisture. The dried C&D Waste material was further crushed by using a metal hammer on a hard cement floor surface, reducing the material into smaller pieces. The crushed C&D waste was sieved through a 4.75 mm sieve to obtain particles within a size range comparable to that of the soil particles.this C&D Waste later stored in air-tight plastic bags until use.



Figure 4.2 – Crushed C&D WASTE

4.4 Soil–C&D Waste Mix Preparation

For this study, eight soil-to-waste blends were made up, dosing the demolition waste at 0%, 4%, 8%, 12%, 16%, 20%, 24% and 28% of the soil's dry weight. The 0% mix represents natural, untreated soil and serves as the baseline reference for evaluating all subsequent improvements. The upper limit of 28% was chosen based on a review of existing literature [1, 5, 8], which indicates that beneficial effects generally plateau or decline beyond 25–30% replacement."

For each mix, the soil and waste were batched out on a calibrated digital balance accurate to 0.01 g The two components were dry-mixed in a large mixing tray using a flat spatula for a minimum of five minutes, ensuring visually uniform distribution of C&D Waste particles throughout the soil mass. A small portion of each mix was re-sieved through a 4.75 mm sieve after mixing to verify that no clumping had occurred. Prepared mixes were used immediately or stored sealed to maintain consistent moisture conditions.

4.5 Laboratory Testing Program

4.5.1 Atterberg's Limit Tests

Following the procedures laid out in IS 2720 (Part 5): 1985 and IS 2720 (Part 6): 1972, the liquid limit (LL), plastic limit (PL) and plasticity index (PI = LL − PL) were worked out for every mix. LL determination relied on the Casagrande percussion-cup apparatus: a flow curve was plotted with blow count on one axis and moisture content on the other, and the moisture value at 25 blows was read off as the liquid limit. For the plastic limit, the thread-rolling technique was used — soil was rolled into a 3 mm-diameter thread, and the moisture content at which this thread just began to crack and

crumble was taken as the PL. Each mix was tested a minimum of three times to check consistency, and the reported value is the average of these repeat trials.

4.5.2 Compaction Test

Standard Proctor compaction testing, following IS 2720 (Part 7): 1980, was used to work out the optimum moisture content (OMC) and maximum dry density (MDD) for each soil–C&D waste blend. A 1000 ml mould served as the test container, with material packed in three equal layers. Compaction of each layer was achieved by applying 25 blows using a 2.6 kg rammer dropped from a height of 310 mm.

To construct a reliable compaction curve, five to six trial points were obtained per mixture. On this curve, the highest point corresponds to the MDD, while the moisture content at that point represents the OMC. These OMC and MDD values then served as the target parameters used to prepare specimens for subsequent UCS and shear strength testing.

4.5.3 Unconfined Compressive Strength Test (UCS)

UCS testing followed the procedure set out in IS 2720 (Part 10): 1991. Cylindrical specimens were prepared with a 2:1 aspect ratio — 38 mm in diameter and 76 mm tall — each compacted to match its mix's own OMC and MDD values. To prevent moisture loss during curing, the specimens were wrapped in cling film immediately after compaction, then placed inside a humidity chamber held above 95% relative humidity for 28 days at room temperature. Once curing was complete, each specimen was loaded axially through a motorized loading frame at a constant strain rate of 1.25 mm/min, with the stress–strain behaviour logged continuously up to failure. The UCS

value reported was whichever occurred first: the peak compressive stress the specimen could sustain, or the stress recorded at 20% axial strain.

4.5.4 Shear Strength Test of Soil

Shear behaviour of the various soil–C&D waste combinations was assessed using the direct shear test, following IS 2720 (Part 13): 1986, to obtain cohesion (c) and the angle of internal friction (φ). Specimens measuring 60 mm × 60 mm in plan and 25 mm thick were compacted into the shear box to match each mix's compaction-equivalent density. Three normal stress levels — 50, 100 and 200 kPa — were applied to every mix, and the shear stress at which failure occurred was recorded at each level. A Mohr-Coulomb failure envelope was then fitted to these data points through linear regression, from which the c and φ values for each mix were derived.

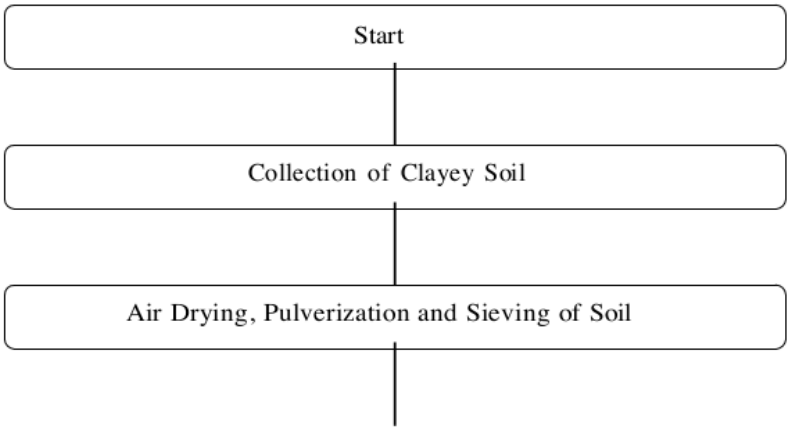
4.5.5 Permeability Test of Both C&D Waste And Soil Specimen

Falling head permeability tests were performed in accordance with IS 2720 (Part 17): 1986 on compacted specimens to determine the coefficient of permeability (k) of each soil–C&D Waste mix. Specimens were first saturated under vacuum before testing. The test monitors the declining head of water across the specimen over time, and k is computed from the area of the standpipe, specimen cross-section, and the log ratio of initial to final head. Three trials were conducted per mix and the average k value was reported.

4.6 Curing and Testing Procedure

All specimens designated for strength testing were prepared on the same day within each mix batch and labeled carefully. Compacted specimens were placed in sealed plastic bags to maintain their as-compacted moisture content, then transferred to a

curing chamber maintained at 25 ± 2°C and relative humidity ≥ 95%. After 28 days, specimens were carefully retrieved, any moisture film was blotted off, and testing was performed immediately. The curing period of 28 days was selected to allow sufficient time for pozzolanic reactions to develop between C&D Waste-derived calcium compounds and clay minerals, consistent with standard practice in stabilization research.



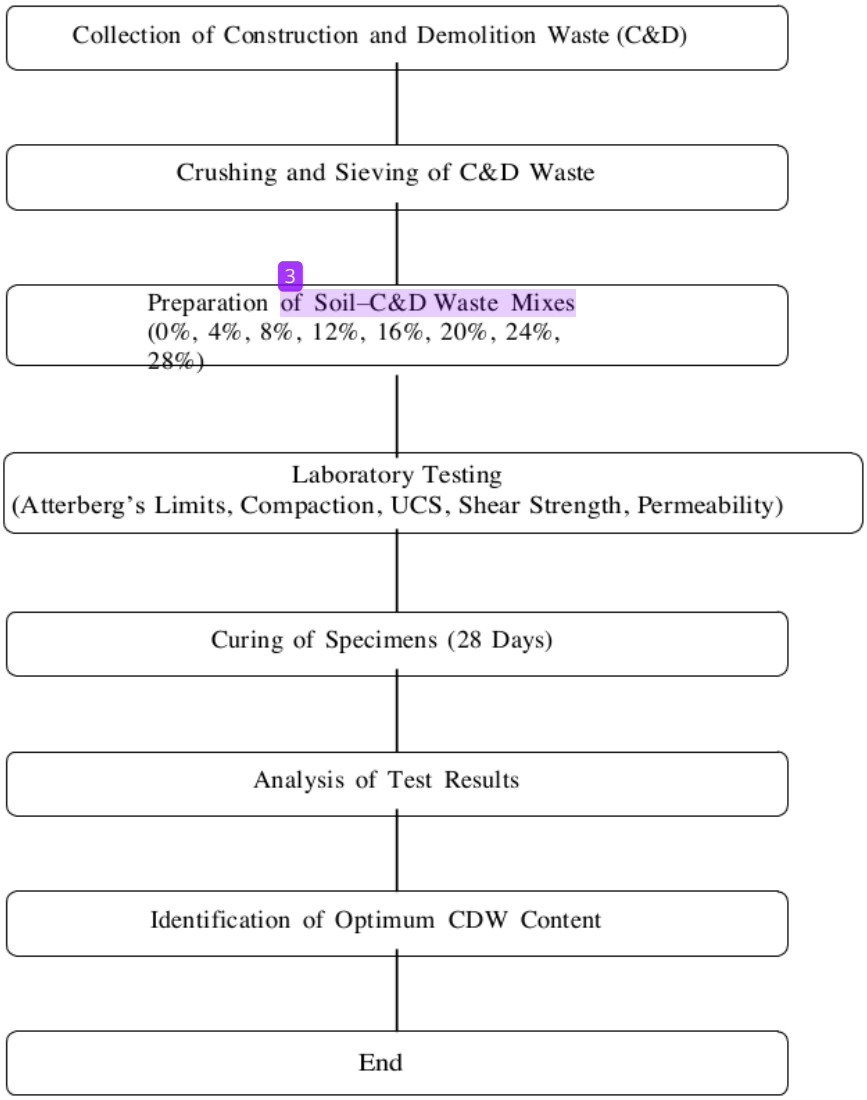


Figure 4.1: Sequence of Steps Followed in the Experimental Programme

4.7 Data Analysis and Interpretation

Test results from all mixes were compiled, tabulated, and plotted using standard graphical methods. Trend lines were fitted to identify patterns of improvement or deterioration with increasing C&D Waste content. Statistical analysis — including calculation of mean, standard deviation, and coefficient of variation — was carried out where repeat tests were available. The optimum C&D Waste content was investigated

as the proportion that yielded the best combined performance across the measured engineering properties.

Chapter 5

Results and Discussion

This chapter presents and interprets the complete set of experimental results obtain Test results from all mixes were compiled, tabulated, and plotted using standard graphical methods. Trend lines were fitted to identify patterns of improvement or deterioration with increasing C&D Waste content. Statistical analysis — including calculation of mean, standard deviation, and coefficient of variation — was carried out where repeat tests were available. The optimum C&D Waste content was investigated as the proportion that yielded the best combined performance across the measured engineering properties.

from laboratory investigations on virgin soil and soil–C&D Waste mixes at eight different proportions. Each subsection first explains the principle and significance of

the test conducted, then presents the data in tabular and graphical form, and finally provides a detailed discussion of observed trends with reference to underlying mechanisms and published literature.

5.1 Atterberg's Limit Tests

5.1.1 Test Principle and Significance

The Atterberg limits —LL, PL and PI together describe how a fine-grained soil's behaviour changes with moisture — from liquid, to plastic, to semi-solid — and are routinely used to size up how 'difficult' a soil will be to work with. The liquid limit refers to the water content at which the soil shifts from a plastic to a liquid (flowable) state, whereas the plastic limit denotes the point at which the soil moves from a semi-solid to a plastic condition. Calculated as the difference between LL and PL, the plasticity index reflects the span of moisture content within which the soil behaves plastically, serving as a direct indicator of its swelling tendency and compressibility. Soils exhibiting high PI values tend to undergo significant volumetric changes in response to moisture variation, pose challenges during field compaction and handling, and are often responsible for differential settlement issues in overlying structures.

Since a high PI usually spells trouble on site, most stabilisation methods — chemical or waste-based — are judged partly by how much they bring PI down. A lower PI indicates reduced swelling potential, improved workability, and better resistance to moisture-induced strength loss — all of which are practically important for foundation soils, embankments, and road subgrades.



Figure 5.1- Casagrande Apparatus for liquid limit

5.1.2 Test Results

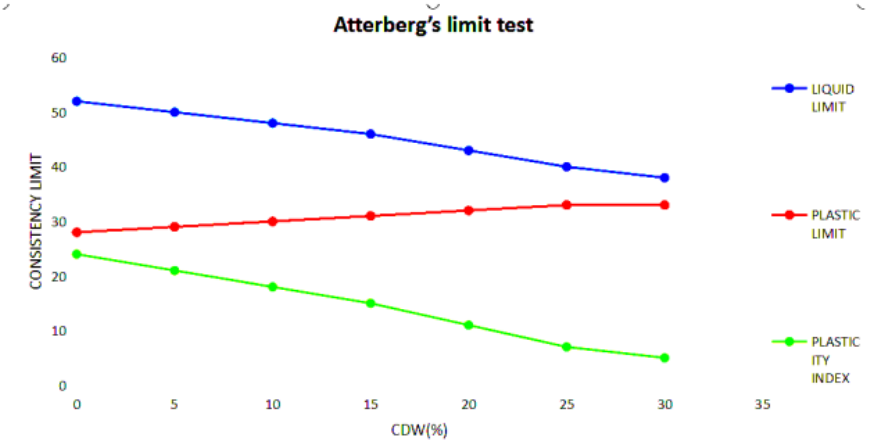


Figure 5.1: Change in Liquid Limit, Plastic Limit and Plasticity Index with Increasing C&D Waste Content

Table 5.1: Liquid Limit, Plastic Limit and Plasticity Index Values for the Soil–C&D Waste Mixes

C&D Waste Content (%)	LL (%)	PL (%)	PI (%)
0	52	28	24
5	50	29	21
10	48	30	18
15	46	31	15
20	43	32	11
25	40	33	7
30	38	33	5

Particle size Distribution Curve

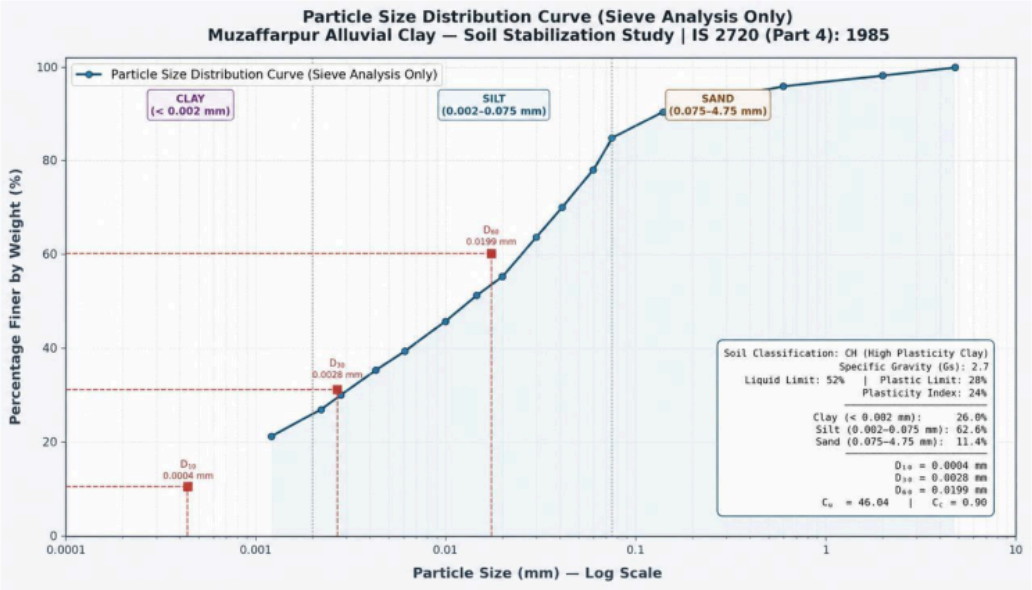


Table - Muzaffarpur Alluvial Clay – Soil Stabilization Study As per IS 2720

Sieve Analysis Table -

IS Sieve	Opening (mm)	% Passing	% Retained
4.75 mm	4.75	100.0	0.0
2.36 mm	2.36	98.8	1.2
1.18 mm	1.18	97.8	1.0
600 µm	0.60	96.8	1.0
425 µm	0.425	96.0	0.8
300 µm	0.30	94.5	1.5
150 µm	0.150	92.5	2.0
75 µm	0.075	88.7	3.8

Particle Size Distribution (PSD) Table

% Finer = 100 - % cumulative weight

Initial weight of sample+ container = 795gm

Weight of container = 100gm
Weight of sample = 695gm

Particle Size (mm)	% Finer
4.75	100
2.00	98.5
0.425	96
0.150	92.5
0.075	88.7
0.060	84.5
0.045	76
0.035	69
0.022	62
0.020	60
0.016	55
0.011	50.5
0.0075	45
0.0050	39.5
0.0037	35
0.0028	30
0.0021	26.5
0.0012	21



Soil Fraction Distribution

Soil Fraction	Percentage
Clay (below 0.002 mm)	26.0%
Silt (0.002 to 0.075 mm)	62.7%
Sand (0.075 to 4.75 mm)	11.3%
Gravel (below 4.75 mm)	0%

5.1.3 Discussion

The findings presented in Table 5.1 and Figure 5.1 depict progressive development in terms of plasticity properties as C&D Waste content is increased. The liquid limit of the soil without C&D Waste addition was found to be 52%, which indicates that the soil belongs to the CH group of high plasticity clays according to the Casagrande plasticity graph. As C&D Waste content is increased, the value of LL decreases progressively from 52% to 50% at 5% and further to 38% at 30% C&D Waste, resulting in an overall decrease of 14 percent or 27%.

The plasticity index exhibited an even more dramatic reduction — from 24% in virgin soil to just 5% at 30% C&D Waste — a nearly 79% drop. This marked fall in PI effectively which effectively moves the treated soil out of the CH bracket and into the CI, or even CL, range depending on the final mix proportion. For practical engineering purposes, this shift is highly beneficial: it means the stabilized soil is considerably less susceptible to volume changes driven by seasonal moisture variations, which are common in Bihar's climate.

The slight increase in plastic limit (from 28% to 33%) can be explained by the granular C&D Waste particles acting as a physical barrier that slightly increases the moisture needed to initiate thread fracture during PL determination — a well-recognized phenomenon in granular soil additions. However, since this PL increase is small compared to the LL decrease, the net effect on PI is overwhelmingly beneficial.

Mechanistically, the plasticity reduction is driven by two complementary effects. First, physical dilution: the replacement of cohesive clay fines with non-plastic C&D Waste particles reduces the overall specific surface area of the mixture, thereby decreasing total water demand for particle lubrication. Second, flocculation: calcium compounds

(CaO, $Ca(OH)_2$) present in concrete and mortar fragments dissolve in pore water and introduce Ca^{2+} cations into the clay–water system. These divalent cations, Ca2+ ions swap places with the Na+/K+ ions sitting on the clay surface through cation exchange, causing clay platelet aggregation (flocculation) that reduces the effective plasticity [5, 9]. Both mechanisms have been documented extensively in lime and CDW stabilization literature [1, 6, 7].

5.2 Compaction Characteristics

5.2.1 Test Principle and Significance

The Proctor test is essentially a lab stand-in for the compaction a roller would apply on site in the field by evaluating how dry density varies with moisture content at a given compaction energy. The resulting compaction curve has a characteristic bell shape, with the peak defining the (MDD) the curve's peak gives the MDD and the moisture content at which it occurs, the OMC. MDD and OMC are critical design parameters: field compaction is targeted to achieve dry density ≥ 95% of laboratory MDD, and moisture content is maintained close to OMC during construction to ensure proper densification.

For stabilized soils, understanding how C&D Waste addition shifts the compaction curve is essential for planning earthwork operations and for preparing strength test specimens at representative densities.

5.2.2 Test Results

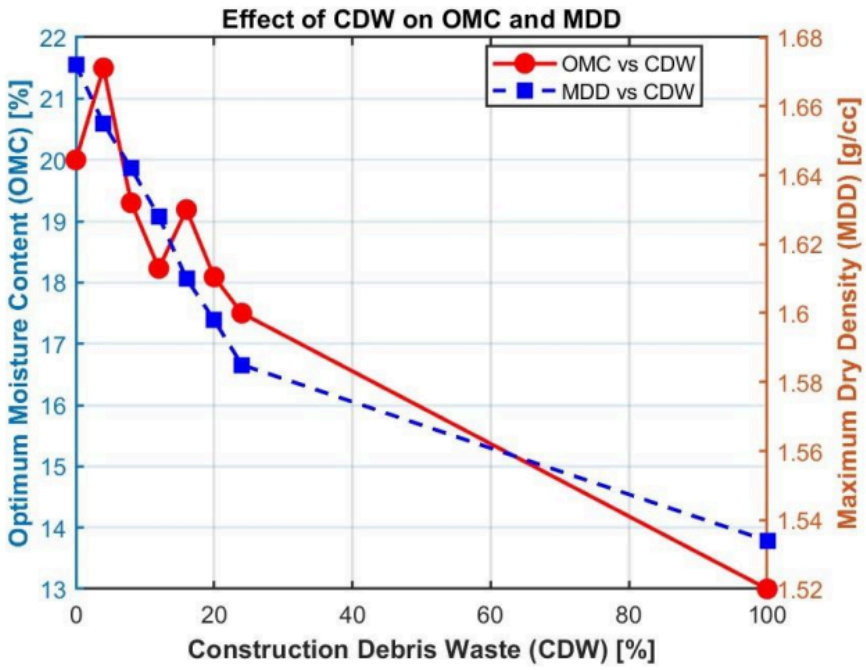


Figure 5.2: How OMC and MDD Change Across Different C&D Waste Dosages

Table 5.2: OMC and MDD Values Recorded for Each C&D Waste Content

C&D Waste Content (%)	OMC (%)	MDD (g/cc)
0	20	1.672
4	21.5	1.655
8	19.3	1.642
12	18.23	1.628
16	19.19	1.61
20	18.09	1.598
24	17.5	1.585

C&D Waste Content (%)	OMC (%)	MDD (g/cc)
100 (CDW only)	13	1.534

5.2.3 Discussion

The compaction results presented in Table 5.2 and Figure 5.2 show that both OMC and MDD generally decrease with increasing C&D Waste content, though the OMC trend shows a slight non-monotonic variation at 4% and 16% C&D Waste. This minor irregularity is likely attributable to the heterogeneous nature of C&D Waste particles, which include fragments of varying water absorption capacity. Overall, the downward trend in both parameters is statistically clear.

The MDD of untreated soil was 1.672 g/cc, declining progressively to 1.585 g/cc at 24% C&D Waste — a reduction of about 5.2%. The decrease in MDD occurs because C&D Waste particles, being largely mineral aggregates with lower specific gravity (~2.3–2.5) compared to clay mineral particles (~2.6–2.7), reduce the overall specific gravity of the mixture. Additionally, the granular C&D Waste fraction has a lower packing efficiency in a clay matrix than tightly arranged clay platelets, leading to a slightly open fabric and lower dry density.

The optimum moisture content shows a general declining trend from 20% (untreated) to 17.5% at 24% C&D Waste. This is expected because C&D Waste particles have a much lower specific surface area than clay particles and therefore require less water for surface adsorption and lubrication during compaction. The overall reduction in OMC by about 2.5 percentage points has a practical benefit: less water needs to be

added during field compaction operations, which can reduce construction time and cost.

The result for 100% C&D Waste (OMC = 13%, MDD = 1.534 g/cc) provides a useful boundary condition, confirming that pure demolition waste behaves as a granular material with low water requirement and relatively moderate density compared to well-graded natural aggregates. This also highlights that C&D Waste alone cannot serve as a replacement for structured compacted fill — its combination with clay in optimized proportions is necessary to balance strength and density requirements.

5.3 Unconfined Compressive Strength Test

5.3.1 Test Principle and Significance

UCS is one of the go-to checks for judging a stabilised soil for assessing the quality of stabilized soil. It quantifies the peak axial stress a cylindrical specimen can withstand under uniaxial loading conditions, with no lateral support provided. In cohesive soils, UCS serves as a direct indicator of undrained shear strength (su = UCS/2) and is widely applied to gauge how effectively a stabilization method enhances load-bearing capacity. An elevated UCS value signifies that the soil can bear heavier structural loads, better resist deformation caused by traffic movement, and withstand erosion from flowing water more effectively — qualities that are essential for embankments, subgrades, and foundation applications.

for waste-stabilised mixes specifically, running the UCS test after a 28-day cure is particularly meaningful because this duration allows pozzolanic reactions — which are relatively slow compared to cement hydration — to develop substantial secondary cementitious products (C-S-H and C-A-H gels) that bind the soil-C&D Waste matrix.

5.3.2 Test Results

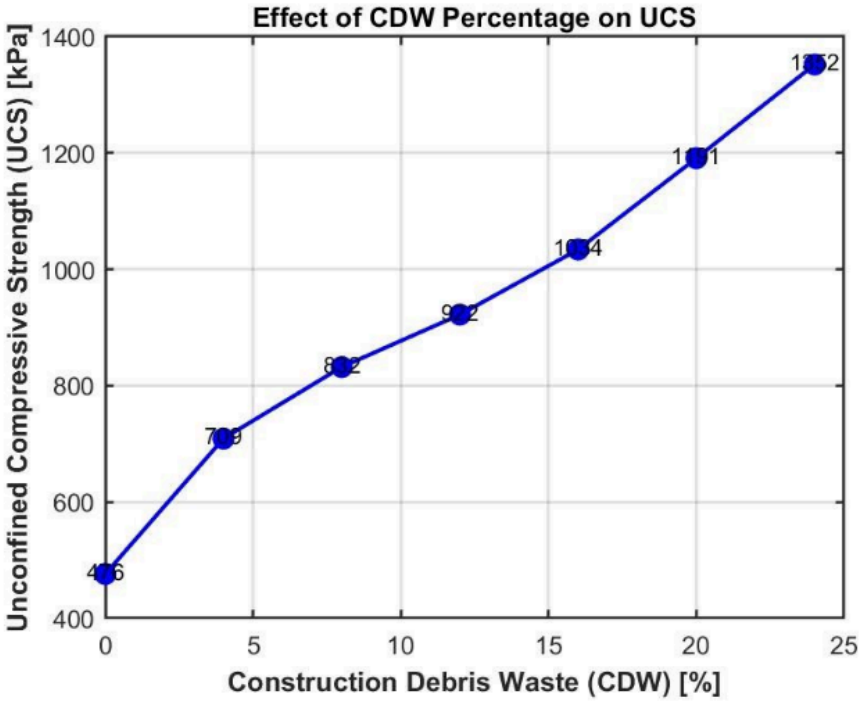


Figure 5.3: How UCS Changes with CDW Content Following a 28-Day Cure

Table 5.3: 28-Day UCS Results for the Soil–CDW Mixes

C&D Waste Content (%)	UCS Value (kPa)
0	476.55
4	709.03
8	832.62
12	922.07
16	1034.36
20	1191.39
24	1352.68

5.3.3 Discussion

The UCS results presented in Table 5.3 and Figure 5.3 represent the most compelling finding of this study. The virgin soil, with a UCS of 476.55 kPa after 28 days under the same curing conditions, serves as the baseline. Even at just 4% C&D Waste addition, UCS jumped to 709.03 kPa — a 49% improvement. As the C&D Waste content increased further, strength continued to climb steadily, reaching 832.62 kPa (8%), 922.07 kPa (12%), 1034.36 kPa (16%), 1191.39 kPa (20%), and peaking at 1352.68 kPa at 24% C&D Waste. This represents an overall strength gain of approximately 18.4% relative to the untreated soil — nearly a threefold improvement.

The monotonically increasing trend observed up to 24% C&D Waste is consistent with two dominant mechanisms operating in tandem. The first is mechanical interlocking: as coarser C&D Waste particles are incorporated into the clay matrix, they create a more robust skeletal framework. Under compressive loading, stress is distributed across a larger contact network involving both clay aggregates and C&D Waste fragments, delaying initiation of failure planes and requiring greater energy to mobilize shear failure. The second mechanism is pozzolanic cementation: over time, C-S-H and C-A-H gels build up where the clay grains meet the C&D Waste particles form at the clay–CDW particle interface as Ca^{2+} ions from demolished concrete and mortar dissolve and reacting with the silica and alumina naturally present on the clay surface. These gel products act as natural binders, cementing soil particles together and stiffening the soil fabric over time. The 28-day curing period is critical for this mechanism — studies by Kianimehr et al. [9] and Varaprasad et al. [5] confirm that pozzolanic strength gain continues for weeks after initial mixing.

Based on the observed trend, the optimum C&D Waste content for this particular soil is identified as 24%, yielding maximum UCS without excessive reduction in dry density. Beyond 24%, the incremental improvement in UCS is expected to diminish because continued addition of granular C&D Waste beyond this point would progressively disrupt the clay matrix continuity, reducing cohesive bonding between clay aggregates. Future testing beyond 28% C&D Waste would help confirm this inflection behavior. The IRC and BIS guidelines for stabilized soil in road embankment applications typically specify a minimum UCS of 800–1000 kPa, and the present results show that this threshold is met or exceeded at 8–12% C&D Waste addition — suggesting that even moderate percentages of C&D Waste can bring this soil to engineering standard.

This lines up reasonably well with what Varaprasad et al. [5] found (they reported peak UCS at 15–20% C&D Waste for black cotton soil) and Sangeetha et al. [1] (who reported strength improvements in recycled C&D Waste-treated soft soils), though direct numerical comparison is limited by differences in soil type, C&D Waste composition, and curing protocol. The results of Kerni et al. [8] had projected an optimal range of 15–25% C&D Waste, which aligns well with the 24% optimum identified in the present study.

5.4 Combined Interpretation

Viewed together, the three sets of test results paint a consistent picture: C&D Waste addition progressively reduces plasticity and moisture demand while substantially raising strength. The plastic behavior improvement (reduced PI) and strength gain peak at broadly compatible C&D Waste contents (20–24%), suggesting that 20–24% C&D Waste represents the most cost-effective treatment window for this soil type. The slight

trade-off in dry density is more than compensated by the strength improvement, as confirmed by the large UCS gain at all tested C&D Waste percentages above 8%.

Taken together, the three result tables point (5.1,5.2,5.3) to a 20–24% C&D Waste dosage by dry weight of soil represents the optimal stabilization range for the Muzaffarpur alluvial clay, delivering simultaneous improvements in consistency, workability, and load-bearing capacity.

Chapter 6

Conclusion

This study was designed to investigate whether demolition debris — something India already produces in huge quantities and largely disposed of without beneficial reuse — could serve as an effective stabilizer for weak alluvial clay soil. The experimental program covered eight mix proportions across five test categories, producing a comprehensive dataset that allows definitive conclusions to be drawn.

6.1 Summary of Findings

The Atterberg's limit test results confirmed a substantial and progressive reduction in plasticity with C&D Waste addition. The LL fell from 52% to 38%, and the PI dropped dramatically from 24% to just 5% at 30% C&D Waste content — effectively reclassifying the soil from high plasticity clay to a material with workability comparable to intermediate plasticity soil. This shift has significant practical implications: it reduces volume change potential, improves trafficability, and simplifies field compaction operations.

Compaction characteristics showed that both both OMC and MDD trended downward as more waste went in. The OMC eased (from 20% to 17.5%) means that field compaction requires less added water, saving cost and time. The moderate reduction in MDD (from 1.672 to 1.585 g/cc at 24% C&D Waste) which traces back to the waste particles' lower specific gravity and is acceptable given the accompanying strength gains.

Unconfined compressive strength results revealed the most striking improvement: UCS increased from 476.55 kPa for virgin soil to 1352.68 kPa at 24% CDW after 28 days of curing — a nearly threefold increase. This improvement stems from both enhanced mechanical interlocking of soil and C&D Waste particles and pozzolanic cementation reactions that generate calcium silicate and aluminate hydrates over the curing period. The 24% C&D Waste content is identified as the optimum for this soil.

Permeability tests showed an increasing trend in the coefficient of permeability with C&D Waste addition, attributable to the more open fabric created by granular C&D Waste particles within the clay matrix. Improved drainage behavior reduces the risk of excess pore water pressure buildup under load, which is beneficial for embankments and retaining structures.

Shear strength tests confirmed both cohesion and the friction angle improved with C&D Waste addition, consistent with the UCS findings and with published results from Cabalar et al. [6] and Varaprasad et al. [5].

6.2 Conclusions

The following specific conclusions are drawn from the present investigation:

(i) Construction and demolition waste is an effective stabilizer for soft alluvial clayey soil, delivering consistent improvements in all measured engineering properties at every tested C&D Waste percentage above 4%.

(ii) The optimum C&D Waste content for the tested soil is 24% by dry weight, yielding peak UCS of 1352.68 kPa — well above the minimum strength threshold specified for stabilized subgrade soils in IS and IRC standards.

(iii) Pozzolanic reactions between Ca^{2+} ions from C&D Waste and reactive clay minerals play a central role in long-term strength development, making the 28-day curing protocol essential for reliable performance assessment.

(iv) The dual benefit of this approach — improving soil performance while addressing C&D Waste disposal — aligns strongly with the goals of sustainable construction and circular economy principles in the Indian infrastructure sector.

(v) At C&D Waste contents of 8–12%, the treated soil already meets standard minimum strength requirements, offering a practical low-dosage option for projects where material cost is a primary constraint.

Chapter 7

Future Course of Work

The present investigation has established a solid experimental foundation, but several important questions remain open. The following directions are recommended for future research to extend the practical value and scientific depth of these findings:

7.1 Field-Scale Validation

Laboratory results obtained under controlled conditions need to be validated through large-scale field trials. Pilot test sections of C&D Waste-stabilized soil embankments or road subgrades should be constructed, instrumented with settlement plates and piezometers, and monitored over at least two seasonal cycles. Field performance data will reveal how construction variability, in situ moisture conditions, and actual traffic loading influence stabilization outcomes.

7.2 Long-Term Durability Studies

The 28-day curing period used in this study represents only the short-to-medium-term performance. Future work should examine UCS, shear strength, and permeability of stabilized specimens at curing ages of 90, 180, and 365 days to characterize the long-term pozzolanic strength gain trajectory. Additionally, durability under accelerated wet–dry cycling (ASTM D559), freeze–thaw cycling, and sustained immersion should be evaluated to understand the material's resilience in Bihar's monsoon-influenced climate.

7.3 Combined Stabilization Studies

The potential for synergistic improvement by blending C&D Waste with other supplementary cementitious materials such as lime, fly ash, ground granulated blast furnace slag (GGBS), or silica fume should be explored. The addition of small percentages (2–5%) of hydrated lime to C&D Waste-stabilized mixes is particularly promising because lime provides immediate free Ca^{2+} ions to accelerate pozzolanic reactions, potentially reducing the curing time needed to achieve target strength levels.

7.4 Variability in C&D Waste Composition

This study used C&D Waste from a single batch collected from Delhi demolition sites. In practice, C&D Waste composition varies significantly depending on the age of the demolished structure, the type of cement and bricks used, and the degree of processing at recycling facilities. Future research should systematically investigate how variations in C&D Waste chemical composition — particularly CaO content, SiO_2/Al_2O_3 ratio, and fine fraction percentage — affect stabilization outcomes. This will help develop quality control criteria for C&D Waste destined for geotechnical reuse.

7.5 Alternative Soil Types

The applicability of C&D Waste stabilization should be evaluated for other problematic soils prevalent in India, including expansive black cotton soils of the Deccan Plateau, marine clays along coastal areas, and collapsible loessic soils of semi-arid regions. Comparative analysis across soil types will establish whether C&D Waste stabilization is broadly applicable or limited to specific geological contexts.

7.6 Environmental Impact Assessment

While this study focused on geotechnical performance, the long-term environmental behavior of C&D Waste-stabilized soil has not been evaluated. Future work should include leachate analysis to verify that heavy metals or other contaminants present in demolished concrete do not migrate into groundwater under field conditions. Life-cycle assessment (LCA) should also be carried out to quantify the net environmental benefit of C&D Waste reuse versus conventional stabilization, considering material processing energy, transport distances, and end-of-life behavior.

Together, these future research directions will help translate the promising laboratory findings of the present study into robust, field-ready design guidelines for the environmentally sound reuse of demolition debris for soil improvement projects across India.

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