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URBAN MINING COMMINUTION TECHNOLOGICAL APPLICATIONS AS THE MOST IMPORTANT PART OF CIRCULAR ECONOMY, A REVIEW

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Abstract: Mankind needs materials for civilisation. The earth sciences & engineering (exploration, extraction and processing of natural and anthropogenic resources) has been supplied raw- and commodity materials for production. Recently, it is evident that a better management with natural resources is necessary and therefore the concept of circular economy was born. Its first leg is the system level optimization of the production – consumption cycle by optimal energy usage, circular-minded design, and circular-minded behaviour of the society, optimised and elongated use of products, re-use, re-manufacture and so on. However, as the name circular economy implies the second leg, namely the circulation of the materials is the most important element. The concept of urban mining means the mining and processing, therefore reclaiming compounds and elements from any kind of anthropogenic origin stocks, including buildings, infrastructure, industries and products (in and out of use). This review paper compiles examples from the literature showcasing industrial applications of urban mining waste-to-material recycling, focusing on cases where mechanical processing of man-made raw materials is essential, thus necessitating comminution and classification processes. Flow types of anthropogenic raw materials are reported to EU authorities regularly, therefore subcategorization of waste types follows the EU nomenclature. Characteristic comminution machines and main types of stressing and in some cases characterising separation units are presented which are illustrated by a few selected application examples.

Keywords: *circular economy, urban mining, stock and flow types of anthropogenic raw materials, waste crushing and grinding*

1. INTRODUCTION AND AIM

The challenges to the sustainability of human life on earth have intensified in recent times, as it has now become generally evident that it is under threat. As an answer for sparing and managing natural resources, the concept of the circular economy and urban mining was born. The scientific vocabulary of these relatively new areas was clarified probably by Cossu and Williams (2015). According to Cossu and Williams (2015) the terminology Landfill Mining represents the activities involved in extracting and processing wastes which have been previously stocked in particular kinds of deposits (municipal landfills, mine tailings, etc.). Urban Mining extends landfill mining to the process of reclaiming compounds and elements from any kind of anthropogenic stocks, including buildings, infrastructure, industries, products (in and out of use), and environmental media receiving anthropogenic emissions. Circular economy is even a much wider term, because it covers all the economic and social impacts too, including how to design fully recyclable products and so on, meaning everything that facilitates the real material circular flow. Fig. 1 illustrates a material balance on Earth. The two legs of the circular economy and the scientific vocabulary are clearly visible on this figure. For human civilisation materials are needed, and the earth sciences & engineering - meaning the exploration and extraction of natural- and anthropogenic resources and the processing of the mined virgin- and secondary raw materials - supplies all the necessary geogenic origin materials for mankind.

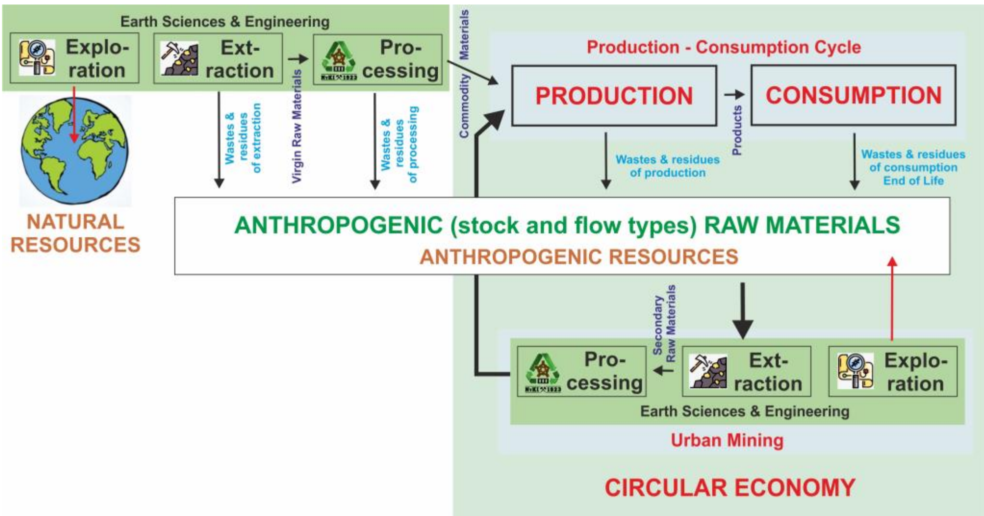

Figure 1
Urban mining as the most important part of the circular economy

In the English-speaking world, the terms "raw materials" and "commodity materials" are generally not distinguished; however, the role of mineral- and waste processing cannot be well explained without this. Mineral processing upgrades the mined virgin raw materials and produces commodity materials for production. Similarly waste processing upgrades the mined secondary raw materials and produces commodity materials also. The first leg of the circular economy falls into the system level optimization of the production – consumption cycle and this is a really wide area. It necessitates optimal energy usage, circular-minded design, and circular-minded behaviour of the society, optimised and elongated use of products, reuse, re-manufacture and so on. However, we still think that the most important part of the circular economy is the second leg, namely how we can gain raw materials from anthropogenic resources by urban mining and inside this the real challenge is not the waste mining but rather how the waste is processed. Unfortunately, wastes are typically multi-material systems and this is where the challenge lies. The stocked materials may represent a significant source of resources, with concentrations of elements often comparable to or exceeding natural stocks. A definition distinguishing between "stock" and "flow" resources, either anthropogenic or natural is necessary. The origin of natural stocks can be either geogenic or biogenic and many times geogenic natural stocks are called "virgin" (Winterstetter et. al. 2016). Annual stocks of materials held in geological deposits, groundwater reservoirs, household and industrial buildings, infrastructure and scrap products may not vary much over time. However, annual flows of materials may change considerably from year to year, depending upon the prevailing economic situation, fashion, technical innovations, etc. Nevertheless, from both anthropogenic stock and flow resources, secondary raw materials are produced. Resource Recovery includes materials recycling as well as the energy that can be generated by treating and managing wastes (waste-to-energy recovery). Materials Recycling (or waste-to-material recycling) aims to transform selected wastes into materials that can be used again in the manufacture of new products. The mining and processing of virgin geogenic raw materials have always been with us for as long as humans have lived, since without materials there can be no civilized life on earth.

Therefore, the current task is to transfer the known technologies of mining and mineral processing to the field of urban mining including waste processing. The first comprehensive paper applying this concept was probably written by Ambros (2023). Ambros (2023) reviewed the typical gravity concentration units and their applications in mineral processing and then investigated the possible applications of that mechanical process for waste upgrading. Another new scientific term we have to learn is the Distinct Urban Mine (DUM). The materials and resources recoverable from individual urban spaces differ. The uniqueness of an urban mine is due to factors such as the composition and concentration of post-production and post-consumption materials of interest as well as the demographic profile of the urban space. This delimited space, unique in its material composition and concentration is called a Distinct Urban Mine (DUM) (Ongondo et. al. 2015). As with a traditional mine, a DUM requires prospection to determine its viability. Information such as size, concentration of materials and grade of resources of interest and its location within the wider anthroposphere is necessary. According to Ambros (2023) the miners of the present will gradually become recyclers in the future since there will be more copper, iron, and zinc (and other metals) in the cities than in the earth's crust after 2050 (considering current known reserves).

Taking this introduction into account it was concluded that a review of technological applications of comminution and classification in the field of urban mining could be useful for the scientific community. Data on the continuously generating wastes, by-products and other residues, namely the flow types of anthropogenic raw materials are reported to the national and EU authorities regularly, therefore it is aimed first to give a summary of these statistical waste categories and sub-categories according to the EU nomenclature. Then focusing only on the waste-to-material recycling the characteristic comminution machines and main types of stressing and in some cases characterising separation units are presented which are illustrated by a few selected application examples. The typical upgrading concept is well-known in mineral processing. Every time mechanical pre-processing is needed, namely comminution and classification are necessary to release the valuable components and generate narrowly distributed particle size or shape fractions, as they enable effective upgrading. Then if there is a difference in any intrinsic feature of the component materials, the materials can be upgraded by physical separation when different particles go into products because of forces, namely concentrates - rich in the useful components - and tailings - hopefully poor in the useful components - can be produced. If the particles of the feed of different materials are sorted by manual- or sensor-based sorting (SBS), this kind of upgrading requires mechanical pre-treatment also. After the mechanical pre-upgrading - when the big mass of non-useful components has been discarded - mechanical-, chemical-, thermal- or biological processes can be used for the extraction of the useful components. Without mechanical pre-concentration, it is certain that no subsequent non-mechanical waste recycling process can be economically viable. Therefore, the role of comminution is very important for urban mining.

Before going further, let's review the conclusions of Ambros (2023) about the three competing upgrading processes (upgrading at density, SBS and froth flotation), because similar conclusions are expected for the comminution. Most plastics, due to their low density and hydrophobic properties, may be considered as the urban mining equivalent of coal in mineral processing. Therefore, methods like jigging, counter-current flow separation and dense media separation can effectively separate polymers when the material feed is adequately liberated. Centrifuge gravity separation also shows potential for isolating microplastics from soil and sediments (Ambros, 2023). Gravity concentration is promising for producing recycled aggregates from construction and demolition waste (CDW), especially for coarse aggregates (>4.75 mm). However, processing fine CDW (<4.75 mm) remains underexplored, possibly due to direct applications in backfilling and geotechnical fields (Ambros, 2023). And most importantly, gravity separation is increasingly challenged by two fronts: sensor-based sorting (SBS) in the processing of coarse materials and froth flotation in the treatment of fine-sized materials. However, there is an intermediate size range (about 0.75–5 mm) where these techniques face technical difficulties and in which gravity separation typically excels, particularly for treating construction and demolition waste (CDW) and microplastics. Also, SBS (sensor-based sorting) typically can effectively sort particles within a limited range of sizes, with a recommended maximum size ratio of about 3 between the smallest and largest particles (Ambros, 2023). This is why classification is important.

As the last element of the introduction, a short summary of comminution machine names is necessary, however this is widely applied and generally known. If comminution happens on the size range of coarser than about 0.5-1 mm, the process is called crushing and the machines are called crushers, for a smaller size range the process is called grinding and the machines are called mills. The minerals are typically brittle materials and therefore jaw, gyratory, cone, roll, impact, hammer and other crushers can be applied for crushing and ring, ball, planetary, vibrated, stirred media and other mills can be applied for milling in mineral processing. Generally speaking, wastes are typically non-brittle materials, therefore rotary shears, rotary cutters, rotary shredders and translatory shears can be applied for waste processing.

2. FLOW TYPES OF SECONDARY RAW MATERIAL STOCKS

According to EU statistics, 776.3 million tons of waste was generated, excluding major mineral waste in the EU in 2020 (Eurostat online data code: env_wasgen). At the time of generation, this whole mass of waste can be considered as a flow type of anthropogenic secondary resource. It consists of solid wastes as 25.2% household wastes; 21.5% manufacturing wastes; 11.5% other sectors' wastes; 5.9% energy wastes; 5% construction wastes; 2.7% agriculture, forestry and fishing wastes; 1% mining and quarrying wastes and non-solid 27.4% wastewater. Some of this waste mass will be charged in deposits and landfills and later that will become a stock type of resource. Table 1 shows comminution and classification waste-to-material recycling application examples according to the subcategorization of the generated solid wastes.

2.1. Agriculture, forestry and fishing wastes

Total waste generation by entities of Section A – Agriculture, forestry and fishing – in EU countries in 2016 was about $2.6 \cdot 10^9$ tonnes, meaning an average 40 kg/capita waste generation (Komor and Bujanowitz-Haras, 2019). **Agriculture waste** comprises Crop waste (rice husk, wheat straws, sugarcane bagasse), Animal waste (animal excreta, dead animals), Processing waste (packaging material, fertilizer cans) and Hazardous waste (pesticides, insecticides). Typical agricultural waste recycling processes are composting (producing nutrient-rich compost), biogas generation (digesters convert waste into biogas and that is an energy source), mulching (solid waste can be used as mulch to protect the soil), biomass conversion (thermo- and biochemical conversion of the waste into valuable products) and the recycling of packaging materials (Yang et. al. 2021). A variety of comminution machines of brittle and non-brittle materials are used for recycling agricultural wastes but only on a small scale, mainly as auxiliary pre-processes. For crop waste comminution hammer crushers or mills can be applied because the beating, impacting and shearing types of stressing are beneficial in this case. For animal waste comminution, axial gap rotary shears are beneficial because of the shearing and tearing stress.

Table 1.

Summary of waste sub-categories and examples for their recycling options and applied comminution equipment

Waste category	Waste sub-category	Recycling option examples	Comminution and classification equipment	Types of stressing
Agriculture, forestry and fishing wastes	Agriculture (crop) waste	Composting. Biogas generation. Biomass conversion (thermo- and biochemical conversion)	Hammer crushers Hammer mills	Beating impacting shearing
	Agriculture (animal)	Using the useful parts and disposing of the residues	Axial-gap rotary shears	Shearing tearing
	Forestry	Mulching (solid waste can be used as mulch to protect the soil) Waste-to energy recovery Decomposition	Swing hammer mills Cutting mills (tip point speed can reach 100 m/s)	Cutting shearing
	Fishing	Producing value-added products e.g., peptides, proteins, collagen, chitin, oil. Procedures as acid extraction, enzymatic hydrolysis and fermentation.	The role of mechanical pre-processing by comminution and classification is not so important for this waste stream.	
Mining and quarrying wastes and metallurgical slags	Mining and quarrying wastes	Waste rock (materials overlying), Overburden (low grade minerals) and Beneficiation wastes (residues of mineral processing) Primary aim: producing secondary raw materials.	Full spectrum of brittle materials comminution equipment. Crushers: Jaw, gyratory, cone, roll, impact, pin mill, hammer, hammer shredder. Mills: ring, media, planetary, vibrated, stirred media, jet, cutting, SAG, attrition mills, tower mills, HPGR (high pressure grinding rolls).	Compressing beating impacting shearing
	Metallurgical dusts and slags	Recovery of the valuable metals by hydro-, pyro- or bio-metallurgical processes after mechanical pre-processing. Complex utilisation. Producing cement additives.	Grinding; media mills, namely ball mills, autogenous mills (AG) and pebble mills. Ring mills for blast furnace slag.	Compressing, shearing
Manufacturing	Production specific, non-production specific	Quality assurance discarded. Technological (e.g. red mud of alumina production), Amortization wastes. Non-production-specific wastes.	Bring these materials back into their own production system. All types of wastes so all types of comm. equipment.	

Wastes of energy production	Residues of fuels incineration. (coal combustion-CCR, waste incineration residues)	CCRs is being used in cement, cellular concrete, fly ash lime bricks, fly ash lime gypsum block, building tiles; as admixture in cement concrete, timber substitute products; as aggregate in concrete, road and building block; as pozzolana.	Tumbling ball mill or high energy density mill (HEM) like the planetary ball mill, vibratory mill or stirred media mill.	Compressing shearing
	Residues of solar energy generation	c-Si PV modules: dismantling, shredding, SBS upgrading, pre-concentrates go to distinct waste recycler. FirstSolar and ANTEC Solar GmbH technologies for CdTe PVmodules. Shredding, slow leaching drum, glass separation, sodium hydroxide precipitation of metal compounds.	Specialised hammer crushers hammer mills	Beating impacting shearing
	Residues of wind energy generation	100 % waste-to-material recycling is possible.	Suitable comminution eq. for steel, Al, Cu, polymer materials, concrete, etc…	
	Residues of nuclear energy generation	Reprocessing of Spent nuclear fuel (SNF) by fission and activation products, and so-called minor actinides producing high-level solid packed waste (HLW).	Comminution is not applied typically	
Construction & Demolition wastes (CDW)	Excavated soil	Processed CDW and composted eucalyptus bark (CEB) were used at lab scale to make new soil.	Typically on-site handling with normal soil excavators.	
	Concrete aggregate	Producing recycled concrete aggregate (RCA). Producing controlled Low-Strength Materials (CLSM). Producing new binders.	Multiple stages. 1st stage: horizontal axis jaw crushers and beater rolls.2nd stage: Cone crushers, impact crushers	1.Compr. bending. 2.Compr. impacting.
	Asphalt aggregate	Producing Recycled asphalt aggregate (RAA) or Pyrolysis RAA.	Toothed rolls and hammer crushers	Shearing beating
	Wood waste	See forestry waste		
	Metal waste	Metallurgical processing	Guillotine shears, alligator shears	Shearing
	Mixed CDW	Removing contamination. Production of new construction materials. Production of lower utilization fills materials.	Crushers for brittle materials comminution.	Compressing shearing

Post-consumer wastes	Municipal solid wastes (MSW)	Waste-to-material recycling of SMSW and some RMSW. Waste-to-energy recovery, RDF (refuse derived fuel). Biomass conversion.	Axial gap rotary shear and swing type hammer shredder. For RMSW: Low-speed rotary shredders for pre-shredding and radial gap rotary shears for final.	Shearing and complex tearing stress
	EoL Rubber tyres	Waste-to-material-recycling or energy recovery	Multiple stages: Steel cords removing by hook, axial gap rotary shears, then radial gap rotary shears and finally cutting mills.	Shearing cutting
	EoL Batteries	Extracting precious and structural components	Hammer shredders. Issues: fire and explosion hazard, hazardous dust emission	Tearing
	EoL Refrigerators	Waste-to-material recycling. Issue: Freon gases.	Hammer shredders. Chains can serve as hammers. Nitrogen atmos-phere.	Tearing
	EoL Vehicles	Waste-to-material recycling. Waste-to-energy recovery.	High mass swinging hammer shredders	Tearing
	WEEE (electric and electronic waste), EoL TV devices. EoL Com-puters.	Extracting precious and structural components	Hammer shredders and hammer crushers. PCB - high-speed hammer crusher and beater mill.	Tearing shearing beating

Regarding **Forestry wastes,** the conventional treatment of agroforestry waste includes landfilling, thermal management, and decomposition which is accompanied by their own share of disadvantages (Gupta et. al., 2022). To date, mills used for comminuting lignocellulose have been developed for materials with brittle material properties, whereas biogenic materials show almost brittle to viscoelastic properties. It has not yet been clarified whether the principles applicable to brittle materials can be utilized for the comminution of renewable raw materials. Developing new comminution machines for this purpose and enhancing energy efficiency to achieve necessary particulate sizes and properties for subsequent processes is of the utmost importance (Eisenlauer and Teipel, 2020). For wood comminution cutting mills with the main stress type cutting and shear stress and swing hammer mills with mainly impact stress can be used (Eisenlauer and Teipel, 2020). Sometimes, the peripheral speed of hammer mills' tip point applied for wood comminution can reach 100 m/s.

Fishing (fish) waste is not only a major environmental problem, but also a huge economic loss. For this reason, a better fish-waste management is needed to overcome these important issues. The use of fish by-products could contribute to the development of products with high commercial value, and consequently, to economic growth. Fishing wastes could become an enormous resource for the production of value-added products e.g., peptides, proteins, collagen, chitin, oil and enzymes with several potential applications. The extraction and purification techniques are mainly based on procedures as acid extraction, enzymatic hydrolysis and fermentation (Coppola et.al., 2021). The role of mechanical pre-processing by comminution and classification is not so important for this waste stream.

2.2. Mining and quarrying wastes and metallurgical slags

Mining and quarrying wastes are typically produced during ferrous metals -, non-ferrous metals -, industrial minerals - and coal mining and processing. Millions of tons of waste rock (materials overlying the area to be mined and which are moved in order to gain access to the orebody), overburden (low-grade minerals) and beneficiation wastes (residues of mineral processing) are produced by the global mining industry (Matinde et. al. 2018). The mining sector produces commodity raw materials for the production and the liberation of the useful minerals requires comminution (crushing and grinding). Comminution is more effective by the application of open and closed comminution and classification cycles and it is really important because of the high energy demand of this process. The comminution - only in the mining sector - requires about 1 % of the world’s total generated energy (Jeswiet and Szekeres, 2016). As it is widely recognised the energetic efficiency of comminution plays a crucial role, because a slight efficiency increase represents considerable energy saving. The full spectrum of brittle materials comminution machines from coarse crushing, from the jaw crusher towards grinding to fine- and ultrafine grinding with stirred media mills is used for mineral processing and these units can be mainly applied for the recycling too of these waste streams. This topic is really widely covered in the literature (Jeswiet and Szekeres, 2016; Matinde et. al. 2018).

Metallurgical dusts and slags, in 2020, world iron slag production was estimated to be between 310 million and 380 million tons, and steel slag production was estimated to be between 180 million and 270 million tons. The yield of copper slag reaches nearly 70 million tons each year worldwide. The residues and by-products of metallurgy still typically contain some valuable metals and some hazardous elements. It means that the freshly generated wastes and the stocked ones in deposits represent an environmental hazard and a potential secondary raw material at the same time. The primary aim of metallurgical dusts and slags recycling is the recovery of the valuable metals by hydro-, pyro- or bio-metallurgical processes (Tian et. al. 2021). That is also typical that only the valuable metal content recycling is not economical the higher mass ratio of other components utilisation has to be also implemented. This is the well-known complex utilisation. As an example copper slag can be used for construction of the top layer, base course and substructure of roads where it can be used as soil or aggregate, unbound, bituminous or hydraulically bound. Other target utilisation of metallurgical residues is a kind of construction industry or geotechnical usage, such as cement or concrete additive or other forms (Klaffenbach et. al. 2023). The applied most important comminution application of metallurgical residues recycling is the grinding; media mills, namely ball mills, autogenous mills (AG) and pebble mills are generally used (Metin Can and Mercan, 2023). The most important direct utilisation of granulated blast furnace slag is the cement additive application. Ring mills with stress-type of material bed compression are typically applied on-site for the residue's processing.

2.3. Manufacturing wastes

Manufacturing waste refers to the materials left over during the production process of new products. Other names for this type of waste include factory waste, industrial waste, construction waste, and production waste. Wastes of producers and service providers can be subdivided as production-specific wastes (QA – quality assurance - discarded or bad products, technological e.g. red mud of alumina production or slag of iron production and the amortization - worn out production machines). Non-production-specific wastes (e.g. packing materials, office paper and office computer) are also generated during production, but these wastes are characterised into other waste streams in this paper. More than two-thirds of manufacturing waste originates from biological sources, such as sludge from wastewater and inedible food waste. There are various reasons behind QA defects in mid-production products in different industries. Some examples are: pharmaceutical industry (failed stability testing, contamination, incorrect labelling), food production (microbiological contamination, chemical contamination and allergen cross-contamination), technology production (functionality testing, quality control defects and safety testing), automotive (durability testing, quality control checks, safety standards). The primary aim of production-specific waste utilisation is to bring these materials back into their own production system. If it is not possible their materials should be used as raw materials for other products production. Since the entire production scale is very extensive, so is the scale of waste materials generated; therefore all the different brittle (mineral like) and non-brittle types of waste materials occur. Typical recycling technologies for typical waste materials are described for the other waste streams in the paper.

2.4. Wastes of energy production

Energy production is essential for humanity and right now that results huge mass of waste and residues generation. According to a recent study (Mirletz et.al. 2023) the specific waste generation ratio of the main energy-producing sectors will be as follows up to 2050. The percentage of each sector is determined as mass percentage. Fossil fuels incineration and waste-to-energy residues (97.95%), EoL solar panels - PV (1.84%), wind energy residues, mainly EoL turbine blades (0.18%) and nuclear energy generation residues, mainly spent or unprocessed fuel (0.03 %).

Residues of fuels incineration: Coal and lignite-fired power plants residues are called "coal combustion residues" (CCR) and these typically include the fly ash separated in different stages of the flue gas cleaning system, bottom ash and boiler slag. It is generated in an enormous high quantity worldwide, almost 800 million tons/year. The major utilisation of CCR is in cement, concrete, bricks, wood substitute products, soil stabilisation, road base/embankment, and consolidation of ground, land reclamation and for agriculture. CCRs is being used as a raw material in cement, cellular concrete, fly ash lime bricks, fly ash lime gypsum block, building tiles; as admixture in cement concrete, timber substitute products; as aggregate in concrete, road and building block; as pozzolana in lime pozzolana (Asokan et. al. 2005; Mucsi, 2016). The mechanical activation of CCR is a promising technology and that significantly increases the waste-to-material recyclability of this waste stream. The combined utilisation of mineral processing wastes with CCR is also a promising new area. Equipment of mechanical activation might be the traditional tumbling ball mill or high energy density mills (HEM) like the planetary ball mill, vibratory mill or stirred media mill (Mucsi, 2016; Mucsi et. al. 2019). It is an interesting situation that the residues of the waste-to-energy utilisation of many waste streams, such as the municipal solid wastes (MSW), other combustible wastes, hazardous wastes are also potential secondary raw materials and represent hazard to the environment too. The processing and the application of waste incineration residues might be similar to CCR. As an example, MSW fly ash and slag can be utilised as precursors in low-range alkaline cements after mechanical activation by grinding (Cristelo et. al. 2020).

Residues of solar energy generation: at the end of 2016, the cumulative global PV waste reached 250,000 metric tons, while it is expected that by 2050 that figure will increase to 5.5–6 million tons. Much PV waste currently ends up in landfills. Given the heavy metals present in PV modules, e.g. lead and tin, this can result in significant environmental pollution issues. However, because of the valuable components like silver and copper, methods for recycling solar modules are being developed worldwide. The recycling process of c-Si PV modules (crystalline silicon) begins with the removal of the cables, junction box and frame from the PV module. Then, the module is shredded and the liberated structural components are upgraded by sensor-based sorting. For PV panels shredding specialised hammer crushers are used, when the basic machine is optimised for this waste stream. The separated waste materials are then sent to specific recycling processes associated with each material. According to the FirstSolar and the ANTEC Solar GmbH developed technologies the recycling of the CdTe PV modules process starts with the shredding of the modules into large pieces and subsequently in to small fragments (5 mm or less) by a hammer mill. During the next 4–6 h the semiconductor films are removed in a slow leaching drum. The remaining glass is exposed to a mixture of sulfuric acid and hydrogen peroxide aiming, to reach an optimal solid–liquid ratio. After that process, the glass is separated again. The next step is to separate the glass from the larger ethylene vinyl acetate (EVA) pieces, via a vibrating screen. The glass is cleaned and sent to recycling. Sodium hydroxide is used to precipitate the metal compounds. This process recovers 90% of the glass for use in new products and 95% of the semiconductor materials for use in new solar modules (Lunardi et. al. 2017).

Residues of wind energy generation: the main EoL wind energy generation materials are ferrous and non-ferrous metals, polymers, glass and concrete (Tazi et. al. 2019). Recently, some wind turbine producers (Vestas, Siemens Gamesa) announced the production of 100 % recyclable turbine blades. Carbon Rivers' recycling technology (carbonrivers.com) uses pyrolysis to break down the resins and polymers with intense heat in the absence of oxygen and separates from the inorganic fiberglass reinforcement. The process converts organic products back into raw hydrocarbon products called syngas and pyrolysis oil, which can be used for energy production. This gives the process a net positive energy output. The separated recycled glass fibre can then be cleaned and collected for direct reuse in the manufacturing of new products.

Residues of nuclear energy generation: about 440 nuclear reactors operate globally, providing approximately 10 percent of the world's electricity. Nuclear power plants (NPPs) produce negligible quantities of waste compared to other energy sources. Based on the calculations provided by the International Atomic Energy Agency (IAEA), if spent nuclear fuel (SNF) is not reprocessed, a 1000 MW(e) nuclear reactor produces around 30 tons of high-level solid packed waste annually (HLW). HLW represents high risk, therefore, proper management and safe decommissioning of HLW and SNF are the major aspects of energy production by NPPs. SNF may be considered either as waste, which will eventually be packaged and disposed of, or reprocessed to recover uranium and plutonium followed by the conditioning of residue in the form of HLW containing mainly fission and activation products, and so-called minor actinides. Several countries, instead of reprocessing the SNF, plan to dispose of it in deep geological formations. The increasing bulk of the SNF stream will be problematic as the use of nuclear power increases. Nuclear recycling is the most effective method to solve this problem. Efficient recycling of HLW from SNF decreases ~4–6% of the waste repository volume and decreases the amount of time required (by a factor of 100) during the isolation of residual waste (Alwaeli and Mannheim, 2022).

2.5. Construction & Demolition wastes

The management of construction and demolition waste (CDW) and its correct final destination has become a global problem due to the growth of urbanization. At the same time, there is a need to recover soils degraded by mining, a source of raw material for the production of inputs and materials necessary for urbanization itself. Published in 2008, the EU decree-law 46/2008 establishes the legal framework of CDW management, including prevention, reuse, and the operations of collection, transport, storage, treatment, recovery and disposal. Some key points are: the responsibility to manage CDW belongs to the producer; uncontaminated soils and rocks must be used at the construction site or another site; CDW which cannot be reused has to be sorted at the construction site (for reuse or recycle) or delivered to a licensed waste operator; CDW landfilling is only possible after sorting and it is subject to taxation (Kamino et.al. 2019). If CDW is watched through the glasses of processing the characterising material parts are the "contaminants", namely metals, plastics, soil and woods; the remaining "useful", the brittle components (concrete aggregate, brick, ceramic, tile, etc.) and the finer particulate binding materials. It is logical to separate the "contaminants" first and process them separately using the technology according to the material. The mentioned full-scale comminution arsenal for brittle materials used primarily in mineral processing can be used for the brittle part of CDW.

Excavated soil: CDW can be used for the improvement of degraded areas by open-pit mining. According to Santos and Tubino (2021), processed CDW and composted eucalyptus bark (CEB) were used at a lab scale to make new soil for the degraded areas.

Concrete aggregate: the most important recycling option of separated concrete aggregate CDW is the production of the so-called recycled concrete aggregate (RCA) by suitable comminution and classification unit operations. The comminution typically happens in multiple stages, for coarse crushing horizontal axis jaw crushers and beater rolls can be used. Major stress of the first unit is compressing and some bending; ones of the second unit are mainly beating and some compressing. For the second comminution stage cone crushers (compressing) and impact crushers (impact) are applied. The challenge is whether the quality of the concrete made from RCA is satisfactory or not. According to McNeil and Kang (2013) the aggregate properties are most affected by the residual adhered mortar on RCA. Because of this, RCA is less dense, more porous, and has a higher water absorption capacity than natural aggregate (NA). While RCA and NA have similar gradation, RCA particles are more rounded in shape and have more fines broken off in Los Angeles abrasion and crushing tests. The other recycling target of RCA is the production of new binder or the production of concrete without cement. Fine and coarse recycled concrete aggregate (RCA) with slag or fly ash was used to produce Controlled Low-Strength Materials (CLSM) using only recycled and by-product materials without the need to add Portland cement. In addition to the hydraulic activity of slag and high-calcium fly ash (HCFA), their pozzolanic reaction was activated by the alkalis and calcium hydroxide present in the residual paste of the RCA (Achtemichuk et.al. 2009). When cement substituting materials are produced from CDW, fine grinding is necessary and lately intensive research is going on for the application of the so-called HPGR (high pressure grinding rolls) technology.

Asphalt aggregate: asphalt pavement consists of aggregates resulting in a waste material at end of its life. The aggregates can be reused as basic material for asphalt or cementitious binding agents. In both scenarios, the recycled aggregates should provide a good bond with the binder to achieve strength. Setiadji et. al. (2022) report on the - so-called - pyrolysis method. Three types of aggregate were used: virgin aggregate (VA), recycled asphalt aggregate (RAA), and RAA after removing the thin asphalt film using the pyrolysis method, designated as pyrolysis recycled asphalt aggregate (PRAA). The Pyrolysis method is a unique new surface treatment method to remove and stabilize the residual asphalt film by heating and is expected to contribute to increasing the mechanical properties of the mortar due to an aggregate-to-mortar bond improvement. The pyrolysis method applied on RAA had a number of advantages: the compression strength increased, and the absorption decreased, reducing the formation of a water film surrounding the aggregate during the cement hydration process. The pyrolysis procedure did not have any impact on the tensile strength for both the RAA and PRAA; however, the overall tensile strength decrease was relatively low. For the comminution of waste asphalt aggregates toothed rolls and hammer crushers can be used.

Mixed C&D is now identified that some sources of mixed CDW contain a variety of potentially harmful compounds. Various building materials contain heavy metals including lead (pipe solder, paint, batteries, flashing), arsenic (treated wood), cadmium (paints, batteries), and mercury (electrical switches, lights, thermostats). Asbestos is a component of some building materials such as cement siding, roofing mastic, pipe insulation, and floor tiles. Therefore suitable recycling technologies are important (Khandani et. al. 2023). Tehran mixed CDW after the demolition of EoL infrastructure typically contains sand and cement, concrete, brick, soil, mosaic, ceramic tile, plaster, stone and other materials. After the coarse crushing with a jaw crusher of the recycled aggregate and adding 8% Portland cement as binder good quality underground mine backfilling material was made of up to 5 MPa compressive strength (Khandani et. al. 2023).

2.6. Post-consumer wastes:

Municipal solid wastes (MSW). Main types depend on the collection system, these are the one and multi-component selectively collected MSW (SMSW), such as plastic-paper-metal, plastic-paper, glass and so on, selectively collected green MSW and the residual one (RMSW). The concept of a typical mechanical RMSW processing technology starts with pre-comminution, then sieving. The so-called "bio-fraction" is the fine product of sieving, the course product goes into a multi-stage physical separation (magnetic, eddy current, flow separator, sensor-based sorting, etc.) technology. As it was pointed out earlier the comminution of brittle particles is really widely investigated and applied in mineral processing. There are standard methods, such as investigating single particle breakage events for the characterisation of the process and later designing the machine. However, the comminution of non-brittle materials - such as most of the regular post-consumer wastes - represents a new challenge. Rácz and Csőke (2021) made a pioneering work in this field carrying out repeated single particles breakage tests with real waste particles. Shear and complex tearing stresses were applied on the particles in axial gap rotary shear and swing type hammer shredder. The results proved that the developed single-particle comminution test method is appropriate to investigate the breakage behaviour of real waste particles. Measuring the breakage probability by this method, the effect of different machine and stress types, and the operating parameters on the particles' breakage behaviour can be investigated. The obtained results can also be used both in shredders' operation and design. For RMSW processing low-speed rotary shredders are typically used for pre-shredding and radial gap shears are used for the comminution of the separated RDF (refuse derived fuel).

EoL Rubber tyres: the EoL (End of Life) tyres can be comminuted in multiple stages. Sometimes the two main steel cords are removed first with a machine, where a hook tears them out through a hole of an armour. Axial gap shears, then radial gap shears and finally cutting mills can be applied when metals are removed. The comminution itself of **EoL batteries** is not problematic, hammer shredders are generally applied. However, the other circumstances, namely the fire and explosion hazard and the hazardous dust emission of dry technologies are the challenge. **EoL refrigerators** can be comminuted by hammer shredders. Many times, one or more considerable mass chains serve as hammers. The first some units, including the first comminution stage of EoL refrigerator recycling plants are working in neutral nitrogen atmosphere which collects the released gases, typically the Freon. The working gas then cleaned and regenerated. **EoL Vehicles**, not only cars, but buses, trains, trucks and ships represent a huge material source after their normal life cycle. The typical first comminution stage of EoL vehicles processing is the pre-shredding with high mass swinging hammer shredders. **Waste electrical and electronic equipment (WEEE), EoL TV devices, EoL Computers** represent source for precious metals and structural materials. Main comminution machines used for WEEE shredding are the hammer shredders and hammer crushers. **Recycling of used printed circuit boards (PCB)** is a widely investigated area; many technological options are available (Abbadi et. al. 2024). For waste PCB comminution - among others - high-speed hammer mills, swing-hammer mills, impact crushers and cutting mills can be applied.

3. STOCK TYPES OF SECONDARY RAW MATERIALS

In a recent paper Mirletz et.al. (2023) projected the cumulative mass of different waste streams, namely many of the stock types of anthropogenic secondary raw materials are listed. According to this projection 70350 mill. tons of municipal solid wastes, 45500 mill. tons of coal ash, 12355 mill. tons of plastic waste, 1876 mill. tons of E-waste, 249 mill. tons of oily sludge and about 120 mill. tons of solar panels will be deposited somewhere by 2050. If we take into account the mineral deposits, namely gangue and tailing stockpiles and tailing ponds and the entire built infrastructure (buildings, roads) we can feel the huge amount of stocked anthropogenic materials. According to our vision there is no waste, just secondary raw materials; so the possibilities of urban mining are really promising.

4. Conclusion

This review paper gives only a brief glimpse into the findings of our literature survey. However, we believe that our systematic approach enhances comprehension, clarifies scientific vocabulary and provides insight into the potential urban mining applications of mineral processing. Additionally, a comprehensive overview and categorization of flow and stock types of anthropogenic secondary raw material sources are provided.

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