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Report on Construction and Demolition Waste treatments

Université de Liège

Hanoï University of Civil Engineering

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Foreword

This document has been produced in the framework of the project 8.3 WalDeCoViet between Université de Liège (ULiège) and Hanoï University of Civil Engineering (HUCE) on the topic « *Matériaux recyclés de haute qualité : mise en place d'une filière de valorisation de déchets de construction et de démolition au Vietnam*» with the financial support of Wallonia-Brussels International and the Government of the Republic of Vietnam.

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Introduction

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 primarily produce, also called « secondary resources » - is not new to humans. This is particularly true in the agricultural field, with the phenomenon being more recent in industry. The use of certain industrial waste materials progressed simultaneously with the development of heavy industry, a logical correlation considering that the waste generated by the coal or iron industries could easily be assimilated into aggregates or integrated into binders.

Over time, the supply of by-products, initially limited in quality but abundant in quantity, has become increasingly diversified, as the petroleum, plastics chemical and rubber industries have developed.

The integration of recycled materials within the road industry and civil engineering has been evolving gradually over the past fifty years and has experienced significant acceleration 30 years ago driven by the increased demand for materials, both in terms of quantity and quality. Initially, waste primarily served as backfill or aggregates but has since found application as binders and additives.

Civil engineering typically requires four main types of materials, namely:

- *Filling materials*, which have low requirements and are consumed in large quantities, primarily for embankments. However, they have to be locally sourcedand transported over as short a distance as possible due to cost;
- *Aggregates*, which must meet various specifications depending on their intended use within structures and the treatment techniques applied. Quality

requirements can be high, even severe for the surface layers, to ensure that the finished products are of comparable quality to traditional materials;

- *Binders*, which require very precise specifications and must maintain constant properties over time. Employed in small quantities and competitive with expensive products (cement & bitumen), they may undergo pre- packaging and bear higher transportation costs;
- *Activators*, which will be used in small quantities, which can cause problems of collection, storage, distribution and regularity.

While the technical, economic and ecological benefits of using secondary resources in industry are evident, their use also poses a certain number of challenges:

- technical requirements to be suitable for incorporation into the composition standardized materials;
- economic optimization of possible jobs;
- social impact on employment in companies supplying noble products;
- environmental effects.

Therefore, beyond any technical question on their use, various questions must be asked:

- How can waste find its place in an industry and, in general, in a highly standardized society?
- What level of consistency and what controls are necessary to ensure that the waste always remains within the ranges where it has demonstrated its capacity for use?
- How can the long-term durability of materials incorporating waste be assessed and ensured?

- What is the exact influence on the environment?
- What socio-economic problems may arise in traditional industrial activities?

1. Methods of treatment and management of waste

1.1. Treatment methods for waste management

Waste treatment is a process which is performed prior the recycling process. Its purpose is to improve the characteristics of recycled waste before mechanical or physical treatment maximizing sorting upon arrival, removing impurities as well as reducing volume among other tasks. Three possible treatment methods where identified (Christensen, 2011): mechanical, thermal and biological treatments:

- Mechanical treatments primarily involve size reduction, sorting and compaction. It can be conducted separately or in conjunction with other two treatment types.
- Thermal treatments involve full or partial incineration at high temperature (pyrolysis/gasification) leading to changes in physical and chemical characteristics of waste.
- Biological treatments involve composting (degradation of organic waste) and anaerobic digestion (degradation of organic waste in absence of oxygen). The resulting methane gas serves as a source of energy and the residues from the process are used as land fertilizer.

Most of the waste 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.

1.2. 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.

1.2.1. Impact crusher

It consists of a crankcase housing rotor garnished with beaters (Fig. 1). Waste entering the crusher is propelled by the beaters and collided against impact plates. The resulting impact, amplified by self-crushing, breaks the materials into finer fractions. The impact crusher is the most used type due to its ability to produce very fine fractions. It is, however, subject to substantial wear and it is limited by the initial size of waste to be processed (Fig. 2).

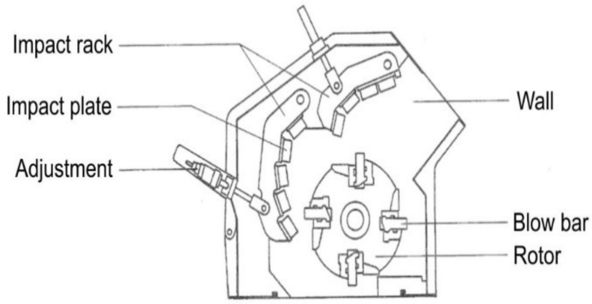

Figure 1: Impact crusher (Gorle & Saeys, 1991)

Figure 2: JXSC impact crusher

1.2.2. Jaw Crusher

This crusher consists of two jaws, one fixed and the other one mobile (Fig. 3). With a regular back-and-forth motion of the mobile part, waste is caught between the jaws and breaks under the applied pressure. This type of crusher can be used to process bulky waste like concrete slabs (depending on the crusher opening) (Fig. 4). However, jaw crushers cannot produce very fine particles from raw waste and generally require a secondary crushing. Wear is less important compared to the impact crusher.

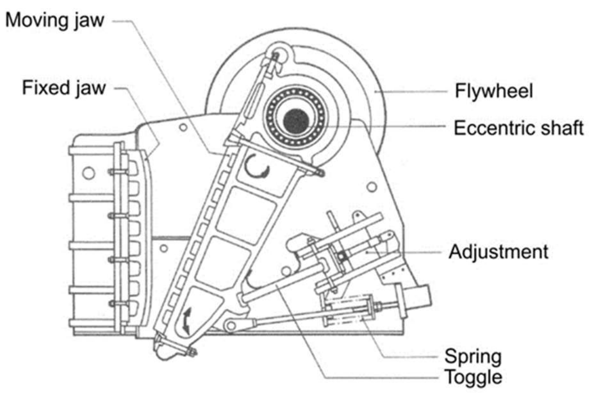

Figure 3 : Jaw crusher (Gorlé and Saeys, 1991)

Figure 4: (JXSC jaw crusher, 2018)

1.2.3. Other types

There are other types of crushers, but their use is less widespread, such as cone crushers where waste is crushed using a rotating cone (Fig. 5).

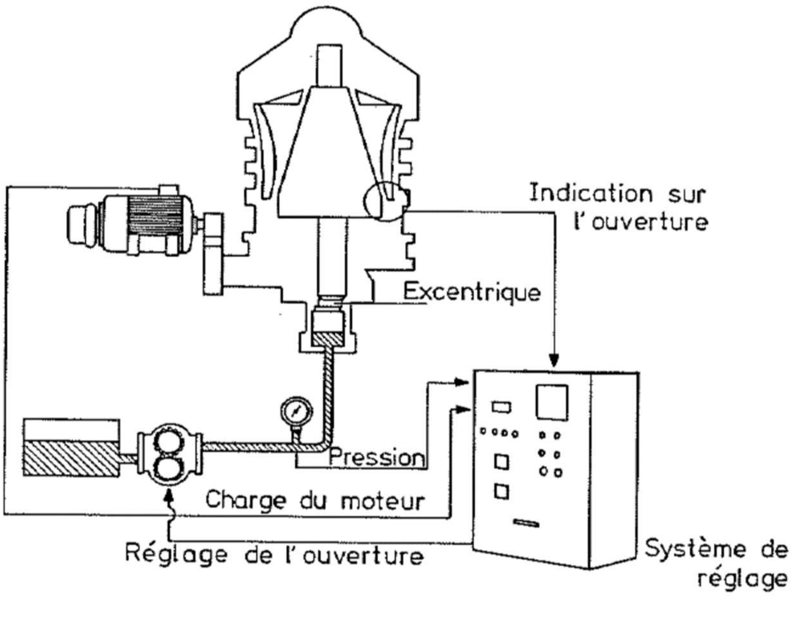

Figure 5: Cone crusher installation (J.H. Colombel, 1992)

Another type of crusher is depicted in Fig. 6: the materials rotate through adjustable grids, so the fragments – of demolition concrete in this case – are consistently ejected in the air rather than 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 present the advantage of separating the concrete and the reinforcement but also to be the sole processing technique focused on breaking concrete waste through tension. As concrete has a low tensile strength compared to its compressive strength, this method can save a significant amount of energy compared to more traditional crushing techniques..

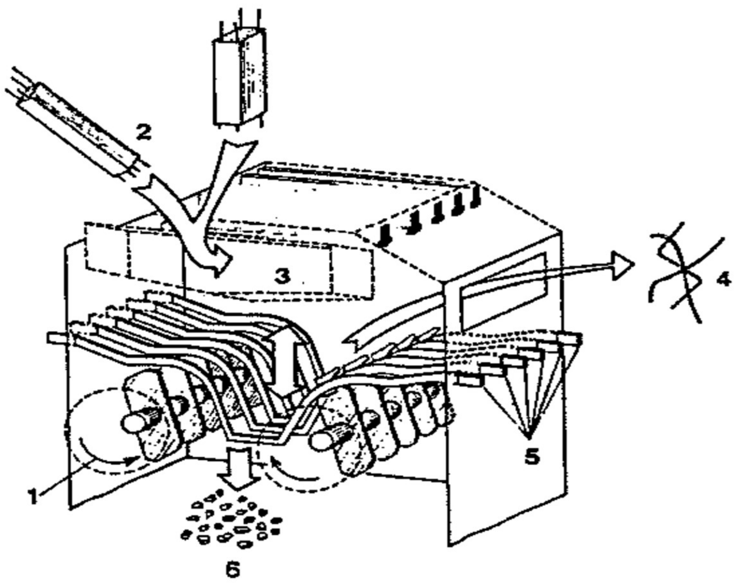

Figure 6: Diagram of a reinforced concrete crushing installation (De Pauw, 1992)

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, the choice and the combination the different types of equipment is essential to the production of a product that will be suitable for the intended application. According to the survey by Delvoie et al. (2019), the jaw crusher appears to be the most prevalent crusher type in 90% of the recycling plants surveyed. This is followed by the impact crusher utilized in 60% of the recycling plants surveyed. The Cone crusher is used in 20% of the recycling plants surveyed.

1.3. Purification techniques

Specific separation systems are used for removing foreign materials.

1.3.1. Steel reinforcement

Typically, the crushing machines used can process reinforced concrete with steel diameter not exceeding 15 mm. For specific treatment, installations supporting larger diameters can be designed. Steel is removed by using an electromagnet band (Fig. 7) positioned above a conveyor belt transporting the crushed materials. The recovered steel can be recycled as scrap in steel companies.

1.3.2. Plastics, wood and paper

Wood and papers can be removed by manual sorting on a low speed conveyor belt. Alternatively, , pneumatic separators can be used as a technical solution to sort wood and paper. The waste enters an airstream and is blown varying distances based on their shape and nature (Fig. 8). These separators require the additional installation of cyclones and filters to purify the air of fine particles. Investment costs are high as well as energy consumption. Another purification possibility is to separate impurities via wet process. Waste goes through a bath where lighter fraction including wood, paper and synthetic materials are eliminated by flotation. Washing waters charged with fine particles require purification in which can be achieved using hydrocyclones batteries combined with a settling basin. These installations require a lot of space. Water can be reused in a closed circuit with periodical replenishments.

Figure 7 : electromagnet band for extracting steel

Figure 8 : paper sorting device

The purification techniques described above are only applicable to fixed installations. For mobile installations, the process is limited to iron extraction and manual sorting. Grading of crushed material is done with one or more screens according to the desired particles size.

2. Specific waste treatment and applications for Construction and Demolition Waste

Construction and demolition activities in the European Union (EU) generate, per year, up to 850 million tons of Construction and Demolition Waste (C&DW). Since 2020, it is expected that 70% of this waste should be recovered (Villoria Sáez and Osmani, 2019). The construction sector in the EU has been identified as the highest producer of waste accounting for 35% of the total waste generated.

It is difficult to define a specific composition for construction and demolition waste (C&DW) (in percentage terms) as it varies between specific sites and it dependent on the construction habits of the region and/or country. There are also likely to be considerable differences between the composition of construction waste and of demolition waste.

An estimate made by the Walloon Government under the Walloon Waste Plan Horizon 2010 provides the following breakdown of construction and demolition waste per source:

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

The composition of C&DW heavily depends on the type of the demolished structure and the materials used during its construction. Generally, waste produced during construction work is classified into 3 main categories (Regnier, 2000): inert, industrial and hazardous waste. However, this classification can be reduced to two main categories of waste coming respectively from (i) road works and civil engineering and (ii) buildings.

By-products of road and civil engineering field work are typically clean (almost exclusively inert waste) and are easily recoverable due to their propensity to be generated during a selective demolition process. In contrast, waste from buildings varies in nature, size, and dangerousness.

Waste treatment plants have adopted a selective reception policy for demolition materials. All materials are not accepted and rejected materials are landfilled by demolition companies. In most cases, materials received by waste treatment plants are accepted with costs for the producer. If a fee is applied, it is higher the lower the quality of the waste received is lower. This concept of quality is based on two criteria: cleanliness and homogeneity. Thus, there are five main categories of materials:

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

Generally, the materials received are stored according to their quality and ease of processing with approximatively 93% being clean materials, including 60% clean concrete. Road waste which results from road repairs mainly consists of bituminous material, gravel, slag and smaller proportions of old clay or concrete pipes.

2.1. Type of treatment installation

Demolition wastes are 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 structures and can be moved with appropriate handling machines;
- Fixed: installations are mounted on foundations.

The treatment of C&DW is done at specific plants, such as the one in Glasgow, Scotland (Fig. 9). Depending on the composition of waste and the required end product, a series of operations including initial screening, crushing, magnetic separation, manual separation of impurities, mechanical grinding, etc. are undertaken (Medina et al., 2015).

Figure 9: C&DW recycling process (source: (Medina et al., 2015))

2.2. *Concrete*

Concrete is undeniably the most commonly used material in the construction sector. It is typically composed of fine and coarse aggregates bonded together by cement. Therefore, aggregates are natural resources that constitute concrete. The global demand for construction aggregates used is growing at an annual rate of 4.7 % with a global demand of 26.8 billion metric tons in 2011 valued at around $201 billion (about €170 billion) (Indian Concrete Journal, 2008). In Europe (EU28+EFTA, 2015) the demand for aggregates is 2.7 billion tons per year, representing an annual turnover of an estimated €15 billion. This European demand accounts for about 10 % of the global demand in aggregates and translates to approximatively 5 tons per capita per year ((UEPG, 2017); (Delvoie et al., 2019)).

Several steps are commonly required for the preparation recycled concrete aggregates (Fig. 10).

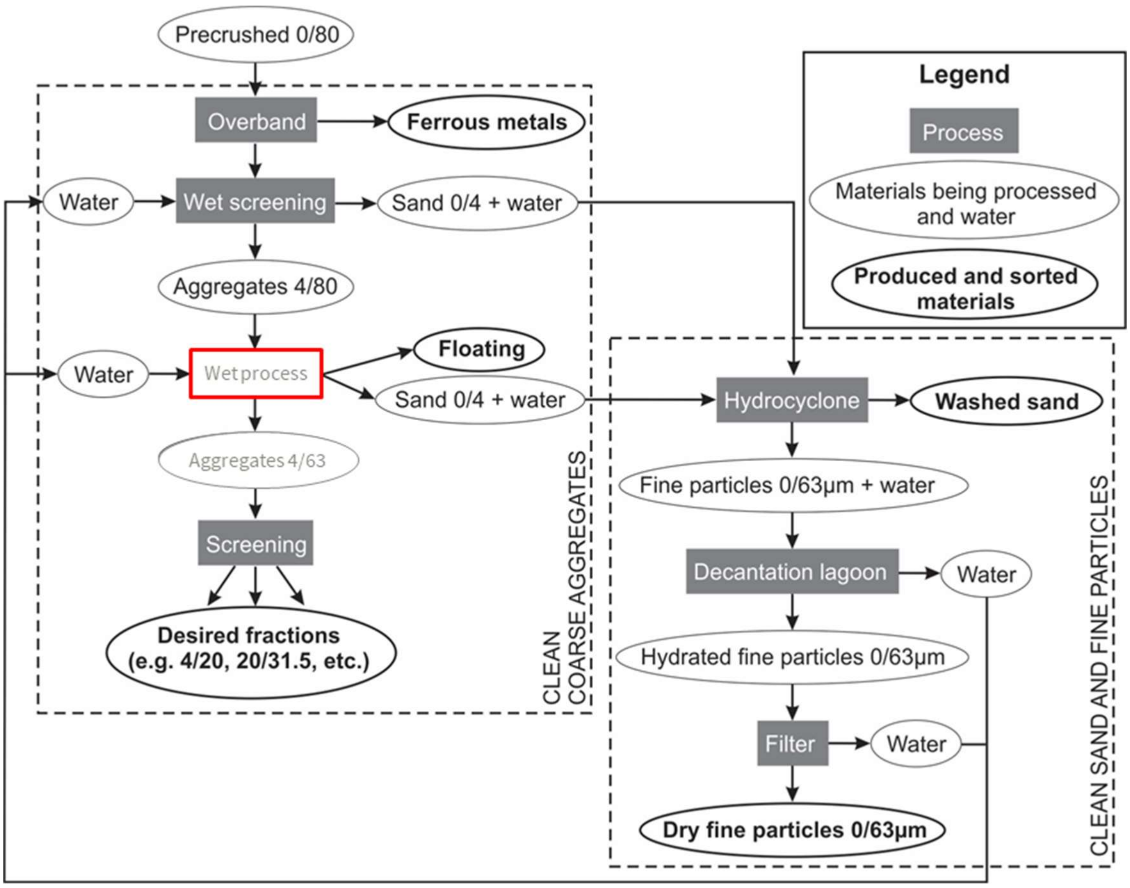

Figure 10: Recycling process (Courard et al., 2023).

The reuse of C&DW generates savings in terms of natural resources, particularly aggregates, while also contributing to environmental preservation by reducing the need to open new mining areas and reducing associated energy. Recycled construction aggregates have the potential to lower construction costs and some studies even reported improved properties at a certain substitution rate (Tam et al., 2018).

More recently the incorporation of recycled aggregates in structural concrete has been addressed in the European standard EN 206 “Concrete – Specification, performance, production and conformity" (CEN, 2016; NBN, 2023). However, it only permits the use of coarse recycled aggregates and their use is restricted to the less severe environmental conditions. Table 1 shows limits for the replacement of natural normal-weight coarse aggregates by coarse recycled aggregates in relation to exposure classes according to Belgian standard. 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 1: Maximum percentage of replacement of coarse aggregates (% by mass) according to NBN B15-201 (NBN, 2023)

Type de granulats	**Classes d'environnement selon la NBN B 15-001**						
	E0	EI	EE1	EE2	EE3,EA1	ES1, ES2,ES3	EE4, ES4, EA2, EA3
Béton armé							
Type A+	-	**30%**	**30%**	**20%**	**20%**	0%	0%
Type B+	-	**20%**	0%	0%	0%	0%	0%
Béton non armé							
Type A+	-	**50%**	**50%**	**20%**	**20%**	0%	0%
Type B+	-	**20%**	0%	0%	0%	0%	0%

2.1. Bricks

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-pressed 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 molds and firing in a kiln;
- Sand lime bricks: Obtained by mixing sand, fly ash and lime; molded under pressure and more often form a more uniform shape than clay bricks;
- 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 colors 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 10000C. They have high concentration of calcium oxide from fly ash and they are described as 'self-cementing'.

Bricks are one of the most environmentally 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 puts back to use material and cuts down mining of new raw material. Demolished bricks can be crushed and allow to produce new aggregates and sand materials (Grellier et al. 2020). They can be reused after demolition (Fig. 12) or be crushed (Fig. 11), for example by a jaw crusher, and then used in landscape or for concrete production. Attention must be paid in this case to their 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 or even to produce new bricks.

Figure 11: Recycling bricks: Crushing (Sharma, 2017)

Figure 12: 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 for making money by selling recycles bricks.

2.4. Mixes

Mixes (RU) are representing C&DW in which different types of materials can be present (Table 2): 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.

Table 2: 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}	$\leq 0{,}01$	$FL_{NS}0.01$
$FL_S + FL_{NS}$	≤ 1	$FL_{total}1$		$\leq 0{,}05$	$FL_{NS}0.05$
	≤ 3	$FL_{total}3$		$\leq 0{,}1$	$FL_{NS}0.1$
$X + R_G$	≤ 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

3. Other types of waste

3.1. Coal fly ashes

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).

3.1.1. 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).

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): LOI is classically limited to 5% max. 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).

3.1.2. 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).

3.1.3. 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 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.

3.2. Gypsum

Gypsum is one of the most common sulphate and one of the most mineral binder. Its main component is calcium sulphate ($CaSO_4.2H_2O$) 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. 13).

Figure 13: Gypsum extraction plant (“Photo Gallery,” n.d.)

Gypsum is recyclable and, among its products (Fig. 14), 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).

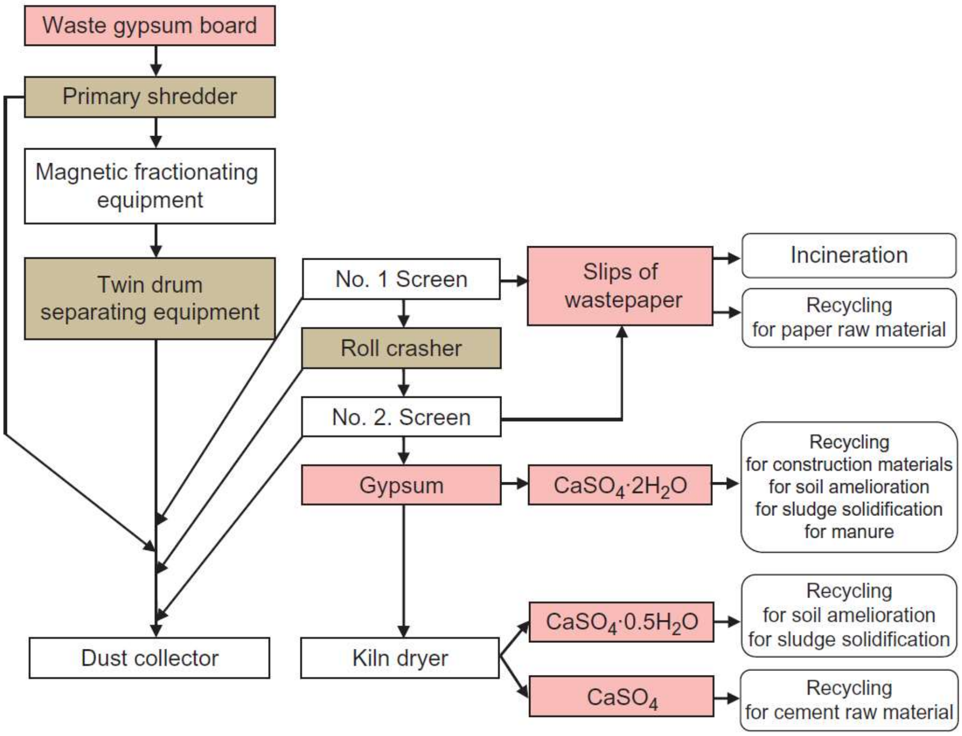

Figure 14: Flow diagram of recycling gypsum board waste (Lushnikova and Dvorkin, 2016)

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 tons 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 3: 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. 15).

Of all the gypsum waste (Table 3), 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;
- 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.

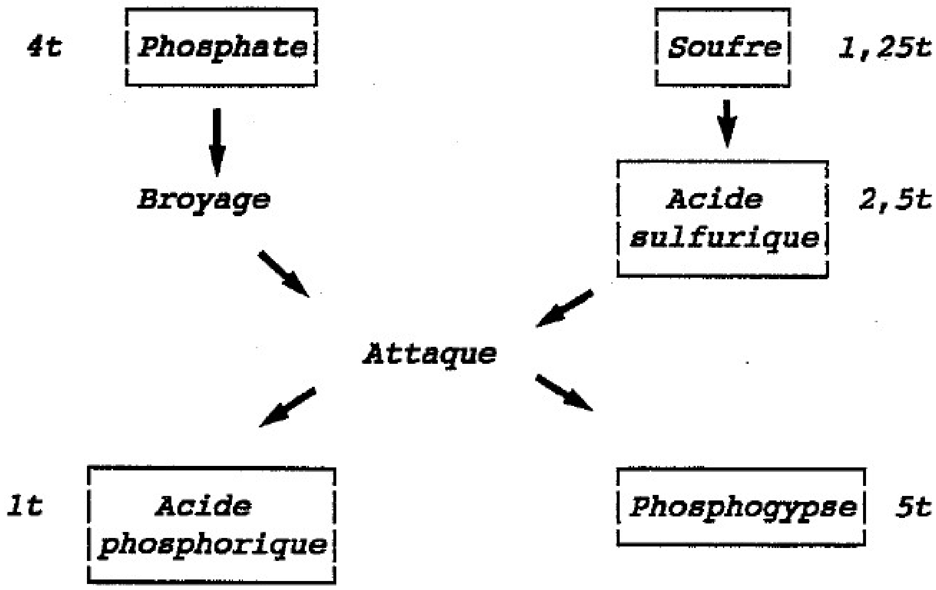

Figure 15: Principles of phosphogypsum production (Courard, 2020)

3.3. 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.

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

- *Black shales*: no combustion;
- *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.

Black shales 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.

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.

The main characteristics of calibrated crushed red shales 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 ". Crushed red shales are also used in realization of runways and road pavements, decoration of green spaces, decoration of garden paths or pedestrian paths, soil stabilization of sport grounds, lean concrete realization and as raw materials to make bricks.

3.4. Bituminous waste

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

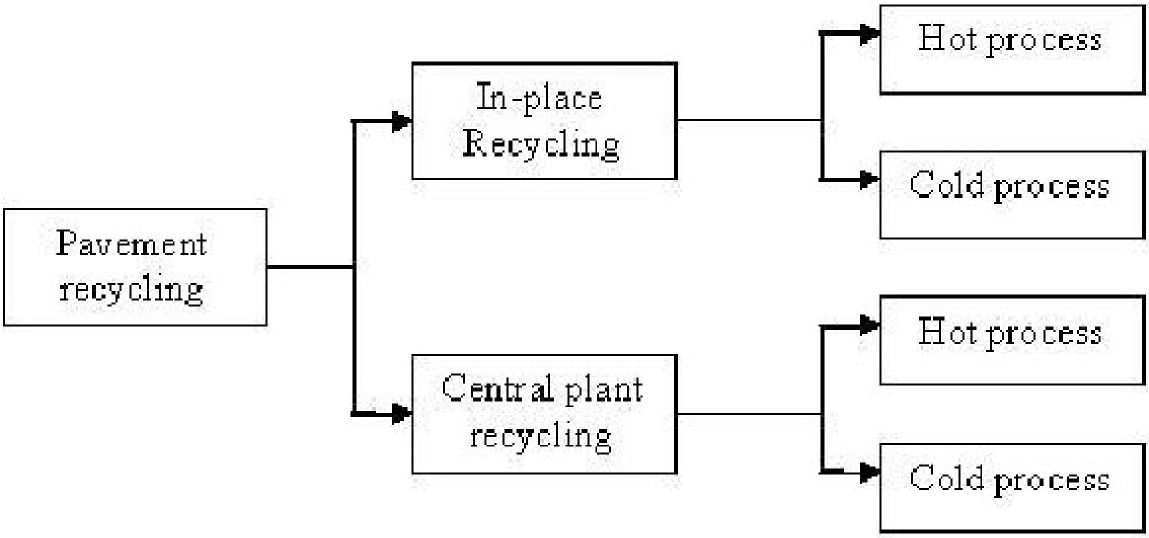

Figure 16: Classification of recycling methods based on processes (Aravind and Das, 2006)

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

4. Conclusions

The ever-growing global population increases the demand for raw materials but the availability of these resources is steadily declining. In response, many governments, in collaboration with industries, are working hard to ensure that recycled material and secondary raw materials will play pivotal roles in economic growth by 2050. This requires a concerted effort to minimize waste generation and promote resource reuse, marking a transition from a linear to a circular economy.

The sustainability of recycling initiatives 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 broader societal impact encompassing factors such as nuisance, environmental sustainability, global warming, etc. Effective recycling requires widespread adoption by the population because it is part of a comprehensive sustainable development policy addressing social, environmental and economic aspects.

The beneficial impact of reusing and recycling waste on environmental protection and preservation is undeniable. Although the reuse of waste offers significant savings on natural resources, the cost associated with treatment can be a burden when expecting high quality of end products. Nonetheless, increasing end users' awareness about the importance of using recycled or secondary raw materials can shift purchasing towards prioritizing sustainability over economic considerations. While today, the costs appear to be the most important factor and a significant barrier, educating the younger generation about the advantages of using recycled materials, could, in the future, change their consumer preferences therefore greatly increasing the demand for products that include recycled materials.

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