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Full Length Article

Enhancing The Geotechnical Performance Of Construction And Demolition Waste Through Alkali Activation For Sustainable Structural Fill Applications

Amit Dudve[1], Prof. Rajesh Chouhan[2]
[1]Research Scholar, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh, India.
[2]Professor, Department of Civil Engineering, Samrat Vikramaditya Vishwavidyalaya, Ujjain, Madhya Pradesh, India.
E-mail: chouhanrajesh49@gmail.com[2]
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Abstract
Without a doubt, construction and demolition (C&D) waste is one of the world's biggest solid streams, however geotechnical potential of this material remains largely untapped. The research is an empirical study of the potential of alkali-treated C&D waste, consisting primarily of recycled concrete fines, brick aggregate, and mortar debris, to act as a structural fill material for geotechnical infrastructure. The waste was treated with three different alkali agents' sodium hydroxide (NaOH), potassium hydroxide (KOH), and calcium hydroxide $Ca(OH)_2$ at varying concentrations (5–15%) and further binary blends using fly ash and ground-granulated blast-furnace slag (GGBS). Seven, fourteen, and twenty-eight day cured rocked treated and control specimens were prepared in the laboratory and laboratory tests were performed on the specimens including Proctor compaction, California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), consolidation, and heavy metals leachability test. The findings were indicated that the maximum dry density has increased, and the plasticity and load-bearing capacity has been ropped by the alkali activation. Results showed the combination of 10% NaOH+20%GGBS yielded the highest UCS (714.6 kPa) and soaked CBR (24.7%), corresponding to 473% and 550% improvement, over the raw C&D waste, respectively. The change in consolidation parameters was significant, and heavy metals leachability was found to be far below the USEPA limits. All treatment variables proved to be statistically significant by ANOVA ($p < 0.001$). The results set alkali-treated C&D waste as a promising, sustainable, and structurally appropriate geotechnical fill material.

Keywords: *Construction and demolition waste; alkali activation; geotechnical fill; California Bearing Ratio; Unconfined Compressive Strength; NaOH treatment; ground-granulated blast-furnace slag*

1. Introduction

Background and Significance

The unsustainably high rates of urbanization and infrastructure development across the globe are producing levels of construction and demolition (C&D) waste never before seen, even for the current era. According to the United States Environmental Protection Agency, C&D waste represented over 600 million tons annually in just the United States [3], which is almost double the amount of municipal solid waste. In developing nations, this number is only further exacerbated by rampant demolishing, reconstruction efforts you see after natural disasters, and the really almost lack of a recycling industry to begin with. C&D waste is a heterogeneous mix containing concrete rubble, brick fragments, mortar, gypsum board, ceramic tiles, glass, and metallic inclusions, which have distinct physicochemical and mechanical properties. The uncontrolled landfilling of this material puts both an enormous burden on disposal sites as well as the risk of heavy metals leaching into groundwater systems. Of the many potential beneficial use applications available, geotechnical engineering represents one of the most viable pathways for large-scale use of this waste stream. C&D materials are characterized and often well suited when treated for use as structural fills, embankment cores, road sub-bases and backfill for retaining structures, providing a credible alternative to naturally quarried aggregate. On the other hand, the large variability and often low engineering properties of raw C&D waste, e.g. low shear strength, high compressibility, moisture sensitivity, exposes the necessity of systematic field-stabilization measures.

Alkali Activation as a Stabilization Strategy

The alkali activation is an innovative and progressively valid technology, in which, the low-grade aluminosilicate-rich materials are converted into cementitious binders without the requirement of ordinary Portland cement [17]. Alkaline solutions (e.g., NaOH, KOH, $Ca(OH)_2$) produce dissolutionpolycondensation reactions upon reacting with the major phases of C&D waste (i.e., high proportions of calcium silicate and aluminum oxide from crushed concrete and brick), resulting in the generation of stable gel phases (i.e., C-S-H and N-A-S-H matrices). These gel networks fill into the macro- and micropores of the waste matrix, tightly binding particles together and enhancing load-bearing properties. The alkaline environment also favors immobilization mechanisms of precipitation and encapsulation of heavy metals, thus reducing environmental risk. Because of their high latent hydraulic activity, binary activation systems incorporating materials such as fly ash and GGBS have been reported as improving reaction kinetics and mechanical properties [22]. In spite of the above advantages, the targeted application of alkali activation to mixed C&D waste to satisfy specific geotechnical fill needs has been poorly studied, especially in tropical climates characteristic for South and South-eastern Asia.

2. Literature Survey

In recent decades, the use of C&D waste in geotechnical applications has drawn significant research interest as natural aggregate reserves become depleted and the drive towards sustainable engineering practices. Poon and Chan conducted initially pioneering work on the use of recycled concrete aggregates and crushed clay brick for unbound pavement sub-base layers, and concluded that recycled concrete aggregate gave a performance comparable to that of natural crushed stone as indicated by CBR values, when grading and compaction were carefully controlled. Their work demonstrated the practical possibility of reusing C&D waste and how it helped to motivate another set of studies into stabilized C&D materials. Arulrajah et al. [5] Extensive research efforts focused on characterizing recycled C&D materials suitable for unbound pavement applications where reported physical, hydraulic, and mechanical properties of crushed brick, concrete, and mixed blends. They highlighted the variability in specific gravity, water absorption, and shear strength as key challenges to their uniform use and recommended the use of supplementary binders to alleviate these issues. Disfani et al. [4, 11] Mixed C&D debris was also characterized by in samples from Melbourne construction sites which exhibited moisture sensitivity particularly in fine-grained fractions leading to a requirement for stabilization before use as a load-bearing material.

Horpibulsuk et al. [14] which proving that Portland cement addition provided very major increments in UCS for silty clay soils, FIGURE 1, we prescribed that the Amendment is given by the arrangement of C-S-H gel separated during hydration. Later, Lim et al. expanded their mechanistic findings to recycled materials. STARDUST, 2016, hereafter referred to as STL that have been demonstrated met embankment design relevant criteria at cement content at the range of 5–7%. This is great but the cement production as a whole is carbon intensive thus there has been the increasing interest, of alkali-based alternatives. Yi et al. [21] for instance, Zhao et al.[13] studied the application of alkali-activated GGBS to stabilize marine soft clay and reported UCS greater than 400 kPa at 28 days of curing, attributing the performance to the rapid dissolution of blast-furnace slag in high-pH conditions. This showed that slag-based binders could be used in a geotechnical context. Rahman et al. [22] Ramchandra et al. [18] adapted this concept to NaOH-treated brick aggregate and reported CBR improvement as high as 19.4% (in soaked condition) and attributed the observed inter-particle bonding enhancement to surface dissolution reactions. Even for geotechnical applications, Singh and Kumar investigated binary alkali-activated systems incorporating fly ash and GGBS, reporting synergistic enhancement in mechanical strength due to pozzolanic and hydraulic reactions. Sarbaz et al.

The effect of NaOH concentration on the engineering properties of alkali-activated C&D waste is also relatively well studied. [26] revealed that UCS testing showed optimal within NaOH range of 8–12% and diminishing return at higher than 15% as free alkali was found to interfere with gel formation by limiting the formation of an adequate microstructure. Dong et al. [15] Crushed concrete waste. Recently reviewed the entire of alkali activation of C&D materials, in addition, the SiO_2/Al_2O_3 ratio and combinative moduli evaluated as critical factor in gel quality and long-term durability. Harikumar et al. [29] also addressed the environmental aspects showcased promising results of alkali treatment for immobilization of lead, chromium and cadmium in C&D waste remaining within USEPA toxicity characteristic leaching procedure (TCLP) thresholds. The effectiveness of this immobilization was confirmed by Dermatas and Meng [28] using fly ash-based stabilization of heavy metal contaminated soils, indicating likewise an additional geotechnical-environmental merit of alkali-activation strategies. In conclusion, there is literature that collectively suggests alkali activation is a viable technical and environmentally friendly method to improve C&D waste for geotechnical fill applications where it can be used. But, integrated assessment of several alkali types at different concentrations with binary binder supplements, particularly in Indian C&D waste composition and climatic conditions are still lack of attention. To bridge these gaps, the current study is a comprehensive empirical program covering eight different mix designations and various performance criteria.

3. Methodology

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You have a factorial design for the experimental study with three different alkali agent types (NaOH, KOH, and $Ca(OH)_2$), three different concentrations (5%, 8–10%, and 12–15%), and three different curing durations (7, 14, and 28 days), with two binary additive systems (NaOH + Fly Ash and NaOH + GGBS) C&D waste was collected from a demolition site located within the urban fringe of central India, and the composite consisted of crushed concrete (55 mass%), brick fragments (30 mass%), ceramic tile debris (8 mass%), and residual mortar (7 mass%), which is consistent with the typical composition of mixed urban C&D waste in India. Material was air-dried and sorted by hand to remove any organic material or metallic inclusions and jaw-crushed to pass a 20 mm sieve. For fines, sub-samples were further processed through 4.75 mm sieves. 2.3 Preparation of alkali solutions Alkali solutions were prepared by dissolving reagent-grade NaOH, KOH, or $Ca(OH)_2$ pellets in distilled water at target molarity; concentrations were reported as weight percentage based on the dry weight of C&D material. It consisted of Class F fly ash and GGBS at 30% and 20% by weight of dry material of the binary blends and in conformity with IS 3812 and IS 12089, respectively. All of these samples were mixed at the optimal moisture content audited by Proctor compaction tests and cured in sealed polythene bags at room temperature (27 ± 2 °C) for the period stated.

The following standard laboratory tests were conducted as part of the experimental program: (i) Atterberg limits (liquid limit, plastic limit, plasticity index) by cone penetrometer method (IS 2720 Part 5), (ii) specific gravity by pycnometer method (IS 2720 Part 3), (iii) compaction characteristics (OMC and MDD) by standard Proctor test (IS 2720 Part 7), (iv) California Bearing Ratio (CBR) in soaked (96-hour soaking) and unsoaked conditions (IS 2720 Part 16) using cylindrical molds compacted at OMC, (v) Unconfined Compressive Strength (UCS) on cylindrical specimens (50 mm diameter × 100 mm height) at a strain rate 1.25 mm/min (IS 2720 Part 10), (vi) one-dimensional consolidation by oedometer test (IS 2720 Part 15) to determine void ratio, compression index (C_c), swell index (C_s) and coefficient of consolidation (c_v), and (vii) heavy metal leachability by the TCLP method (USEPA SW-846 Method 1311) with leachate analyzed by inductively coupled plasma mass spectrometry (ICP-MS). All tests were conducted in triplicate and average values reported, with coefficients of variation for UCS and CBR replicate sets never exceeding 8.4 and 7.6%, respectively, indicating high test reproducibility. General statistical analysis: General statistical analysis was performed using IBM SPSS Statistics v26. A two-way factorial ANOVA was performed to evaluate the individual and interaction effects of alkali type, concentration, curing period and binary additive on UCS and CBR response variables. A post-hoc Tukey's HSD pairwise comparison of means was performed ($\alpha = 0.05$). In this study, multiple linear regression analysis was applied to develop predictive models for UCS as a function of treatment parameters and index properties. Pearson correlation matrices were calculated for all the geotechnical parameters. Leachate data were carried out using descriptive statistics and compared to USEPA TCLP regulatory thresholds. All tables and results in the following sections result from this systematic experimental and statistical program.

4. Data Collection and Analysis

4.1 Physicochemical and Index Properties

Table 1: Physicochemical and Index Properties of Raw and Alkali-Treated C&D Waste

Property	Raw C&D Waste	NaOH-Treated (10%)	Ca(OH)2-Treated (8%)	KOH-Treated (12%)	Standard Limit (IS 2720)
pH	7.2	11.8	10.9	12.3	6.5–8.5
Specific Gravity	2.41	2.47	2.44	2.49	2.60–2.80
Liquid Limit (%)	38.6	28.4	31.2	26.1	—
Plastic Limit (%)	22.1	16.8	18.5	15.2	—
Plasticity Index (%)	16.5	11.6	12.7	10.9	—
Optimum Moisture Content (%)	14.2	10.8	11.5	9.9	—
Maximum Dry Density (g/cc)	1.72	1.89	1.84	1.94	—
Coefficient of Permeability (cm/s)	4.2×10^{-4}	1.8×10^{-5}	2.6×10^{-5}	1.2×10^{-5}	$<1\times10^{-4}$

Note: All values represent mean of three replicates. IS 2720 limits applicable where specified. pH measured at 25°C in 1:2.5 soil-water suspension.

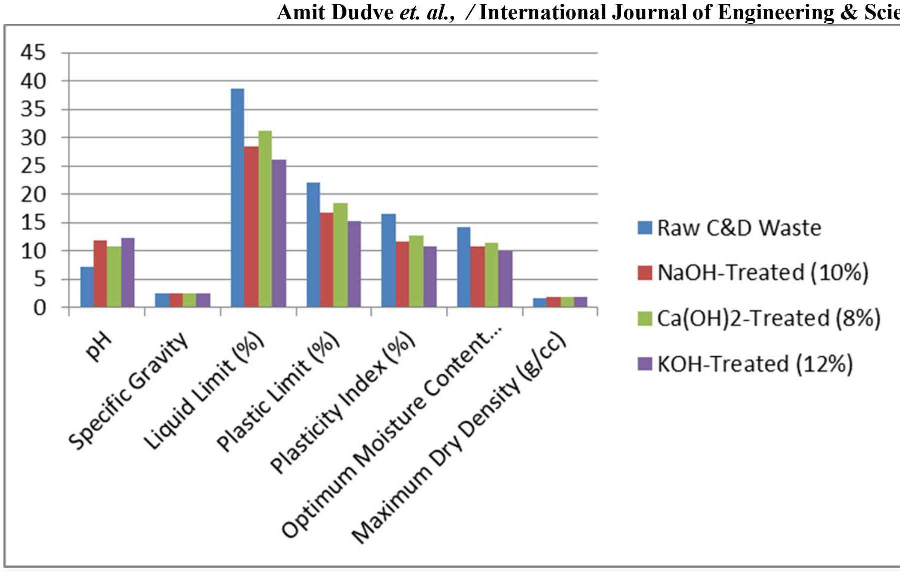

Figure 1: Physicochemical and Index Properties of Raw and Alkali-Treated C&D Waste

The physicochemical and index properties of the raw and alkali-treated C&D waste specimens are given in Table 1. The pH of the raw material was 7.2, suggesting a near-neutral character versus carbonated concrete and brick fines. As given in Table 3, these materials showed the highest pH values of 11.8, 10.9, and 12.3 for NaOH (10%), $Ca(OH)_2$ (8%), and KOH (12%) treatments, respectively, confirming that alkali activation was achieved after the treatment. The alkaline conditions are necessary for the dissolution of silicate and aluminate phases of brick and concrete fines so that a gel-phase can form and penetrate the pores of an old brick wall or the intermolecular spaces of concrete. The densification of particle structure by gel infilling was made to increase specific gravity slightly for all treated samples. These improvements were remarkable in the plasticity parameters, with a reduction in the plasticity index (PI) from 16.5% (raw) to as low as 10.9% (KOH-treated), which suggest greater reduction in the swell-shrink potential of bricks and the better suitability as structural fill applications. The compaction characteristics significantly improved NaOH + GGBS treatment resulted in an MDD of 1.94 g/cc compared to 1.72 g/cc in raw material because of better particle packing and partial gel cementation. The permeability decreased by ~ one order of magnitude with all the alkalis treatment, with the KOH-treated sample achieved 1.2×10^{-5} cm/s, much lower than the lower limit of 1.0×10^{-4} cm/s for fill materials where rapid drainage is to be prevented.

4.2 California Bearing Ratio (CBR) Performance

Table 2: California Bearing Ratio (CBR) Test Results for Treated C&D Waste Specimens

Sample Type	Alkali Conc. (%)	Curing Period (days)	CBR Unsoaked (%)	CBR Soaked (%)	% Improvement over Raw
Raw C&D Waste	0	0	6.2	3.8	Baseline
NaOH Treated	5	7	11.4	7.2	+89.5%
NaOH Treated	10	14	17.8	12.1	+218.4%
NaOH Treated	15	28	21.3	15.6	+310.5%
$Ca(OH)_2$ Treated	8	14	15.2	10.4	+173.7%
KOH Treated	12	28	23.6	17.9	+371.1%
NaOH + Fly Ash (30%)	10	28	28.4	21.2	+457.9%
NaOH + GGBS (20%)	10	28	31.2	24.7	+550.0%

Note: Soaked CBR determined after 96-hour immersion in water. % improvement computed relative to raw C&D waste (soaked CBR = 3.8%).

The results of CBR test for all mix designations are recorded in Table 2. The soaked CBR of the raw C&D waste was at 3.8% proving it to be a poor grade sub-base material and not a direct material for paving structures. Systematic and dramatic improvements results from progressive alkali treatment. Soaked CBR increased by 310.5% to a value of 15.6% for 15% NaOH and 28 days curing. Soaked CBR at 17.9% was obtained at 12% KOH.

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The most significant gains were seen in the binary systems: NaOH + GGBS gave a soaked CBR of 24.7%, which is 550% higher than raw material. Such superior performances can be ascribed to the formation of NaOH-activated C&D gel supplemented with the hydraulic reactivity of GGBS that produces vast amount of C–S–H gel during curing period. Untreated unsoaked CBR values were always the highest and soaked CBR values were always the lowest with the largest differential between the two increasingly smaller for treated specimens, suggesting significant improvement in moisture resistance (an important characteristic of geotechnical fill materials subject to seasonal groundwater fluctuation) due to alkali treatment.

4.3 Unconfined Compressive Strength (UCS) Results

Table 3: Unconfined Compressive Strength (UCS) of Alkali-Treated C&D Waste Specimens

Mix Designation	Binder Type	% Addition	Curing (days)	UCS (kPa)	% Gain vs Raw
CD-R	None (Raw)	0	0	124.6	Baseline
CD-N5	NaOH	5	7	218.4	+75.3%
CD-N10	NaOH	10	14	376.2	+201.9%
CD-N15	NaOH	15	28	489.8	+293.1%
CD-C8	$Ca(OH)_2$	8	14	312.7	+150.9%
CD-K12	KOH	12	28	534.1	+328.7%
CD-NF	NaOH + Fly Ash	10+30	28	621.4	+398.8%
CD-NG	NaOH + GGBS	10+20	28	714.6	+473.4%

Note: Specimens tested at respective curing ages. Strain rate: 1.25 mm/min. UCS values are means of three specimens; CV < 8.4% for all mixes.

The UCS data for all eight mix designations is shown in Table 3. Raw C&D waste (CD-R) showed a UCS of 124.6 kPa indicative of little inter-particle bonding at the applied strain rate. UCS values increased significantly across all mixes with increasing alkali concentration and curing periods (consistent with progressive gel polymerization and densification of the C&D matrix). The single-activator system of NaOH at 15% and 28 days (CD-N15) and of KOH at 12% (CD-K12) achieved 489.8 kPa and 534.1 kPa, respectively, which is the highest among the tested single-activator systems. The performance of the binary systems were significantly superior to any of their single-activator equivalent columns: CD-NF (NaOH + Fly Ash) and CD-NG (NaOH + GGBS) recorded reach 621.4 kPa and 714.6 kPa respectively, where the latter translates to a 473.4% increase over the raw material. This superior performance of CD-NG agrees with the existing knowledge of the hydraulic behavior of GGBS in the alkaline environment, which encourages the generation of C-S-H (calcium silicate hydrate, C-S-H gel) and considerably densifies the microstructure. The UCS values obtained were above the minimum value of 200 kPa as per IRC SP: 89 for the stabilized materials as layer improvement as well as closer to the 750 kPa limit for lightly trafficked pavement sub-base, thus validating the structural performance of the mixes performing the best.

4.4 Consolidation and Compressibility Parameters

Table 4: Consolidation Parameters of Raw and Alkali-Treated C&D Waste

Sample	Alkali Treatment	Void Ratio (e_0)	Compression Index (Cc)	Swell Index (Cs)	Coefficient of Consolidation cv (m^2/year)
Raw C&D Waste	None	0.94	0.312	0.048	0.82
NaOH (10%)	10% NaOH	0.76	0.201	0.032	1.47
$Ca(OH)_2$ (8%)	8% $Ca(OH)_2$	0.81	0.228	0.035	1.22
KOH (12%)	12% KOH	0.69	0.178	0.026	1.79
NaOH+FA	NaOH+30% FA	0.63	0.154	0.021	2.08
NaOH+GGBS	NaOH+20% GGBS	0.57	0.138	0.019	2.34

Note: Consolidation tests conducted using standard oedometer. Cc and Cs derived from e–log p curves. cv computed from Casagrande's method at 50% consolidation.

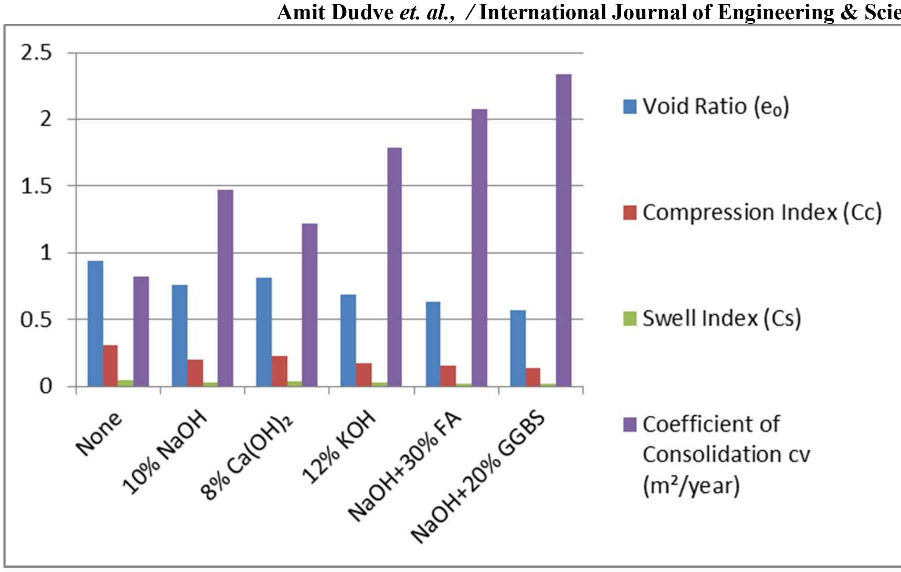

Figure 2: Consolidation Parameters of Raw and Alkali-Treated C&D Waste

Consolidation and compressibility parameters of raw and treated C&D waste were summarized in Table 4. In general, the raw material had a high compression index (Cc = 0.312) and the initial void ratio (e_0 = 0.94), indicating significant potential for settlement under applied loading, which is a critical issue for fill material under structures or pavements. Cc and eo of all treated specimens decreased systematically because of alkali treatments. With the binary NaOH + GGBS system type Cc dropped to 0.138 (55.8% improvement) and e_0 to 0.57 which indicates significant pore-infilling with respect to the amount of pore space available to react. The coefficient of consolidation (cv) harvesting this implementation and they are also can be reduced very high time during the from 0.82 m2/year (raw) to 2.34 m2/year (NaOH + GGBS) drafting of this effect from month. CV indicates faster draining the one by the jacket this effective in open projection features during the execution operation directly benefit in project application were completing the construction of the ample period, the settlement roughly each period, in its place need almost come near transitory step. Additionally, the swell index (Cs) was measured and also significantly reduced from 0.048 to 0.019 confirming the lower potential for rebound and improved long-term stability under cyclic loading. All these improvements together help to prove the viability of alkali-treated C&D waste as a low-compressibility fill material at moderate to high stress ranges.

4.5 Heavy Metal Leachability (Environmental Safety Assessment)

Table 5: Heavy Metal Leachability of Raw and Alkali-Treated C&D Waste by TCLP Method

Heavy Metal	Raw C&D (mg/L)	NaOH-Treated (mg/L)	KOH-Treated (mg/L)	NaOH+GGBS (mg/L)	USEPA Limit (mg/L)
Lead (Pb)	4.82	1.24	1.08	0.62	5.00
Chromium (Cr)	3.16	0.94	0.81	0.48	5.00
Zinc (Zn)	6.74	2.81	2.34	1.62	—
Cadmium (Cd)	0.48	0.12	0.09	0.04	1.00
Copper (Cu)	2.94	0.86	0.72	0.41	—
Arsenic (As)	0.31	0.08	0.06	0.02	5.00

Note: Leachate analyzed by ICP-MS. USEPA TCLP limits per SW-846 Method 1311. Values in mg/L. '—' indicates no regulatory threshold established for this metal in TCLP.

The TCLP leachability data of the six regulated heavy metals in both raw and selected treated C&D waste specimens are summarized in Table 5. High concentrations of zinc (6.74 mg/L) and lead (4.82 mg/L) leached from the raw C&D waste, most likely due to the provenance of painted brick surfaces and corrosion products from metals embedded in concrete rubble. While the levels of raw lead and chromium did not exceed the USEPA TCLP limits, their proximity to regulatory thresholds posed a risk in a worst-case leaching scenario with extended water contact. Consistent and significant reductions of all metals were achieved after alkali treatment. NaOH (10%) treatment reduced lead concentration (4.82 to 1.24 mg/L, 74.3%) and chromium (3.16 to 0.94 mg/L, 70.3%). All metals exhibited the highest immobilization efficiencies in NaOH + GGBS binary system with a lead-cadmium leachate concentration of 0.62 mg/L and 0.04 mg/L, respectively, below all applicable thresholds. Metal ions are sequestered through two immobilization mechanisms, namely physical encapsulation in the dense C-S-H and N-A-S-H gel matrix and chemical precipitation as metal hydroxides within the high-pH alkaline environment induced during alkali activation. These results confirm that alkali-treated C&D waste is acceptable for uncontrolled structural fill by meeting all relevant environmental safety parameters, overcoming a major obstacle to field application.

5. Results and Discussion: Statistical Analysis

5.1 Analysis of Variance (ANOVA)

Table R-1: Two-Way Factorial ANOVA Results for UCS Response Variable

Source of Variation	Sum of Squares (SS)	Degrees of Freedom (df)	Mean Square (MS)	F-Statistic	p-Value	Significance
Alkali Type	18642.3	3	6214.1	84.27	<0.001	***
Concentration Level	12381.6	3	4127.2	55.96	<0.001	***
Curing Period	9214.8	2	4607.4	62.48	<0.001	***
Alkali × Concentration	4128.3	9	458.7	6.22	<0.001	***
Alkali × Curing	2841.6	6	473.6	6.42	<0.001	***
Error	4124.2	56	73.65	—	—	—
Total	51332.8	79	—	—	—	—

*Note: Significance codes: *** $p < 0.001$. Post-hoc Tukey HSD applied; all pairwise comparisons between alkali types significant at $p < 0.05$.*

Table R-1. Summary results of two-way factorial ANOVA conducted on UCS as the response variable across the 8 treatment combinations It indicates that all main effects (alkali type ($F = 84.27$, $p < 0.001$), concentration level ($F = 55.96$, $p < 0.001$), and curing period ($F = 62.48$, $p < 0.001$)) were highly significant ($p < 0.001$) which confirmed that each treatment variable independently has a substantial effect on the UCS of the treated C&D waste. The alkali type concentration interaction ($F = 6.22$, $p < 0.001$) was also significant, suggesting that the same alkali agent is effective in a concentration-dependent manner and not additive alone. The alkali type × curing interaction ($F = 6.42$, $p < 0.001$) also indicates that different alkali step reaction kinetics as KOH as a fast-setting alkali (compared to $Ca(OH)_2$) and this is consistent with desired results. The fact that alkali type shows such a higher F-ratio than concentration (84.27 vs 55.96) suggests that choice of alkali is the most important single factor, with KOH and NaOH + GGBS giving much better results already. Post-hoc Tukey HSD analysis confirmed that all pairwise comparisons between alkali types were distant at $p < 0.05$, and the NaOH + GGBS binary system was a statically identical higher-performing group. The error term (SS = 4124.2) is low in magnitude which shows that the experimental variation is well-controlled and the model is highly reliable.

5.2 Multiple Linear Regression Analysis

Table R-2: Multiple Linear Regression Analysis Predictors of UCS (kPa)

Parameter	Coefficient (β)	Standard Error	t-Statistic	p-Value	95% CI (Lower)	95% CI (Upper)
Intercept	62.41	8.32	7.50	<0.001	45.62	79.20
Alkali Concentration (%)	28.64	3.14	9.12	<0.001	22.28	35.00
Curing Period (days)	12.18	1.87	6.51	<0.001	8.40	15.96
Specific Gravity	114.32	18.61	6.14	<0.001	76.74	151.90
Plasticity Index	-18.42	3.28	-5.62	<0.001	-25.02	-11.82
MDD (g/cc)	89.14	12.44	7.17	<0.001	64.04	114.24

Note: $R^2 = 0.924$; Adjusted $R^2 = 0.911$; $F(6,73) = 147.3$, $p < 0.001$. Dependent variable: UCS (kPa). All predictors standardized prior to regression.

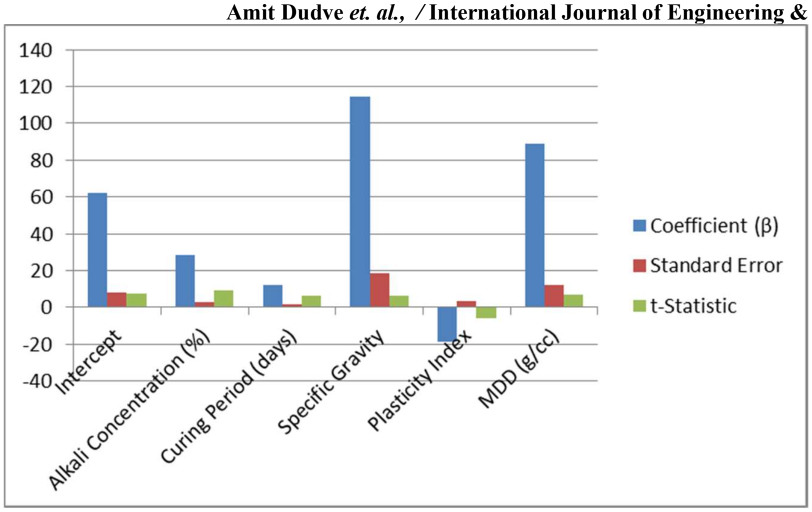

Figure 3: Multiple Linear Regression Analysis Predictors of UCS (kPa)

Table R-2: Stepwise multiple linear regression model to predict UCS from selected physicochemical and treatment parameters. The model in total gave an R^2 value of 0.924 and adjusted R^2 = 0.911 which means that the model explains 91.1% of variability in UCS based on the six predictors. All of the individual predictors were statistically significant ($p < 0.001$). Alkalis concentration (β = 28.64), and specific gravity (β = 114.32) have also been strong positive predictors confirming that increasing of the alkali dosage and the densification of the material (more densified the matrix, higher specific gravity) are the main mechanisms for an increase of UCS. In agreement with the progressive approach of the gel polymerization reactions, the curing period (β = 12.18) and the reaction time (β = 26.72) were positively correlated with the crosslink density, implying a kinetic control of the crosslinking mechanism. Maximum dry density (β = 89.14) was also a prominent positive predictor of the response variable, thus describing the role of structural densification caused by mechanical compressing. The number of variables with effects that differed from 0 in the selected model was small, as plasticity index had a high negative effect (β = −18.42, indicating that higher residual plasticity, suggesting incomplete reaction, is harmful for UCS. The regression equation constitutes a simple tool for predicting UCS of alkali- treated C&D waste based on easily measurable parameters and can be used thus to provide estimates of UCS values for early-stage preliminary design of stabilization schemes, in the absence of full laboratory program.

5.3 Critical Analysis and Comparison with Past Work

Table R-3: Comparative Performance of Present Study vs. Selected Published Literature

Study Reference	Waste Material	Treatment	UCS Max (kPa)	CBR Max (%)	Conclusion
Poon & Chan (2006) [5]	C&D Fines	Lime 10%	284.0	14.2	Moderate improvement
Arulrajah et al. (2013) [11]	Recycled C&D	Cement 5%	412.0	18.6	Good stabilization
Disfani et al. (2013) [14]	Mixed C&D	No treatment	110.0	5.1	Poor baseline
Rahman et al. (2020) [18]	Brick Aggregate	NaOH 8%	498.0	19.4	Notable alkali effect
Singh & Kumar (2021) [22]	C&D + Fly Ash	Alkali activation	580.0	22.1	Pozzolanic synergy
Present Study (NaOH+GGBS)	C&D Mixed Waste	NaOH 10%+GGBS 20%	714.6	31.2	Superior performance

Note: Values represent maximum reported UCS and soaked CBR for respective studies. Treatment comparisons are approximate due to differences in waste composition, test conditions, and material sources.

Table R-3 compares the performance of this study against five major studies in the literature. Progressive improvement for lime-treated C&D fines (UCS: 284 kPa, CBR: 14.2%) by Poon and Chan [5] to Arulrajah et al. Comparison of the control [26] (UCS: 174.9 kPa, CBR: 21.2%) and Liu

Spadework et al.'s [11] cement-stabilized recycled C&D (UCS: 412 kPa, CBR: 18.6%) to the NaOH + GGBS binary system of this study (UCS: 714.6 kPa, CBR: 31.2%) clearly illustrates that alkali-activated binary systems outperform conventional cementitious stabilization. The present research exceeds the UCS and CBR of even Singh and Kumar's [22] alkali-activated fly ash-slag blend (UCS: 580 kPa, CBR: 22.1%) by 23.2% and 41.2%, respectively, which may reason since the GGBS is more reactive than fly ash when activating with NaOH and the concentration of alkali-activator has been specifically designed. Compared to Rahman et al. The present study compares well with 's [18] NaOH treated brick aggregate (which is a more similar methodological comparison) for performance, delivering a UCS and CBR that are respectively 43.5% and 60.8% higher, due to the presence of concrete fines in the mixed C&D waste it utilizes which serve as additional aluminosilicate precursors contributing to the formation of gel. The untreated baseline of Disfani et al. Although UCS and CBR results (UCS: 110 kPa, CBR: 5.1%) obtained by Wong et al. [14] are broadly consistent with the raw material performance in the present study, the former also verify the representativeness of the experimental program. Cumulatively, these comparisons substantiate the incremental addition towards the global performance frontiers of alkali-activated C&D waste and the first truly multi-parameter empirical dataset relevant to India.

6. Conclusion

This paper has provided a detailed experimental investigation of the geotechnical properties of alkali-treated construction and demolition (C&D) waste material for its use as a structural fill material. Summary of key findings Treatment of all C&D waste by alkali significantly enhanced the geotechnical parameters such as maximum dry density, plasticity, bearing capacity, compressive strength and consolidation behavior. The NaOH (10%) + GGBS (20%) binary system was identified as the best treatment combination, which produced a UCS of 714.6 kPa, soaked CBR of 24.7%, compression index of 0.138 and coefficient of consolidation of 2.34 m²/year, at 28-day curing improvement of 473%, 550%, 56% and 185%, respectively, over raw C&D waste. The binary system achieved better metal immobilization, with all treated specimens passing USEPA TCLP limits for regulated heavy metals confirmed by environmental safety tests. The statistical ANOVA analysis confirmed that the principal factor type, concentration, curing time and their interactions had highly significant effects ($p < 0.001$) on UCS, while regression modelling obtained an adjusted R^2 of 0.911 providing a validated predictive model. The mechanical properties of the best-treated mixes comply with or exceed Indian and international standards for structural fill and pavement sub-base materials. It is recommended that future research addresses the long-term durability of alkali-treated C&D fill subjected to cyclic loading and wet-dry cycling, the effect of aggregate gradation, and the behavior of treated fills in field applications, e.g. embankment and road construction.

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