Reuse of Waste Materials in Geotechnical Practice

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Abstract. Waste material is an inevitable outcome of most human and industrial activities, lacking enduring value. A significant amount of waste is being generated from various sources such as industrial and domestic activities, driven by population growth and economic expansion. To address these challenges, methods like re-use and recycling are crucial in mitigating the adverse impacts of waste by reducing landfill deposition. Recycling not only helps in conserving natural resources but also diminishes energy consumption. Recently, there has been increasing interest in re-using waste materials as substitutes in geotechnical and geo-environmental applications. For the efficient utilization of waste, it is essential to systematically understand its characterization, various technical aspects, and environmental implications, along with their interrelationships. This study aims to explore the potential of using different by-products and waste materials such as fly ash, shredded waste tires, and recycled concrete aggregates as geomaterials. By doing so, it endeavours to contribute to sustainable practices in geotechnical engineering. Overall, the re-use of waste materials constitutes a significant area of research aimed at fostering sustainability in geotechnical engineering practices.

1 Introduction

1.1 Waste material

Waste material is broadly defined as any material resulting from human and industrial activities that lacks enduring value. Economic growth and improved living standards in many regions have contributed to a rise in both the quantity and complexity of waste generated. India faces significant environmental challenges stemming from waste generation, compounded by deficiencies in waste collection, transportation, treatment, and disposal infrastructure.

The existing waste management systems in India are struggling to handle the escalating volumes of waste generated by expanding urban populations. This inadequacy not only adversely affects the environment but also poses risks to public health. As a result, there is an urgent need for improved waste management strategies and infrastructure in India to

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effectively address these challenges and mitigate their environmental and health impacts. In worldwide, the waste materials generation is always on the increasing trend and growing volume of waste material has prompted interest in developing new ways to reuse them. Efficient waste material utilization should minimize the environmental impact and maximize conservation of natural resources.

1.1.1 Generation and characteristics

The generation and management of waste present unique challenges across different contexts. In developed countries, the per capita waste generation is typically higher due to greater consumption levels. However, they often face significant challenges in managing even these smaller quantities of waste. The principal source of different wastes is from residential (i.e. Scrap tires, batteries, food wastes and glass etc.), industrial (i.e. Hazardous wastes, fly ash and special wastes etc.), commercial (i.e. Plastics, wood, and metals etc.), construction (i.e. Demolished concrete aggregates, steel, and dirt etc.) and agricultural (i.e. pesticides and spoiled food wastes etc.). The increasing generation of waste is a growing global concern driven by rising populations and consumption patterns.
Safe and efficient disposal of waste materials poses significant challenges to waste management systems worldwide. The rate of waste generation influenced by several factors, including population density, economic status, level of commercial activity, culture, and urbanization. Central Pollution Control Board (CPCB) of India depicts the waste generation per capita has increased at an exponential rate in the range of 0.26 kg/day to 0.85 kg/day [1]. Further, it is estimated that 80 to 90% of these wastes are disposed-off in landfills without proper management practices and leading to open burning, air, water and soil pollution [2]. As per CPCB of India, the waste per capita generation comparison presented in Figure 1.

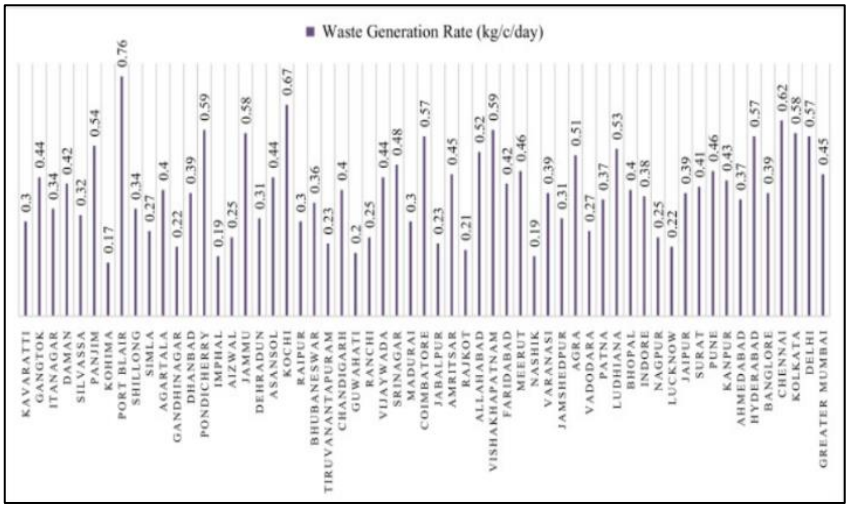


Fig. 1. Waste generation rate in Indian cities [1]

Figure 2 depicts that India approximately generated 31.6 million tonnes of waste in 2001 and subsequently in the year 2011, the waste generation increased to 47.3 million tonnes. It is predicted that by 2041, the waste generation further increased to 161 million tonnes i.e. 5 times increase in four decades [3]. As per latest information according to the State of India's Environment 2023 report, solid waste generation in India is estimated to be around 150 million tonnes per day. In worldwide, the generation of waste is expected to be approximately 27 billion tonnes per year by 2050, especially the one-third will be from Asian countries like

China and India. Figure 3 depicts the regional waste generation trends in the world and its projection from the year 2016 to 2050, which is estimated to be doubled by the year 2050.

year	population ($\times 10^6$)	*per capita* generation (kg per day)	total waste generation (x 10^3 Tonnes per year)
2001	197.3	0.439	31.63
2011	260.1	0.498	47.30
2021	342.8	0.569	71.15
2031	451.8	0.649	107.01
2036	518.6	0.693	131.24
2041	595.4	0.741	160.96

Fig. 2. Estimated population growth and its impact on waste generation [3]

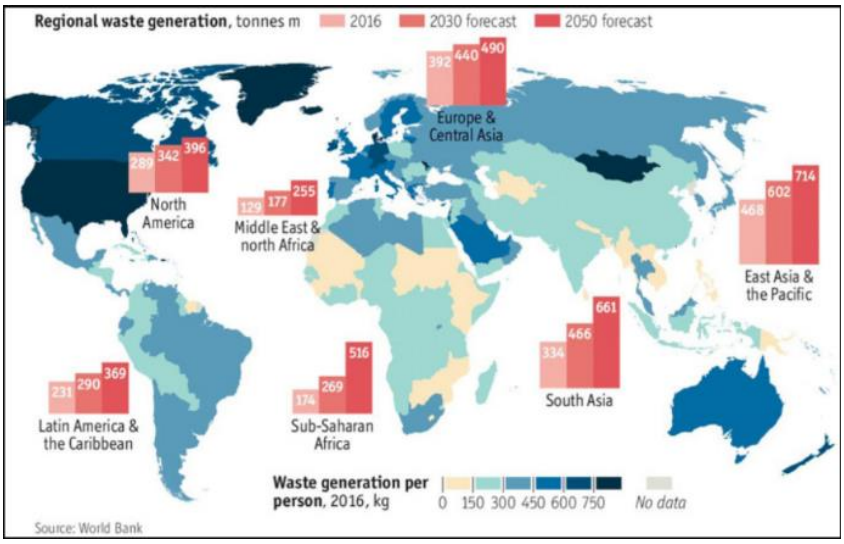


Fig. 3. Global waste generation trend and its projection [4]

Understanding future waste generation quantities and the characterization of waste is crucial for planning and implementing appropriate waste management and treatment strategies.

1.1.2 Environmental impacts

Uncontrolled, open dumping of waste on the peripheries of cities poses significant environmental and human health risks. This practice leads to the degradation of valuable land resources and creates long-term problems that affect both the environment and public health. The issues arising from indiscriminate dumping and open burning of waste led to urban air pollution.

In dumping site, this uncontrolled burning tends to release fine particles which cause of respiratory disease and cause smog [5]. In Mumbai, every year 22 000 tonnes of pollutants emits into the atmosphere due to open burning of wastes including of scrap tyres [3].

In literature reference of [6] investigate the environmental pollution and health associated effects due to waste landfilling and open dumping. This study reveals that the various environmental pollution problems due waste landfilling namely, (a) underground water pollution (b) air pollution (c) soil pollution and (d) health impacts due to pollution of underground water and the emissions of gases as depicted graphically in Figure 4.

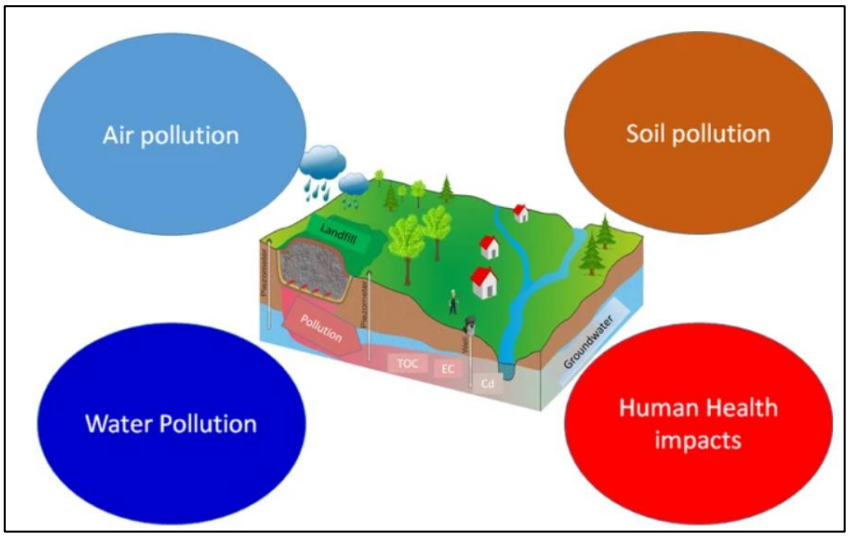


Fig. 4. Environmental impacts due to waste landfilling and open dumping [6]

Good waste management systems considerably mitigate these problems associated with improper waste disposal/open dumping.

1.2 Waste management practices

With increasing populations and rapid urbanization, the volume of waste generated has been increased which necessitate the implementation of sustainable waste management practices. Solid waste management is a comprehensive discipline involving the control of the generation, collection, storage, transfer and transport, processing, and disposal of solid wastes.

Effective management must consider public health, economics, engineering, conservation, aesthetics, and other environmental factors. Sustaining these practices is essential for both developed and developing countries, as well as for different settings such as urban and rural areas, and among residential, commercial, and industrial waste producers.

By adopting the "Three Rs" (Reduce, Reuse, and Recycle) and integrating various waste management strategies, both developed and developing countries can reduce environmental impacts, conserve resources, and protect public health.

Below Figure 5 represents the options adopted by specific regions from North America to East Asia and pacific [7]. Out of all, the recycling option found to be least, and this option must be enhanced/explored for higher consumption of waste and accordingly, elaborated herewith.

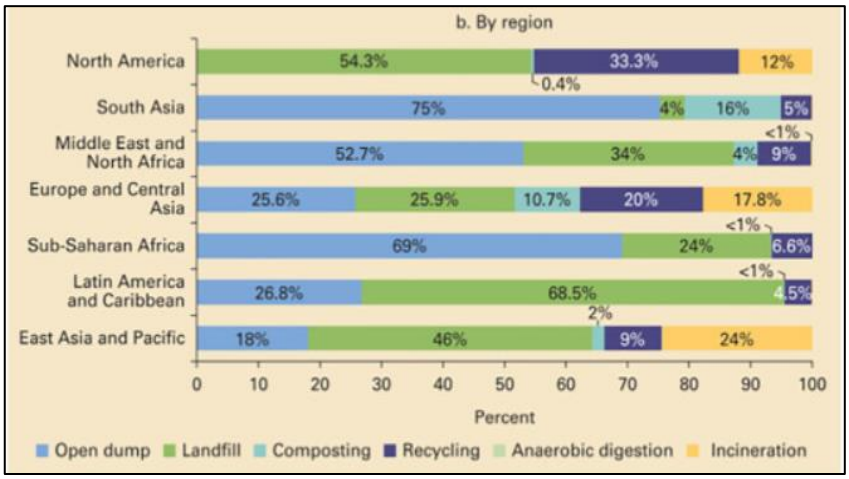


Fig. 5. Environmental impacts due to waste landfilling and open dumping [7]

1.2.1 Recycling

Recycling is a crucial method in sustainable waste management, involving the transformation of waste materials into new products that can be reused. This process not only helps in managing waste effectively but also offers environmental and economic benefits.

1.2.2 Recycling - Importance

The following are the recycling importance as follows:

- Recycle helps to minimize waste and saving of fossil
- Recycle helps to optimize use of available resources & reduced cost.
- Recycle helps to enhance organizational performance, credibility, & sustainability.
- Recycle leads to reduce the usage of fresh raw materials.
- Recycle helps to preserve natural resources and reduction of energy usage.
- Recycle helps to reduce air, water, and solid waste pollution.
- Recycle helps to reduce financial expenditure in the economy.

1.2.3 Recycling - Benefits

Recycling Saves the Earth - Recycling different products will help the environment. For example, paper is produced from trees, and its production leads to deforestation, habitat loss, and decreased biodiversity. By recycling paper, reduce the need to cut down trees, preserving forests and the ecosystems they support. By recycling various products, significantly reduce the strain on natural resources, minimize environmental pollution, and promote sustainability.

Recycling saves energy - Recycling often requires less energy than producing new from raw materials. For instance, recycling paper takes a lot less energy than creating new paper from trees. This energy saving reduces the environmental impact of energy production, including less energy to process recycled materials than to process virgin materials.

Recycling Mitigate Global Warming and Reduce Pollution - By saving energy in industrial production processes, recycling helps to lower the overall emissions of carbon dioxide (CO_2) and other greenhouse gases and minimizes the fuel use that emits harmful gases etc.

Recycling Reduces Waste Products in Landfill - Recycling diverts waste from landfills, reducing the risk of soil & groundwater contamination from landfill leachate. It also prevents the waste accumulation that degrades the land quality and disrupts the ecosystems.

Recycling helps to save Money - Recycling is not only benefit to the environment but also offers economic advantages. Recycling provides more ways to reduce expenditure for individuals, businesses, and municipalities etc. By selling recyclable materials tends to reduce production costs, and purchasing recycled products led to significant economic benefits too.

In literature reference of [8] aimed to use the Artificial Intelligence (AI) in recycling waste and in-turn using it to produce electric energy instead of fuel. When using this Artificial Intelligence in waste recycling, the waste collection process will achieve an unprecedented level of sustainability.

1.3 Geo-sustainability

1.3.1 Sustainability

It is an effective approach that helps to use of today's resources in an efficient manner for ensuring that resources are available and sufficient to meet today's and tomorrow (i.e. future generation) needs.

1.3.2 Sustainable development

A goal that is achieved by following a set of sustainability principles. Accordingly, the Sustainable Development Goals (SDGs) have been introduced by United Nation (UN). The 17 SDGs (as depicted in Figure 6) and 169 targets were adopted by all member states of UN in 2015, for the period 2016 to 2030 to address global environmental challenges by more sustainable approach.

Fig. 6. United Nation Sustainability Development Goals (UN SDGs)

1.3.3 Sustainable practices in civil engineering

Due to urbanization and infrastructure development, adopting sustainable practices is essential to reduce the environmental impact and to ensure a healthier planet for future generations. Few of the key sustainable practices followed in the civil engineering that can provide the way towards a sustainable future.

- *Green Building Design and Construction* - This involves the use of eco-friendly materials, adopting energy-efficient technologies, and implement innovative designs that reduce need of resources consumption and waste generation.
- *Selection of Sustainable material* - These uses recycled and locally available materials. Sustainable materials not only decreased resource usage but also reduce the increase of waste generation and result to a circular economy.
- *Energy-Efficient Structures* – Adopting smart/automated transportation systems, encouraging public transit, and integrating renewable energy sources into construction projects can substantially reduce greenhouse gas emissions and energy consumption. Sustainability in construction shown in Figure 7.

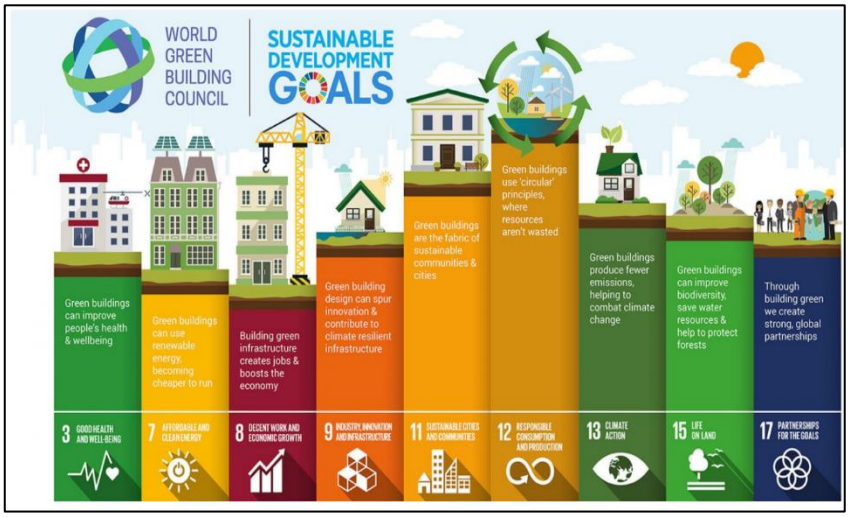


Fig. 7. Sustainability in construction: SDGs by the World Green Building Council

1.3.4 Sustainable practices in geotechnical engineering

Geotechnical engineering plays a vital role in the construction industry and has the potential to impact on sustainable development. Utilizing waste materials in geotechnical engineering is a wise choice and is also one step towards accomplishing overall sustainable development. Research has been progressed in previous studies include (1) Use of environment friendly materials in geotechnical constructions, (2) re-use of waste materials, (3) energy efficient ground improvement techniques, (4) bio- engineering techniques, (5) efficient use of geosynthetics, (5) sustainable foundation engineering practices, (6) implementation of geo-ethics in practice etc.

Recent studies in geo-sustainability are based on the common notions of sustainability like recycling, use of alternate materials and adoption of alternative technologies etc. Use of waste materials in geotechnical applications can lead to environmental and economic benefits,

contribute to sustainable construction practices. However, it is crucial to address the challenges associated with material quality, regulatory compliance, technical performance, and public perception to fully understand these benefits. By careful management, research, and stakeholder engagement, waste materials can become a viable resource in geotechnical engineering.

1.4 Sustainable Geo-material

In recent years, sustainability research in geotechnical engineering has increasingly explored the utilization of waste materials for ground improvement and construction applications. Here's is a study of how different waste materials such as fly ash, shredded waste tires, and Recycled Concrete Aggregates (RCA) can be beneficially utilized in geotechnical engineering field.
Wastes are generally considered as aggregates like material. Especially, dust wastes like Fly ash, cement kiln dust etc. are generally contributes to the physico-chemical properties of the material by entering a chemical reaction on fine-grained soils.
In other hand, the aggregate wastes like shredded waste tires, Recycled Concrete Aggregates, Natural fibers etc. generally to improve the physical & engineering properties of coarse-grained soils.
This study is to explore the possibilities of using different by-products like fly ash, shredded waste tires, and Recycled Concrete Aggregates (RCA) as geomaterials considered for beneficial re-use in geotechnical engineering practice.

1.4.1 Fly ash

Coal is used as a major source of energy throughout the world. Fly ash produced by burning of pulverized coal in a coal based thermal power plant. The burned pulverized coal produces almost 80% of fly ash and remaining will be bottom ash. If fly and bottom ash disposed into the pond it is termed as pond ash. The Indian fly ash powder size ranges from 1 to 150 µm and which is finer than Portland cement [9].
The morphology study of fly ash powders by scanning electron microscopy is shown in Figure 8(a) & Figure 8(b). The Energy Dispersive X-ray Spectroscopy (EDS) analyses the composition of fly ash powders depicted in Figure 8(c), depicts the presence of elements like silicon, calcium, aluminium, iron, oxygen etc. with other minor elements [10].
Generation and utilization percentage of fly ash in India for the last two decades can be seen in Figure 9. Increase of time, the gap between the generation and utilization has been decreased. More than 500 million tons of fly ash produced in a year globally out of that only 25 to 30% is re-utilized in different sectors [11]. In few previous decades, a percentage of fly ash has been used majorly in the construction industry.
When fly ash is mixed with free lime, it chemically reacts to form cementitious materials, strengthen the properties of the concrete. This has been successfully utilized in the construction industry for over 50 years, but its use is still lacking due to understanding its characteristics itself and the properties of fly ash mixed concrete [12, 13, 14].
Utilization of industrial by-products like fly ash for soil improvement/stabilization in the field of geotechnical engineering is a sustainable and cost-effective technique. Fly ash is an effective agent for chemical and/or mechanical stabilization of soils.
Fly ash when mixed with soil improves the properties of soil like density, water content, plasticity, strength & compressibility performance and hydraulic conductivity of soils etc. can be investigated with the conventional soil laboratory equipment.

Most of the previous research on the use of waste materials for ground improvement which has reported composite material of soil and materials like fly ash and lime can improve the soil's mechanical properties [15, 16].
Figure 10 represents the application of fly ash in various fields of engineering. At initial stage, the fly ash utilize starts from structural engineering, then gradually shifted towards chemical and other engineering applications. Especially for bulk utilization, the fly ash could be applied in geotechnical or transportation sectors.

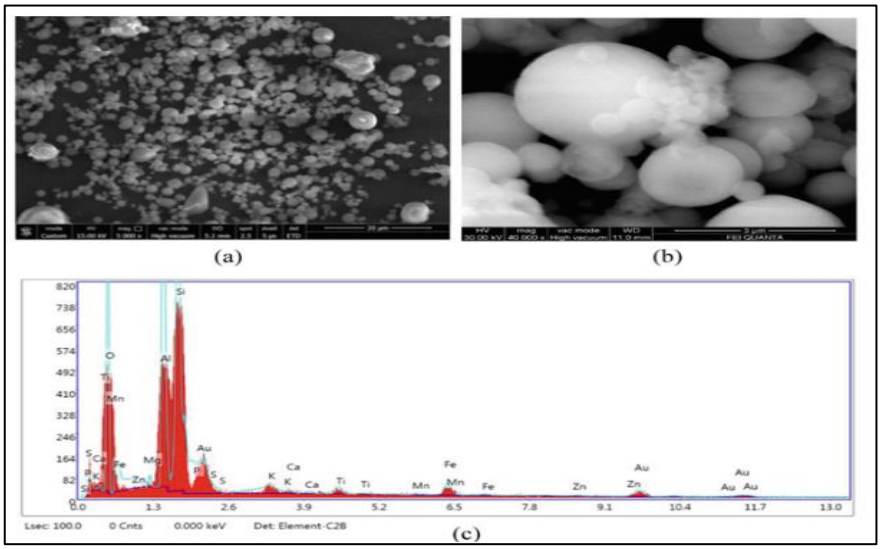


Fig. 8. Flyash powder: (a) Low magnification (b) High magnification (c) EDS of fly ash powder [10]

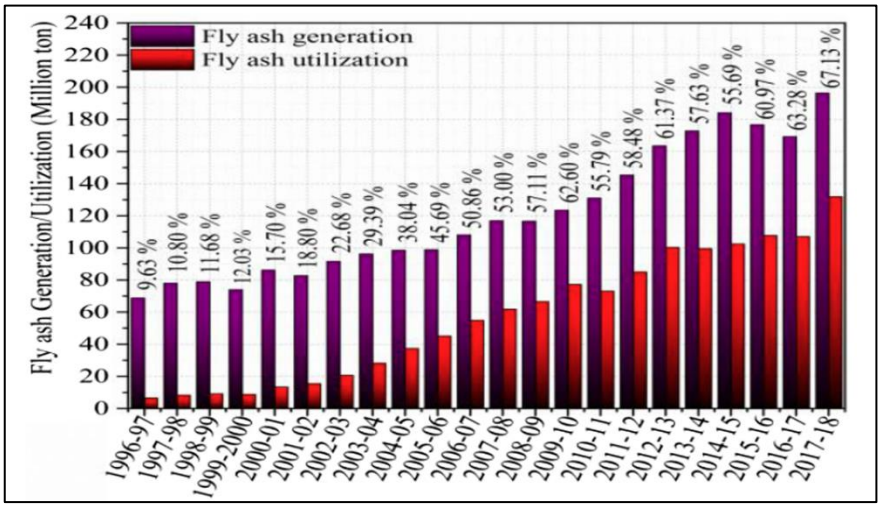


Fig. 9. Flyash generation and utilization trend in India [11]

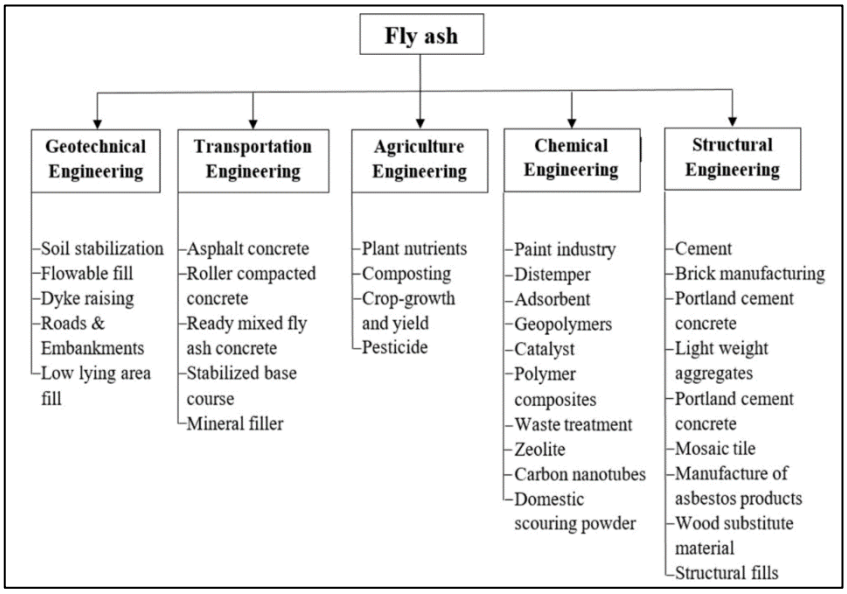


Fig. 10. Fly ash applications in different areas of engineering [11]

1.4.2 Shredded waste tires

Generation of waste tires may increase due to urbanization in developing countries such as India where the vehicles demand has been increasing trend and its accumulation in large volumes poses threat to the environment. Approximately, the 2.7 billion of waste tires are generated annually in worldwide, out of which 40% are from upcoming markets like India, China, South America, Eastern Europe, and South Africa as depicted in Figure 11. As per Expert Market Research (EMR), the Indian tyre market attained a volume of 179.16 million units in 2023. Durin the year 2024-2032, the market is estimated to grow annually at a Compound Annual Growth Rate (CAGR) of 6.68% which will reach a volume of 263.26 million units by 2032. Scrap/waste tires consist of rubber, steel wire and textile. To utilize scrap tires, it must undergo shredding process and shredded waste tires are classified as per Figure 12.

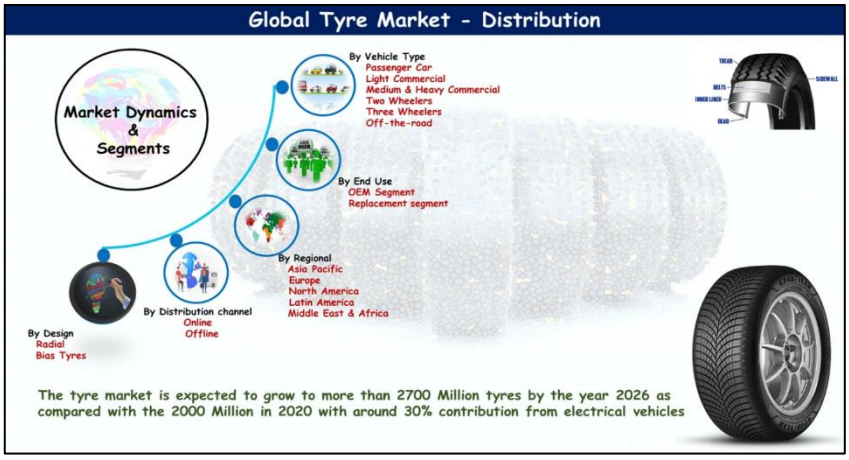
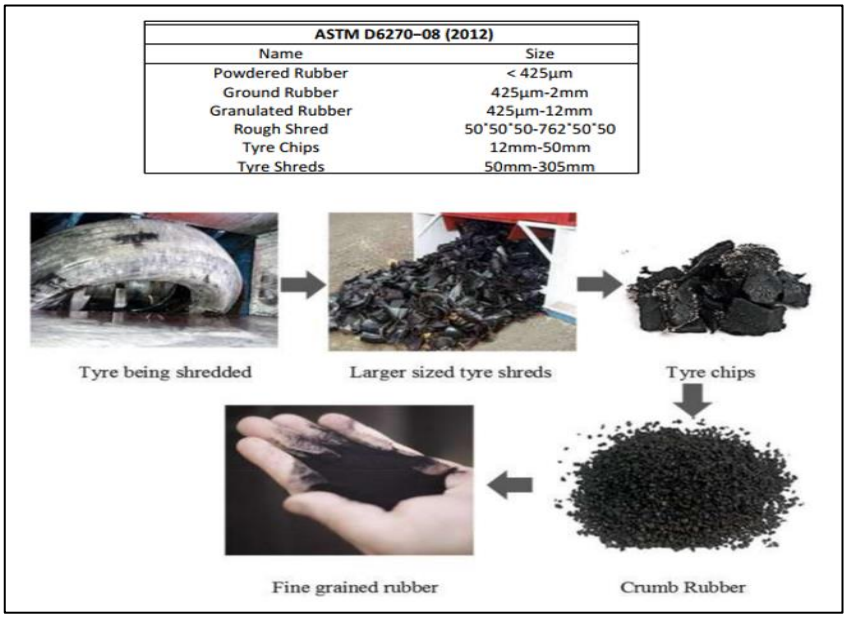


Fig. 11. Global tire market distribution [17]



ASTM D6270–08 (2012)	
Name	Size
Powdered Rubber	< 425µm
Ground Rubber	425µm-2mm
Granulated Rubber	425µm-12mm
Rough Shred	50˜50˜50-762˜50˜50
Tyre Chips	12mm-50mm
Tyre Shreds	50mm-305mm

Fig. 12. Visual representation for type of processed scrap tires

Four advantages in use of waste tires may be offered in geotechnical applications; (1) Reduce environmental health hazards (2) Decrease landfill space in turn reduce costs to maintenance (2) conserve natural soil and its cost saving benefit, (3) act as soil reinforcement, (4) act as energy dissipater when subjected by dynamic loads. Waste tires can be used alone or mixed with soil as geo-material in civil engineering applications [18-21]. Effect of shredded waste tires on shear strength, stiffness and compressibility characteristics of soil can be investigated with appropriate soil laboratory equipment. Figure 13 shows the life cycle of tires and civil engineering applications of scrap tyres.

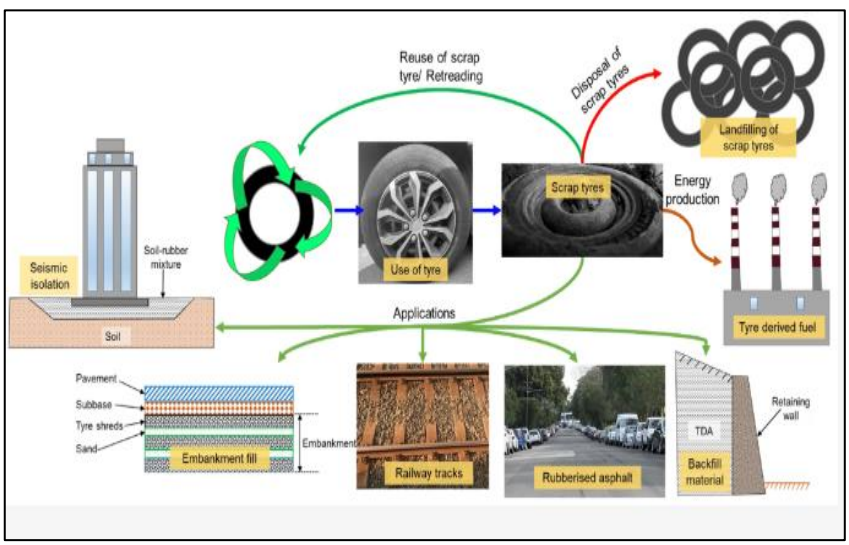


Fig. 13. Application of scrap tires in civil engineering [22]

1.4.3 Recycled Concrete Aggregate

Due to urbanization and industrialization, many old buildings are being demolished after its life, resulting massive amounts of Construction Waste (CW). India's CW production of 150 million tons annually contributes to 35%-40% of the global Construction & Demolition (C&D) waste, yet only 1% is recycled in India according to the estimation of Centre for Science and Environment. In worldwide, C&D waste has been recognized as a substantial portion of solid waste, contributing almost 30%-40% of global every year [23]. As per demolition and construction waste management global market report 2023, the market size is expected to increase to $243.56 billion in 2027 at a Compound Annual Growth Rate (CAGR) of 6.6%. Recycled Concrete Aggregate (RCA) is a result of the demolition activities of concrete structures and buildings. Concrete is crushed into aggregates of different sizes depending on the applications. Typically, the particle sizes ranging from 20 mm to 38 mm. RCS properties dependents on the various factors such as properties of original concrete, age, and type of crusher used etc. Overview of RCA production process is depicted in Figure.14.

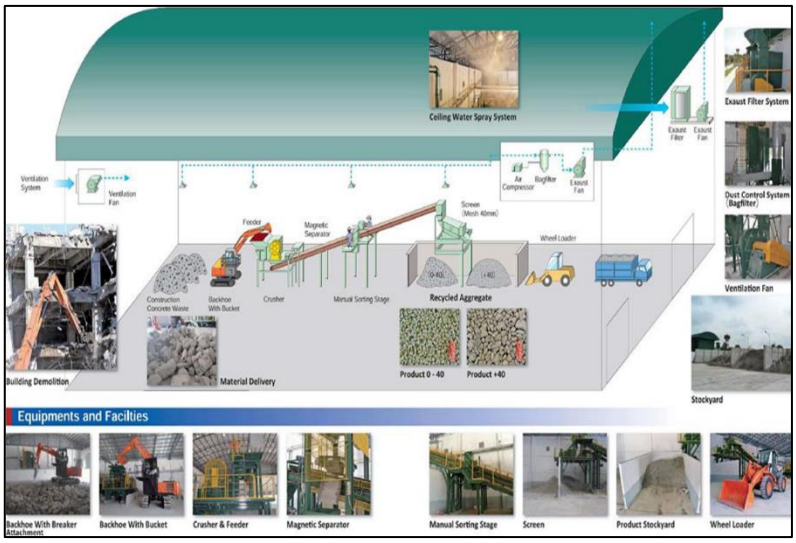


Fig. 14. Overview of Recycled Concrete Aggregate (RCA) manufacturing process [24]

Fig. 15. Some of RCA applications in geotechnical engineering [27]

Recycled concrete aggregate (RCA) could be an effective "earthen" material used for geotechnical engineering applications, such as backfill, ballast, or foundation soil [25]. Effect of this RCA material on strength, stiffness and compressibility characteristics of soil can be investigated with appropriate soil laboratory equipment. Reuse of C&D waste, mainly in geotechnical engineering, may substitute natural granular materials which is possible to use in the construction of roads [26], in ground improvement (stone columns created by dynamic or vibro replacement) and means of steel gabion or polymer mattresses filling [27] as shown in Figure 15.

2 Conclusions

With the world population increasing, the amount of waste generation is growing rapidly, and it causes a huge rise in the cost of waste disposal and environmental hazards. Identifying the feasible and cost-effective sustainable solutions for waste material disposal, including recycling, is a responsibility shared among scientists, engineers, researchers, and governments. Currently, the applications of waste by-products like Fly ash, Shredded waste tires and Recycled Concrete Aggregates etc. in geotechnical engineering is one of great interest in research and development as explored in this study. As the previous studies confirmed that the re-use of waste materials such as Fly ash, Shredded waste tires and Recycled Concrete Aggregates etc. could be better alternative materials in geotechnical engineering projects. Re-use of these waste materials can be used as a soil stabilizer/ reinforcing material with its application being used in various structures such as embankments, pavement, retaining walls, landfill, subgrade in roads etc. Accordingly, the information provided will be highly valuable for engineers and contractors to insight alternative solutions and promotes the rational use of sustainable geo-materials in various applications.

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