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Black Cotton Soil Stabilisation Using Waste Glass Powder

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Abstract—**Black cotton soil (BCS) is one of the most problematic expansive soils found across central and western India, particularly in Maharashtra, Madhya Pradesh, Gujarat, and Andhra Pradesh. Its dominant montmorillonite clay mineralogy causes severe swelling upon wetting, extreme shrinkage upon drying, low bearing capacity, and high plasticity all of which make it structurally unsafe for civil engineering applications in its natural state. Conventional stabilisers such as Portland cement and hydrated lime, while effective, are energy-intensive, carbon-emitting, and economically demanding at scale. This study investigates waste glass powder (WGP) a silica-rich, pozzolanic industrial by-product as a sustainable alternative stabilising agent for BCS. Glass powder is produced by crushing discarded glass to a fineness below 75 µm, at which particle size its amorphous SiO_2 content (> 70%) reacts with calcium hydroxide to form calcium silicate hydrate (C-S-H) compounds. Soil samples were prepared with WGP additions of 0%, 2%, 4%, 6%, and 8% by dry weight and subjected to five standard IS-code laboratory tests: Specific Gravity (IS 2720-3), Sieve Analysis (IS 2720-4), Atterberg Limits (IS 2720-5), Standard Proctor Compaction (IS 2720-7), and Unconfined Compressive Strength (UCS). Results consistently identify 6% WGP as the optimum dosage: Plasticity Index (PI) decreased from 14.24% to 11.69% (18% reduction), Maximum Dry Density (MDD) increased from 1.87 g/cc to 1.93 g/cc, Optimum Moisture Content (OMC) decreased from 19.60% to 18.40%, and UCS peaked at 230 kN/m² (2.35 kg/cm²) representing a 109% improvement over untreated BCS. These findings confirm that waste glass powder is an effective, eco-friendly, and cost-efficient stabiliser for black cotton soil with strong potential for sustainable road subgrade and foundation applications.**

I. INTRODUCTION

Black cotton soil (BCS), also known as expansive soil or Regur, is a highly problematic geomaterial widely distributed across approximately 20% of India's land area, predominantly spanning Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, and Karnataka. Its defining characteristic is a mineralogical composition dominated by montmorillonite a smectite clay mineral with an extraordinarily high specific surface area (up to 800 m²/g) and a strong affinity for water molecules. This mineralogy drives the soil's infamous volumetric instability: BCS can swell by 20–30% in volume upon wetting during monsoon seasons and shrink dramatically upon desiccation in summer, generating deep shrinkage cracks that can extend to depths of 1–2 metres.

The engineering consequences of BCS are severe and well-documented. Structures founded on untreated BCS routinely experience differential settlement, foundation heave, cracking in walls, floors and pavements, tilting of columns, and in extreme cases, complete structural failure. Road pavements constructed on BCS subgrades suffer from rutting, potholes, longitudinal cracking, and premature failure due to the repeated volumetric cycles. The low shear strength, low California Bearing Ratio (CBR typically < 3%), and high compressibility of BCS make it unsuitable as a foundation or subgrade material without prior treatment.

Soil stabilisation is the primary engineering solution to this problem. Traditional chemical stabilisers ordinary Portland cement (OPC), hydrated lime ($Ca(OH)_2$), and Class-F fly ash have been used for decades with moderate success. Cement and lime increase soil stiffness through cation exchange, flocculation, and pozzolanic cementation; however, both carry significant drawbacks. OPC production emits approximately 0.83–0.90 tonnes of CO_2 per tonne of clinker, contributing roughly 7–8% of global anthropogenic CO_2 emissions. Lime is energy-intensive to produce and raises safety concerns during handling. The global movement toward sustainable and circular-economy construction practices have therefore accelerated research into industrial waste materials as partial or full replacements for conventional stabilisers.

Waste glass powder (WGP) has emerged as one of the most promising candidates. India is among the top-ten glass-producing nations globally, generating an estimated 3 million tonnes of post-consumer glass waste annually, of which approximately 65% is currently landfilled or downcycled [1]. Glass is composed primarily of amorphous silica (SiO_2 > 70%), alumina (Al_2O_3), calcium oxide (CaO), and sodium oxide (Na_2O). When mechanically ground to a particle size below 75 µm, the large specific surface area activates the amorphous SiO_2, enabling a pozzolanic reaction with calcium hydroxide in the presence of moisture to form C-S-H (calcium silicate hydrate) and C-A-H (calcium aluminate hydrate) gels. These gels are the same cementitious compounds responsible for strength in ordinary Portland cement paste, and they effectively bind soil particles, reduce inter-particle spacing, lower plasticity, and improve compressive strength.

This study investigates the influence of WGP on the fundamental geotechnical properties of black cotton soil sourced from Jalgaon, Maharashtra, using WGP dosages of 0%, 2%, 4%, 6%, and 8% by dry weight. Five laboratory tests were performed following Bureau of Indian Standards (BIS) IS-code procedures to systematically characterise changes in particle characteristics, consistency limits, compaction behaviour, and unconfined compressive strength.

Fig. 1: Black Cotton Soil Sample Collected from Jalgaon, Maharashtra (Characteristic Dark Colour and Cloddy Texture)

Fig. 2: Waste Glass Powder (WGP) Prepared from Discarded Glass, sieved through 75 µm IS Sieve

II. GLASS WASTE SCENARIO IN INDIA

India's glass industry spans four primary segments: flat glass, container glass, specialty glass (borosilicate, optical), and glass fibre reinforcement. The All-India Glass Manufacturers Federation (AIGMF) estimated the total glass market value at over INR 250 billion in FY 2023, with projected growth at a Compound Annual Growth Rate (CAGR) of 6–8% through 2030 [2]. The flat glass market is expected to reach 2.58 million metric tonnes (MMT) in 2025, expanding to 3.59 MMT by 2030 [3]. The container glass segment alone has an installed production capacity of approximately 14,000 tonnes per day (TPD), operated by roughly 27 large, medium, and small-scale producers across India [4]. Key manufacturing clusters are located in Firozabad (Uttar Pradesh) which accounts for nearly 70% of unorganised sector glass production and in Gujarat, Maharashtra, Andhra Pradesh, and Karnataka.

Despite this scale of production, India's glass waste recycling infrastructure remains underdeveloped.

Unlike aluminium (recycling rate ~98%) and paper (~80%), glass recycling is economically challenging due to high collection costs, contamination from mixed colours, and the relatively low market price of cullet (crushed recycled glass). As a result, only approximately 35% of India's glass waste is formally recovered and recycled; the remaining ~1.95 MMT is either landfilled or downcycled into low-value road ballast [5]. Glass is non-biodegradable and can persist in the environment for over one million years, making its accumulation in landfills a long-term ecological concern.

The geotechnical application of WGP as a soil stabiliser represents a particularly well-suited circular-economy pathway. The production of WGP from waste glass requires only mechanical crushing and dry milling operations that consume approximately 15–25 kWh per tonne, compared to 3,500–4,500 kWh per tonne for OPC clinker production. Furthermore, WGP-based stabilisation eliminates CO_2 emissions associated with cement manufacture. India has vast tracts of BCS-affected land in its road network and built environment; channelling even a fraction of the country's annual glass waste output into BCS stabilisation would simultaneously resolve two major sustainability challenges.

III. LITERATURE REVIEW

A comprehensive review of published research on WGP as a geotechnical stabiliser is presented below. The literature spans sandy soils, expansive clays, weak subgrades, and black cotton soil, and collectively supports WGP as a versatile and effective stabilising agent.

Keramatikerman, Chegenizadeh & Nikraz [6] (IJEAST, 2020) conducted a detailed experimental investigation on yellow sand stabilised with WGP in combination with Portland cement Type II. WGP was added at 0%, 2%, 4%, and 6% and tested at curing ages of 3, 7, 14, and 28 days. Standard Proctor compaction results showed that WGP increased MDD and decreased OMC, attributed to the void-filling effect of fine glass particles. UCS values improved significantly at 4%–6% WGP due to pozzolanic reactions, and strength consistently increased with curing time. The study concluded WGP is an effective supplementary stabiliser and recycling-beneficial additive.

Niyomukiza et al. [7] (Global NEST Journal, 2023) evaluated the influence of WGP at 3%, 5%, 7%, and 9% on expansive clay soils in Uganda. UCS increased consistently up to 7% WGP and declined at 9%, establishing 7% as the optimum dosage. Swell potential was significantly reduced at all WGP dosages, attributed to pozzolanic C-S-H compound formation that increased bonding and stiffness between clay particles. The study quantified a 40% reduction in free swell at 7% WGP, supporting WGP as a volume-stabilising additive for expansive soils.

Zaid M. & Noor S.A. [8] (International Journal of Geotechnical Research, 2018) investigated WGP at 3%, 5%, 7%, and 9% on an A-7-5/ML classified weak subgrade soil from Iraq. Liquid Limit, Plastic Limit, and Plasticity Index all decreased consistently with increasing WGP content. UCS peaked at 7% WGP and declined at 9%. CBR values showed remarkable improvement increasing 2.5, 3.3, 5.2, and 9.4 times at 3%, 5%, 7%, and 9% WGP respectively confirming WGP as a high-performance subgrade stabiliser.

Pawar & Rasal [9] (IJAEM, 2021) studied crushed waste glass for BCS stabilisation at 0%, 5%, and 10% and conducted Standard Proctor, CBR, and UCS tests. CBR improved significantly at 5–10% crushed glass, attributed to angular particle interlocking within the soil matrix. The study confirmed that even coarser crushed glass particles (not powder) positively affect BCS engineering properties, and endorsed crushed glass as a low-cost, locally sourced stabiliser for expansive subgrade soils in Indian highway construction.

Sai Kumar et al. [10] (IJRPR, 2023) investigated WGP at 0%, 5%, 10%, 15%, and 20% for subgrade soil stabilisation. Optimal results were reported at 10% WGP for their specific soil, with significant improvements in CBR (up to 4.5× the untreated value) and compaction characteristics. The authors highlighted the environmental benefit of diverting glass waste from landfills and recommended WGP as a viable component of green road construction in India.

Michael B. [11] (JEST via DOAJ) studied the synergistic use of WGP and ordinary Portland cement for stabilising high-plasticity clayey soils. The WGP-cement combination outperformed cement alone at equivalent dosages, with the optimum combination identified as 6% WGP + 4% OPC. The study demonstrated that WGP acts as a supplementary cementitious material (SCM), accelerating and augmenting the pozzolanic reaction in the soil-cement system.

The collective findings of the reviewed literature consistently support 6–7% WGP as the optimum dosage range for fine-grained expansive soils, validate multi-parameter improvements across plasticity, compaction, and strength, and confirm the environmental co-benefit of beneficial glass waste utilisation. The present study extends this evidence base to black cotton soil sourced specifically from the Khandesh region of Maharashtra.

IV. MATERIALS AND METHODOLOGY

A. Black Cotton Soil Collection and Characterisation

Black cotton soil for this study was collected from an exposed natural deposit at a construction site in Jalgaon, Maharashtra a region in the Khandeshi belt known for deep, well-developed BCS profiles associated with the Deccan Trap basaltic parent rock. The soil was collected from a depth of 0.3–1.0 m (sub-surface layer, below topsoil) to avoid organic contamination. Representative bulk samples (approximately 50 kg) were transported to the laboratory in sealed bags to preserve in-situ moisture.

In the laboratory, the soil was air-dried under shade for 72 hours to avoid thermal alteration of clay minerals, then pulverised using a rubber mallet to disaggregate clods. The disaggregated soil was passed through a 4.75 mm IS sieve to remove gravel particles and achieve a uniform working fraction. The processed soil was stored in labelled airtight containers at room temperature until testing. Visual characterisation confirmed the characteristic dark grey-to-black colour, fine texture, and slightly waxy (slickenside) surface when moist, consistent with montmorillonite-dominant BCS.

Fig. 3: Fine Texture of Air-Dried Black Cotton Soil After Disaggregation and Sieving (4.75 mm IS Sieve)

B. Waste Glass Powder Preparation

Waste glass materials were sourced from multiple discarded glass streams: clear and coloured glass bottles, broken flat window glass from construction demolition sites, and rejected laboratory glassware. The collected glass was first thoroughly washed with water to remove adhering dirt and dried completely in a ventilated shade area to avoid moisture retention. The dried glass was crushed in a jaw crusher to produce coarse cullet fragments (< 10 mm), followed by further milling in a ball mill. The milled product was sieved through a 75 µm IS sieve (No. 200 ASTM equivalent). Material retained above 75 µm was returned for further milling; the fraction passing 75 µm was collected and stored in sealed airtight bags as the working WGP.

The WGP appeared as a fine, white-to-off-white powder with a glassy lustre. Its primary chemical composition is amorphous silicon dioxide (SiO_2 > 70%), with smaller proportions of calcium oxide (CaO), sodium oxide (Na_2O), magnesium oxide (MgO), and aluminium oxide (Al_2O_3). The high amorphous SiO_2 content, as confirmed in published XRD and XRF studies of similar waste glass [6,7], confirms the pozzolanic activity of the prepared WGP. The specific gravity of the WGP was determined as approximately 2.50, which is lower than the BCS matrix and accounts for the slight reduction in mix specific gravity observed with increasing WGP content.

C. Mix Design and Experimental Programme

Five mix levels were investigated, as detailed in Table I. The WGP content was varied from 0% (untreated control) to 8% by dry weight of soil, in increments of 2%. This range was selected based on prior literature indicating optimum dosages in the 4–8% range for fine-grained expansive soils. For each mix level, a minimum of three replicate specimens were prepared and tested to ensure statistical reliability.

Table I: Mix Identification BCS + WGP

Mix ID	WGP (%)	Description
M0	0%	Control Untreated BCS
M1	2%	BCS + 2% WGP
M2	4%	BCS + 4% WGP
M3	6%	BCS + 6% WGP ★ Optimum
M4	8%	BCS + 8% WGP

D. Sample Preparation Protocol

Step 1: Oven-dry the required quantity of BCS at 105°C for 24 h. Weigh the required mass of WGP corresponding to the target mix percentage.

Step 2: Thoroughly dry-mix BCS and WGP on a clean non-absorptive surface using a trowel for a minimum of 5 minutes until a visually uniform blend is achieved.

Step 3: Gradually add distilled water to the blend while mixing continuously. Adjust to a moisture content slightly below the anticipated OMC. Store in airtight polyethylene bags for 24 h to achieve moisture equilibration throughout the specimen.

Step 4: Compact the moistened mix into the appropriate testing mould (Proctor mould for compaction; cylindrical mould for UCS) using specified compaction energy as per the relevant IS code.

E. Laboratory Tests and Procedures

(i) Specific Gravity Test IS 2720 Part 3 (1980): Specific gravity (Gs) was determined using a 50 mL density bottle and distilled water, with oven-drying at 105–110°C for 24 h. The formula applied: $Gs = (W_2 - W_1) / [(W_2 - W_1) - (W_3 - W_4)]$, where W_1 = empty bottle, W_2 = bottle + dry soil, W_3 = bottle + soil + water, W_4 = bottle + water. Duplicate readings were taken for each mix and averaged.

(ii) Grain Size Analysis (Sieve Analysis) IS 2720 Part 4 (1985): Oven-dried soil (500 g) was passed through a nest of IS sieves ranging from 4.75 mm to 75 µm, mechanically shaken for 15 minutes. The percentage retained and cumulative percentage passing were computed for each sieve size, and the particle-size distribution curve was plotted on semi-logarithmic scale. The analysis confirmed the fine-grained nature of the BCS, with > 85% of particles finer than 75 µm.

(iii) Atterberg Limits IS 2720 Part 5 (1985): Liquid Limit (LL) was determined using the standard Casagrande percussion cup apparatus. Soil paste at varying moisture contents was tested, and the flow curve (moisture content vs. number of blows) was plotted. LL was read as the moisture content corresponding to 25 blows. Plastic Limit (PL) was determined by the thread-rolling method the moisture content at which a 3 mm diameter soil thread just begins to crumble. Plasticity Index (PI) was computed as PI = LL – PL. All tests were performed in triplicate for each mix level.

(iv) Standard Proctor Compaction IS 2720 Part 7 (1980): Compaction tests were performed using the standard Proctor mould (volume = 944 cm^3, diameter = 10.2 cm) with a 2.6 kg rammer falling through a drop height of 310 mm. The soil-WGP mix was compacted in three equal layers, each receiving 25 uniformly distributed blows. At least five moisture-density points were collected for each mix by testing samples at incremental moisture contents spanning the expected OMC. Dry density (γ_d) was plotted against moisture content and the peak of the resulting parabolic curve gave the MDD and corresponding OMC.

(v) Unconfined Compressive Strength (UCS): UCS specimens were prepared as cylindrical samples with a height-to-diameter ratio of 2:1 (diameter 38 mm, height 76 mm), compacted at the OMC and MDD of each respective BCS-WGP mix level. Specimens were wrapped in cling film and cured at ambient temperature (25 ± 2°C) for 7 days. Axial compression was applied using a motorised strain-controlled loading frame at a rate of 1.25 mm/min. The peak deviator stress at failure was recorded as the UCS value. Three specimens per mix were tested and the mean UCS was reported.

V. RESULTS AND DISCUSSION

A. Specific Gravity

The specific gravity of untreated BCS was determined as 2.705, which lies within the expected range of 2.60–2.80 for black cotton soils dominated by montmorillonite and illite clay minerals. As WGP was progressively incorporated into the soil matrix, specific gravity showed a marginal decreasing trend, as presented in Table II and Fig. 8. This behaviour is consistent with the lower Gs of glass powder (~2.50) relative to the soil mineral fraction. The magnitude of the decrease is small (2.705 to 2.709) and has no adverse implications for the engineering performance of the mixed soil.

Table II: Specific Gravity of BCS-WGP Mixtures

WGP (%)	W_1 (g)	W_2 (g)	W_3 (g)	W_4 (g)	Gs
0%	626	929.00	1824.00	1633	2.705
2%	626	945.54	1834.97	1633	2.718
4%	626	962.00	1845.24	1633	2.715
6%	626	978.38	1855.44	1633	2.712
8%	626	994.68	1865.58	1633	2.709

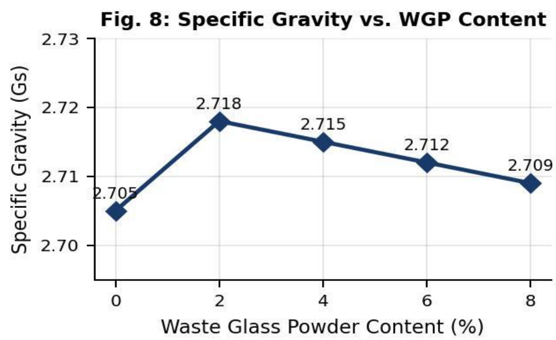

Fig. 8: Specific Gravity (Gs) vs. WGP Content

B. Atterberg Limits

The Atterberg limits are the most critical index properties for characterising expansive soils. The untreated BCS exhibited a Liquid Limit of 32.04%, a Plastic Limit of 17.80%, and a Plasticity Index of 14.24%, classifying it as a medium-to-high plasticity clay (Inorganic Clay of Medium Plasticity CI, per IS 1498). Table III presents the Atterberg limits for all BCS-WGP mixes.

With increasing WGP dosage, the LL showed a general declining trend, reaching a minimum of 30.79% at 6% WGP. The PL increased progressively from 17.80% to 19.40% as WGP increased from 0% to 8%. The resulting PI decreased from 14.24% at 0% WGP to a minimum of 11.69% at 6% WGP a reduction of 2.55 percentage points or 18%. At 8% WGP, the PI marginally increased to 12.15%, indicating a slight reversal of the plasticity-reduction trend. This reversal suggests that beyond 6% WGP, excess glass powder particles begin to occupy the inter-aggregate space in a manner that interferes with the soil fabric rather than enhancing it.

The mechanism underlying PI reduction is the disruption of the diffuse double-layer (DDL) surrounding montmorillonite clay particles. The high SiO_2 content of WGP reacts with Ca^{2+} ions present in the soil pore water to form C-S-H gels that coat clay particle surfaces, neutralise negative surface charges, and reduce the affinity for water molecules. This cation exchange and cementation phenomenon reduces both the Liquid Limit (less water can be absorbed at the soil surface) and the range of plastic behaviour, producing a lower, more stable PI. The 18% reduction in PI at 6% WGP is geotechnically significant it moves the BCS from the CI (medium plasticity) toward the CL (low plasticity) boundary on the Casagrande plasticity chart, indicating meaningfully improved workability and reduced swell potential.

Table III: Atterberg Limits of BCS-WGP Mixtures

WGP (%)	LL (%)	PL (%)	PI (%)	Classification
0% (Control)	32.04	17.80	14.24	CI
2%	31.33	18.20	13.13	CI
4%	31.24	18.70	12.54	CI
6% ★	30.79	19.10	11.69	CI→CL
8%	31.55	19.40	12.15	CI

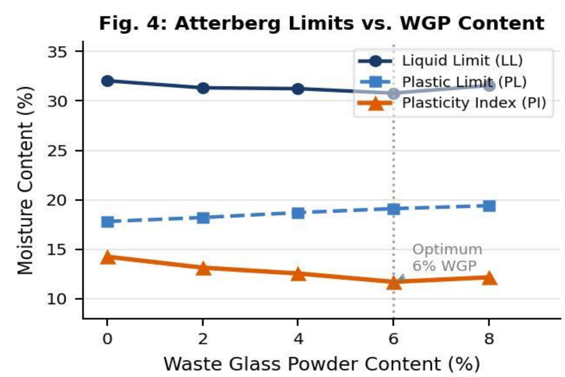

Fig. 4: Atterberg Limits (LL, PL, PI) vs. WGP Content Note PI minimum at 6%

C. Standard Proctor Compaction

The compaction characteristics Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) determine the field compaction targets for soil improvement applications. Table IV presents compaction results for all BCS-WGP mixes.

MDD increased steadily from 1.87 g/cc (untreated) to 1.93 g/cc at 6% WGP, representing a 3.2% improvement in dry unit weight. Concurrently, OMC decreased from 19.60% to 18.40% at 6% WGP. At 8% WGP, MDD slightly decreased to 1.92 g/cc while OMC increased to 18.90%, again confirming 6% as the optimum WGP content for compaction.

The observed behaviour is attributable to two mechanisms operating in concert. First, the fine glass powder particles (predominantly sub-75 µm) act as a granular micro-filler, occupying inter-aggregate voids within the soil matrix and improving the overall particle packing efficiency directly increasing dry density. Second, the pozzolanic reaction between WGP and soil moisture consumes some of the available water to form C-S-H gels, thereby reducing the amount of free water needed to achieve optimum lubrication of the soil fabric, which lowers the OMC. At 8% WGP, excess glass powder begins to dilute the soil matrix and may introduce micro-scale agglomerations that disrupt uniform packing, causing a slight reversal in both MDD and OMC.

Table IV: Compaction Characteristics of BCS-WGP Mixtures

WGP (%)	OMC (%)	MDD (g/cc)	Improvement in MDD
0% (Control)	19.60	1.87	Baseline
2%	19.20	1.89	+1.1%
4%	18.80	1.91	+2.1%
6% ★	18.40	1.93	+3.2%
8%	18.90	1.92	+2.7%

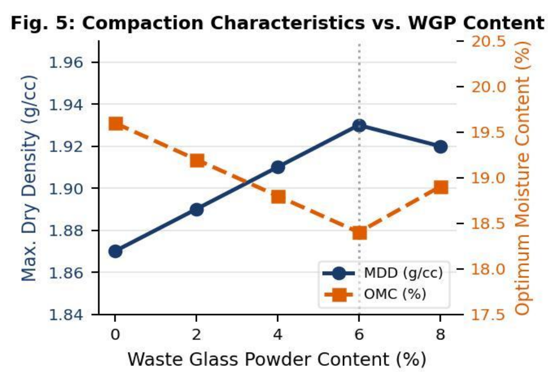

Fig. 5: Compaction Characteristics (MDD and OMC) vs. WGP Content

D. Unconfined Compressive Strength (UCS)

UCS is the most direct measure of soil strength improvement under stabilisation. It represents the maximum axial compressive stress a cylindrical, laterally unconfined soil specimen can sustain. Table V and Fig. 6 present UCS results for all BCS-WGP mixes tested at 7 days curing age.

The untreated BCS exhibited a UCS of only 110 kN/m² (1.12 kg/cm²), reflecting its inherently low cohesive strength. This value is well below the threshold typically required for road subgrade stabilisation (minimum UCS of 200 kN/m² at 7 days curing). With progressive WGP addition, UCS increased consistently: to 145 kN/m² at 2% WGP (+31.8%), 185 kN/m² at 4% WGP (+68.2%), and peaked at 230 kN/m² at 6% WGP (+109.1%). At 8% WGP, UCS declined to 205 kN/m² still a 86.4% improvement over untreated BCS, but below the 6% optimum.

The peak UCS of 230 kN/m² at 6% WGP exceeds the IRC SP:72 and IS 9214 recommended thresholds of 200 kN/m² for chemically stabilised subgrade, confirming that WGP-stabilised BCS at 6% dosage is fit-for-purpose as a road subgrade material. The strength gain is primarily driven by the progressive formation of C-S-H and C-A-H cementitious products through the pozzolanic reaction between the amorphous SiO_2 in WGP and $Ca(OH)_2$ present in the soil pore environment. These reaction products form a three-dimensional gel network within the soil pore space, binding soil particles, reducing pore volume, and increasing inter-particle bonding. The 7-day curing period captured early-age pozzolanic strength; longer curing (28 days) would be expected to yield even higher UCS values, as pozzolanic reactions are characteristically slow-setting compared to OPC hydration.

The decline in UCS at 8% WGP (205 kN/m²) is consistent with observations in the literature for over-dosage of pozzolanic stabilisers. Beyond the optimum, excess glass particles occupy space without forming additional cementitious bonds, act as defect planes within the consolidated soil matrix, and may reduce the homogeneity of the specimen, leading to premature failure under axial loading.

Table V: UCS Results for BCS-WGP Mixtures (7-Day Curing)

WGP (%)	UCS (kN/m²)	UCS (kg/cm²)	% Change vs. Control
0% (Control)	110	1.12	Baseline
2%	145	1.48	+31.8%
4%	185	1.89	+68.2%
6% ★	230	2.35	+109.1%
8%	205	2.09	+86.4%

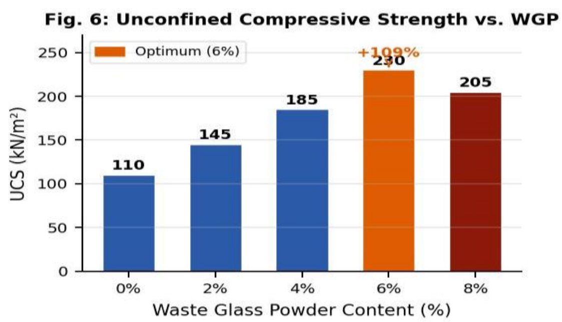

Fig. 6: UCS (kN/m²) vs. WGP Content Bar Chart Showing Peak at 6%

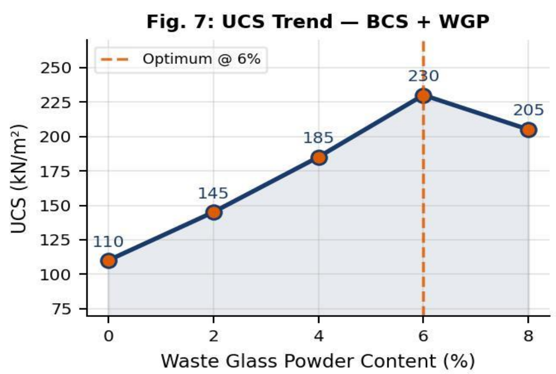

Fig. 7: UCS Trend Line BCS + WGP (0–8%), Optimum Marked at 6%

E. Integrated Discussion and Sustainability Analysis

The multi-parameter test results from all five laboratory investigations converge unambiguously at 6% WGP as the optimum stabiliser dosage for the black cotton soil tested. At this dosage, PI is minimised (11.69%), MDD is maximised (1.93 g/cc), OMC is minimised (18.40%), and UCS is maximised (230 kN/m²). This four-way convergence provides exceptionally robust evidence for the optimum, as it is simultaneously confirmed by index properties (Atterberg limits), compaction behaviour, and mechanical strength.

The pozzolanic reaction mechanism SiO_2 (WGP) + $Ca(OH)_2$ + H_2O → C-S-H + C-A-H provides a unified mechanistic explanation for all observed improvements. The C-S-H/C-A-H gels produced are dense, low-permeability cementitious phases that: (a) coat montmorillonite platelet surfaces and suppress cation exchange/swelling; (b) fill inter-aggregate voids, increasing dry density; (c) bond soil particles into a rigid, cohesive micro-fabric that resists deformation under axial load.

From a sustainability standpoint, the use of WGP for BCS stabilisation offers measurable environmental benefits. The avoided OPC at equivalent performance would generate approximately 0.85–0.90 tonnes of CO_2 per tonne. Based on typical field application rates (30–50 kg WGP per m³ of stabilised subgrade at 6% dosage), a 1-km stretch of road (7 m wide, 300 mm treated depth) would utilise approximately 63 tonnes of WGP, diverting this volume from landfill and displacing the need for the equivalent mass of cement stabiliser. India's road construction programme (Bharat Mala Pariyojana targeting 65,000 km of national highway) presents a significant potential offtake market for WGP-based stabilisation at scale.

VI. CONCLUSION

This study has evaluated waste glass powder (WGP) as a stabilising agent for black cotton soil (BCS) sourced from Jalgaon, Maharashtra, through a rigorous programme of five standard laboratory tests conducted at WGP dosages of 0%, 2%, 4%, 6%, and 8% by dry weight. The following key conclusions are drawn:

1. Natural BCS from Jalgaon exhibited high plasticity (PI = 14.24%, classified CI per IS 1498), low dry density (MDD = 1.87 g/cc), high OMC (19.60%), and very low unconfined compressive strength (UCS = 110 kN/m²), confirming its unsuitability for direct use in construction without treatment.

2. The addition of WGP progressively reduced the Plasticity Index from 14.24% to a minimum of 11.69% at 6% WGP an 18% reduction indicating meaningful suppression of the montmorillonite-driven expansive behaviour and improved soil workability.

3. Maximum Dry Density increased from 1.87 g/cc to 1.93 g/cc (+3.2%), and Optimum Moisture Content decreased from 19.60% to 18.40% at 6% WGP, demonstrating improved compaction efficiency and reduced sensitivity to moisture variation during field compaction.

4. Unconfined Compressive Strength peaked at 230 kN/m² (2.35 kg/cm²) at 6% WGP a 109% improvement over untreated BCS. This value exceeds the IRC SP:72 / IS 9214 recommended thresholds of 200 kN/m² for chemically stabilised subgrade, confirming fitness-for-purpose for road subgrade application.

5. The optimum WGP dosage is conclusively identified as 6% by dry weight of soil, at which all four key performance parameters (PI, MDD, OMC, UCS) simultaneously reach their optimal values a multi-parameter convergence that provides strong and unambiguous evidence for this dosage.

6. Beyond 6%, properties deteriorated at 8% WGP across all measured parameters, confirming that over-dosage of pozzolanic stabilisers disrupts the soil fabric rather than enhancing it. Precise dosage control is essential for practical field implementation.

7. The pozzolanic reaction mechanism whereby amorphous SiO_2 in WGP reacts with Ca $(OH)_2$ in the soil environment to form C-S-H and C-A-H gels provides a unified mechanistic explanation for all observed improvements in plasticity, compaction, and compressive strength.

8. With India generating approximately 3 million tonnes of glass waste annually and recovering only ~35%, the use of WGP in BCS stabilisation offers a technically sound, economically viable, and environmentally beneficial recycling pathway. WGP production requires only crushing and sieving (~20 kWh/tonne), compared to ~4,000 kWh/tonne for OPC manufacture, and eliminates the ~0.85 tonne CO_2/tonne associated with cement production.

9. Waste glass powder is recommended as a viable, sustainable, and eco-friendly alternative to conventional stabilisers (cement, lime) for BCS treatment in road subgrade, embankment, and shallow foundation applications. Future research should investigate: (a) UCS at extended curing ages (14 and 28 days); (b) California Bearing Ratio (CBR) of optimum-WGP mixes; (c) free swell and swell pressure measurements; (d) long-term durability under wetting-drying and freeze-thaw cycles; and (e) large-scale field trials on actual road projects in the Khandesh region of Maharashtra.

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