



Dr. B. C. Roy
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Evaluating the Environmental and Economic Viability of Using Industrial By-Products in Embankment and Subgrade Construction

Pradip Pal

Dept. of Civil Engineering
Dr. B.C Roy Polytechnic
Durgapur, India
pradip.pal@bcrc.ac.in

Saptarsi Batabyal

Dept. of Civil Engineering
Dr. B.C Roy Polytechnic
Durgapur, India
saptarsi.batabyal@bcrc.ac.in

Tanmoy Mondal

Dept. of Civil Engineering
Dr. B.C Roy Polytechnic
Durgapur, India
tanmoy.mondal@bcrc.ac.in

Ishita Banerjee

Dept. of Civil Engineering
Dr. B.C Roy Polytechnic
Durgapur, India
ishita.banerjee@bcrc.ac.in

Arijit Kumar Banerji

Dept. of Civil Engineering
Dr. B.C Roy Polytechnic
Durgapur, India
arijit.banerji@bcrc.ac.in

ABSTRACT

The creation of transportation infrastructure (especially roads/highways) necessitates a great deal of natural materials that form the embankment and subgrade layers. Such reliance on natural virgin aggregates and soils has led to excessive depletion of natural resources through resource exploitation and ecological damage. Concurrently, industrialization leaves a great deal of by-products and wastes in its wake with immense disposal and leachate/pollution concerns. Therefore, industrial by-products as sustainable alternatives in the creation of embankments and subgrades, i.e., fly ash, blast furnace slag, red mud, steel slag, quarry dust, construction and demolition (C&D) waste, become more and more desirable. This review paper examines the geotechnical, environmental, and economic parameters of such materials for a performance-based evaluation of success, advantages, and disadvantages. Specific attention on laboratory studies, field applications, stabilization ability, and sustainability evaluates the materials as replacement candidates for conventional materials. The results found that with proper investigation and treatment of industrial by-products, the sustainability of a project can be enhanced from an environmental and economic perspective without sacrificing engineering performance standards.

Keywords - Industrial by-products, Embankment construction, Subgrade stabilization, Sustainable materials, Geotechnical properties, Environmental impact

1. INTRODUCTION

Infrastructure construction is one of the most decisive indicators of economic and sociological development for any nation. Roads and railroads, tracks and embankments need proper connectivity and logistics (Zhao, Xiao and Dai, 2021) [1]. Thus, conventional materials over the years in various facets of construction have been naturally occurring soil, sand and crushed stone. However, such virgin materials have been

extensively and excessively utilized to the point where the not-so-eco-friendly adverse effects are quarry depletion, land degradation, increased energy usage and resultant transportation of greenhouse gas emissions, to name a few, are becoming increasingly apparent. At the same time, increased industrialized populations have increased by-product and waste generation. Disposing of by-products and wastes requires extensive terrestrial land use for landfill capabilities, resulting in inefficient land use and subsequent soil and groundwater pollution for environmental degradation (Siddiqua, Hahladakis and Al-Attiya, 2022) [2]. Therefore, integrating industrial by-products and wastes with civil engineering projects is an efficient solution to the material acquisition and waste disposal problem.

The purpose of this review paper is to evaluate the material performance, engineering behavior, environmental feasibility, cost-in-use factors as well as case studies and implementation challenges where industrial by-products could serve as an alternative material in sub-grades and embankment construction to determine the green and economic feasibility of such a venture.

2. OVERVIEW OF INDUSTRIAL BY-PRODUCTS USED IN EMBANKMENT AND SUBGRADE CONSTRUCTION

In pavement/highway engineering, the **embankment** and subgrade are the elements which form the road above natural ground level for appropriate drainage and support (Mazurowski, 2021) [3]. Subgrade is the lowest layer before any pavement goes on top, it's the load bearing element which transfers traffic loads to the subgrade ground below. It also

acts as the support for the pavement layers above. Therefore, the strength/stability and durability of these layers dictate how effective the pavement will be constructed above it. The optimum characteristics of subgrade/embankment are:

- Shear strength and compaction characteristics
- Minimized compressibility and high stability under pressure
- Erosion resistant and no change in volume
- Natural, sustainable materials

However, with sustainability efforts increased and sources of natural soils diminished, the need for alternatives has increased and thus opened the door for industrial byproducts to act as possible replacements for natural soils. Industrial by-products are substances generated from a certain industrial operation, but they are neither the finished, sought-after product, nor properties make such materials likely for secondary or continued use (Ude, 2024) [4]. The following industrial by-products are the most commonly researched relative to embankment and subgrade materials:

2.1 Fly Ash

Fly ash is a fine powdery fractional residue of combustion from pulverized coal generated at thermal power stations (Alterary and Marei, 2021) [5]. Its composition includes silica, alumina, and unburned carbon. It exists in spherical particles, high workability and possesses self-compaction characteristics. Low ash coal fly ash works as Class C fly ash (due to calcium oxide, self-cementation) while Class F fly ash requires an activator (lime) for the stabilization process. Fly ash as an embankment material reduces dead load, works as a drainage material and equals pozzolanic strength for long durations. In addition, an embankment-type function of fly ash reduces the fly ash occurrence which must be otherwise treated and stored relative to thermal power stations.

2.2 Blast Furnace Slag

Ground granulated blast furnace slag (GGBS) is the by-product of iron production relative to steel plants (Ahmad *et al.*, 2022) [6]. It is a granular glassy substance whose composition includes calcium silicates and alumino-silicates. Air cooled slag provides a rough terrain surface for coarse fill. Granulated slag may be used for subgrade stabilization mixed with cement or lime. GGBS as filler material for earth increases bearing capacity for soils with the additive percentage ratio. Also, with a specific addition ratio to soils, GGBS decreases permeability which helps stabilize water penetration and increases life.

TABLE:1- ENGINEERING PROPERTIES OF SELECTED INDUSTRIAL BY-PRODUCT MATERIALS

Material	Specific Gravity	Particle Size	Plasticity Index	pH	Remarks
Fly Ash (Class F)	2.2	10-100 μm	Non-Plastic	7-8	Pozzolanic Light weight

Fly Ash (Class C)	2.3	10-100 μm	Non-Plastic	10-11	Self Cementing
Blast Furnace Slag	2.9	0-5mm	Non-Plastic	7-9	High Strength, Low Permeability
Steel Slag	3.2	0-20mm	Low	9-10	Expansive
Red Mud	2.8	0-200μm	Non-Plastic	11-13	Requires neutralization
Quarry Dust	2.6	0-4mm	Low	7-8	Readily available, improves CBR
C&D Waste	2.7	0-20mm	Low	7-8	Variable Properties depending on source

2.3 Steel Slag

Steel slag is a by-product from steel production efforts; it is of high specific gravity and hard, angular shaped materials which help as coarse aggregates for embankment fill/base materials (Loureiro *et al.*, 2022) [7]. In addition, free lime and magnesia exist within steel slag which can expand; therefore, steel slag must be weathered or chemically stabilized before an addition project occurs. Stabilization occurs, but the ultimate strength and durability obtained with steel slag versus the other materials is higher.

2.4 Red Mud

Red mud is a by-product formed relative to bauxite ore during alumina production. It has a high alkaline composition which makes red mud inadequate for disposal as a filling material; therefore, cement or lime stabilization or mixed stabilization neutralization makes it a filler material with low permeability characteristics for embankments. Red mud is the most stabilized by-product but potentially the most practically used after stabilization parameters are determined.

2.5 Quarry Dust

Quarry dust is created from crushed rock; quarry dust findings are particles that generally have highly angular characteristics which help as suitable additives to soft soils (Sukkarak *et al.*, 2025) [8]. Thus, quarry dust has been found to improve dry density and California Bearing Ratio (CBR) findings for subgrade filler when used in suitable proportions. Quarry dust is readily accessible from construction sites as immediate access without added excess vehicle emissions of sourcing elsewhere and additive to the project.

2.6 Construction & Demolition Waste

Construction and demolition waste (C&D waste) is resultant from the demolition/renovation of constructions which include concrete bricks, tiles, etc. Used as filler material after crushing/sieving, C&D Waste has enough strength and durability over time assessed for low to medium traffic roads with minimal impact upon them. In addition, it increases the circular economy through recycling efforts as opposed to going to landfills.

3. GEOTECHNICAL PERFORMANCE EVALUATION

With respect to the geotechnical properties of these industrial by-products, a test series both in the lab and field are necessary to determine whether or not these are good options for embankment or subgrade materials to prevent eventual settlement and failure (Riyad *et al.*, 2021) [9]. The properties tested in this regard are compaction characteristics, shear strength, compressibility and CBR.

TABLE:2-COMPACTION CHARACTERISTICS OF NATURAL SOIL AND SOIL-FLY ASH MIX

Parameter	Soil	Soil + 20% Fly Ash
Maximum Dry Density (g/cm ³)	1.65	1.55
Optimum Moisture Content (%)	14	17

Observation: Fly ash reduces dry density but increases optimum moisture content, requiring more water for proper compaction.

Calculation of dry density using compaction formula:

$$\text{Dry Density} = \frac{\text{Wet Density}}{1 + \frac{\text{Moisture Content}}{100}}$$

Assuming wet density after compaction = 1.82 g/cm³:

$$\text{Dry Density} = \frac{1.82}{1 + \frac{17}{100}} = \frac{1.82}{1.17} \approx 1.555 \text{ g/cm}^3$$

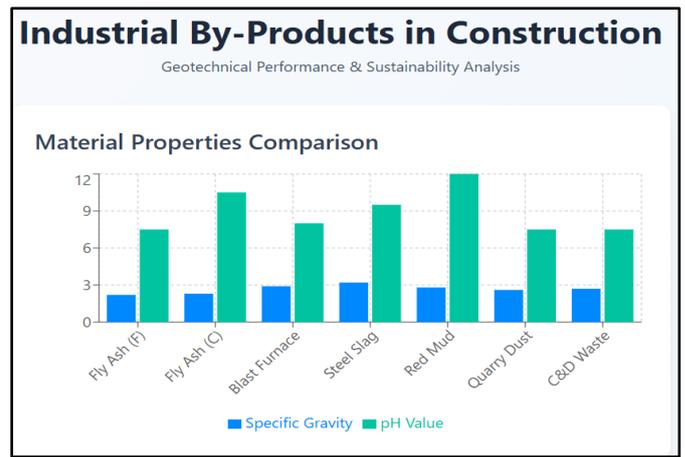


FIGURE 01: MATERIAL PROPERTIES COMPARISON OF INDUSTRIAL BY-PRODUCTS

(Source: Author-generated figure based on data compiled from published literature) [10]

3.1 Compaction Characteristics

In respect to compaction characteristics, naturally occurring soils all indicate a maximum dry density and optimum moisture content greater than by-products in question but as fly ash and red mud indicate satisfactory compaction with lime and cement, it's enough to justify suitability. The fact that steel slag and quarry dust are more massive materials that have a greater dry density is an asset in relation to load dispersal (Hidalgo and Verdugo, 2025) [11].

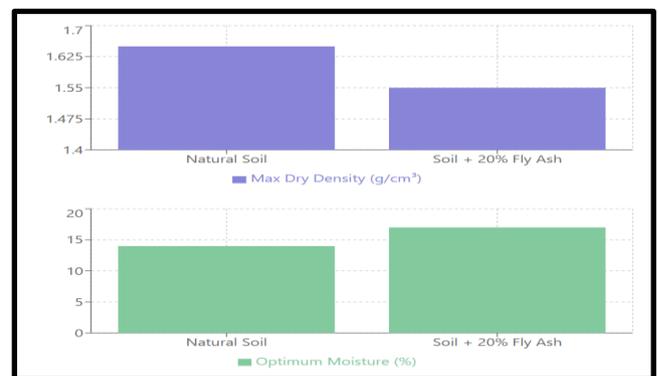


FIGURE 02: EFFECT OF FLY ASH ADDITION ON COMPACTION CHARACTERISTICS (MAXIMUM DRY DENSITY AND OPTIMUM MOISTURE CONTENT) OF SOIL.

(Source: Developed by the authors using data reported in previous studies) [12]

3.2 Shear Strength

The most important parameter for stability for an embankment is shear strength; fly ash with lime or cement offers excellent cohesive/inter friction angle properties while steel slag, blast furnace slag and C&D all have high shear strengths boasting construction from the rough face, angular particles and innate strength; the by-products have

the attributes of rough and weakened materials that offer satisfactory shear strength for the endeavor.

3.3 Bearing Capacity and CBR

CBR values of the industrial by-products vary widely depending on composition but more so compaction characteristics after placement. However, fly ash with composites of lime and cement have better properties than quarry dust and steel slag as CBR values are between 10%-60% which will assist in sub-base and sub-grade placement suitability (Rai *et al.*, 2021) [13]. This is important as steel slag has pozzolanic reactions from the water content in curing.

3.4 Settlement and Compressibility

Settlement and compressibility indicate that lightweight by-products like fly ash have the most limited total settlement characteristics (Zhang *et al.*, 2023) [14]. Therefore, these are a suitable option for placement on soft soils; however, it's crucial for adequate compaction and drainage to be rendered to ensure no differential settlements occur with heavy products that settle easier. Heavy materials (slag, C&D) have the least compressibility (most stable).



FIGURE 03: RANGE OF CALIFORNIA BEARING RATIO (CBR) VALUES OF VARIOUS INDUSTRIAL BY-PRODUCTS FOR PAVEMENT APPLICATIONS.

(Source: Compiled and illustrated by the authors based on sustainability considerations reported in earlier studies) [15]

4. ENVIRONMENTAL VIABILITY

4.1 Conservation of Natural Resources

Use of industrial by-products reduces the need for virgin aggregates and virgin soils. It also anticipates quarrying and unnecessary displacement of ground cover that would otherwise be animal nesting grounds and nature.

4.2 Landfill Diversion

Landfill waste equates to leachate, poor air quality and space; by using industrial waste it places less demand on landfills and materials that would otherwise cause issues in a landfill are instead recycled for construction for which they are most useful.

4.3 Reduced Embodied Energy, Reduced Carbon Footprint

Transferring virgin aggregates from pit to project through additional processing is energy suck; using what is already there in the form of industrial by-product reduces embodied energy, carbon footprint (Etheredge, 2025) [16]. Fly ash, for example, is far more natural and less processed than cement or crushed stone.

4.4 Leachate Potential and Toxicity Testing

There are problematic by-products such as red mud, certain slags that carry heavy metal or alkaline concerns; leachate testing must be done for what is more environmentally sound. However, stabilization with lime, cement and pozzolanic binders can properly stabilize contaminants to prevent leaching where it will not negatively impact surrounding areas. In situ testing shows that generally, with some exceptions, it passes the environmental standards.

4.5 Sustainability, Circular Economy

Recycling occurs within a circular economy which means by-products are utilized within a circularized life cycle as opposed to a disposition approach to them that makes them waste or considers them waste (Sánchez-García *et al.*, 2024) [17]. By using industrial by-products one incorporates a sustainable triangle of economic feasibility, environmental practicality, social benefit.



FIGURE 04: COMPARATIVE SUSTAINABILITY PERFORMANCE OF INDUSTRIAL BY-PRODUCTS IN TERMS OF RESOURCE CONSERVATION, LANDFILL DIVERSION, CARBON REDUCTION, COST EFFECTIVENESS, AND ENGINEERING PERFORMANCE.

(Source: Compiled and illustrated by the authors based on sustainability considerations reported in earlier studies) [18]

5. RESULTS AND DISCUSSIONS

5.1 Material Acquisition Costs

Industrial by-products are materials acquired from neighboring plants, which means that acquisition costs could be minimal. Thus, if development is spread across and widely enough, the most significant cost hurdle will be transportation. Therefore, acquisition of by-products is most favorably located in an industrial site within the vicinity of the construction site.

5.2 Transportation

Transportation is a relatively inexpensive venture acquired within the vicinity of construction set up. For example, fly ash, slag, etc. can be acquired within a 50-100 km radius. Beyond this radius, it becomes too expensive to ensure transportation.

5.3 Processing

Certain materials require processing (crushing, sieving, treatment (stabilization)) for proper use (Bekkouche *et al.*, 2022) [19]. Process costs for these materials should be on par with or less than that of natural materials. For example, steel slag needs to be aged/stabilized so it doesn't expand; this is a process that is not too expensive to facilitate.

5.4. Disposal + Decreased Environmental Acquisition Costs

Companies pay for disposal and therefore, less use means that while it is being used for disposal, it is not being used up. In addition, reduced emissions facilitate reduced environmental acquisition costs - similarly to LEED credits or other green credits for internationally/nationally sponsored opportunities.

5.5 Life Cycle Cost Assessment

Life cycle cost assessment is an extended life cycle assessment of the material from construction to maintenance to disposal; therefore, when materials are assessed in their life cycles, the initial costs of industrial by-products become more appealing (Barbhuiya and Bhusan Das, 2023) [20]. This is because less money needs to be invested upfront at construction with these cheaper alternatives - and their cost effectiveness comes from their life cycle success which ultimately reduces other re-construction costs over time.

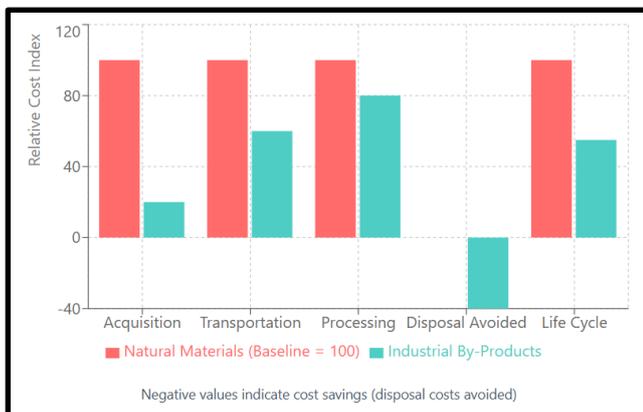


FIGURE 05: RELATIVE LIFE-CYCLE COST COMPARISON BETWEEN NATURAL CONSTRUCTION MATERIALS AND INDUSTRIAL BY-PRODUCTS.

(Source: Author-generated figure based on economic and life-cycle cost trends reported in published literature) [21]

5.6. Stabilization/Improvement Methods

Many industrial by-products require stabilization for ideal performance. The following stabilizations are recognized and utilized:

- **Lime Stabilization:** This holds pozzolanic reactivity with fly ash and red mud, strength gain enhancements and plasticity reduction.
- **Cement Blending:** Cement presents cementitious adhesion which is needed for blends with slag and quarry dust.
- **Geosynthetics Connection:** Geosynthetics such as geotextiles or geogrids can be stabilized with by-products for tensile inclusions and drainage.
- **Chemical Stabilization:** pH or carbonation stabilization occurs with red mud and steel slag (Duraismy and Chaunsali, 2025) [22].
- **Blending with Native Soils:** A less aggressive treatment with native soils for engineered needs provides sufficient strength gain while allowing proper workability and environmental safety.

5.7. Case Histories and Applications

The following successful field applications suggest that these industrial by-products act as beneficial materials for subgrades and embankments:

- Fly ash fill areas have been established next to thermal power plants with them being stabilized in place over time without major settlement/leaching.
- Steel slag has been used in a mutually beneficial manner as a base course for roadways.
- Quarry dust and construction/demolition (C&D) wastes have been utilized in low-volume/rural roads where sufficient compaction/stabilization efforts were made (Sangeetha *et al.*, 2022) [23].
- Composites of by-products such as fly ash and slag or quarry dust have shown beneficial mechanical and durability enhancements for blending.

These examples in the field illustrate that such materials behave no differently than traditional materials when sufficient design, blending, quality control and placement observation is completed.

5.8 Limitations/Disadvantages

However, despite performance advantages of successful use, limitations still inhibit increased use:

1. **Material Properties Variability:** These are not homogenous by-products. Testing must be conducted on an itemized, site-specific level.
2. **Leaching/Environmental Concerns:** Unstable materials without proper treatment for stabilization can leach negative elements into subgrades.
3. **Societal/Legal Feasibility:** Professional codes of ethics do not yet exist to regulate such efforts.
4. **Logistical Feasibility:** Transporting and stockpiling such lightweight/fine materials such as fly ash can be challenging (Juho Lehmusto *et al.*, 2024) [24].
5. **Technical Feasibility:** Engineers must be trained to design and construct safely with unconventional materials.

These challenges require support from producers, researchers and regulators to move toward a successful cohesive solution.

5.9 Future Directions

This indicates future construction will rely on waste re-purposing and resources, thus, future research for construction is likely to include

- Treatment/stabilization methods via nano-materials or polymers
- LCA and carbon accounting impacts
- Performance based impacts for by-product reuse
- Composite stabilizations with recycled plastics or fibers and cross-industries
- Digitalized and AI impacts for on-site in situ mixing considerations

These "greener" construction regulations applied worldwide implement the idea of government regulated industrial by-products on such a larger, feasible scale.

6. CONCLUSION

The application of industrial by-products in construction as temporary and permanent geotechnical solutions (embankments, subgrades) is a financially favorable next step for increasingly sustainable constructed solutions as fly ash, slag, red mud, quarry dust, C&D waste, etc. are low-cost materials with great engineering properties, and treatment and stabilization for use minimizes necessary applied amounts needed for construction due to physical properties favoring performance-based characteristics over virgin materials. The less virgin materials excavation occurs and alternative materials disposal occurs - the better - minimized transportation expectations lower carbon emissions. Furthermore, economies of scale favor substitution percentages as lower costs of applied/deployed/transported unit materials in comparison to costs of applied (or not) industrial by-products (disposal costs) at lower applied/per unit deployed costs. Negatives presented against the application of industrial by-products are inferred from variable uncertainties and environmental acceptability; however, as part of geotechnical construction stabilization solutions mitigate hydraulic conductivity for all projects and simultaneously reduces leachate concern through engineered solutions with stress-based stabilization means consideration in situ stress effectively replaces virgin materials.

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