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Content

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1. Overview of the deliverable

In this deliverable, CirclELab aims to show the required characteristics of the wastes to become valuable products and how these processers are made. The aim is to gather together data on wastes produced per economic activity in four countries (Belgium, Hungary, Italy and Spain) and analyse them with an objective of identifying the most important types and quantities of wastes; the focus will be oriented to the development of a methodology which will be proposed based on a disruptive toolkit that will allow students of 10-18 years old and their teachers to experience a recycling process with their hands. It will present the characteristic of wastes to become valuable products and the process through which wastes become products through recycling, by method of common and basic teaching concepts like pictures, paints, videos, etc. and visit to recycling plants to introduce and teach students recycling process or circular economy in schools, and students will be able to link common products with wastes and to understand that what is waste for one can be a resource for the other.

2. Introduction

Sustainability is a recurring word today together with a growing awareness of the linear model with its economic rationale: take - make - dispose. In a linear economy, mined raw materials are processed to make products which are later thrown away as waste after use. This practice is now seen as a problem and it has become evident that a new approach need to be considered. The inputs in the current lineal economy are becoming limited (Michelini et al., 2017) and the output are detrimental to the ecosystem. It was observed that, over the last century, the linear economy led to dependency on imported raw

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material in most countries in the world, especially in EU countries where up to 20% and 30% of all resources were imported (Ragossnig and Schneider, 2019). Consequently, the increased consumption of materials generated massive waste that require extra management. In 2016, EU produced up to 1.8t of waste per capita annual basis (Ragossnig and Schneider, 2019). Such quantities of waste are very challenging and a good opportunity to reconsider a shift from inefficient linear economy (Michelini et al., 2017) and put into play the alternative and regenerative circular economy.

Circular economy encourages closing loops (EU, 2015) and measures that consider a complete whole cycle of materials and aim to identify sustainable practices that shift to long lasting design, repair and recycling. This is a regenerative approach where things are not lost but constantly repurposed to serve new function. Rather than designing a degenerative systems, design a regenerative one over time and alleviate the problem of materials import dependency to some extent through waste management and material recovery through recycling.

Environmental quality cannot be improved via economic growth and if people do not engage in waste management and recycling of resources, reserves of resources will vanish on earth very soon. Therefore, Increasing the rate of waste management and recycling is the way to maintain and improve the environment (George et al., 2015). Recycling is now significantly considered in most of developed economies. A model by (George et al., 2015) showed that circular economy can only come into existence if countries recycle and reuse more waste for consumption and production. Recycling of waste, which is seen as a substitution of primary resources by secondary resources – material that may resemble waste - (Ragossnig and Schneider, 2019), material that should cease to be considered as waste (European Parliament and the Council, 2008), has the potential to reduce environmental impact by providing secondary as sustainable and alternative materials while securing environmental protection.

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3. Waste generation

It is recognised that the global source of resources is approaching limitations while the need for resources has been globally growing very fast in the last decade (Haas et al., 2015). The world generates 0.74kg of waste per capita per day (Fig. 1). In 2016, it was estimated that 2.01 billion tonnes of municipal and solid waste were generated. Estimations shows by 2050, waste generation will outpace the global population growth by more than double and the word is expected to generate up to 3.40 billion of tonnes of waste annually (Kaza et al., 2018). It was also show that there was a correlation between volume of waste produced and income levels and urbanisation rates. Therefore, prediction shows that low-income countries will generate more than three times of waste in 2050. Waste generation is expected to triple and many governments have started to make decision of how raw materials should be consumed in order to better manage produced waste which is degrading our ecosystem and contaminating our planet by, for example, causing flooding due to clogged drains, transmitting diseases, increasing respiratory problems, etc. (Kaza et al., 2018).

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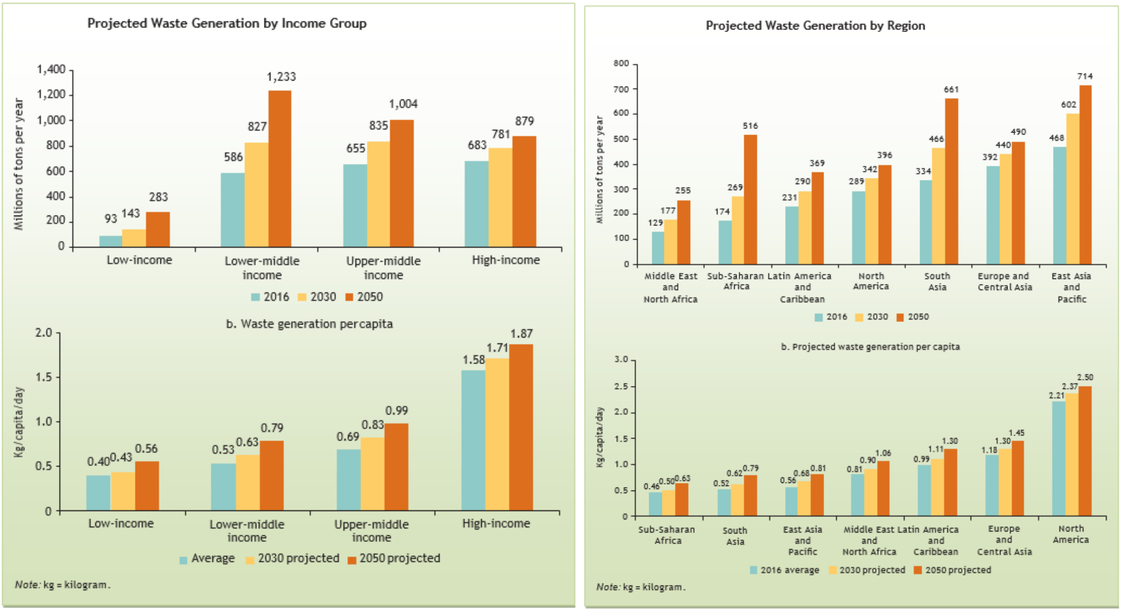

Figure 1: Projection of waste generation (adapted from (Kaza et al., 2018))

Only 4 gigatons per year (Gt/yr) (more or less 10%) of the generated 41 Gt/year of waste materials are recycled per year (Haas et al., 2015).

The type of waste is very important when considering the process to recycle. We may consider that (DGSIE, 2012):

- 83% of waste is in solid form,
- 10% of the waste is in pasty form,
- 7% of waste is in liquid form.

Regarding specifically the production of industrial waste, most of them are inorganic waste (70%) while only 25% organic waste are available.

Moreover, we have to consider that some wastes are valuable – they have an economic value - which means that they can be reintroduced on the market even a treatment is needed (Fig. 2).

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	Metal content and value estimated for a typical cell phone		Metal content and value for 500 million obsolete cell phones in storage in 2005[2]	
Metal	Wt[1] (g)	Value	Wt[3] (t)	Value
Copper	16	$0.03	7,900	$17 million
Silver	0.35	$0.06	178	$31 million
Gold	0.034	$0.40	17	$199 million
Palladiun	0.015	$0.13	7.4	$63 million
Platinum	0.00034	$0.01	0.18	$3.9 million
Total			8,102	$314 million

Figure 2: Rare earths and critical metals. Shortage or negligence? (adapted from Pirard, 2013)

Globally speaking, we are living in a limited world: energy, raw materials, space (urban planning) and capacity of adaptation of the environment are limited. That’s why it is needed to introduce the 3R theory as a way of life: **Reduce**, **Reuse** and **Recycle** are the 3 concepts we must have in mind when considering resources consumption. It is now important to modify our behaviour.

CirclElab project is focusing on **Recycling**.

4. Waste generation in the EU

In 2016, EU-28 generated wastes that amounted to 2,538 million tonnes (Fig. 3) where construction and demolition contributed to 36.4% of the total waste generated followed by mining and quarrying with a share of 25.3% (European Environment Agency, 2019). Of all the wastes produced, these two economic activities are classified as major mineral wastes and their share of waste generation covers up to two third of the total wasted generated in 2016 in EU-28.

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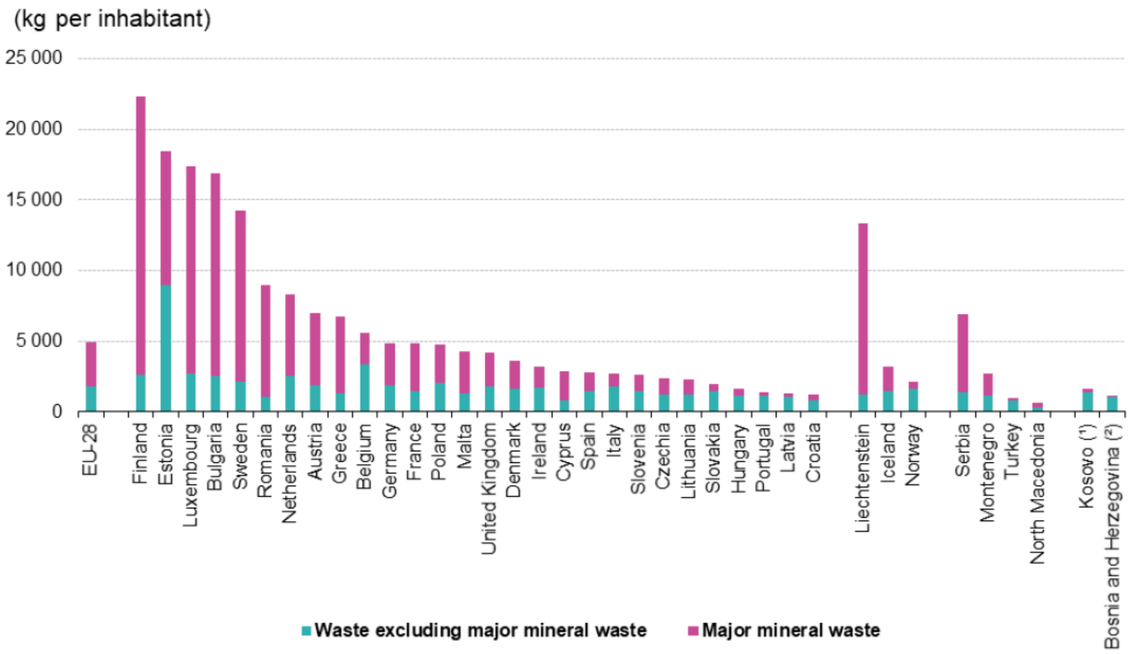

Figure 3: Waste generated in 2016 in Kg per inhabitant (Eurostat, 2019a)

While annual waste generation is projected to increase up to 70% by 2050, the scaling of circular economy is expected to make a significant contribution to achieve climate neutrality by decoupling the need resource and economic growth. For this to be achievable, circular economy will have to provide to citizens functional, safe, affordable, and high quality products that are designed for reuse, and enabling remanufacturing and high-quality recycling (European Commission, 2020). Therefore, creation of well-functioning competitive secondary raw materials will contribute to preventing a mismatch between raw material and secondary raw material.

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5. Wastes generated in Belgium, Hungary, Italy and Spain

As part of CirclELab project, this work focuses on waste produced in the four countries concerned by the project: Belgium, Hungary, Italy and Spain; it uses waste data produced in each country to identify the 5 top most important wastes in terms of quantity generated. Used data were sourced from Eurostat statistics (Eurostat, 2019a). To identify the top five wastes generated for each country, wastes data were collected and analysed for each individual country. The results of the analysis are presented on Figure 4, 5, 6 and 7.

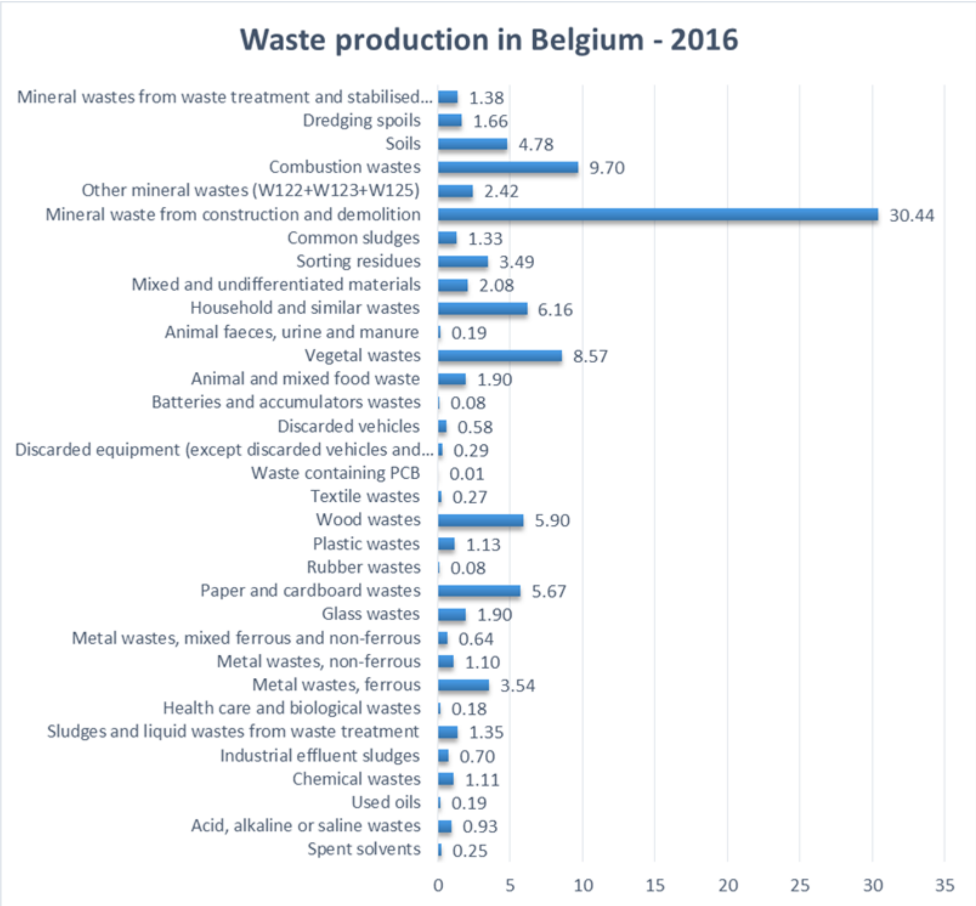

Figure 4: Percentage of waste produced by economic activity in Belgium

The top five waste produced in Belgium are:

1. Mineral waste from construction and demolition
2. Combustion wastes
3. Vegetal wastes
4. Household and similar wastes
5. Wood wastes

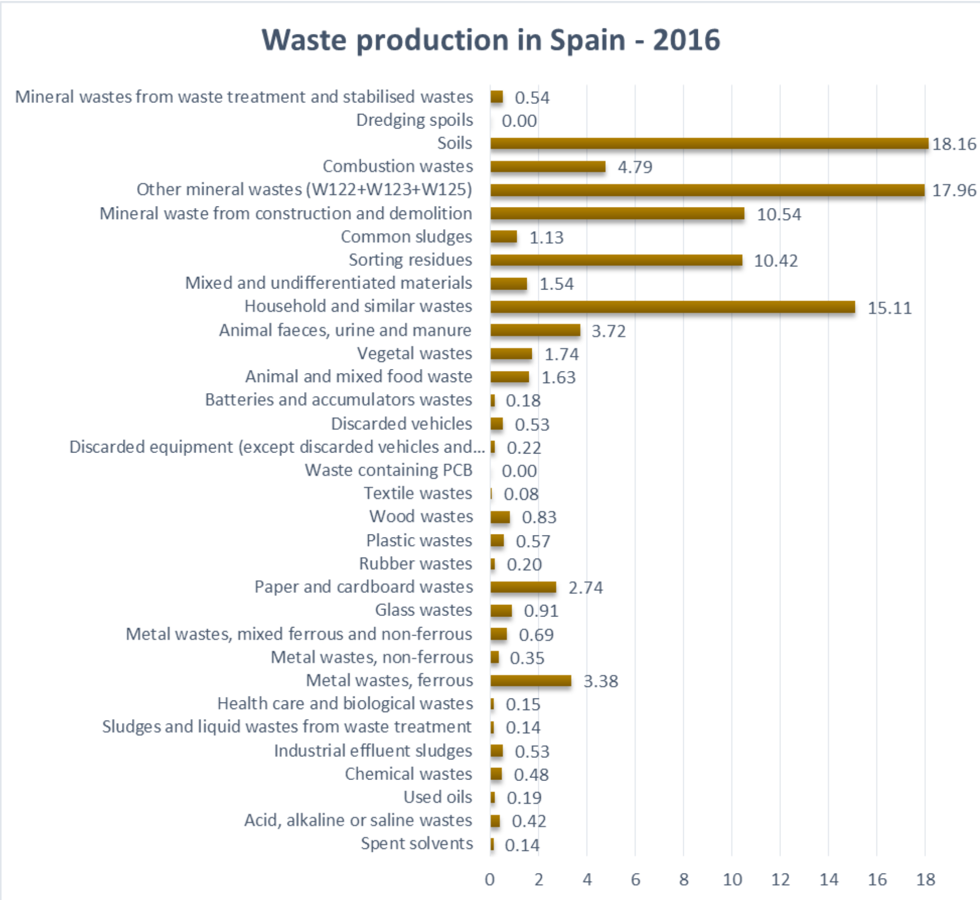

Figure 5: Percentage of waste produced by economic activity in Spain

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The top 5 wastes produced in Spain are:

1. Soils wastes
2. Other mineral wastes (W122+W123+W125)[1]
3. Household and similar wastes
4. Mineral waste from construction and demolition
5. Sorting residues

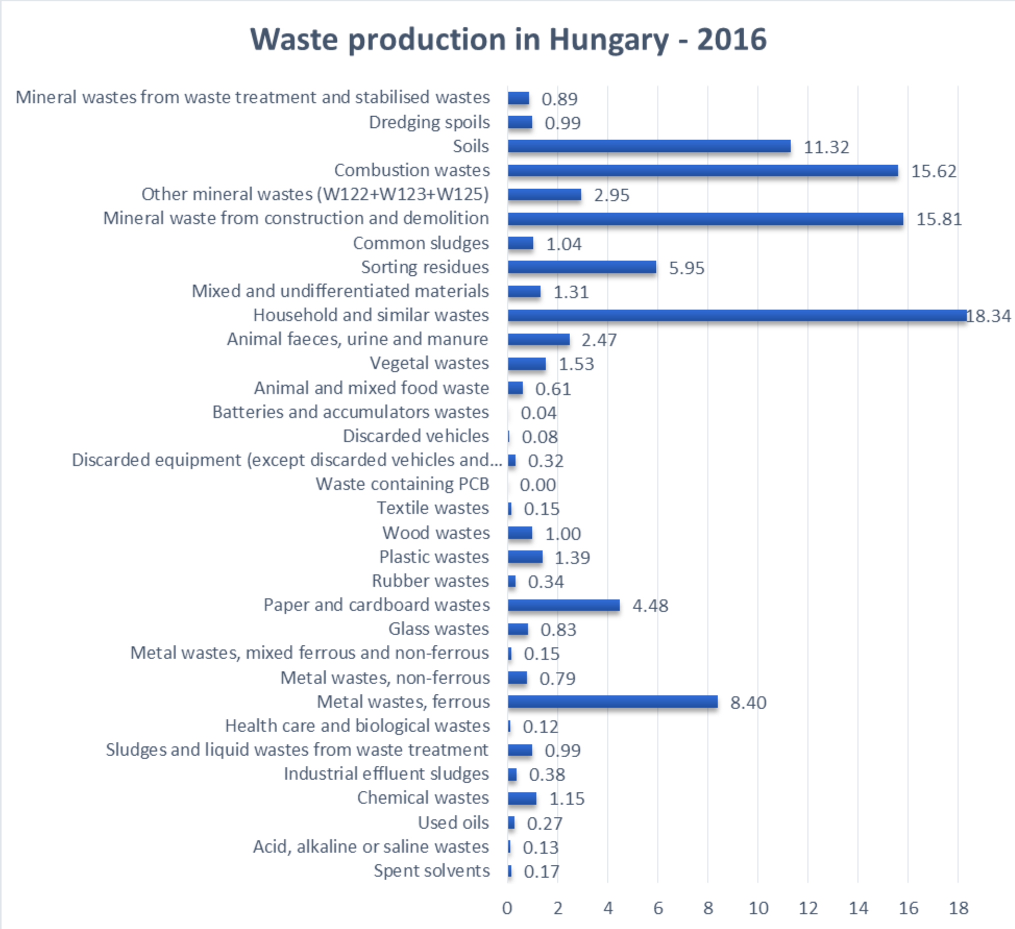

Figure 6: Percentage of waste produced by economic activity in Hungary

[1] This wastes are: asbestos wastes (W122), waste of naturally occurring minerals (W123) and various mineral wastes (W125)

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The top 5 wastes produced in Hungary are:

1. Household and similar waste
2. Mineral waste from construction and demolition
3. Combustion wastes
4. Soils waste
5. Metal wastes, ferrous

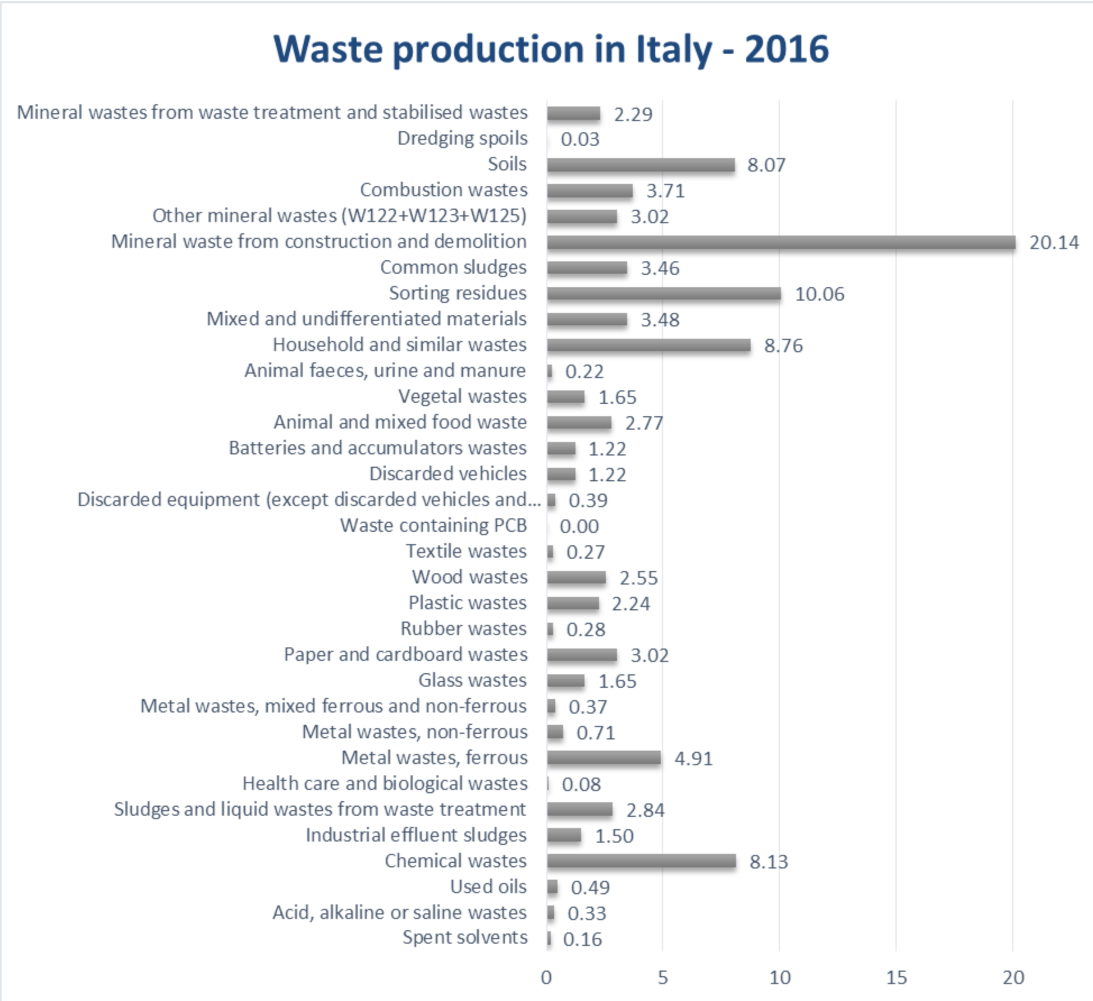

Figure 7: Percentage of waste produced by economic activity in Italy

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The top 5 wastes produced in Italy are:

1. Mineral waste from construction and demolition
2. Sorting residues
3. Household and similar wastes
4. Chemical wastes
5. Soils wastes

The results of the analysis showed that the top 5 wastes produced was different for each individual country. Therefore, the identification of the top wastes produced for all four countries was found not to be trivial. To identify the top wastes produced, two possibilities arose: firstly to ignore the ranking and take all the 10 main types of waste constituting the 5 top wastes produce in each country (Table 1).

Table 1: 10 main wastes generated in Belgium, Hungary, Italy and Spain (2016)

10 main wastes produced in the four courtiers
Mineral wastes from construction and demolition
Household and similar wastes
Soils wastes
Combustion wastes
Sorting residues wastes
Other mineral wastes (W122+W123+W125)[1]
Metal wastes, ferrous
Paper and cardboard wastes
vegetal wastes
chemical wastes

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The second possibility was to sum-up the shares for the four countries of each individual type of waste and from the score, identify the 5 top wastes representing all four countries (Fig. 8).

Figure 8: Scores for wastes produced by economic activity in the 4 countries

As a summary, the top five wastes which are common for the four countries involved in this project are:

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1. Mineral wastes from construction and demolition
2. Household and similar wastes
3. Soils wastes
4. Combustion wastes
5. Sorting residues wastes

6. Recent history and minimum requirements for recycling

The idea of using all the products resulting from a manufacturing process - and therefore including the by-products, which are products different from that which one wants to produce in principal, the waste being the ultimate by-product - is not new to humans. This is particularly true in the agricultural field, the phenomenon being more recent in industry. In this area, the development of the use of certain wastes was done in parallel with the development of heavy industry, which seems normal insofar as the wastes produced by the coal or iron industries were relatively easily assimilable to aggregates or incorporated into binders (Table 2).

Table 2: waste recovered in France in the construction sector (J.H. Colombel, 1992)

Type of waste	Year
Study on granulated blast furnace slag for cemeteries	1880
Accepted in France in	1928
Already used for metro in	1900
Crystallised blast furnace slag for ballast *Up to 1.25 10^6 tonnes recovered*	1885 1952
Expanded blast furnace slag –patent in	1900

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Crystallised blast furnace slag for roads	1955
Black or red coal shales	1950's
Fly ashes (roads)	Around 1960
Fly ashes - cement	1960-65
Gravels – Fly ashes	1968
Fly ashes - lime – gypsum	1968

Over time, the supply of by-products, which was initially limited in quality and very large quantitatively, has become more and more diversified, as the petroleum, plastics chemical and rubber industries have developed.

The use of recycled materials within the road industry and civil engineering has been done gradually for fifty years and has experienced a significant acceleration from 30 years, due to the increased demand for materials, both in quantity and in quality: if, at the outset, the waste was used mainly as backfill or aggregates, it was later used as binders and additives.

The needs of civil engineering can be indeed of four main types of materials, namely:

- ***Filling materials***, on which there are low requirements and consumed in large quantities, for embankments but transportable over short distances due to costs;
- ***Aggregates***, which must meet various specifications depending on the place they will occupy in the structures and the treatment techniques used. The quality requirements can at this level become high, even severe for the surface layers, to lead to finished products of quality identical to that of traditional materials;
- ***Binders***, which must meet very precise specifications and whose properties must remain constant over time. Employed in small quantities and competitive with expensive products (cement & bitumen), they may experience pre-employment packaging and bear higher transportation costs;

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- *Activators*, which will be used in small quantities, which can cause problems of collection, storage, distribution and regularity.

If the technical, economic and ecological interest appears clearly in the relationship between the supply of by-products and the needs of industry, it is also clear that the use of such products poses a certain number of difficulties:

- technical ability to enter into the composition of materials (standards);
- suitability for the use of materials using this waste;
- economic optimization of possible jobs;
- social impact on employment in companies supplying noble products;
- effects on the environment.

Therefore, beyond any technical question on the use of this or that secondary raw material, various questions must be asked:

- How can waste find its place in an industry and, in general, in a highly standardized society?
- What regularity to request and what controls should be put in place so that the waste used always remains in the ranges where it has demonstrated its capacity for use?
- How to observe and ensure the long-term durability of the materials used?
- What is the influence on the environment?
- What socio-economic problems can arise in conventional industrial activities?

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7. Methods of treatment and management of waste

Although considered an engineering discipline later, around more than one century, waste management, especially solid waste management has been a concern since the human civilisation (Christensen, 2011). This section highlights the most common methods of treatment and management of waste.

Note that this chapter is inspired by the work of **Delvoie et al. (2019)** performed within SeRAmCo project (https://www.nweurope.eu/projects/project-search/seramco-secondary-raw-materials-for-concrete-precast-products)

7.1. Treatments methods for waste management

Treatment of waste is a process which is performed prior the recycling process. Its purpose is to improve the characteristics of the recycled waste before mechanical or physical treatment by sorting as much as possible waste arrival and removing impurities as well as reducing volume, etc. Three possible types of treatment where identified (Christensen, 2011): mechanical treatment, thermal treatment and biological treatment.

Mechanical treatments involve mostly size reduction, sorting and compaction, can be operated separately or combined with the two other treatment types.

Thermal treatments involves full or partial incineration at high temperature (pyrolysis/gasification) leading to changes in physical and chemical characteristics of waste.

Biological treatment is about composting (degradation of organic waste) and anaerobic digestion (degradation of organic waste in absence of oxygen). The end result give

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methane gas which is used as source of energy and the residues of the process are used as land fertiliser.

Most of the wastes receive mechanical treatments consisting of two phases, a reduction of the particle size followed by a purification stage where the quality of the waste is increased. After that, the waste is treated according to the different available applications.

7.2. Size reduction

Crushing is performed in order to prepare waste materials for further purifying treatments or for calibration. It can be done using different systems and devices.

7.2.1. Impact crusher

It consists of a crankcase inside which there is a rotating rotor garnished with beaters (Fig. 9). Wastes entering the crusher are driven by the beaters and struck against impact plates. Due to the impact produced which is amplified by self-crushing, materials are broken into finer fractions. The impact crusher is the most used type of crusher because it allows producing very fine fractions of materials. However, it induces the biggest wear and it is limited by the primary size of waste to be treated (Fig. 10).

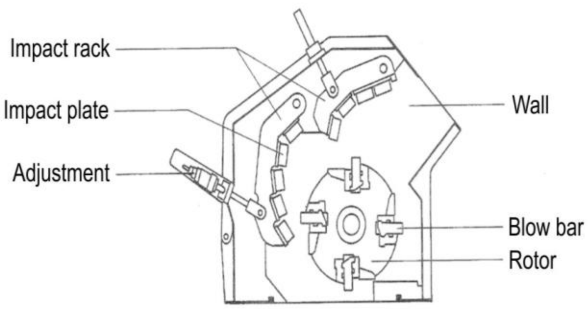

Figure 9: Impact crusher (Gorle & Saeys, 1991) **Figure 10**: (JXSC impact crusher, 2018)

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7.2.2. Jaw Crusher

This crusher is composed of two jaws, one of which is fixed and the other one is mobile (Fig. 11). By a regular back-and-forth motion of the mobile part, waste is stuck between the jaws and breaks under pressure. This type of crusher also allows to treat bulky waste like concrete slabs that can be very large (depending on the crusher opening) (Fig. 12). However, jaw crusher does not allow to produce very fine particles from raw waste and generally requires a secondary crushing. Wear is less important than for the impact crusher.

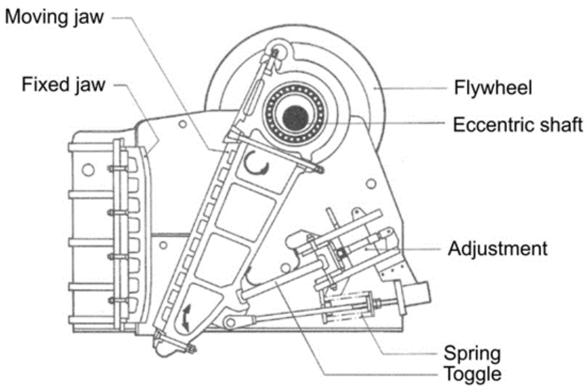

Figure 11 : Jaw crusher (Gorlé and Saeys, 1991) **Figure 12**: (JXSC jaw crusher, 2018)

7.2.3. Other types

There are other types of crushers, but their use is less widespread, in particular cone crushers where waste is crushed using a rotating cone (Fig. 13).

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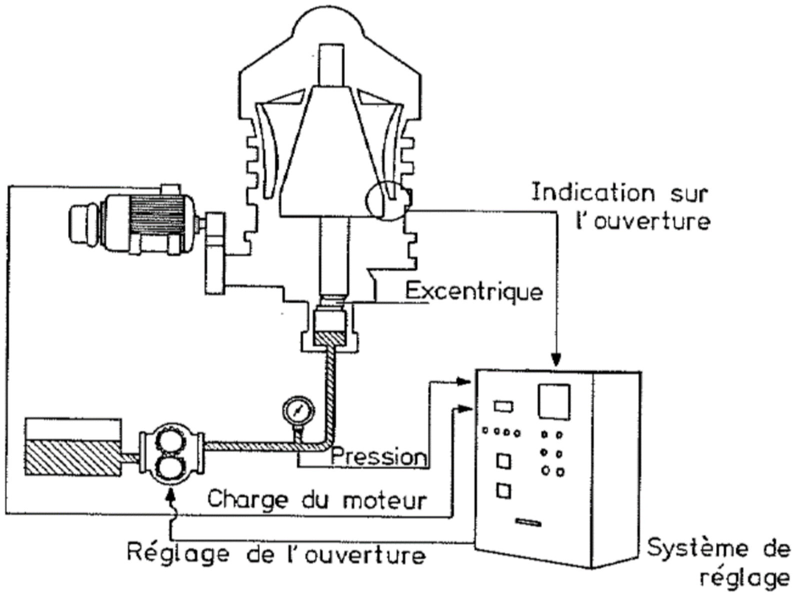

Figure 13: Cone crusher installation (J.H. Colombel, 1992)

Another type of crusher is described on Fig. 14: the materials rotate through adjustable grids, so the fragments – of demolition concrete in this case – are always rejected in the air and not, as usual, crushed between the hammers. These projections break the concrete until the fragments are small enough to fall through the grids. Reinforcements continue to dance above the grids until they get expelled by a shutter intended for this purpose. This system does not only have the advantage of separating the concrete and the reinforcement: concrete is mainly broken by traction. As concrete has a tensile strength that is not very important in comparison to its compressive strength, we can save a lot of energy by using this weakness, which is not the case with other devices needing to crush concrete mainly by compression.

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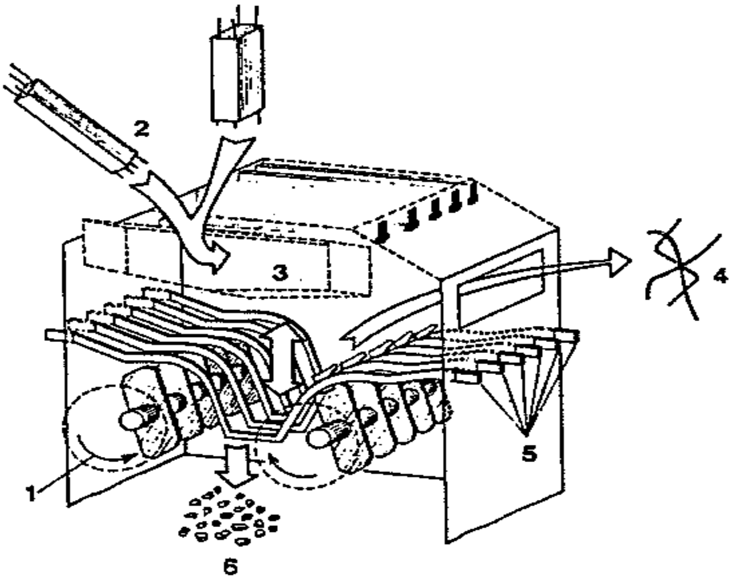

Figure 14: Diagram of a reinforced concrete crushing installation (De Pauw, 1992)

1. Direction of rotation of hammers - 2. Reinforced concrete to be fragmented - 3. Filling opening - 4. Reinforcements - 5. Grids - 6. Fragmented concrete in aggregates

In many cases, it is the choice and the combination of various types of equipment which will provide the most suitable product to the intended application.

According to the survey by Delvoie et al. (2019), jaw crusher appears to be the most used crusher type in 90 % of the concerned recycling plants. This is followed by the impact crusher in 60 % of the concerned recycling plants. Cone crusher is used in 20 % of the concerned recycling plants.

7.3. Purification techniques

Specific separation systems are used for removing foreign materials such as:

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7.3.1. Steel reinforcement

Normally, the crushing machines used can treat reinforced concrete which steel diameter does not exceed 15 mm. For specific uses, installations supporting larger diameters can be designed. Steel is removed by using an electromagnet band (Fig. 15) placed above a conveyor transporting the crushed materials. Steel can be recycled as scrap in steel companies.

7.3.2. Plastics, wood and paper

Wood and papers can be removed by manual sorting close to a low speed conveyor belt. As a technical installation, pneumatic separators can be used. The waste enters an airstream and is driven according to their shape and nature over longer or shorter distances (Fig. 16). These separators require the additional installation of cyclone and filter in order to purify the air of the fine particles contained in it. Investment costs are high as well as energy consumption. The other purification possibility is to separate impurities by wet process. Waste goes through a bath where light fraction including wood, paper and synthetic materials are eliminated by flotation. Washing waters charged in fine particles require a purification that can take place in hydro cyclones batteries combined with a settling basin. These installations require a lot of space. Water can be used in a closed circuit through periodical complements.

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Figure 15 : electromagnet band for extracting steel

Figure 16 : paper sorting device

Purification techniques described above are only applicable for fixed installations. Concerning mobile installations, the process is limited to iron extraction and manual sorting. Classification of crushed material is done on one or more screens according to the desired particles size.

8. Specific waste treatment and application

8.1. Construction and demolition wastes

Construction and demolition activities in the European Union (EU) generate, per year, up to 850 million tonnes of construction and Demolition Wastes (C&DW) and 70% is expected

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to be recovered since 2020 (Villoria Sáez and Osmani, 2019). Construction sector in EU was identified as the highest producer of waste where its share represents 35% of the total wasted generated.

It is difficult to define a specific composition for construction and demolition waste (C&DW) (in percentage terms) as it will vary between sites, regions and countries. There are also likely to be considerable differences between the composition of construction wastes and of demolition wastes.

An estimate made by Wallonia Government under the Walloon Waste Plan Horizon 2010 considers the shares of construction and demolition waste per source as follow:

- 36% from hydraulic and road works;
- 6% from new buildings;
- 6% from renovation works;
- 52% from demolition work (including 21% residential demolition).

Their composition heavily depends on the type of the demolished structure as well as the materials used during its construction. Waste produced under construction is generally classified into 3 main categories (Regnier, 2000): inert, industrial and hazardous wastes. Beyond this classification, it can be seen that the classification can be reduced to two main categories of waste coming respectively from (i) road works and civil engineering and (ii) buildings.

With regard to road and civil engineering by-products, their cleanliness (almost exclusively inert waste), but especially their propensity to be generated in the context of a selective demolition process, makes them easy to be recovered. On the other hand, building wastes are varying in nature, size and dangerousness.

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C&DW deposits result from the demolition of old structures such as buildings, walls, bridges, etc. Their composition depends on the type of demolished structure and materials used during construction.

Waste treatment plants have a policy of selecting demolition materials at the reception. All materials are not accepted; rejected materials are landfilled by demolition companies. In most cases, the materials received are free of charge. In the opposite case, the cost of the reception is decreasing according to their quality. This concept of quality is based on two criteria: cleanliness and homogeneity. Thus, there are five main categories of materials:

1. Clean concrete, whether reinforced or unreinforced, without coating or plaster;
2. Clean but composite materials (coated, bricks, tiles, gravel, stones and boulders, etc.);
3. Mixed materials with a low content of plaster and wood (masonry, reinforced concrete, etc.);
4. Bad quality materials with a wood and waste content greater than 10% (masonry, reinforced concrete, etc.);
5. Others (earthy materials, etc.).

Generally, the materials received are stored according to their quality and ease of processing. They are composed of 93% clean materials, including 60% clean concrete. Road waste is the material that results from road repairs. It is mainly bituminous material, gravel, slag and smaller proportions of old clay or concrete pipes.

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8.1.1. Type of treatment plant

Generally, demolition waste can be recycled in installations specially designed for this purpose. There are 3 types of installations:

- Mobile: installations are mounted on trailers or semi-trailers and can easily be transported from one site of operation to another;
- Semi-mobile: installations are mounted on metallic constructions and can be moved with appropriate handling machines;
- Fixed: installations are mounted on foundations.

The treatment of C&DW is done at specific plants, for example: a processing plant in Glasgow, Scotland (Fig. 17). Depending on the composition of waste and the required end product. A series of operations such as (Medina et al., 2015): Initial screening, crushing, magnetic separation, manual separation of impurities, mechanical grinding, etc. are undertaken.

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Figure 17: C&DW recycling process (source: (Medina et al., 2015))

8.1.2. Concrete[2] (17.01.01)

Concrete is no doubt the most commonly use construction material in the construction sector. It is most commonly composed of fine and course aggregates bonded together by cement. Therefore, aggregates are natural resources that constitute concrete. It is estimated that the global demand for aggregates used in construction is growing 4.7 % annually and in 2011 the global demand was 26.8 billion metric tonnes with a cost of $201 billion (about €170 billion) (Indian Concrete Journal, 2008). The European (EU28+EFTA,

[2] This classification of wastes is based on "Guidance on classification of waste according to EWC-Stat categories "Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics, Version 2, December 2010.

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2015) aggregates demand is 2.7 billion tonnes per year, representing an annual turnover of an estimated €15 billion. This European demand represents about 10 % of the global demand in aggregates and accounts for 5 tonnes per capita per year ((UEPG, 2017); (Delvoie et al., 2019)).

Statistics coming from the UEPG (Union Européenne des Producteurs de Granulats) reveal some specific trends on the European market (UEPG, 2017) (Fig. 18).

Russia produced up to 706 million tonnes (mt) of aggregates in 2017, followed by Germany, Turkey, France, Poland, UK and Italy. At the other end of the scale were the smallest countries, namely Malta, Montenegro, Iceland, Luxembourg and Northern Macedonian, with less than 5mt each ("UEPG - Annual Reviews," n.d.). Taking into account EU28 plus EFTA countries, 46% of the production was as crushed stone; the sand & gravel component represented 38%, which saw a slight decline compared to 2016 (see Figure 18). Recycled concrete aggregates constitute 6% to 8% of aggregates used in Europe where Belgium is among the greatest users (Aslani et al., 2018). Recycled aggregates are from recycling waste from demolition of concrete and it is worth to note that aggregates make 70% to 80% of the concrete mixture (Verian et al., 2018).

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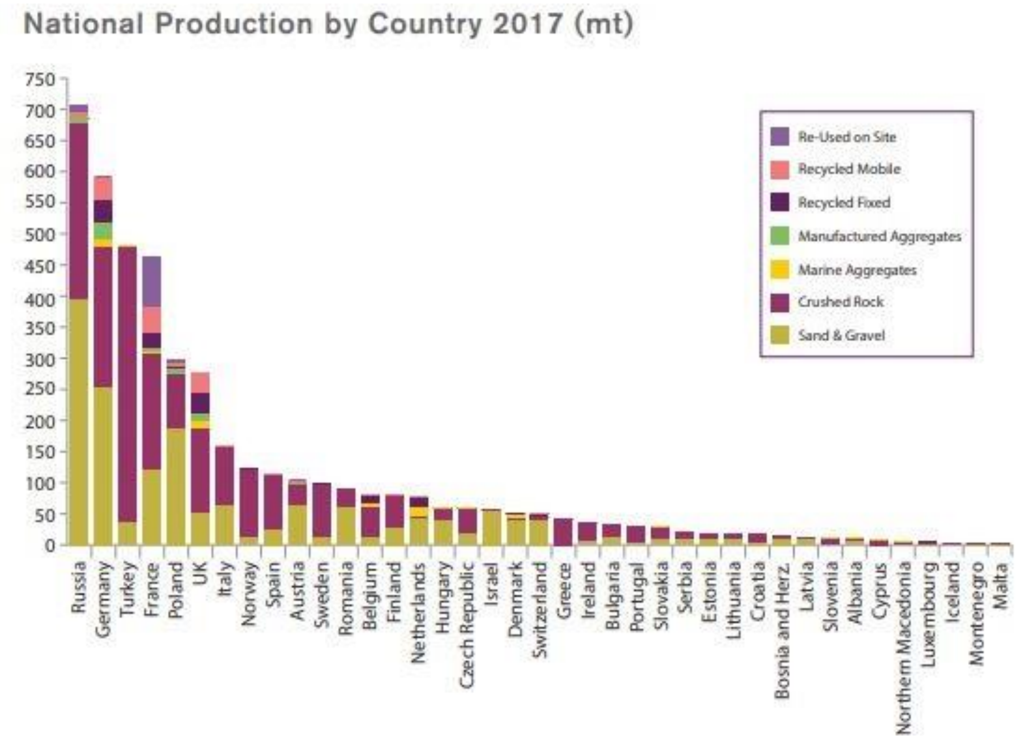

Figure 18: Aggregates production in Europe in 2017 by country and type ("UEPG - Annual Reviews," n.d.)

Different steps are generally needed for concrete recycled aggregates preparation (Fig. 19).

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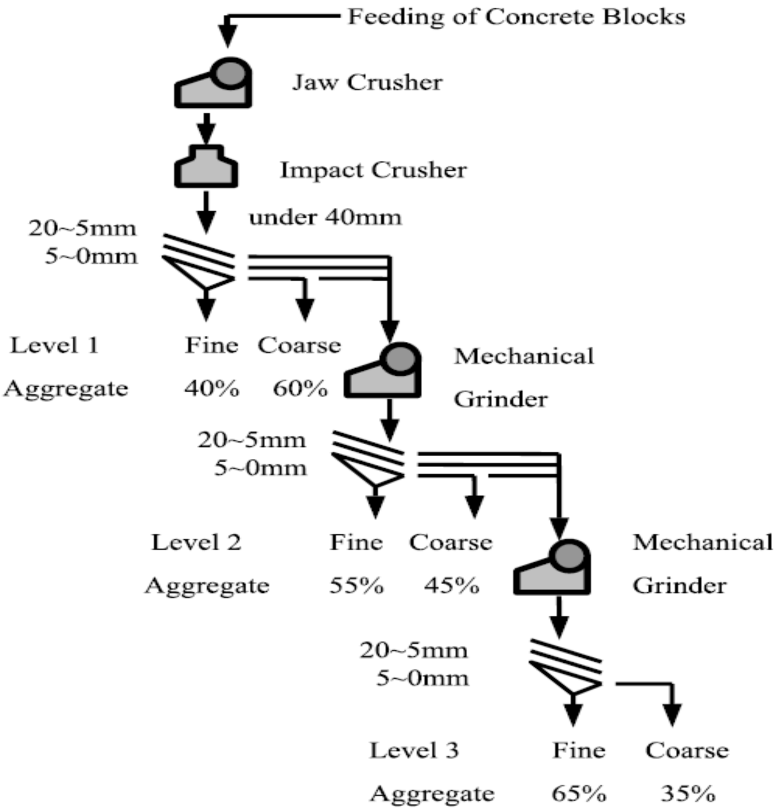

Figure 19: Recycling process (Nagataki et al., 2004).

The reuse of Construction and Demolition Wastes generates savings in terms of natural resources in aggregates and make contribution in preservation of environment by reducing the need to open new mining areas and energy associate. Recycled construction aggregates may also reduce construction costs and some studies even reported improved properties at a certain level of proportion (Tam et al., 2018).

Recently the use of recycled aggregates in structural concrete has been included in the European standard. EN 206:2013+A1. “Concrete – Specification, performance, production and conformity” (CEN, 2016) only concerns the use of coarse recycled aggregates; their use is restricted to the less severe environments. Table 3 shows limits for the replacement

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of natural normal-weight coarse aggregates by coarse recycled aggregates in relation to exposure classes. This table is valid for coarse recycled aggregates (categories Type A and B) conforming to standard EN 12620 (CEN, 2013a). Detailed requirements for recycled concrete aggregates and recycled masonry aggregates such as acid-soluble chloride ion content, water soluble sulphate content, fines content, flakiness index, resistance to fragmentation, oven dried particle density, water absorption are restricting their use in concrete (Grellier et al., 2020)

Table 3: Maximum percentage of replacement of coarse aggregates (% by mass) according to EN 206:2013+A1 (CEN, 2016)

Recycled aggregate type	Exposure classes			
	X0[c]	XC1, XC2[c]	XC3, XC4, XF1, XA1, XD1[c]	All other exposure classes[a]
Type A: (Rc_{90}, Rcu_{95}, Rb_{10}, Ra_1, FL_2, XRg_1)[d]	50%	30%	30%	0%
Type B[b]: (Rc_{50}, Rcu_{70}, Rb_{30}, Ra_5, FL_2, XRg_2)[d]	50%	20%	0%	0%

[a] Tyep A recycled aggregates from a known source may be used in exposure classes to which the original concrete was designed with a maximum percentage of replacement of 30%.
[b] Tyep B recycled aggregates should not be used in concrete with compressive strength classes > C30/37.
[c] X0: Exposure class for no risk of corrosion or attack; XC1 to XC4: Exposure classes for risk of corrosion induced by carbonation (XC1: Dry or permanently wet; XC2: Wet, rarely dry; XC3: Moderate humidity; XC4: Cyclic wet and dry); XF1: Exposure class for risk of freeze/thaw attack (Moderate water saturation, without de-icing agent); XA1: Exposure class for risk of chemical attack (Slightly aggressive chemical environment); XD1: Exposure class for risk of corrosion induced by chlorides other than from see water (Moderate humidity).
[d] Rc_{90}: mass percentage of concrete products is higher than 90% (50% for Rc_{50}); Rcu_{95}: mass percentage of concrete products and unbound aggregate is higher than 95% (70% for Rcu_{70}); Rb_{10}: mass percentage of clay masonry units (i.e. bricks and tiles) is lower than 10% (30% for Rb_{30}); Ra_1: mass percentage of bituminous materials is lower than 1% (5% for Ra_5); FL_2: volume percentage of floating material is lower than 2%; XRg_1: other non-floating materials (i.e. clay, soil, plastic, gypsum) and glass is lower than 1% (2% for XRg_2).

All over Europe, more than 5500 companies with around 8000 production plants are producing concrete precast products (CPP). It is estimated that the sector generated 24 billion euro in 2015 according to European Federation of the Precast Concrete Industry (BIBM, 2016). The European Federation of the Precast Concrete Industry estimates that about 25% of concrete production is represented by concrete precast products (Delvoie et al., 2019).

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8.1.3. Bricks (17.01.02)

Bricks are rectangular blocks used in construction sector to form parts of buildings (Fig. 22). The history of bricks can be traced back 8300 BC where brick was the main construction material for up to 10000 years and is able to resist many centuries (Fiala et al., 2019). Bricks are commonly used in construction of walls and paving. Bricks are easy to handle, resisting in compression, require low maintenance and can be used in construction of complex structures such as arches and chimneys. Bricks are resisting to weather conditions if they are not too porous and they can full-fill functional and esthetical needs (Designing Buildings WiKi, 2020).

Bricks are, since the 19th century until now, basic constructional point (Fiala et al., 2019). They are created using raw material found below the surface or shallowly stratified in natural environment. Though bricks made from concrete and calcium-silicate are commonly found, bricks are essentially made of clay which is mined from either open-pits or underground. Bricks comes in different shapes (radial, angled, bullnose bricks etc.) and for different function. They can be solid, can be perforated with holes through them, etc. Thin mix makes soft-mud bricks whereas thicker mix gives dry-press bricks. To achieve higher strength, force is required to press and to fire it longer. Depending on method of manufacture, bricks can be classified as follow (Designing Buildings WiKi, 2020):

- Common burnt clay bricks: obtained by pressing the mixture into moulds and firing in a kiln.
- Sand lime bricks: Obtained by mixing sand, fly ash and lime; moulded under pressure and more often form a more uniform shape than clay bricks.

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- Engineering bricks: They are dense, strong and manufactured at high temperature. This improve their bearing capacity and resistance to chemicals and they are damps-proof. They are generally used in ground works, sewers, retaining walls, etc.
- Concrete bricks: They are made of concrete and can even be used below dumps-proof level. They come in different colours if pigment is added during fabrication.
- Fly ash clay bricks: They are made from a mixture of fly ash, cement, sand and water at around 1000^0C. They have high concentration of calcium oxide from fly ash and they are described as 'self-cementing'.

Brick is one of the most environmental friendly construction material and can be recycled without any danger (Fiala et al., 2019). Acquiring material required to make bricks can be costly and harmful for the environment, therefore, recycling bricks put back to use material and cut down mining of new raw material. Demolished bricks can be crushed and allow producing new aggregate and sand materials (Grellier et al. 2020). They can reused after demolition (Fig. 22) or be crushed (Fig. 21), for example by a jaw crusher, and then used in landscape or for concrete production. Attention must be paid in this case to its high porosity which may induce an increase of water consumption but a decrease of mechanical performances. Bricks can also be crushed in very fine material to be used in place of sand of even to produce new bricks.

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Figure 20: Recycling bricks: Crushing (Sharma, 2017) **Figure 21**: Pallets of used bricks

Here are some ways to use restored material from bricks recycling: in construction material for projects such as historical restoration projects, reclaimed bricks can be used in construction of walkways, landscape projects, artistic projects, projects that demand aged looks, etc. There are unlimited ways to recycle and reuse bricks and recycling them is a great idea for the protection of environment and also making money by selling recycles bricks.

8.1.4. Mixes (17.01.07)

Mixes (R_U) are representing C&DW in which different types of materials can be present (Table 4): natural stones, bricks, unbonded materials, low quality concrete, stabilized sand, cement mortar screed, … and even metallurgical slags. These materials are usually of lower quality and mainly used for embankments and holes filling, sometimes foundations.

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Table 4: Categories for the constituents of coarse recycled aggregates (EN 933-11)

Constituents	Limiting content (% by mass)	Category	Constituents	Limiting content (% by mass)	Category
R_C	≥90	R_C90	R_B	≤10	R_B10
	≥70	R_C70		≤30	R_B30
	<70	R_C declared		≤50	R_B50
	No requirements	R_CNR		>50	R_B declared
$R_C + R_U$	≥90	$R_{CU}90$		No requirement	R_BNR
	≥70	$R_{CU}70$	R_A	≤1	R_A1-
	≥50	$R_{CU}50$		≤5	R_A5-
	<50	R_{CU} declared		≤10	R_B10-
	No requirements	$R_{CU}NR$	FL_{NS}	≤0,01	$FL_{NS}0.01$
$FL_S + FL_{NS}$	≤1	$FL_{total}1$		≤0,05	$FL_{NS}0.05$
	≤3	$FL_{total}3$		≤0,1	$FL_{NS}0.1$
$X + R_G$	≤0.2	$X\ R_{G0.2}$			
	≤0.5	$X\ R_{G0.5}$			
	≤1	$X\ R_{G1}$			

Constituents (according to prEN 933-11): R_C concrete, concrete products and mortars; R_U unbound aggregates, natural stones and aggregates treated with hydraulic binders; R_A bituminous materials; R_B masonry units of clay-based materials (bricks, tiles, etc.), masonry unit of calcium silicate-based materials, non-floating cellular concrete; R_G glass; FL_s floating stone materials; FL_{NS} stony materials that do not float; X deleterious materials, cohesive materials, plastics, rubber, ferrous and non-ferrous metals, putrescible materials

8.1.5. Bituminous (17.03.02)

Bituminous mixes are obtained from a proportion of various components to serve for pavement construction material, especially surfacing material for road construction. The mix is designed to obtain pavement which is durable, resistant against shear deformation while exposed to high temperatures, easily workable and compactable, and resistant to premature cracking (Ingham, 2013) The main bituminous mix ingredients are: coarse and fine aggregates, and hydrocarbon binder (bitumen). Bituminous mixes where first produced in 1870s and by 1930, they had become extensively available (Ingham, 2013). In road construction, while rigid pavement has the upper layer made of concrete, flexible or

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flexible-composite pavement has bituminous mixes on their upper layer. A variety of bituminous mixes and types can be found to suit different circumstance (Ingham, 2013).

Historically, oil crisis in 1970s, increased cost of binder (Zaumanis et al., 2014) and with the continuous need of bituminous mixtures, a large amount of waste is generated. It has become more difficult and costly to access raw materials needed for bituminous mixture. Therefore, the desire to make sustainable pavements has brought a need to develop procedure to recycle and re-use bituminous mixes (de la Roche et al., 2013). The main techniques used involved hot recycling and cold recycling through emulsion of foamed bitumen. The technology of cold or warms emulsion/foam can incorporate up to 100% recycled aggregates content while hot technique can be limited (de la Roche et al., 2013).

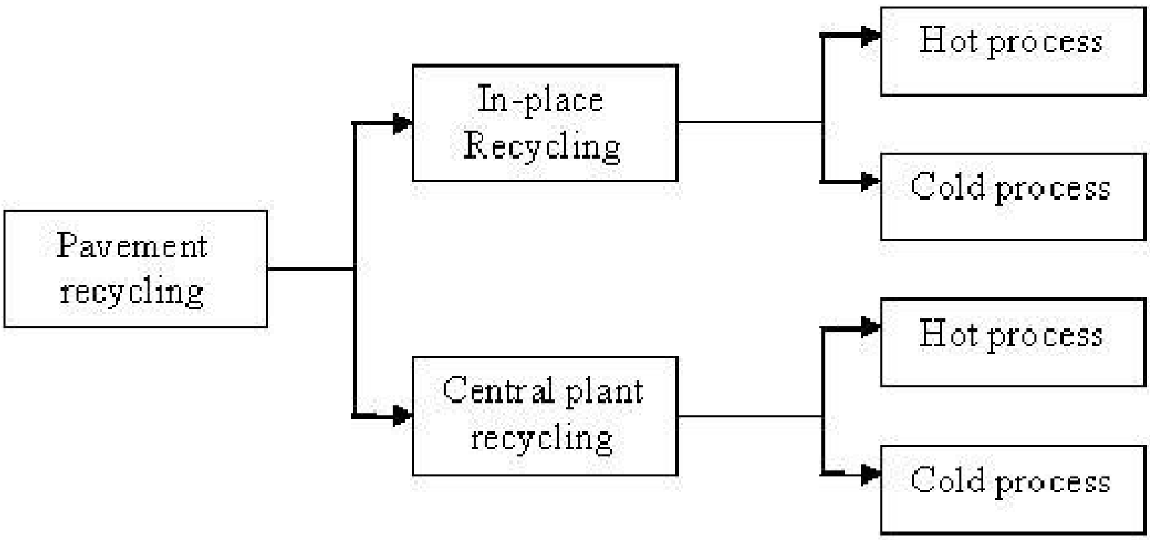

Figure 22: Classification of recycling methods based on processes (Aravind and Das, 2006)

- Hot process: This process involve heating where the intended bituminous mixture to be recycled is heated to facilitate removal of material.

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- Cold process: This process does not involve any heating. It allows the recovery of bituminous materials from pavement to be recycled without addition of heat.

Figure 23 shows that there is a possibility of in-place recycling and central plant recycling. Each has its advantages and disadvantages depending on various situation. For example, while the in-place recycling can be beneficial within the city area and can reducing transportation cost, the main advantage of central plant recycling is that the recycle mix performance and properties are comparable to that of virgin and requires less laying workspace (Aravind and Das, 2006).

Other techniques includes rejuvenators, products designed to restore original properties of binders which can retard bituminous surface treatment among other benefits. This technique is not cost effective, and therefore, not so much used.

8.1.6. Gypsum (17.01.04)

Gypsum is one of the most common sulphate and one of the most mineral binder. Its main component is calcium sulphate ($CaSO_4 \cdot 2H_2O$) and has a neutral ph. when compared to lime or cement based materials (Lushnikova and Dvorkin, 2016). Gypsum is desirable for its decorative attractiveness given its white colour. As a binder, gypsum is energy saving when compared to lime and cement which means that it is less pollutant (Lushnikova and Dvorkin, 2016). As a building material, gypsum properties offers numerous advantages and among its prefabricated products include: ceiling panels, dry wallboards and flooring panels. Quarried or mined to be processed into a variety of products, the quality of gypsum have been known and used for centuries. It has been used by artists, architects and builders in various forms (Fig. 24).

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Figure 23: Gypsum extraction plant ("Photo Gallery," n.d.)

Gypsum is recyclable and, among its products (Fig. 25), plasterboards are the most recycled and several technologies allow the use of recycled gypsum for production of binders, in the papers industry and in agriculture (Lushnikova and Dvorkin, 2016).

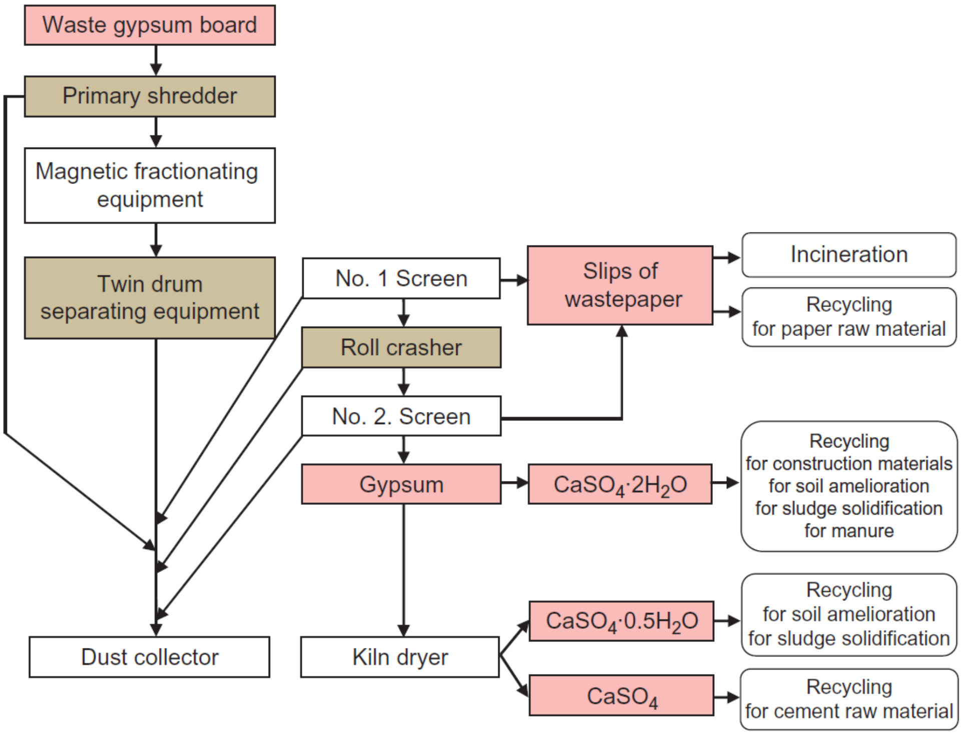

Figure 24: Flow diagram of recycling gypsum board waste (Lushnikova and Dvorkin, 2016)

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Among the industrial waste and by-products, gypsum waste, by the importance of the quantities stored and those produced annually, pose one of the biggest problems to environment. In Belgium in particular, the production of gypsum waste is around 2 to 2.5 tonnes per year, of which only 1/5 is currently recovered, among others in cement and plaster industries. The rest must be landfilled on pouring grounds (Courard, 2020).

Table 5: Classification of types of gypsum waste (Courard, 2020)

Origin	Denomination
Phosphoric acid production	Phosphogypsum
Production of hydrofluoric acid	Fluorogypsum
Boric acid production	Borogypsum
Neutralization of gases containing SO_2 and SO_3 or solutions of H_2SO_4	Sulphogypsum

Phosphogypsum is formed during the wet manufacturing of phosphoric acid from phosphates generally from Morocco, Russia or Florida. The pulverized minerals are treated with sulfuric acid, a process which mainly results in the formation of phosphoric acid, hydrofluoric acid and calcium sulphate (Fig. 26).

Of all the gypsum wastes (Table 5), phosphogypsum is by far the most abundant and can be applied in construction industry after being transformed into semi-hydrate or into anhydrite. The use of phosphogypsum is based on the idea of taking advantage of physical characteristics and chemicals:

- Physics: these are fine materials capable of entering into mixtures such as aggregates or even as a grain size corrector for natural sands;

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- Chemical: calcium sulphate is known to modify the nature of crystallization of blast furnace slag in a basic medium, as well as that of coal fly ash.

The domain of application include the road construction sector (embankments, to form layers…), in road shoulders, in earthworks and in foundation layers.

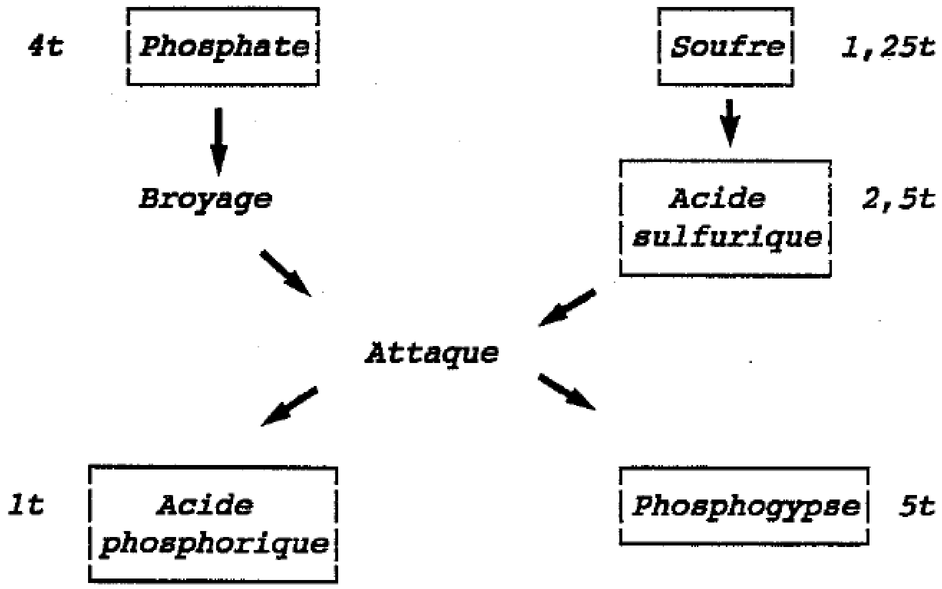

Figure 25: Principle of production of phosphogypsum (Courard, 2020)

8.1.7. C&DW conclusions

As it was mentioned earlier, management of waste has become a global concern where all countries are looking for solution to minimize, if not end, waste generation. C&DW constitute a major share of the waste produced where, instead of land filling it, solutions have been put in place to recover and reuse them through recycling. It was argued that recycled material maybe generally less expensive compared to natural materials and that in Germany, Holland and Denmark, recycling was less expensive than disposal (Rao et al.,

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2007): major factors affecting cost are transportation, pre-sorting on the construction site and availability of natural materials (Delvoie et al., 2019). Most of C&DW recycled products constitute aggregates reused for concrete in lower level application (Rao et al., 2007) and as base pavement materials for road surface layers (Aboutalebi Esfahani, 2020). But more and more upcycling into new applications for structural and structural concrete is possible by means of adapted process (Courard et al., 2018).

8.2. Coal fly ash

Environmental friendliness and good performance as construction material earned fly-ash a place as a potential alternative to ordinary Portland cement. The trend now is to consider using recycled materials and more green materials such as fly ash. It has become a general trend nowadays to consider fly ash based construction materials as alternative to Ordinary Portland Cement (OPC) (Xu and Shi, 2018).

8.2.1. Origin of fly ash

To obtain fly ash, mineral matters and particles in coal will liquefy, vaporise, condense or agglomerate during and after combustion (Xu and Shi, 2018). Thermal power stations burning pulverized coal produce significant amounts of dust called fly ash. Fly ash should be distinguished from other combustion residues: lean coals are ground to a fine particle size and injected into the boiler with an amount of air suitable for the most complete combustion possible. Different ashes are resulting from combustion (Courard, 2020):

- Released with smoke (fly ash);
- Deposited at the bottom of the boiler (furnace bottom ash);
- Partly fallen into the ashtray and possibly soaked in water (ash - boiler slag).

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Combustion is never complete and small grains of coke or fine particles of black carbon remain. Content of unburnt (determined by the LOI (Loss of Ignition) test) will play a fundamental role in properties of fly ash. In particular, these unburnt grains have a high specific surface and, therefore, the amount of water required in cementitious mixes where fly ashes are used will be increased, which will cause the decreasing of mechanical performances of the hardened mixture (compression, resistance to "freezing" cycles, ...) (Courard, 2020): LOI is classically limited to 5% max.

8.2.2. Physical properties and chemical composition

Fly ash are spherical in general (Brouwers and Van Eijk, 2002) and the average apparent density of the grains varies between 1.9 and 2.4 (Courard, 2020). Mineralogical elements in fly ashes can be categorized into two groups: the network formers include SiO_2, Al_2O_3, Fe_2O_3, TiO_2 and P_2O_5, and the network modifiers include CaO, MgO, Na_2O and K_2O (Hemmings and Berry, 1987) where their influencing factors are different and their characteristics were exposed by (Xu and Shi, 2018).

At ordinary temperature, fly ash fixes lime to give a hydraulic binder in the presence of water. This pozzolanic power manifests itself in two phenomena: fixation of the lime by ashes and hardening. The pozzolanic reaction continues for a very long time (more than 2 years). The elevation of ambient temperature, as well as the increase in the fineness of the particles accelerate the phenomenon (Courard, 2020).

8.2.3. Utilization of fly ash as construction material

Usually, the proportion of fly ash in concrete can vary between 15% and 30% by mass of cementitious binder. However, though some studies showed that concerns about early-age strength development of OPC concrete was affected by the addition of fly ash, larger

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proportions of replacement, between 30% and 50%, were observed in large structures such as foundation and dams as a measure of controlling the rise of temperature in concrete (Xu and Shi, 2018). Fly ash has a beneficial effect on durability and strength at later ages.

Fly ash impact on concrete properties (Xu and Shi, 2018) can be summarized:

- Durability: fly ash can improve concrete resistance to sulfuric acid and sulfates. Depending on the proportion of fly ash substitution, fly ash concrete is susceptible to carbonation.
- Mechanical strength: though the presence of fly ash usually reduce early-age strength, due to the pozzolanic reaction, an increase of mechanical strength is observed over 90 days.
- Workability: presence of 0 to 50% of fly ash replacement level will results in slump increase. The slump value will decrease if further replacement increase to 40-70% due to high surface area of fly ash in concrete.

Fly ash is also used in road sector. However its use in road engineering requires significant tonnages compared to cement industry (Courard, 2020). We can consider 3 main categories of employment, namely: embankments, pavements as well as the base and wearing courses.

8.3. Co-combustion fly ash

The combustion of biomass or co-combustion of biomass with coal can reduce coal consumption and minimize the global CO2 emissions. Biomass accounts for more than 4% of the total energy consumption in the European Union and it will increase in the future. However, the storage of biomass fly ash occupies land area and increases the risk of

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contamination of groundwater. Concrete is the largest volume material used for infrastructure developments. Cement production releases about 5-7% of CO_2 emission of all man made. Replacing part of clinker or cement by supplementary cementitious materials is becoming common for the ecological or environmental benefits.

Currently, the use of biomass fly ash is commonly used as a soil supplement to improve the alkalinity of soil for agriculture applications (Jala and Goyal, 2006). Biomass fly ash is also used as a filler material in the construction of pavements for roads. Recent research findings confirm the suitability of biomass fly ash as partial cement replacement in the production of structural concrete in building construction (Berra et al., 2015; Naik et al., 2003; Ramos et al., 2013; Tosti et al., 2018) showed a wider range of a total chemical composition of silica, alumina and ferric compounds between 18.6% and 59.3% for the wood ash samples examined. (Wang et al., 2008) Reported that the wood waste fly ash consisted of particles which were highly irregular in shape with a higher porous surface.

Several researchers had common findings: the use of wood waste ash as a partial cement replacement materials in concrete at all level of cement replacement ranged between 5% and 30%, it reduced the compressive strength of the concrete mix produced relative to Ordinal Portland Cement (OPC) concrete for all curing times (Cheah and Ramli, 2011; Esteves et al., 2012). (Elinwa and Ejeh, 2004) Investigated the compressive strength development of mortar mixes containing biomass fly ash from wood waste as a cement replacement between 5 and 30% at stepped increments of 5%. They observed that mortar mix with 10% of wood waste ash as partial cement replacement material exhibited similar compressive strength as equivalent mortar mix with only OPC mortar at a 60 day curing age. (Rajamma et al., 2009) Investigated the study of new cement formulations incorporated with biomass fly ashes. Two types of biomass fly ashes (similar to class C fly ashes according to European standard EN 450-1) were used as cement replacement

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material at replacement level of 10, 20 and 30% of total binder weight. The results showed that mortar mixes with one type of biomass fly ash content of 10% exhibited higher 28-day compressive strength but lower flexural strength in comparison with equivalent neat OPC mortar. For the other type of biomass fly ash, the compressive strength and flexural strength decreased when the 10% of cement replacement was used. For the higher replacement level of 20 and 30% of total binder weight, the compressive strength relative to equivalent OPC mortar mix decreased. However, biomass fly ash is excluded from addition in concrete according to the standards now.

8.4. Coal shales

Coal comes in mini veins, more or less sloping, separated by intermediate banks of sterile. Due to the extensive mechanization of the extraction equipment in order to increase the productivity, significant quantities of waste rock are extracted at the same time as the coal (in average, one tonne of coal for two tonnes extracted).

The products extracted from the mine include either only waste rock from the digging of galleries, or raw coal sent to the wash house where, by flotation process, separation is realized to obtain: commercial coals, a content of mixed of ashes close to 50% and coal shale. The mixes are used in thermoelectric plants while coal shales are sent to form a spoil tip.

8.4.1. Composition and characteristics of coal shales

Coal shales are composed of: - sandstone: 20 to 40%, - real shale: 50 to 80% and - various slag. The colouring characterizes a more or less significant combustion:

- Black shales: no combustion;

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- Orange shales: partial or weak combustion;
- Red shales: normal combustion;
- Purple shales: significant combustion (verification).

Shales are practically insensitive to water, with the exception of unburned parts, to which the finest parts must be removed to obtain similar performance.

8.4.2. Application in the road sector

Black shale: They are commonly used in embankments, to form layers and for the creation of foundations, and industrial platforms is quite common in some regions. These are good materials for backfilling, easily implemented in 30 to 40 cm layers and easily compacted.

In addition, it can be used as raw material, in particular for the manufacture of bricks, and used in cement factories for incorporation in the mixture or as fuel.

Red shales: The geotechnical characteristics of red shales correspond to those of rocky materials. They are not very sensitive to water, and therefore, they are good fit for embankments in contact with very humid areas: this property comes from combustion which transforms irreversibly the silicate clay insensitive to water. It can also be used to form a layer or as a road surface, for traffic, rural roads, lightly trafficked subdivision lanes or emergency stop lanes.

Calibrated crushed red shales: The main characteristics of these calibrated products are: good mechanical resistance, good angularity of the grains, sufficient hardness, cleanliness and low sensitivity to frost. It has been gradually used over the past fifteen years, for little or medium circular pavements.

Red shales can also be considered as hydraulic binders. The pozzolanicity of red shales has led some to consider the technique of "red shale – all shale - lime ".

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Crushed red shales are also used in realisation of runways and road pavements, decoration of green spaces, decoration of garden paths or pedestrian paths, soil stabilisation of sport grounds, lean concrete realisation and as raw materials to make bricks.

8.5. Waste from mineral metalliferous excavation

Minerals from excavation generate waste and excavated minerals undergo wide range of physical or chemical processing. These processes inevitably produce a significant amount of wastes which can be in solid, liquid or gaseous forms (Matinde et al., 2018). Waste from metalliferous excavation are generally disposed in landfills which can constitute a threat to the environment and need to be integrated in the circular economy model through recycling and re-use of these waste materials and, therefore, reduce waste accumulation. Recycling of these specific materials requires methods and technologies and the market for these secondary raw materials produced after recycling (Table 6).

Ore mills generates tailing, which are leftovers of minerals after processing and extracting valuable ore. Millions of tonnes of waste are globally produced by mining industry; more than 95% end up as waste rocks and mine tailings (Falagán et al., 2017). More often, waste materials, such as mineral tailings, contains significant amount of valuable metals, such as copper, iron, zinc etc. which can be recovered using different and specific methods (Falagán et al., 2017).

Zooming into produced solid wastes, waste rock and tailings represent the largest solid waste quantities generated by mineral resources excavation (Fig. 27). In the process of ore extraction, considerable amount of rock are excavated and transported to waste rock dump. Waste rock are overlaid materials removed to have access to orebody.

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Table 6: Type of waste generated from mining and metals extraction (Matinde et al., 2018)

Type of waste	Comment
Overburden	Soil and rock material removed to access mineral deposits, and which is usually stockpiled. Overburden generally has low potential for environmental contamination, but may be associated with acid rock drainage.
Waste rock	Contains minerals in concentrations considered too low to be economically extracted. Waste rock has a heterogeneous mineralogical composition, chemical, and physical characteristics due to deposition of the wastes from different mine sources. Depending on the mineral being extracted, waste rock is problematic due to the formation of acid rock (mine) drainage.
Mineral beneficiation tailings	Fine barren rock that remains after extracting the valuable components. Tailings can also contain residual chemicals and are usually deposited in the form of water-based slurry into tailings ponds.
Metallurgical slags	Glass-like or amorphous materials produced as by-products in the smelting and refining of metals. Although some slags such as blast furnace slags can be environmentally benign and have found widespread applications in the construction and agricultural industries, the presence of entrained and/or dissolved heavy metals presents challenges to re-use.
Waste water	Emanates from a number of processes, with varying degrees of quality and environmental contamination potential. Typical examples include minewater, process (mill) water, leachate (containing dissolved minerals, chemicals and/or metals), effluent (process water discharged into surface water, often after treatment), and mine drainage water (surface or groundwater with the potential to flow off the mine or industrial site).
Water treatment sludge	Semi-solid residue or slurry remaining after on-site treatment of mine and industrial water and waste water. Sludge may be contaminated with heavy metals and other residual chemicals. The recycling and recovery of valuable metals from mining and industrial sludges is being extensively explored. Depending on the processes, waste treatment sludges are classified as hazardous materials.
Acid mine drainage (AMD)	Generated from mine waste rocks, tailings, and/or mine structures such as closed, active, or abandoned pits and underground workings.
Gaseous and particulate emissions	Atmospheric emissions in the form of particulate dusts and toxic gases such as SO_x, NO_x, CO, CO_2, organometallic compounds, polychlorinated-p-dibenzodioxins and dibenzofurans (PCCD/Fs) emitted during the high-temperature chemical processing of metals. These emissions are classified as hazardous materials in most jurisdictions due to the presence of entrained toxic heavy metals, toxic organometallic compounds, and PCCD/Fs.
Post-consumer waste	Waste material generated by households or commercial, industrial, and institutional facilities in their role as end-users of the products, which can no longer be used for its initial purposes, *e.g.* e-waste.

Tailings originate from mineral beneficiation, where ore is crushed in multiple sizes for separating usable mineral from materials considered as un-usable (waste) (Lu et al., 2018; Lu and Cai, 2012).

Although classified as non-hazardous, tailing should be disposed in time to avoid high occupation of land and pollution of environment (Lu and Cai, 2012); recycling and re-using them is a necessity and can positively contribute to waste management. Waste rock and tailings used as secondary resources cover a range of area where construction industry is a major market these resources (Lu and Cai, 2012; Martinez, 2019):

- Waste rock: construction of roads in subgrade building and fine surface paving, construction of dams, fine and coarse aggregates for concrete production, making bricks, and backfilling mined areas.

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- Tailings: can be classified to coarser of fine size where coarser tailings are used in concrete production as fine aggregates and fine size tailing are used for making wall bricks. Other area of application are floor tiles for construction, soil improvement, sand for construction.

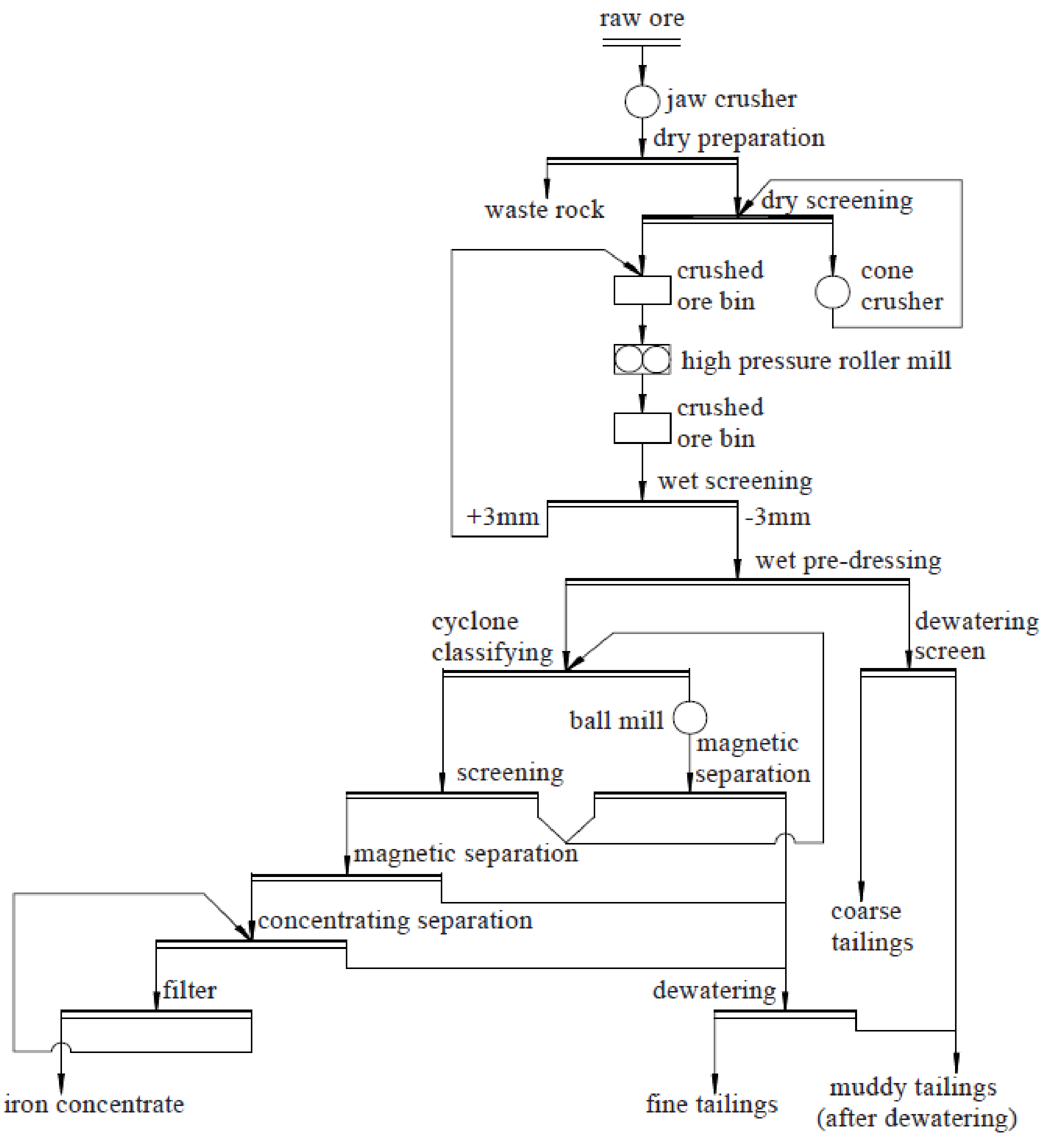

Figure 26: Process of tailings separation for different purposes (Lu and Cai, 2012)

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8.6. Waste electrical and electronic equipment (WEEE)

The fast development of technology lead to production of new innovative equipment and accelerate replacement of old equipment (Fig. 28): management of waste electrical and electronic equipment (WEEE) has become a major challenge.

Home	Hospitals	Government	Private Sectors
• PC • TVs • Radio • Cell phone • Washing machine • Microwave oven • CD player • Fan • Electric iron etc.	• PC • Monitor • ECG device • Microscope • Incubator • X ray machine • MR etc.	• PC • CPU • Printer • Fax • Photocopy machine • Scanner • Fan • Tube light etc.	• PC • Boiler • Mixer • Signal conditioner • Incubator etc.

Figure 27: Four main sources of WEEE (Kaya, 2016a)

Many references are used to identify these wastes: electronic waster (e-waste), electronic scrap (e-scrap), end-of-life (EoL) electronic devices (Izatt, 2016). All these names are used identify un-wanted and scrapped electric and electronic devices. While some have presented classification of these wastes depending on different criteria such as their size (small or large), their use (toys, household goods, etc.) and the ability to be recycled and re-used, WEEE refers to any equipment which is powered by electricity (Izatt, 2016). The global demand of electric and electronic equipment grow year per year and large amounts of WEEE are generated (Fig. 29): up to 47 million tonnes of WEEE were generated in 2017 (Zhang and Xu, 2019). These wastes can challenge environmental preservation if not well managed given that they are complex and may contain toxic organics (Table 7). Matters like plastics, liquid crystals and other organic products can be harmful to health and

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environment. Recycling, re-use and other form of WEEE recovery are being promoted in order to reduce the quantity of such wastes, especially metals given that they are valuable.

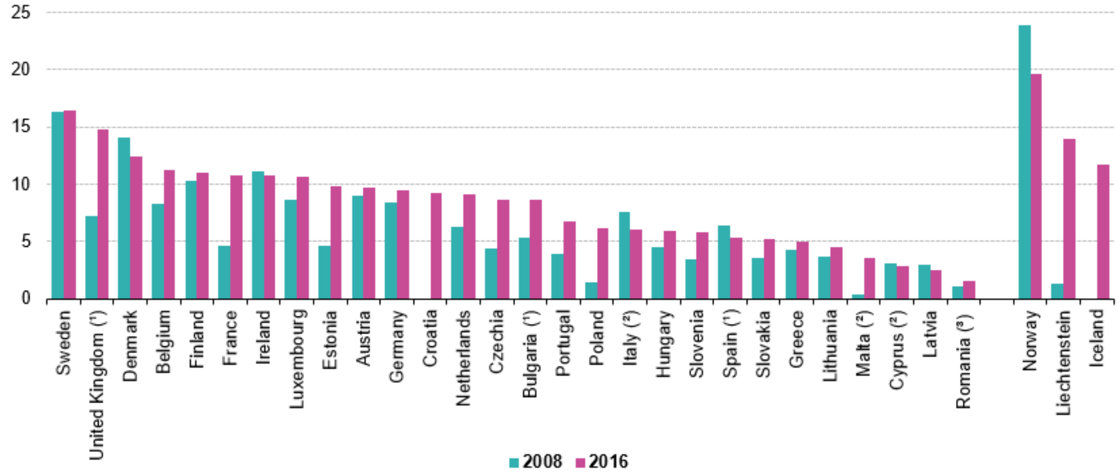

Figure 28: WEEE total collected 2008 and 2016 in EU (Eurostat, 2019b)

Table 7: Typical main components of WEEE (He and Xu, 2014).

Typical WEEE	Main components
Refrigerator	Tubes, liners, condenser, wires, refrigerant
Air conditioner	Heat exchanger, motor, compressor, copper pipe, PCBs, wires, refrigerant
Washer	Tub, drain hose, motor, wires, salt waste
Television	Deflection yoke, demagnetized coil, speaker, PCBs, wires, CRTs, LCD
Computer	Speaker, battery, storage medium, PCBs, wires, CRTs, LCD
Cell phones	Plastic enclosure, battery, storage medium, PCBs, wires, LCD
Printer/duplicator	Roller, toner, PCBs, wires, toner cartridge

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Technologies to recycle these wastes are totally different from those used for mineral separation due to the variety and content of metals and plastics (Zhang and Xu, 2019). Physical separation (Fig. 30) is currently the most environmental friendly way of recycling, including pyro-metallurgical technology, vacuum-metallurgical technology and mild extraction technology (Cao et al., 2016; Kaya, 2016b; Zhang and Xu, 2016). Other technologies for WEEE treatment include (see Figure 30) bio-metallurgical, electro-chemical and supercritical technologies (Zhang and Xu, 2016).

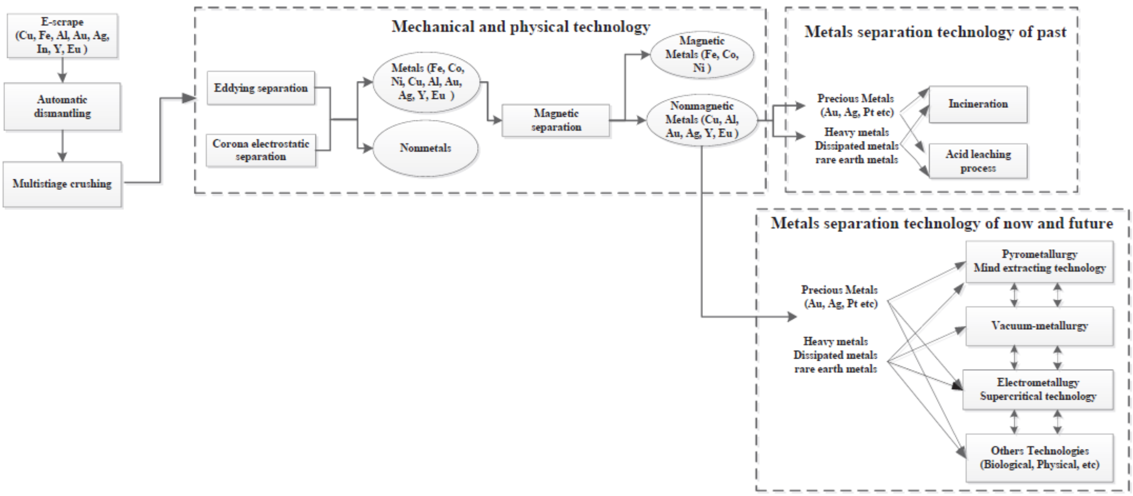

Figure 29: Integrated technology to recycle metals from WEEE (Zhang and Xu, 2016)

In summary, from environmental and economic perspectives, recycling WEEE is very important. It is essential to insure that the process and technology of recycling are environmental friendly, with minimum carbon footprint, and cost effective. The gradual depletion of primary ore has induced a drive to recover valuable metals, in particular those identified as critical materials (Sethurajan et al., 2019) and which can be recovered from WEEE.

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9. Conclusions

The forever growing global population increases the need for raw materials but unfortunately the supplies are decreasing. Many governments are working hard, together with industries, to insure that recycled material and the secondary raw materials will play a major role in economic growth in 2050. This means that waste will be brought to minimum and resources will be reused, shifting from linear to circular economy.

The sustainable aspect of the recycling is to be assessed on two levels: the first, which is the most immediate, is the profitability of the operation itself. The second one is the so-called societal aspect: nuisance, environment, global warming, etc. The development of recycling requires appropriation by the population because it is part of a sustainable development policy: social, environmental and economic.

It is no doubt that reusing and recycling wastes contribute to environment protection and preservation. Although the reuse of waste allows to make savings on natural resources, the cost of treatment can be a burden when expecting high quality of end results. However, if end users become aware of the importance of using recycled or secondary raw materials, the purchase decision will be based on sustainable parameters instead of economic costs. Today, the costs seem a high barrier but if the advantages of using recycled materials are shown to the younger population, in the future when they have the purchase decision, they will only demand products that include recycled materials.

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