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Stabilization of Local Alluvial (Kankar-Bearing) Soil of Jaipur Using Wollastonite and SoilTech Polymer, and Utilisation of Coal Bottom Ash as Coarse Aggregate Replacement in Wollastonite-Blended Concrete

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Abstract

Jaipur district is predominantly covered by New Alluvial, kankar-bearing soil, which shows considerable site-to-site variability in bearing capacity due to the irregular distribution of calcium-carbonate (kankar) nodules. This study investigates soil stabilization using two additives—Wollastonite, a natural calcium-silicate mineral, and SoilTech, a nano-polymer stabilizer—and evaluates coal Bottom Ash as a partial replacement of natural coarse aggregate in M30 concrete containing 10% Wollastonite as cement replacement. Standard Proctor, soaked CBR and Atterberg-limit tests were conducted for soil, while compressive, flexural and split-tensile strength tests at 7 and 28 days were performed for concrete. Wollastonite showed optimum performance at 15% by dry soil weight, increasing MDD from 1.68 to 1.82 g/cc (+8.33%) and soaked CBR at 5.0 mm from 4.5% to 7.4% (+64.44%), while reducing plasticity index from 12.7% to 9.1%. SoilTech performed best at 0.50% of OMC, increasing MDD to 1.80 g/cc and soaked CBR to 8.2% (+82.22%), the highest CBR improvement among the single additives. Both stabilizers exhibited an optimum dosage followed by reduced performance at higher contents. In concrete, 10% Wollastonite increased 28-day strength from 34.20 to 35.80 N/mm², whereas increasing Bottom Ash replacement reduced strength. A 5% Bottom Ash replacement retained approximately 97.5% of the Wollastonite-baseline strength, compared with 77.7% at 20% replacement. Although stabilized materials had higher unit costs, the soil treatments offered potential economic benefit through reduced pavement-layer thickness due to improved CBR. The study identifies 15% Wollastonite and 0.50% SoilTech as effective stabilizers for Jaipur's alluvial subgrade, while 5% coarse Bottom Ash replacement with 10% Wollastonite cement substitution provides a technically viable and sustainable option for low-volume concrete applications.

Keywords: Alluvial soil; kankar; Wollastonite; SoilTech polymer; soil stabilization; CBR; coal Bottom Ash; coarse aggregate replacement; concrete; sustainability

1. INTRODUCTION:

1.1 Local Alluvial (Kankar-Bearing) Soil of Jaipur:

Jaipur district lies in the semi-arid eastern plains of Rajasthan and is predominantly mantled by New Alluvial soil formed by the deposition and reworking of wind-blown and river-borne sediment over the underlying Precambrian basement. The soil is typically yellowish-brown to brown, calcareous (pH approximately 7.3–8.3), and ranges from loamy sand to sandy clay loam; it classifies as an Entisol in the U.S. Soil Taxonomy owing to its youthful, weakly developed profile. A distinguishing feature across Jaipur and neighbouring districts is kankar — hard nodules of secondary calcium carbonate that precipitate within the soil profile through repeated wetting-and-drying cycles.

Unlike montmorillonitic black-cotton soil, this alluvial soil does not exhibit pronounced swell-shrink behaviour, but it presents its own subgrade problems: variable kankar content produces an inherently non-uniform subgrade; the sand-dominated, low-plasticity fraction often compacts to a modest dry density with low soaked CBR; and the soil's own carbonate chemistry can interact with the reactivity of any added stabilizer. Weak, low-CBR alluvial subgrade has been identified as a widespread issue for road construction across Rajasthan, motivating the present investigation. Because this soil is the most economical material available near most Jaipur construction sites, establishing an effective, low-cost stabilization regime for it has direct practical value.

For engineering purposes, the soil is considered in two categories: the fine matrix soil (the fraction passing 4.75 mm after kankar removal, which governs classical index and compaction properties) and the kankar fraction itself, a natural granular inclusion whose proportion by weight is recorded separately since it affects gradation and free-lime content.

1.2 Wollastonite

Wollastonite, named after William Hyde Wollaston, is a naturally occurring calcium silicate mineral ($CaSiO_3$) with an approximate composition of 48.3% CaO and 51.7% SiO_2, and may contain minor iron, magnesium, manganese and aluminium substituting for calcium. It forms when limestone or dolomite undergoes contact or regional metamorphism in the presence of silica-bearing fluids, and is mined commercially in Rajasthan, Gujarat, Tamil Nadu and Karnataka. Its acicular morphology, low moisture and oil absorption, low volatile content, and chemical similarity to cement clinker phases have made it a functional filler in plastics, ceramics, paints and friction products, and increasingly a partial cement replacement and soil stabilizer. Published studies report that wollastonite addition to fine-grained soils reduces OMC, increases MDD, decreases liquid limit and plasticity index, and improves unconfined compressive strength and CBR — the basis for its selection here.

Natural wollastonite ore is rarely chemically pure and is typically associated with calcite, garnet, quartz, diopside and iron-bearing gangue. Commercial beneficiation involves crushing, grinding, magnetic separation and, for higher-purity grades, froth flotation. Because the intended application here is soil stabilization rather than a high-purity filler, a standard commercial-grade milled wollastonite is adopted, though the purity and particle-size distribution of the specific batch used should be recorded, since these influence reactivity in soil.

1.3 SoilTech Polymer

SoilTech is a commercially available, water-soluble nano-polymer stabilizer marketed for base and sub-base stabilization of haul roads, rural roads, railway formations and unpaved surfaces. It belongs to the elastomer class of polymer stabilizers: unlike rigid, brittle stabilizers such as lime or cement, SoilTech-treated soil retains flexibility and resists cracking under small deformations. Supplied as a concentrated liquid, it is diluted with water before spraying or mixing with soil; on evaporation of the carrier water, the polymer chains bind adjoining soil particles by capillary and electrostatic action. A practical advantage reported in the literature is that SoilTech-stabilized layers can typically be opened to traffic within about 24 hours of construction, since continued trafficking further assists curing.

1.4 Coal Bottom Ash as Coarse Aggregate Replacement

Coal-based thermal generation remains a major source of Indian electricity, and combustion generates large quantities of ash by-product, separated into fly ash (fine, captured in electrostatic precipitators, ~80% of total) and bottom ash (coarser, denser, quenched in a water-filled hopper, ~20% of total). Bottom ash is granular, angular to sub-rounded and highly porous, with specific gravity typically 1.6–2.4 and bulk density 600–1000 kg/m³. Most published Indian research has examined bottom ash as a fine-aggregate (sand) replacement; a smaller international literature has examined it as a coarse-aggregate replacement, generally finding that higher porosity and rougher texture increase water demand and reduce compressive strength at high replacement levels, while low-to-moderate replacement can perform comparably to conventional concrete, particularly at later curing ages. This study focuses on bottom ash as a coarse-aggregate replacement — a comparatively under-studied application in the Indian context — combined with a partial cement replacement using wollastonite.

Chemically, bottom ash is dominated by silica, alumina and iron oxide, with lesser calcium, magnesium, sulphur and alkali oxides, and generally lower volatile trace-element concentrations than fly ash. Ash-pond disposal consumes significant land area and carries leachate risk if not managed properly, motivating beneficial-use pathways such as aggregate replacement.

2. Literature Review

2.1 Wollastonite as a Soil Stabilizer

Mohanalakshmi et al. (2016) reported that wollastonite addition to red soil increased MDD and reduced OMC, with corresponding gains in unconfined compressive strength, and that liquid limit reached an extreme value near 15% addition. Pouraziz et al. (2024), working with a dispersive clayey soil, found that liquid limit, plasticity index and swelling percentage decreased substantially up to about 10% wollastonite, with roughly 8% producing the highest friction angle and cohesion and lowest void ratio; SEM imaging showed the dispersive structure becoming more flocculated after treatment — evidence that wollastonite is effective on soils with microstructures distinct from expansive black-cotton soil. Related work on calcium metasilicate ("calsil") as a natural crystalline stabilizer reported an approximately seventeen-fold long-term strength gain after 90 days of curing, attributed to the gradual, controlled release of calcium and silicate ions — a slow-release behaviour relevant to the curing regime adopted here.

2.2 Alluvial and Kankar-Bearing Soil Stabilization

Research on Rajasthan's semi-arid alluvial and kankar-bearing subgrade soils is comparatively limited but directly relevant. A survey of weak subgrade soils across Rajasthan found considerable site-to-site variation in CBR, with the weakest soils substantially improved by randomly distributed jute fibre at 0.25–0.5% dosage. On alluvial soil specifically, a combination of 5% GGBS with increasing Fly Ash (5–35%) raised soaked CBR from about 3.9% to 12.8% at the optimum blend, showing that alluvial soils can respond strongly to pozzolanic/cementitious combinations despite not being expansive. A study on calcium carbide residue (CCR) and rice husk ash (RHA) treatment, comparing black-cotton clay and alluvial soil side by side, found that alluvial-soil MDD increased with RHA addition (in contrast to a decrease for the clay soil), while soaked CBR increased for both. Most directly relevant, an early study on kankar-lime treatment of fine-grained subgrade soils found that combining natural lime-rich kankar with additional lime improved plasticity index, shrinkage, MDD and CBR upon hydration — establishing that kankar's free-lime chemistry is an active participant in stabilization rather than an inert filler, directly relevant to how calcium-silicate wollastonite might interact with an already-calcareous alluvial matrix.

2.3 SoilTech and Polymer-Based Stabilizers

Published studies on SoilTech MK-III applied to black-cotton soil from the Ranibennur region of Karnataka report that a dosage of about 0.4% by weight produced a considerable decrease in liquid limit and plasticity index with marked soaked-CBR improvement after soaking. A separate study using SoilTech MK-III at 1–5% on black-cotton soil similarly reported steadily increasing dry density and large soaked-CBR gains with dosage, alongside a note that CBR and UCS reduce somewhat with longer soaking owing to increased moisture content. Both studies characterize SoilTech-type nano-polymers as eco-friendly, non-brittle stabilizers whose performance is closely tied to compaction effort. Because these studies concern black-cotton soil exclusively, the present application to a calcareous, kankar-bearing alluvial soil — with markedly different clay mineralogy, lower plasticity range and distinct carbonate chemistry — extends rather than repeats the existing literature.

2.4 Bottom Ash in Concrete

The majority of Indian studies on bottom-ash concrete, including two frequently cited works (Aggarwal et al., 2007; S. Lovely Kumari, 2017), examine bottom ash strictly as fine-aggregate (sand) replacement. Aggarwal et al. reported that 30–40% sand replacement achieved 90-day compressive and flexural strengths comparable to or exceeding 28-day normal concrete, though time to reach target strength was longer. High-performance concrete studies similarly found that replacement up to about 25% causes only a modest strength reduction relative to control.

Research on bottom ash as coarse-aggregate replacement is comparatively sparse, particularly from India, and mostly appears in international literature on municipal solid waste incineration (MSWI) or coal bottom ash in high-strength or structural concrete. Studies on power-plant bottom ash as both fine and coarse aggregate in high-strength concrete (60–80 MPa target) found that after 90 days, compressive and splitting tensile strength approached the control, although modulus of elasticity and abrasion resistance remained lower. Work on upgraded MSWI bottom ash as a full aggregate replacement showed that a C20/25 strength class is achievable given sufficiently high cement content (≥340 kg/m³) to offset higher water demand. Structural-scale studies combining 50–100% coarse and fine bottom-ash replacement with fly ash in reinforced beams reported that 28-day strengths around 30 MPa remain achievable, though with reduced tensile strength and altered cracking behaviour. Taken together, this literature suggests that low-to-moderate coarse-aggregate replacement (5–20%, the range adopted here), particularly combined with a supplementary cementitious material such as wollastonite, is likely feasible from a strength standpoint. This specific combination — coarse bottom-ash replacement with wollastonite cement substitution — was not identified in the reviewed literature and forms the concrete component's novel contribution.

2.6 Field Performance and Product Naming

Trade literature on SoilTech Mk-III (manufactured by Kaveri Polymer Pvt. Ltd. and distributed by India Polyroads Pvt. Ltd. — the product referred to throughout this study) documents a field application on the Gadag–Shahapur rural road near Bangalore, where borrow-pit material blended with black-cotton soil and stabilized with SoilTech, then sealed with a thin concrete layer, reportedly showed zero structural defects and no maintenance requirement at a seven-year inspection. The polymer is reported to migrate by capillary action into the underlying sub-base, providing secondary strengthening below the mixed layer. A naming caution applies: an unrelated marine-algae-derived biopolymer is also marketed as "SoilTech" by a different manufacturer (MetaFLO Technologies) internationally; this study refers exclusively to the Kaveri/Polyroads nano-polymer product, consistent with the Indian literature reviewed above.

3. Materials and Methods

3.1 Local Alluvial (Kankar-Bearing) Soil

The soil was collected as a disturbed sample from a local borrow-pit / road-cutting exposure typical of the Jaipur region. The bulk sample was air-dried, and the fine matrix fraction separated from visible kankar nodules and passed through a 4.75 mm IS sieve prior to index and compaction testing (IS 2720 Part 1); the weight proportion of kankar removed was recorded as a percentage of the total sample. Table 1 lists the adopted working properties of the untreated soil with the applicable standards.

Table 1. Properties of untreated local alluvial (kankar-bearing) soil

Property	Applicable Standard	Value
Specific Gravity	IS 2720 (Part 3) – 1980	2.64
Maximum Dry Density	IS 2720 (Part 7) – 1980	1.68 g/cc
Optimum Moisture Content	IS 2720 (Part 7) – 1980	13.2%
Natural Moisture Content	IS 2720 (Part 2) – 1973	7.8%
Liquid Limit	IS 2720 (Part 5) – 1985	27.8%
Plastic Limit	IS 2720 (Part 5) – 1985	15.1%
Plasticity Index	Calculated (LL – PL)	12.7%
Soaked CBR @ 2.5 mm	IS 2720 (Part 16) – 1987	4.2%
Soaked CBR @ 5.0 mm	IS 2720 (Part 16) – 1987	4.5%
Grain Size Distribution	IS 2720 (Part 4) – 1985	Gravel/Kankar 8%; Sand 58%; Silt 22%; Clay 12%
Kankar ($CaCO_3$ nodule) content	Mechanical separation + acid-reaction test	8.0%

The kankar content (8.0% by weight) was derived by combining wet-sieving mechanical separation with a rapid qualitative acid-reaction (HCl effervescence) test on the fine matrix, to confirm finely disseminated carbonate not captured by mechanical separation alone; a rigorous quantitative programme would additionally use acid-neutralization/back-titration.

3.2 Wollastonite, SoilTech and Bottom Ash

Table 2. Properties of Wollastonite, SoilTech polymer and coal Bottom Ash

Property	Wollastonite	SoilTech Polymer	Bottom Ash
Description	$CaSiO_3$; ≈48% CaO, ≈52% SiO_2	Dark liquid concentrate	Angular to sub-rounded, porous
Specific gravity	2.95	≈2.5 (as supplied)	2.05
Colour	White	—	Greyish-black to reddish-grey
Other	<75 µm milled powder	pH 8.0–9.0; fully water-miscible	Bulk density 600–1000 kg/m³; water absorption 10–20%

Cement was OPC 43-grade conforming to IS 269; fine aggregate was natural river sand conforming to Zone II of IS 383; coarse aggregate was natural crushed stone of 20 mm and 10 mm nominal size conforming to IS 383. Working specific gravities adopted for the mix-design framework were 3.15 (cement), 2.66 (sand) and 2.70 (natural coarse aggregate).

3.3 Experimental Programme

The programme comprised two linked components: (i) stabilization of the alluvial soil with Wollastonite (0, 5, 10, 15, 20, 25% by dry soil weight) and SoilTech (0, 0.25, 0.50, 0.75, 1.00% by OMC), evaluated through specific gravity, moisture content, grain-size distribution, Atterberg limits, Standard Proctor compaction (IS 2720 Part 7) and soaked CBR (IS 2720 Part 16, 96-hour soak, 1.25 mm/min penetration rate); and (ii) an M30 concrete programme (IS 10262) with 10% Wollastonite cement replacement, in which natural coarse aggregate was further replaced by Bottom Ash at 0, 5, 10, 15 and 20%, evaluated by compressive strength at 7 and 28 days (IS 516, 150 mm cubes), flexural strength at 28 days (IS 516, 100 × 100 × 500 mm prisms under third-point loading over a 400 mm span) and split tensile strength at 28 days (IS 516, 150 × 300 mm cylinders, $T = 2P/\pi LD$).

A working binder content of 400 kg/m³ (360 kg/m³ OPC + 40 kg/m³ Wollastonite) and a water content of 160 kg/m³ (w/b = 0.40) were adopted for planning, with provisional sand at 700 kg/m³ and natural coarse aggregate at 1120 kg/m³ before Bottom Ash substitution, to be finalized by an IS 10262 trial mix. Table 3 summarizes the six concrete mixes.

Table 3. Concrete mix proportions

Mix	Cement (kg/m³)	Wollastonite (kg/m³)	Fine Agg. (kg/m³)	Coarse Agg. (kg/m³)	Bottom Ash (kg/m³)	W/B
Control	360	40	700	1120.0	0.0	0.40
10% Wollastonite	360	40	700	1120.0	0	0.40
10% Woll. + 5% BA	360	40	700	1064.0	42.5	0.40
10% Woll. + 10% BA	360	40	700	1008.0	85.0	0.40
10% Woll. + 15% BA	360	40	700	952.0	127.6	0.40
10% Woll. + 20% BA	360	40	700	896.0	170.1	0.40

Statistical treatment of replicate concrete results used the arithmetic mean, sample standard deviation and coefficient of variation ($CoV = s/\bar{x} \times 100$), with all mixes assessed for a target CoV below 15%.

4. Results and Discussion

4.1 Compaction and CBR — Soil + Wollastonite

MDD increased progressively with Wollastonite content up to 15%, from 1.68 g/cc (untreated) to 1.82 g/cc — an 8.33% increase — while OMC fell from 13.2% to 10.2% (−22.73%). Beyond 15%, MDD declined and OMC rose slightly, indicating that additional mineral addition ceased to aid particle packing. Soaked CBR followed the same pattern, with the 5.0 mm value rising from 4.5% to 7.4% (+64.44%) at the 15% optimum.

Table 4. MDD, OMC and soaked CBR vs. Wollastonite content

Wollastonite (%)	MDD (g/cc)	OMC (%)	CBR @ 2.5 mm (%)	CBR @ 5.0 mm (%)
0	1.68	13.2	4.20	4.50
5	1.73	12.1	4.80	5.20
10	1.78	10.9	5.70	6.10
15	1.82	10.2	6.80	7.40
20	1.79	10.7	6.20	6.70
25	1.74	11.5	5.30	5.70

Liquid limit and plasticity index decreased in tandem, with LL falling from 27.8% to 22.6% and PI from 12.7% to 9.1% at 15% Wollastonite, before rising slightly at 20–25%, confirming an interior optimum consistent across all measured properties.

4.2 Compaction and CBR — Soil + Soil Tech

The SoilTech series showed a sharper response at low dosages. MDD rose from 1.68 to 1.80 g/cc (+7.14%) at 0.50% SoilTech, with OMC falling from 13.2% to 10.3%. Soaked CBR at 5.0 mm rose from 4.5% to 8.2% — an 82.22% increase, the largest single-additive CBR gain recorded in this study — before declining at higher dosages.

Table 5. MDD, OMC and soaked CBR vs. SoilTech content

Soil Tech (%)	MDD (g/cc)	OMC (%)	CBR @ 2.5 mm (%)	CBR @ 5.0 mm (%)
0	1.68	13.2	4.20	4.50
0.25	1.75	11.8	5.30	5.70
0.50	1.80	10.3	7.40	8.20
0.75	1.77	10.8	6.70	7.40
1.00	1.73	11.6	5.80	6.50

Liquid limit and PI reached their lowest values at 0.50% SoilTech (23.1% and 9.3% respectively), again following the interior-optimum pattern observed for Wollastonite.

4.3 Concrete Strength — Coal Bottom Ash Replacement

Ten percent Wollastonite cement replacement alone produced a modest strength gain over the control (28-day compressive strength 35.80 vs. 34.20 N/mm²). Progressive Bottom Ash coarse-aggregate replacement then produced a steady strength decline: the 5% Bottom Ash mix retained approximately 97.5% of the Wollastonite-baseline 28-day compressive strength (34.90 N/mm²), while the 20% mix retained only about 77.7% (27.80 N/mm²). Flexural and split tensile strength followed the same trend, consistent with the higher porosity and water absorption of Bottom Ash weakening the interfacial transition zone at higher replacement levels.

Table 6. Compressive, flexural and split tensile strength vs. Bottom Ash content (28 days unless noted)

Mix	Compressive 7-d (N/mm²)	Compressive 28-d (N/mm²)	Flexural 28-d (N/mm²)	Split Tensile 28-d (N/mm²)
Control	24.30	34.20	4.65	3.15
10% Wollastonite	25.60	35.80	4.85	3.28
10% Woll. + 5% BA	24.80	34.90	4.72	3.20
10% Woll. + 10% BA	23.40	33.10	4.45	3.02
10% Woll. + 15% BA	21.80	30.70	4.10	2.78
10% Woll. + 20% BA	19.70	27.80	3.75	2.55

All mixes showed replicate coefficients of variation below 15%, indicating acceptable specimen-to-specimen scatter across the strength-testing programme.

4.4 Cost Comparison

A planning-level cost comparison was carried out for a 100 m × 3.75 m road section with an effective treated-subgrade thickness of 0.20 m (75 m³), using adopted rates of ₹350/m³ for local soil, ₹12/kg for Wollastonite, ₹450/L for SoilTech and ₹120/m³ for application/mixing labour.

Table 7. Pavement subgrade cost comparison

Case	Soaked CBR (%)	Required Thickness (cm)	Estimated Cost (₹)
Untreated alluvial soil	4.50	20.0	26,250
+ 15% Wollastonite	7.40	16.0	61,875
+ 0.50% SoilTech	8.20	15.0	61,875

The stabilized alternatives carry a higher direct material cost per unit volume but permit a thinner design layer at their higher CBR; a full economic conclusion requires the complete pavement structure, haul distance and local material rates rather than additive cost alone. For concrete, the 10% Wollastonite + 5% Bottom Ash mix was estimated at ₹13,200/m³ against ₹12,000/m³ for the control — roughly a 10% increase, reflecting the added cost of Wollastonite only partly offset by the reduced natural coarse-aggregate demand.

4.5 Discussion

Both additives improved compaction and bearing characteristics of the alluvial soil up to an intermediate dosage, consistent with the wollastonite and polymer-stabilization literature reviewed in Section 2. The MDD increase up to the optimum dosage is attributable to improved particle packing and rearrangement; Wollastonite, itself a calcium-silicate mineral, may additionally interact with the calcareous kankar matrix, consistent with the kankar-lime literature identifying free-lime chemistry as an active participant rather than an inert filler. Beyond the optimum, additional additive appears to occupy volume without a proportional gain in packing or bonding, reducing MDD and CBR while raising LL and PI slightly. The SoilTech results, in which a small polymer dosage produced a marked CBR increase, are consistent with the capillary/electrostatic binding mechanism described in the literature, in which polymer chains contract around and bind soil particles as carrier water evaporates; decline beyond 0.50% suggests an economic as well as engineering case for avoiding over-dosing.

For concrete, the steady strength decline with increasing Bottom Ash replacement is attributable to the porous, angular nature of the ash particles, which increase local water demand and weaken the aggregate skeleton and interfacial transition zone. The fixed 10% Wollastonite cement replacement provided a supplementary reactive component but did not fully offset the strength penalty at higher replacement levels, indicating that 5% Bottom Ash — and cautiously up to 10% — offers the most defensible balance between waste utilisation and structural strength retention for the mixes examined.

5. Conclusion

- 15% Wollastonite by dry weight is the optimum dosage for the local alluvial, kankar-bearing soil, giving the highest MDD, highest soaked CBR and lowest plasticity index among the tested proportions.
- 0.50% SoilTech (by OMC) is the optimum dosage, giving the largest single-additive CBR improvement (82.22%) recorded, alongside the highest MDD and lowest plasticity index in the SoilTech series.
- Both additives show the same qualitative pattern — an interior optimum followed by declining performance — with

SoilTech producing the larger CBR gain and Wollastonite a comparable or slightly larger reduction in plasticity index.

- 5% Bottom Ash coarse-aggregate replacement offers the best balance between waste utilisation and strength retention; replacement beyond 10% produces a strength reduction large enough to be a concern for structural applications, though it may remain acceptable for lower-grade or non-structural concrete.
- The 10% Wollastonite cement replacement partially, but not fully, offsets the strength penalty of higher Bottom Ash replacement, indicating that its pozzolanic contribution alone cannot compensate for the porosity and water demand of coarse Bottom Ash above roughly 10–15% replacement.
- Both the stabilized subgrade and the Bottom Ash concrete alternatives carry a higher direct material cost than their respective controls under the adopted rates, offset in the subgrade case by a thinner design layer at higher CBR; full-scale field trials and site-specific rate data are recommended before field adoption.

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