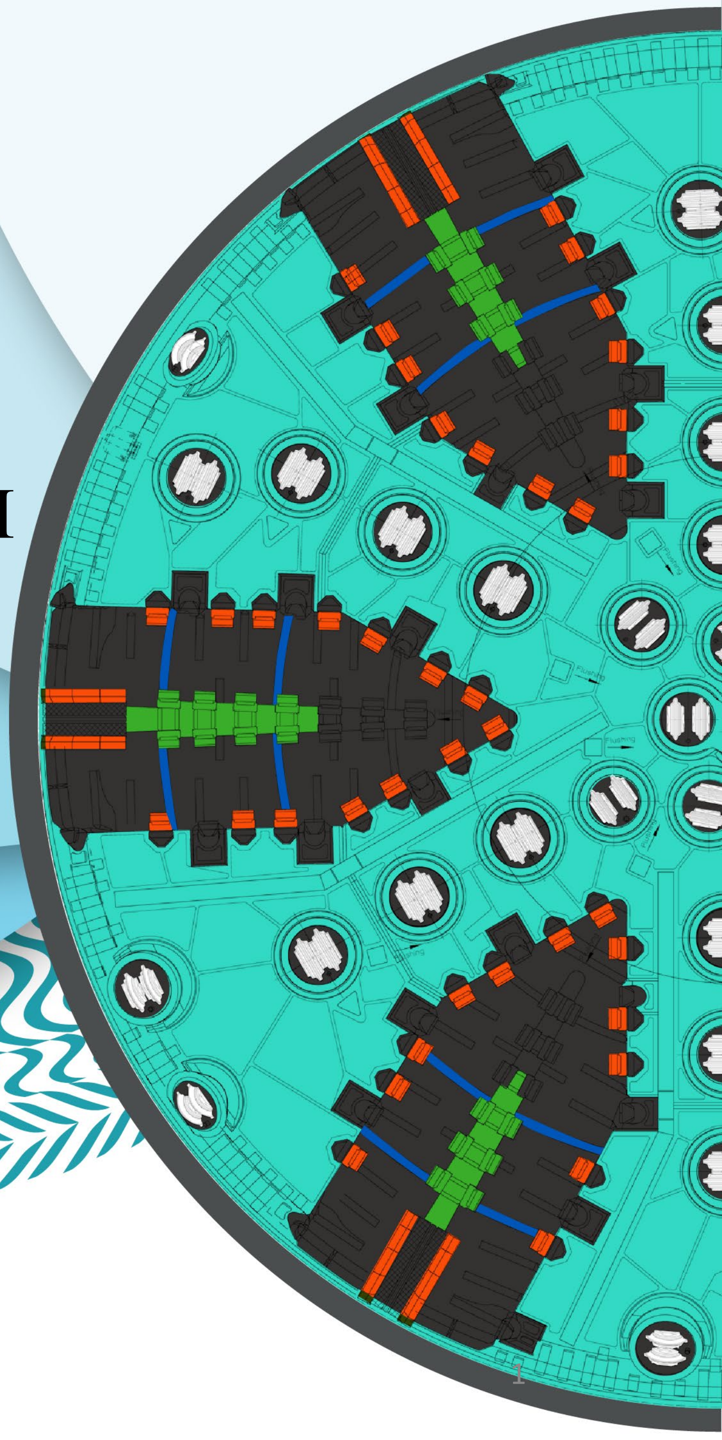
Standing Committee on Concrete Technology
Annual Concrete Forum 2023

# A CASE STUDY OF GGBS CONCRETE FOR CRITICAL STRUCTURE AND EARLY STRENGTH IN TRUNK ROAD T2 PROJECT

by Christine COURTEL



T2主幹路及茶果嶺隧道
TRUNK ROAD T2 AND CHA KWO LING TUNNEL

土木工程拓展署
Civil Engineering and Development Department

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B. Case study in Hong Kong: The use of GGBS* concrete for critical structures on T2 Trunk project

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* Ground Granulated Blast furnace Slag

# A. BACKGROUND

1. The **need to reduce carbon** footprint
2. The **near end of the PFA*** production by Hong Kong power stations
3. **Hong Kong specification** in term of use of cementitious supplementary materials (SCM)
4. Need **to include critical elements** in the process of reduction of concrete carbon footprint

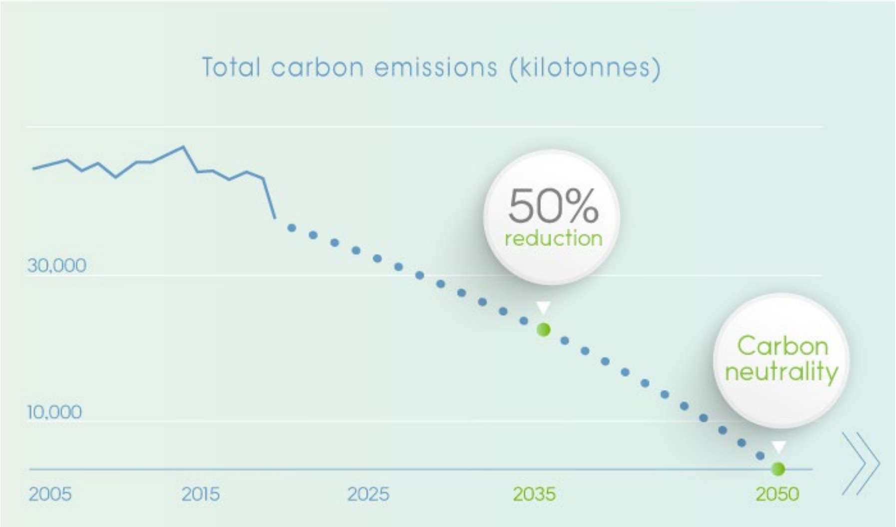
*Black Point Hong Kong Power Station (CLP)*

*Lamma Island Hong Kong Power Station (HK Electric)*

* Pulverized Fuel Ash

# A 1. THE NEED TO REDUCE CARBON FOOTPRINT

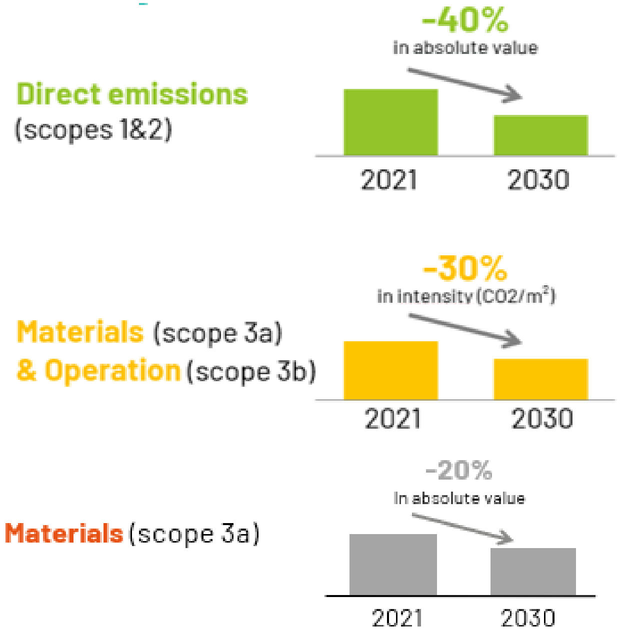
**Hong Kong Roadmap to carbon neutrality**




*Source: Hong Kong's Climate Action Plan 2050*

It was estimated in 2021 that **concrete production** accounts for around **8% of the world's total carbon dioxide** emissions

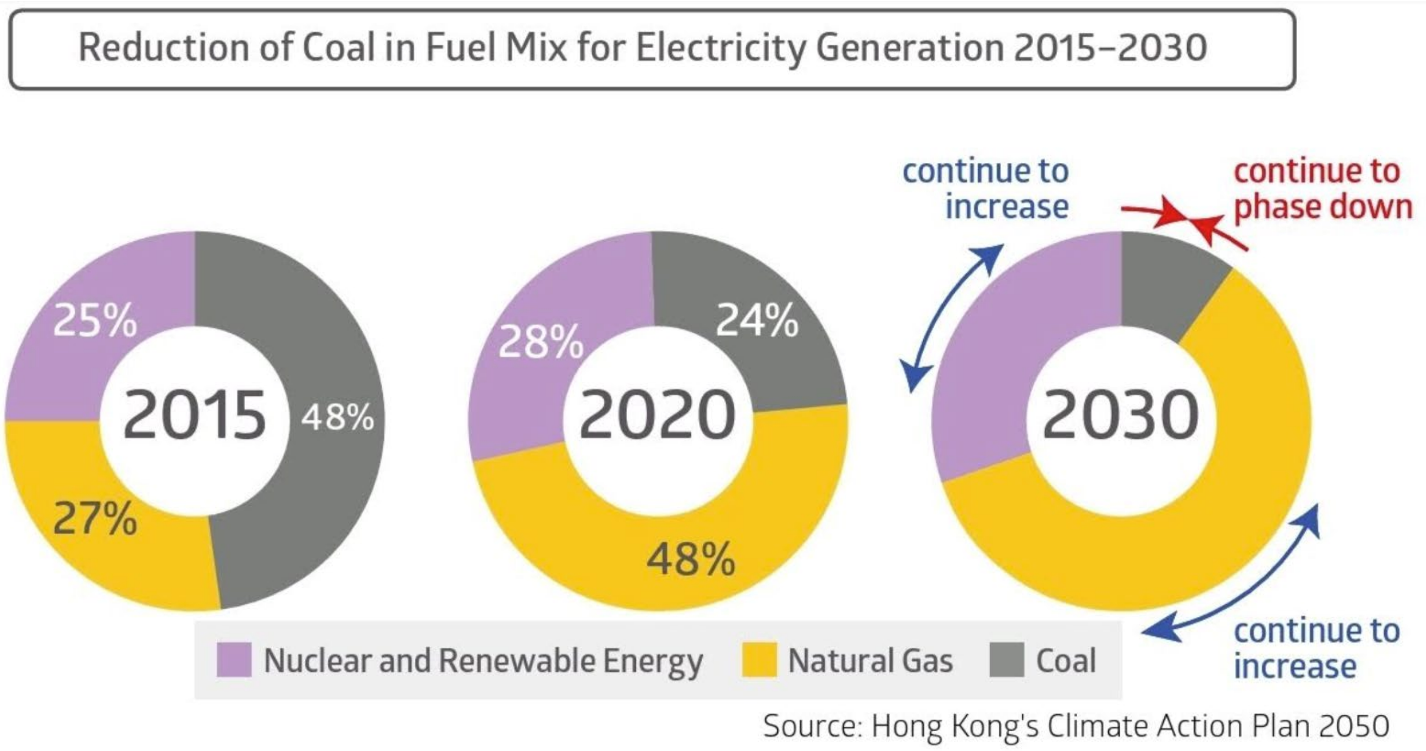
**Bouygues & Dragages HK commitment to reduce $CO_2$ emissions in compliance with "COP 21 Paris Agreement" i.e. 30% $CO_2$ reduction by 2030**




**Government and Company commitments**

# A 2. THE NEAR END OF THE PFA* PRODUCTION BY HONG KONG POWER STATIONS

* Pulverized Fuel Ash




**The use of coal in Hong Kong for electricity production is quickly coming to an end**

→This implies the end of the use of the local PFA (as PFA is a by-product of the coil power station)

**No more coal used to produce electricity = No more PFA**

# A 3. THE HONG KONG SPECIFICATION IN TERM OF USE OF SUPPLEMENTARY CEMENTITIOUS MATERIALS (SCM)

## CEDD general specification GS 2006 restrictions:

- **PFA, GGBS and Silica fume (CSF) are the only SCM** referred to in the specification
- **GGBS is not allowed to be used in conjunction with PFA**
- GGBS dosage has to be between **35% and 75%** of the total cementitious content for normal conditions

**Strong limitations in the use of supplementary cementitious materials**

# A 4. NEED TO INCLUDE CRITICAL ELEMENTS IN THE PROCESS OF REDUCTION OF CONCRETE CARBON FOOTPRINT

- **GGBS** only recently **re-introduced in Hong Kong**
- GGBS presently **mostly used for mass concrete**, foundation, substructures or base slabs due to its durability and low heat properties and because of the **lower concrete early strength when dosed at high percentages of GGBS.**
- **Since PFA is coming to an end**, concrete mixes with **GGBS shall be also used for any permanent works** in Hong Kong Tunnel projects including concrete structures for which concrete properties have **to comply with specific criteria such as minimum early strength** linked to cycles of production.

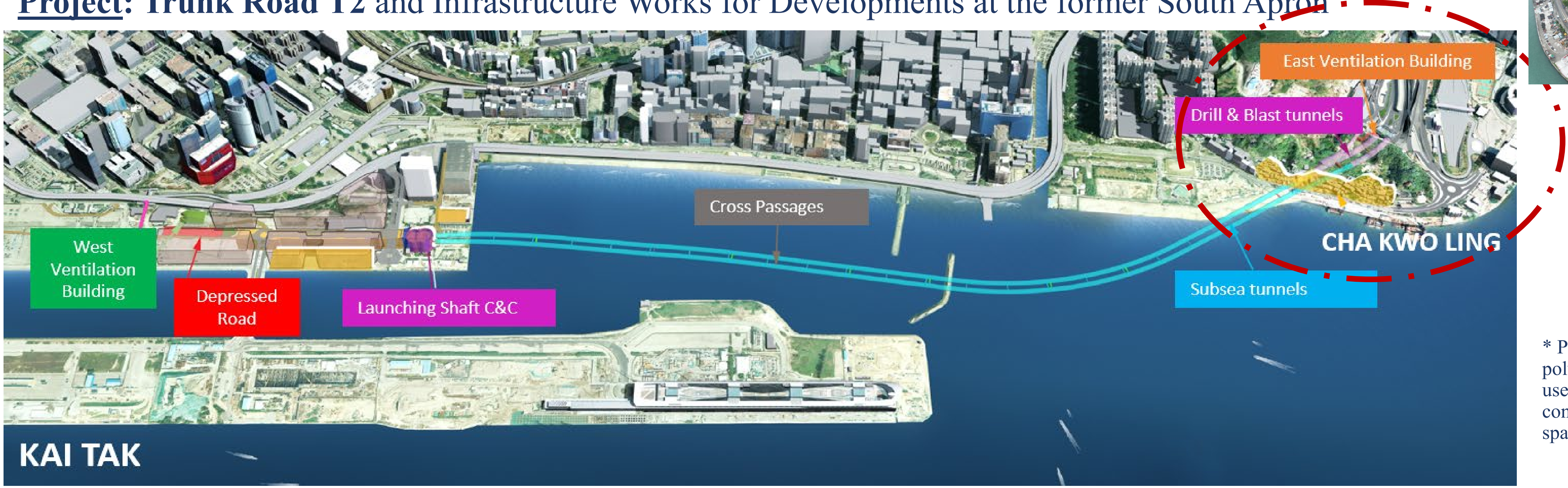
**GGBS concrete mixes with PP fiber for precast segments, lining, overhead ventilation duct (OHVD) and internal structures shall now be designed and used in the permanent tunnel structures.**

# B. CASE STUDY IN HONG KONG: THE USE OF GGBS CONCRETE FOR CRITICAL STRUCTURES ON T2 PROJECT

1. Case study purpose
2. The use of **GGBS concrete on T2 project**
3. Design of **GGBS concrete mixes with PP fibres** for OHVD structures
4. **Specificities** of the selected structures for this case study
5. Comparison of **early strength with GGBS concrete** with an equivalent PFA-based concrete
6. **Carbon footprint** – GGBS concrete mixes versus PFA concrete mixes
7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and **control of the in-situ early strength through the maturity** calculated based on the history of the in-situ temperature

# B 1. CASE STUDY PURPOSE

**Project: Trunk Road T2** and Infrastructure Works for Developments at the former South Apron




* PPF : monofilament polypropylene fibres used to reduce concrete explosive spalling under fire

The purpose of the case study was **to verify the feasibility to use a concrete made with GGBS in conjunction with polypropylene fibres (PPF*), for permanent tunnel structures** to reduce the CO2 emission without affecting the cost of the concrete mix nor the cycle of production

→ For this, we have **selected two special critical applications** in term of site requirements

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*Contract No.: ED/2018/04* *Client: Civil Engineering and Development Department (CEDD)*
*Contract type: Design & Build Contract* *Consultant: HMJV* *Contractor: Bouygues Travaux Publics*

# B 2. THE USE OF GGBS IN CONCRETE ON T2 PROJECT

- **GGBS concrete** has been **used since mid 2022**:

| Concrete Mix | Location poured in 2022-2023 | Structural Concrete | To be continuous 2024 |
|---|---|---|---|
| 20/20 (60% GGBS) | General use, CKL Tunnel, CUE, DPR, WVB, EVB, etc. | Non-structural | Drainage + CKL Tunnel, OHVD Massfill |
| 25/20 (60% GGBS) | CP Side, Subsea Tunnel | Non-structural | Invert Slab + Parapet + parapet CKL |
| 30/20 (60% GGBS) | Road Drainage, Launching shaft Cut & Cover, CKL Services Gallery, Road Sections | Non-structural | Drainage |
| 45/20 (40% GGBS) | West Ventilation Building (Wall, slab) | Structural & non-structural | West Ventilation Building |
| 60/20 (40% GGBS) | West Ventilation Building (Wall, column) | Structural & non-structural | West Ventilation Building |

- **GGBS concrete to be adopted in tunnel structure elements with PP fibres:**

| Concrete Mix | Location | When | Structural concrete |
|---|---|---|---|
| 45/20 (36% GGBS) +1kg PPF | East Ventilation Building Overhead Ventilation Duct (OHVD) | Mid of 2024 | Structural |
| 60/20 (40% GGBS) +1kg PPF | CKL Tunnel OHVD | Mid of 2024 | Structural |

# B 3. DESIGN OF GGBS CONCRETE MIXES WITH POLYPROPYLENE FIBRES FOR OHVD SLABS

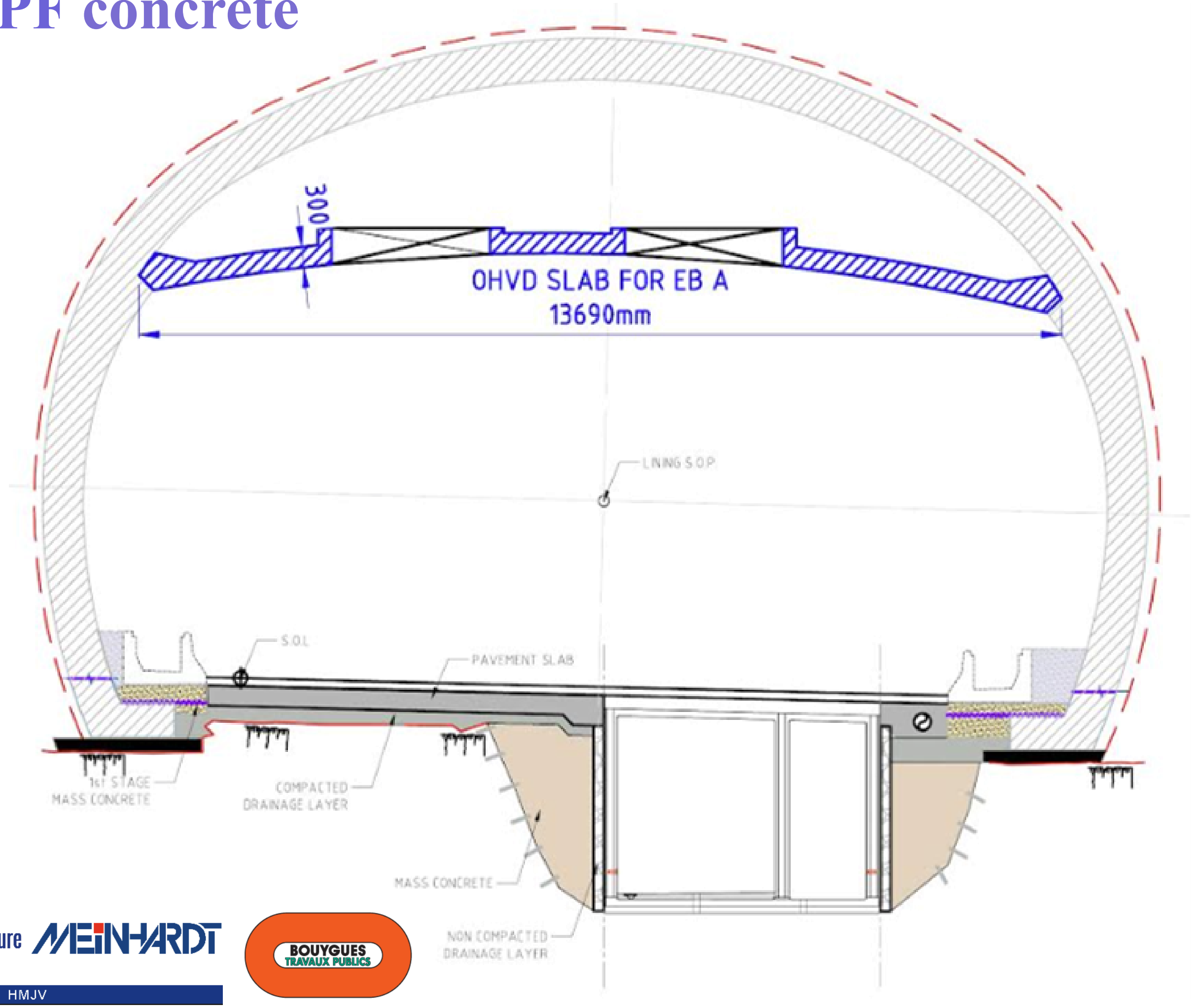
## B 3.1 GGBS concrete: EASTBOUND A OHVD slab

### 60/20 GGBS CSF PPF concrete

**Curved structure**

40% GGBS
8% CSF
1 kg/m$^3$ PPF

- ❑ 500 mm design flow
- ❑ 2h30 mn workability retention
- ❑ 300 mm thickness
- ❑ 13.7 m span
- ❑ Striking the day following the pour




*Pictures of the concrete of a similar structure*

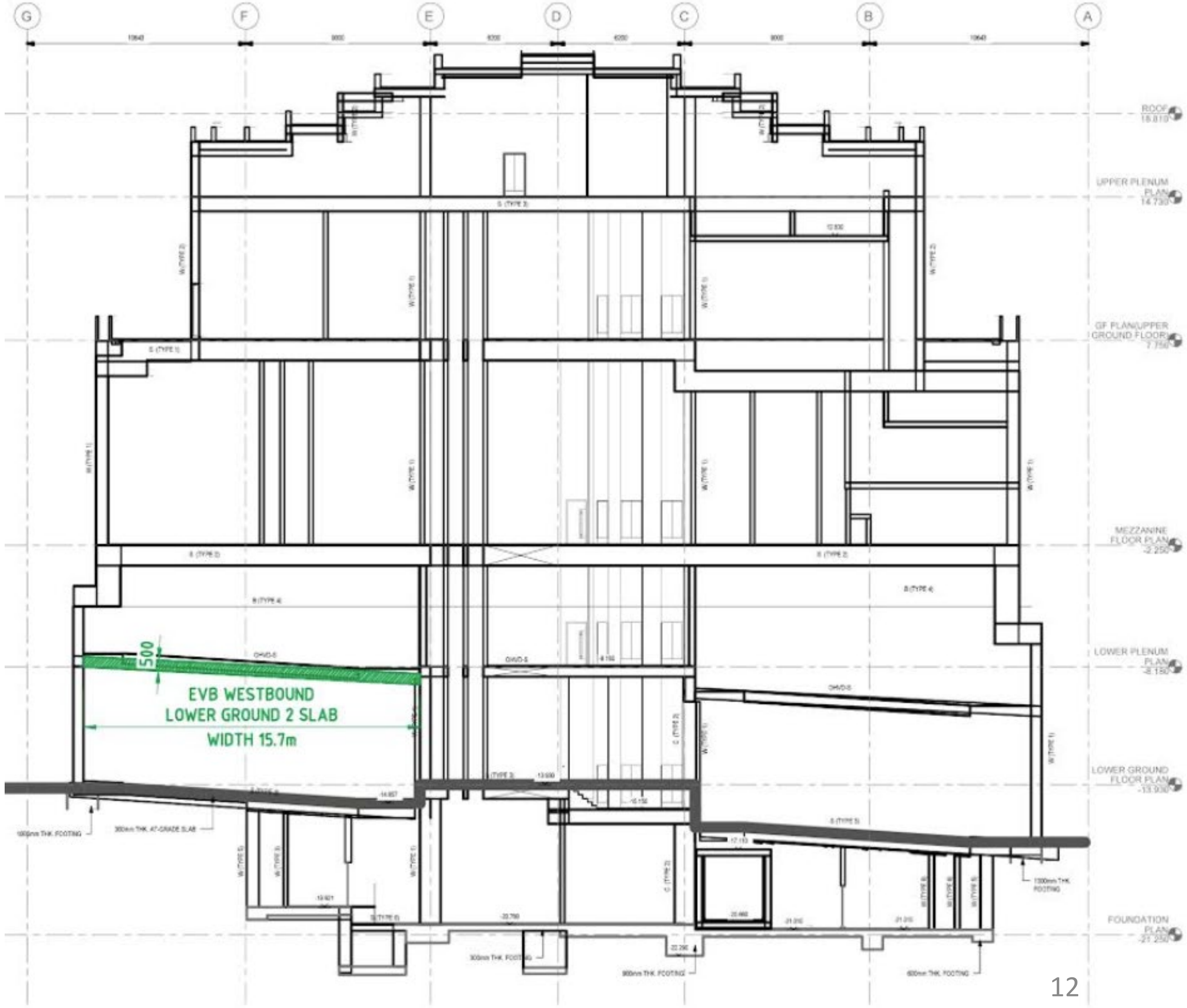
# B 3.2 GGBS concrete: East Ventilation Building Westbound LG2 slab

## 45/20 GGBS PPF concrete

**Inclined structure**

36% GGBS
1 kg/m$^3$ PPF

- ❑ 550 mm design flow
- ❑ 2h30 mn workability retention
- ❑ 500 mm thickness
- ❑ 15.7 m span
- ❑ Striking the day following the pour



# B 4. SPECIFICITIES OF THE SELECTED STRUCTURES FOR THIS CASE STUDY

Concrete mixes with PP Fibres and GGBS 45D/20 and 60D/20 have been designed for Tunnel OHVD in such a way to suit the specific site production needs:

1. **Due to the curved surface of slab**, requirement from the site to get supplied with a **design flow of only 500 mm** for the tunnel OHVD (and 550 mm for the inclined EVB OHVD)

2. **Striking** of OHVD slab formwork **the day following the pour**

3. **Workability retention of minimum 2.5 h** (due to site and tunnel access)

4. **Bouygues policy**, **to ensure the quality** of the PP fiber concrete, is that the **PP fibres have to be imperatively added at the batching plant** by the supplier (it means that addition of PP fiber on site is not an option to reduce the final flow)

# B5. Comparison of early strength with an equivalent PFA-based concrete

## The use of GGBS in Tunnel inclined OHVD 45/20 concrete with polypropylene fiber

Trials performed at CSL Hong Kong testing Laboratory (2023)

| Concrete mix details | | | |
|---|---|---|---|
| 45D/20 (raw materials sourced by Anderson Concrete Limited)<br>Design flow: 550 mm +/- 50 mm<br>The study focus on 45/20D PPF 550 mm flow, 2h30 mn flow retention for casting inclined OHVD structures at T2 | | | |
| Cementitious components combination (from Green Island Cement Co Ltd) | 50% OPC + 50% GGBS | 75% OPC + 25% PFA | 64% OPC + 36% GGBS |
| concrete grade | 45/20 | 45/20 | 45/20 |
| Total Cementitious Content (kg/m3) | 450 | 480 | 450 |
| Design Flow | 550 mm | 550 mm | 550 mm |
| 6 mm PPF (Sika fibermesh 150) | 1 | 1 | 1 |
| **OPC content in kg/m3** | **225** | **360** | **288** |
| PFA content in kg/m3 (from GIC) | 0 | 120 | 0 |
| GGBFS content in kg/m3 (from GIC) | 225 | 0 | 162 |
| W/C (not included admixture) | 0.35 | 0,35 | 0.35 |
| **Concrete test results** | | | |
| Age of concrete | Concrete compressive strength in Mpa (tested on 100 mm concrete cubes cured at 27C) | | |
| 16h | 0.7 | **4.1** | < **5.9** |
| 22h | | **10.5** | **10.5** |
| 3d | 33.9 | 47.9 | 40.6 |
| 7 day | 48.0 | 58.1 | 55.4 |
| 28 day | 63.7 | 78.7 | 74.6 |

# B 6. Carbon footprint – GGBS concrete mixes versus PFA concrete mixes

- Comply with Carbon Rating Platinium (as per CIC benchmark)

CONSTRUCTION INDUSTRY COUNCIL 建造業議會 HKGBC 香港綠色建築議會

## Benchmark – Ready-mixed Concrete

CIC Green Product Certification - Carbon Labelling Scheme
Benchmark for Ready-mixed Concrete Products
(2019 rev.1)

| Concrete Grade | C30 | C35 | C40 | C45 | C50 | C60 | C70 | C80 |
|---|---|---|---|---|---|---|---|---|
| $E_{da}$ | 296 | 323 | 350 | 373 | 396 | 443 | 490 | 490 |
| Certification Level | ($kgCO_2e/m_3$) | | | | | | | |
| Platinum | <252 | <275 | <298 | <318 | <337 | <337 | <417 | <417 |
| Gold | 252-280 | 275-306 | 298-332 | 318-354 | 337-375 | 337-420 | 417-465 | 417-465 |
| Silver | 281-310 | 307-339 | 333-367 | 355-391 | 376-415 | 421-464 | 466-514 | 466-514 |
| Bronze | 311-340 | 340-372 | 368-403 | 392-429 | 416-455 | 465-509 | 515-563 | 515-563 |
| Green | >340 | >372 | >403 | >429 | >455 | >509 | >564 | >564 |

- **Reduction of carbon footprint when compared with PFA concrete** of similar properties:
  - **Grade 45: 15.67 % reduction**
  - Grade 60: 3.11 % reduction

Note: proven reduction although limited due to the high constraints from the site conditions (in particular: production cycle, no additional cost of the concrete mix)

$CO_2$ emission Calculation by Alliance Concrete supplier using CIC default emission factor

- G45 25% PFA, 1 kg PPF, 550 mm flow,`2.5h flow retention: 354.21 kg/m$^3$
- G45 36% GGBS, 1 kg PPF, 550 mm flow, 2.5h flow retention **298.69 kg/m$^3$**
- G60 35% PFA, 8% SF, 1 kg PPF, 500 mm flow 2.5h flow retention 284.29 kg/m$^3$
- G60 40% GGBS,, 8% SF, 1 kg PPF, 500 mm flow 2.5h flow retention **275.45 kg/m$^3$**

Carbon emission Calculation by Concrete supplier using CIC default emission factor

# B 7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and control of the in-situ early strength through the maturity calculated based on the history of the in-situ temperature (ASTM C 1074)

**The maturity method is a technique that is used to evaluate the in-situ concrete strength based on the temperature history of the in-situ concrete**

## Main advantages of using the maturity method

- ✓ Allows **optimization of the cycle of production (and thus of the percentage of SCM)** because :
  - ❑ The **in-situ concrete is gaining strength earlier than cubes specimens** due to the in-situ concrete temperature rising during the hydration.
  - ❑ The thicker will be the cast element, the most effective will be the insulation applied if any, and the faster will be the gain in early in-situ strength.
- ✓ Provides a **representative and continuous measure of in-situ concrete strength gain unlike strength of 100 mm cubes kept at ambient temperature.**
- ✓ **Reduces the cost and time of concrete testing** (thanks to less cubes sampling and testing)

# B 7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and control of the in-situ early strength through the maturity calculated based on the history of the in-situ temperature (ASTM C 1074)

**Maturity control is performed by Bouygues in Hong Kong for more than 30 years**

This concrete maturity method has been **widely used by Bouygues / Dragages Hong Kong on its Tunnel projects** to control the in-situ early strength (prior striking tunnel lining and OHVD), on its bridges and building jobs (prior post tensioning, lifting precast elements) using **exclusively Arrhenius law for calculation of the maturity** (refer to **ASTM C 1074**) as this exponential function has proved to provide the most accurate prediction of the in-place strength at early age

We do **not use the Nurse Saul function** (dated 1951) because it is based on the assumption that the rate of concrete strength is a linear function of the temperature which is **not representative especially at early age.**

# B 7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and control of the in-situ early strength through the maturity calculated based on the history of the in-situ temperature (ASTM C 1074)

**Recommended formula based on Arrhenius Equation for describing the rate of chemical reactions and its dependence on temperature**

## The maturity is expressed in e.h (Equivalent Age in hour at 20°C)

$$t_e = \sum_{0}^{t} e^{\frac{-E}{R}\left(\frac{1}{T} - \frac{1}{T_r}\right)} \Delta t$$

where

$t_e$ = the equivalent age at the reference temperature,
$E$ = apparent activation energy, J/mol,
$R$ = universal gas constant, 8.314 J/mol-K,
$T$ = average absolute temperature of the concrete during interval $\Delta t$, Kelvin, and
$T_r$ = absolute reference temperature, Kelvin.

The value of the **activation energy (E) is** depending on the concrete mix and is determined:

- through testing of the compressive strength of cubes cured at different temperatures and different ages
- based on the principle that **the maturity/strength relationship is the same for a given concrete whatever is the history of temperature (= ASTM C1074)**
- based on the calculation of the corresponding concrete maturity values

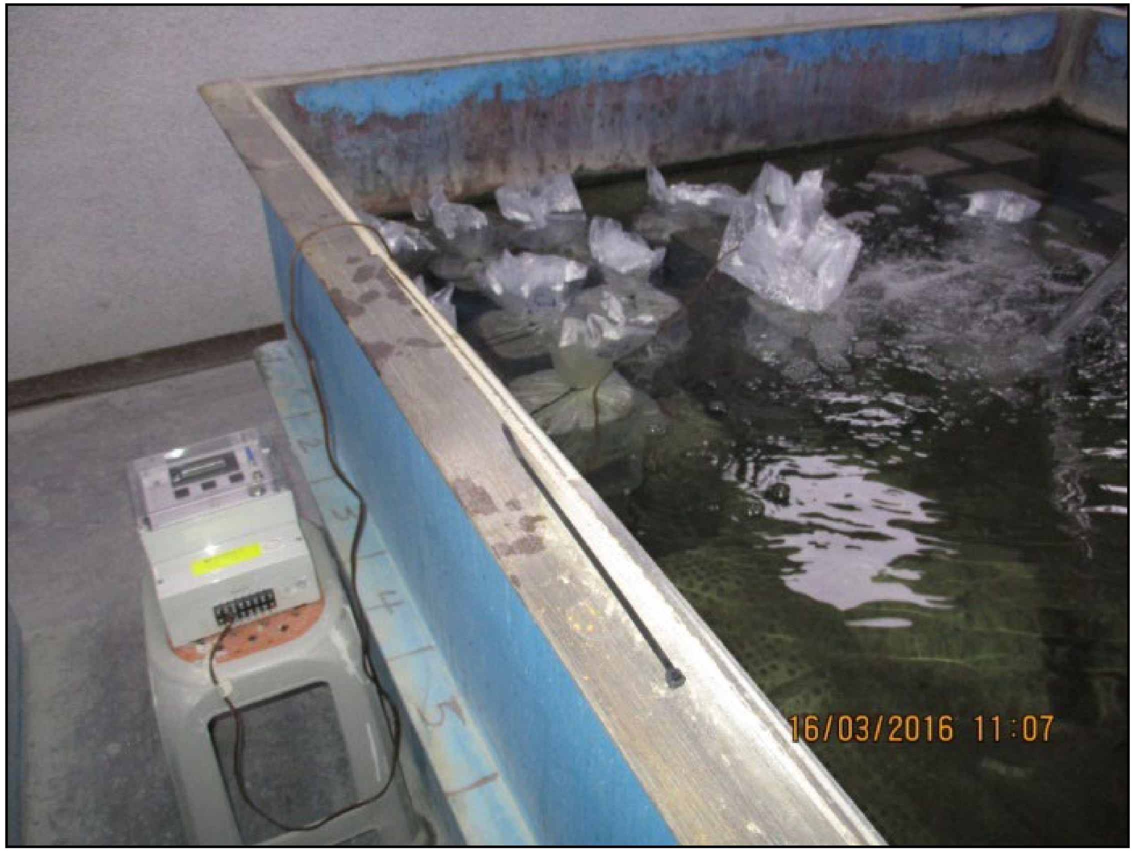
# Development of the strength/maturity relationship performed for the case study (T2 project - 2023)

## (casting and testing cubes cured at three different temperatures in a Hong Kong concrete testing laboratory)


# Another example of development of the strength/maturity relationship performed by Bouygues (Dragages Hong Kong) in 2016 on Liantang CEDD project (lining and OHVD)

**(casting and testing cubes cured at three different temperatures in a Hong Kong concrete testing Laboratory)**






# B 7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and control of the in-situ early strength through the maturity calculated based on the history of the in-situ temperature (ASTM C 1074)

## Maturity/strength relationship for 45/20D GGBS PPF

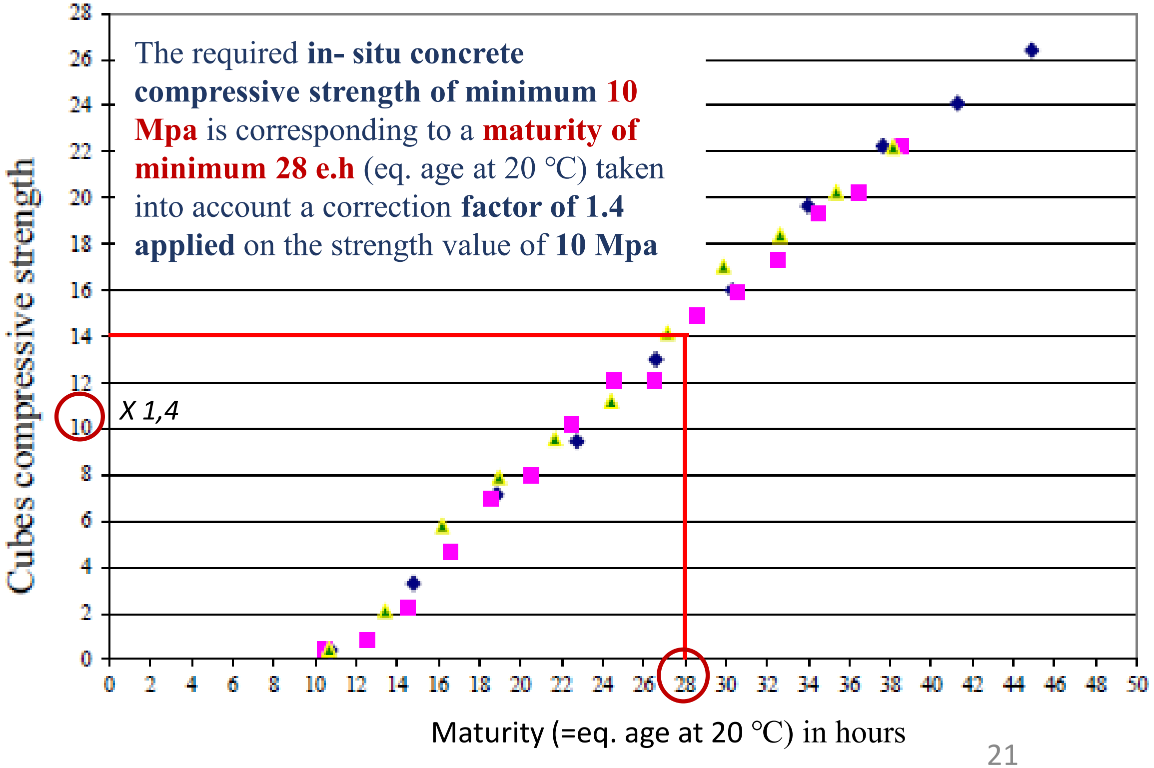
**Determination of the correlation curve maturity/compressive strength corresponding to the concrete mix 45/20D 36% GGBS + 1 kg PPF, flow 550 mm**

Table of compressive test results at early age for cubes cured in three different temperature conditions and calculations of the corresponding maturity values (date of cast: 26/09/23)

Activation Energy: 28000

| Time (h) | Concrete Temperature © | | | Cubes compressive strength (Mpa) | | | Maturity (= equivalent time at 20°C) ASTM C1074 (Arrhenius law) | | |
|---|---|---|---|---|---|---|---|---|---|
| From end of casting (2h after batching) (= time of starting the maturity) | Curing temperature condition 1 | Curing temperature condition 2 | Curing temperature condition 3 | with curing temperature condition 1 | with curing temperature condition 2 | with curing temperature condition 3 | with curing temperature condition 1 | with curing temperature condition 2 | with curing temperature condition 3 |
| 0 | 24.0 | 24.0 | 24.0 | | | | | | |
| 2.0 | 37.5 | 28.0 | 21.5 | | | | 3.0 | 2.5 | 2.2 |
| 4.0 | 37.9 | 28.1 | 21.0 | | | | 6.9 | 5.2 | 4.3 |
| 6.0 | 38.4 | 28.1 | 20.7 | 0.4 | | | 10.8 | 8.0 | 6.4 |
| 8.0 | 39.6 | 28.1 | 20.5 | 3.3 | 0.45 | | 14.8 | 10.7 | 8.4 |
| 10.0 | 38.5 | 28.4 | 20.3 | 7.15 | 2.1 | 0.4 | 18.8 | 13.4 | 10.5 |
| 12.0 | 38 | 28.7 | 20.3 | 9.45 | 5.8 | 0.85 | 22.7 | 16.2 | 12.5 |
| 14.0 | 37.3 | 28.2 | 20.2 | 13 | 7.9 | 2.3 | 26.6 | 19.0 | 14.5 |
| 16.0 | 36.3 | 28.1 | 20.6 | 16 | 9.55 | 4.7 | 30.3 | 21.7 | 16.5 |
| 18.0 | 36.2 | 28.1 | 19.9 | 19.65 | 11.2 | 6.95 | 34.0 | 24.4 | 18.6 |
| 20.0 | 36.1 | 28.2 | 19.6 | 22.25 | 14.15 | 8 | 37.6 | 27.1 | 20.5 |
| 22.0 | 36 | 28.3 | 19.8 | 24.1 | 17.05 | 10.2 | 41.3 | 29.9 | 22.5 |
| 24.0 | 36 | 28.3 | 20.2 | 26.4 | 18.4 | 12.05 | 44.9 | 32.6 | 24.5 |
| 26.0 | 35.9 | 28.4 | 20.2 | | 20.25 | 12.05 | | 35.4 | 26.5 |
| 28.0 | 35.8 | 28.5 | 19.9 | | 22.2 | 14.9 | | 38.1 | 28.5 |
| 30.0 | 35.8 | 28.4 | 19.6 | | | 15.9 | | | 30.5 |
| 32.0 | 35.8 | 28.3 | 19.4 | | | 17.35 | | | 32.5 |
| 34.0 | 35.8 | 28.1 | 19.9 | | | 19.3 | | | 34.5 |
| 36.0 | 35.8 | 28.0 | 20.2 | | | 20.2 | | | 36.5 |
| 38.0 | 35.8 | 27.8 | 20.5 | | | 22.25 | | | 38.5 |

**The curve of concrete maturity *vs* compressive strength obtained from plotting the maturity (=eq. age at 20 °C) and the early strength of the cubes cured in 3 different temperature conditions**



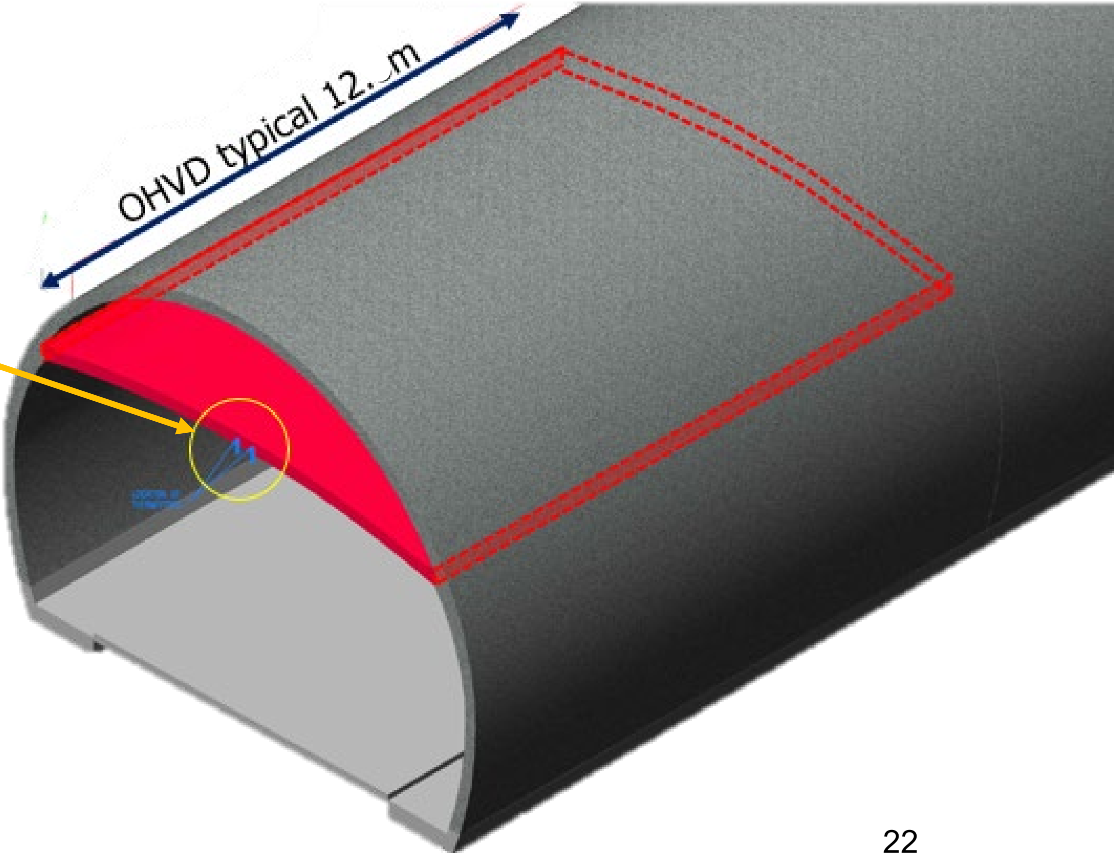



**One maturity value is corresponding to one compressive strength value whatever is the temperature history (for a given mix)**

# B 7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and control of the in-situ early strength through the maturity calculated based on the history of the in-situ temperature (ASTM C 1074)

## Locations of temperature monitoring used to calculate the maturity

*T2 Tunnel section (OHVD)*



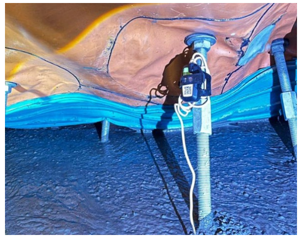

- Locations of the sensors for monitoring the concrete temperature used to calculate the maturity shall be **embedded at a depth of not more than 5 cm** and **where concrete is poured last** (stop end side)
- Temperature sensors shall be installed before concreting
- **Maturity shall start** to be recorded **only once the pour is completed**

- **OHVD formwork can be struck once the concrete has reached the maturity corresponding to the criteria of required minimum strength prior striking**

# B 7. Determination of maturity/strength relationship and activation of energy using Arrhenius law and control of the in-situ early strength through the maturity calculated based on the history of the in`- situ temperature (ASTM C 1074)

## How do we monitor the concrete maturity ?

**By recording the history of temperature from casting and by calculating the maturity (ASTM C1074).**



This can be done using:

- **A temperature reader** using concrete **temperature sensors** embedded in concrete at the critical location and the time and temperature data logged using remote monitoring and data acquisition systems

OR

- A **maturity meter that records temperature and time** using thermocouples embedded in the in - situ concrete at the critical location and that calculates and provides the maturity value using ASTM C 1074 selected law (based on the maturity constant established for the given mix and input in the maturity meter)

# C. THE WAY FORWARD TO CONCRETE CARBON NEUTRALITY

**To increase the percentage of supplementary cementitious materials to a maximum, it is recommended to** (non exhaustive list of actions):

- Use concrete maturity method to control the in-situ concrete strength (or test early strength on cubes cured in Temperature Matched Curing Bath that monitor and match in-situ concrete temperature)
- Adapt the method of construction (including equipment for concrete placing when required)
- **Use adapted additives**
- **Use methods of concrete curing that increase its early strength** (insulation, steam curing)
- **Adapt the concrete specification**
- Adopt a combination of the above proposals

# USE ADAPTED ADDITIVES

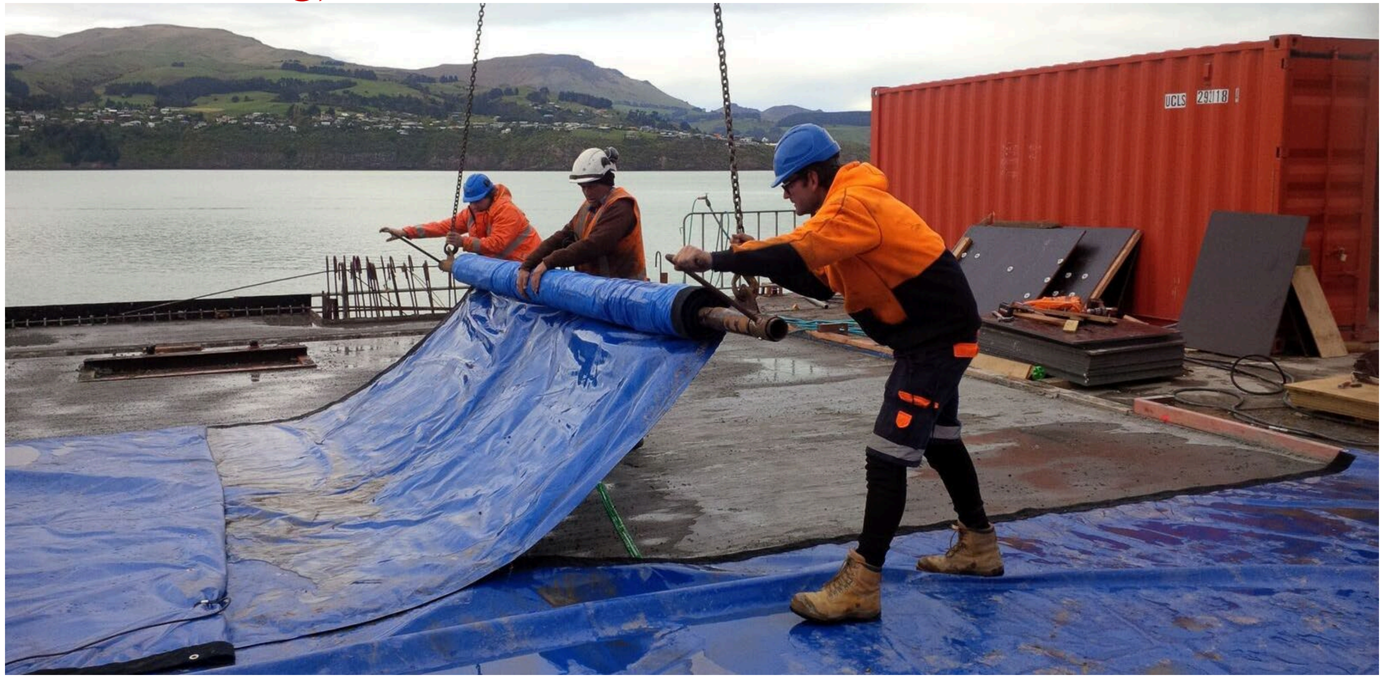
With significant increase of the cost of the concrete mix, there is a way forward to carbon neutrality:

- Using additives already on the market such as **new generation admixtures and/or specific SCM that** allow to design and adopt concrete mixes with **at least 75% GGBS and achieve the required early strength.**
- Using **slag activator that could allow to push the percentage of SCM up to 100%,** meaning concrete without any OPC* (i.e. zero clinker).

As the use of such additives has implication on the cost of 1 $m^3$ of concrete and therefore competitiveness of contractors, **the development and use of such new generation of extremely low carbon concrete will be made possible in the countries where the Governments and Clients will impose specific very low values of maximum $CO_2$ emission on the concrete.**

* Ordinary Portland Cement

# USE METHODS OF CONCRETE CURING THAT INCREASE ITS EARLY STRENGTH
(insulation, steam curing)



Such blankets trap heat and moisture and provides high early age curing temperature. This has beneficial effects on the strength gain of concrete at early age. They are recommended to be used for OHVD if required by the cycle.

The in-situ temperature monitoring and corresponding calculated maturity (or testing early strength on cubes cured in Temperature Matched Curing Bath) allows to consider the **positive effect of the thermal curing on the in-situ concrete early strength.**

# ADAPT THE CONCRETE SPECIFICATION

The **prohibition from the specification to use GGBS in conjunction with PFA** and the reference to **only GGBS, PFA and CSF** as SCM **prevents** the construction industry in Hong Kong **from** optimizing the properties and quality of the concrete and the **reduction of the carbon footprint.**

The use of a combination of GGBS and PFA could, depending on the application, **greatly optimize the reduction of OPC and, at the same time, the properties of the concrete**. We have experienced it on large Tunnel projects in Australia including for concrete mixes with PP fiber.

The GGBS is coming from a by-product of the iron-making, specifically from the blast-furnaces used to make iron that has to be imported in Hong Kong. Thus, producing concrete with GGBS, as the major cementitious component, will make **Hong Kong construction industry highly dependent on the supply of GGBS** that could be **one day an issue.**

Therefore, it is **recommended that Hong Kong also allow the use of SCM other than GGBS and PFA such as CALCINED CLAY, NATURAL POZZOLANA AND LIMESTONE as well as combinations of them.**

# D. Conclusion

Our case study has demonstrated that the use of **GGBS concrete with PPF is a solution** for **casting critical structures in the tunnels** and is a way forward to **reduce the concrete carbon footprint.**

As long as:

✓concrete mix with GGBS is specifically **designed for given needs.**

✓**the in-situ early compressive strength** is evaluated **before striking using maturity method for production optimization** with a **representative maturity function** such as the Arrhenius equation (or/and by testing cubes cured using a Temperature Matched Curing Bath).

# D. Conclusion

**Changes** in Specification and construction methods, use of new admixtures and new SCM, new design of concrete mixes **must be urgently implemented** by the Government, the Clients, the Engineer, the contractors and the suppliers of concrete, cementitious materials and admixtures **to succeed in the challenge of carbon neutrality.**

If we really want to move forward to zero carbon emission, **it is necessary** and urgent **that criteria** linked to maximum concrete $CO_2$ emission (and/or minimum percentages of SCM) be **clearly stipulated in future contracts, so that the Contractors implement the necessary solutions.**

# Thanks for your attention