

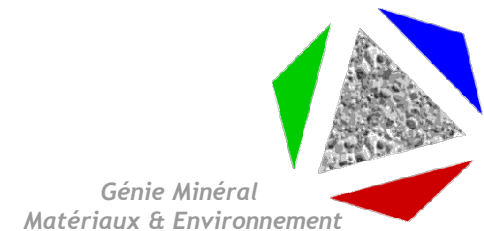
Transforming wastes into secondary resources: challenges for construction industry

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Warsaw lecture, December 18th, 2018



Global context



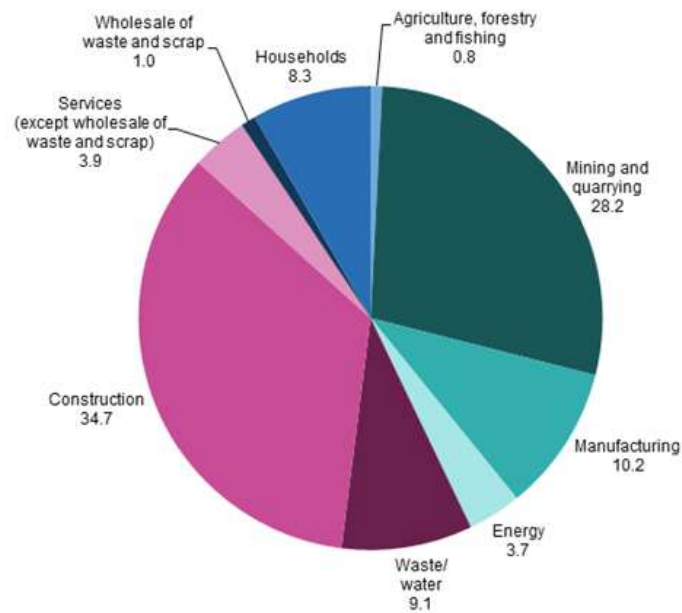
What to do?



Global context

- We produce wastes
 - Between **3.4 to 4 billions tons/year** or from 80 to 126 tons/second!
 - Each day, human activity is contributing for more than 10 billions kg wastes
 - According to Pike Research, we produced 74 millions tons of electric and electronic wastes in 2014 (2346 kilos/second)!

Global context



Source: Eurostat (online data code: env_wasgen)

■ We produce wastes

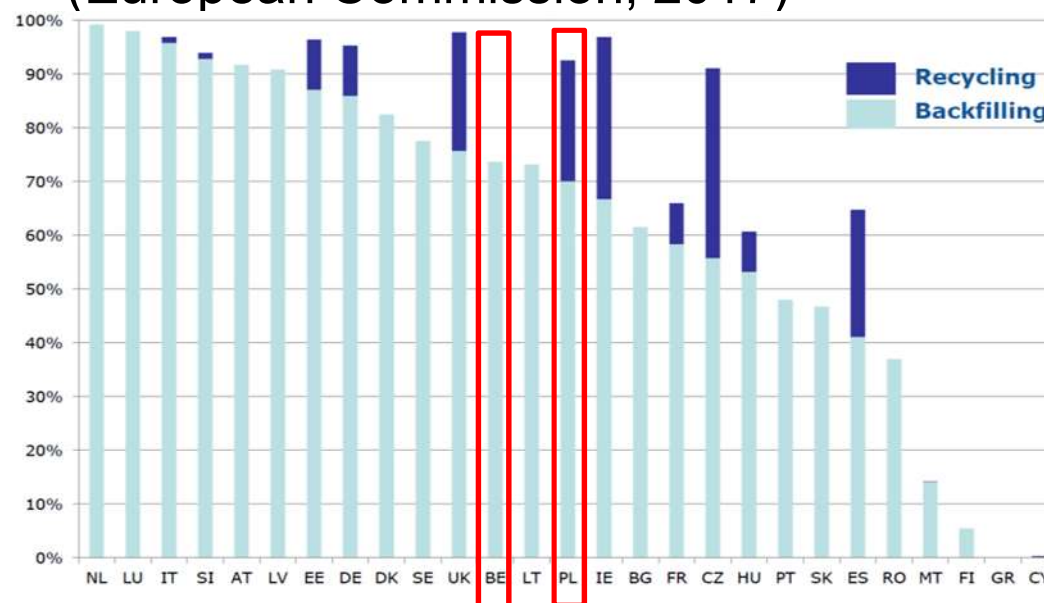
- In EU28 countries, the total waste production by economic activities and households accounted for **2.50 billion tons** (4931 kg per capita) in 2014. **CDW** is estimated to **34.7 %** of the total wastes.

Global context

■ We produce wastes

- Annual production of recycled aggregates accounted for 202 million tons in 2015

- Percentage of CDW recovery in the EU27 countries in 2011 (European Commission, 2017)



UEPG, 2018, <http://www.uepg.eu/statistics/estimates-of-production-data/data-2015>

Global context

- We produce wastes
 - construction area is producing more or less than 40% of CO₂
 - *construction area is consuming 40% of energy produced*
 - *construction area is consuming between 40 and 50% of natural resources as primary raw materials*



Global context

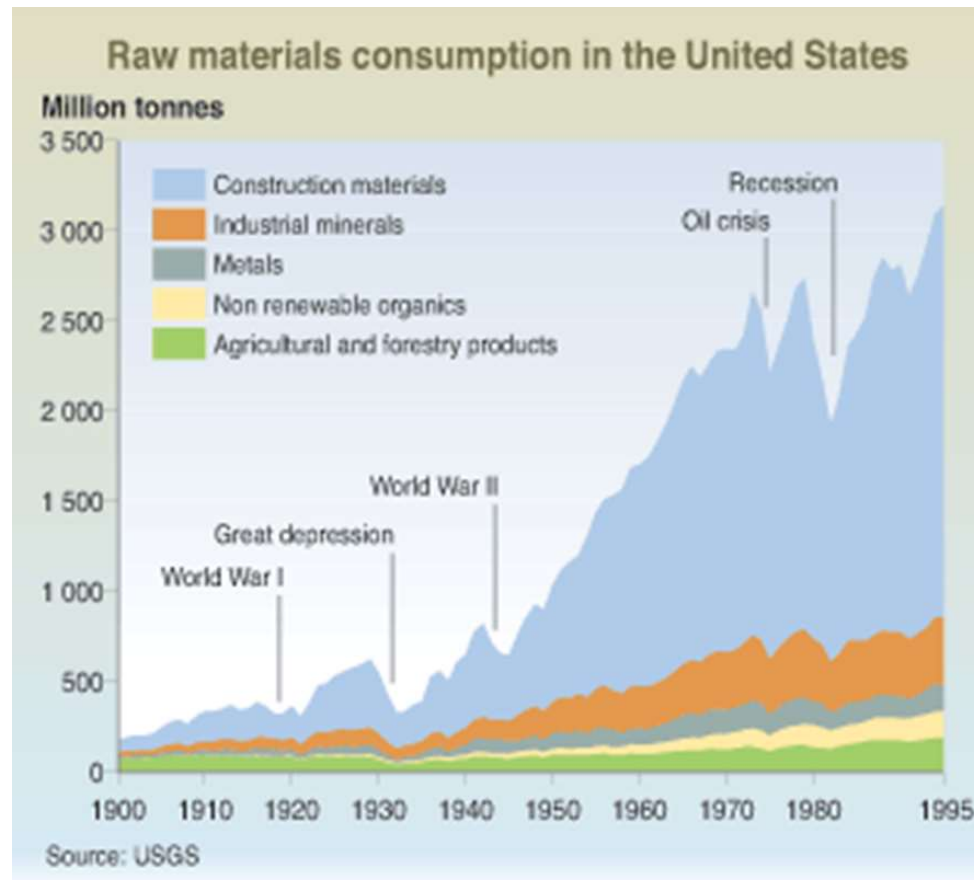
■ We need materials

- *construction area is producing more or less than 40% of CO₂*
- construction area is consuming 40% of energy produced
- construction area is consuming between 40 and 50% of natural resources as primary raw materials



Global context

- We need materials



Global context

- We need construction materials
 - ▣ Concrete: **more than 9 billions tons/year** (= 30000 arches of La Défense in Paris)
 - ▣ For the EU28 plus EFTA countries, the total 2015 **aggregates production** is estimated just on **2.66 billion tons**. The primary materials came from 26,000 quarries and pits, operated by 15,000 companies (UEPG, 2018, <http://www.uepg.eu/statistics/current-trends>)

2015 National Production by Country (mt)

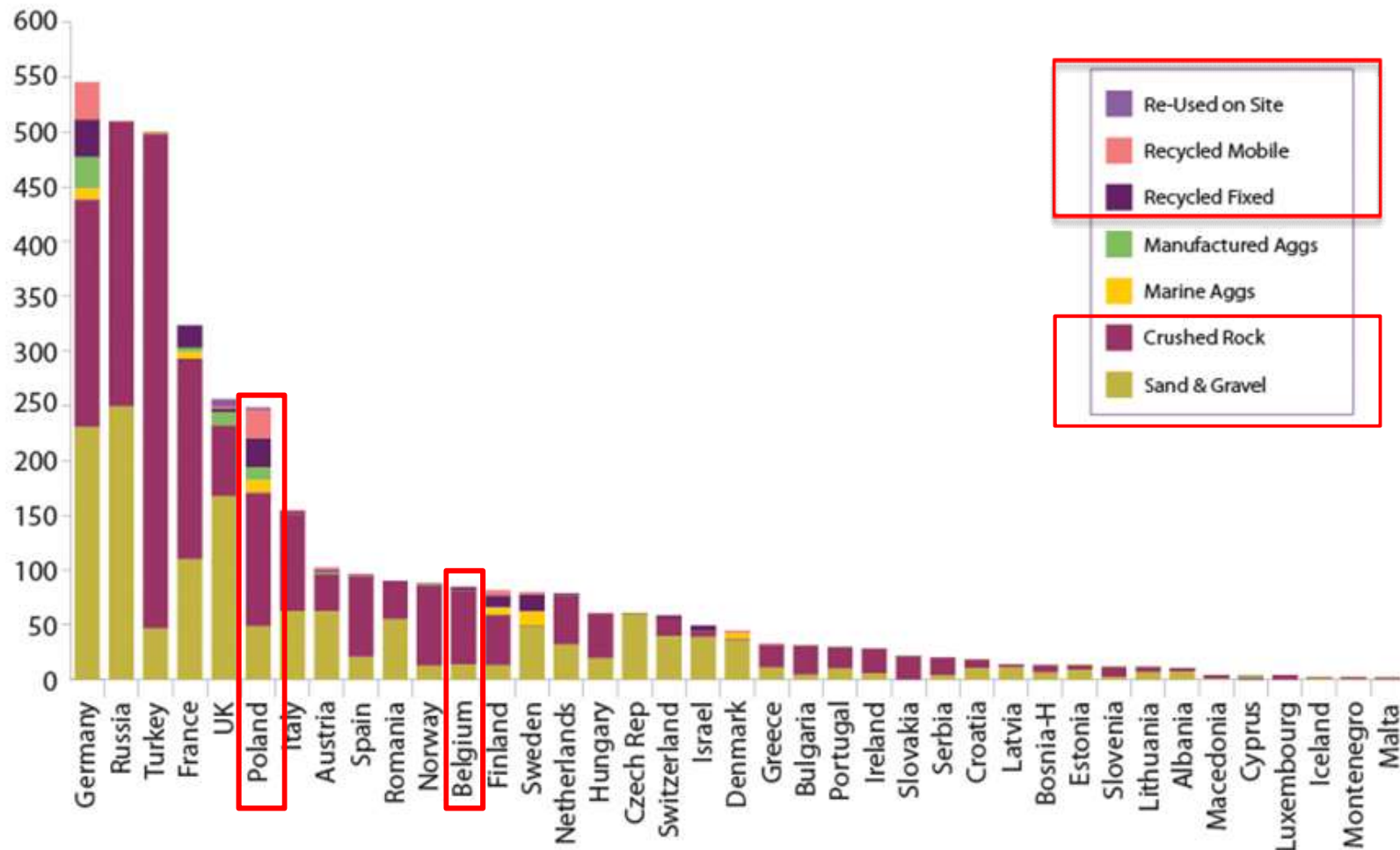


Figure 1 Aggregates Production (in millions of tonnes by country and type)

Global context

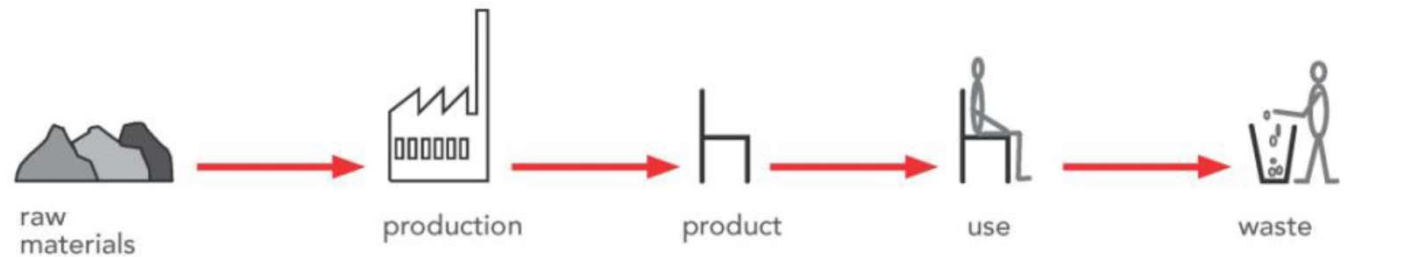
- We are living in a limited world
 - Energy
 - Raw materials
 - Space
 - Maximum capacity of resilience of nature
- Ascertainment → behaviour
- **Deposit ↔ market**

Objectives

- Using CD&W as sub-base and base material in road construction (“less noble”)
- Meeting Sustainable Development Goals: recovery targets to **70%** of construction and demolition wastes (CD&W) by **2020** in European Union (Directive 2008/98/EC)
- Reducing use of natural aggregates (preservation of natural resources)

What to do?

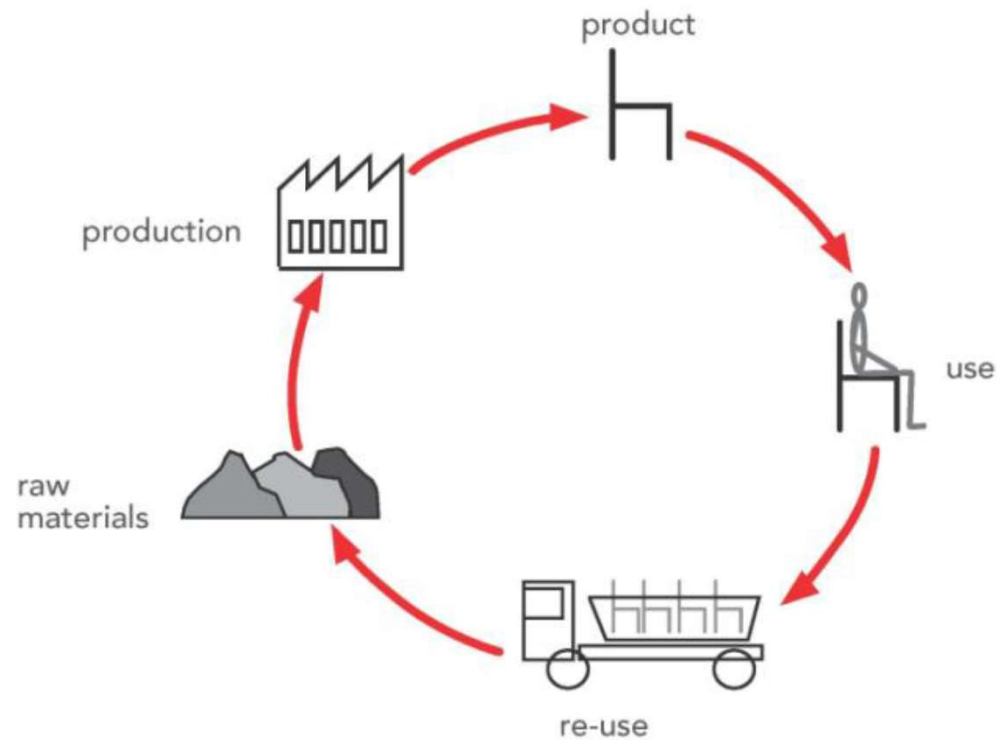
Sustainable development



OLD LINEAR ECONOMY - is about ownership

SOURCE: S. BECKERS (d'après M. BRAUNGART –EPEA, Cradle to Cradle)

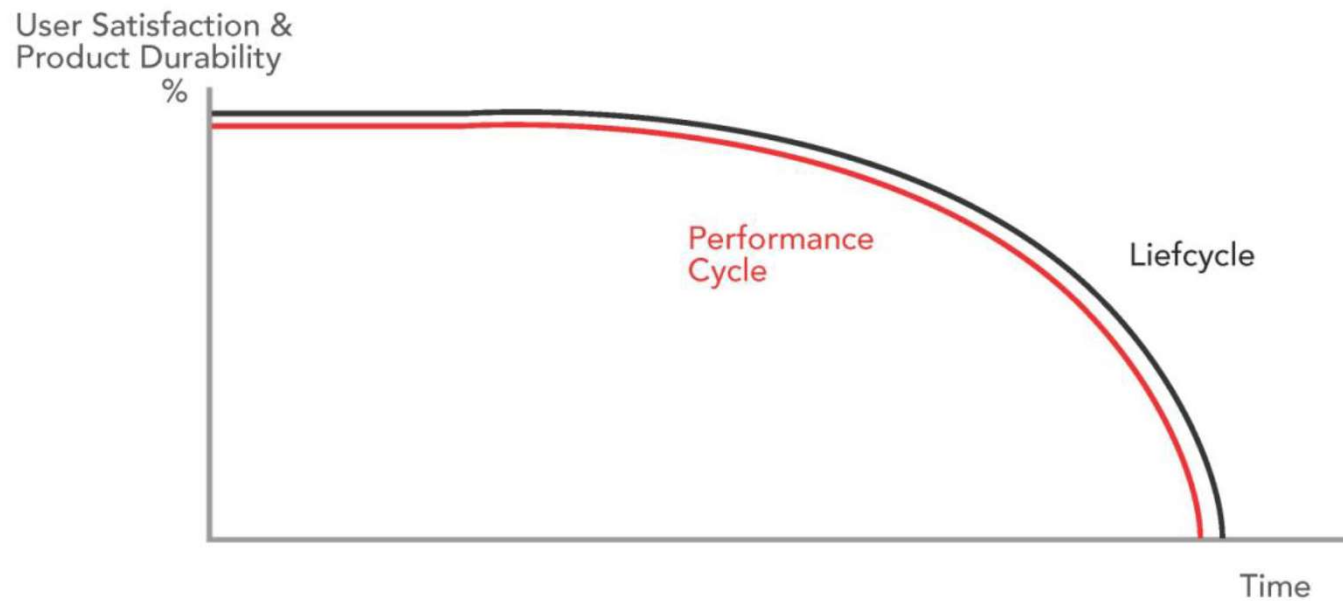
Sustainable development



C2C - TECHNICAL NUTRIENT CYCLE

SOURCE: S. BECKERS (d'après M. BRAUNGART –EPEA, Cradle to Cradle)

Sustainable development



Life cycle versus Performance cycle

SOURCE: S. BECKERS (d'après M. BRAUNGART –EPEA, Cradle to Cradle)

Sustainable development

- Recycling is part of the strategy for global waste management called the **3 R**:
 - *reduce*, which includes everything about the reduction of waste production,
 - *reuse*, which includes the processes that give a new use to used products,
 - *recycle*, which indicates the process of waste treatment by recycling.

*Since 1970,
the Möbius strip
is the universal logo for recyclable materials*



Sustainable development

- Limit the consumption of raw materials and the production of waste by developing new production processes
- Promotion of responsible (eco-consumption)
 - Avoid hyper packaging (shaving stick)
 - Promote bio-sourced or recycled packaging (glass bottle vs PET bottle)
- Reduce throw-away behaviour
 - Washable tableware vs. disposable
 - Cloth diapers



Sustainable development

- Limit the consumption of raw materials and the production of waste by developing new production processes
 - « Clean » products (labels)
 - Incitatives: taxes
- Storage of ultimate wastes



How to select?

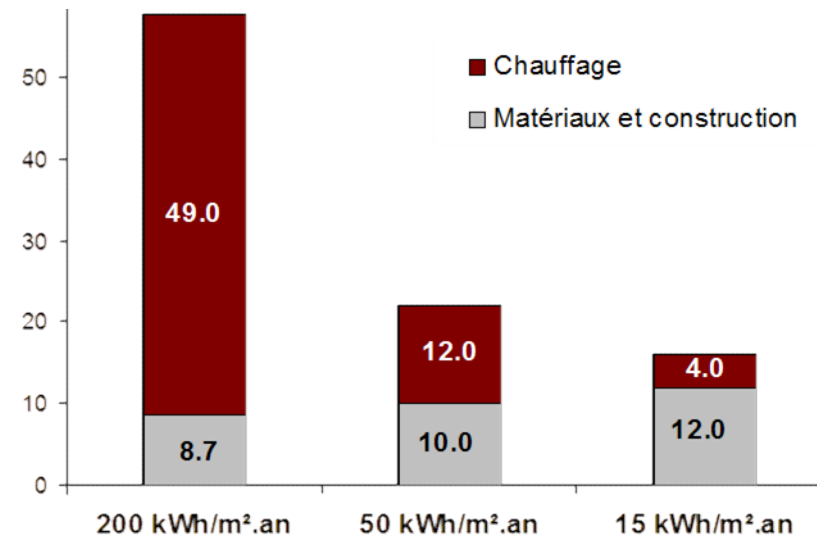
Sustainable development

Prevention: développement of alternative materials and techniques for building industry

Increasing energy performances of buildings (Zero energy building)

Increase of relative weight of materials vs environmental impacts

Needs for new materials



(Source : G. Escadeillas, *Métamorphoses*, Liège, 2011)

Sustainable development

Grey energy, in kWh/m³ or T, associated to a material: takes into account the energy (fuel, coal, electricity, ...) used for extraction, transformation and manufacturing of a unit of final product

Material	Grey energy(kWh /m ³)
Brick (silicates)	700
Silico-calcareous brick	350
Synthetic cover	3300
Cementitious cover	1100
Steel product	57000
Wood	180
Chipboard (bonded with formaldehyde resin)	2000
Fiber chipboard	1400
Expanded PS (insulating)	450
Wood cellulose insulation	50

Sustainable development

Consumption of
energy for 1m³
reinforced
concrete

Materiau/operation	Energy (GJ)
Cement	1.58
Sand and aggregates	0.27
Steel Reinforcement	2.25
Formwork	0.43
Transport and casting	0.34
Demolition and waste treatment	0.27
TOTAL	5.14

Sustainable development

■ Packaging for eggs

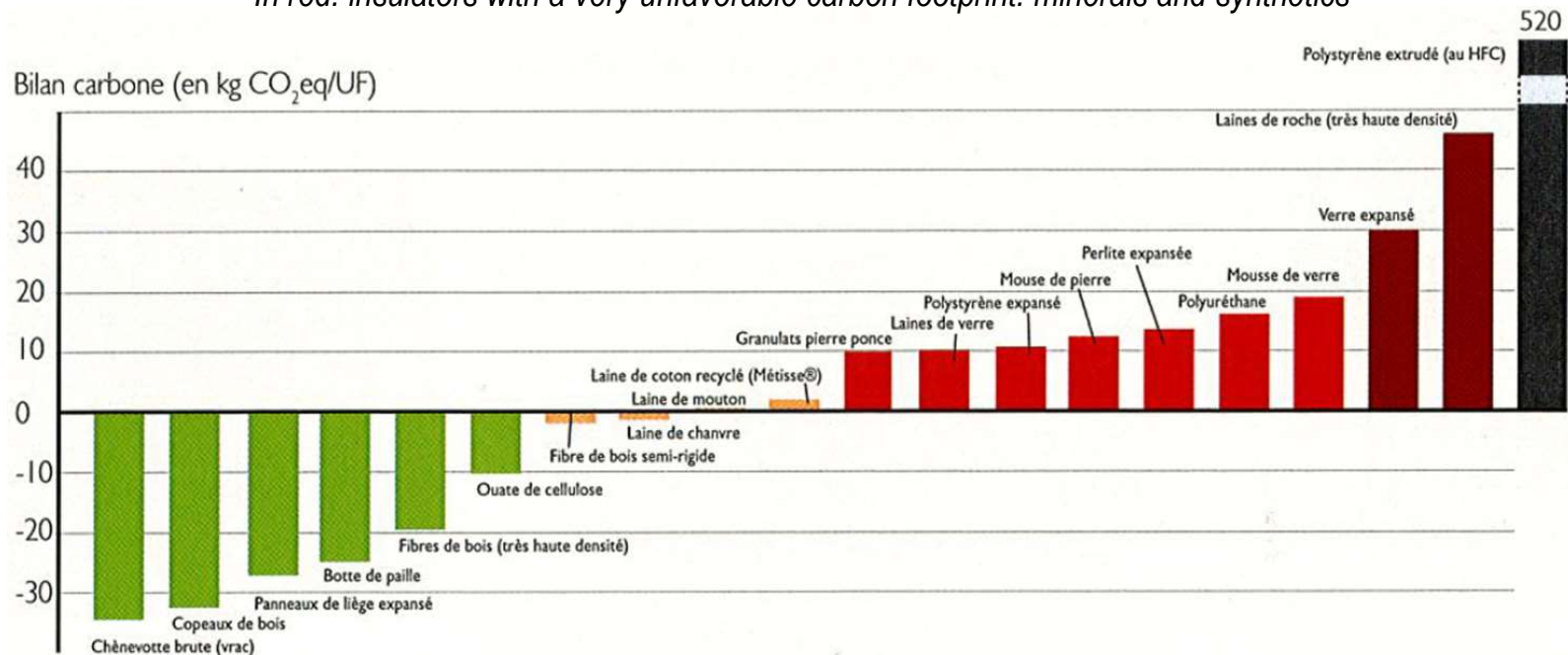
Emballages pour œufs	PS	mousse PS	pulpe de bois
Poids emballage gr	23.6	15.9	45.6
Consommation énergie %	100	67.5	85.4
Pollution air %	15.3	10.3	100
Pollution eau %	48.9	33.0	100

Sustainable development

In green: positive CO² captation

In yellow : neutral : vegetable wool

In red: insulators with a very unfavorable carbon footprint: minerals and synthetics



« Bilan CO₂ » de 1 m² de divers isolants pour une épaisseur correspondant à une résistance thermique de 5 m²K/W.

What is recycling?

Materials recovery, it is ...

- To make profit
 - Pillaging of abbeys, castles, industries,...
 - Selective collection of paper and cardboard
 - Replacement of natural aggregates by recycled ones
- To preserve
 - Historical witnesses: preservation of heritage
 - Sentimental witnesses
- To save the means
 - Columns at the Royal Theatre of Liège
 - Melting of bells during war

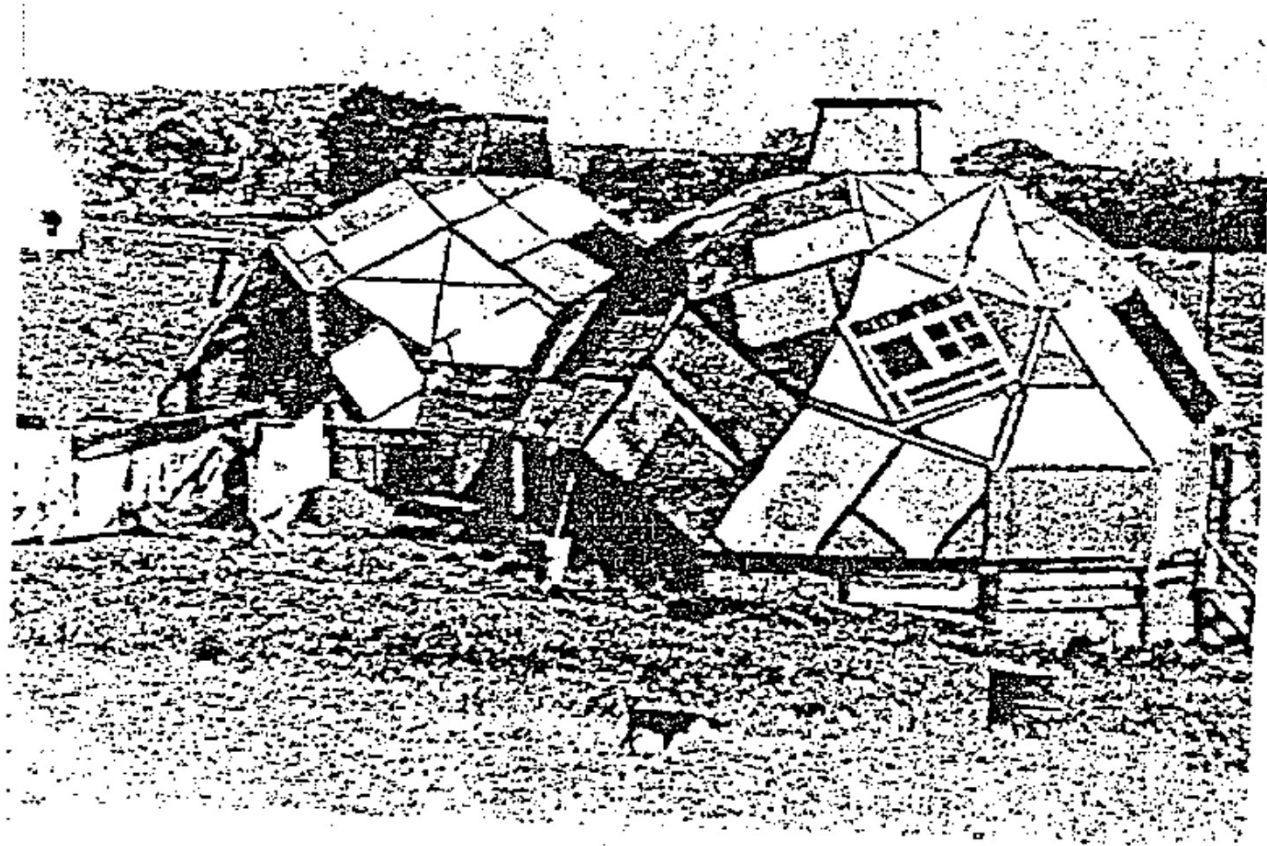
Materials recovery, it is ...

- To save raw materials:
 - Recycled steel saves iron ore;
 - Each ton of recycled plastic saves 700 kg of crude oil;
 - Recycling 1 kg of aluminium saves about 8 kg of bauxite, 4 kg of chemical products and 14 kWh of electricity;
 - Each ton of recycled cardboard saves 2.5 tons of wood;
 - Each sheet of recycled paper saves 1 liter of water and 2.5 W of electricity in addition of 15 g of wood.

Materials recovery, it is ...

■ To contest

Domes in recycled materials, built by hippie community, supervised by Buckminster Fuller, Colorado, 1965
Source: Elfers, J. & Schuyt, M., « Les bâtisseurs de rêves »



Materials recovery, it is ...

■ To contest

Mobile guardrail made
up of scrap iron
(School Notre-Dame
des Missions,
Charenton)
Source: Architecture
d'aujourd'hui, 179
(1975)



Materials recovery, it is ...

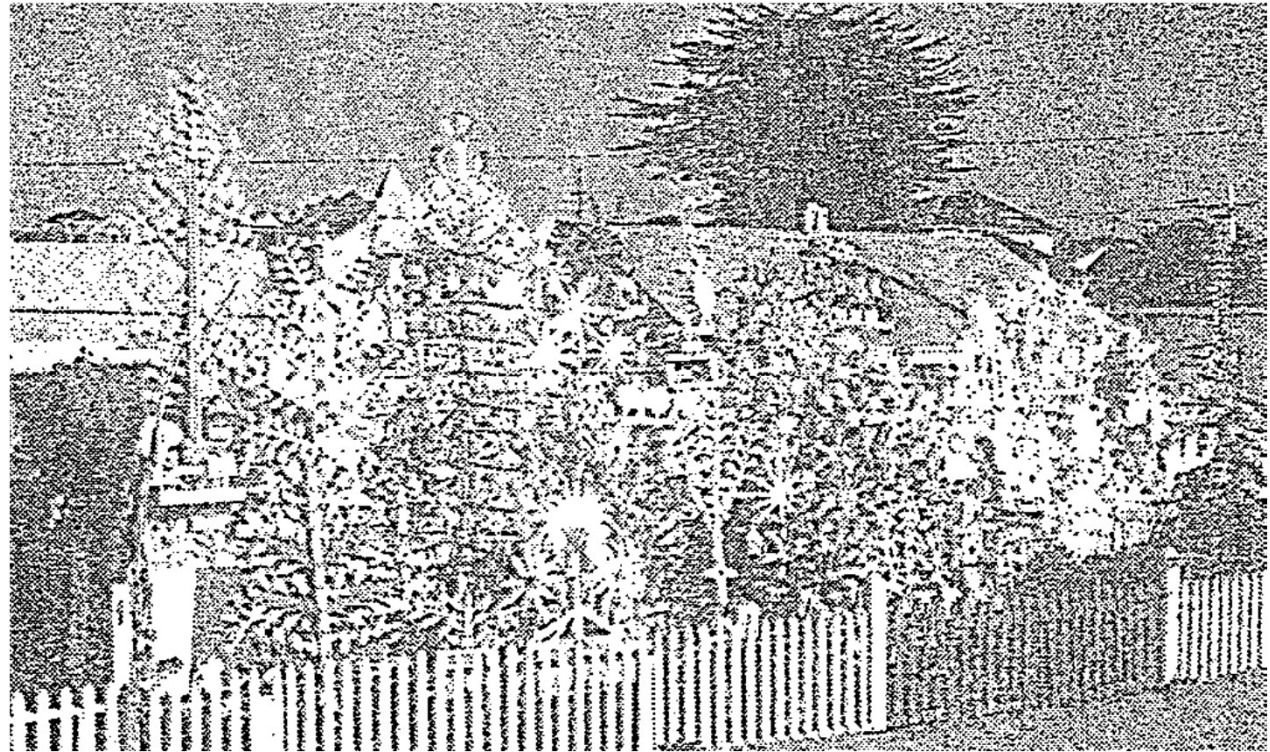
- To build



the Postman Cheval's Ideal Palace (*Photo G. Thérin*)

Materials recovery, it is ...

- To build

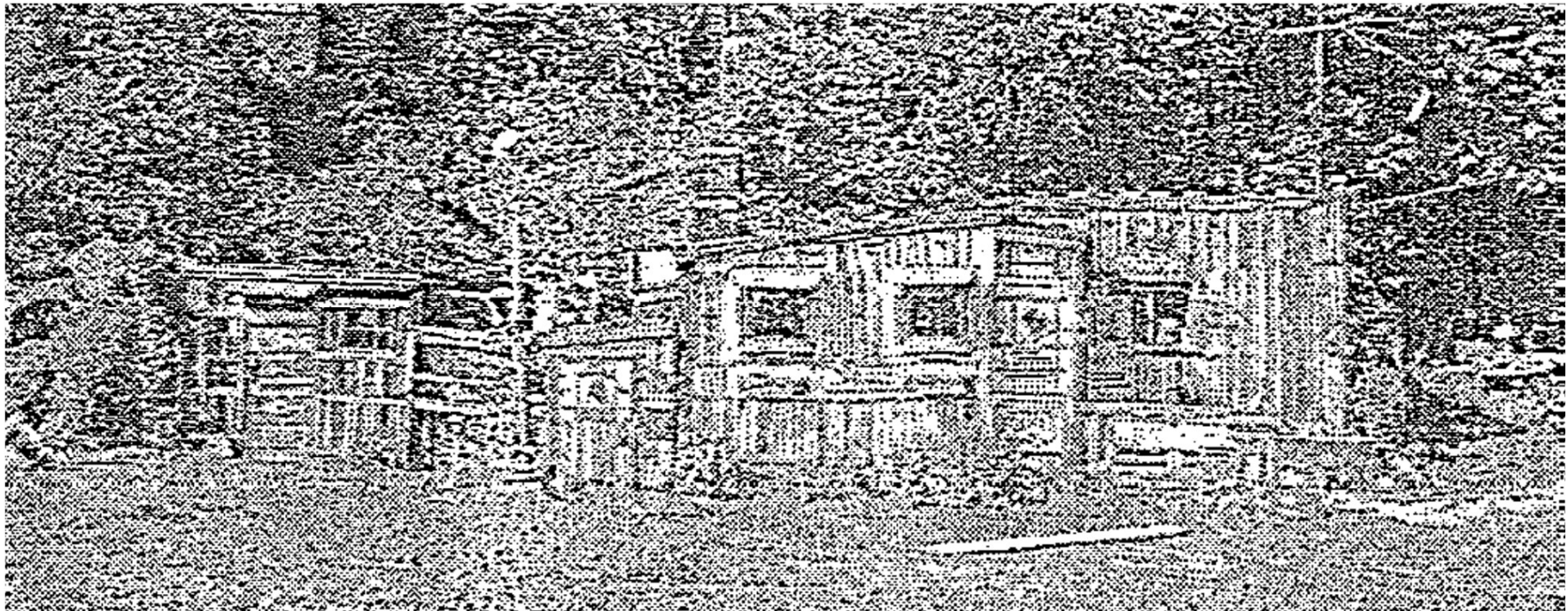


The recovered wooden garden of R. Gabriel (Euréka, Californie)

Source: Elfers, J. & Schuyt, M., « Les bâtisseurs de rêves »

Materials recovery, it is ...

- To build



Wooden house of Fred Burns, Belfast, Maine
Source: Architecture d'aujourd'hui, 179 (1975)

Materials recovery, it is ...

- To build



www.paperhouserockport.com

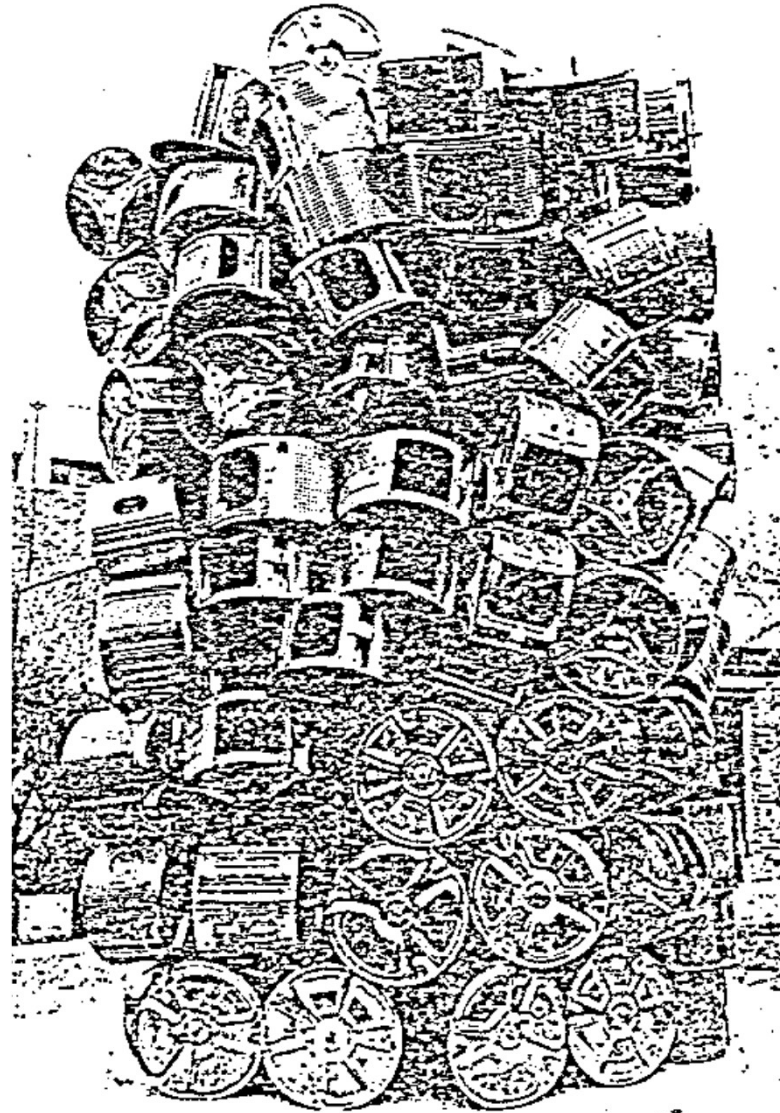
Furniture in the paper house of
Elis Stenman (Pigeon Cove,
Massachusetts
Source: Elfers, J. & Schuyt, M.,
« Les bâtisseurs de rêves »



***desk and chair - section of wall,
which is made of old newspaper and
varnished***

Materials recovery, it is ...

- To create



Arman: accumulation

Source: BT n°977, avril 1986

Materials recovery, it is ...

- To create



**Baldaccini, César - *"Compression"* -
*Compression 1960 – Compressed metal,
exhaust pipe from automobiles***



**Baldaccini, César - *"Compression"* -
*(1960)***

Materials recovery, it is ...

- To create



Airport of Bruxelles - National

Materials recovery, it is ...

■ To live and survive

Houses of poor merchants from Bangkok
Source: Gabor, M., « Maisons sur l'eau »



Pickers of waste in a slum in
Jakarta in Indonesia



Legal and regulator aspects

European directives « environment »

- Unique act (1987): official recognition of the environment:

"Environmental protection requirements shall be a component of the Community's other policies"

(title VII, article 130R)

European directives « environment »

- Directive 91/156/CEE (March 18th, 1991)
 - Priorities: waste recovery and recycling, and their valorisation, including under thermal form.
 - Principle of proximity: waste should no longer be considered as goods moving freely.
 - Local plans to eliminate waste: *States may take the necessary measures to prevent the movement of waste which were not in accordance with their waste management plans.*
 - Regulation CEE 259/93 from 1st February 1993 organise the surveillance and the control of the transfer of waste inside, at the entry and at the exit of the European Union.

Construction products directive

- Council directive 89/106/CEE, related to the rapprochement of laws, regulations and administrative provisions of the Member States relating to **construction products** (1988, modified by the directive 93/68/CEE (1993)).
- Objectives:
 - insure the free circulation of the whole of construction products, by the harmonisation of national legislations concerning the essential requirements of these products according to health, security, well-being.*

Construction products directive

- Six **essential requirements** form the basis of regulatory and national legislative systems
- To allow the erection of construction works which fulfill, for a period of life that is economically reasonable, the essential requirements of the :
 - Mechanical and stability resistance: stability and durability of mechanical resistances;
 - Security in the event of fire;
 - Thermal environment, lighting, air quality, humidity and noise;
 - Safety of use;
 - Protection against noise;
 - Energy economy and thermal insulation.

Construction products directive

- Essential requirements ➡ interpretative documents elaborated by technical committees ➡ technical specifications:
 - European harmonized standards (EN);
 - European technical approvals assessing the ability of a product for intended use, in the case of no harmonized norm, no national norm nor mandate of harmonized norm.

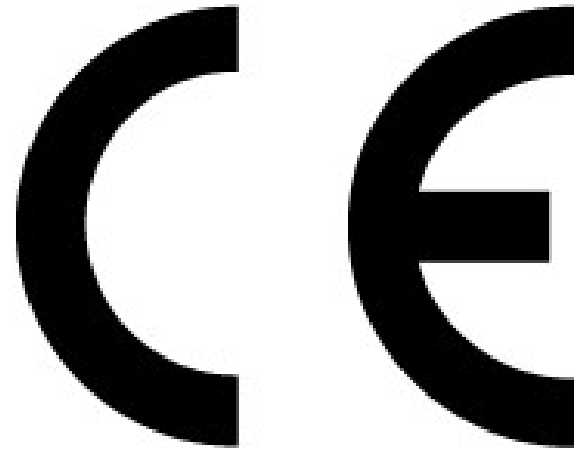
Construction products directive

- Harmonized part from European norms: respect of essential requirement for construction works, of test methods and possibly of the performances of the product (minimal values or classes).

Conformity of the harmonized
part of the norms

CE marking

*This marking is not a brand
or a label*



Construction products directive

- Example: **CE marking** of aggregates from construction (June 2004)
- Changes:
 - National norms: different aggregates in function of the kind of the product
 - European norms: reference to application fields.
 - example: the EN 12620 norm « Aggregates for concrete » includes as gravels as sand used for the making of concrete.
- New norms: apply to not only natural aggregates, but also to artificial and recycled aggregates with a level of equality with natural aggregates,
 - positive impact
 - « the lack of experience with this kind of aggregates requires prudence »
 - test methods inspired by « classic » methods related to natural aggregates.
- Affixing of CE marking: obligatory accompanying of the implementation of a system of control of the quality ➡ adapt the fabrication process of their products

Construction products directive

- Waste and by-products recycling in construction
- Essential requirement n°3 ***"Hygiene, Health and Environment"***
 - thermal environment ;
 - lightings ;
 - air quality ;
 - humidity ;
 - noise.

Construction products directive

- The CPD provides that: *the construction work must be designed and built in such a way that it will not be a threat to the hygiene or health of the occupants or neighbours by for example :*
 - ❑ emission of toxic gases ;
 - ❑ presence in the air of particles or dangerous gas ;
 - ❑ emission of dangerous radiations ;
 - ❑ water or soil pollution or contamination ;
 - ❑ Defects of water evacuation, smoke or solid and liquid waste ;
 - ❑ presence of humidity in or on the part of the construction work.

General conditions of recycling

General conditions for valorisation

- Balance between the deposit and the market
 - Example: demolition and construction of roads
 - On-site recycling = 50% of the total economy
 - 70% transport/travel costs
 - 20% cost of materials
 - 10% dumping charges in landfill.
- Brake on recycling
 - Transport
 - Rules

General conditions for valorisation

□ Transport

- Transport price = $f(\text{quantity, distance})$
- Independent of the quality
- Interesting recycling if
 - Far landfill
 - High dumping charge
 - Expensive raw materials and difficult supply

□ Rules

- *a material has not specification because it is new and not used*
- *A material is a few used because it is uncovered by specifications*

General conditions for valorisation

- Evaluation of the opportunity of recycling
 - Technique
 - Waste characterisation
 - Durability
 - Consistency of the properties
 - Logistic et economic
 - Deposit and transport
 - Consistency of the production
 - Conditioning
 - Localisation

General conditions for valorisation

- Evaluation of the opportunity of recycling
 - Environmental et economic
 - Decrease of the quantities in landfill
 - Regulatory obligation to eliminate
 - Taxation

We don't recycle ...
anything,
anyhow,
at any price.

History of recycling

History of recycling

- Coal and steel industries
 - Recycled waste in France in the field of construction

Kind of waste	Year
study of the use of granulated slag in cement plants	1880
<i>acceptation in France in</i>	1928
<i>but use for the metro from</i>	1900
study of crushed slag in ballast	1885
1,25 10 ⁶ tons	1952
expanded blast furnace slag – patent in	1900
beginning of granulated slag use in roads	1955
Pre-crushed slag in roads	1970
Black or red coal schist	1950s
coal fly ashes (road)	About 1960
ashes - cement	1960-65
Gravelly soil - ashes	1968
ashes - lime - gypsum	1968

History of recycling

- Coal and steel industries
- Oil, plastic, rubber, chemical industries
- Balance (waste, road industry and civil engineering)
 - after world war II
 - *reconstruction*
 - *dynamiting lock of Berendrecht*
 - important acceleration for 20 years (huge demand and requirement of materials) both in quantity and quality (backfill, aggregates, binders, additives,...)

History of recycling

■ Needs in civil engineering:

- materials, sur lesquels pèsent de faibles exigences et consommés en grande masse, consommés en grandes masses dans les remblais mais transportables sur de faibles distances en raison des coûts;
- aggregates, which must answer the diverse specifications depending on the place they will stand in the structures and used processing techniques. The quality requirement can become high, even strict for surface layer, to lead to end-products with identical qualities to traditional materials ones;

History of recycling

■ Needs in civil engineering:

- binders, which must answer the very precise specifications and whose properties must stay constant in time. Used in small quantities and competitive for expensive products (cements, bitumen), they can have preliminary conditionings and support more expensive transport costs;
- activators, which will be used in small quantities, and so that can cause problems of collection, storage, distribution and regularity.

History of recycling

- Divers questions must be asked:
 - How can waste find their place in a industry and, in general way, in a very much standard society?
 - Which regularity must be asked and which control must be set up to always keep used waste in the range where their ability to work is proved?
 - How can we observe and insure the long term durability of the materials?
 - What is the influence on the environment?
 - Which socio-economic problems can suddenly appear in the classic industrial activities?

Characterization of recycled concrete aggregates

Flow sheet for material processing

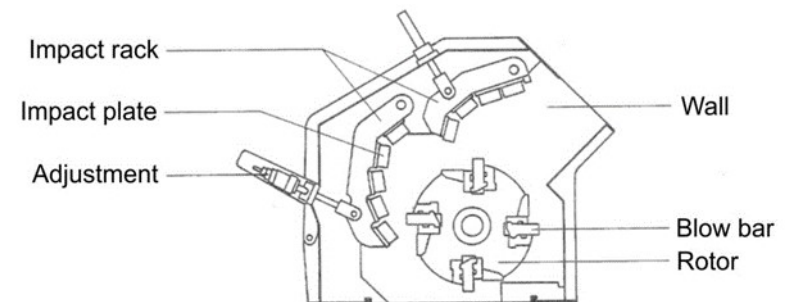
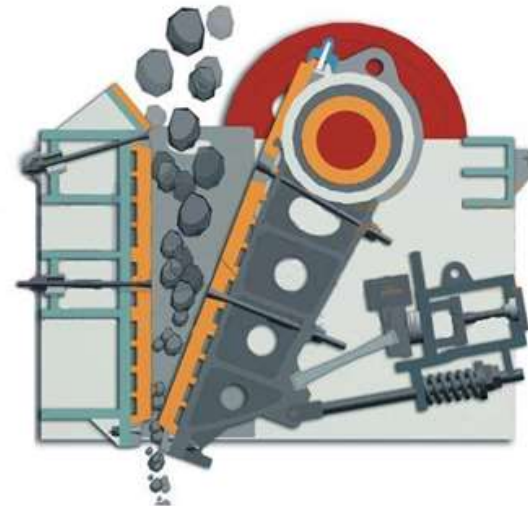


Flow sheet for material processing



Material processing

- Impact crusher
 - allows producing very fine fractions
 - induces the biggest wear
 - limited by the primary size of waste to be treated
- Jaw crusher
 - to treat bulky waste like concrete slabs
 - does not allow to produce very fine particles
 - generally requires a secondary crushing



Shape analysis

- *Shape analysis is based on parameter analysis from 2D projection of particles on glass plate*



Vacuum dispersion



Image analysis



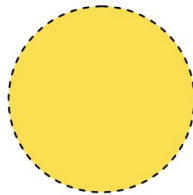
OCCHIO 500Nano (0.5 μm ~2 mm)

Shape analysis

■ Parameter analysis from 2D projection



?



Traditional equivalent volume (area) diameter

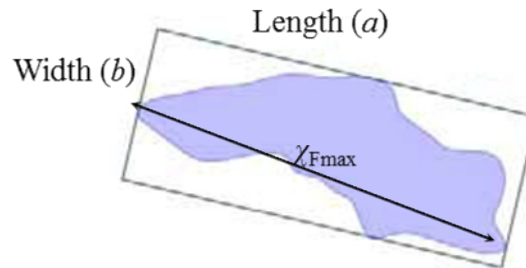


Maximum inscribed diameter

Shape analysis

► Parameter analysis from 2D projection

$$\text{Elongation} = 1 - \frac{b}{a}$$



$$\text{Bluntness} = \frac{1}{\sqrt{\bar{V}} - 1}$$

$$\bar{V} = \frac{1}{N} \sum_i^N \left(1 + \frac{r_{\max}}{r_i}\right)^2$$

Bluntness describes the maturity of the particle in the abrasion process

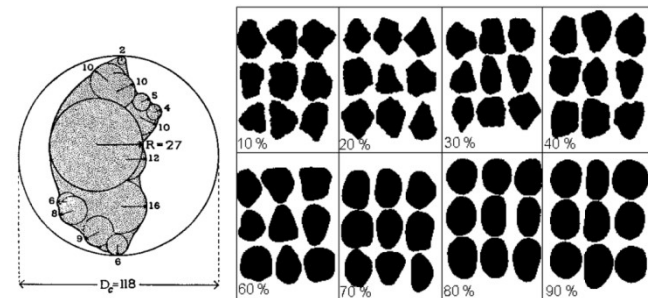
$$\text{Circularity} = \sqrt{\frac{4\pi A}{P^2}}$$

$$\text{Roundness} = \frac{4A}{\pi \chi_{F\max}^2}$$

$$\text{Solidity} = A/A_c$$

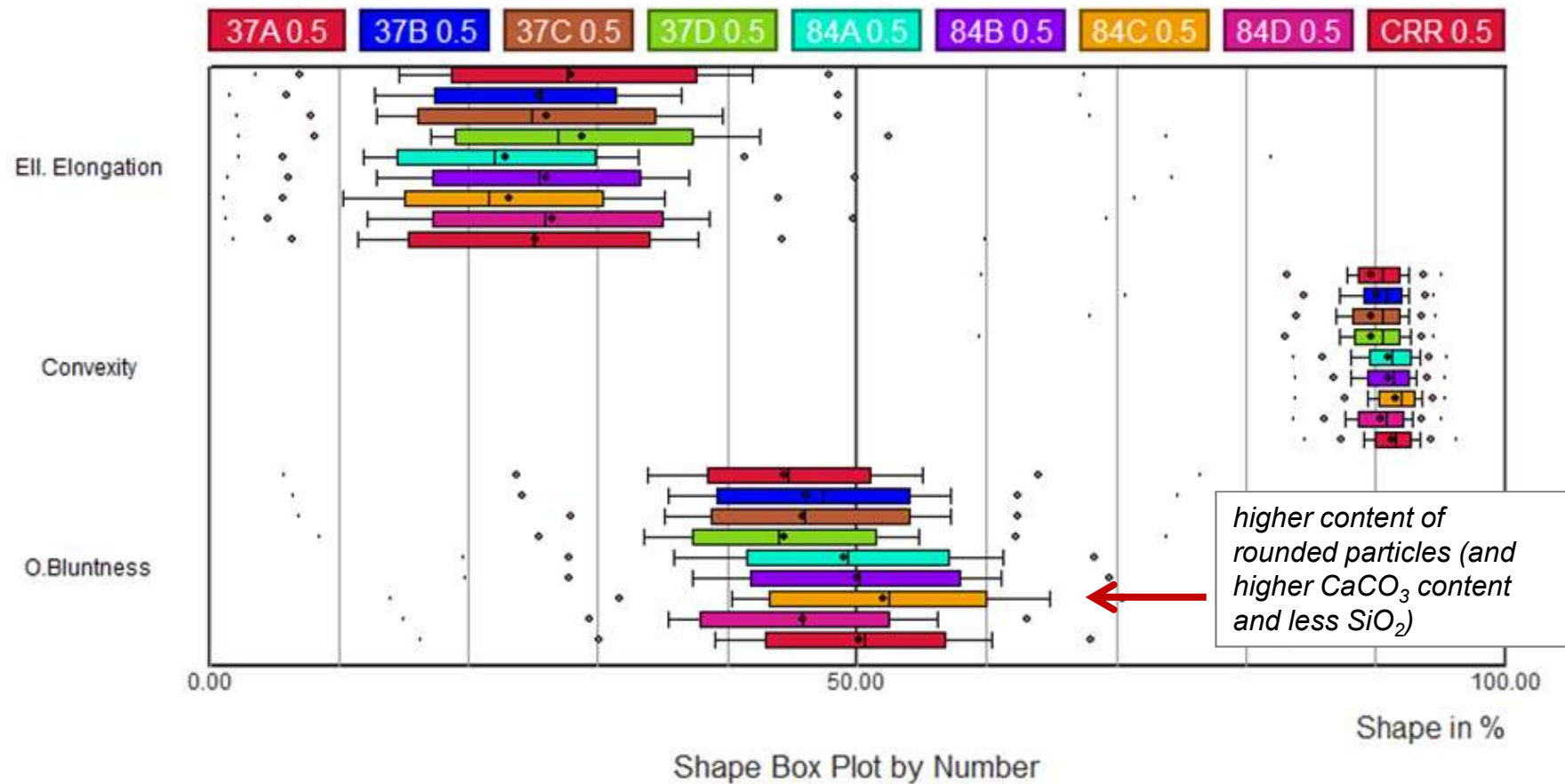


Krumbein's chart



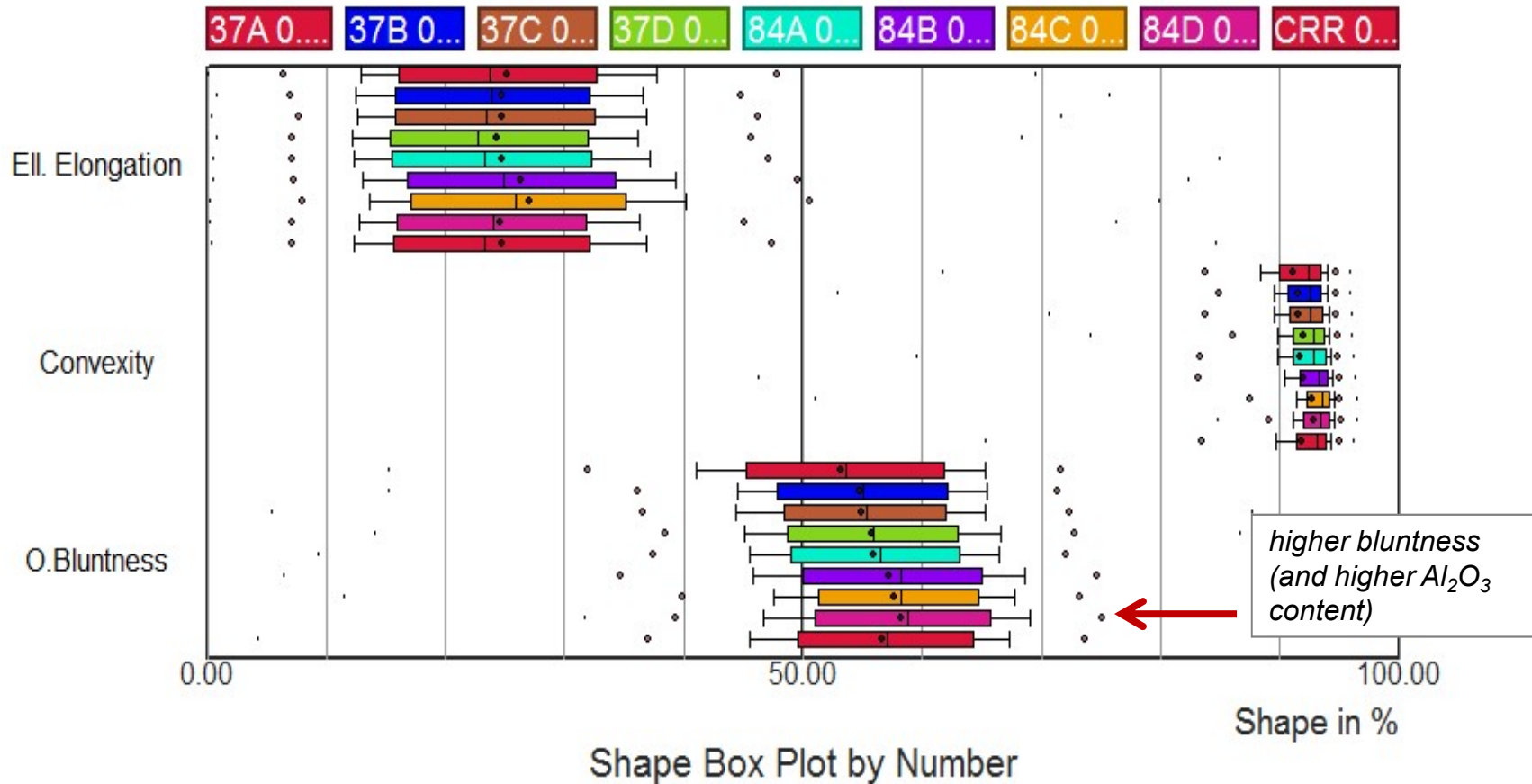
Shape analysis

► *Samples: 0.5 to 1mm*



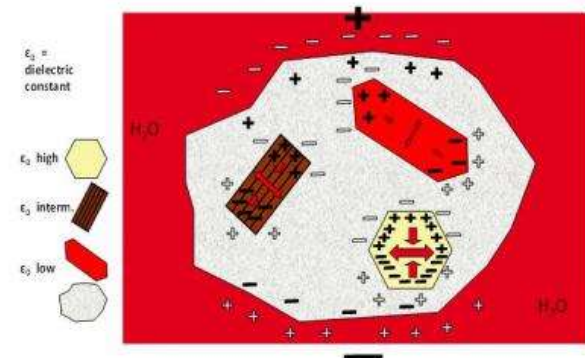
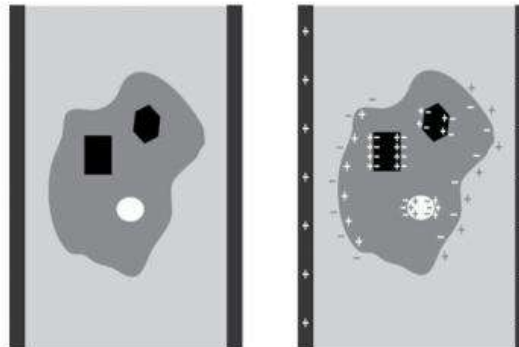
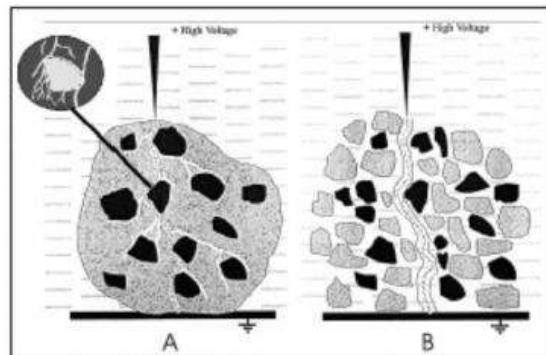
Shape analysis

- Samples: 0.063 to 0.125mm



Material processing

- *Electro-dynamic fragmentation*
 - *Fracture and liberate the sample into its constituent sub-populations while retaining their natural intact sizes: resulting liberated particles often have their surfaces relatively clean and free of matrix material*



Properties of concrete blocks made with recycled concrete aggregates

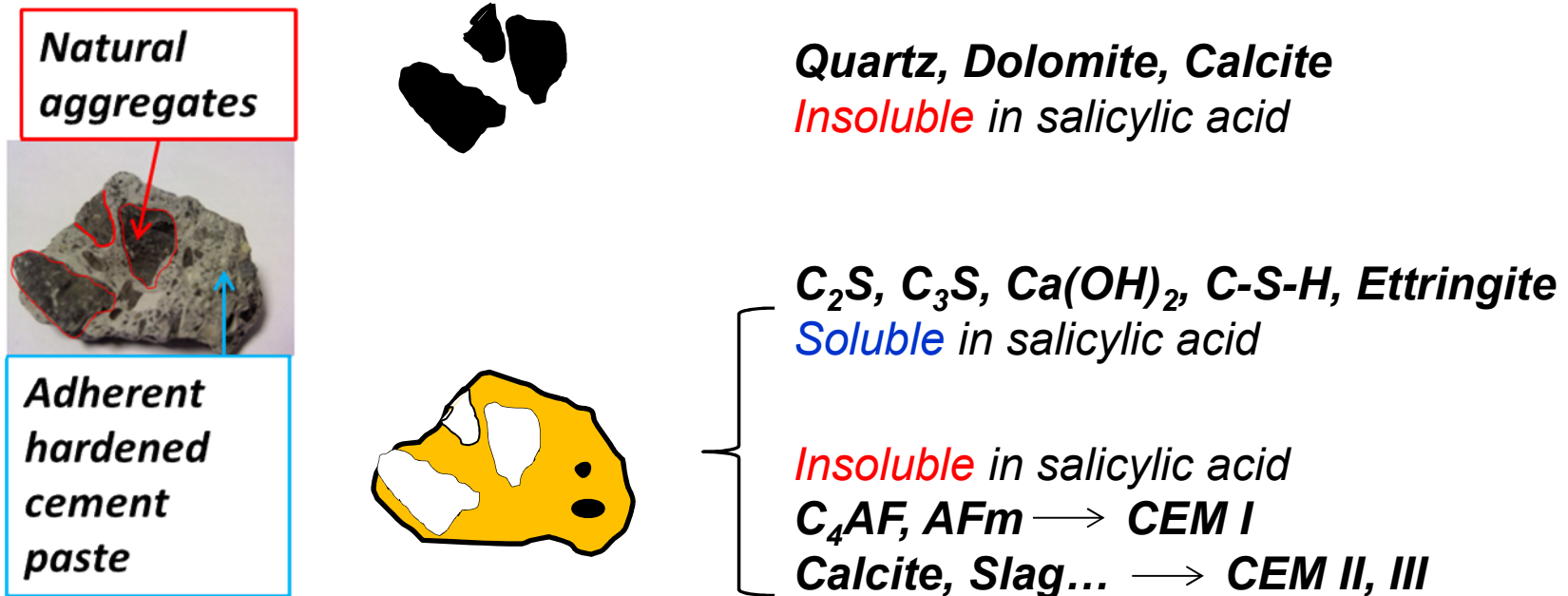
Materials

- RCA manufactured in laboratory
 - Old concrete from block wastes (C8/10 from Prefer Company)
 - Crushing (jaw crusher in laboratory, opening $\approx 10\text{mm}$)
 - Separation of RCA by sieving ($0/20\text{mm}$)
 - Four granular classes: $0/2$ - $2/6.3$ - $6.3/14$ - $14/20$



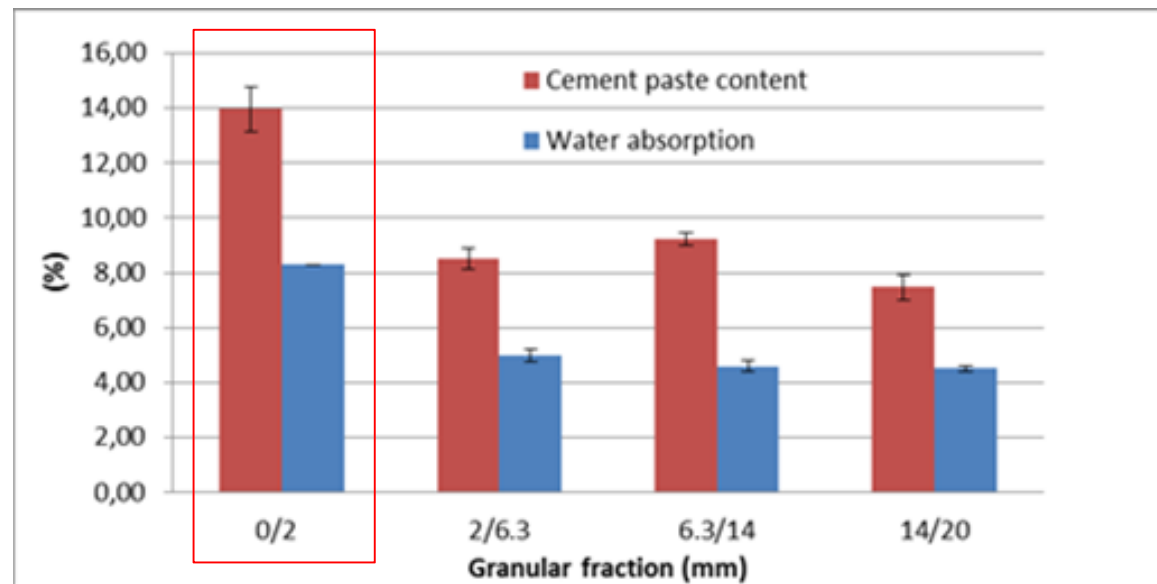
Properties of RCA

- Hardened Cement Paste Content (CPC) of RCA
 - Principal soluble and insoluble phases in salicylic acid and methanol dissolution (*Zhao et al., 2013. Journal of Sustainable Cement-Based Materials 2, 186-203*)



Properties of RCA

■ Water absorption W_A (EN 1097-6)



- CPC and W_A of 0/2mm fraction larger than three coarse fractions
- Recycled sand presents higher CPC and W_A than CRCA

Materials

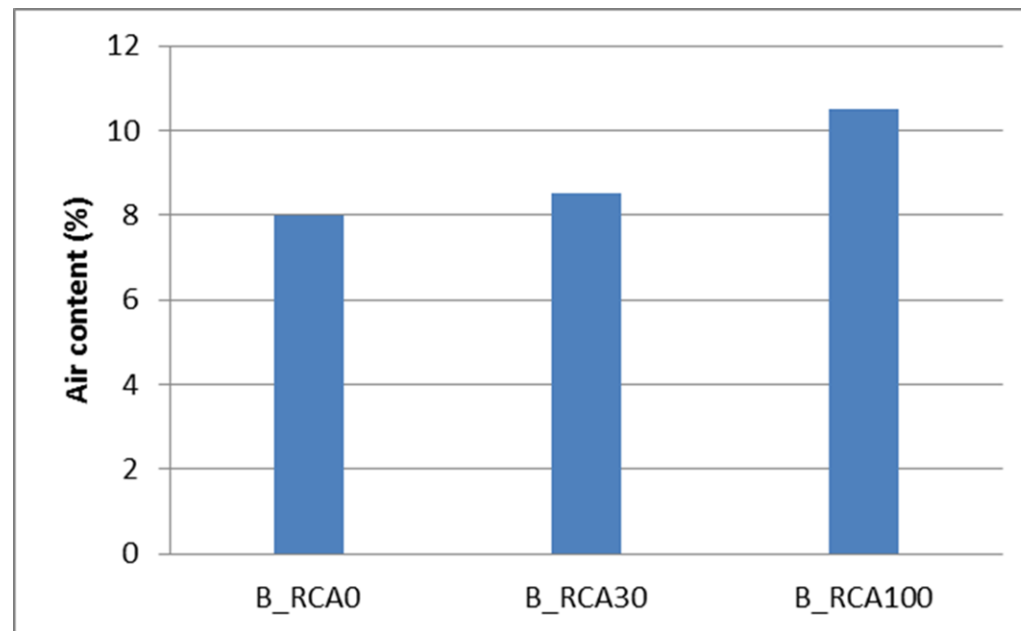
■ Mix design

	<i>B_RCA0</i>	<i>B_RCA30</i>	<i>B_RCA100</i>
NA 2/7 (kg)	1080	754	0
RCA 2/6.3 (kg)	0	302	1008
NS 0/2 (kg)	825	825	825
Cement (kg)	150	150	150
Efficient water (kg)	105	105	105
Absorbed water (kg)	13.12	26.00	56.20
W_{eff}/C	0.70	0.70	0.70

- Different substitution rates of NA 2/7 by the same volume RCA 2/6.3 (0, 30, 100%)
- Same W_{eff}/C ratio - cement CEM III/A 42.5
- Pre-saturation of aggregates in the mixer **5 min** before the addition of cement by half of total water

Properties

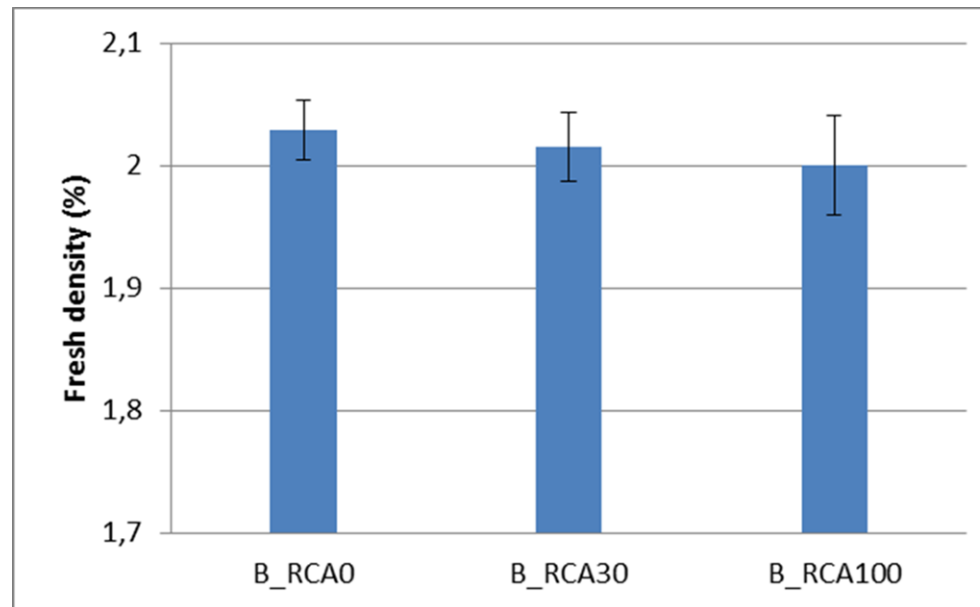
- Fresh properties of concrete (zero slump)



- The air content of concrete increases when the substitution of recycled aggregates increases

Properties

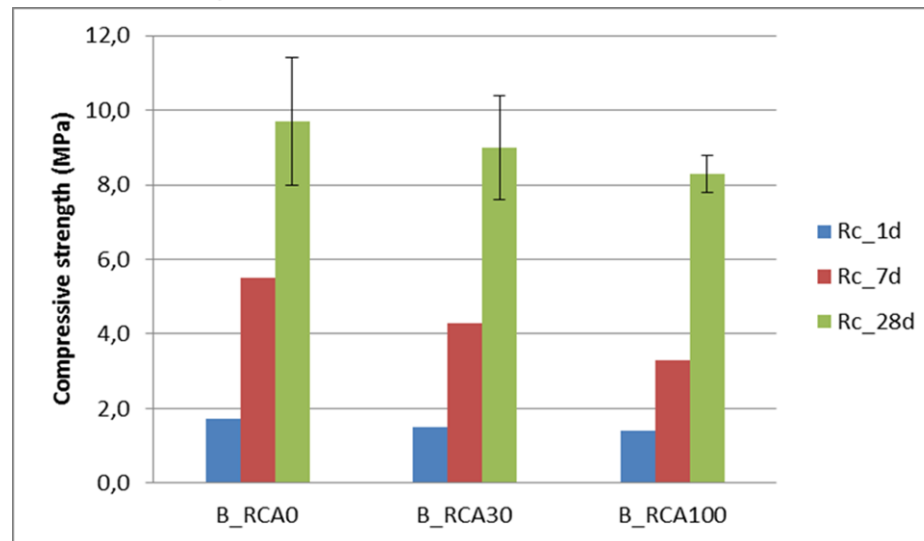
■ Density of fresh concrete



- The density of fresh concrete slightly decreases when the substitution of RCA increases

Properties

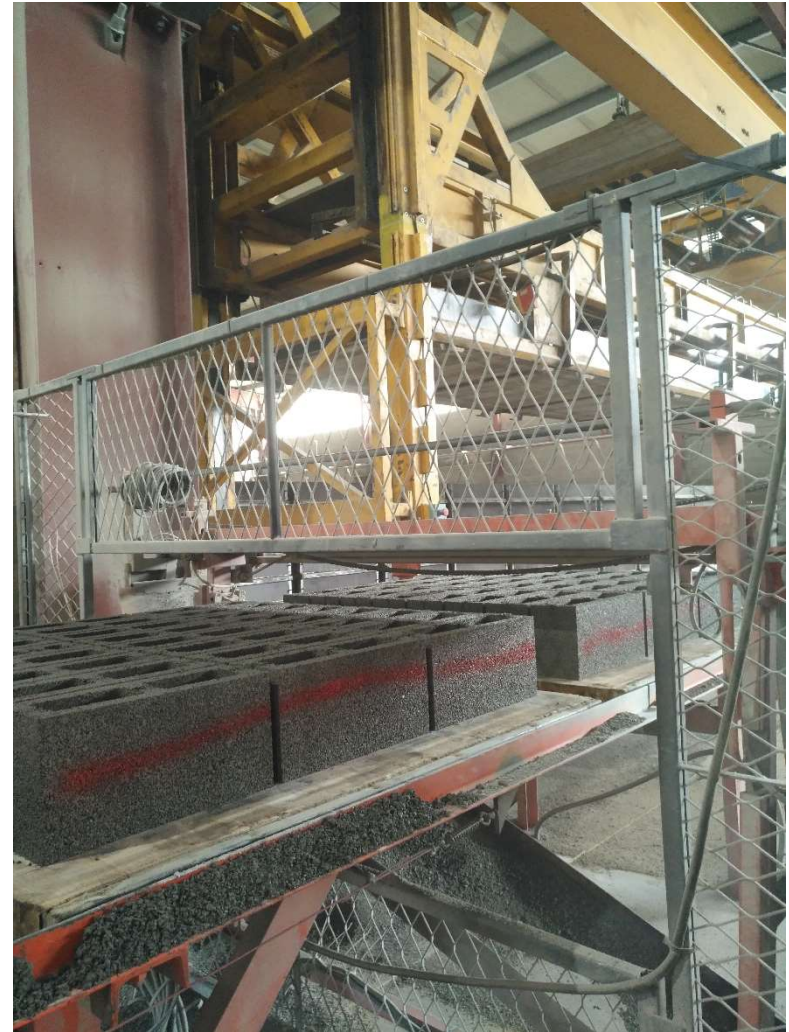
■ Compressive strength



- Compressive strengths of concretes with RCA are slightly lower than those of concrete with natural aggregate
- Compressive strength of concrete made with 100% RCA at 28 days is 8 MPa (14.4% decrease)

Conclusions

- Feasibility of using RCA obtained from old concrete block wastes in the new concrete blocks
 - Recycled sand possesses significantly higher cement paste content and higher water absorption than coarse RCA
 - Compressive strength of concrete blocks slightly decreases as the substitution of RCA increases;
 - R_c of B_RCA100 could reach 8 MPa after 28 days without increasing the cement content of the concrete mix



Coal shales

Coal shales

- Origin

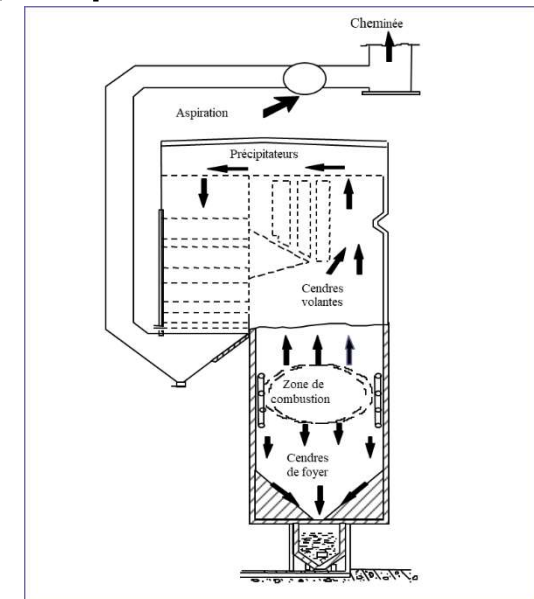
terril de Loos-en-Gohelle (62, France)



Coal shales

■ Origin

- ❑ coal: mini veins, more or less steep, separated by sterile interlayers
- ❑ important quantity of slag: on average, **one ton of coal for two tons extracted**
- ❑ raw coal sent to the washer : by flotation, separation of :
 - commercial coal
 - mix with high ash content (near 50%)
 - coal shales from a washer
- ❑ mix: thermoelectric power plants
- ❑ coal shales: storage on hills



Coal shales

- Combustion phenomenon
 - huge quantity of shales
 - oxidation of coals and pyrites: exothermic reaction (temperatures from 800 to 1500°C)
 - 2-5 % of pyrite apt to be oxidized
 - oxidation of pyrites :
$$\text{FeS}_2 + 7 \text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 2 \text{FeSO}_4 + 2 \text{H}_2\text{SO}_4$$
 - bacterial action of the ferrous sulphate :
$$4 \text{FeSO}_4 + \text{O}_2 + 2 \text{H}_2\text{SO}_4 \rightarrow 2 \text{Fe}(\text{SO}_4)_3 + 2 \text{H}_2\text{O}$$
 - exothermic reaction of the ferric sulphate with pyrite :
$$2 \text{Fe}(\text{SO}_4)_3 + \text{FeS}_2 + 8 \text{H}_2\text{O} \rightarrow 15 \text{FeSO}_4 + 8 \text{H}_2\text{SO}_4$$
- production of **heat** and **acidification** of the environment

Coal shales

- Combustion phenomenon
 - combustion: black coal shales → burned coal shales (= red shales)
 - black shales : no combustion;
 - orange shales : partial or weak combustion;
 - red shales : normal combustion;
 - purple shales : substantial combustion (vitrification).

Coal shales

■ Composition

- sandstone : 20 to 40 %;
- shales : 50 to 80 %;
- various slag

■ Granulometry

- from 0/200 to 0/300 mm

■ No effect of water

- irreversible transformation of clays into silicates
- except non-burned parts, to which we have to remove the thinnest parts to obtain similar performances.

Coal shales

- Composition
 - Pozzolanic properties

Type of oxides	Content (%)
SiO ₂	50
Al ₂ O ₃	30
Fe ₂ O ₃	7
CaO	3
MgO	2
SO ₃	0,6
K ₂ O	3,5
Na ₂ O	0,7

Coal shales

■ Mechanical properties

Properties	Average	Dispersion
Friability of sands	19	15 - 24
Los Angeles	29	25 - 32
Dynamic fragmentation (frost sensitivity)	25	19 - 31
Micro-Deval in presence of water (wear resistance)	22	13 - 41

Coal shales

■ Applications: black shales

□ roads

- road surface layer, creation of road embankment and industrial platforms,
- good materials for landfill,
- easy implementation and compaction by layers from 30 to 40 cm thick
- dry density (1,8 T/m³)

□ raw material

- manufacturing of bricks,
- cement plants: incorporation as raw materials and/or as fuel

Coal shales

- Applications: red shales
 - geotechnical characteristics: idem rocky materials with fines that are low-sensitive to water
 - OK for landfill in contact with high-humidity areas
- Uses
 - road surface layer or road embankment,
 - runway, rural roads, residential district roads (not heavy traffic)
 - emergency lanes

Coal shales

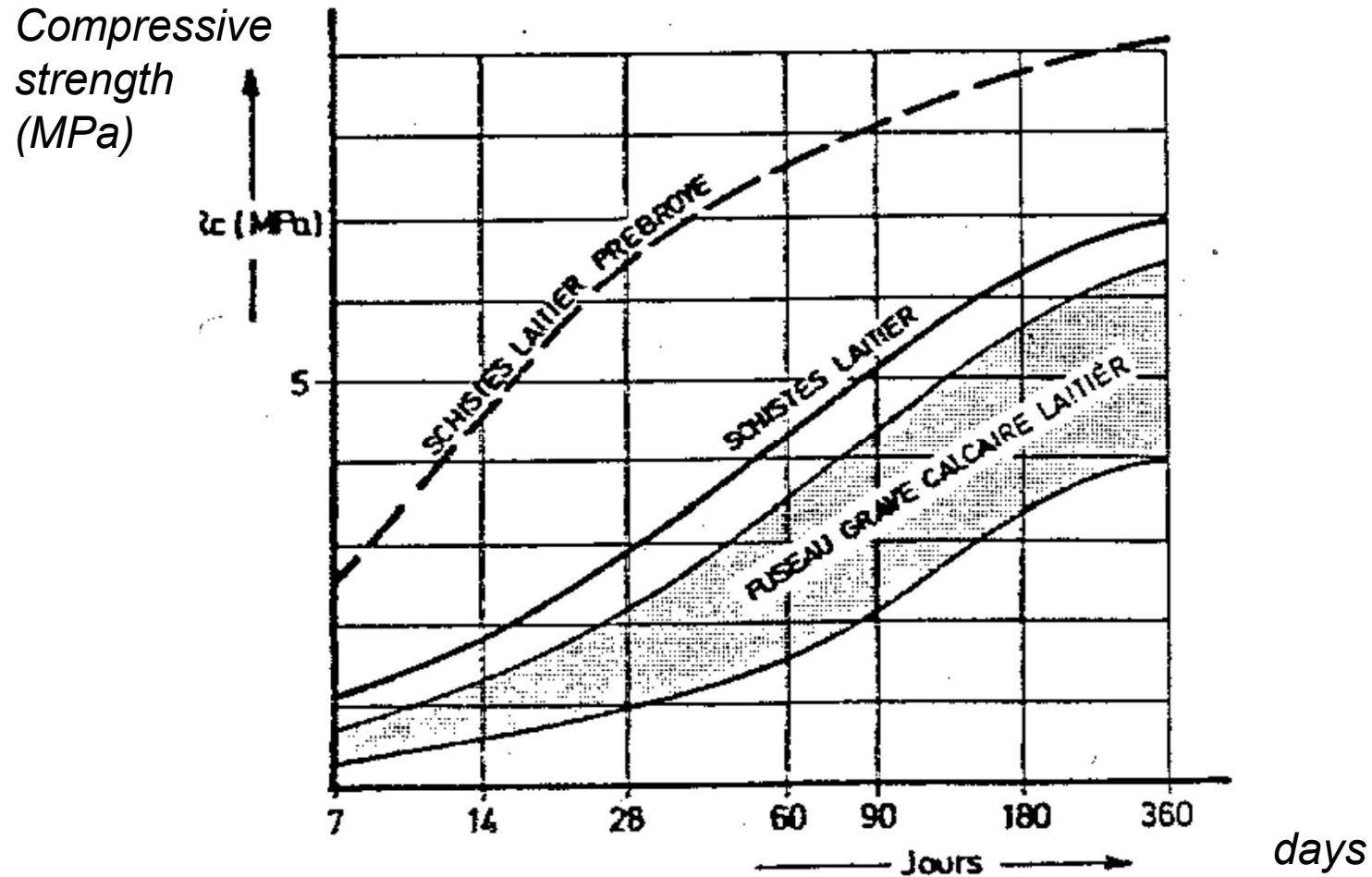
■ Applications: calibrated red shales

- good mechanical resistance
- good grain angularity
- sufficient hardness
- cleanness
- low-sensitivity to frost

■ Treatment with binder

- shales – blast furnace slag – lime : 85 % of shales 0/20 - 15 % of slag with a part % of lime
- shales – fly ashes – lime : 85 % of shales 0/20 - 13 % of silico-aluminous fly-ashes - 2 % of lime
- shales – blast furnace slag – ashes – lime : 85 % of shales 0/20 - 7,5 % of granulated slag - 7,5 % of ashes – a part % of lime

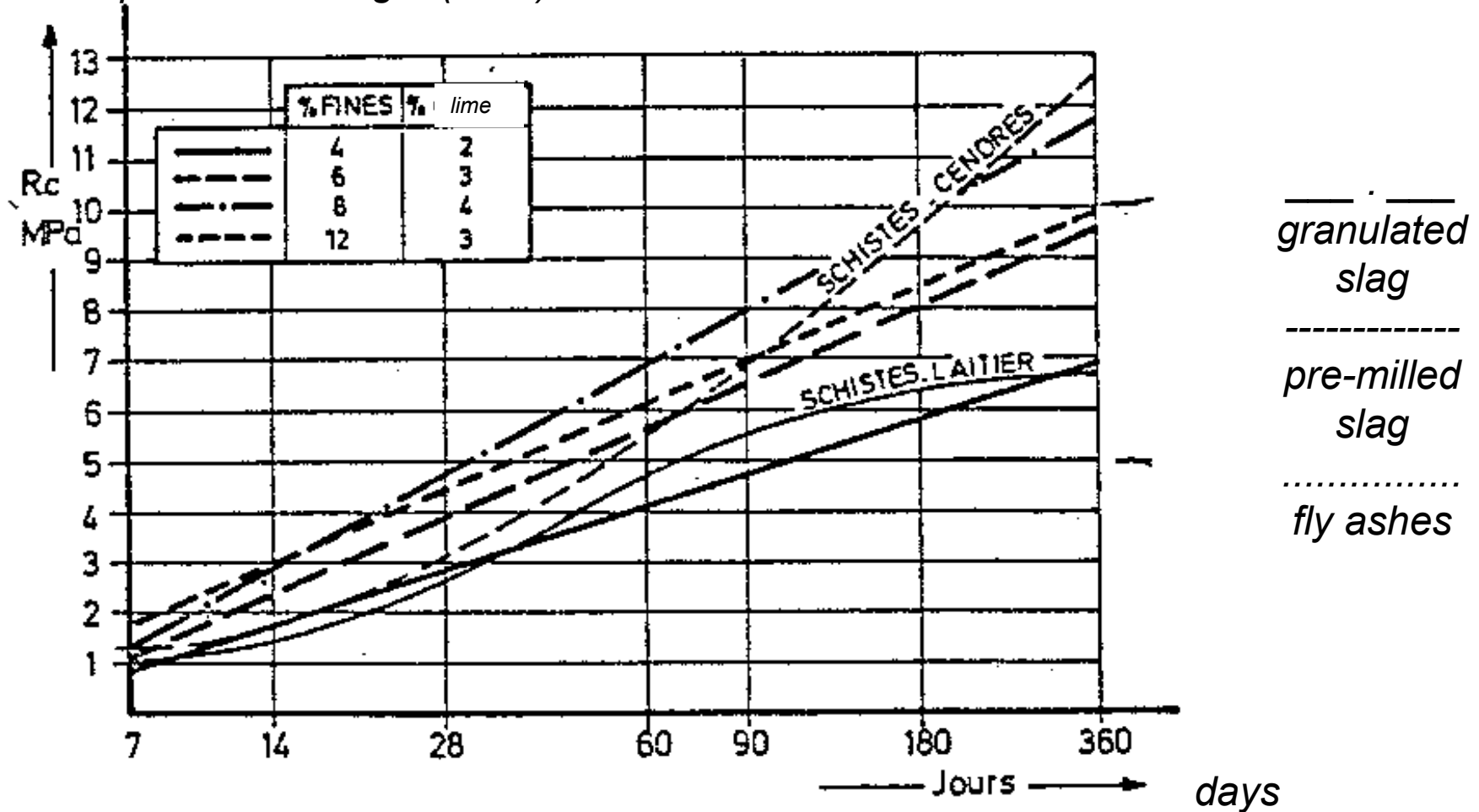
Coal shales



Shales – slags. Influence of the nature of the slag on the compressive strength

Coal shales

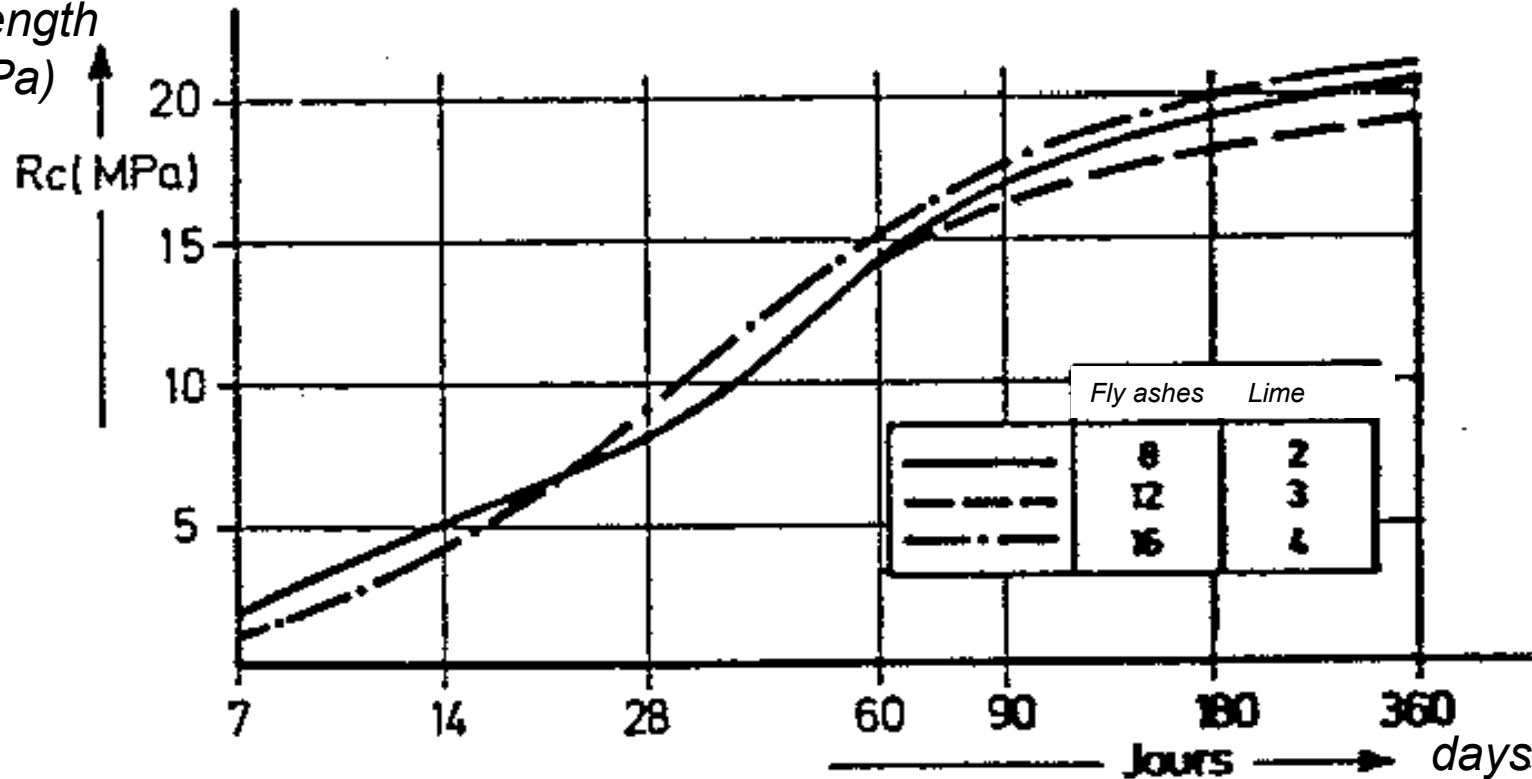
Compressive strength (MPa)



Shales – all shale. Influence of the binder : fine shales - lime

Coal shales

Compressive
strength
(MPa)



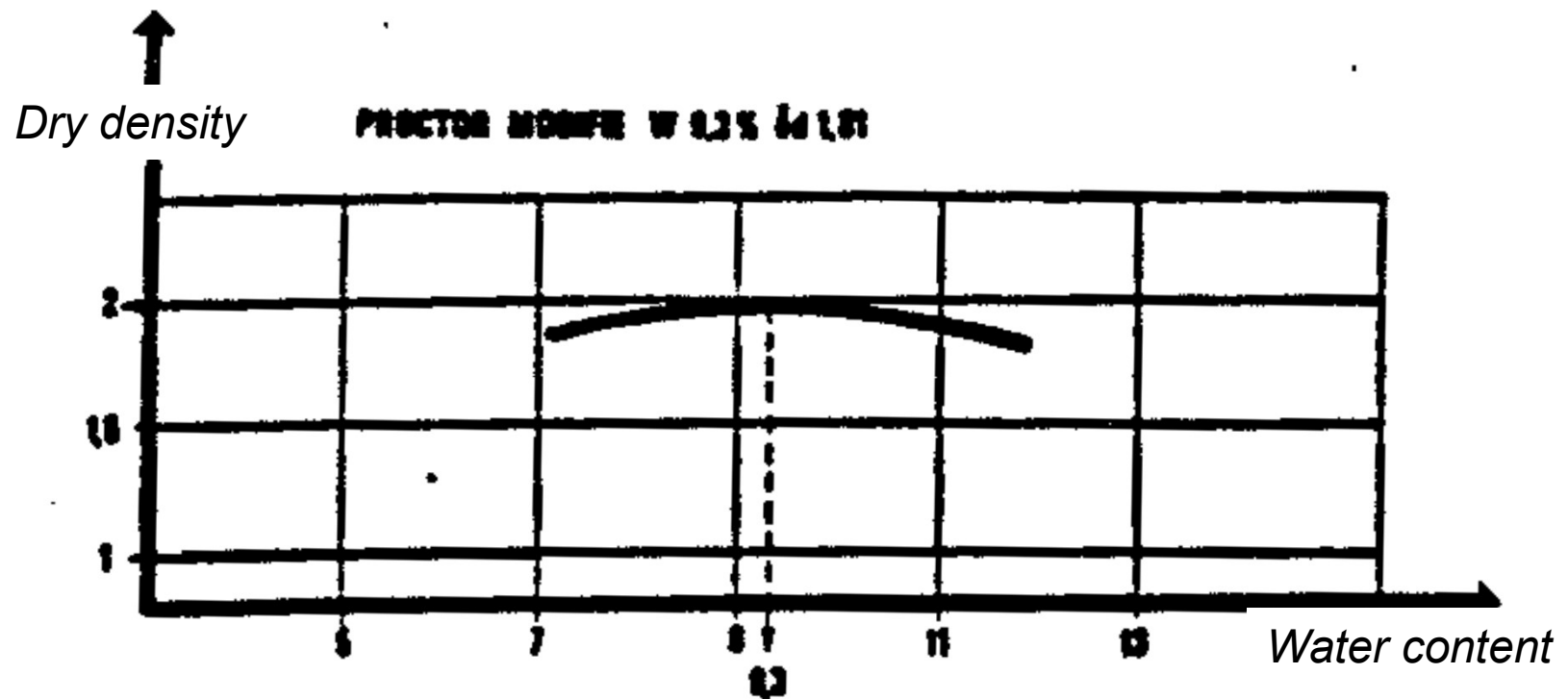
Shales – ashes. Influence of the binder content

Coal shales

- Proctor compaction of shales – slags - lime
 - dry density curve to the O.P.M. of slate shale (1,95 to 2 T/m³): poorly optimized technique;
 - dry density to the O.P.M. significantly lower than that of limestone slags (2,25 T/m³) → significant economic interest.
 - utilisations: ternary mixtures made up of shales are mostly used for surface and foundation layers of new or widening roadways

Coal shales

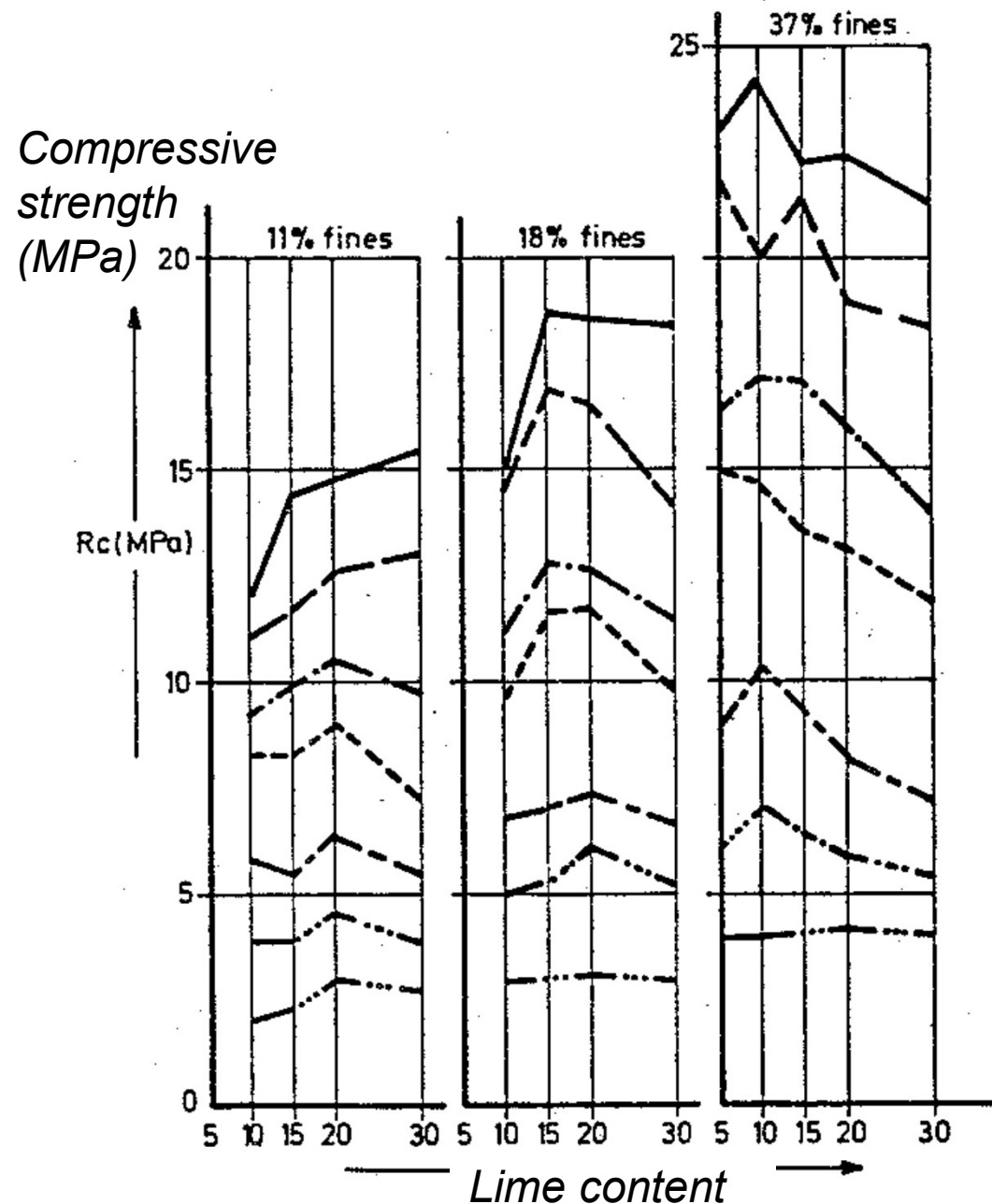
- Proctor compaction of shales – slags – lime



Coal shales

*Pozzolanicity of shales.
Variation of the compressive
strengths depending on the
lime content in the shale-
lime binder.*

*from bottom to top: 7, 14,
28, 60, 90, 180, 360 days*



Coal shales

- Regulation in Wallonia: characteristics of red shales usable in road construction:
 - the red shale does not present shades of grey or reddish grey on its surface or on the break;
 - the passing material through a 0.080 mm sieve does not exceed 7 %;
 - the plasticity index of the passing material through a 0,400 mm sieve is not measurable;
 - the sand equivalent is not less than 30 %;
 - the water stability is not less than 90 %.

Geothermy

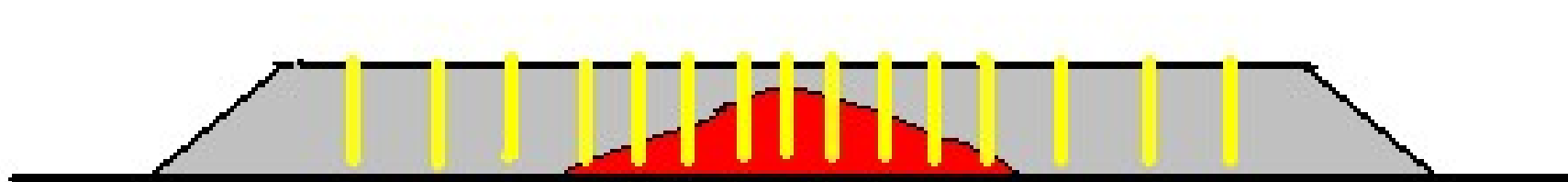
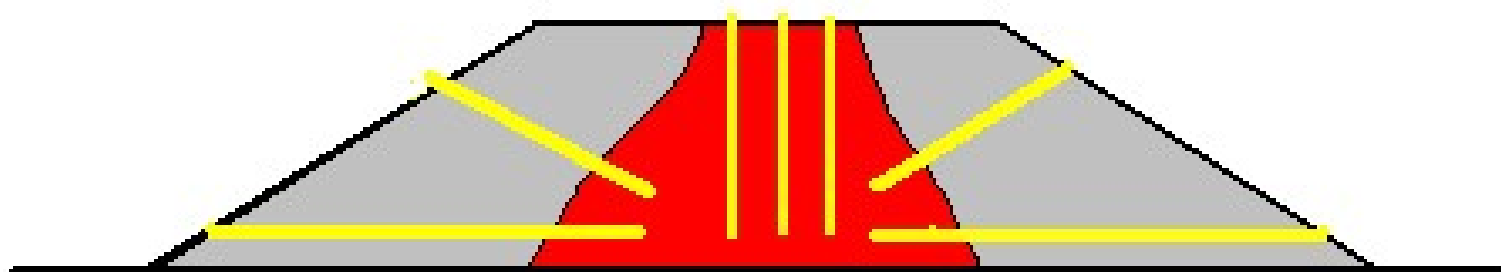
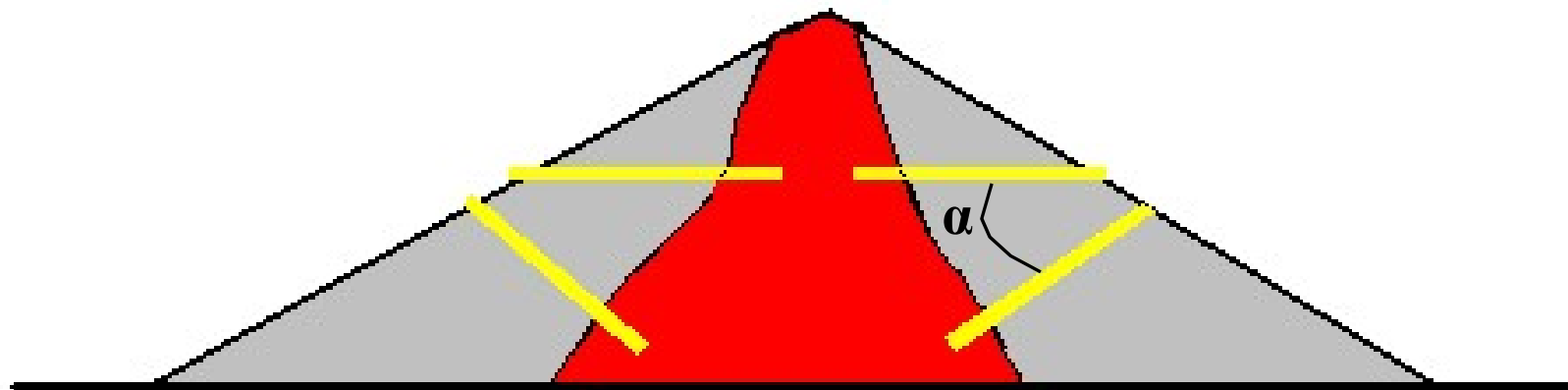
Combustion of slag heaps

□ **3 combined causes:**

- ▣ Increase in temperature due to the oxidation of pyrite and coal (300-400°C to initiate combustion)
- ▣ Supply of oxygen (initiated on the sides exposed to the prevailing winds)
- ▣ Presence of disseminated coal

□ **Consequences:**

- ▣ Harmful gases/particles (CO, H₂S, HAP, heavy metals in traces...)
- ▣ Pockets of « water-gas »
- ▣ Instabilities
- ▣ Burned materials of better quality (water sensitivity/compactness)
 - red shales



Drilling (continuation)



Spider excavator



Conventional drilling machine

- « Spider » excavators
 - Designed for difficult terrain
 - Can be equipped to make micropiles or other anchoring devices
 - Small diameter, max. 60 m depth

- Various methods to size wells. Numerical modeling is another tool to design wells.

Thermal valorisation of slag heaps

■ Drilling

- Horizontal drillings inclined towards the heart (conic heap)
- Vertical drilling (flat heap)
- Rotary drilling or auger (shallow, consistent ground)
- Never less than 5 m in between two drilling
- The smaller the diameter, the better the energetic efficiency of the well
- Re-sloping prior?



Advantages/Disadvantages

- Slag heaps represent an important heat source that is easily accessible (not only the geothermal gradient is exploited)
- Acid medium!
- **Recent heaps** have the best geothermal potential
 - Temperature still very high
 - Oxidation likely to extend
 - Less coal
 - Less interest for recovery
 - Less risk of combustion
 - Less linked to cultural and regional heritage

Advantages/Disadvantages

■ **Hottest heaps**

- The extraction of heat can reduce the risk of combustion provided that the heat exchanger wells are not more permeable to oxygen than the heap
- Significant damage to facilities if combustion begins
- Combustion is interesting to exploit afterward
- Adaptation of materials depending on the internal temperature of the heap
 - In the absence of loading, the PEHD deforms as soon as the temperature is continuously higher than 80°C

Advantages/Disadvantages

- **Low temperature heaps**

- Two-way heat pump for cooling in summer (increases the lifetime of the setup)

- **Drilling:** most delicate step

- Low compacity → less drilling energy
- Circulation of the machines
- Stability study considering perturbations
- Risk of sudden release and explosion of gas pockets produced during combustion (red shales)

MOOC recycling



The poster features a background of wood chips. At the top, there are two red stamp-like boxes: one saying 'COURS GRATUIT!' and another saying 'Ouvert à tous! Inscrivez-vous dès maintenant!'. To the right is the 'MOOC LIÈGE université' logo. The central graphic is a large, stylized 'S' shape made of wood chips, with the words 'CONSTRUIRE' and 'CYCLER' in black and 'RE' in green, forming the word 'CONSTRUIRECYCLER'. Below this, there are three green arrow icons pointing to the following questions:

- ▶ Qu'est-ce qu'un déchet ?
- ▶ Pourquoi retarder le plus possible le moment où un objet devient un déchet ?
- ▶ Comment mieux valoriser des déchets dans le cadre de la construction et de la rénovation d'un bâtiment ?

At the bottom left, a dark blue box contains the following text:

Fin des inscriptions
01 janvier 2019

Début du Cours
15 novembre 2018

Fin du cours
10 janvier 2019

At the bottom right, there are logos for 'FUN FRANCE UNIVERSITÉ NUMÉRIQUE' and 'LIÈGE université', followed by the text 'Plus d'infos et Inscription sur www.fun-mooc.fr' and a QR code. At the very bottom, it says 'Un MOOC est un cours en ligne, gratuit et libre d'accès.'

https://www.news.uliege.be/cms/c_9884429/fr/nouveau-mooc-construirecycler

Acknowledgment

- Cooperation project Wallonia Brussels International/Poland «**Bio-sourced and recycled materials for sustainable construction**»



Wallonia



Acknowledgment

- VALDEM INTERREG FWVL research project
 - “Integrative solutions for the valorization of CDW for transborder circular economy” - <http://www.valdem-interreg.eu>
- SeRaMCo INTERREG NWE research project
 - “Secondary Raw Materials for Concrete Precast Products (introducing new products, applying the circular economy)” - <http://www.nweurope.eu/seramco>



- PREFER Company