

Further classes of materials and applications

building & construction materials
carbon structures based materials
nanomaterials
apparel & textiles
paper

wood: see Biomass course prof. Zanetti/Tondi

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building & construction materials

carbon structures based materials

nanomaterials

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paper

wood: see Biomass course prof. Zanetti/Tondi

- Cement (hydraulic binder)
- Concrete
- Aggregates (coarse, fine)
- Clays (calcined)
- Supplementary cementitious materials (SCM)
- Wood (see course II semester Zanetti/Tondi)
- Metals (see course Dabalà: steel, Al, Cu)
- Bricks (often clay-based)
- Composite (see previous lecture)
- New materials generations (biobased, biomimetics: see interactive seminar Dr. Lorenzo Costanzo)

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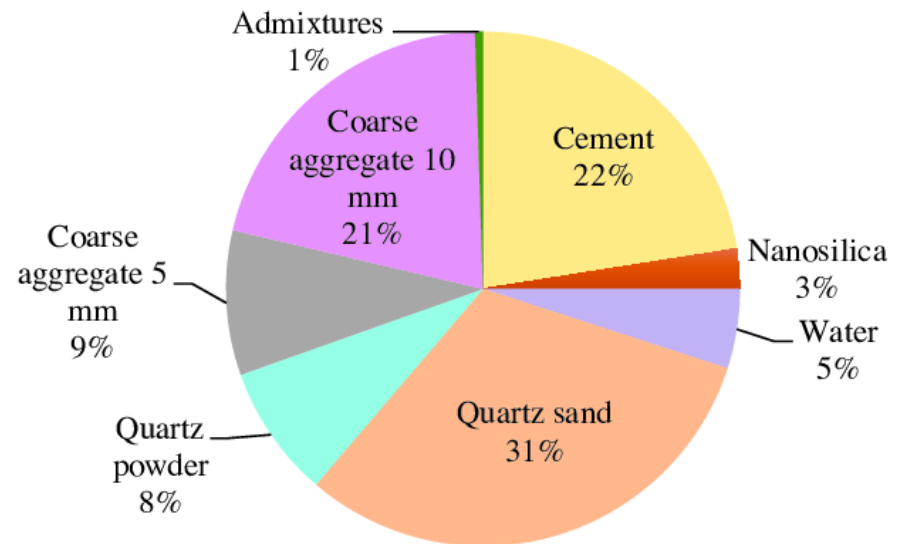
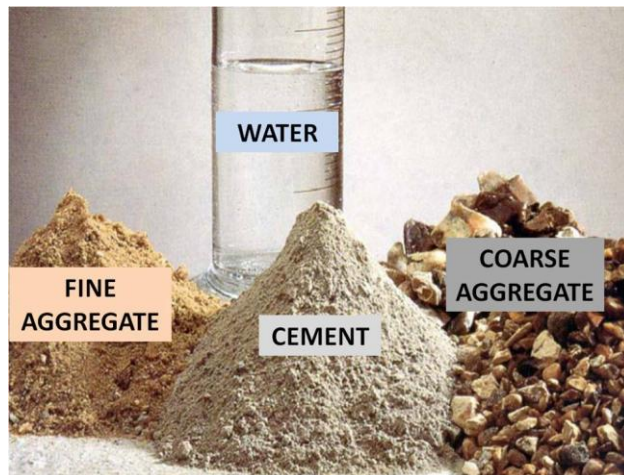
Translations in Italian

Cement	cemento
Concrete	calcestruzzo
Gravel	ghiaia, breccia
Quarrying	cava
Kiln	forno, fornace
Clinker	clinker
Limestone	calcare
Mortar	malta
Plaster	intonaco

See all terms here: <https://www.buzzi.com/cement-in-nutshell>

Cement (concrete)

Concrete (= calcestruzzo) is a structural construction material composed of **cement** (= cemento), (the hydraulic binder) fine aggregates (sand and/or gravel = ghiaia) and coarse aggregates mixed with **water** which hardens with time. **Portland cement** is the commonly used type of cement for production of concrete.



Source of picture: (2015). Improvement of Concrete Durability by Nanomaterials. Procedia Engineering. 125. 608-612.

Average composition of concrete

Cement (concrete)



Basics materials of concrete composition.

Source of figure: Makul, Natt & Fediuk, Roman & Amran, Mugahed & Zeyad, Abdullah & Azevedo, Afonso & Klyuev, Sergey & Vatin, Nikolai & Karelina, Maria. (2021). Capacity to Develop Recycled Aggregate Concrete in South East Asia. Buildings. 11. 234.

10.3390/buildings11060234.

Cement (concrete)

- Cement (as concrete) is the **most consumed material worldwide**, second only to water
- In **2025**, global cement consumption was approximately 3.9 billion tons, with China accounting for around 46% of total demand and the European Union consuming roughly 170–180 million tons.
- On a global scale, the cement and concrete industry accounts for about 10–13% of global GDP (source: <https://www.cementirholding.com/en/sustainability/sustainability/cement-sector-and-challenges-of-sustainability>)
- Unique for:
 - Its manufacturing
 - Its technological/applicative properties
 - Its mechanical features
 - Its durability
 - Its affordability
 - Its cost

Manufacturing of cement

There are four stages in the manufacture of Portland cement:

- (1) crushing and grinding the raw materials (e.g. limestone, silico-aluminates)
- (2) blending the materials in the correct proportions
- (3) burning the prepared mix in a [kiln](#), and produce the clinker
- (4) grinding the burned product, known as “[clinker](#),” together with some 5 percent of [gypsum](#) ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, to control the time of set of the cement).

<https://www.youtube.com/watch?v=5Jbdk7DBm74>

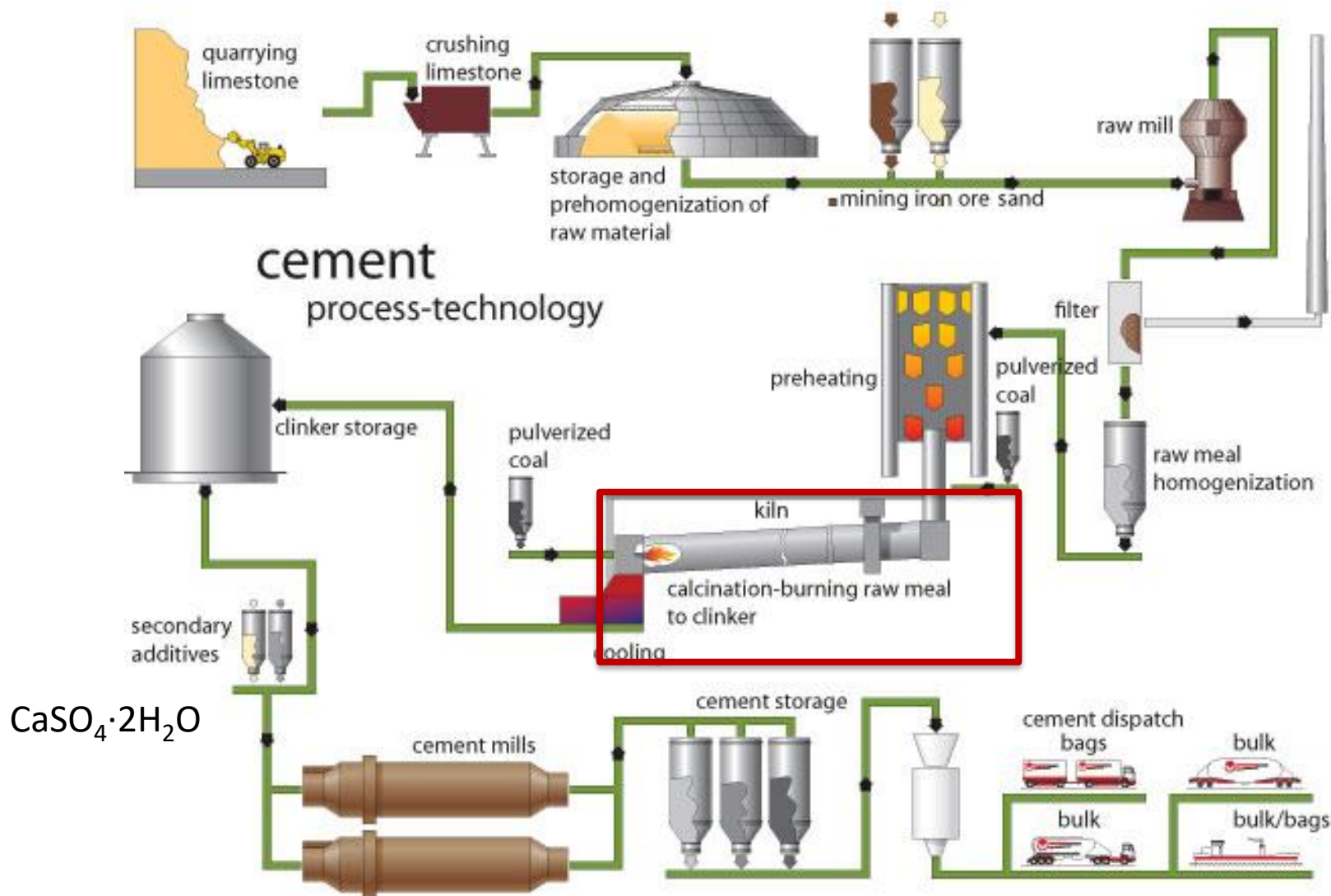
Source: Ecole Normale de Cement



High Quality Portland Cement Clinker

Source of figure: <https://www.goodmaxgroup.com/>

Manufacturing of cement



Source of figure: <https://constructioncost.co/cement-production-process.html>

Chemical composition and notation

Portland cement is made up of four main compounds:

- tricalcium silicate ($3\text{CaO} \cdot \text{SiO}_2$) C_3S
- dicalcium silicate ($2\text{CaO} \cdot \text{SiO}_2$) C_2S
- tricalcium aluminate ($3\text{CaO} \cdot \text{Al}_2\text{O}_3$), and a C_3A
- tetra-calcium aluminoferrite ($4\text{CaO} \cdot \text{Al}_2\text{O}_3\text{Fe}_2\text{O}_3$) C_4AF

In an abbreviated notation differing from the normal atomic symbols, these compounds are designated as **C_3S , C_2S , C_3A , and C_4AF** , where C stands for calcium oxide (lime), S for silica, A for alumina, and F for iron oxide.

Small amounts of uncombined lime (CaCO_3) and magnesia (MgO) also are present, along with alkalis and minor amounts of other elements.

Portland Cement

India/UK	USA (ASTM)	Typical Compounds ³
OPC (IS 269, IS 8112 and IS 12269)	Type I ¹	C ₃ S 55%, C ₂ S 19%, C ₃ A 10%, C ₄ AF 7%, MgO 2.8%, SO ₃ 2.9%, Ignition loss 1.0%, and free CaO 1.0% (C ₃ A < 15%)
	Type II ¹	C ₃ S 51%, C ₂ S 24%, C ₃ A 6%, C ₄ AF 11%, MgO 2.9%, SO ₃ 2.5%, Ignition loss 1.0%, and free CaO 1.0% (C ₃ A < 8%)
Rapid hardening Portland cement (IS 8041:1990)	Type III ¹	C ₃ S 57%, C ₂ S 19%, C ₃ A 10%, C ₄ AF 7%, MgO 3.0%, SO ₃ 3.1%, Ignition loss 0.9%, and free CaO 1.3% Its seven day compressive strength is almost equal to Types I and II 28 day compressive strengths.
Low heat Portland cement (IS 12600:1989)	Type IV	C ₃ S 28%, C ₂ S 49%, C ₃ A 4%, C ₄ AF 12%, MgO 1.8%, SO ₃ 1.9%, Ignition loss 0.9%, and free CaO 0.8% (C ₃ A < 7% and C ₃ S < 35%)
Sulphate resisting Portland cement (IS 12330:1988)	Type V	C ₃ S 38%, C ₂ S 43%, C ₃ A 4%, C ₄ AF 9%, MgO 1.9%, SO ₃ 1.8%, Ignition loss 0.9%, and free CaO 0.8% [C ₃ A < 5% and (C ₄ AF) + 2(C ₃ A) < 25%]
PSC (IS 455:1989, IS 12089:1987)	Type IS	Made by grinding granulated high-quality slag with Portland cement clinker

TYPE I – GENERAL USE CEMENT

Ordinary Portland Cement (OPC) type 1 or general purpose is the most used of all cements and is suitable for all uses where special properties of other types are not required, with an average rate of heat evolution and strength development. It is used where cement or concrete are not subject to specific exposures, such as sulfate attack from soil or water, or an objectionable temperature increase due to the heat generated by hydration. Its uses include sidewalks and pavements, reinforced concrete buildings, bridges, railway structures, tanks, deposits, sewers, water pipes and masonry units.

<https://thecementinstitute.com/portland-cement-types/>

Portland Cement

Constituent	Ordinary Portland cement % by Weight
Lime (CaO)	64.64
Silica (SiO ₂)	21.28
Alumina (Al ₂ O ₃)	5.60
Iron Oxide (Fe ₂ O ₃)	3.36
Magnesia (MgO)	2.06
Sulphur Trioxide (SO ₃)	2.14
N ₂ O	0.05
Loss of Ignition	0.64
Lime saturation factor	0.92
C3S	52.82
C2S	21.45
C3A	9.16
C4AF	10.2

Cement = Hydraulic binder → **sets** and **hardens** due to the **reaction with water**

High Temperature Chemistry



Si + Al + Fe

Ca

1450°C



OPC Clinker

C_3S

C_2S

C_3A

C_4AF

Al (+ Fe+ Si)

Ca + S

1350°C

CSA Clinker

$\text{C}_4\text{A}_3\text{\$}$ C_2S

C_3A C_4AF

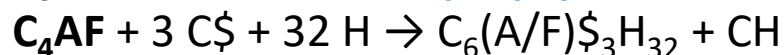
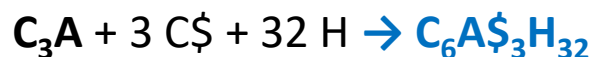
CaSO_4

Room Temperature Chemistry

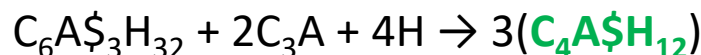
Ordinary Portland Cement (OPC):



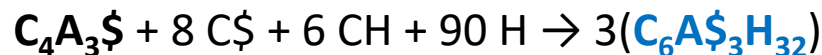
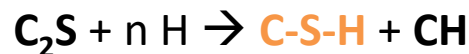
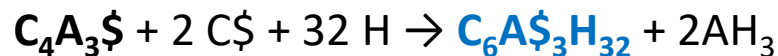
(calcium silicate hydrate ($3\text{CaO} \cdot 2\text{SiO}_2 \cdot 3\text{H}_2\text{O}$))



further conversion to:



CSA cement (special calcium aluminate):



C = CaO, S = SiO₂, A = Al₂O₃, Fe = Fe₂O₃, \\$ = SO₃, H = H₂O

Courtesy Prof. Enrico Boccaleri, Università del Piemonte Orientale

Cement chemist notation: $C_3S + H \rightarrow C-S-H + CH + \text{heat}$

Standard notation: $Ca_3SiO_5 + H_2O \rightarrow (CaO) \cdot (SiO_2) \cdot (H_2O)(\text{gel}) + Ca(OH)_2$

Balanced: $2Ca_3SiO_5 + 7H_2O \rightarrow 3(CaO) \cdot 2(SiO_2) \cdot 4(H_2O)(\text{gel}) + 3Ca(OH)_2$ (approximately; the exact ratios of the CaO , SiO_2 and H_2O in C-S-H can vary)

Due to the nature of the chemical bonds created in these reactions and the final characteristics of the particles formed, **the process of cement hydration is considered irreversible**, which makes methods of cement recycling challenging

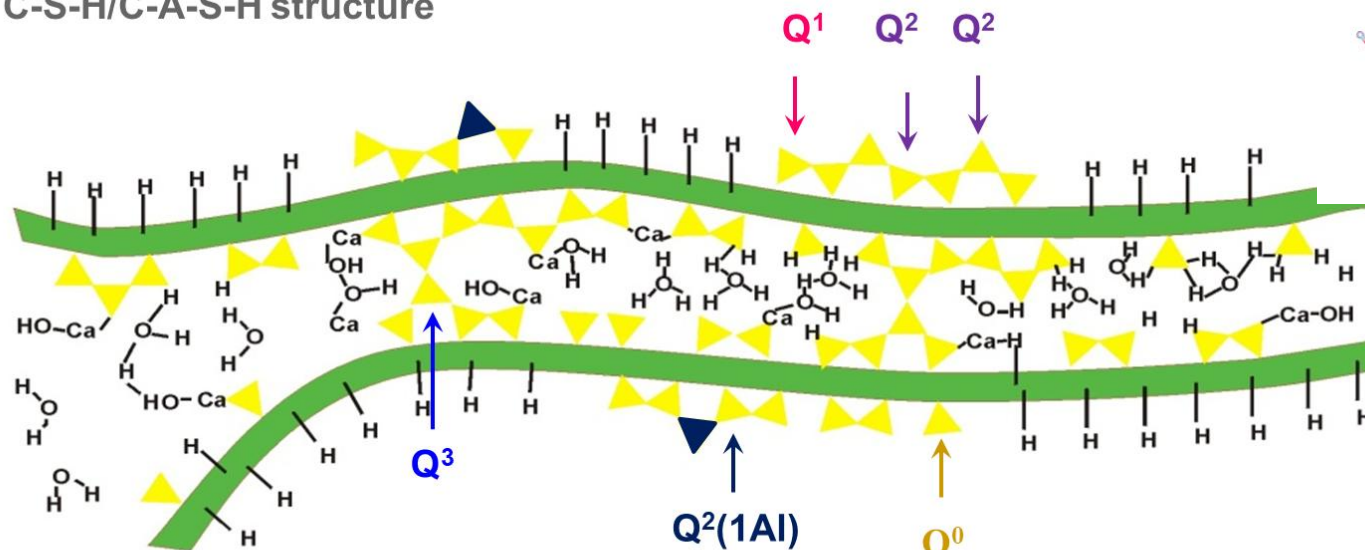
FURTHER STAGES

- During the initial stage of hydration, the parent compounds react, and the breaking of their chemical bonds generates a **significant amount of heat**.
- Then, for reasons that are not fully understood, hydration comes to a stop. This **quiescent**, or **dormant**, period is extremely important in the placement of **concrete**. Without a dormant period there would be no cement trucks; pouring would have to be done immediately upon mixing.
- Following the dormant period (which can last several hours), the cement begins to **harden**, as CH and C-S-H are produced. This is the cementitious material that binds concrete components together.
- As hydration proceeds, water and cement are continuously consumed.

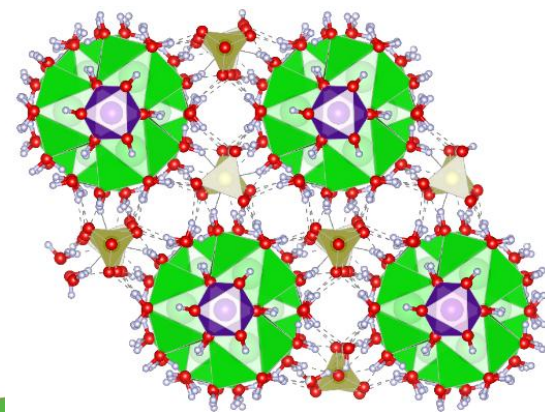
Hydration products

Low-crystalline tobermorite structure

C-S-H/C-A-S-H structure



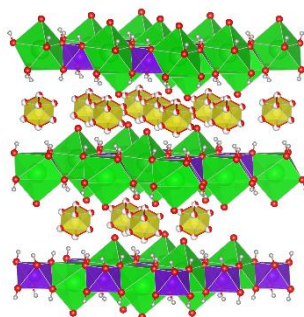
Crystalline structure



Ettringite

Green = Ca^{2+} polyhedra,
Violet = Al^{3+} octahedra
Yellow = SO_4^{2-}

Nanocrystalline and
low ordered structure



Green: CaO backbone
Yellow: Silicate tetrahedra

Courtesy Prof. Enrico Boccaleri, Università del
Piemonte Orientale

Mechanical properties

- The strength developed by Portland cement depends on its composition and the fineness to which it is ground (→ effect of morphology and size distribution).
- The C_3S is mainly responsible for the strength developed in the first week of hardening and the C_2S for the subsequent increase in strength.
- The alumina and iron compounds that are present only in lesser amounts make little direct contribution to strength.

- | | |
|--|---------|
| - tricalcium silicate ($3CaO \cdot SiO_2$) | C_3S |
| - dicalcium silicate ($2CaO \cdot SiO_2$) | C_2S |
| - tricalcium aluminate ($3CaO \cdot Al_2O_3$), and a | C_3A |
| - tetra-calcium aluminoferrite ($4CaO \cdot Al_2O_3Fe_2O_3$) | C_4AF |

- *Clinker* is a nodular material produced in the kilning stage during the production of cement and is used as the binder in many cement products.
- The lumps or nodules of clinker are usually of diameter 3-25 mm and dark grey in color.
- It is produced by heating limestone and **clay** to the point of liquefaction at about 1400°C-1500°C in the rotary kiln.
- Clinker, when added with gypsum (to control the setting properties of cement and ensure compressive strength) and ground finely, produces **cement**.

<https://civiltoday.com/civil-engineering-materials/cement/108-what-is-cement-clinker-clinker-definition-composition-types-uses>



Source of figure: <https://cementplantsupplier.com/>

The four main components of clinker are:

Alite: approximately tricalcium silicate (typically about 65% of the total) $(3\text{CaO} \cdot \text{SiO}_2)$ C_3S

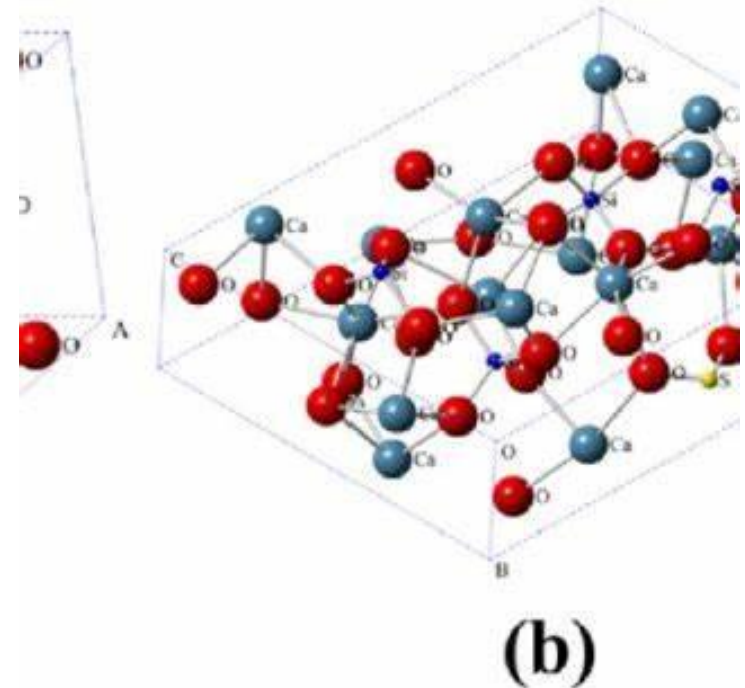
Belite: approximately dicalcium silicate (typically about 15% of the total) $(2\text{CaO} \cdot \text{SiO}_2)$ C_2S

Aluminate: approximately tricalcium aluminate (typically about 7% of the total) $(3\text{CaO} \cdot \text{Al}_2\text{O}_3)$

Ferrite: approximately tetracalcium aluminoferrite (typically about 8% of the total) $(4\text{CaO} \cdot \text{Al}_2\text{O}_3)$, C_4AF

Other substances may be present in small amounts

<https://civiltoday.com/civil-engineering-materials/cement/108-what-is-cement-clinker-clinker-definition-composition-types-uses>



Alite crystal structure

Source of figure: Construction and Building Materials. 182. 156-166.

	Clinker	Cement
1	Clinker is a nodular material which is used as the binder in cement products.	Cement is a binding agent that sets and hardens to adhere to building units such as stones, bricks, tiles etc.
2	Clinker is a granular substance containing spherical pellets of diameter 3-25 mm.	Cement is such a fine powdery substance that each pound of cement contains 150 billion grains.
3	Clinker is produced inside the kiln during the cement manufacturing process . Raw mix is heated and then rapidly cooled to produce the marble-sized pellets of clinker. Read: Clinker Manufacturing Process	Cement is produced by grinding clinker (added with different active ingredients to achieve the desired properties of cement) into a fine powder.
4	The composition of a typical good quality clinker for general use: 37-72% of $3\text{CaO} \cdot \text{SiO}_2$; 6-47% $2\text{CaO} \cdot \text{SiO}_2$; 2-20% $2\text{CaO} \cdot \text{Al}_2\text{O}_3$; 2-19% $4\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot \text{Fe}_2\text{O}_3$ Read: What is Cement Clinker? Composition, Types & Uses	Composition of the most common type of cement: 85% clinker, 1.5-3.5% gypsum by SO_3 content, and up to 15% admixtures. Read: 8 Main Cement Ingredients & Their Functions
5	The primary use of clinker is to manufacture cement.	Cement is used in construction to make concrete as well as mortar and to secure the infrastructure by binding the building blocks. It is also used for water-proofing, filling or sealing gaps, and making decorative patterns.

Cement (concrete) and its impact

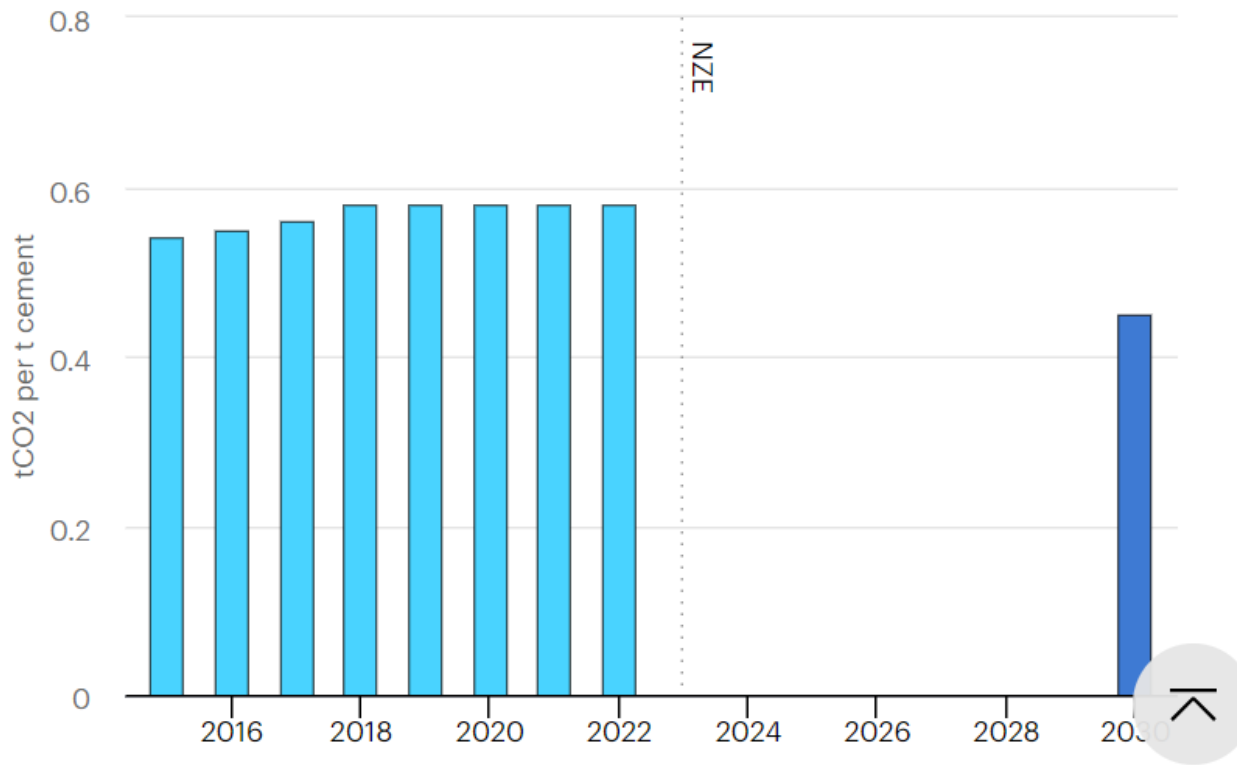
- **1 ton of clinker = 0.6-0.8 ton of CO₂**
- High environmental impact for GHG emissions (**6-7% of the global CO₂ emissions due to cement production**)
- The EU buildings sectors uses as much as 1.6 billion tonnes (Gt) of materials per year
- Use of **non renewable resources** (i.e. mineral feedstocks, fuel)
- Ca. 60% of emissions are intrinsic due to the use of limestone (CaCO₃) as Ca source
- **No current alternatives** to cement and concrete
- Construction has the highest overall carbon (40%) and waste footprint

CO₂ emissions by sector



Cement (concrete) and its impact

Direct emissions intensity of cement production in the Net Zero Scenario, 2015-2030



Open ↗

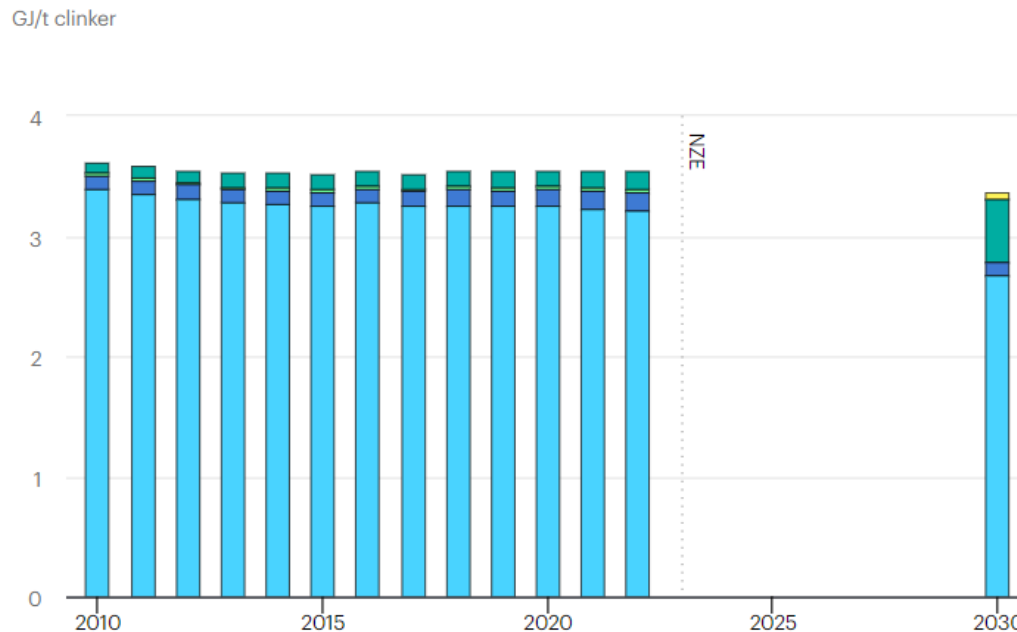
Cement emissions intensity has remained relatively stable since 2018, at just under 0.6 t CO₂ per tonne of cement produced, following several years of modest increase largely due to an increasing clinker-to-cement ratio in China.

<https://www.iea.org/energy-system/industry/cement>

Cement (concrete) and its impact

Global thermal energy intensity of clinker production by fuel in the Net Zero Scenario, 2010-2030

Open 



IEA. Licence: CC BY 4.0

● Fossil fuels
 ● Non-renewable waste
 ● Commercial heat
 ● Bioenergy and renewable waste
 ● Hydrogen
 ● Solar thermal and geothermal

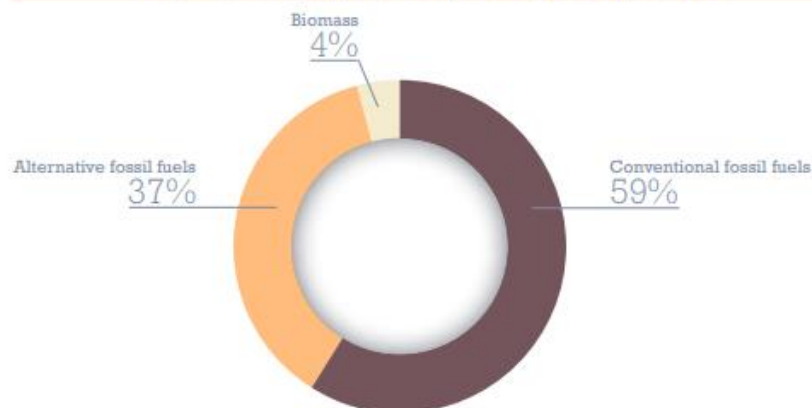
Fossil fuels continued to be the main source of thermal energy for the sector (90% share) in 2022, followed by bioenergy and renewable waste (4%) and non-renewable waste (4%). The adoption of low carbon fuels is key to reduce the share of fossil fuels to 79% and non-renewable waste to 3% by 2030 in line with the NZE Scenario, which sees bioenergy and renewable waste increasing to 16% and hydrogen to 2% of the total thermal energy share.

<https://www.iea.org/energy-system/industry/cement>

Energy for the kiln

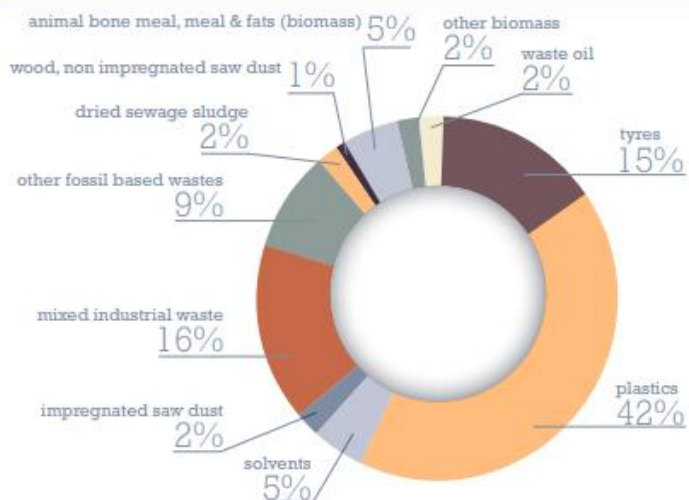
Breakdown of fuels

Thermal Energy Consumption by fuel type 2014



Breakdown of alternative fuels

Alternative fuels breakdown 2014



Due to the characteristics of the production process, the cement industry is capable of co-processing:

- alternative fuels, which have a significant calorific value (e.g. waste oils)
- materials which have a significant mineral component (e.g. industrial slags)
- materials that have both a calorific value and provide mineral components (e.g. used tyres and industrial sludges)

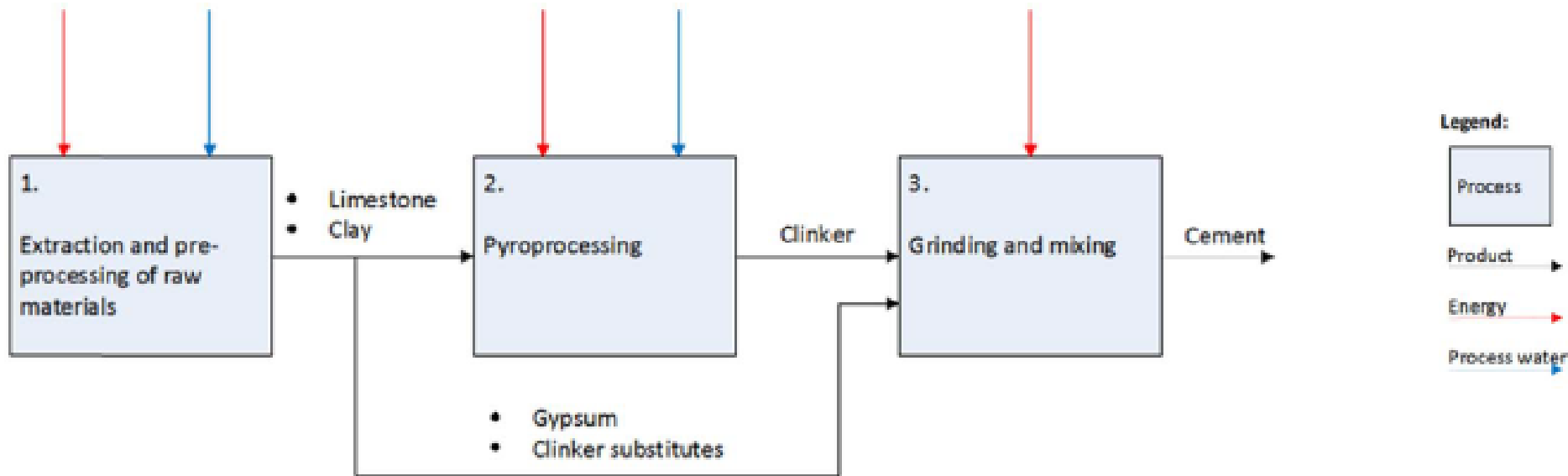
Source:

https://circulareconomy.europa.eu/platform/sites/default/files/cement_concrete_the_circular_economy.pdf

Water footprint of cement

Cement is an inorganic material that binds other materials, like sand or gravel, together. It is hydraulic binder, which means that **water is needed for the chemical reactions** in order to harden.

Concrete is a mixture of cement, water, sand and other aggregates, such as gravel or crushed stone.

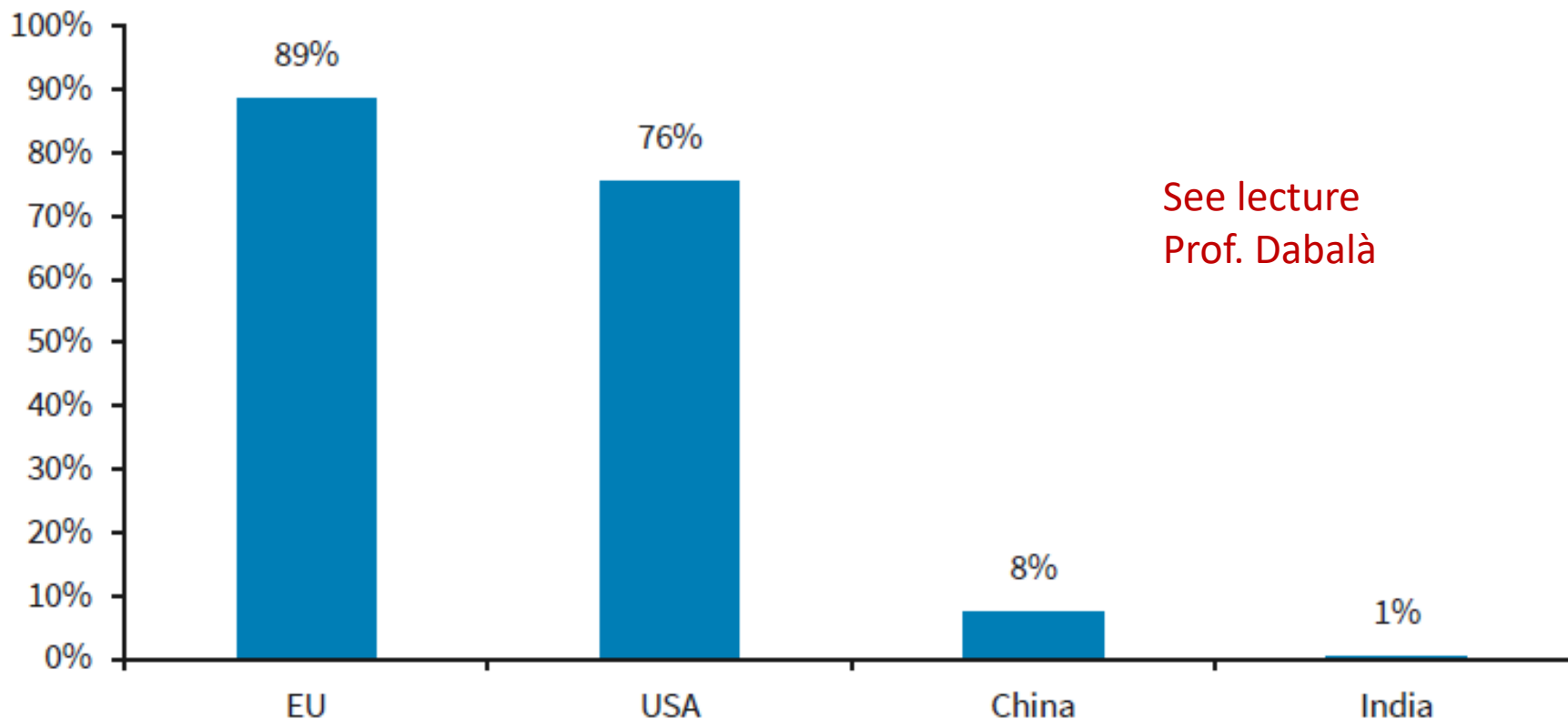


The cement production chain. Every step needs the **input of energy (red arrows) and water (blue arrows)** and results in the output of products (black arrows). Source of figure: Water Resources and Industry 19 (2018) 1–12

Construction and its impact

- Construction has the highest carbon and waste footprint
- Recovery rates for construction materials vary considerably by region, up to 80% in weight
- Roadbuilding, extremely materials intensive, is the main outlet, currently, for secondary materials
- Close to half steel production used for building/construction
- 1/3 of global GHG emissions is used in buildings for heating, hot water, cooking
- Large amount of waste in terms of volume/weight due to mineral waste (ca. 60%) from construction activity

Recovery rates for construction and demolition waste



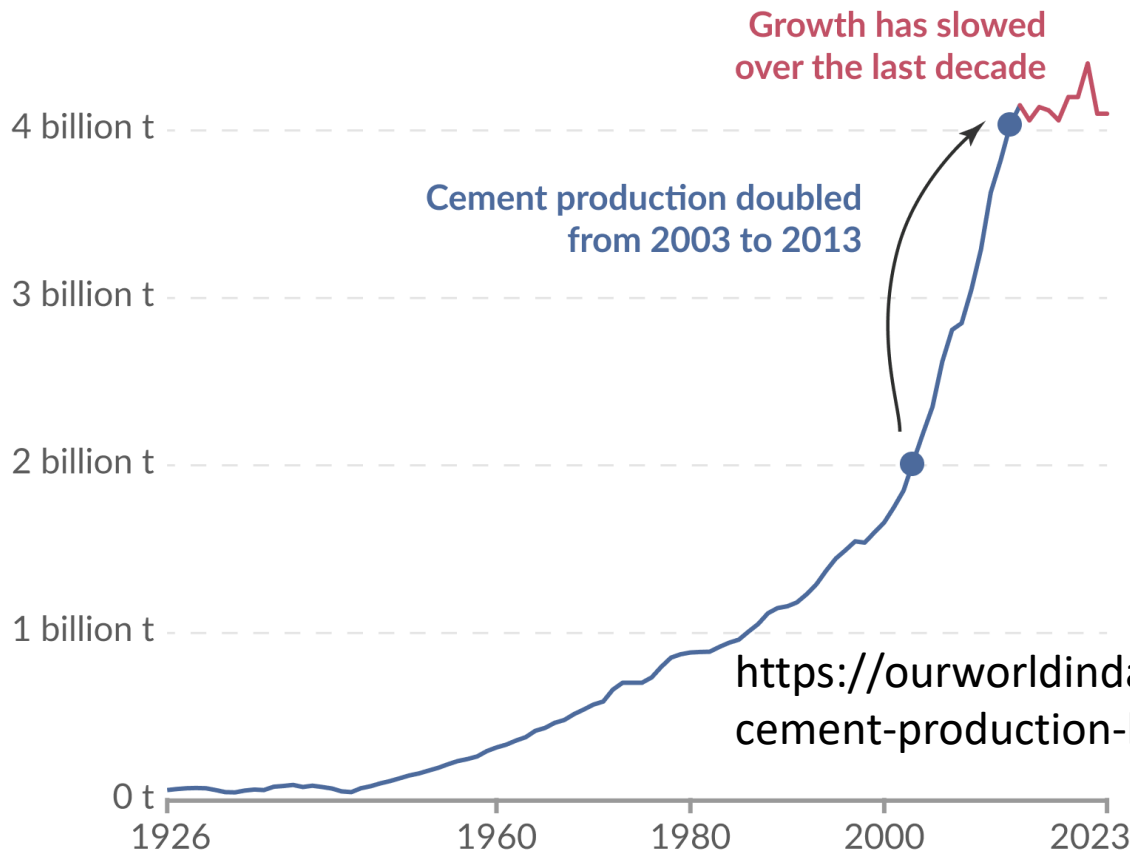
See lecture
Prof. Dabalà

Source of figure: Detritus Journal for Waste Resources & Residues and Barclays Research

Global cement production

Our World
in Data

The growth in global cement production has slowed over the last decade after rapid growth in the 1990s and early 2000s.



<https://ourworldindata.org/data-insights/global-cement-production-has-plateaued-over-the-last-decade>

Waste in construction and demolition: a case study

Next slides not discussed being part
of the lectures of prof. Dabalà
I leave them only as integrating data

Waste in construction and demolition: a case study

ENVIRONMENTAL ISSUES

RELATED TO REQUALIFICATION



WASTE PRODUCED

SOLID WASTE

WASTE WATERS



ReLOAD
RESEARCH LAB OF ARCHITECTURAL DESIGN

Slides Courtesy Prof. Lavagnolo

Waste in construction and demolition: a case study

TOTAL WASTE PRODUCTION

Waste category								
Country	Total waste	Chemical and medical wastes (subtotal)	Recyclable wastes (subtotal)	Equipment (subtotal)	Animal and vegetal wastes (subtotal)	Mixed ordinary wastes (subtotal)	Common sludges	Mineral and solidified wastes (subtotal)
European Union	2.494.698.677	54.963.427	234.537.464	16.159.084	88.665.555	286.165.065	18.491.293	1.795.716.789
Percentages	100%	2%	9%	1%	4%	11%	1%	72%

72% = 1.8 billion tons

TOT WASTE COMING FROM CONSTRUCTION ACTIVITIES (ton/y)

1.301.125.990 ton/year = 72%

Slides Courtesy Prof. Lavagnolo

Waste in construction and demolition: a case study

SOLID WASTE

COMING FROM:

- DEMOLITION ACTIVITIES
- CONSTRUCTION ACTIVITIES

CHARACTERIZED BY

UNCERTAINTIES



- THEIR PRODUCTION
- THEIR CHARACTERIZATION
- THE LEGISLATIVE FRAMEWORK

See lecture
Prof. Dabalà

Waste in construction and demolition: a case study

INDUSTRY OF CONSTRUCTIONS AND DEMOLITIONS: ONE OF THE LARGEST PRODUCERS OF SOLID WASTE GLOBALLY



INCREASING

- Building of new structures
- Renovation
- Rebuilding
- Repair
- Demolition works
- Infrastructure development projects

Waste in construction and demolition: a case study

CATEGORIES	TIME: 2014	ton/y
Chemical and medical wastes (subtotal)		830.007
Glass wastes		855.022
Paper and cardboard wastes		695.703
Rubber wastes		26.899
Plastic wastes		932.147
Wood wastes		8.729.866
Textile wastes		23.091
Waste containing PCB		18.960
Discarded vehicles		11.574
Batteries and accumulators wastes		48.234
Animal and vegetal wastes (subtotal, W091+W092+W093)		1.394.342
Mixed ordinary wastes (subtotal, W101+W102+W103)		7.253.920
Common sludges		149.258
Mineral and solidified wastes (subtotal)		818.304.355
Soils		442.417.938
Metallic wastes (W061+W062+W063)		19.434.674
TOT WASTE COMING FROM CONSTRUCTION ACTIVITIES		1.301.125.990

Waste in construction and demolition: a case study

WASTE FROM CONSTRUCTION ACTIVITY

CONSIDERING THAT THE TOTAL WASTE PRODUCTION IN EUROPE WAS ABOUT

2.500 million tons

AND THAT THE AMOUNT OF WASTE PRODUCED FROM CONSTRUCTION
ACTIVITIES EXCLUDING THE SOIL (CAT. 17 05 04)

859 million tons



IT RESULTS THAT THE WASTE COMING FROM CONSTRUCTION (AND DEMOLITION)
ACTIVITIES REPRESENT THE **35%** OF THE TOTAL WASTE PRODUCTION IN EUROPE

Waste in construction and demolition: a case study

LEGISLATIVE FRAMEWORK

EXTREMELY DIFFICULT TO UNDERSTAND DUE TO THE FACT THAT IT CHANGES VERY RAPIDLY

THERE IS ALSO A LACK OF HOMOGENEITY
IN TERMS OF STATISTICS, DATA RECORDED AND DEFINITIONS

SUBJECT IS HARD TO BE STUDIED AND DATA ARE DIFFICULT TO BE COMPARED

SINCE C&DW PRODUCTION REPRESENTS MORE THAN 35-40% OF TOTAL WASTE IN EUROPE, IT IS ALWAYS MORE AN IMPORTANT TOPIC TO ENSURE A SUSTAINABLE DEVELOPMENT