Reuse of Municipal Solid Waste in Construction

Subjects: Engineering, Civil | Engineering, Environmental

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Society is highly dependent on natural resources such as rocks (aggregates) and minerals. Although they are an abundant resource on the planet, their recovery is slow in terms of human lifespan, and from this fact, they are considered non-renewable resources. The construction industry currently consumes around 3000 million tons of natural resources annually and is responsible for 34% of greenhouse gas emissions into the atmosphere. An alternative to reduce this over-extraction is the substitution of aggregates and cement for municipal solid waste (MSW), which represents the application of the circular economy principles. This approach and the waste management hierarchy are described, with a focus on the Latin America and the Caribbean situation. MSW is composed of several fractions, such as organic waste, paper, cardboard, metals, plastic, and glass, among other valuable materials. Areas of opportunity for their reuse in the construction industry have been demonstrated worldwide: a) plastics as substitutes for aggregates or reinforcing fibers, or replaced construction elements such as bricks; b) glass in the production of concrete, mortar, and asphalt pavement; c) paper as a hygrothermal and lighting regulator in buildings, among others.

Keywords: green economy ; construction materials ; environmental impacts ; aggregate mining ; Latin America and the Caribbean ; inclusive recycling

1. Introduction

Municipal solid waste (MSW) comprises household waste, commercial waste, and institutional waste, as well as residues collected from street cleaning services, public areas, and private sectors [1]. Worldwide, 2.01 billion tons of MSW were produced in 2016 [2], which has environmental impacts on local, regional, and global scales. These impacts are exacerbated if MSW is not managed in an environmentally sound manner, and this is the case for at least a third of the MSW produced in the world [2]. Conventionally, MSW has been used as an energy source through incineration; however, this process generates acid gases, polychlorinated dioxins, and other persistent organic pollutants [3], for which it faces strong public opposition. The European Environment Agency, among others, has proposed preventing the generation of waste through a circular economy approach, promoting the adoption of technologies and solutions that lead to greener and healthier cities, such as the generation of hydrogen gas, bioethanol, or fertilizers from MSW [4]. Thus, a sustainable approach consists of comprehensive waste management, prioritizing value chains that recycle or reuse it.

The construction industry deeply influences the three pillars of sustainability: economy, society, and environment [5]. Concerning the latter, the construction sector consumes around 40% of primary energy use [6] and contributes to 34% of greenhouse emissions [7], both at the global level. These emissions derive from the energy used directly in buildings (for heating, cooling, ventilating, or water heating) and the energy embodied in on-site construction operations and in the products and services required for construction operations [6]. As far as material flows are concerned, this sector is responsible for 50% of resource consumption and 15% of freshwater use worldwide [8]. Thanks to these material flows, in 2020, the mass of anthropogenically constructed or modified matter exceeded that of living biomass, reaching about 1154 Tt [9]. This corresponds to a rate of 30 Gt per year [9]. Of this amount, at least 94% corresponds to materials directly associated with the construction industry, such as concrete, bricks, and asphalt [9]. In this way, the global consumption of virgin stone materials such as sand and gravel was 44 Gt in 2017 and is expected to increase to 86 GT in 2060 [10]. Obviously, such intense use of materials leads to enormous waste flows, which are primarily generated as construction and demolition waste (CDW) at the end of the life of buildings and built infrastructure. Global CDW generation was estimated at 3 billion tons in 2012 by considering only 40 countries [11]. Other estimations consider that CDW accounts for 30% to 40% of total solid waste produced in the world [5][8].

1.1. The Waste Management Hierarchy and the Circular Economy

Since the early 1980s, the waste hierarchy principle has emerged as the predominant paradigm of solid waste management. One of the earliest precedents of this principle is the “ladder of Lansink”, which was proposed in the Dutch parliament as a preferential order for waste management options: landfill, incineration, energy recovery, recycling, reuse, and reduce, with "landfill" and "reduce" as the least and the most acceptable practices, respectively [12]. One important distinction was made between reuse and recycling, which refer, respectively, to the new use or application of waste in its original form, and to the practice that converts waste into new products with some physicochemical reprocessing. As recycling requires more energy than reuse, and potentially new material inputs, the former option is lower in hierarchy than the latter. This scheme was embodied in the U.S. Pollution Prevention Act of 1990 and is now in most of the world's regulations. The waste hierarchy is almost always presented in pyramidal form, as in the Waste Framework Directive 2008/98/EC of the European Union or in the Waste and Climate Change Strategy Framework of the United Nations Environmental Programme [13] (**Figure 1**a). However, waste hierarchy is not fixed, and the positions of some options (i.e., incineration) in the hierarchy do not have a general consensus and remain contentious [1].

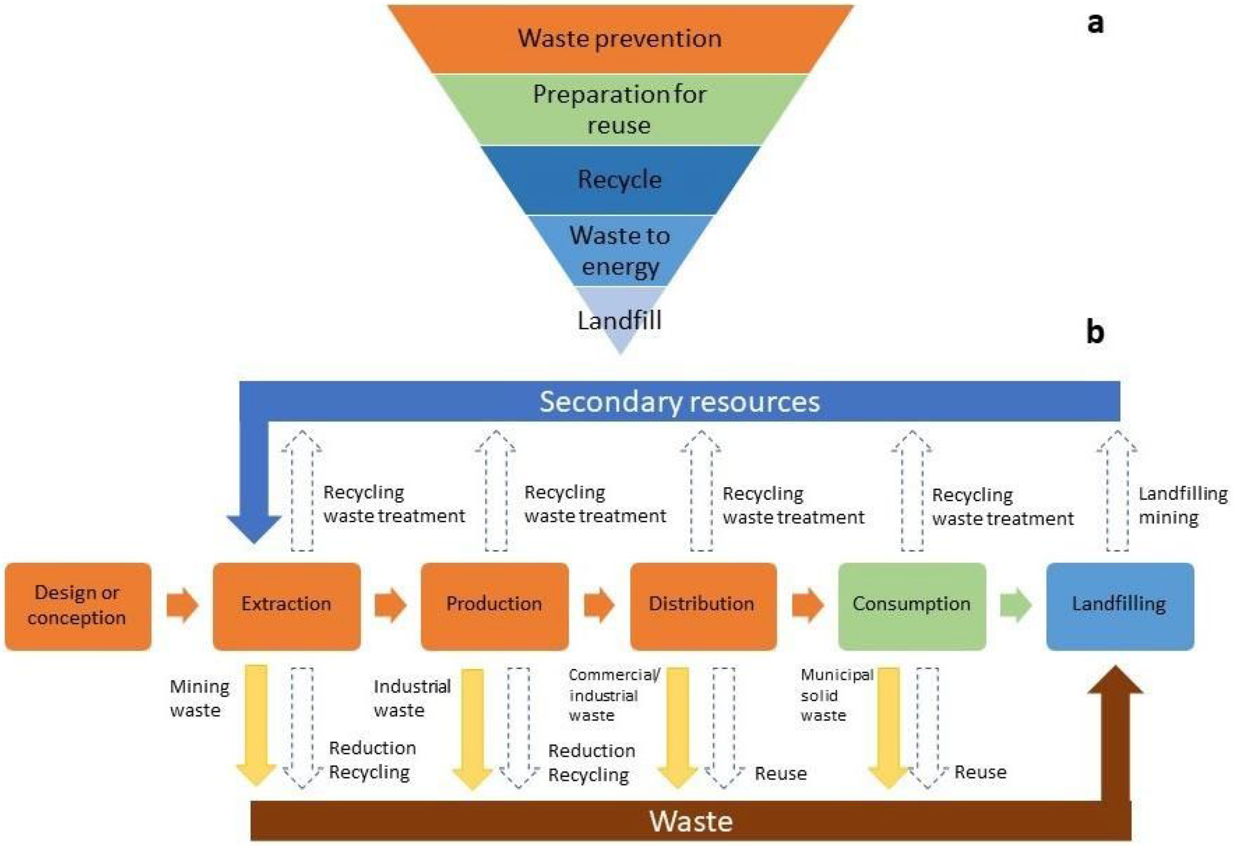

Figure 1. (**a**) Waste hierarchy principle according to the Waste and Climate Change Strategy Framework of the United Nations Environmental Programme [13]; (**b**) waste as a secondary resource (adapted from Chang and Pires [1]). In both diagrams, pre-use, use, and post-use phases appear in orange, green, and blue, respectively.

This paradigm relies on the conception of waste as a resource rather than as a public health problem. Waste becomes a secondary material derived from each life cycle stage of products, which can be redirected to the same production process or to others, used for energy production or new applications increasingly enabled by technological advances (**Figure 1**b) [1]. As in the pyramidal hierarchy, landfilling is only a marginal option for the waste fraction that cannot be reintroduced in this "circularized" system, and is not the main waste destination as it occurs today.

The ultimate goal of the circular economy is to optimize resource use towards closed material loops inspired by natural biogeochemical cycles. This slows down material circulation and produces less waste, pollution, and emissions while using less energy. Over time, the waste-managing options were enlarged with additional "Rs"; for instance, Reike et al. [14] recognize 10 Rs (Refuse, Reduce, Resell/Reuse, Repair, Refurbish, Remanufacture, Repurpose, Recycle, Recover energy, and Re-mine).

1.2. Circular Economy Initiatives in Latin America and the Caribbean (LAC)

The concept of circular economy is gaining momentum in LAC countries, which are designing or even implementing policies, public initiatives, and roadmaps [15]. Additionally, schemes of shared producer responsibility are being increasingly incorporated, either in the general waste law or in specific regulations for a particular waste stream [16]. In 2021, a Circular Economy Coalition from Latin America and the Caribbean was launched, with the aim of developing a common regional vision with a holistic approach, and being a platform for sharing knowledge and tools and supporting the transition to the circular economy [17]. For this, the mining and extractive sector, waste recycling and management, and bioeconomy have been identified as priorities [15]. The circular economy is also increasingly considered a strategy to increase environmental and economic resilience in the context of post-COVID-19 recovery [15].

By virtue of the burden that MSW represents for the cities in LAC, several of them have designed their own circular economy plans. For instance, in Buenos Aires, Argentina, the Green City Plan was launched in 2012 to reduce MSW [15], and, in 2021, a Circular Economy Network was launched to foster responsible consumption, recycling, and reuse of resources in the industry [18]. Mexico City has recently banned single-use plastics and announced its Action Plan for a Circular Economy, which couples environmental goals with green job creation. This plan contemplates proper waste management infrastructure, the creation of cooperatives specialized in waste management, and education campaigns [19].

One of the distinctive features of these initiatives in the LAC countries, while also being their main challenge, is the relation between circular economy and inclusive recycling. Inclusive recycling situates within the larger scope of environmental justice, which stands against the neoliberal extractivist model, supports a justice-oriented approach to solving environmental degradation, and recognizes the right to resources for historically marginalized groups, among other crucial socioeconomic aspects. Inclusive recycling considers the urban poor more than just consumers and has been defined as waste management systems that prioritize recovery and recycling while recognizing and formalizing the role of recyclers as key actors in such systems [20]. Around 3.8 million of urban inhabitants of the LAC countries make their living from informal recycling, most of them in unsanitary conditions [21]. Chile and Brazil have made progress in the inclusion of informal recyclers (or “waste pickers”) in new waste management systems [15], but Bolivia, Colombia, and Ecuador stand out in this process, mainly due to the actions undertaken by national organizations of informal recyclers. Because of this, around 1500 of them are formally paid by the city of Bogotá, Colombia, for their services in collecting and transporting recyclable materials [21]. Informal recyclers are considered a major driver for more sustainable waste management [22], and key to building just and livable cities in the LAC region [15].

2. Municipal Solid Waste and Its Use in Construction

2.1. Plastics

Recycling and reuse of plastic waste (PW) in construction allow for reducing the environmental problems that it causes and improving certain properties of conventional materials. The applications of plastics to construction materials can be classified into three categories: (i) addition to concrete, as substitutes for aggregates or reinforcing fibers; (ii) incorporation into asphalt; and (iii) emerging applications, whether to build the base and sub-base of highways and roads, manufacture new composites that replace conventional materials (such as wood), or replace construction elements (such as bricks).

PW can be incorporated into concrete as aggregates or as fibers, although the first case is the most frequent; likewise, most of the reports refer to the use of polyethylene terephthalate (PET) [23]. An obvious advantage of the replacement of conventional materials by PW is that its low weight reduces the density of the concrete and therefore the dead weight of the work, which can be beneficial in certain cases [24]. As a general trend, the replacement of natural aggregates (up to 30–40%) by PW coarse aggregates increases the slump in the concrete [23][25][26], which is commonly used to indicate workability. An opposite trend is found when natural aggregates are replaced by fine PW [23].

Plastics can also be used as reinforcing fibers to improve the tensile strength of concrete. In practice, these fibers are mostly virgin polypropylene (PET or low-density polyethylene are used to a lesser extent), have a length of 30 to 60 mm and a cross-section of 0.6 to 1 mm^2, and allow control of the plastic shrinkage and drying shrinkage [27].

In general, the addition of fibers (natural or from recycled PW) improves the performance of concrete, increasing toughness, ductility, and impact resistance while reducing its weight and density, thus improving the strength-to-weight ratio of concrete [28]. Recycled fibers have the characteristic of controlling cracking due to plastic shrinkage and drying uniformity [29]. The presence of recycled fibers in the concrete does not affect the appearance of cracks, in addition to delaying their propagation compared to natural fibers [30]. The addition of fibers also reduces the permeability of concrete, which positively affects its durability; additionally, fibers reduce free water in the mix when it rises to the surface and forms a cement paste on the surface, known as laitance [31]. The main drawbacks of this concrete modification are the possibility of reducing workability and the higher costs associated with natural fibers compared to fibers derived from PW [32], and the lack of data regarding its durability. Also, their associated impurities and their different degrees of degradation have not allowed for standardizing the mechanical properties of the resulting concrete.

As far as emerging applications are concerned, PW has replaced a fraction of aggregates in the base and sub-base construction of pavements, for which improvements in deformation resistance and load-bearing capacity have been determined [24][33].

2.2. Glass

Glass is a very versatile and inert material. However, it is not biodegradable, so once it is disposed of, it can remain in nature as waste for at least a million years before it decomposes naturally [34]. If one ton of glass is reused in the cement industry, 560 kg of sand, 190 kg of soda ash, 176 kg of limestone, and 64 kg of feldspar can be preserved [35]. Its reuse as a ground powder in the clinker production process helps reduce air pollution [36]. This makes it an attractive reusable material because concrete is the most used construction input worldwide.

When glass is crushed and sieved, it acquires engineering properties similar to sand and other fine materials [37]. For example, substituting natural aggregates with glass improved the workability of concrete thanks to its non-absorbent properties. This improvement may depend on the particle size of the replaced aggregates, so it is important to determine their ideal granulometry [37]. It has been found that adequate glass amounts for the replacement of fine aggregates vary between 20–30% and between 10–20% for replacing coarse aggregates [36].

The use of glass as fill material in roads is another sustainable alternative, since among its proven advantages are the improvement in the thermal susceptibility of its surfaces, its fatigue performance, the increase in its resistance to plastic deformation, and rutting at high temperatures [34]. When there are expansive clay soils in the subgrade layer, replacing the natural material with low percentages of glass (of the same size as sand) acts as a non-chemical treatment that improves its mechanical properties by reducing vertical and horizontal deformations in this layer's matrix [38].

This waste has also been used in the production of cellular concrete, which has low weight, low density, high fluidity and is self-compacting. In addition, it contains little aggregates and is a thermal and acoustic insulator [39]. A total of 10% crushed glass smaller than 38–45 µm mixed with cement and superplasticizers has been used to produce this type of concrete. It was found that the finer the glass, the less alkali–silica reaction occurred, thanks to its significant pozzolanic activity [39]. In other words, aggregates can be replaced by up to 10% with glass waste of any size without significantly affecting the material's strength.

2.3. Paper and Cardboard

Worldwide, around 4 billion trees are felled each year to produce 450 million tons of paper and cardboard [40]. Once disposed of, they represent the largest volume accumulated in landfills after glass and plastic. Fortunately, their recycling capacity is very wide and there are examples of their use in construction materials, such as mortar and cement, due to its non-hazardous nature [41]. For example, this waste was used as cardboard pulp to partially replace the cement content in boardcrete, which is a material that can replace bricks in buildings thanks to its cellulose content, which acts as a fibrous material [40]. Its main advantage is that it is a permeable, solid, and heterogeneous material that facilitates heat transfer by conduction [40]. One disadvantage is that there are no regulations suitable for the manufacture and testing of this material, so future studies must be based on adapting procedures established for other construction materials.

Haigh et al. [42] used kraft fibers to improve the mechanical properties of concrete. This type of fiber comes from the cellulose of the plants and trees from which the paper or cardboard was initially obtained. Utilizing a complex chemical treatment (chemical sulfate method), the scholars eliminated the lignin adhered to the fibers to increase their dispersion and random size. It was mentioned that to improve the mechanical and durability properties of these fibers, it is necessary to modify their matrix and give a pretreatment to reduce their degradation [41]. An advantage of recycling this waste as fibers is that they are non-abrasive, high-strength, low-density, and inexpensive. As a disadvantage, its degradation can weaken the fiber and make it brittle, reducing the useful life of the material in which it is used [42].

2.4. Ashes from the MSW Incineration

One of the procedures used to reduce the waste volume is incineration, which allows MSW mass reduction by up to 70–90% while producing energy [43]. However, dangerous pollutants produced by incineration, namely particulates (PM_{10}), acid gases (as NOx and SO_2), heavy metals, polychlorinated dibenzo-p-dioxins and furans, polycyclic aromatic hydrocarbons and polychlorinated biphenyls, generate widespread concern about their impact on the population exposed [3][44]. Several adverse health effects, such as some neoplasia, congenital anomalies, infant deaths, and miscarriage have been associated with waste incineration, particularly in old facilities [45]. However, these risks appear to be minimized in modern MSW incinerators, as indicated by a national-scale study that found no evidence for increased risk of a range of birth outcomes, including birth weight, preterm delivery, and infant mortality, in relation to exposure to PM_{10} from incinerators operating under current European standards [46].

In an incinerator, the solid product is recovered as bottom ash (BA) and fly ash (FA). BA is a mixture of particles with a heterogeneous composition that varies from silt and clay to gravel. If metals are recovered through vitrification and physical separation, BA can be transformed into a safe material suitable for reuse [47]. These ashes represent about 80% of the incinerated raw material. Hence, their recovery is a very important area of opportunity [48]. Among their varied applications, BA can be employed as an alternative light aggregate [48], while FA can be a source of lime in the cement industry. Besides, ashes have been used as a cement replacement in mortar production [49], among other examples.

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