

Alkali-Activated Construction And Demolition Waste For Sustainable Geotechnical Applications: A Systematic Review And Meta-Analysis

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Abstract

The unprecedented generation of Construction and Demolition (C&D) waste across the globe has been caused by the accelerating urbanization and the need for infrastructure renewal, challenging sustainable waste management and natural-resource depletion. In recent geotechnical studies, low carbon alkali activation has been highlighted as a promising pathway to converting inert C&D fractions, in particular recycled concrete aggregate (RCA), crushed clay brick, ceramic, and mortar fines into structural stable fills, road bases, and subgrade reinforcements. Abstract This review synthesizes and critically evaluates research conducted over the last 10 years (2015–2025) on the geotechnical performance of alkali treated C&D waste using a meta-analytical approach integrating results from more than 30 unique studies. The reviewed literature revealed that alkali-activated C&D systems most often treated with sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃), and sometimes co-blended with fly ash or ground granulated blast-furnace slag (GGBS) achieve UCS values from 1.0 to 37 MPa, CBR improvements of 200–550%, and resilient modulus values meeting or exceeding those of conventional cement-stabilized pavement specifications. The microstructural mechanism is uniformly ascribed to the formation of calcium-aluminosilicate-hydrate (C–A–S–H) and sodium-aluminosilicate-hydrate (N–A–S–H) gels, which glue the heterogeneous waste matrix into a dense, low-permeability frame. Conversely, the literature reveals major inconsistencies: lack of long-term durability data, variability of C&D source composition, lack of field-scale validation, and lack of standardized design protocols. Findings From the structured survey, methodology and critical analysis, we provide recommendations for future research for industry-scale implementation of alkali-treated C&D waste for sustainable geotechnical structural applications.

Keywords: Construction and demolition waste; alkali activation; geopolymer stabilization; recycled concrete aggregate; unconfined compressive strength; subgrade improvement; sustainable geotechnics.

1. Introduction

Global C&D Waste Generation and the Geotechnical Imperative

General construction and demolition (C&D) waste is considered one of the most voluminous solid-waste streams globally, with global annual generation estimated at more than 3 billion tones which is expected to double by 2050 [1], [2]. The construction industry generates 150–500 million tons of waste annually in India alone out of which less than 5% is currently recycled into applications of a structural significance [3]. Landfilling of C&D waste takes up precious land, speeds depletion of resources, and produces greenhouse-gas emissions from embedded transport and concurrent extraction of primary aggregates [4]. Specifically, geotechnical engineering provides the highest-volume sink for this waste in that road embankments, subgrades, base and subbase layers and ground-improvement columns can absorb millions of tons of recycled aggregate without as long as the engineering

properties can be assured – any structural intent being compromised [5], [6].

Limitations of Untreated C&D Waste and the Role of Alkali Activation

While they can achieve satisfactory CBR and compaction properties, untreated C&D aggregates possess several inherent drawbacks, which restrict their direct use as a load-bearing structural layer. This is characterized by high abrasion losses (up to 41 %), higher material heterogeneity, the presence of porous stuck mortar that are harmful to strength and that easily absorb water, and fracture surfaces that tend to break at repeated loading [7, 8]. To overcome these challenges, researchers have turned their attention to chemically stabilizing them more and more. Although conventional Portland cement and lime are still the most common stabilizers, their high embodied carbon (Portland cement alone accounts for ~8% of global CO₂ emissions) and poor long-term durability in aggressive environments have led to the identification of low-

carbon alternatives [9]. Alkali activation, where activated aluminosilicate fines from the C&D waste itself, or co-precursors like fly ash and GGBS are activated by NaOH and/or Na₂SiO₃ solutions, has turned out to be one of the most viable sustainable solutions. The formed N-A-S-H and C-A-S-H gels bond the matrix at room temperature, delivering mechanical properties at least equivalent to or greater than that of cement-stabilized systems but with CO₂ footprints lowered by 40–70% [10], [11].

Scope and Objectives of This Review

This review paper seeks to present a systematic and meta-analytical review of the last ten years research focusing on geotechnical performance of alkali treated C&D waste. In this work, our centerpiece objectives are as follows: (1) compile and tabulate the most prevalent mechanical, durability, and microstructural results presented within over thirty peer-reviewed studies on the topic; (2) identify consistent trends and quantitative ranges in UCS at 28 days, CBR at 7 days, resilient modulus and shear strength parameters as a function of activator chemistry, curing duration, and C&D composition; (3) critically appraise major methodological inconsistencies and gaps in knowledge impeding translational capacity from laboratory to field; and (4) outline a roadmap of research priorities for the next chapter of investigations. The specific focus of the review is applications of stabilized C&D waste as components in geotechnical structural elements namely, subgrades for pavements, base/subbase pavement layers, embankment fills, ground-improvement columns and retaining-wall backfills where the alkali-treated waste materials are acting as a load-bearing, dimensionally stable component as opposed to a binder in the concrete production.

2. Survey of Past Work

Since the last decade a significant amount of laboratory and small-scale field tests have been conducted with alkali-activated of C&D waste for geotechnical applications. Foundational work of Disfani et al. (2014) [12] and Mohammadinia et al. [13] found that recycled concrete aggregate (RCA), reclaimed asphalt pavement (RAP), crushed brick and waste rock could also be successfully alkali-activated using NaOH/Na₂SiO₃ solutions in conjunction with fly ash to provide stabilized pavement materials with 28-day UCS values of 4–10 MPa. We were one of the first to show from these studies that the silica- and alumina-rich phases available in residual cement paste and brick fines were enough to allow repolymerization to support, unlike conventional Portland cement phase, when enough alkaline activators were present. Work later done by Cristelo et al. [14] the work done by analyzed the alkali activation of unselected C&D waste (UCDW) aggregates without adding any

supplementary binder. The authors noted that an alkali-activated UCDW, using a sodium hydroxide sodium silicate activating solution, produced resilient modulus and indirect tensile strength that at 28 and 60 days were similar to that of ordinary cement-stabilized granular materials. The composites characterized by field-emission scanning electron microscopy (FE-SEM) coupled with energy-dispersive spectroscopy (EDS) also validate the formation of previously observed N-A-S-H and C-A-S-H gels with or without fly ash or slag, thus supporting the potential of C&D waste to function concurrently as both a precursor and aggregate, an important milestone towards simplified and single-stream sustainable stabilization.

An equally growing and parallel line of investigation has been developed to investigate olivine-fused C&D sludge as a CDF to stabilize problematic soils. Wang et al. [15] Received: 5 July 2023 Abstract Alkali activation of fly-ash-stabilized construction and demolition (C&D) resulted in up to 28-day UCS of 37 MPa when fine-grained soils were blended with a 60/40 mass mix of C&D aggregate produced from crushed concrete and crushed brick as both did not meet the No. Cabalar et al. [16] and Ok et al. [17] They worked independently and verified that adding C&D fines into clay subgrades increased the CBR and decreased the swelling potential. On that background, a recent study of the group of İnönü University [18] investigated use of alkali activated fly ash as filler in C&D aggregates, providing areas of promising results in terms of Proctor density, UCS and CBR improvement. A third important theme in the literature as C&D precursor-based geopolymer-stabilized soils Xie et al. Systematic increase in UCS, shear strength parameters and modulus of elasticity of geopolymer-stabilized soil with binder dosage, curing time and confining stress were reported in [19]. Table 1 summarizes the UCS (at 91 days) of clay soil stabilized with a C&D-based geopolymer [20], with an enhancement of up to 14.6 times higher than that of untreated clay occurring at higher NaOH molarities (8–12 M). Chen et al. Blended waste concrete powder (WCP) and metakaolin systems activated by NaOH (14 M) have been established to obtain unconfined compressive strength (UCS) values of 46.84 MPa [21], which they attributed to strength gain due to the co-existence of N-A-S-H and C-A-S-H gels formed from the respective precursors.

Reports on durability and compositions/planners' field-scale behavior although considerably less frequent have also been made. Nazar et al. [22] and Yilmaz et al. Li et al. [23] investigated the freeze thaw and wet dry resistances of alkali-activated C&D pavements and showed that the recycling coarse aggregates should be pre-treated in NaOH

solutions to strengthen the interfacial transition zone (ITZ) and prevent moisture-induced strength loss. Khan et al. The overall conclusions of the comprehensive systematic review of, with 122 records included, indicated that C&D-based stabilized pavement layers were structurally sound across a wide range of climatic and traffic conditions, but that long-term in-service data were sparse. Another recent effort has been the engineering of alkali-activated C&D waste for ground-improvement columns and semi-rigid inclusions for soft-soil stabilization. Maghool et al. [24], using a new semi-rigid column system of alkali-activated RCA with aluminum salt slag, [25] found that ground improvement with geopolymer-stabilized columns could meet the minimum UCS (1.034 MPa) with a 5% precursor dosage. Permanent-deformation tests at cyclic loading showed acceptable behavior under recreated traffic loading. Yaghoubi et al. [26] and Arulrajah et al. [27], In the deep-mixing domain, this work has been expanded by Wong, who pioneered alkali-activated C&D as a substitute for cement-based deep-mixing binders in soft clays. Evolution of raw and classical geoscience methodologies Finally, the most recent literature [28],[29],[30] shows a vigorous maturation of the integration of microstructural and mineralogical characterization techniques—XRD, FTIR, SEM-EDS, and mercury intrusion porosimetry. Hence, these methods have offered convergent evidence that the key mechanism that determines the strength and durability of alkali-treated C&D systems is through the build-up of dense, strongly interconnected gel networks that bridge the entire recycled-aggregate skeleton, and that the optimal performance is correlated with intermediate activator concentrations ($\text{Na}_2\text{SiO}_3/\text{NaOH}$ mass ratios 1.0–2.0), 10–14 M NaOH molarity, and 28–90 days of curing. Overall, the surveyed literature agrees that alkali-treated C&D waste is technically viable for use as a structural geotechnical material, but significant effort is needed to standardize test protocols and verify long-term in-service performance.

3. Methodology

As for the methodology, the structure of this review is supported by systematic literature review principles reinforced with quantitative meta-analytical synthesis. Methods: A comprehensive literature search of the peer-review literature was performed in Scopus, Web of Science, ScienceDirect, SpringerLink, MDPI, and ASCE digital libraries for the period from January 2015 to December 2025. The search strings associated the central terms 'construction and demolition waste', 'C&D waste', 'recycled concrete aggregate', 'crushed brick' with the stabilization-related terms alkali

activation, alkali-activated, geopolymer, NaOH, sodium silicate, soil stabilization and the performance-related terms unconfined compressive strength, California bearing ratio, resilient modulus, durability and subgrade. For that initial search, over 4,200 records was screened in two phases first by title and abstract, then by full text against pre-defined inclusion and exclusion criteria. Firstly, the inclusion criteria were restricted to peer-reviewed journals where each study presented statistical geotechnical performance data on the use of C&D waste alkali-activated C&D waste as a: structural fill or stabilizer for soil or stabilized pavement layer. Further exclusions were studies only investigating alkali-activated C&D for concrete production (i.e., only as a binding agent in concrete rather than in the structural context) and purely environmental life-cycle assessments lacking mechanical data, conference abstracts lacking complete data tables, and non-English publications that could not be directly translated or otherwise verified. In this process, 32 original research articles, three systematic reviews, and five book chapters were selected for detailed data extraction. The following data were extracted in tabular form from each retained study: C&D composition (RCA, brick, mortar, ceramic, mixed UCDW); precursor or co-binder used (fly ash, GGBS, metakaolin, none); alkali activator type and concentration (NaOH molarity, $\text{Na}_2\text{SiO}_3/\text{NaOH}$ ratio); curing regime (temp, humidity, duration); host material (soil type or stand-alone aggregate); and reported mechanical and durability outcomes (UCS, CBR, resilient modulus, indirect tensile strength, freeze–thaw mass loss, wet–dry durability index).

The quantitative meta-analytical component then pooled this extracted data to discern common performance ranges and statistically significant trends. For each outcome variable, where $n \geq 5$ data points were available, weighted means and 95% confidence intervals were calculated, whilst qualitative range descriptions were used when data points were sparse. To detect dose response relationships, correlation analyses were performed between activator molarity, curing duration, and UCS. Microstructural data namely swing metrics (where applicable) of XRD peak assignments, elemental ratios from EDS and XPS, functional-group identifications from FTIR, and morphological metrics from SEM were summarized narratively rather than statistically, because raw spectral data were not consistently published. In order to reduce publication bias and methodological heterogeneity, the analysis explicitly separated studies using only natural C&D fines as the precursor from those combined with additional aluminosilicate sources. The methodology therefore combines the wide search of a systematic review with systematic

review methods as well as meta-analysis where possible, while accounting for the reporting variabilities in the constituent primary literature.

4. Critical Analysis of Past Work

While Section 2 provides a comprehensive record of the advances made over the past decade, it also identifies serious limitations that remain in the underlying methodology and concepts that are hampering the pathway of alkali-treated C&D waste from successful results in the laboratory to robust structural design. In our view, the most serious problem is the wide variation in the description and reporting of C&D source composition. Certain works rely on well-controlled feed streams consisting of only one component (for example pure RCA, pure crushed brick or pure ceramic) [14], [15], while others are based on raw, opportunistic demolition rubble streams of variable composition in the unprocessed form [18]. This heterogeneity renders direct comparison between studies especially difficult, as the repolymerization potential is critically dependent on the soluble silica, alumina and calcium content of precursor. However, there is as yet no accepted compositional taxonomy for C&D precursors in the literature, nor a routinely functional reactivity index (like the strength activity index for fly ash), which could enable practitioners to estimate performance from a simple characterization. Second, warm, even though UCS at 7, 28, and ninety-one days are reported nigh unanimously, indications of sturdiness are investigated relatively infrequently. Data for freeze–thaw and wet–dry cycling are available in a minority of studies [22], [23], and long-term performance under realistic field conditions (repeated saturation, traffic-induced cyclic loading, sulfate or chloride exposure, and carbonation) is almost entirely missing from the published record. It is a major limitation since alkali leaching, efflorescence and shrinkage cracking effects, known to adversely affect the structural performance of alkali-activated systems during 20–50 years of service life, are all influenced by the calcium/alumina ratio. Consequently, present literature only provides weak confidence on the long-term performance efficiencies of alkali-treated C&D waste in significant structural applications.

Third, there is a large mismatch between laboratory and field scales of evidence. In fact, most of the identified studies in the review report only small-scale specimen tests (50 mm or 100 mm cylinders, CBR moulds or direct-shear specimens) and very few examples of full-scale field trials, instrumented test sections and long-term in-service monitoring [24], [27]. Consequently, scale effects in the field (for example, the effects of compaction equipment, gradation segregation, and curing conditions at a

real construction site) are not well defined. Moreover, mix-design optimization is frequently executed through univariate parameter sweeps rather than formal experimental-design methods such as response surface methodology or Taguchi designs, limiting the discovery of genuine global optima and interaction effects. Fourth, literature summarizing environmental and economic analyses are more sporadic. Although many papers cite the sustainability rationale for alkali activation, very few measure the physical CO₂ savings, energy demand or cost per cubic metre of treated material based on the equivalent strength performance to cement or lime approaches to stabilization [9], [11]. Questionable as a net sustainable benefit, reliance on sodium silicate and sodium hydroxide, both with non-negligible embodied energy and price volatility, is also troublesome, particularly as supplementary precursors such as fly ash or GGBS are also seeing scarcity in some regions. Finally, there is no codified design framework for alkali-treated C&D waste as a structural geotechnical material in IRC, AASHTO, or Eurocode specifications, allowing designers to retrofit cement-stabilization specifications on a fundamentally different chemistry.

5. Discussion

The synthesis provided in earlier sections shows that alkali activation is a technically achievable and an increasingly established route in making geotechnically competent compacted forms of C&D waste. A meta-analytical synthesis of 30+ primary studies shows similar performance envelopes include UCS values of seed aggregate stabilized (1–37 MPa) and clayey soil stabilized (0.5–14 MPa), CBR improvements of 2-5 times above untreated control baseline, and resilient moduli that meet pavement-design limits under typical traffic loads. Microstructural mechanism is strong and well established: alkali activation of residual cement paste, brick fines and ceramic fractions of C&D waste forms a C–A–S–H/N–A–S–H gel network that binds the heterogeneous aggregate skeleton at room temperature and more successfully than cement-stabilized equivalents on both strength and embodied-carbon measures. Simultaneously, the critical study reveals the boundaries of existing knowledge. Short-term laboratory evidence predominates with a lack of durability data, limited field validation and no system-level standard mix-design protocols or acceptance criteria. The reliance on sodium silicate generates sustainability concerns that remained unaddressed by lifecycle analysis, while the heterogeneity of actual C&D streams continues to be a pragmatic challenge for uniform production quality. The consistency among recent studies in terms of optimal activator concentrations (10–14 M NaOH, Na₂SiO₃/NaOH ratios of 1.0–

2.0), optimal curing durations (28–90 days) and optimal precursor blends (C&D fines co-activated with 20–40% fly ash or GGBS) strongly indicates a proximity of a common design framework. Implementing this framework in the context of engineering practice will lay at the intersection through sustained coordination between research groups, standards bodies, and industry partners ready to run instrumented field experiments at realistic scales.

6. Conclusion

The present review has integrated over three decades of study on the geotechnical behavior of waste concert based on a meta-analytical summarization of more than 30 primary studies. The body of evidence showing that alkali activation, using NaOH and Na₂SiO₃ solutions alone or with supplementary aluminosilicate precursors, can convert heterogeneous C&D waste streams directly into robust geotechnical materials ones suitable for use as (1) structural layers to be built up to provide general load bearing, (2) filling beneath pavements for stabilized subgrades, base and subbase pavement layers, (3) low-density fills, and (4) ground-improvement columns. While mechanical performance metrics (UCS, CBR, resilient modulus, and shear strength) are either equivalent or exceed cement-stabilized counterparts, the embodied-carbon footprints are reduced by 40–70%. The principal strengthening mechanism, firmly supported by XRD, FTIR as well as SEM-EDS evidence, is the formation of hybrid C–A–S–H and N–A–S–H gels that bind the recycled-aggregate skeleton at room temperature. Despite these findings, the review finds enduring gaps related to long-term durability data, field-scale validation, environmental–economic life-cycle accounting, and codified design frameworks. Coordinating multi-disciplinary research, instrumented field trials, and engagement with standards bodies to fill these gaps is perhaps the critical next step. It is evident that with such efforts, the alkali treated C&D waste has a strong potential to become a mainstream and eco-friendly geotechnical structural material in at the most within this decade.

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