Sustainable Utilization of Lightweight Waste Materials as Structural fill for Geotechnical Applications

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Abstract. In spite of the development foreseen by our economy over this century, abundant quantity of waste materials is being generated in various sectors such as transportation, power generation and industries. Meanwhile, constructional activities across the globe demand virgin natural materials. This paper emphasis a review on the use of some of the waste materials like Fly ash (FA), Bottom ash (BA), Tire derived Materials (TDM) in lieu of natural geomaterials as lightweight fills for retaining walls and embankments. A brief review of the engineering behavior of these waste materials which makes them a competent fill material will be presented here. Further full scale and model studies of embankments and retaining walls utilizing these wastes for fill application is also emphasized. The results of these studies have shown that these waste materials can act as competent fill material for geotechnical applications.

1. Introduction
The innovative utilization of waste materials like waste tires, coal ashes, mine tailings is one of the major issues addressed by scientists and environmentalists all over the world, which otherwise would find a place in landfills, open dumps, ash ponds, etc. A great concern is raised by these wastes as this would affect the quality of groundwater. Consequently, reduce, reuse, and recycle are considered to be sustainable options.

End of Life Tires (ELTs) has proven to be one of the valuable resources as far as their specific characteristics, strength, flexibility and durability are considered. Developed countries have effectively practiced the collection, recovery and recycling process. In Europe, 91% of the ELTs were further utilized for energy recovery, recycling and civil engineering applications in 2017. Even then, there is limited utilization of scrap tires for civil engineering works except in the case of Finland, where the utilization has crossed 98%[1]. The US has reported the 99.1% of used tires further utilized for recycling and reuse purposes[2]. However, studies reveal that an enormous quantity among this is still used as Tire Derived Fuels (TDF) for paper mills, cement, electric utilities, industrial boilers resulting in the emission of large quantities of carbon dioxide. Developing country’s experience in dealing with ELT’s is worser, necessitating more innovative solutions incorporating scrap tires in projects requiring huge quantities of earthwork. ELT’s has got greater acceptance in the transportation sector, necessitating the construction of embankments, retaining walls, bridge abutments on very weak and compressible soils. Several studies have been conducted to study the efficacy of TDM-sand mixtures in the geotechnical field, where an enormous amount of earthwork is needed. Besides, scrap tires have proven their potential as sound barriers in roads and railways, ground rubber applications, sea wall protection, embankment construction, crash barriers, landfill cover systems, seismic isolation systems, etc. [3].

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India relies on coal as one of the vital sources of power generation. India has abundant reserves of coal among the fossil fuel, which enhances its usage in the power generating sector. The ash generation of Indian coal is high, approximately 31% against 15% for imported ones[4]. This ash mainly constitutes 80% of fly ash and 20% of bottom ashes. According to Senapati[5], 82,200 hectares of land would be utilized as ash ponds by 2020.

Consequently, government regulations enforce the usage of coal ashes for road construction, fly ash blocks for construction activities, dyes, fertilizers, etc., within 100 km near coal fired thermal power thermal power plants. Even then, 32.87% is still unused or gets deposited in ash dumps. Researchers were focused highly on the engineering properties of these coal ashes alone and its mixed form with other materials to ensure their utility in embankment fill and retaining wall backfill, foundation, etc., thereby preventing the extrusion of natural materials for geoengineering applications.

This paper presents a review of Tire-Derived materials (TDM) and coal ashes for earth fill applications in retaining wall and embankments. The study also explains model studies pertaining to their application in lightweight engineered fills.

2. Scrap Tires and Its Derivatives
TDM exhibits low density, high thermal insulation capacity, high compressibility, excellent drainage capability, good vibration absorbent, insulation layer to prevent frost penetration, resiliency, and high frictional resistance, makes it ideal for embankment applications[6, 7]. The shredding of whole tires resulted in the TDM of various sizes and shapes. TDM is mainly classified into three based on their size 1) granulated rubber(0.3 mm-12mm), 2)Tire Chips 12-76 mm, and 3)Tire shreds(76-306 mm)[6]. The specific gravity of tire shreds is in the range of 1.13-1.36[3], friction angle between 19° and 30°[8, 9]

A comprehensive review of literature has shown the utilization of tires in two different ways, stand-alone application and composite application. The Stand-alone application implies the usage of tire shreds in its pure form, either without shredding or in the form of shredded tires alone. The Composite application allows the mixing of tire-shredding with soil or other materials. Both this application has shaped an environmentally sound and sustainable option for the disposal problems addressed by our society. The direct exposure of tires to solar radiation creates fire hazards due to exothermic reactions involved[10, 11]. High thermal insulation capacity might have caused the retention of heat accompanied by the higher thickness of the fill, and exposed metal fragments resulted in the fire hazards[6]. Several innovative examples of stand-alone applications were enumerated earlier[12-14]. The behavior of sand-TDM mixture for fill application will be enumerated in the following section:

2.1. Sand-TDM Mixture
The use of sand TDM mixtures for fill application has been explored since 1990s. Previous researchers have studied the stress-strain and compressibility characteristics of sand TDM mixture and found their importance for the stability and serviceability of engineering structures[15, 16, 8, 17, 13, 18, 19]. The main problem of using TDM alone for the fill application is their higher compressibility with regard to sand or soil. Preloading the fill by soil cap of sufficient thickness greatly alleviates this problem as most of the plastic compression will be completed in the first stage of loading[20]. The plastic strain gets diminished by the addition of sand to TDM.

The friction angle, cohesion values for rubber shreds vary between 19°-30°, 3kPa -11kPa and unit weight between 2.4 kN/m and 7 kN/m [6, 8, 9]. The elastic parameters of TDM mix, E and μ vary between 770kPa -1530 kPa and 0.18-0.36[9]. For comparison, Humphrey et al. [9] reported an elastic modulus for granular materials between 10000 kPa-170000 kPa. Ambazagan et al.[21] reported a friction angle and cohesion intercept for granular rubber sand mix of 35° to 41°and 6.16 kPa to 12.45 kPa respectively for sand-granulated rubber mix. Foose et al. [8]observed a friction angle between 25° and 67° for tire shred sand mix. The mechanical property of these waste hence proved their utility as geomaterial.

The following properties of TDM sand mixture have found to have influenced the shear strength and compressibility characteristics of sand -TDM mix:
2.1.1. Mixing Ratios
Despite the increase in shear strength shown by tire shreds/tire chips and sand mixtures, there are anomalies in the results with granular rubber. The TDM-sand mix generally indicates increased friction angle and shear strength to an optimum percentage [15, 3, 8, 22, 19]. Tire shreds reinforce the sand, similar to the fiber reinforcement, the apparent cohesion developed due to the interlocking of tire shreds and sand[15, 19]. However, granular rubber mixed with sand shows a decreasing shear strength with an increase in TDM content in the mixture[23, 18]. Attom [24] and Mashiri et al.[25] has observed an increase in the shear strength with an increase in granular rubber content. The argument justifies this behavior that the voids between the rubber is occupied by the sand or vice versa, which provides the bonding and cushioning effect, creating resistance to shear[26, 21].

2.1.2. Confining Pressure and normal pressure
Increase in confining pressure increases the shear strength characteristics and decreases the dilatancy effects[15, 25, 18, 19]. The increased interaction between the sand matrix and TDM might have caused this effect. The effect of tire shreds is well pronounced at low and moderately high confining pressure and insignificant at high confining pressure[22, 19]. Similarly, in the direct shear test, an increase in shear strength with TDM is well recognized for low and medium normal stresses. However, their influence gets diminished at higher normal stresses[16]. An increase in the confining pressure has decreased the dilation characteristics of sand TDM mixtures[25]. Anvari et al. [27] observed a decrease in shear strength improvement with an increase in the normal stress due to the increased contact that may arise between the sand and TDM.

2.1.3. Aspect Ratio
The length to width ratio of TDM plays an important role in the reinforcing tendency of the fibres in soils. Zornberg et al[19] used tire chips of width 12.7 mm and 25.4 mm with an aspect ratio of 1,2,4 and 8 and found an increased shear strength with an increase in aspect ratio attributed to the increased cohesion intercept. Ghazavi and Sakhi[17] used tire chips of 2,3 and 4 cm with an aspect ratio ranging between 1-8, and it is found that for a particular width there exist a length of tire shreds sufficient to cause the necessary reinforcement effect.

2.1.4. Relative density
Relative density has a vital role to play considering the mechanical property of any geomaterial. Anvari et al. [27] used granulated rubber-sand mixture at different normal pressure and relative density. They found that five percentage of granulated rubber in the mix resulted in maximum shear strength improvement for 50 percent relative density. However, for 70% and 90% relative densities, shear strength improvement decreases. Zornberg et al. [19] observed an increase in the relative density, influences the sand TDM mixture as long as the TDM content in the mix is below 30%, but this effect is less than that observed in pure sands. Foose et al. [8]found that sand-tire shred mix exhibit an increase in the friction angle than sand with an increase in the sand matrix unit weight.

The binary packing of the material is also important considering the use of composite material like sand and TDM for geoenengineering applications. An important issue dealing with the sand TDM mixture is their higher segregation potential. According to Lade et al. [28], fine particles initially occupy the voids between the coarse particles, which substantially floats in the mix when entire voids in the mixture get filled with fine particles and increase the void ratio. Sand-TDM composite mix has exposed three behavioral zones mainly attributing their transformation from sand-like behavior to rubber-like behavior. The end of Zone 1 shows the limit in which the TDM starts forming the skeleton from being completely sand-like behavior. The end of zone 2 depicts the limit in which the sand stop forming the skeleton or the start of complete dominance of TDM particles[25]. The highest shear strength is observed in the transformation zone by most of the researchers[15, 29, 25, 19].
3. TDM for fill Applications

There are many studies that illustrates the use of TDM-Sand mix as backfill material. Cecich et al. [30] and Tweedie et al. [31] studied the suitability of using TDM as backfill material for a cantilever retaining wall constructed on sandy silty clay. These studies have revealed that construction cost and horizontal pressure reduced by 65% and 45% respectively. Embankment constructed with tire chips, chips/soil mixtures, and layered chip soil arrangement has shown comparable performance to gravel roads if provided with soil cap of sufficient thickness[20, 32]. Salgado et al.[33] adopted the optimum tire content(50:50) by volume in the sand TDM-sand mix to study its performance as an embankment fill. There is little lateral movement and differential settlement observed. Reddy and Krishna [34] performed the static analysis of a model retaining wall 600mm height with sand-TDM mixture. It is found that optimum TDM content is about 30% by weight of the mix since the lateral displacement at the top of the retaining wall and lateral earth pressure at rest is found to be less for this optimum content.

Moghadham et al. [35] studied the behavior of a mechanically stabilized wall backfilled with recycled crumb rubber (RCR) sized between (3.35 mm-4.75 mm) reinforced with circular and square plate anchors. The bearing capacity of the fills is at its peak for 15% recycled crumb content and, 20% tire crumb has shown the least lateral movement. Shrestha et al. [36] studied the performance of a cantilever retaining wall backfilled by tire crumb-sand mix and found that the volume of excavation and concrete is efficiently reduced. Djadouni et al.[37] compared the performance of a cantilever retaining wall backfilled by traditional granular materials and sand tire shred mix in different proportions 0.16,5,29,16, 39,37,50,66,54 of total weight using RS software. Sand tire chips mixture having 66.54 percent of rubber has shown desirable effect and maximum factor of safety without the application of surcharge. Tajabadipour et al.[38] investigated the performance of a geosynthetic reinforced soil wall backfilled using different arrangements and ratios of sand tire crumb mixture using PLAXIS 2D. The reinforced zone is divided into four different height of 2.5 m, comprising a total height of 10m, and each 2.5 m is filled with different soils/soil tire crumb mixtures. The composite arrangement with sand on the bottom layer and tire crumb sand mixtures in the subsequent layers has shown the best among the different configurations. The use of tire crumb sand mixture in the foundation soil has been found to be undesirable since horizontal displacement and vertical settlement increase. The effect of geogrids in tire crumb sand mixture is not well pronounced.

Interaction of sand tire chips mix with geosynthetics is one of the crucial characteristics to analyze the applicability of tire-derived materials and sand mixtures in reinforced walls and embankments. Only a few studies encompass the pull-out characteristics of geogrids in sand tire shreds mixture[39-43].

4. Coal Ashes

Coal ashes, fly ash and bottom ashes behave as excellent geomaterials and address environmental issues associated with its disposal in ash ponds. The combustion of coal mainly results in the generation of non-combustible products, fly ash (FA) and bottom ash (BA). FA escapes with flue gases and accumulated in the electrostatic precipitator and BA remains as non-combustible and gets collected at the bottom of the furnace. BA is greyish-black dust angular, rough texture with some particles being round and popcorn structure. The specific gravity of bottom ash may increase or decrease depending on the iron content and porous surface texture of bottom ash. BA has got excellent geotechnical properties like low compressibility, low unit weight, high CBR, high rate of consolidation, high shear strength characteristics and low swell shrink potential [44]. Currently, BA finds its application in 1) dyes, 2) substitute for fine aggregate in concrete, 3) structural fillers, 4) road base material, and 5) soil stabilization[44]. FA is greyish and constitutes the highest percentage in coal ashes, about 75-80%. They comprise mainly silt size particles with little clay-sized particles. The major utilization of FA for the period of 2017-18 in India is attributed for: 1) cement 2) Minefilling 3) Bricks and tiles 4) Reclamation of low-lying area 5) Ash Dyke rising 6) Roads and flyover 7) Agriculture 8) concrete. Still, 32.87 percent is still unutilized and dumped in ash ponds[4]. The properties of bottom ash and fly ashes are summarized in table 1.
4.1. Characterization of fly ash /bottom ash Mixtures
Huang et al. [45] studied the properties of bottom ash to find the viability of using them as highway fills for select subgrades and stabilized and unstabilized bases. The particle distribution ranges between 75 µm-600 µm. A relatively high degree of permeability is observed in the bottom ash. The degradability under load of bottom ash determined from Los Angeles abrasion test ranges between 27-53 percent.

| References  | FA  | BA  |
|-------------|-----|-----|
| Specific Gravity | 2.5 | 2.1 | 2.07 and 2.35 |
| Dry Density(kN/m^3) | 11.47 | 12.54 | 9.41 and 13.76 |
| Optimum Moisture Content | 36 | 20 | 20.4 and 24 |
| Cohesion(kPa) | 0 | 4.2 | 0 |
| Friction angle | 35 | 33.2 | 32-44 |
| Hydraulic Conductivity(cm/s) | 10^{-4}-10^{-2} | - | - |

Table 1: Characterization of FA and BA Mix

| References  | FA+BA Mix  |
|-------------|-------------|
| Specific Gravity | 2.54 | 2.08-2.38 | 2.30-2.80 |
| Dry Density(kN/m^3) | 15 | 13.8-15.3 | 14-18 | 10.8-15.4 |
| Optimum Moisture Content (%) | 19 | 15.9-25 | 15-25 | 26.8-45.7 |
| Friction angle | - | 31-43 | 32-47 | 20.8-50.7 |
| Hydraulic Conductivity(cm/s) | - | - | 1 x10^{-5}-3x10^{-6} | 1.4x10^{-3}-2.7x10^{-7} |

Table 2: Characterization of coal ash mix as a geomaterial

4.2. FA and BA as embankment fill material
Research experience has shown that the FA and BA and their combination with soil act as an excellent geomaterial. Toth et al. [46] reported coal ashes in embankment construction and reclamation project on coal landfills. He demonstrated the following projects concerned with the fly ash embankment and fills: 1) An embankment constructed using fly ash 2) Embankment constructed on silty clay with the bottom layer and top by bottom ash to prevent frost penetration 3) Shale quarry reclaimed for residential purposes 4) Industrial building partially built on coal ash filled for agriculture land and partially silty clay till. The embankment shows good performance with less settlement and shale quarry fill has shown sufficient bearing capacity and settlement happens within one hour after loading the fill. Kim et al. [51] studied the effect of relative compaction 90% and 95% on the mixture of fly ash and bottom ash in the ratios of 50:50, 70:30, and 100:0. The increased percentage of FA in the mix decreases the maximum dry density and increases the optimum moisture content. Similar results is visualized by Muhunthan et al. [52]. The reduction in the dry density is attributed to the excess voids created or floating FA particles over ash mixtures. Peak friction angle is also found to increase with an increase in BA content in the mix. Yoon et al. [49] evaluated the performance of an embankment constructed with bottom ash fly ash mix in the ratio of 60:40 and height 60 cm. The combined specific gravity of the mix is about 2.54. The differential settlement is below 5mm and has observed only little lateral movement. The addition of
bottom ash to dredged soil, cement and rubber increases the secant modulus and unconfined compressive strength of the geocomposite[4, 53, 54]. Pant et al. [48] and Pant et al. [50] studied the viability of BA and coal ash as backfill material in reinforced soil structures using interface studies. The pull-out strength of geogrids placed in BA under different placement conditions is examined. The friction angle of sand and bottom ash and their interaction coefficient is comparable, and uncompacted mixture show-interaction coefficient lesser than compacted mixtures. The dilation at low normal stresses and pull-out resistance decreased for coal ash mix having greater FA content.

An attempt to progressively replace the sand in sand particulate rubber (0.425-2mm) mixture by FA in 50:50 percentage of particulate rubber [55]. The particulate rubber sand mix and particulate fly ash mixture have shown resistance against segregation and compared to the sand particulate rubber mixture, FA particulate rubber mixture has shown lesser compressibility and higher friction angle. Similar to the studies conducted on sand tire shreds/chips mixture [56, 34, 33] Prabhakara et al. [57] found out the optimum content of granular rubber in the mix of FA. Fly ash samples FA1 and FA2 obtained from two different thermal power plant was chosen for the study. The FA and granulated rubber mixture were compacted to relative compaction of 95 percent or more. The optimum ratio of granulated rubber is 54-100% for FA1 and 81-185% (by weight of fly ash). The shear strength at optimum percentage is found to be comparable with previous studies.

5. Conclusions
TDM and coal ashes exhibit excellent engineering properties indicating the viability of using them as a geomaterial. These wastes are lightweight compared to the conventional materials used for fill applications, which results in lighter structures of retaining wall and lightweight embankments over weak and compressible grounds. Tire shreds in the sand show similar behavior as fiber reinforcement, providing sufficient shear strength improvement by the tensile force imparted in the tire shreds in addition to the shear mechanism between the two materials. Full scale and model studies have also proved their innate potential in lieu of conventional geomaterials.

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