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Sustainable Pavements and Road Materials

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Cold recycling for road construction and maintenance

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Outline

- General context
- Cold recycling: Materials, Techniques and Mixtures
- Curing process
- Findings from laboratory testing on lab-produced mixtures
- Findings from laboratory testing on plant-produced mixtures
- Findings from pavement testing on plant-produced mixtures
- Conclusions

The Sustainable Development Goals (United Nations, 2015)

INDUSTRY, INNOVATION AND INFRASTRUCTURE

- **Investment in infrastructure and innovation are crucial drivers of economic growth and development**. With over half the world population now living in cities, mass transport and renewable energy are becoming ever more important, as are the growth of new industries and information and communication technologies.

- Technological progress is also key to finding lasting **solutions to both economic and environmental challenges**, such as providing new jobs and promoting energy efficiency. **Promoting sustainable industries, and investing in scientific research and innovation, are all important ways to facilitate sustainable development**.

RESPONSIBLE CONSUMPTION AND PRODUCTION

- **Achieving economic growth and sustainable development requires that we urgently reduce our ecological footprint by changing the way we produce and consume goods and resources**. Agriculture is the biggest user of water worldwide, and irrigation now claims close to 70 percent of all freshwater for human use.

- **The efficient management of our shared natural resources, and the way we dispose of toxic waste and pollutants, are important targets to achieve this goal**. **Encouraging industries, businesses and consumers to recycle and reduce waste** is equally important, as is supporting developing countries to move towards more sustainable patterns of consumption by 2030.

- A large share of the world population is still consuming far too little to meet even their basic needs. Halving the per capita of global food waste at the retailer and consumer levels is also important for creating more efficient production and supply chains. This can help with food security, and shift us towards a more resource efficient economy.

CLIMATE ACTION

- There is no country that is not experiencing the drastic effects of climate change. Greenhouse gas emissions are more than 50 percent higher than in 1990. **Global warming is causing long-lasting changes to our climate system**, which threatens irreversible consequences if we do not act.
- The annual average economic losses from climate-related disasters are in the hundreds of billions of dollars. This is not to mention **the human impact of geo-physical disasters, which are 91 percent climate-related**, and which between 1998 and 2017 killed 1.3 million people and left 4.4 billion injured. The goal aims to mobilize US$100 billion annually by 2020 to address the needs of developing countries to both adapt to climate change and invest in low-carbon development.
- Supporting vulnerable regions will directly contribute not only to Goal 13 but also to the other SDGs. These actions must also go hand in hand with **efforts to integrate disaster risk measures, sustainable natural resource management, and human security into national development strategies**. **It is still possible, with strong political will, increased investment, and using existing technology, to limit the increase in global mean temperature** to two degrees Celsius above pre-industrial levels, aiming at 1.5°C, but **this requires urgent and ambitious collective action**.

European Green Deal (European commission, 2019)

- The European Green Deal is a new growth strategy to transform the EU into a fair and prosperous society, with a modern, resource-efficient and competitive economy
- where there are **no net emissions** of greenhouse gases in 2050 and
- where **economic growth is decoupled from resource use**

Key words and concepts

Assumption:

- Infrastructure and innovation are crucial drivers of economic growth and development.

Needs:

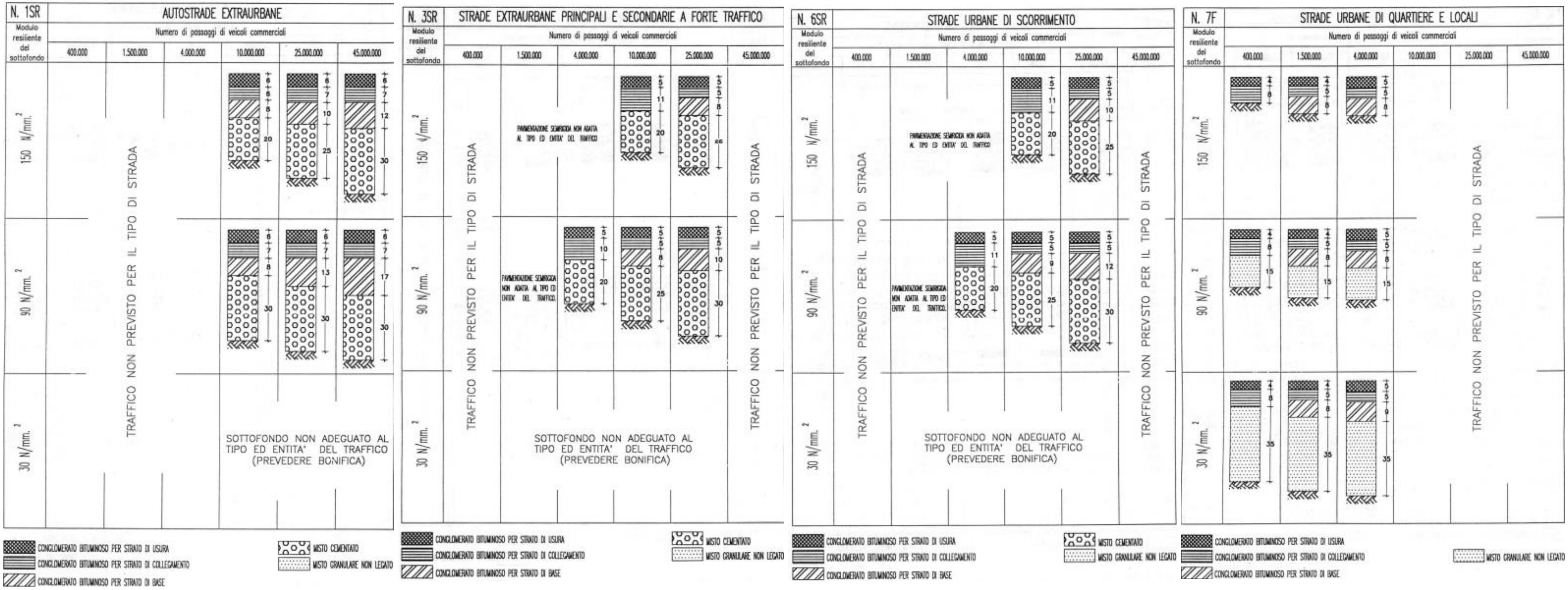
- Solutions to both economic and environmental challenges.

Actions:

- Change the way we produce and consume goods and resources.
- Encourage recycling and reducing waste by an efficient management of natural resources and disposal of waste.
- Develop strategies, also using existing technology, to limit the increase in global mean temperature.

What can we do?

Traditional Italian road structures



CNR, BU 178, Catalogo delle pavimentazioni, 1995.

How can eco-sustainable mixtures be produced?

Objectives

- Preservation of natural resources
- Recycling of materials
- Saving of energy
- Reduction of emissions
- Elimination of transportation

Actions

- Recycled aggregates in place of natural ones
- Cold production in place of hot production
- In situ production

From traditional to eco-sustainable methods, easily…

- Natural aggregates are obtained from **quarries by blasting or from riverbeds by dredging**.
- The production of natural aggregates consists of **removal of rock**, sizing and separating different-sized particles using crushers and screens.
- **Heating** reduces bitumen viscosity.

- Recycled aggregate are obtained from the **processing of inorganic material**.
- The production of recycled aggregates consists of **milling or demolition of constructions**, sizing and separating different-sized particles using crushers and screens.
- **Foam or emulsion** reduces bitumen viscosity.

Terminology and acronyms

- **Cold recycling** (not, or just limited, heating of constituent materials):
  - **Cold Central Plant Recycling** (CCPR)
  - **Cold In-place Recycling** (CIR): partial-depth recycling
  - **Full Depth Reclamation** (FDR): full-depth recycling

Terminology and acronyms

- **Recycled aggregate**: aggregate resulting from the processing of inorganic material previously used in construction action (EN13242).
- Constituents of coarse recycled aggregate (EN 933-11):
  - R_c: concrete, concrete products, mortar, concrete masonry units;
  - R_u: unbound aggregate, natural stone, hydraulically bound aggregate;
  - R_a: bituminous materials;
  - R_b: clay masonry units (i.e. bricks and tiles), calcium silicate masonry units, aerated non-floating concrete;
  - R_g: glass;
  - X: Other materials such as cohesive (i.e. clay and soil), miscellaneous: metals (ferrous and non-ferrous), non-floating wood, plastic and rubber, gypsum plaster;
  - V_{FL}: floating particles.

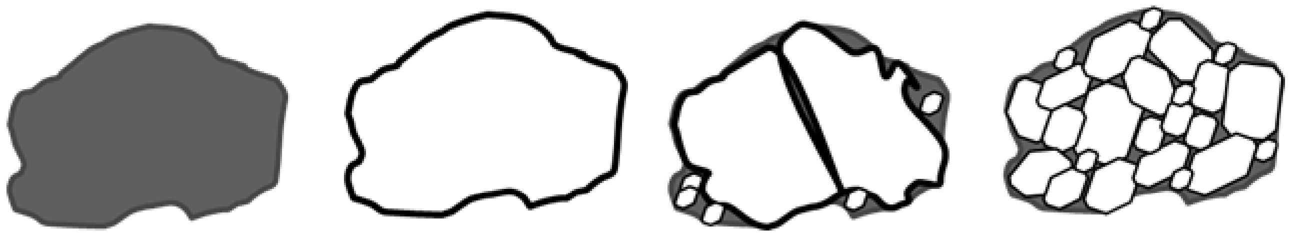
Recycled aggregates

Recycled aggregates

Recycled aggregates

Terminology and acronyms

- **Reclaimed asphalt** (RA): Asphalt reclaimed by milling of asphalt road layers, by crushing of slabs ripped up from asphalt pavements or lumps from asphalt slabs and asphalt from reject and surplus production (EN 13108-8).
- A single particle of RA may include several granular elements and the old bitumen keeps them bound together. The composition cannot be realized from outside (single coated aggregate, two major aggregates with some mastic, conglomerate of small aggregate particles and mastic).
- A single particle of RA can contain intergranular voids and bitumen (which has a lower density than aggregates) causing lower particle density than virgin aggregates.
- The old bitumen seals the superficial aggregate porosity determining a low water absorption.
- The old bitumen can be stiff and aged.



STAR 237-SIB, Chapter 6, RILEM book series, 2018.

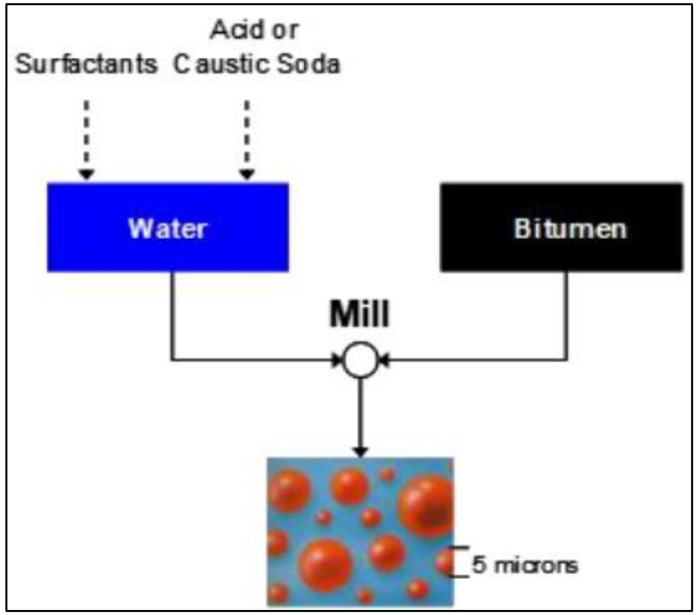
Reclaimed asphalt

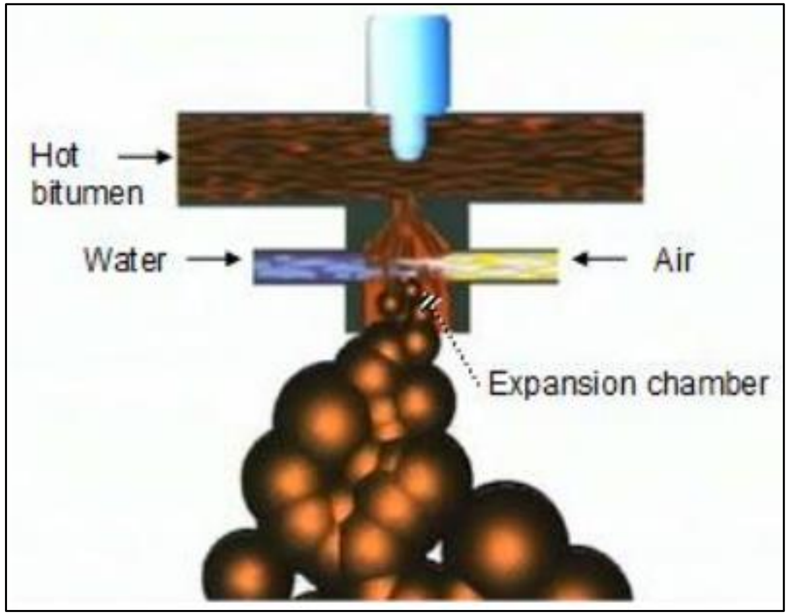
Reclaimed asphalt

Reclaimed asphalt

Terminology and acronyms

- **Bituminous emulsion**: suspension of tiny bitumen droplets in water. Emulsions are made by mixing hot bitumen with water containing emulsifying agents and applying mechanical energy sufficient to break up the bitumen into droplets. The bitumen is held in suspension by an emulsifier (surface active compound) that adheres to each individual droplet, providing it with a charge.
- **Foam bitumen**: thin films of bitumen surrounding the water vapour (steam) in the form of mass of bubbles (foam). The foam bitumen is produced by injecting a small amount of water into hot (> 160°C) bitumen. The water instantly changes state from liquid to vapour, expanding some 1500 times in volume and generating an unstable foam which collapses in less than a minute.





Southern African Bitumen Association, 2021.

Bituminous emulsion versus foamed bitumen

- Mixtures using bituminous emulsion or foamed bitumen show similar performance
- Cement enhances stiffness and strength of the mixture and accelerates the curing process

- Bituminous emulsion covers both fine and coarse aggregates and includes cement (continuous-like binding)
- Bituminous emulsion contains emulsifier which promotes chemical bond between aggregate and bitumen
- SBS-modified bitumen or latex can be used
- Emulsion is generally used at 60°C (or less)
- Emulsion introduces water into the mixture
- Mixture using emulsion can show (also) an asphalt-like behaviour
- Cement regulates the emulsion breaking

- Foamed bitumen distributes to fine particles producing spots of bituminous mastic (non-continuous binding)
- Anti-stripping, foaming and anti-foaming agents can be used depending on bitumen source and production process
- Foam is produced using paving grade bitumen
- Bitumen is generally used at 160°C (or more)
- Foam does not add water in the mixture
- Mixture using foamed bitumen show a granular-like behaviour
- Cement facilitates the foamed bitumen dispersion

Cold Central Plant Recycling (CCPR)

- **RA is processed by a crushing and screening system providing different size fractions**.
- The variability of the RA is **under control**, improving **the quality and the stability** of the overall gradation of the Cold Recycled Mixture (CRM).

Milled RA and processed RA

Cold Central Plant Recycling (CCPR)

- The in-plant production is often performed by means of **mobile facilities** that can be installed near or at the job site or **mix plant for cement treated mixtures can be adapted** by adding an inlet and a storage system for the bitumen emulsion.
- The equipment does **not need heating, dust collection system** and aggregates sieving.
- An **accurate proportioning** of the input materials, as well as a thorough preliminary quality control, **increase the confidence** to obtain mixtures that meet the requirements.

Cold Central Plant Recycling (CCPR)

- After hauling CRM to the jobsite, **pavers are used to laydown** the CRM layer and control its thickness and slope. Layer **thickness** generally changes **between 10 and 25 cm**.
- The compaction is carried out by means of **vibrating smooth drums and pneumatic tire rollers**. The required level of compaction can be achieved more easily by the selection of an appropriate aggregate gradation, water dosage and layer thickness.
- CCPR offer a **high confidence on the mixtures stability and performance** can be obtained.

Cold In-place Recycling (CIR) and Full Depth Reclamation (FDR)

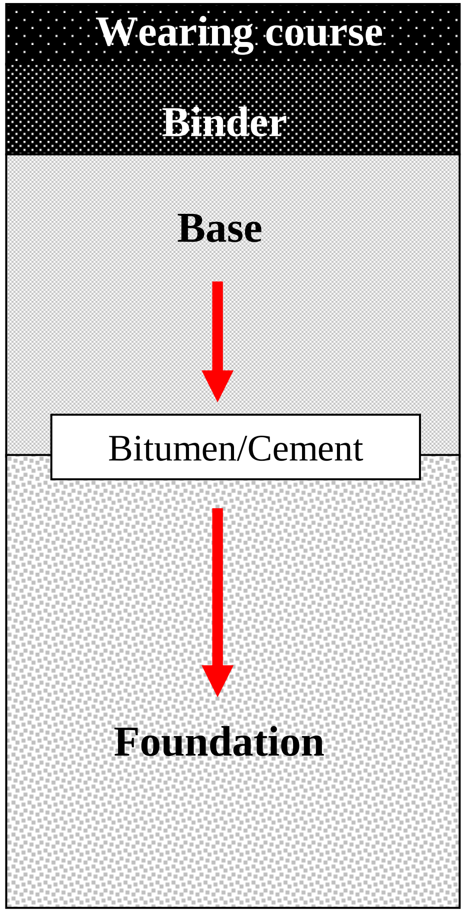
- CIR involves **AC layers** whereas FDR involves both **AC and underlying layers**.
- Virgin aggregates can be added on-site to meet gradation requirements.
- Recyclers **operate in a single or more passes depending on the required fineness and homogeneity level** to be achieved.
- **Milling, mixing and compaction are simultaneously performed on-site** by using a "recycling train".
- a **volumetric container for spreading cement**, **a recycler coupled to a tank truck for the addition of water**, **a tank truck for the bituminous binder** (emulsion or bitumen for foaming), **a vibrating smooth drum roller**, **a pneumatic tire roller** and **a grader** for shaping and levelling.

Cold In-place Recycling (CIR) and Full Depth Reclamation (FDR)

- CIR and FDR **do not require material transportation** (or just limited amount considering water, binders, and aggregates to correct the gradation of the in-situ material to be recycled).
- The use of CIR and FDR lead to **significant economic and environmental advantages** because of the elimination of the haulage. However, in this process **material control is more difficult**.
- Layers **thickness** generally ranges **between 20 and 35 cm**.

Foundation course versus base or binder course

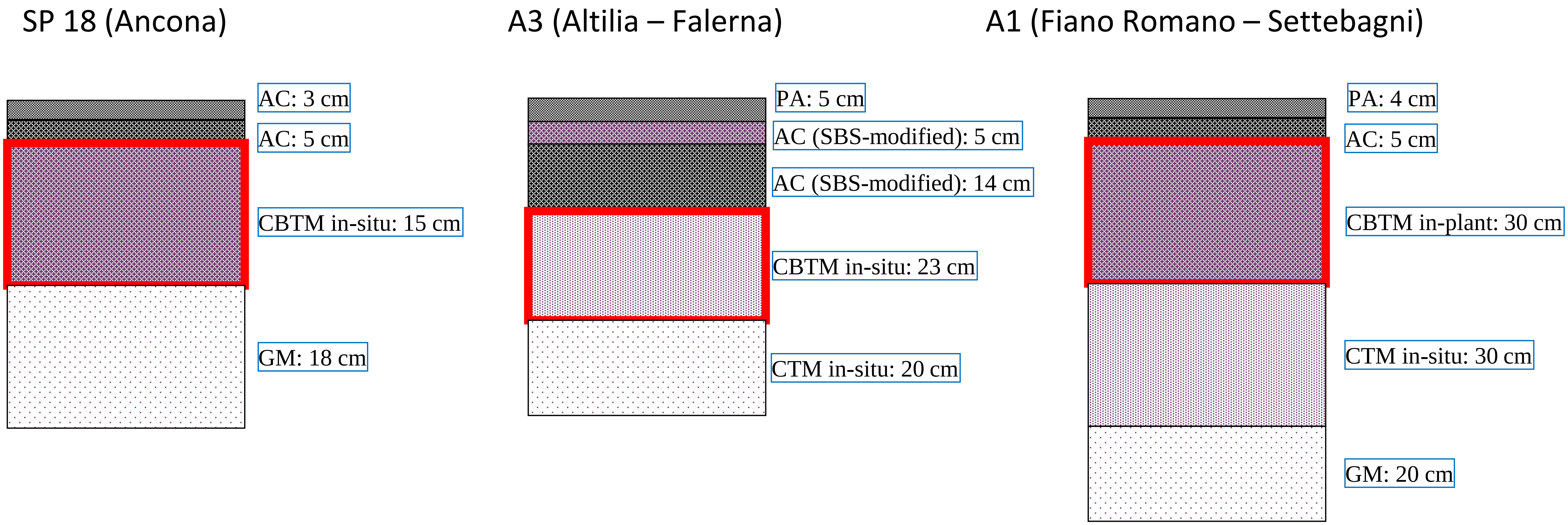
- Base or binder courses:
  - Bitumen/cement > 1
  - **In-plant production** (stability and homogeneity)
  - **Bitumen (residual bitumen from modified emulsion): 2.5 - 3.5%** (about 4.0 - 6.0% of modified emulsion)
  - Cement: 1.5 - 2.5%
  - **(selected) RA: ≥ 80%**
  - Mineral aggregate: ≤ 20% and **Mineral filler: 2 - 4%**



- Foundation or subbase courses:
  - **In-situ production** (thick layers)
  - **Bitumen (foam bitumen or residual bitumen from emulsion): 1.5 - 3.0%**
  - **Cement and/or lime**: 1.5 ÷ 2.5%
  - **RA and recycled materials: ≥ 80%**
  - Mineral aggregate: ≤ 20%

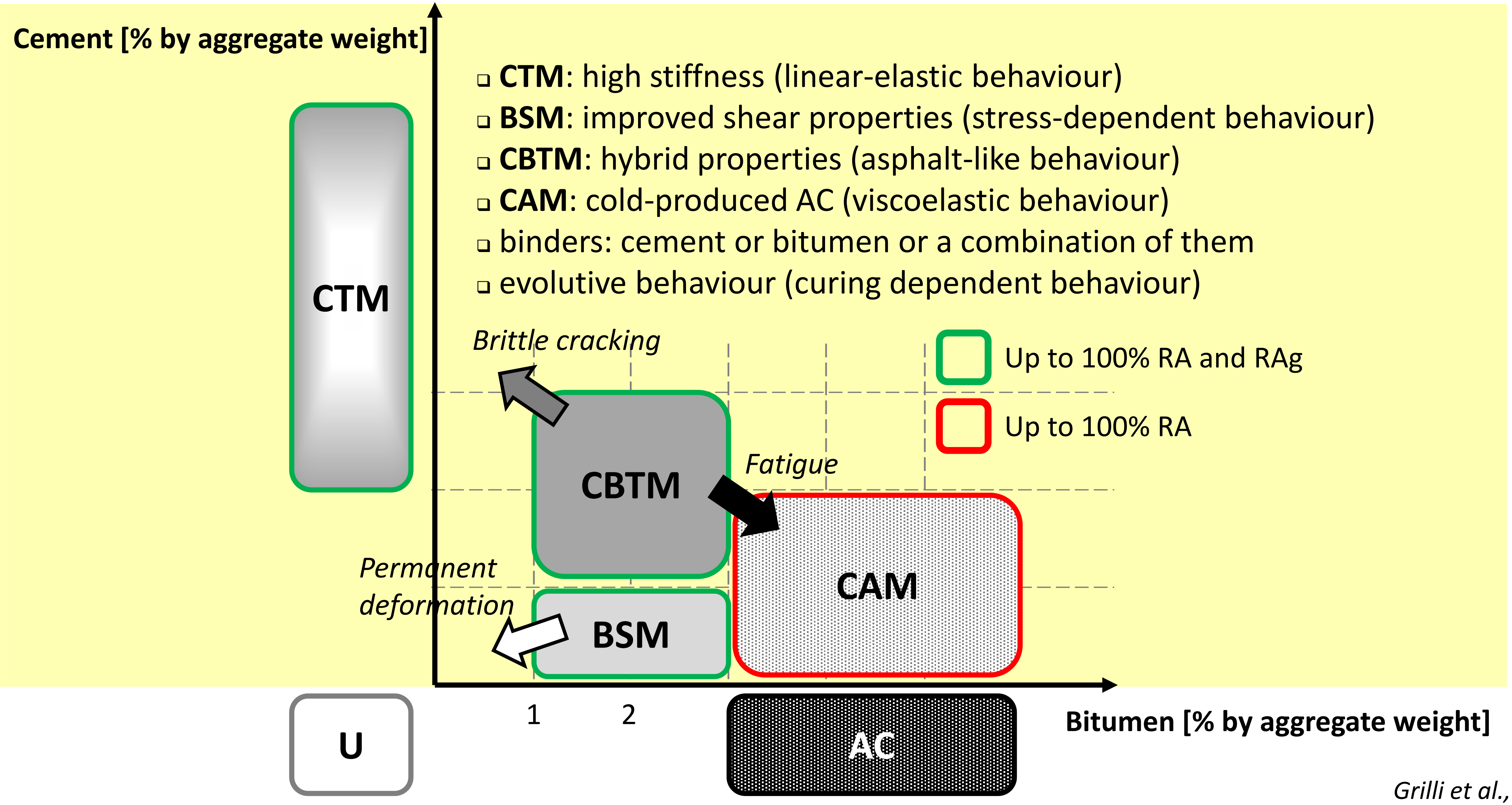
Central plant versus in situ

- Availability of materials
- Performance, homogeneity and stability (position)
- Superficial texture



Conceptual composition of paving mixtures

- **CTM**: high stiffness (linear-elastic behaviour)
- **BSM**: improved shear properties (stress-dependent behaviour)
- **CBTM**: hybrid properties (asphalt-like behaviour)
- **CAM**: cold-produced AC (viscoelastic behaviour)
- binders: cement or bitumen or a combination of them
- evolutive behaviour (curing dependent behaviour)



Grilli et al., 2012.

Curing process

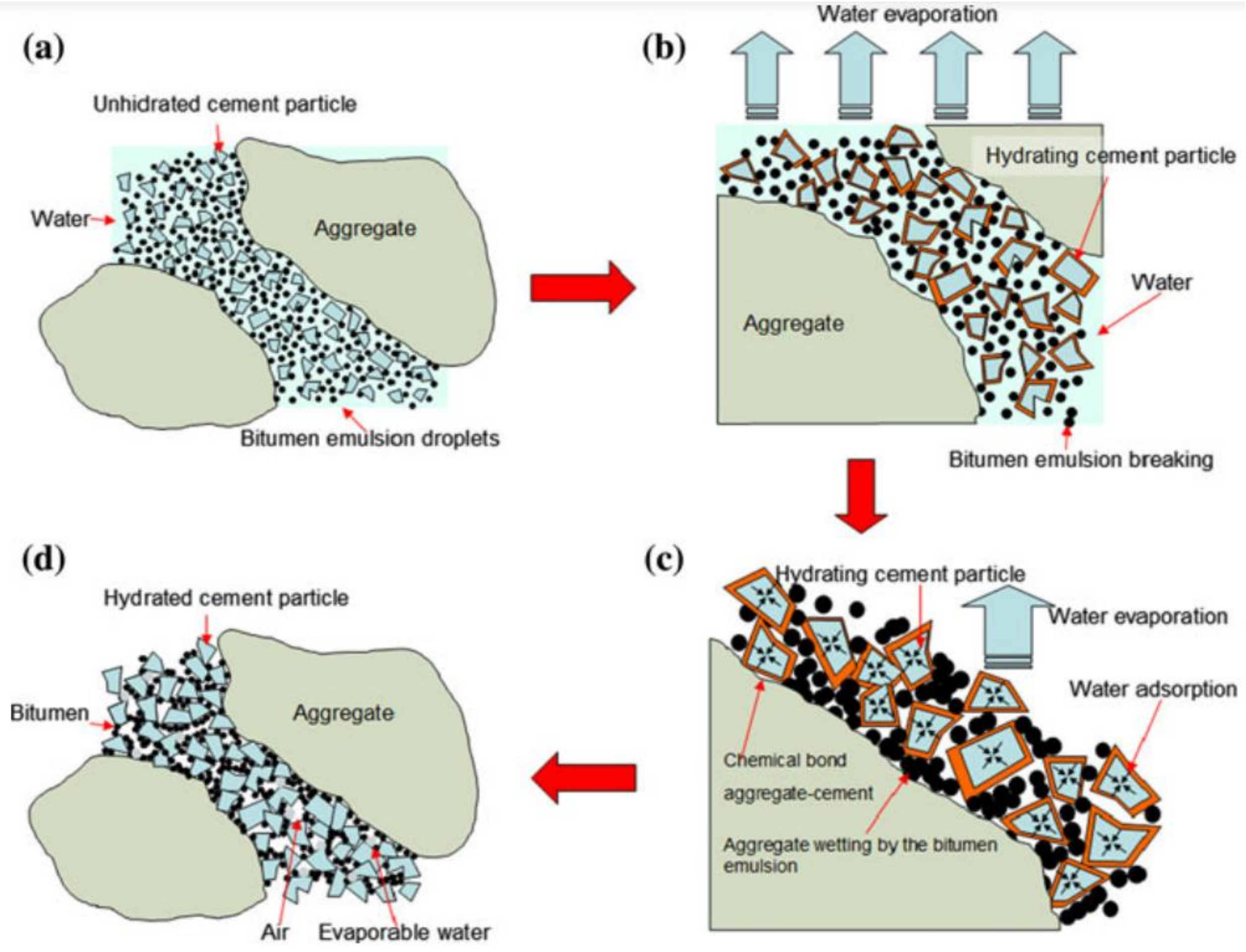
A distinctive feature of CRM is the requirement for a certain curing period to develop the mechanical properties (strength and stiffness). The development of the curing process is influenced by:

- **Material-related factors** (dosage of bituminous and cementitious binders, initial water content);
- **Construction-related factors** (drainage conditions, layer thickness, sealing, compaction level);
- **Environmental-related factors** (temperature, humidity, wind, rainfall).

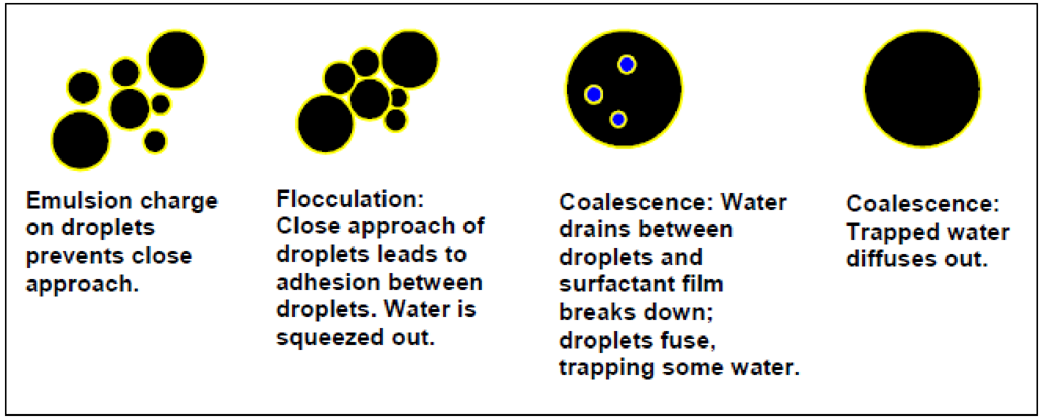
The factors that influence field curing are **extremely variable and difficult to standardize and reproduce**, therefore their simulation in the laboratory for predicting the possible evolution of material properties in the field is particularly challenging.

- The curing process results from different mechanisms:
  - **moisture loss**;
  - **emulsion breaking**;
  - **hydration of cementitious compounds**.

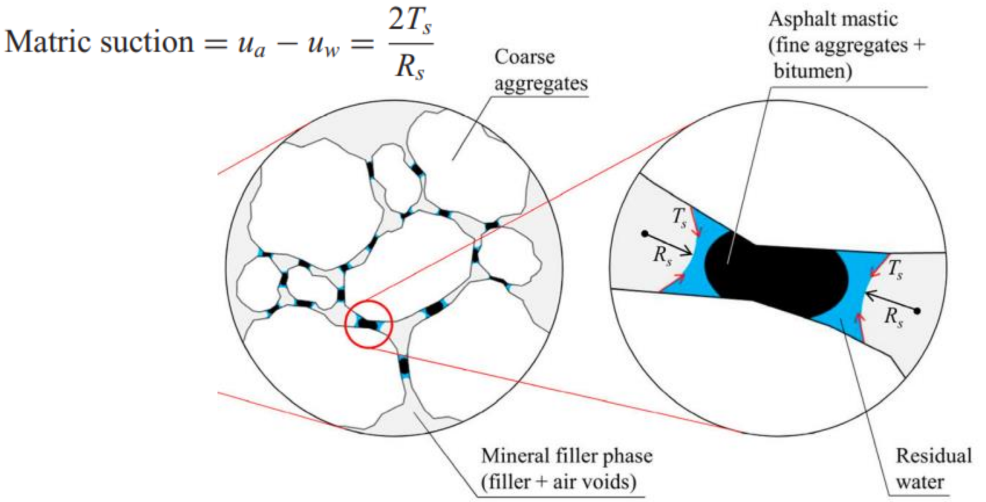
Emulsion breaking, moisture loss and cement hydration



Garcia et al., 2012.

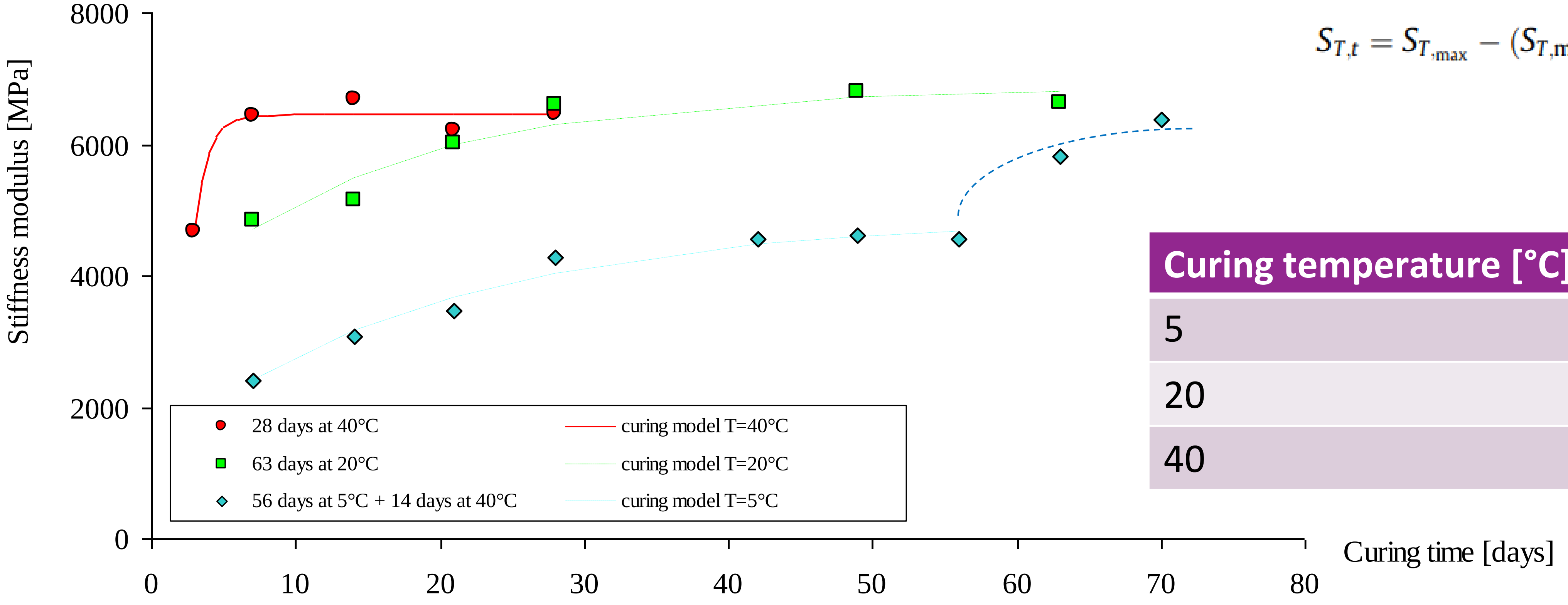


James et al., 2006.



Kuchiishi et al., 2019.

Curing process: Effect of temperature on stiffness

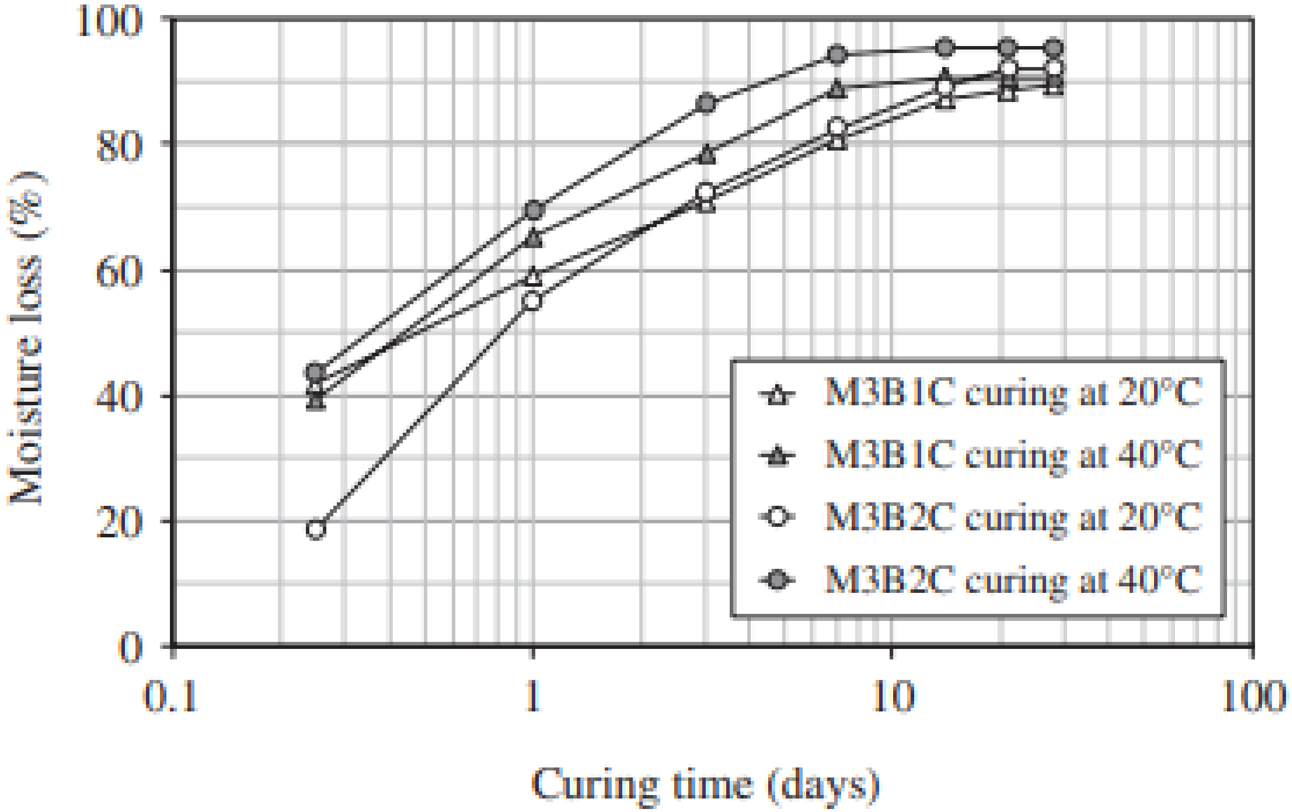


$$S_{T,t} = S_{T,\max} - (S_{T,\max} - S_{T,i}) \cdot e^{-b \cdot (t - t_i)}$$

Curing temperature [°C]	b
5	0.052
20	0.065
40	1.121

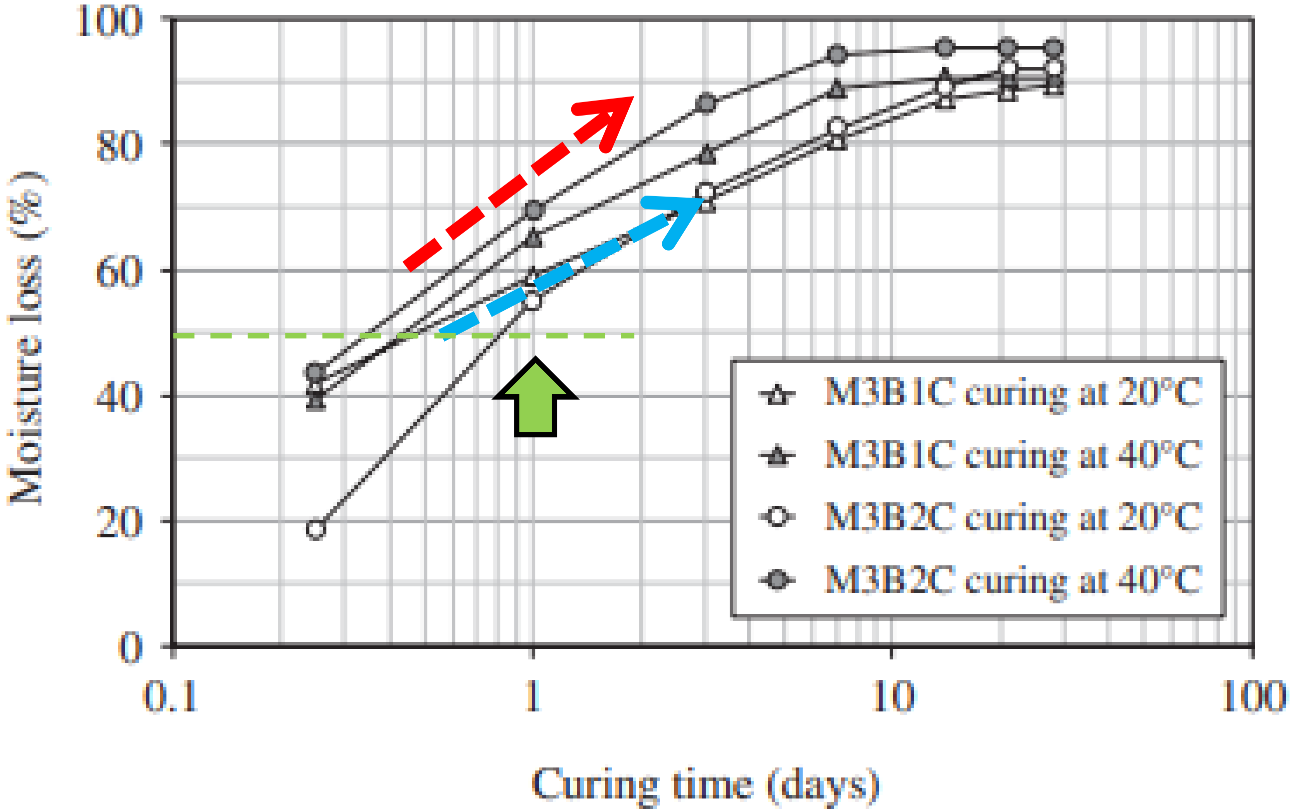
- Stiffness increases as curing time increases
- The higher the curing temperature, the higher the stiffness rate
- Stiffness increases again when rising the curing temperature from 5 to 40°C

Curing process: Effect of temperature and cement dosage on moisture loss



- High moisture loss just after one day and higher rate of evaporation at 40°C
- At 40°C, W_{EQ} was reached after 7 days, while at 20°C W_{EQ} was reached after about 14 days
- M3B2C retained about 7% of the initial water content (W_{EQ} = 0.35%)
- M3B1C retained about 10% of the initial water content (W_{EQ} = 0.50%)

Curing process: Effect of temperature and cement dosage on moisture loss



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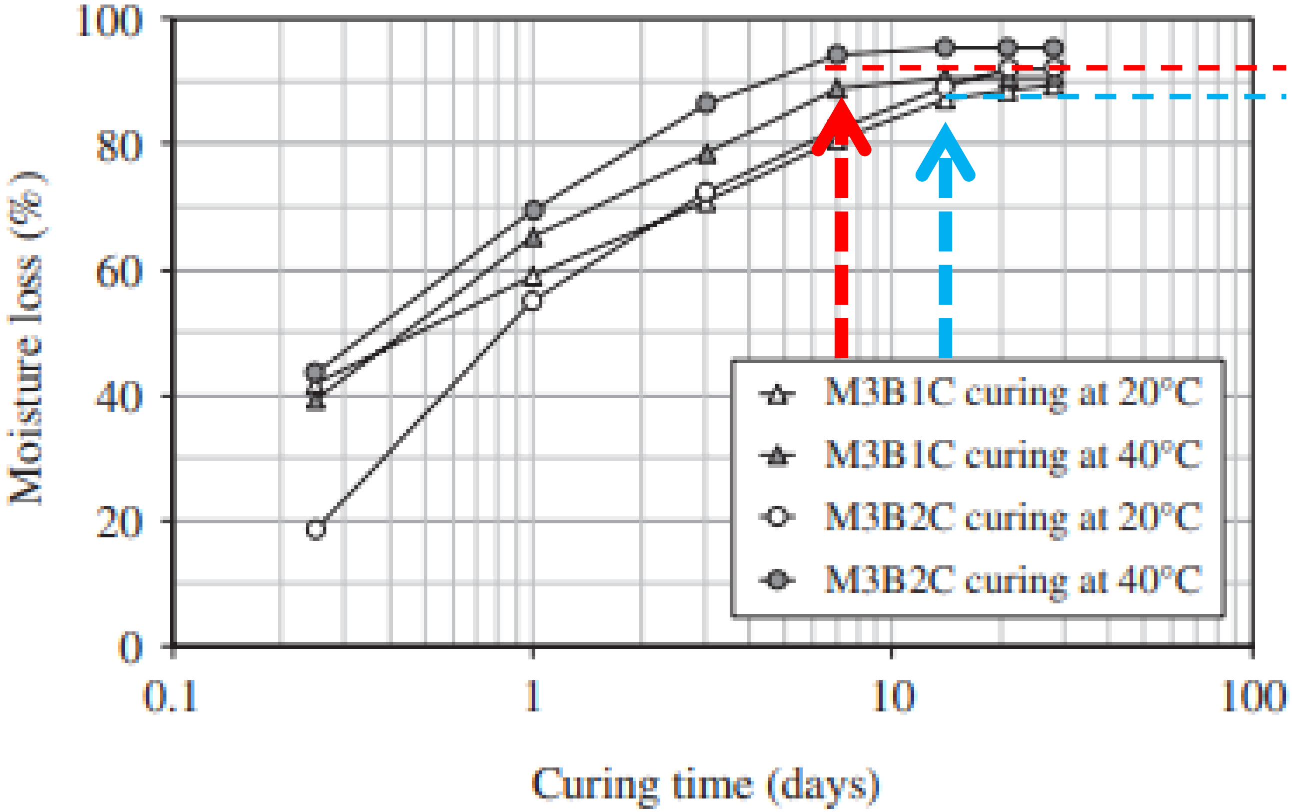

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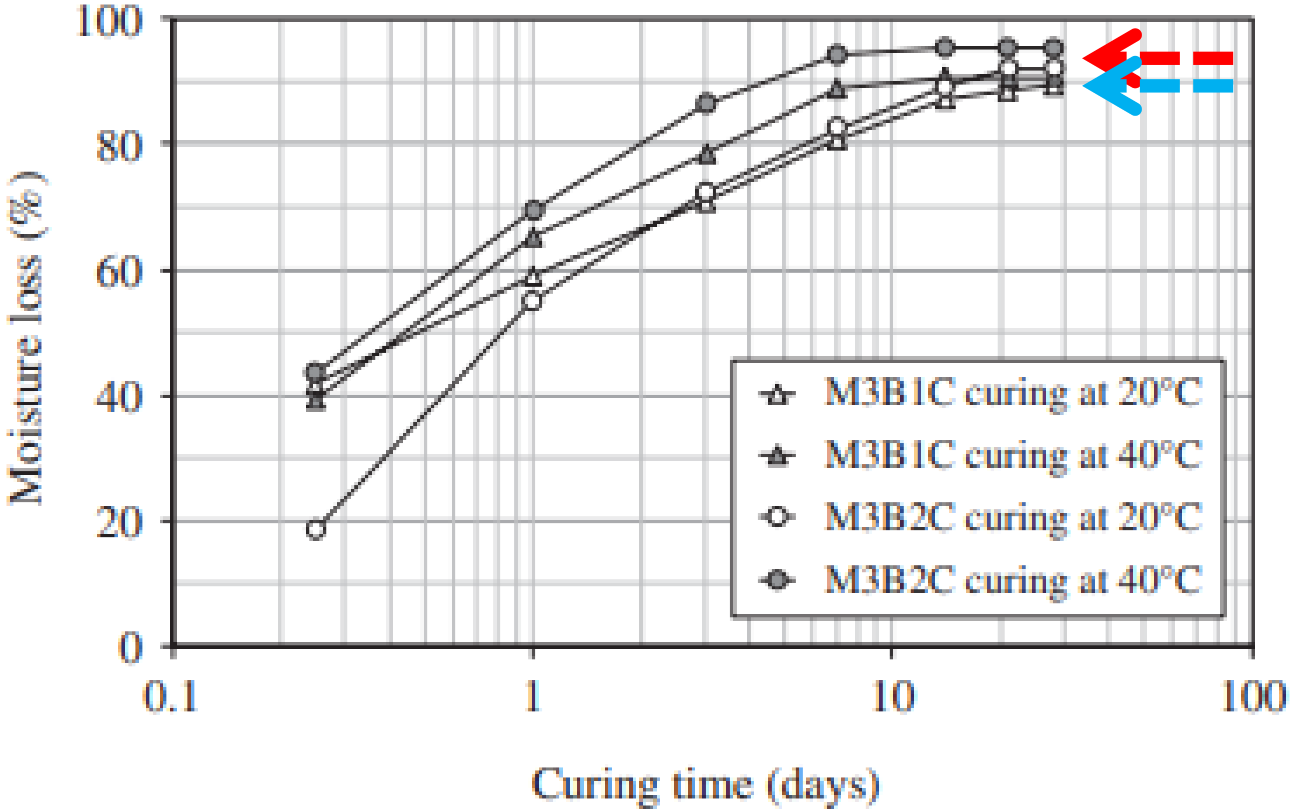

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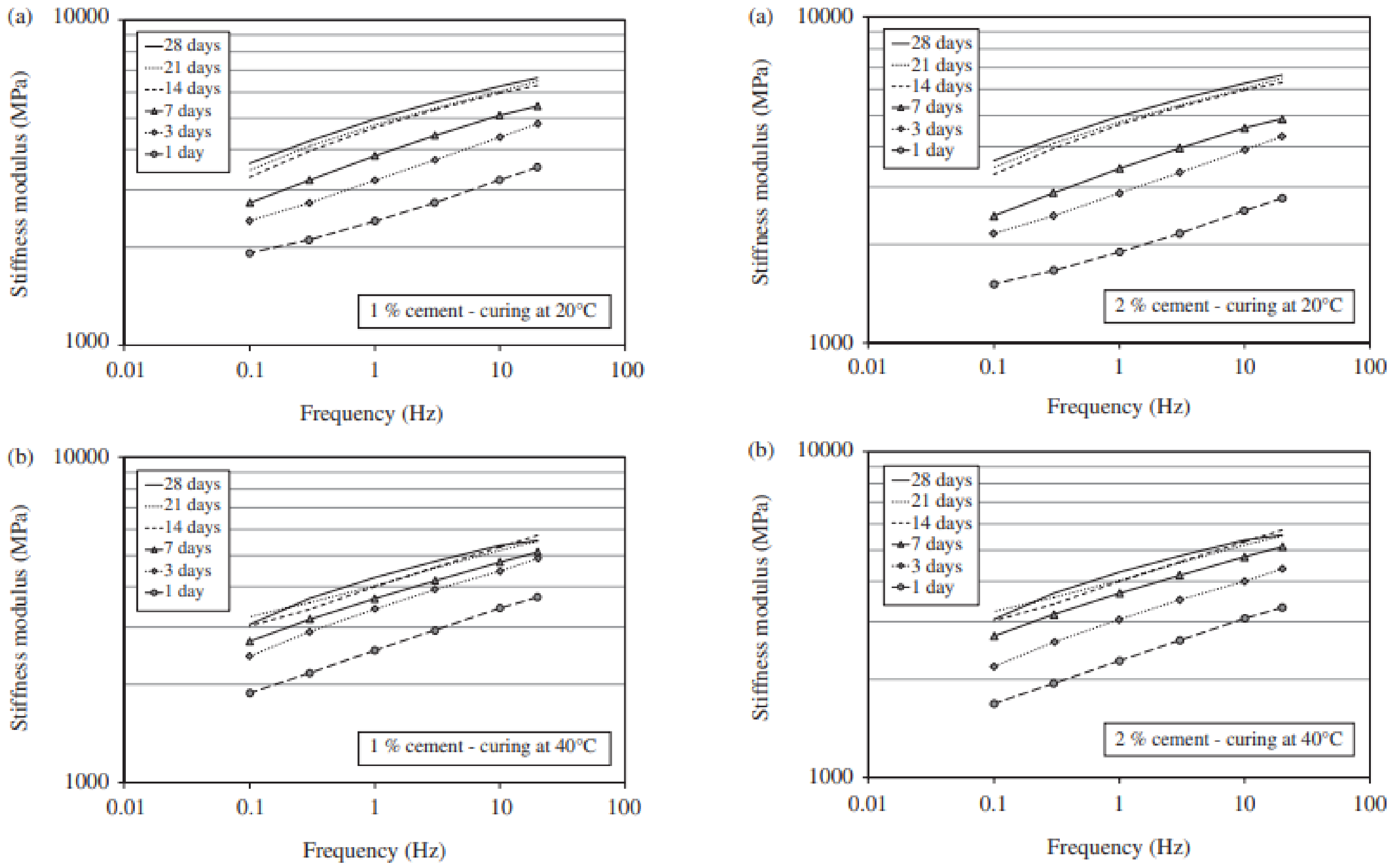
Curing process: Effect of temperature and cement dosage on moisture loss

- W_{EQ} contains the water required by the cement hydration process W_{HY} that is not available for evaporation:
  - $W_{EQ} = 0.50\%$ for M3B1C
  - $W_{EQ} = 0.35\%$ for M3B2C

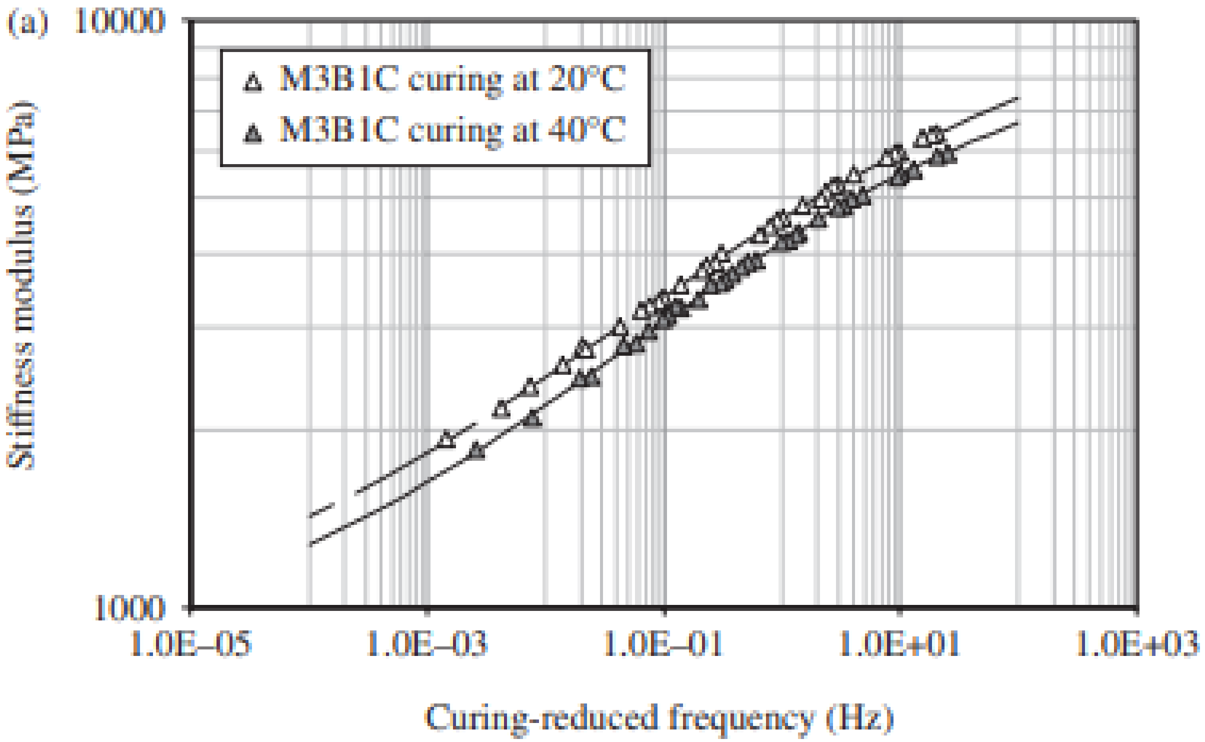
- $W_{HY} = (0.23 + 0.19) \times a \times k \times c_0$
  - where *a* is the degree of hydration of the cement paste, c_0 is the cement dosage relative to the dry aggregate weight and *k* is the fraction of Portland cement clinker in the cement.
- Considering a degree of hydration $a = 0.9$:
  - $W_{HY} = 0.27\%$ for M3B1C
  - $W_{HY} = 0.54\%$ for M3B2C
- M3B1C still contains a residual fraction of water ($W_{EQ} - W_{HY} = 0.23\%$). Probably in impermeable voids.
- M3B2C shows $W_{EQ} < W_{HY}$. Assuming that all the equilibrium water content was employed in the hydration process ($W_{HY} = W_{EQ}$), the degree of hydration is $a = 0.54$, indicating that for the M3B2C mixture **moisture loss by evaporation stopped the hydration process** at about one-half of its potential.

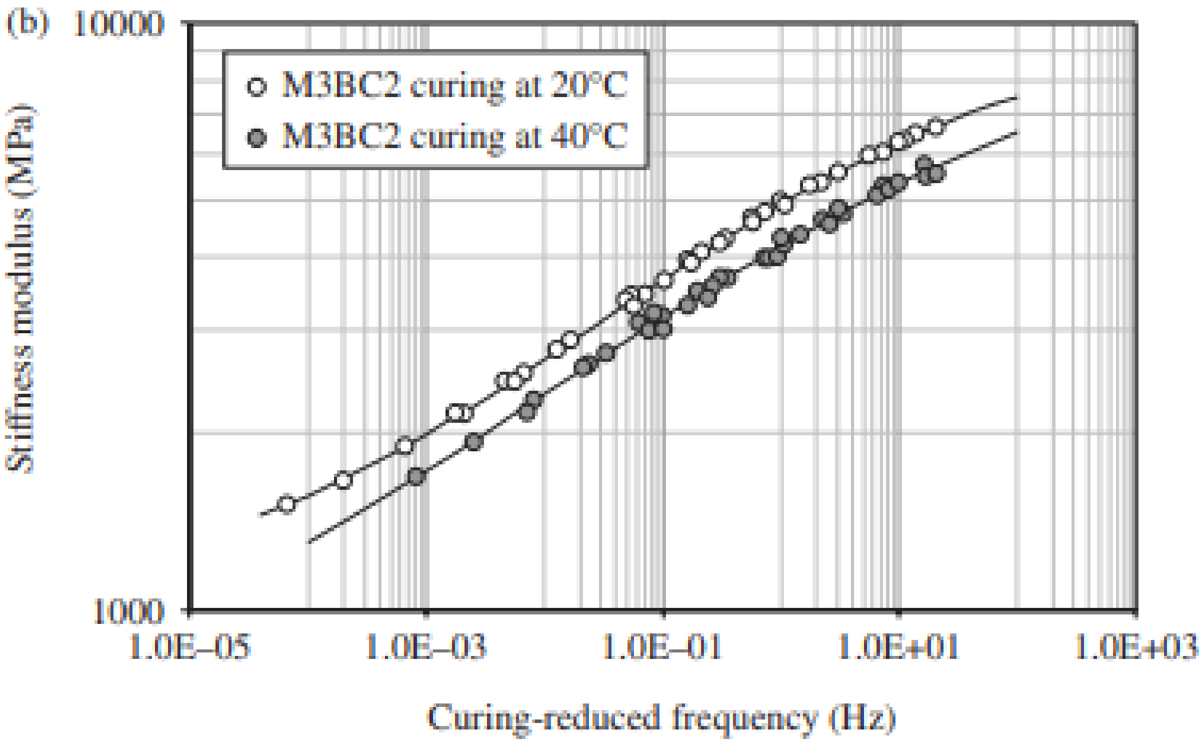
Curing process: Effect of temperature and cement dosage on stiffness



- Stiffness increases as test frequency increases, at both curing temperatures, at any curing time
- Beyond 14 days the distance between iso-curing lines tends to vanish

Curing process: iso-curing master curve





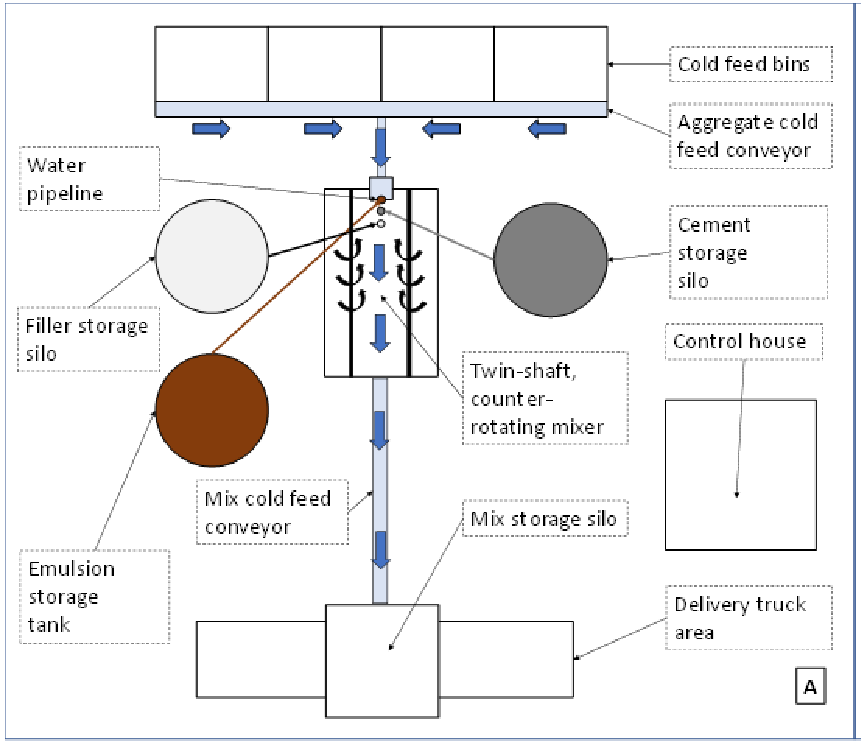
- Curing master curves at 20°C at reference curing time $t_{c,R}$ = 28 days
- Lower stiffness is obtained at 28-day curing when raising the curing temperature from 20°C to 40°C

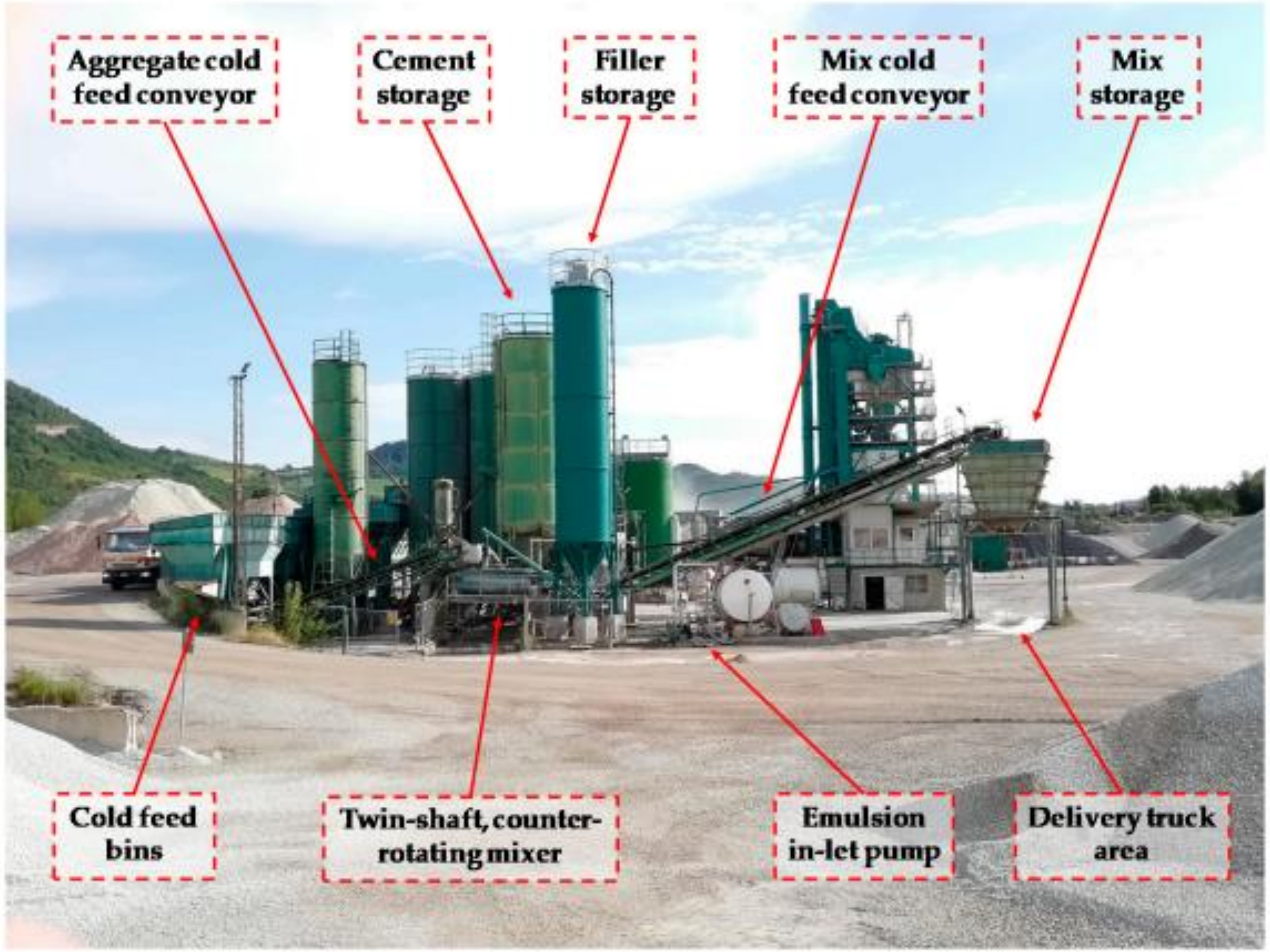
Curing process phases

- First phase: environmental conditions should facilitate moisture loss by evaporation to achieve curing of the bituminous binder (low relative humidity) leaving enough water for cement hydration.
- Second phase: residual water and non-evaporable water present in the mixture should allow to continue the hydration of the cement.

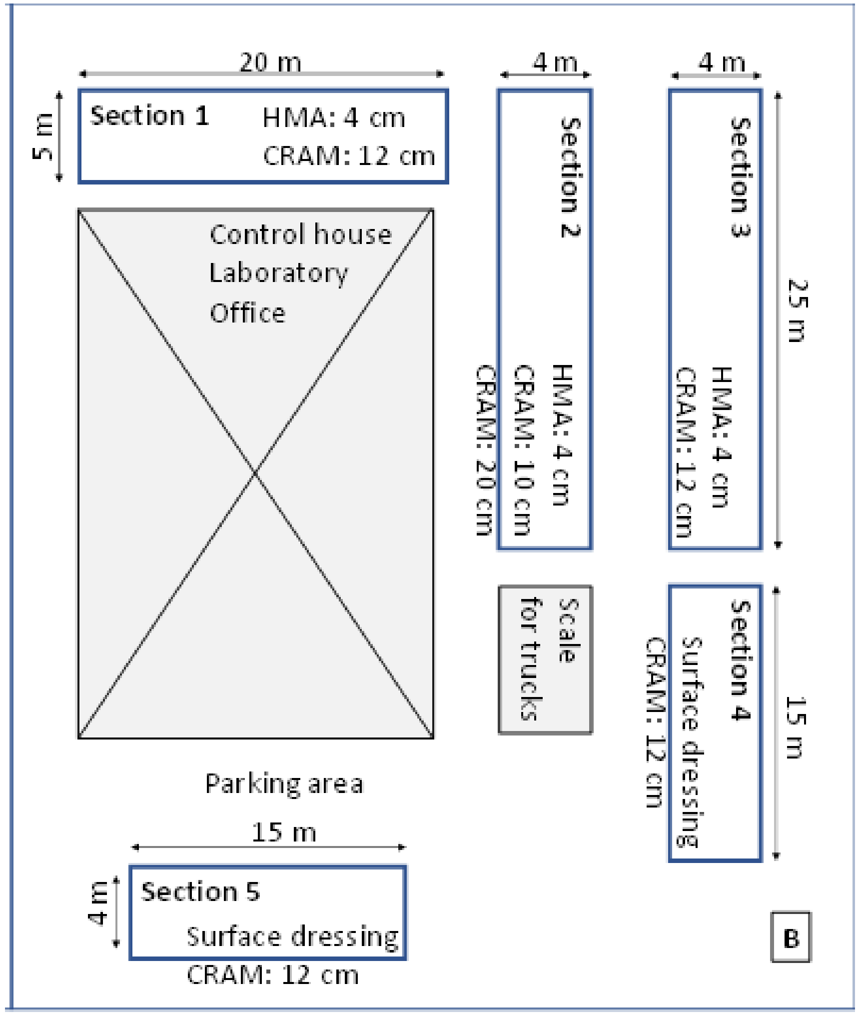
CRM using modified emulsion produced in a mix plant

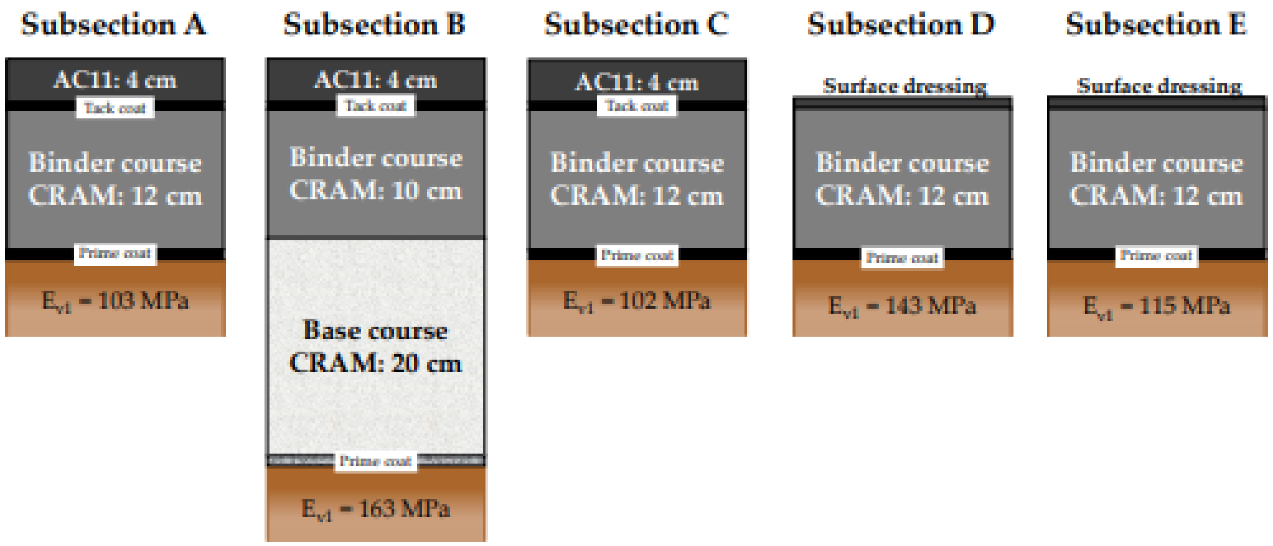
- Mixing plant production: 200 t/h
- The emulsion temperature: 55 °C





Trial sections

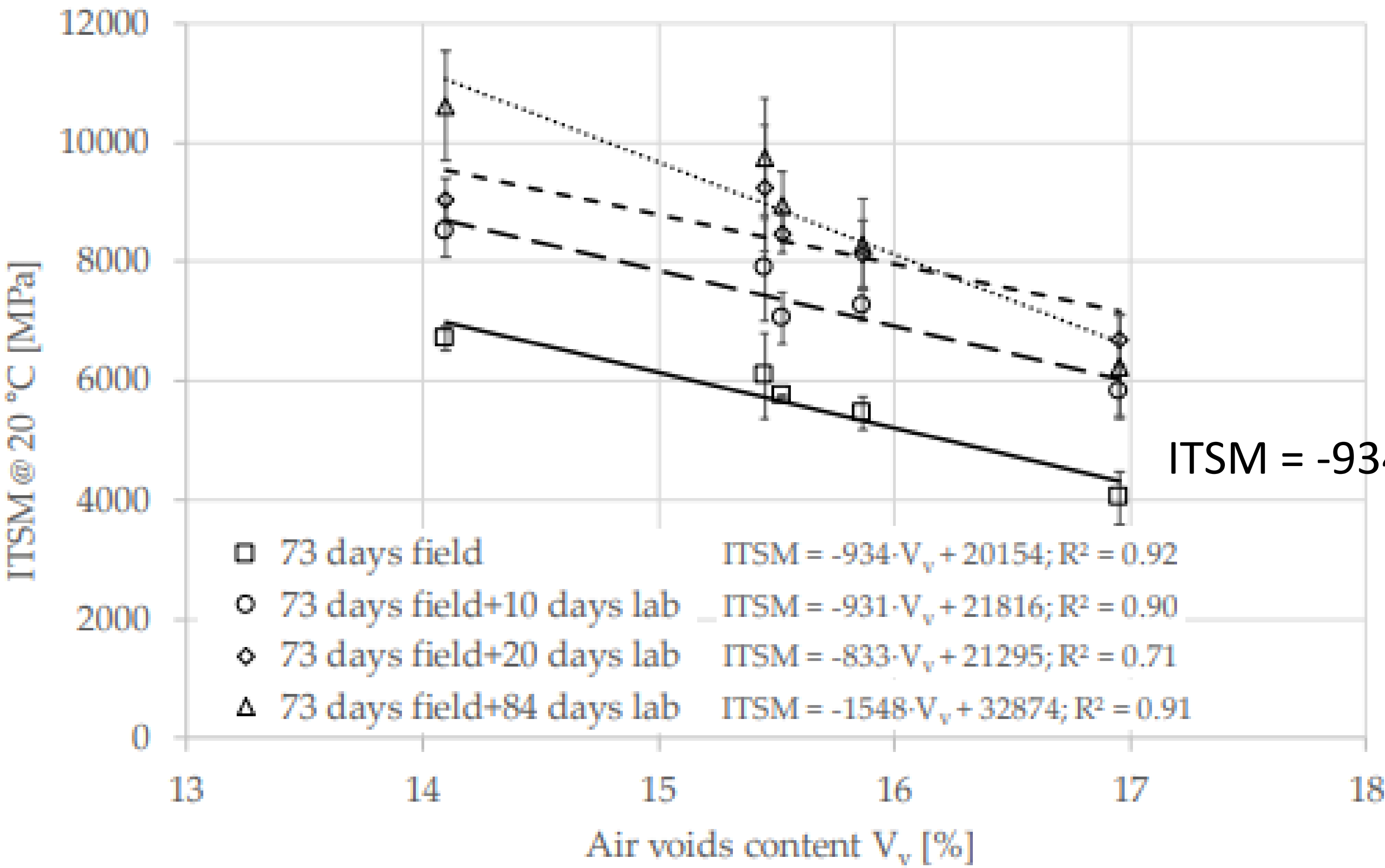




Relationship between stiffness and air voids

Air mean temperature after 60 days:
16°C

Air mean temperature between 60 and 120 days:
24°C



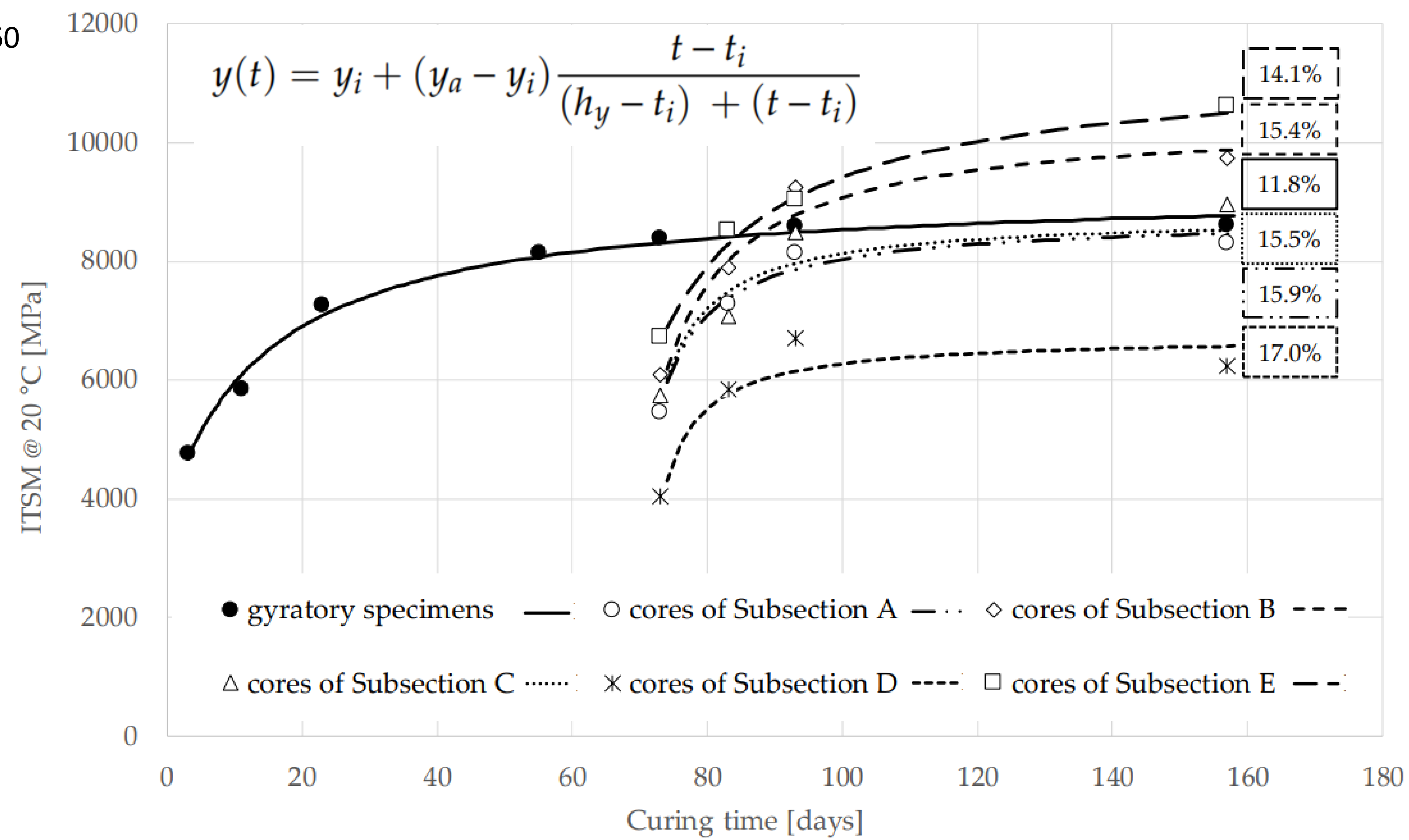
$$ITSM = -934 \times V_v + 20154$$

- ITSM can be considered linearly dependent on the air voids in all the curing conditions
- 1% increase in air voids led to a reduction of ITSM of about 900 MPa

Relationship between stiffness, air voids and curing time

Air mean temperature after 60 days:
16°C

Air mean temperature between 60 and 120 days:
24°C

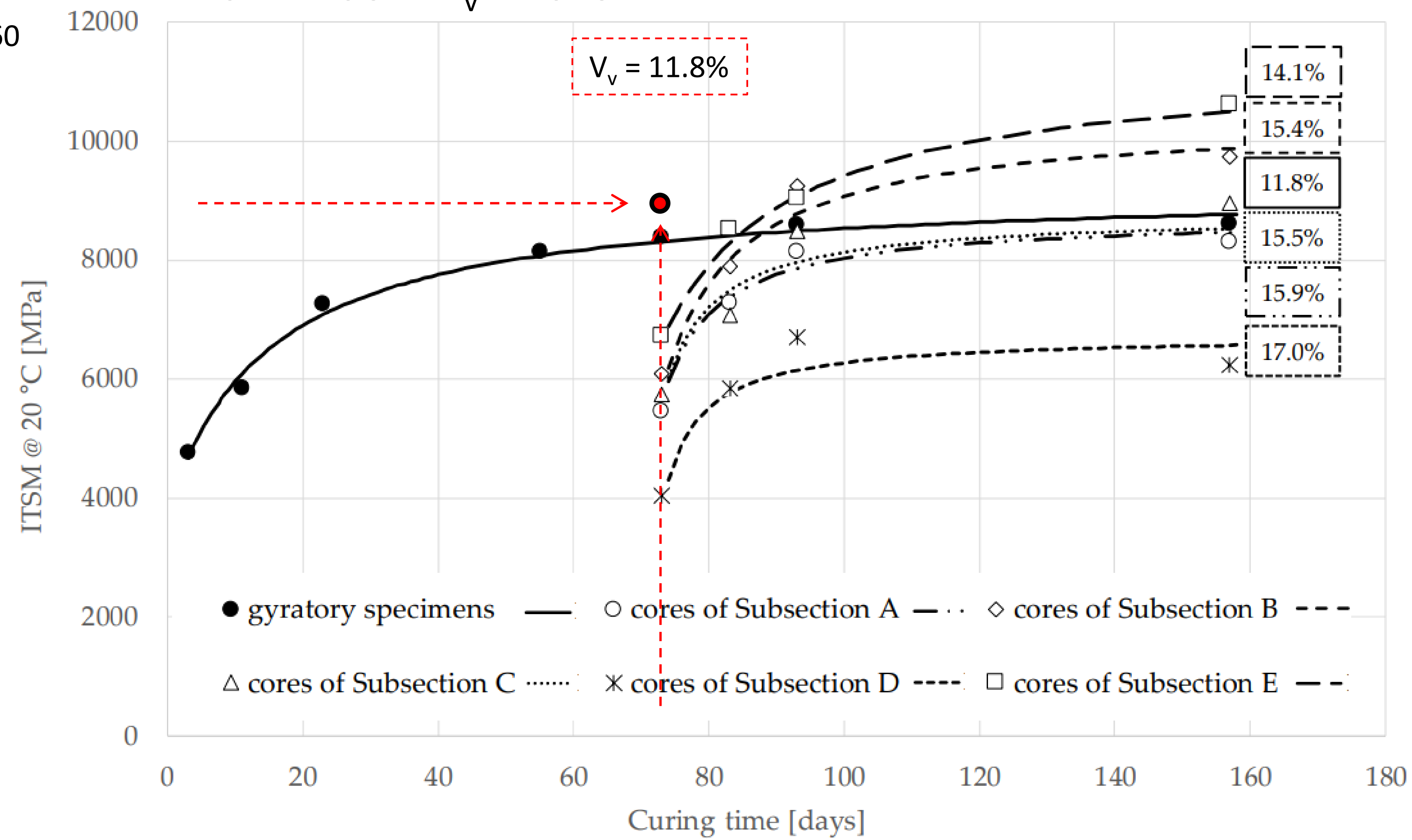


- The difference in ITSM between cores and gyratory specimens, is due to differences in both volumetric properties (the cores had higher voids) and curing conditions (oven-curing vs. field curing)

Relationship between stiffness, air voids and curing time

Air mean temperature after 60 days:
16°C

$ITSM = -934 \times V_v + 20154$

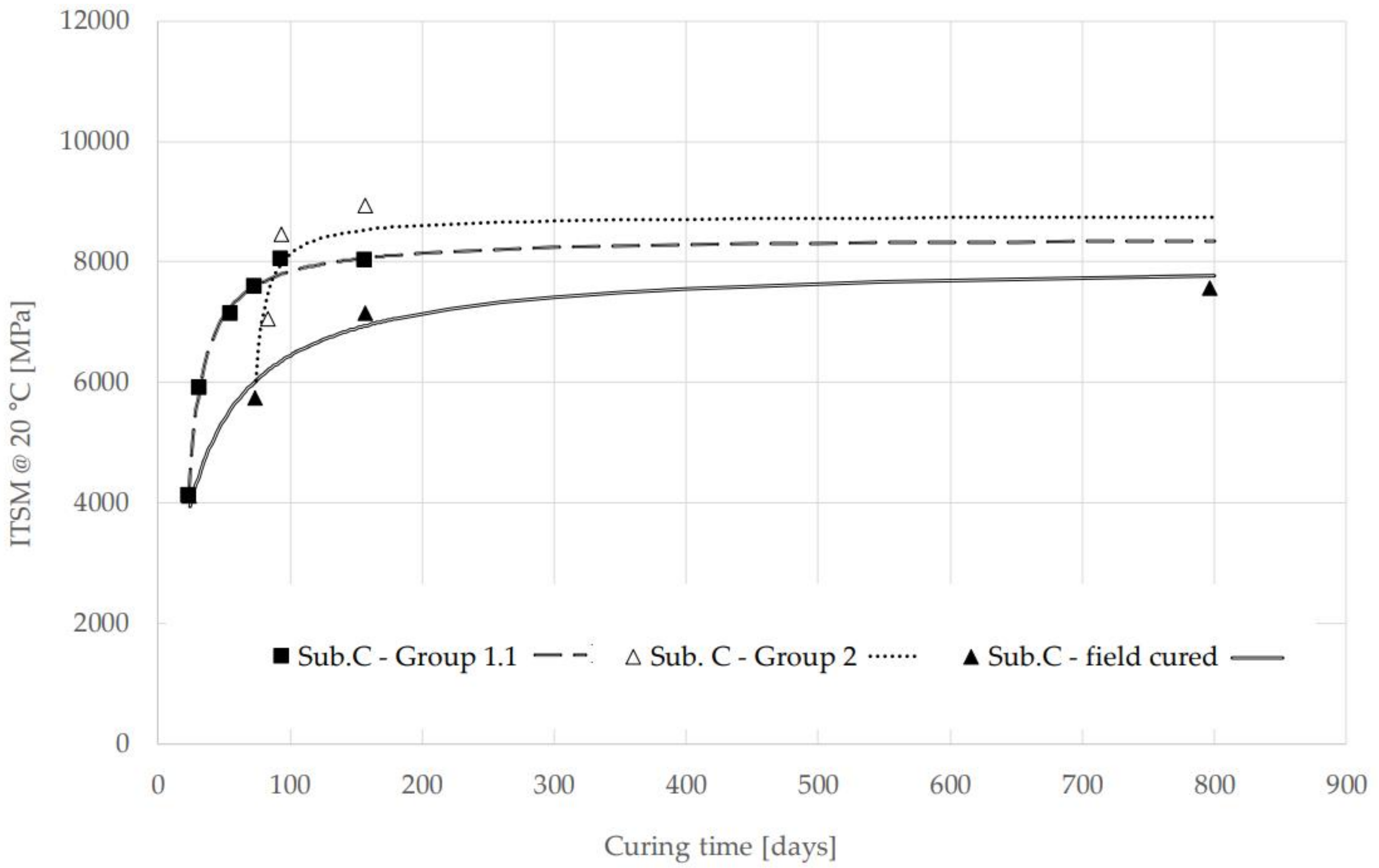


- Field curing did not penalize the stiffness evolution until 73 days
- Accelerated curing in the laboratory may lead to an underestimation of the long-term stiffness

Relationship between stiffness and curing time

Air mean temperature after 60 days:
16°C

Air mean temperature between 60 and 120 days:
24°C

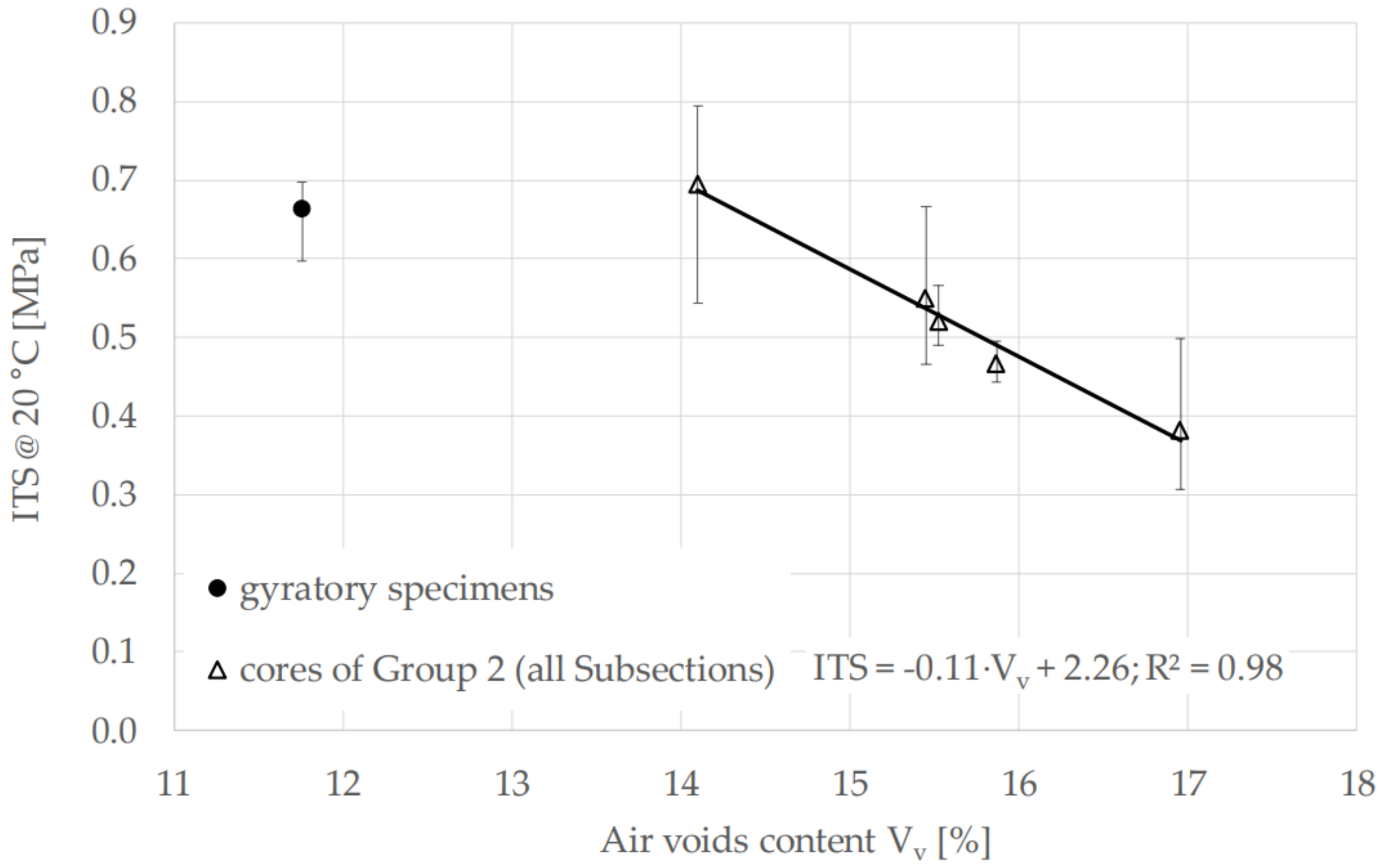


- The asymptotic values are similar to the characteristic value of the field cured material
- If oven-curing is applied after few days (or weeks) of field curing with restricted evaporation, the long-term stiffness is not affected

Relationship between strength, air voids and curing type

Air mean temperature after 60 days:
16°C

Air mean temperature between 60 and 120 days:
24°C

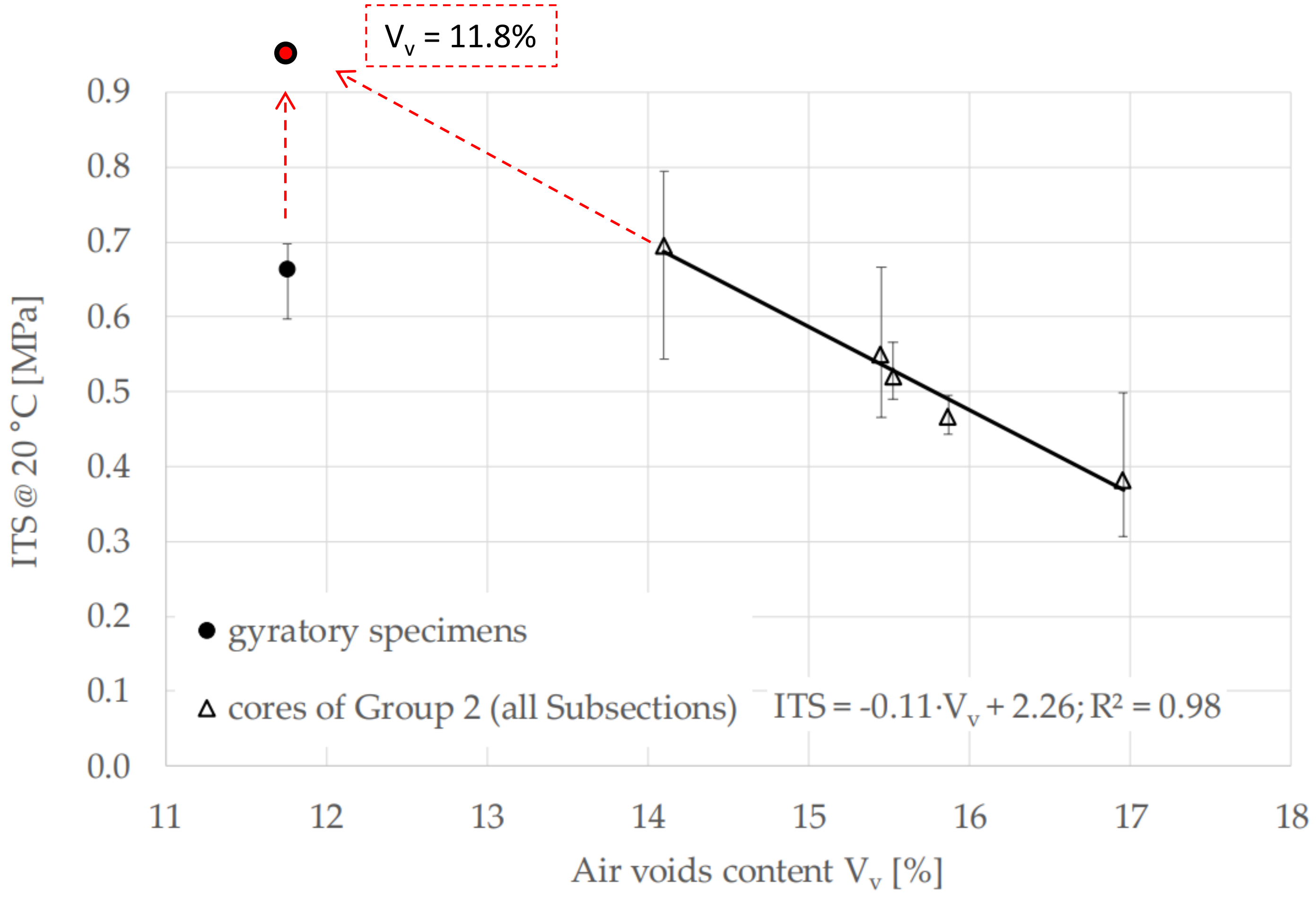


- ITS of the cores and air voids show a linear relationship
- 3% increase in air voids led to approximately a halving of ITS (from 0.69 to 0.38 MPa)

Relationship between strength, air voids and curing type

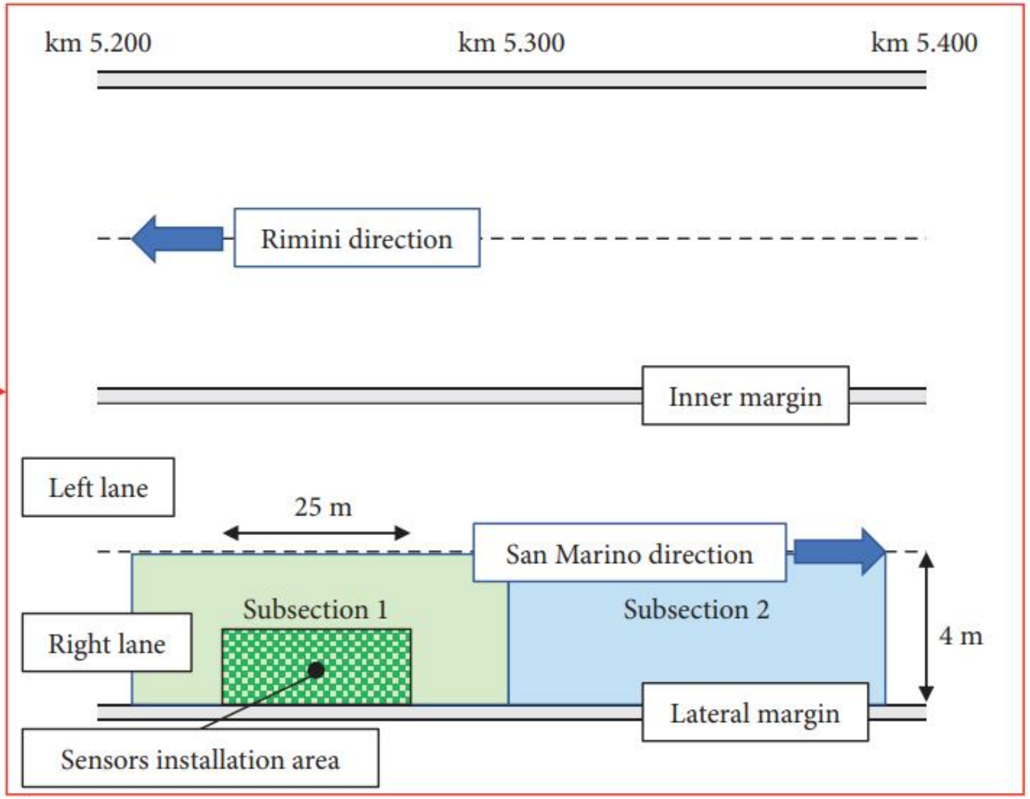
Air mean temperature after 60 days:
16°C

Air mean temperature between 60 and 120 days:
24°C



- the ITS value of hypothetical cores with an air void content of 11.8% (corresponding to the value obtained for the gyratory specimens) would be higher than that provided by the gyratory specimens (0.96 > 0.66 MPa)

Instrumented section



- Four-lane divided highway with an annual average daily traffic of about 4,000 vehicles per day/lane
- The existing pavement consisted in an asphalt concrete course (wearing and binder layers) with a total thickness of 12 cm over an unbound granular base

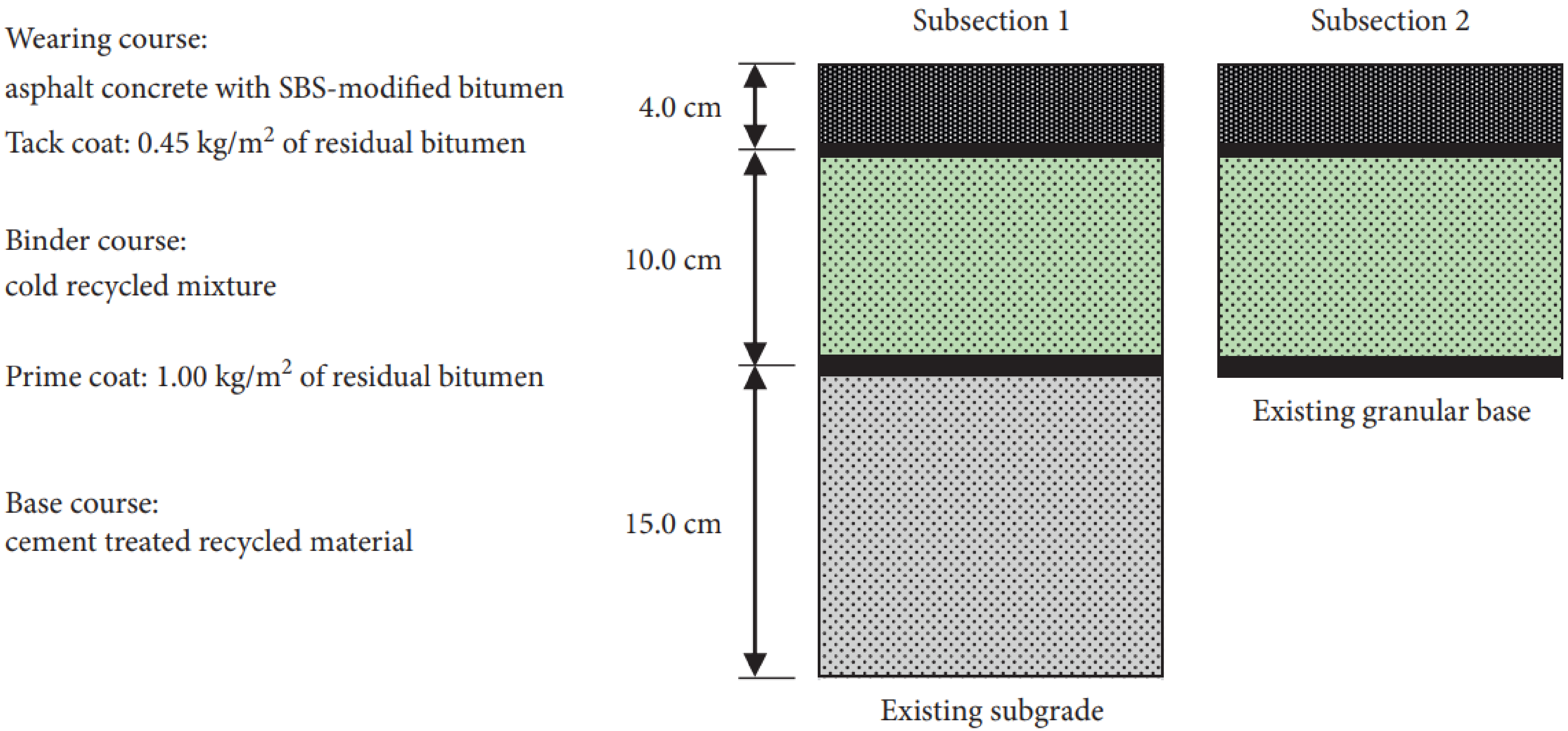
https://www.crabforoere.eu/project-reports/

Distresses

- subsection 1 showed a series of interconnecting cracks caused by repeated traffic loading, high-severity level of the fatigue cracking, combined with a localised depression due to the settlement of the foundation

- subsection 2 showed medium-severity level of the fatigue cracking

Structural design



- The maintenance works produced 226 t of milled HMA and 160 t of milled unbound aggregates
- The CTM base and CRM binder were manufactured recycling 85 t of unbound aggregates and 184 t of reclaimed asphalt (recycled 70% of milled materials)

https://www.cedr.eu/peb-new-materials-and-techniques

CTM base course and prime coat

https://www.crabforoere.eu/project-reports/

CRM binder coarse and HMA wearing coarse

https://www.crabforoere.eu/project-reports/

Installation of the sensors



Installation of the sensors

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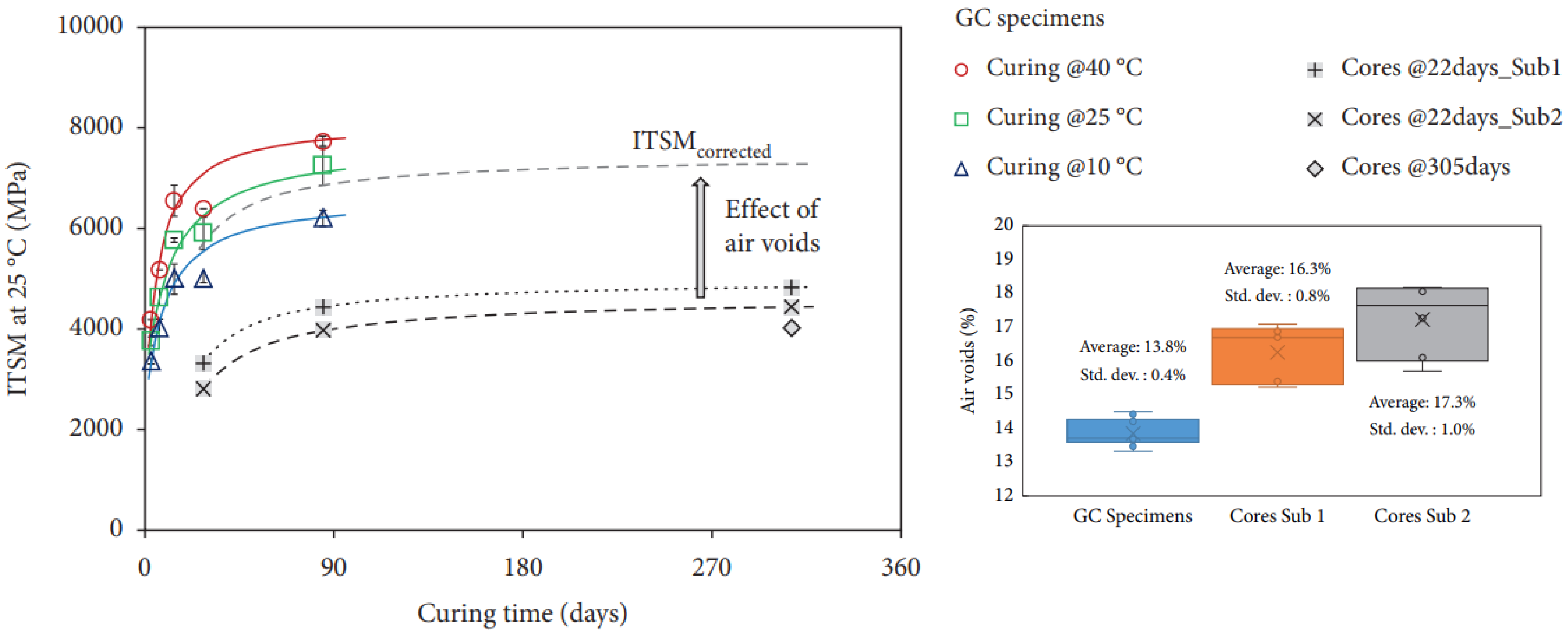
Curing of specimens in comparison with cores

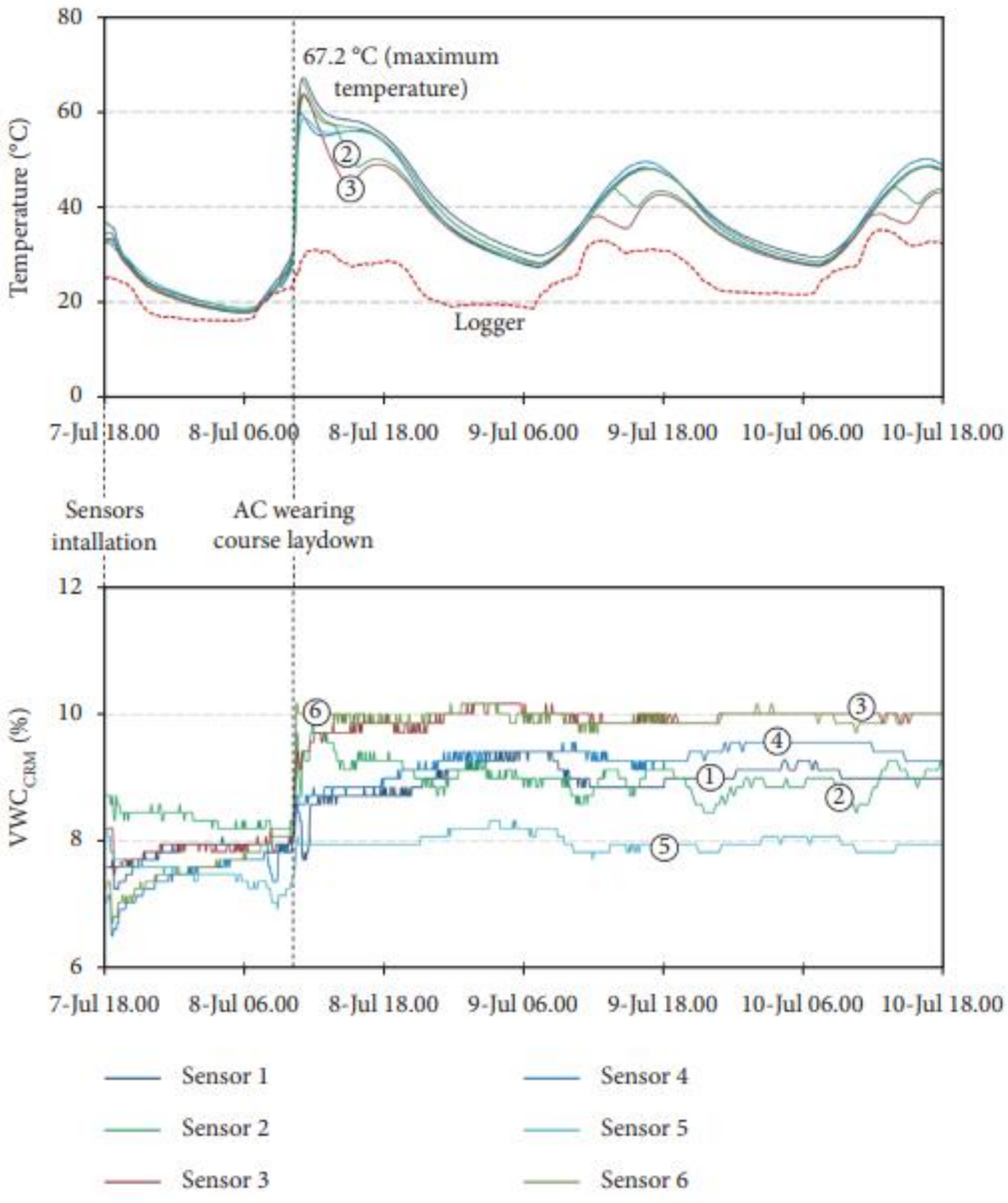


- The curing temperature mainly influences the initial curing rate
- The difference between specimens and cores may be explained by the different compaction levels

Temperature and moisture monitoring

- The temperature of the CRM layer decreased from about of 35°C to about 18° C
- Water evaporation was free from the top surface of the layer and the sensors recorded fairly constant VWG

- Increase of moisture and temperature when the tack coat was applied followed by the laydown and compaction of the AC wearing course
- The average CRM temperature and moisture in the first month was about 37°C and 4.4% respectively
- Considering the full year, the median value of the average daily temperature of CRM layer was 16.7°C (max 53.1°C; min -0.7°C)



Conclusions

- Sustainable development and cost-effective procedures:
  - Savings of energy and virgin materials;
  - Reduction of emissions, transportation, disposal of materials;
  - Recycling of demolition materials.
- Technical benefits:
  - construction time;
  - safe working place;
- Design approaches:
  - Balancing stiffness and flexibility;
  - Good performance.

- **Recycling techniques match social benefits and high-quality construction methods**
- **A "warm" invitation to use cold techniques!**

Thank you for you attention!

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Early curing

- The curing conditions immediately after compaction determine the microstructure of the material (distribution and location of cementitious and bituminous bonds).
- Immediate oven-curing and free evaporation (laboratory conditions), bituminous bonds are favoured with respect to cementitious bonds
- When evaporation is restricted (field curing), the cementitious bonds are favoured leading to a higher long-term stiffness.
- When oven-curing is applied a few days/weeks after compaction (i.e., when the mixture microstructure is already formed in sealed conditions), the stiffness development will be accelerated with a small effect on its long-term value
- The humidity of the material subjected to oven-curing and free evaporation may be totally different from the field. Therefore, the evolution of the cementitious and bituminous bonds will be different because humidity enhances the former and penalizes the latter