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Experimental Investigation Into the Effect of Crushed Tiles Waste on Kaolin Clay Soil

Garima Kumari
PG Student
Department of Civil Engineering
BIT Sindri, Dhanbad, Jharkhand, India

Dr. Maya Rajnarayan Ray
Associate Professor
Department of Civil Engineering
BIT Sindri, Dhanbad, Jharkhand, India

Abstract* – This Soft clay soils present significant geotechnical challenges due to low shear strength, high compressibility, and substantial volume changes. This research presents an experimental investigation into the utilization of crushed waste tiles as a sustainable material for stabilizing kaolin clay soil. A series of laboratory tests were conducted to evaluate the physical, index, compaction, and strength characteristics of untreated kaolin clay and clay blended with varying percentages (0%, 3%, 6%, 9%, 12%, 15%, and 20%) of crushed tile waste. Experimental results revealed that kaolin clay is classified as ML (soil of low plasticity) according to the USCS and A-7-6 according to AASHTO, with a liquid limit of 47.80%, plastic limit of 31.88%, and plasticity index of 15.92%. Incorporating crushed tile waste resulted in a systematic reduction in both Liquid Limit (from 47.80% to 32.60%) and Plasticity Index (from 16.10% to 8.50%), significantly enhancing soil workability. Specific gravity gradually decreased from 2.57 to 2.48 due to the lower apparent specific gravity of crushed tile particles (2.308). Standard Proctor compaction tests demonstrated that the Maximum Dry Density (MDD) increased from 1.360 g/cc (untreated) to a peak value of 1.590 g/cc at 12% crushed tile content, accompanied by a reduction in Optimum Moisture Content (OMC) from 21.50% to 16.30%. Unconfined Compressive Strength (UCS) tests demonstrated an increase from 103.43 kPa for untreated soil to a maximum peak of 168.50 kPa at 12% crushed tile addition (representing a 62.9% strength gain). Beyond 12%, excessive coarse tile particles slightly reduced the dry density and strength. Therefore, 12% crushed tile waste is identified as the optimum dosage for stabilizing kaolin clay soil, providing a dual benefit of soil engineering enhancement and sustainable C&D waste management.

Keywords - Kaolin Clay; Crushed Waste Tiles; Soil Stabilization; Atterberg Limits; Maximum Dry Density; Unconfined Compressive Strength; Sustainable Geotechnics.

I. INTRODUCTION

Soft clay soils represent a widespread geotechnical challenge in civil engineering construction worldwide. Due to their high moisture absorption capacity, high compressibility, low bearing capacity, and low shear strength, untreated clay soils often suffer from excessive settlement and stability failures when subjected to foundation or pavement structural loads. To mitigate these soft soil hazards, traditional soil stabilization techniques have relied heavily on chemical binders such as Ordinary Portland Cement (OPC), hydrated lime, and industrial pozzolans. However, the manufacturing process of traditional OPC generates extensive carbon dioxide emissions (~0.8 to 1.0 ton of CO_2 per ton of cement produced), prompting geotechnical researchers to explore sustainable, low-carbon, and waste-derived alternative materials for ground improvement.

Over the past two decades, extensive research has been devoted to evaluating various industrial by-products, mineral additives, and waste materials for clay soil stabilization. Li and Ding [1] examined the physical and mechanical property improvement of Portland cement by incorporating metakaolin and ultra-fine slag, demonstrating that mineral additives significantly refine matrix microstructure and strength. Kavak and Baykal [2] investigated the long-term behavior of lime-stabilized kaolinite clay over extended curing periods up to 10 years, showing that pozzolanic reactions generate permanent strength gains and major increases in elastic modulus. Saeeda et al. [3] conducted physico-chemical characterizations of lime-stabilized tropical kaolin clay, confirming through FESEM and XRD analysis that strong alkaline conditions promote the formation of calcium aluminum silicate hydrate (CASH) cementitious products. Alrubaye et al. [4] explored soft kaolin clay stabilization utilizing combinations of silica fume and lime, noting substantial enhancements in deviator stress and unconfined shear strength. Abdullah et al. [5] presented an ambient-temperature stabilization method for kaolin clay using fly-ash geopolymer blended with ground granulated blast furnace slag (GGBFS), establishing that GGBFS substitution dramatically accelerates early strength development and durability against wetting-drying cycles. Xu and Yi [6] further confirmed the viability of multi-industrial by-products for soft clay stabilization. More recently, innovative physical and granular column reinforcement strategies have gained prominence: Zaini et al. [7] analyzed soft kaolinitic soil improvement using encapsulated crushed tile columns, proving that granular inclusions improve bearing capacity and accelerate consolidation. Kazmi et al. [8] evaluated the shear strength and consolidation behavior of kaolin clay reinforced with granular columns backfilled with recycled crushed waste glass. Gupta and Kumar [9] performed mechanical and microstructural investigations on soft kaolin clay stabilized by GGBS and dolomite-based geopolymers, demonstrating high strength gains through dense calcium-aluminosilicate hydrate (C-A-S-H) network formation. Furthermore, Zaini et al. [10] utilized bottom ash waste granular columns to enhance the lateral load capacity and shear strength of soft kaolin clay soils.

Despite these advancements, ceramic and tile wastes generated from construction and demolition (C&D) activities represent millions of tons of landfilled waste annually. Waste ceramic tiles are durable, hard, water-resistant, and possess

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high angular friction and physical stability. When crushed into granular sizes, waste tiles can serve as an effective non-cohesive mechanical stabilizer to enhance soil grain packing, reduce plasticity, and increase shear strength. The primary objective of this study is to systematically evaluate the effect of crushed tile waste content (0% to 20%) on the physical properties, Atterberg limits, compaction parameters (MDD and OMC), and Unconfined Compressive Strength (UCS) of soft kaolin clay, identifying the optimal waste replacement ratio for sustainable ground improvement.

II. MATERIAL AND EXPERIMENTAL METHODOLOGY

A. *Material Used*

1) Kaolin Clay: Commercially available pure kaolin clay soil was utilized as the base cohesive soil in this investigation. Kaolin clay is a hydrous aluminum silicate mineral $[Al_2(Si_2O_5)(OH)_4]$ characterized by uniform properties, making it an ideal reference soft clay soil for controlled laboratory evaluation. The baseline index properties of untreated kaolin clay include a specific gravity of 2.57, liquid limit of 47.80%, plastic limit of 31.88%, and plasticity index of 15.92%.

2) Crushed Tile Waste: Broken waste ceramic tiles were collected from local construction and demolition waste sites. The waste tiles were manually cleaned, broken, crushed using a jaw crusher, and sieved to obtain particles passing through standard sieves. The crushed tile waste exhibits a well-graded sand texture (SW under USCS / A-1-a under AASHTO), with an apparent specific gravity of 2.308, liquid limit of 29.73%, and plasticity index of 4.09%.

B. *Experimental Testing Program*

Laboratory testing was conducted in accordance with ASTM and British (BS) standards across seven distinct blend proportions: 0% (control kaolin), 3%, 6%, 9%, 12%, 15%, and 20% crushed tile waste by dry weight of soil. The test series comprised:

- Specific Gravity Test (ASTM D854 / Pycnometer method)
- Grain Size Distribution (BS 1377: Part 5 / Wet Sieve and Hydrometer Analysis)
- Atterberg Limits Tests (ASTM D4318 / Cone Penetrometer Method for Liquid Limit & Plastic Limit)
- Standard Proctor Compaction Test (ASTM D698 / ASTM D4253 to determine MDD and OMC)
- Unconfined Compressive Strength Test (ASTM D2166 on cylindrical specimens strain-controlled at 1 mm/min)

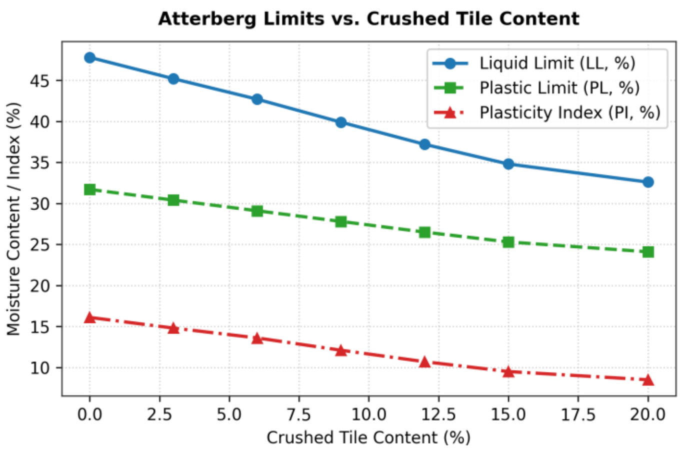
III. RESULTS AND DISCUSSION

A. *Effect on Atterberg Limits and Plasticity*

Atterberg limit tests demonstrate the water-holding capacity and plastic behavior of fine-grained soils. As detailed in Table I and illustrated in Fig. 1, the addition of crushed tile waste causes a significant, consistent reduction in both Liquid Limit (LL) and Plasticity Index (PI). Untreated kaolin clay exhibited an LL of 47.80% and a PI of 16.10%. With increasing crushed tile replacement from 3% to 20%, LL decreased continuously to 32.60% while PI decreased to 8.50%. This marked decline in plasticity occurs because non-plastic granular crushed tile particles replace plastic clay minerals, reducing the overall diffuse double-layer thickness and specific surface area available for water absorption. Lower plasticity directly translates into improved soil workability, easier field compaction, and reduced swell-shrink potential.

TABLE I. ATTERBERG LIMITS OF KAOLIN CLAY WITH VARYING CRUSHED TILE CONTENT

S. No.	Material and Proportion	Liquid Limit	Plastic Limit	Plasticity Index
1.	Kaolin Clay (0%)	47.8	31.7	16.1
2.	Kaolin Crushed Tile (3%)	45.2	30.4	14.8
3.	Kaolin Crushed Tile (6%)	42.7	29.1	13.6
4.	Kaolin Crushed Tile (9%)	39.9	27.8	12.1
5.	Kaolin Crushed Tile (12%)	37.2	26.5	10.7
6.	Kaolin Crushed Tile (15%)	34.8	25.3	9.5
7	Kaolin Crushed Tile (20%)	32.6	24.1	8.5



B. *Particle Size Distribution (Grain Size Analysis)*

Wet sieve analysis was conducted on the base kaolin clay soil. As presented in Table II and plotted in Fig. 2, over 89.70% of kaolin clay particles pass through the 0.075 mm (75 µm) sieve size, confirming a predominant silt and clay fraction. In contrast, the crushed tile waste consists of particles predominantly ranging between 10 mm and 0.063 mm (fine gravel to fine sand sizes), yielding a coefficient of uniformity $C_u = 60$ and curvature $C_c = 2.67$ (classified as well-graded sand

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SW). Mixing well-graded crushed tile waste with fine kaolin clay optimizes the overall particle packing matrix.

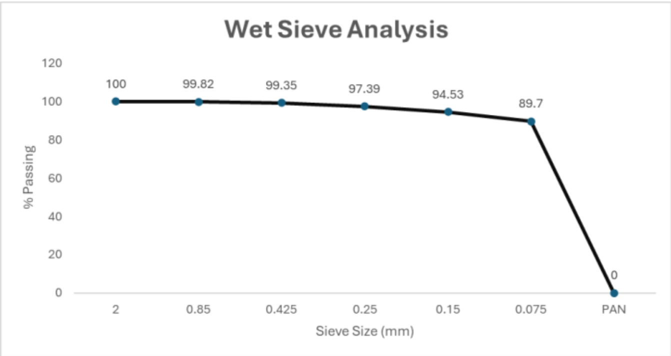

Fig. 2. Particle Size Distribution Curve of Base Kaolin Clay Soil

C. Specific Gravity Analysis

Specific gravity is a fundamental physical property reflecting mineral composition and solid grain weight. The specific gravity of pure kaolin clay was measured as 2.57, whereas crushed tile waste exhibited a lower specific gravity of 2.308 (owing to high porous texture and carbon content). As detailed in Table III, blending crushed tile waste into kaolin clay causes a gradual, systematic reduction in composite specific gravity from 2.57 (0% tile) down to 2.48 (15% tile). This light-weighting effect is beneficial for constructing embankments over soft, low-bearing subgrades where reducing foundation overburden stress is desirable.

TABLE III. SPECIFIC GRAVITY OF KAOLIN CLAY AND CRUSHED TILE BLENDS

S. No.	Material and Proportion	Specific Gravity
1.	Crushed Tile	2.308
2.	Kaolin Clay	2.57
3.	Kaolin Clay + Crushed Tile (3%)	2.55
4.	Kaolin Clay + Crushed Tile (6%)	2.53
5.	Kaolin Clay + Crushed Tile (9%)	2.51
6.	Kaolin Clay + Crushed Tile (12%)	2. 51
7.	Kaolin Clay + Crushed Tile (15%)	2.48

D. Compaction Characteristics (MDD and OMC)

Standard Proctor compaction tests were performed to evaluate the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC). As summarized in Table IV and illustrated in Fig. 3, untreated kaolin clay achieved an MDD of 1.360 g/cc at an OMC of 21.50%. Incorporating crushed tile waste increased MDD progressively to a peak maximum of 1.590 g/cc at 12% crushed tile addition, while OMC decreased systematically to 16.30%. The increase in dry density is attributed to the superior mechanical packing efficiency when dense, angular tile grains occupy interstitial voids within the clay matrix. Simultaneously, lower water absorption by non-plastic ceramic particles reduces the moisture required for maximum compaction. Beyond 12% replacement (i.e., at 15% and 20%), MDD declined to 1.530 g/cc and 1.300 g/cc, respectively. This post-peak drop occurs because excessive coarse tile particles replace heavier clay-tile contact points with porous particle clusters, creating grain repulsion. Thus, 12% crushed tile represents the optimum compaction blend.

TABLE IV. STANDARD PROCTOR COMPACTION RESULTS (MDD AND OMC)

S. No.	Material and Proportion	OMC (%)	MDD (g/cc)
1.	Kaolin Clay	21	1.36
2.	Kaolin Clay + Crushed Tile (3%)	19.8	1.42
3.	Kaolin Clay + Crushed Tile (6%)	18.6	1.48
4.	Kaolin Clay + Crushed Tile (9%)	17.4	1.54
5.	Kaolin Clay + Crushed Tile (12%)	16.3	1.59
6.	Kaolin Clay + Crushed Tile (15%)	15.7	1.57
7.	Kaolin Clay + Crushed Tile (20%)	15	1.53
8	Crushed Tile	10.40	1.30

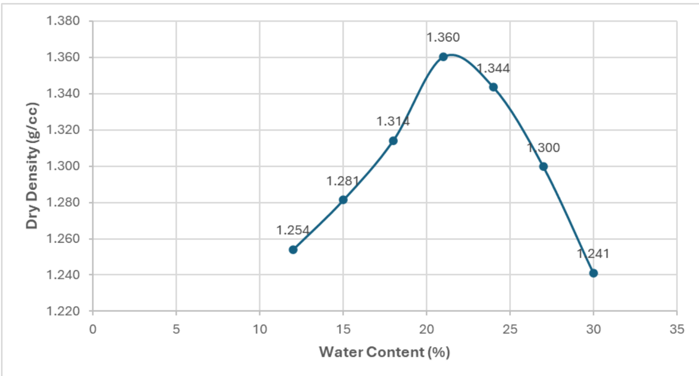

Fig. 3. Variation of Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) with Crushed Tile Content (%)

E. Unconfined Compressive Strength (UCS) Performance

Unconfined Compressive Strength (UCS) is the critical engineering parameter governing soil load-bearing capacity. As detailed in Table V and illustrated in Fig. 4, untreated kaolin clay exhibited an initial UCS of 103.43 kPa (corresponding to an undrained shear strength $C_u = q_u/2 = 51.72$ kPa). The inclusion of crushed tile waste generated a prominent strength gain, increasing UCS to 118.20 kPa at 3%, 134.20 kPa at 6%, 151.80 kPa at 9%, and reaching a maximum peak value of 168.50 kPa at 12% crushed tile addition. This represents an impressive 62.9% net improvement in compressive load-carrying capacity compared to untreated soil. The strength gain is governed by enhanced grain-to-grain frictional interlocking, increased internal friction angle, and tight void filling. Beyond 12% (at 15% and 20%), UCS slightly decreased to 163.20 kPa and 151.40 kPa due to insufficient clay binder matrix to encapsulate coarse tile particles. This confirms 12% crushed tile content as the ultimate optimum formulation for kaolin soil stabilization.

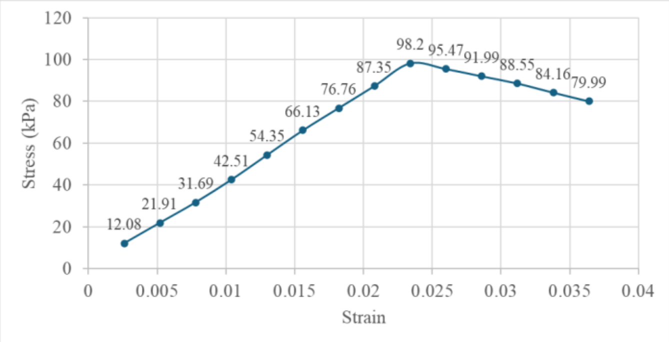

Fig. 4. Unconfined Compressive Strength (UCS)

IV. CONCLUSION

This experimental research investigated the feasibility of utilizing crushed waste tiles to improve the engineering, compaction, and strength characteristics of soft kaolin clay soil. Based on comprehensive laboratory testing, the following major conclusions are drawn:

1) Workability & Plasticity Reduction: Untreated kaolin clay exhibited a Liquid Limit of 47.80% and Plasticity Index of 15.92% (classified as ML / A-7-6). Incorporating crushed tile waste continuously reduced Liquid Limit to 32.60% and Plasticity Index to 8.50% at 20% addition, significantly lowering soil plasticity and swell potential while enhancing field handling and workability.

2) Light-Weighting Effect: Blending crushed tile waste (specific gravity 2.308) reduced composite specific gravity from 2.57 to 2.48, providing a light-weighting effect suitable for construction over weak, low-bearing subgrades.

3) Compaction Enhancement: Standard Proctor tests revealed that Maximum Dry Density (MDD) increased from 1.360 g/cc (untreated) to an optimal peak of 1.590 g/cc at 12% crushed tile content, while Optimum Moisture Content (OMC) decreased from 21.50% to 16.30%.

4) Strength Improvement: Unconfined Compressive Strength (UCS) increased dramatically from 103.43 kPa (untreated clay) to a maximum peak of 168.50 kPa at 12% crushed tile addition, representing a 62.91% increase in compressive load capacity due to optimized grain packing and frictional interlocking.

5) Optimal Dosage: 12% crushed tile waste by dry weight is identified as the optimum replacement level. Higher replacement levels (>12%) result in minor strength reductions due to particle repulsion and lack of fine matrix bonding.

In summary, utilizing 12% crushed tile waste provides an eco-friendly, cost-effective ground improvement solution that significantly enhances soft kaolin clay performance while promoting sustainable recycling of C&D waste.

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