Review

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Use of Alternative Materials in Sustainable Geotechnics: State of World Knowledge and Some Examples from Poland

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Review

Use of Alternative Materials in Sustainable Geotechnics: State of World Knowledge and Some Examples from Poland

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Featured Application: This article presents in a systematic way the origin of alternative materials considered for use in geotechnics, mainly in strengthening weak soils. A concise review can help designers and contractors of earthwork projects in choosing the appropriate soil additive(s) and methods, with this article also highlighting pertinent bibliographic sources regarding the various waste materials.

Abstract: Geotechnical engineering projects carried out within the framework of the low-emission economy and the circular economy are the subject of many publications. Some of these studies present the use of various waste materials, as soil additives, for improving geomechanical behavior/properties. Many of these materials are eagerly used in geoengineering applications, primarily to strengthen weak subsoil, or as a base layer in road construction. Information on individual applications and types of these materials is scattered. For this reason, this article briefly discusses most of the major waste materials used for achieving weak soil improvement in geoengineering applications, and highlights pertinent bibliographic sources where relevant details can be found. The presented list includes waste from mines, thermal processes, end-of-life car tires, chemical processes (artificial/synthetic fibers), and from construction, renovation and demolition works of existing buildings and road infrastructure. In addition to the positive impact of using waste instead of natural and raw materials, the paper encourages the reader to ponder whether the waste used really meets the criteria for ecological solutions.

Keywords: sustainable geotechnics; alternative materials; mining wastes; thermal process wastes; rubber wastes; natural wastes; chemical fibers; construction wastes

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1. Introduction

The title of this article refers to sustainable geotechnics (and in a broader sense geoengineering), that is, the activities in the field of civil engineering [1,2] that are undertaken in the spirit of the low-emission economy and the circular economy within the European Green Deal [3]. In the context of geotechnics, such activities are related to, among others, the use of waste materials in soil mixtures, soil–cement mixtures or in the form of independent sub-base layers (e.g. a layer of rubber tires), and the development of technology for works with the minimum possible carbon footprint. Many books and articles have been published in this area. Most of them are dedicated to one specific group of waste material, but not necessarily in geotechnical engineering applications. On the other hand, there are review publications [4], mainly on natural waste materials, whose application in geoengineering in most cases has not gone beyond laboratory investigations [5,6]. In this case, one of the main obstacles is basically the complete lack of legal regulations related to the use of these materials in engineering practice [6]. The work of Jastrzębska et al. [7] is of a slightly different nature, in which the authors synthesize selected waste materials, which they call alternative materials, that is, materials that have lost their status of waste and can be used as substitutes for traditionally used materials. At the same time, the appropriate legal regulations that are in force in Poland are indicated.

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The presented article builds on the work of [7] and at the same time is an attempt to answer the question of whether the various waste materials used actually meet the criteria for ecological solutions.

2. Legal Conditions in Poland

The use of waste materials is regulated by a number of laws and regulations, and by appropriate standards and quality certificates. In Poland, these include, among others:

- Waste Act [8];
- Regulation of the Minister of Climate on the Waste Catalog [9];
- Act for the Prevention and Repair of Environmental Damage [10]
- Construction Law Act [11],
- The Geological and Mining Law Act [12],
- Documents authorizing products to be placed on the market and used in construction – European Technical Assessment (ETA) or National Technical Assessment (NTA).

The use of any waste material must meet legal and environmental requirements, and, at the same time, meet the criteria of applicable standards or guidelines for specific use in construction (an important role of accredited laboratories).

3. Division of Waste Used in Geoengineering

Alternative materials in the context of geotechnical engineering applications include [7]:

- Byproducts generated during the extraction of minerals in the broad sense, in particular hard coal (burnt and unburnt shales), brown coal (rocks and soils from the overburden and interbeds), metal ores, rock salt, rock raw materials, and natural aggregates.
- Waste from industrial production, especially from thermal processes occurring in power plants (fly ash from conventional or fluidized boilers; slags), steelworks (blast furnace and steel slags), and plants producing mineral binders (fine clinker dust).
- Post-consumer, post-renovation, or dismantling products originating from private farms or the construction industry, including the road construction industry (concrete aggregate and construction rubble; ceramic or glass cullet).
- Used rubber materials, including primarily car tires and their shredded parts (tire derived aggregate, TDA).
- Natural products from agricultural, breeding, and food production: plant fibers from various parts of plants, animal fibers, wool, hair, secretions, feathers; coffee grounds; egg or shell shells; ashes from the combustion of biological substances (e.g., from municipal waste, rice husks, coffee husks, wood, etc.).
- Chemical waste in the form of artificial fibers based on natural biopolymers (cellulose, protein, rubber, etc.) and mineral raw materials, and also synthetic fibers produced from synthetic polymers in the processes of polymerization and polycondensation of organic compounds, such as crude oil or coal (polypropylene (PP), polyester (PET), polyethylene (PE), polyvinyl (PVA) fibers), or composite materials.
- Other materials that have ceased to be waste.

Figure 1 presents a schematic division of the alternative materials selected for used in geoengineering applications.

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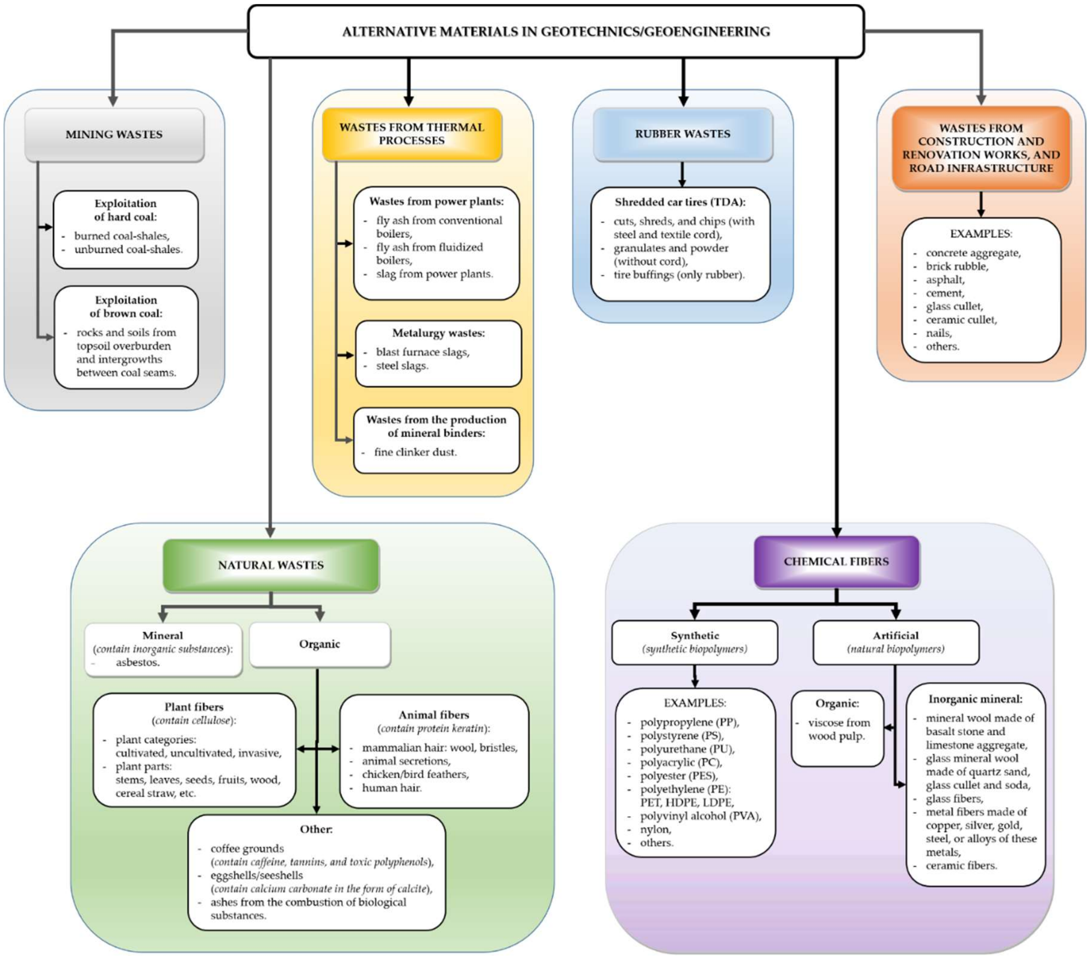

Figure 1. Division of alternative materials for use in geoengineering applications.

4. Industrial Wastes

The group of industrial wastes used in geoengineering includes: unburned black coal-shales, burned red coal-shales (primary waste thermally transformed as a result of spontaneous combustion of the black coal-shales), power plant fly ash/bottom ash, slag and ash from biomass combustion, blast furnace and steel slag, fine clinker dust. A common feature of all these wastes is their very large diversity in terms of mineralogical composition (within the same waste) and their variability of physical and mechanical properties. This fact is influenced by [13,14,15]:

- The extraction process and the method of enriching minerals.
- Method and time of waste storage.
- Conditions (temperature, precipitation).
- Combustion technology (including combustion temperature) and exhaust gas purification, as well as the properties of the input materials.

A good example of such influences, not necessarily beneficial, is the fact of a change in the grain size of the material over time (i.e., reduction of the coarse-grained fraction in favor of the sand and fine-grained fractions) due to weathering changes in the landfill, especially in unburned coal-shale. A similar effect is observed during the deliberate compaction of the mining of shales, for example, in the process of incorporation of the shales into the construction of an embankment or substructure [16]. Although in the case of burned shales, the weathering processes and grain crushing are much weaker and the waste material itself becomes resistant to soaking and swelling due to the effect of exposure to high temperature combustion (causing elimination of clay minerals), changes in physical

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and strength parameters are also observed. This can be evidenced by the change in, among others [17,18,19]:

- Coefficient of uniformity (C_U): **black shale** directly from the mine – C_U = 4–160, fresh from the dump – C_U = 22–170, aged from the dump – C_U = 14–2740, **after burning** (i.e., red shale) – C_U = 25–420.
- Optimum moisture content (w_{opt}): **black shale** directly from the mine – w_{opt} = 7–12%, fresh from the dump – w_{opt} = 9–16%, aged from the dump – w_{opt} = 8–20%, **after burning** – w_{opt} = 8–12%.
- Maximum dry density (ρ_{ds}): **black shale** directly from the mine – ρ_{ds} = 1.7–1.9 Mg/m^3, fresh from the dump – ρ_{ds} = 1.6–1.9 Mg/m^3, aged from the dump – ρ_{ds} = 1.2–2.0 Mg/m^3, **after burning** – ρ_{ds} = 1.6–1.8 Mg/m^3.
- Permeability coefficient (k) at a compaction coefficient equal to I_s = 0.95: **black shale** directly from the mine – $k = 10^{-4}$–10^{-5} m/s, fresh from the dump – $k = 10^{-4}$–10^{-6} m/s, aged from the dump – $k = 10^{-4}$–10^{-8} m/s, **after burning** – $k = 10^{-5}$–10^{-6} m/s.
- Internal friction angle (φ) at I_s = 0.95: **black shale** directly from the mine – φ = 38–47°, fresh from the dump – φ = 36–42°, aged from the dump – φ = 30–46°, **after burning** – φ = 26–42°.
- Cohesion (c) at I_s = 0.95: **black shale** directly from the mine – c = 4–35 kPa, fresh from the dump – c = 21–33 kPa, aged from the dump – c = 10–50 kPa, **after burning** – c = 5–12 kPa.

The basic application of coal-shales is their use as a material for leveling land depressions and sinkholes caused by mining/opencast mining, for the construction of embankments of rivers, streams and water reservoirs, settling tanks and landfills for industrial and municipal waste, construction of railway and road embankments, as well as road construction layers. It should be realized that such a large variability in the geoengineering parameters characterizing a given waste requires a number of basic tests to be performed before its reuse, which include, among others, determination of: composition and grain size parameters, compaction parameters, permeability coefficient, swelling parameters, frost resistance, strength parameters, organic matter content, sand equivalent value of soils and fine aggregate, California Bearing Ratio (CBR), abrasion resistance. In turn, during the use of geoengineering structures containing shales, it is recommended, especially in the first years, to monitor the quality of water in contact with the waste material.

The power plant waste generally does not contain hazardous substances in quantities that could pose a threat to the natural environment [20]. Some of them can be used successfully in geoengineering applications to strengthen, stabilize, or modify the soil and in road/railway works [21,22]. Polish examples of the use of ash–slag mixtures include the construction of municipal roads in Wola Rzędzińska (2016), the provincial road DW 869 Rzeszów-Jesionka (2017/2018) and the Strzyżów bypass along the provincial road no. 988 (2018/2019), as described in [23]. However, there are situations where the insufficiently recognized properties of the waste used on the road base result in serviceability failures of the constructed pavements (Figure 2).

Figure 2. Uplift and settlement of the pavement surface caused by the use of ash addition in the construction of the road embankment layers (source: photo of M. Jastrzębska).

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Slags are used mainly in road construction, mainly as aggregates for the construction of all layers of road structures, subgrades, slopes, and embankments [24,25]. Blast furnace slags can be used for soil stabilization if they meet the requirements of the Standard PN-EN 14227-15:2015-12 [26]. Researchers focus on the risk of releasing heavy metals from steel slags [27], the variability of the compaction parameters of blast furnace slags from heaps [28], and the risk of damage to the structure in which the slags are used with an unfinished decomposition process [29,30]. In turn, to reduce soil swelling, it is recommended to combine the slag with fly ash and lime [31].

A side effect of the production of mineral binders, such as cement/lime, is fine clinker dust [32]. It can be used to stabilize fine-grained soils and sands, increasing the CBR index, increasing compressive strength, increasing optimal moisture content for compaction, and reducing swelling [33]. It can also be used to solidify soils while binding heavy metals [34]. The use of fine clinker dust in the construction of road layers and in earthworks is regulated by the standard [35].

5. Rubber Wastes – Used Car Tires

Rubber waste in geoengineering applications mainly concerns used rubber tires, or rather their crushed parts (Figure 3): pieces ≥ 300 mm, shreds 20–400 mm, chips 10–50 mm, granulate 0.8–20 mm and powder < 0.8 mm. The physical and mechanical parameters of the crushed tires depend on the grain size (fraction), the crushing method, and the impurity content (of steel and textile cord). Due to the fact that TDAs are characterized by low particle density (compared to soils), they are a desirable material for the construction of lightweight road embankments on weak-bearing soils [36]. Other applications in geotechnics [37] include as a backfill material behind retaining structures [38], backfills for culverts and underground pipelines [39], drainage and seepage layers (also in landfills), frost protection layers, thermal insulation layers, and vibration insulation layers [40]. However, each of the mentioned applications requires a series of tests on soil–rubber mixtures (mainly in terms of optimum moisture content for compaction, swelling parameters, and mechanical properties), especially since the results do not show a constant trend, but are variable depending on numerous factors [41,42].

It should be noted that the results of environmental studies [43] did not show significant hazards resulting from the use of TDA in construction work. According to the Regulation of the Climate Minister on the Waste Catalog [9], neither used tires nor products made of them are considered hazardous. However, it is recommended to use worn out tire materials only in an environment with neutral pH and above the level of the groundwater table.

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Figure 3. Examples of various tire rubber waste used in geoengineering applications (source: photo of M. Jastrzębska).

6. Natural Wastes

Within broadly understood sustainable environmental geotechnics, a wide range of natural waste materials are used in the form of, for instance, plant fibers or ashes after combustion, animal fibers, and secondary waste from industrial production, e.g., agricultural, breeding and food production (eggshells, chicken/bird feathers, coffee grounds) (Figure 4). Regardless of the origin of the above-mentioned wastes, their task in a geoengineering context is, among others, to strengthen weak subsoil, reduce swelling and shrinkage of expansive soils, reduce bulk density, prevent the formation of tensile cracks, increase hydraulic conductivity, increase liquefaction resistance, reduce thermal conductivity, control surface erosion, etc. Therefore, the use of natural wastes in geotechnical engineering can take place in the following areas [44–56]:

- For railway and road construction, in stabilizing the substructure of the railway track and the subgrade of temporary/access roads with low traffic intensity, construction sites, parking lots.
- In retaining walls, combining soil stabilization with short fibers or geotextiles with geogrids.
- For the protection of railway embankment slopes, as patches in the local repair of damaged slopes, or to increase the slope inclination angle to reduce the width of the embankment footprint.
- Enhancing the bearing resistance of weak soil deposits (with the addition of cementing agents) to support shallow foundations (thereby avoiding the need for deep or indirect foundations).
- As structural/non-structural fill material in road embankment construction,
- Strengthening weak soils in flood-prone conditions and under landfills,
- Stabilization of expansive soils.
- As a filler material in bricks, plasters, mortar and compacted substrate.
- Production of hybrid composites.

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Figure 4. Examples of natural wastes used in various geoengineering applications (source: photo of M. Jastrzębska).

Natural waste is a group of waste materials that are, on the one hand, the most neutral to the environment (with the exception of coffee grounds, whose use requires confirmation of the absence of toxic compounds using a leachate test [53]), and, on the other hand, it is difficult to precisely categorize due to its diverse biochemical properties related to its microstructure (e.g., see Figure 5) [57], which in turn is influenced by numerous environmental and climatic factors; i.e., those related to plant cultivation and factors related to species (origin of feathers or shells).

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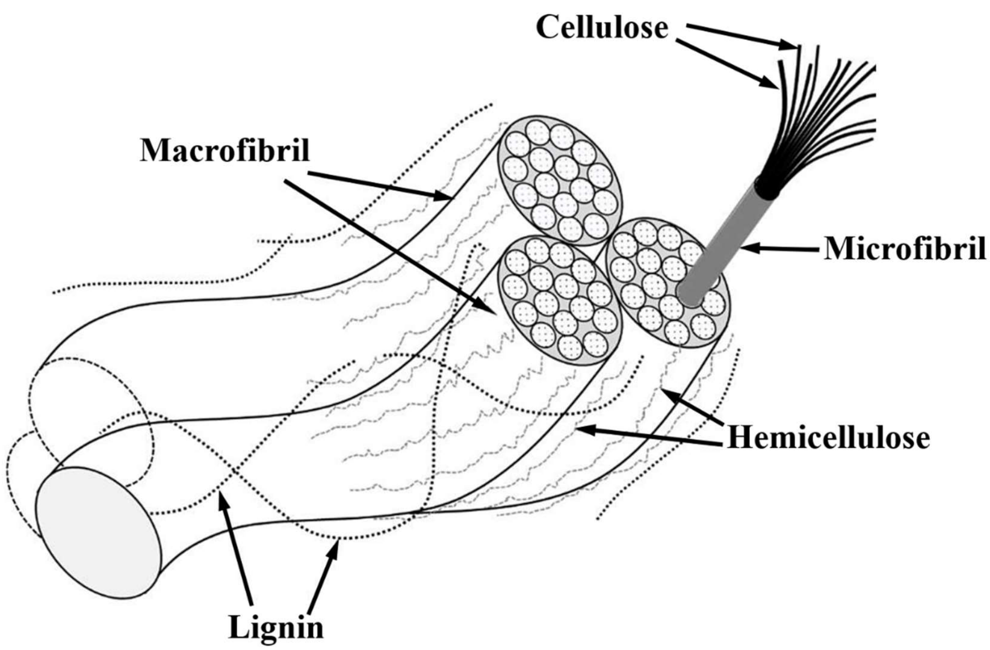

Figure 5. Microstructure of plant fiber (after [57], available via license: CC BY 4.0).

In the case of plant fibers, important parameters influencing the properties of green composite include the following:

- Cellulose and lignin contents, and their mutual proportions [57,58].
- Microfibrillar angle; i.e., the average angle between the fiber axis and the microfibrils (see Figure 5). The smaller the microfibrillar angle, the higher the strength and stiffness of the fiber, while a larger microfibrillar angle provides higher plasticity [59,60].
- Crystallinity index — determines the relative percentage of crystalline material in cellulose [61].
- Shape factor; i.e., the ratio of the length of the fiber to its diameter [57,62].
- Water absorption capacity, which affects the adhesion and friction properties at the fiber–soil interface [63,64].
- Arrangement of the fibers (random, oriented), and the percentage of fibers in the mixture [65].

The issue of fiber adhesion to the soil matrix is a topic of discussion by many researchers. It should be noted that to prevent the negative effects of emerging interphase gaps and the lack of fiber adhesion to the soil, various waterproof coatings have been used since the 1980s, such as asphalt emulsion, rosin and alcohol mixture, paints, bituminous materials, water-soluble acrylic and polystyrene coatings [66,67]. These coatings change the surface properties of the fibers, such as surface energy, polarization, surface area, cleanliness and wettability [58]. An additional effect of such a procedure is the protection of plant fibers against biological degradation in the substrate. Mercerization, which is one of the methods of chemical treatment of natural fibers (i.e., so-called alkaline treatment), plays a similar role [68,69]. In addition, mercerization generally increases the roughness of the fiber surface, which is a desired effect. Among the substances used to treat and coat natural fibers to reduce their biodegradability, the most commonly used are boric acid, borax, carbon chloride, and sodium hydroxide [57]. It is worth remembering that chemical modification is intended to ensure dimensional stability, improve adhesion, reduce water absorption and increase resistance to biological factors [70]. Despite the possible use of such chemical treatments, we can still consider the benefits of solutions based on green geocomposites [6].

Other natural wastes also require special treatments before they can be used, as additives, to strengthen the soil, including:

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- Spent coffee grounds require drying and hardening by geopolymerization at 50°C [45,71,72].
- The preparation of eggshells or shells for further applications in geoengineering consists of washing and cleaning them with fresh water, heating at a temperature of 100°C to 250–500°C, followed by crushing or grinding them. In this form, they are suitable for stabilizing the soil, thereby reducing the consumption of natural lime from limestone, for instance. It is worth mentioning that the use of eggshells in geoengineering applications has been extended to using shells from crustaceans (crabs, lobsters, shrimps) and mollusks (snails, oysters, clams, mussels, and scallops), which can pose a serious problem as natural wastes [73,74].
- The chicken (poultry)/bird feather fibers require particularly careful repeated washing and drying at 50°C [44,75,76].

On the basis of the above examples, and considering the diversity of natural waste materials, there is a need for ongoing testing of new composite mixtures, development of technologies for the production of soil–fiber mixtures on a large scale, along with reasonable use of chemical agents necessary for preventing biodegradation of the composites.

7. Chemical Wastes — Synthetic and Artificial Fibers

The difference between synthetic and artificial fibers can be explain as follows. Artificial fibers are made from biopolymers (cellulose, protein, rubber, etc.) and mineral raw materials found in nature, and subjected to chemical treatment. On the other hand, synthetic fibers are made from polymers (not found in nature) in the process of polymerization and polycondensation of organic compounds, such as crude oil or coal (Figure 1). Most waste synthetic fibers are derived from materials commonly called "plastics" and from the clothing industry, especially sportswear [77,78].

In geoengineering, chemical waste includes materials occurring in the form of synthetic and artificial fibers of different lengths (i.e., as strips and granules from water bottles, woven polypropylene bags, plastic sheets, etc.), which represent an interesting potential alternative to soil reinforcement employing traditional soil stabilization methods [79]. This is due to their sufficient tensile strength, hydrophobicity, low density, chemical resistance, lack of toxicity (according to the authors of this study, this aspect is a potentially controversial issue), low cost, and easy availability [55,77]. Similarly to natural fibers, synthetic fibers can be used effectively to improve the geomechanical properties of weak soils [80,81], including, among others, for achieving increases in the CBR index and the modulus of elasticity of clay soils that make up the lower layer of the road or railway subbase [82–88]. They also reportedly have a beneficial effect in reducing the swelling of expansive soils and increasing the strength of noncohesive soils, often being used in combination with other additives, such as cement or lime [89–93].

It should be noted here that although the proposed methods of soil reinforcement using synthetic fibers are beneficial from an engineering perspective, the authors reporting on such investigations in various publications do not present any discussion or consideration of the potentially significant long-term environmental impacts that may arise from the presence of plastic fibers randomly mixed into the subsoil [94]. Some researchers [94, 95] have drawn attention to this important topic, pointing out (i) the impossibility of removing the myriad of embedded plastic fibers from the soil, and recycling them, at the end of the useful life of the fiber-reinforced earth structure, and (ii) to the potential long-term pollution of the in-soil and groundwater due to the disintegration of the plastic material into increasingly finer-sized particles (i.e., micro- and nano-plastics) [95].

7. Wastes from Construction, Renovation and Demolition of Buildings and Road Infrastructure

This group of waste materials is relatively well recognized in the civil engineering profession, and is widely used in local urban investments [96–101]. Waste from the construction, renovation and demolition of end-of-life buildings and road infrastructure is primarily associated with concrete aggregate and construction rubble (in geotechnical applications, they can be used alone or as a

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mixture with soil), asphalt, and with ceramic and glass cullet (mainly to strengthen expansive soils) [102]; relatively most of the research has been devoted to glass fibers [77,103]. For instance, cullet is most often used in combination with other soil additives, for example cement [104,105]. The wastes mentioned can originate from both industry and households.

8. Summary

This article presented an introduction to the use of various waste materials in geoengineering, mainly to improve the geomechanical behavior/properties of weak soils. The most well-known of them are wastes originating from the mining industry, power plants, steelworks, and construction, renovation, and demolition of end-of-life buildings and roads, with many publications on them reported in the literature. The situation is similar regarding chemical (natural and synthetic) fibers, with their development progressing very dynamically. At the same time, there is growing discussion about the long-term impact of plastic, even biodegradable plastic, on the biosphere [95,106,107].

In turn, interest in natural wastes, especially of fibrous nature, has become very popular in recent years, although this research area has generally not moved beyond the experimental sphere, with still a considerable way to go before reaching wide-scale application in the field. Obstacles include, among others, (i) the need to develop an effective technology to produce soil–fibrous mixtures, along with methods for preventing the biodegradation of the composites (which, depending on the viewpoint, is an advantage or disadvantage of the solution), (ii) the lack of specific legal regulations, including the formulation of practical guidelines/standards, for the use of natural fibers in geotechnical engineering projects and construction, and quality control [6]. At the same time, the long-term impacts of such applications on the natural environment is generally not widely discussed and researched, mainly due to the lack of pertinent field test studies. Another aspect is that when recycling waste materials, the impact of this process on the environment should be reduced, especially in terms of energy and water demand [74] using, for example, renewable energy sources. Moreover, each of these actions should be evaluated, not only in terms of environmental footprint, but also in terms of economic value (considering costs of collection, cleaning, storage, transport, and disposal).

Summarizing the above considerations, the authors would like to express that the main motivation for this article is not to criticize the various proposed soil improvement methods, which seem smart/beneficial from a geotechnical engineering point of view and in achieving waste reutilization. Rather, as also expressed in [94], the aim of this article is to broaden the discussion and increase awareness among the geotechnical engineering community about the potential uses of various so-called waste materials, as well as their possible threats to local environmental contamination, and potential additional energy and water demand.

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