Reference Materials on

Maturity Method for Estimation of Concrete Strength

Practical Guideline

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Contents

Abbreviation

Abbreviation	**Explanation**
AASTHO	The American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BSI	British Standards Institution
CEDD	Civil Engineering and Development Department
CEN	European Committee for Standardization
CIC	Construction Industry Council
Colorado DOT	Colorado Department of Transportation
DEVB	Development Bureau
DTI	Danish Technological Institute
Ea	Apparent Activation Energy
HKQAA	The Hong Kong Quality Assurance Agency
Hong Kong SAR	Hong Kong Special Administrative Region of the People's Republic of China
LCPC	Laboratoire Central des Ponts et Chaussées
LoRaWan	Long Range Wide Area Network
NEN	The Royal Netherlands Standardization Institute
NFC	Near Field Communication
QC	Quality Control
QSPSCTM	Quality Scheme for the Production and Supply of Concrete

Abbreviation	**Explanation**
Texas DOT	Texas Department of Transportation
TSE	Turkish Standards Institution
UHF	Ultrahigh Frequency
VHF	Very High Frequency
w/c	water-to-cementitious ratio

Executive summary

This practical guideline is intended to assist with introduction of good practice for the implementation of the maturity method in the Hong Kong SAR. It includes the necessary definitions, scientific foundation and practical guidance, and advises on the application conditions.

In writing this guideline we sought to cover the essential and the practical issues without being exhaustive. Throughout this guideline references are provided where additional information may benefit the reader.

The guideline covers most of the practical work carried out by the Research Team on behalf of the CIC. The work consisted of identifying the methods and determining their areas of validity and sensitivity for the various stages in the application of the maturity method.

The ambition of this guideline is to allow the development of the maturity method by providing it with a rigorous methodology that ensures its valid application in construction projects in Hong Kong. The final objective of the Research Team will be achieved when concrete maturity is systematically included in the construction specifications when an estimate of concrete compressive strength at early ages is required.

1 Introduction

The maturity method is a well proven non-destructive testing approach with more than 20 years of application throughout the world. Major signature projects such as bridge structures have employed the method without any negative implications having been identified.

The maturity method involves monitoring of the temperature within the concrete structure. Using calculation methods, the degree of hydration reactions corresponds to the hardening of the concrete. The concept of ‘maturity’ makes it possible to translate the temperature in concrete in the curing state to the concrete’s compressive strength. It integrates the thermal history of the concrete with mechanical strength development.

It is one of the best and also an easy method for assessing the early age strength of concrete in the structure, provided that its use complies with the procedures described in this document and a consistent quality in the concrete supply is assured.

Utilisation of the method brings project benefits in terms of:

1. Safety: a more accuracy prediction of concrete strength in early age can reduce the risk of removing the temporary supports before the minimum strength requirements are met.

2. Quality: with the internal and surface temperature of concrete being known, improvements in terms of the curing process (e.g. reduction of early age cracking of concrete) and consistent finish quality (e.g. removal of formwork at the same maturity level) can be achieved.

3. Efficiency: the removal of formwork and supports depends on the early age strength of concrete. With the early age strength of concrete being known, early removal and re-use of formwork is possible and hence could contribute to accelerating the construction. It should be noted though, the pace of the construction process depends also on other processes, such as rebar fixing and concreting processes and not solely on early concrete strength gain per se.

4. Cost saving: The cost saving is associated with optimal use of material and personnel due to planned cycle times, validated concrete quality for reduced concrete finishing costs, optimized concrete procurement and no traditional testing cubes for early concrete strength needed.

5. Carbon reduction: the maturity method data allows the correlation between maturity and compressive strength. In some situations, this can lead to optimisation of concrete mix proportions and hence promote reduction of cement or utilisation of low carbon cement types to meet strength targets. For example, there can be occasions where the concrete strength exceeds unnecessarily the design concrete strength. This can promote investigations on potential reductions of total cementitious materials content and increases of cement replacement materials without compromising the early and later strength targets.

1.1 Scope

This report constitutes a general guideline for the implementation of the maturity method in construction projects.

1.2 Guideline outline

This guideline offers a quick introduction to the application and beneficial uses cases when strength-maturity relationships are adopted in construction projects.

Subsequent sections include:

- Other strength estimation methods in use
- Discussion of the advantages and limitations of the maturity method
- Application rules such as the definition of critical monitoring points and equipment requirements
- References of projects where strength-maturity relationships have been adopted.

A series of annexes are provided and address:

- Theoretical aspects
- Calibration procedures
- Conformity assessment during both initial production and during construction
- Calculation approach

A method of test for estimation of concrete strength by the maturity method is proposed in Annex 5: HK Maturity Test Method. Sample specification clauses for procurement are given in Annex 6: Sample Specification.

1.3 References

A list of local and international references is provided in Table 1 and provide additional context to the method. These documents have been used to produce this guideline. This guideline follows most of the structure of the *LCPC Guide. Resistance of concrete in the structure. Maturity* and is updated to fit local conditions.

Table 1. Summary of local design and execution standards related to concrete construction and international standards related to application of the maturity method

Origin	**Institution**	**Designation**	**Year**	**Ref.**
Code of Practice, Construction Specifications and Execution Standards				
Hong Kong SAR	Buildings Department	Code of Practice for Structural Use of Concrete 2013 (2020 Edition)	2020	[1]

Origin	Institution	Designation	Year	Ref.
	CEDD/DEVB	General Specification for Civil Engineering Works, 2006 Edition	2006	[2]
Europe & United Kingdom	CEN/BSI	BS EN 13670 Execution of concrete structures	2009	[3]
Maturity Method Application Standards				
USA	ASTM	ASTM C1074 Standard Practice for Estimating Concrete Strength by the Maturity Method	2019	[4]
	AASHTO	AASTHO T 325-04 Standard Method of Test for Estimating the Strength of Concrete in Transportation Construction by Maturity Tests	2020	[5]
	Texas DOT	Tex-426-A Estimating Concrete Strength by the Maturity Method	2010	[6]
	Colorado DOT	Colorado Procedure 69-18, Standard Method for Estimating the In-Place Concrete Strength by a Maturity Method.	2019	[7]
Netherlands	NEN	NEN 5790 Determination of strength of fresh concrete with the method of weighted maturity	2001	[8]
Turkey	TSE	TS 13508 Estimating concrete strength by the Maturity Method	2012	[9]
Technical Guides and other references				
France	LCPC	Guide Technique. Resistance of concrete in the structure. Maturity. Resistance du beton dans l'ouvrage. La maturometrie.	2003	[10]
Denmark	DTI - Danish Technological Institute	TI-B 103 (94) Test Method Activation Energy for the Maturity Method. Danish Technological Institute	1994	[11]

2 Strength estimation methods in use

A reliable and accurate estimation of concrete strength is critical and of great benefit as a part of the concrete construction process. In particular, predicting strength enables designers and contractors to:

- Safely release formwork or remove falsework because minimum strength has been achieved;
- Decide when pre- or post-tensioned loads can be applied into the structure;
- Determine the curing time required for cold weather; and
- Decide when to lift precast concrete elements.

In Hong Kong, the traditional methodology for the monitoring of concrete strength on site is cube testing. While this method is well-established, direct, and straightforward to use, it is also labour intensive and time consuming due to the need to wait for the concrete to be tested at regular intervals. This methodology is provided in CS1:2010 Testing Concrete [12].

Other strength test methodologies in use globally include:

- **Rebound Hammer (BS EN 12504-2** [13]**):** also known as the Schmidt Hammer method. This test measures the rebound distance of a hammer, which can then be correlated to a strength value based on cored cylinders previously obtained.
- **Penetration Resistance (ASTM C803** [14]**):** The surface of concrete is exposed to a small projectile which is driven into the concrete. The depth of the penetration achieved can be correlated to the strength of the concrete.
- **Ultrasonic Pulse Velocity (BS EN 12504-4** [15]**):** A velocity of propagation of a pulse of vibrational energy through the concrete is determined. This velocity can be correlated to the elastic modulus and density of the concrete, which can be loosely correlated to the strength.
- **Pullout Test (ASTM C900** [16]**):** A cast-in-place or post-installed metal rod is ‘pulled’ from the concrete. The pulled shape and the force required can be correlated to the concrete compressive strength.
- **Drilled Core (CS1:2010 Section 15** [12]**):** Removal of a core from the placed concrete for use in laboratory compressive strength testing.
- **Cast in Place Cylinders (ASTM C873** [17]**):** A cylinder mold is prepared at the same time as the concrete is poured. This casting is used for destructive laboratory strength testing.

In other regions worldwide, including the USA and Europe, an alternative methodology for estimating early-age strength of concrete, known as the ‘maturity method’, is widely used. This methodology enables the early-age in-situ concrete strength to be estimated in-situ before concrete is placed. This results in benefits including the following:

- Generally: the optimisation of construction scheduling and hence productivity, as well as potentially reducing the overall construction time; and

- In particular: the optimisation of the cycle time, including when post-tensioned tendons may be stressed, when concrete formwork may be removed, and when shoring and re-shoring operations can begin.

Reference should be made to REP001 *Application of Maturity Method for Determination of Early-age Concrete Strength in Hong Kong Construction Industry – Desktop Study* [18]for further discussion of the history and use of strength estimation methods including the maturity method.

It shall be noted that cube testing for compliance with design concrete strength requirement should not be replaced by the maturity method, which is only used for determination of the early-age concrete strength.

3 Maturity method

3.1 Definition

Maturity method is a non-destructive method which evaluates concrete's in-place strength by relating time and temperature measurements to actual concrete strength with empirically derived mathematical formulas, thus enabling users to estimate the strength of the concrete on site in real time without reliance on cube test specimens and laboratory testing.

The method involves direct measurement of the temperature-time history of the concrete on the basis of the direct relationship of concrete strength to hydration temperature history. In practice, the method utilises temperature sensors embedded in the placed concrete. As temperatures are measured during the curing process, real-time data is collected, and the strength development of the concrete can be live-mapped.

The relation between strength and maturity is specific to a concrete mix design, and so pre-calibration of this curve through testing is required for each concrete mix composition.

3.2 Scientific foundation

The maturity method, which can be used for early age strength estimation (less than 14 days) is based on the fundamental assumption that for a given concrete mix design, whenever it is poured, it will have the same compressive strength at its current "maturity index". For example, a given mix design may reach the same compressive strength after 3 days of curing at 23°C as it would after 7 days of curing at 10°C.

The scientific basis for this assumption is the fact that when concrete cures, heat is created due to hydration of the cement. This heat is trapped within the element, and acts to increase the curing rate of the concrete. Hence, we are able to predict the strength of the element based on the variation of temperature within it as it cures.

The relationship between concrete strength and temperature is specific to individual mixture designs. Therefore, a key step in this process is the pre-calibration of this relationship for each mixture.

There are two commonly used mathematical maturity models which can be used to express the combined effect of time and temperature on the strength development of concrete mixtures. These are:

- **Nurse-Saul method:** Known as the Temperature Time Factor, and commonly used in standards and practice documents, this function assumes that the rate of strength development is a linear function of temperature. This method is therefore less frequently used than the Arrhenius method.

Equation of Nurse-Saul method:

$$M = \sum_{0}^{t} [T - T_0]\, \Delta t$$

where:
M = Maturity index or temperature-time factor, in °C·hours,
T = average temperature of concrete during time interval Δt, in °C,
T_0 = datum temperature, in °C, (usually taken as -10 to -12°C if not explicitly calculated) and
Δt = time interval, in hours

- **Arrhenius method:** This method derives from the Arrhenius equation, which considers the apparent activation energy of the cement. This maturity function computes equivalent age at a specific temperature by assuming that the rate of strength development obeys the Arrhenius equation, with an equivalent age at a specified temperature.

  Equation of Arrhenius method:

$$t_e = \sum \left[e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \right] \Delta t$$

where:
t_e = equivalent age at a specified temperature T_s, in hours,
Q = activation energy divided by the gas constant (E_a/R), in K,
T_a = average temperature of concrete during time interval Δt, in K,
T_s = specified temperature, in K, and
Δt = time interval, in hours

Reference should be made to REP001 *Application of Maturity Method for Determination of Early-age Concrete Strength in Hong Kong Construction Industry – Desktop Study* [18] for further discussion of the relevant equations.

3.3 Advantages

When compared to traditional methods based on information from test specimens, the advantages of the maturity method derive from the representativeness of temperature measurements obtained from critical points of the structure.

Benefits of using the maturity method for estimation of early-age concrete strength include the following:

- **Non-destructive test procedure.** Information is gathered through embedded sensors in the concrete. These sensors feed data back which can be logged or retrieved by an external device in real-time without the need to damage the concrete.
- **Real-time.** There is no need to wait for a particular test time or for the results of multiple tests, which may be delayed due to laboratory or site scheduling constraints. The strength of critical points is estimated based on real-time sensor data.
- **Increased reliability**
    - When sensors are functioning correctly, data can be logged without interruption, and so results can be delivered consistently.
    - The actual in-place strength of the concrete is predicted directly.
    - With careful sensor placement, the method may be able to identify local variation in strength for different locations on the structure.
- **Cost efficiencies**
    - Financial savings from early completion of the project.
- **Carbon efficiencies**
    - Anticipation and improved accuracy in estimating compressive strength warrants cement reduction or utilization of alternative low carbon cements.
    - Reduction of carbon from early completion of the project

3.4 Limitations

The method is not applicable, not recommended or its use suspended if one of the following conditions is met:

1. Concrete without production control certification e.g. QSPSC™ administered by HKQAA.
2. Variability in mixture proportions that results from the batching operation is outside the tolerances given by section 8 *Conformity Control* of BS EN 206 [19].
3. A significant change in cement composition or physical properties, cement manufacturer, composition of additions such as fly ash or physical

properties, or fly ash supplier, which requires verification and possibly a new calibration (development of strength-maturity relationship).

4. A change in water-to-cementitious (w/c) material ratio of 0.05 or higher is the maximum tolerable before strengths from the maturity curve deviate significantly from that otherwise predicted. This is valid for w/c up to 0.40. For w/c below 0.40, the maximum tolerable change in w/c is 0.02. It is noted that for high strength concretes with w/c below 0.35, the strength estimates from maturity methods may become less accurate/consistent.
5. If aggregate proportions are changed in excess of those acceptable within BS EN 206 [19], a new strength-maturity curve needs to be developed.
6. If coarse aggregate sources change, for simplicity of process, it shall be assumed that the strength maturity relationship is no longer valid.[1]
7. Apart from the tolerances described herein, the user should also be aware that the limitations on mix design and batching operations and the tolerances specified in the Quality Scheme for the Production and Supply of Concrete are to be respected.

[1] However, in some cases, the strength-maturity curve may remain unchanged only if the heat released by the concrete remains unchanged. To validate this assumption, semi-adiabatic calorimeter method may be employed to compare heat generation between old and new mixes. Alternatively, casting, curing and testing concrete cubes at 3, 7 and 28 days with the new aggregate source may be employed so that strength development between existing and modified mix is compared.

4 Application rules

4.1 Essential concrete mix requirements

The maturity concept assumes that the concrete mix used in the structure is the same as the concrete mix that has been subject to calibration. This requires good production control of the concrete and its constituents, as well as monitoring of variations in terms of mechanical characteristics at early-age.

It is necessary to limit the variations in water dosage within a maximum range of ±10 L/m3 of concrete and to obtain a commitment by the producer of regular performance of the cement utilised e.g. significant change in terms of water demand and the resistance to early-age in accordance with BS EN ISO 196-1 [20]. The time where water was added in the mix and concrete placement shall be recorded.

4.2 Selection of critical monitoring points

This involves studying the locations of critical points in the structure by considering the stresses at the various points and the time corresponding to the application (at the time of striking/ removal of falsework or prestressing / post-tensioning). This work should be carried out by the structural engineer responsible for temporary works or pre-stressing works depends on the application. Once the critical points are selected, the number of sensors and their positions are then determined.

For placement of sensors, the following should be observed:

1. Sensors must be placed at each location where an estimation of the in-place strength of the concrete is desired.
2. Sensors must be placed at all critical locations where the strength of the concrete in-place is of the greatest concern due to structural considerations or exposure conditions requirements.
3. For an important structural element, e.g. one with high public or worker safety consequence in the event of a collapse, it is prudent to place 2 sensors for a given critical point (i.e. to provide sensor redundancy in case one of the two is damaged or disconnected).
4. The locations of the sensors to be implanted must be accurately recorded on a diagram attached to the maturity control procedure, to be established by the responsible engineer for each particular operation.
5. All sensors (with or without a thermocouple wire) should be installed before concreting. Special care should be given on robustly mounting sensors on the desired locations to ensure that no sensor dislocation would occur during concrete casting.
6. All temperature-sensing tips should not be in contact with any steel reinforcement and should be placed in the concrete except for those sensors which are designed to be directly fixed on reinforcing steel.

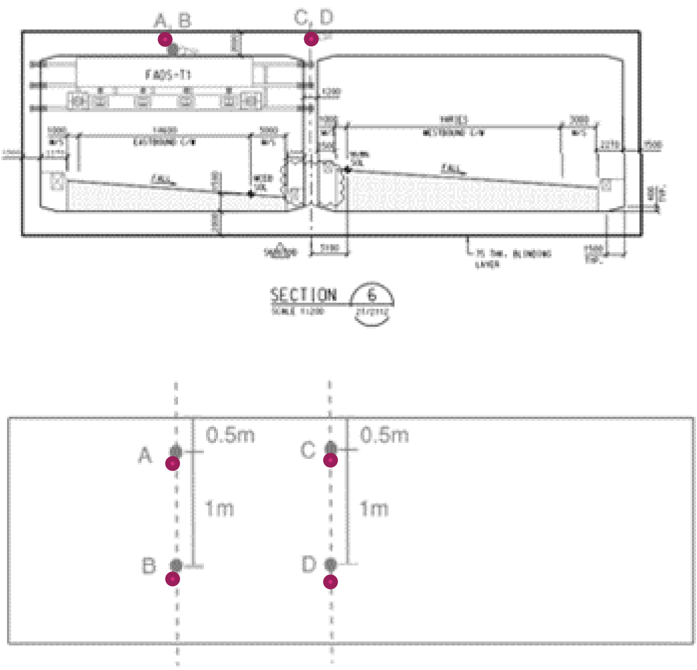
7. Sensing tips must be placed close to surface exposed to ambient temperature or weather conditions. (usually to not more than 50mm from the exposed surface).

Examples of critical points are found below and illustrated in

Figure 1 but should consider location of stress mobilization at time of striking and lowest expected temperature.

1. Middle of span for simple supported beam/slab[2]
2. Middle support for two span continuous beam/ slab [2]

The critical points may vary depending on the application and the above examples are for reference only. Additional examples of critical points include zones next to anchorage ends where post-tension is applied.



Plan view of the roof slab (for indicative only not the actual plan view)
At least 0.5m away from the edge

Locations A, B target maximum positive bending moments and are duplicates. Locations C and D target maximum negative bending moments and are duplicates for redundancy. Temperature sensors shall be placed in sections where stresses are mobilized at time of striking but should consider surfaces where lowest temperature conditions are expected

Figure 1. Indicative locations of temperature sensors during execution of cast-in-place roof slab during cut and cover tunnel construction.

[2] The surface at the top is usually the one exposed to ambient environment and the one with more heat loss. As such, the temperature and consequently, strength, is expected to be the lowest at this region. The bending moment which can cause issues after removal of formwork/falsework is that at the tension side, so at the bottom part of the element usually. The temperature at the bottom, though, will always expected to be greater that the temperature at the top because the former is in contact with the formwork materials, whist the top is often exposed. As such, it is deemed conservative to estimate the strength of the concrete based on the top (exposed) surface temperature at is will always expected to be lower than the strength at the bottom surface at early ages.

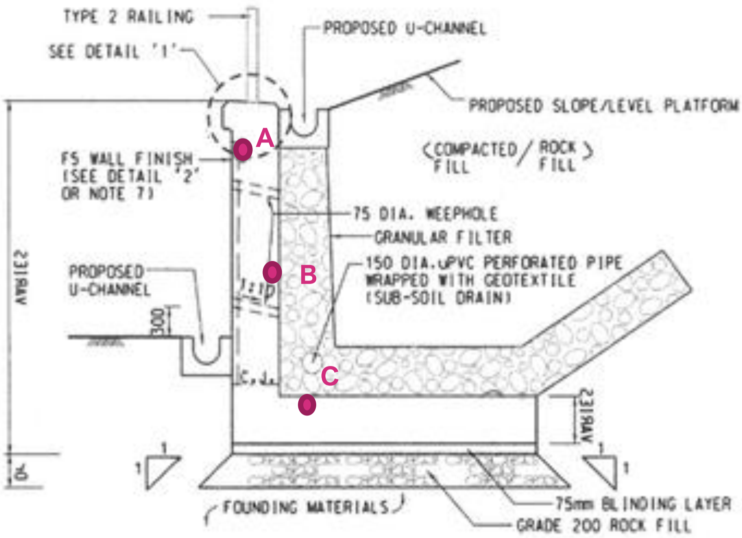
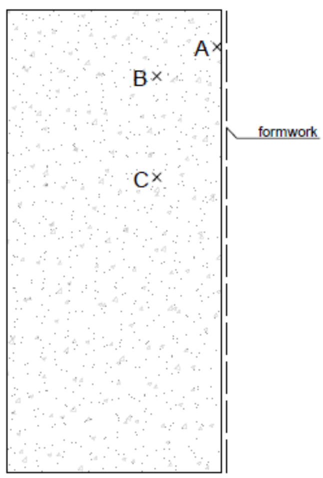
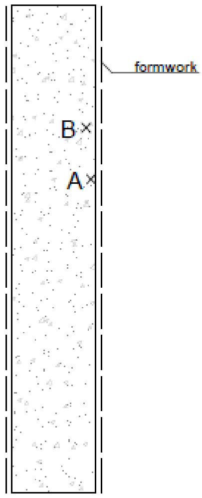
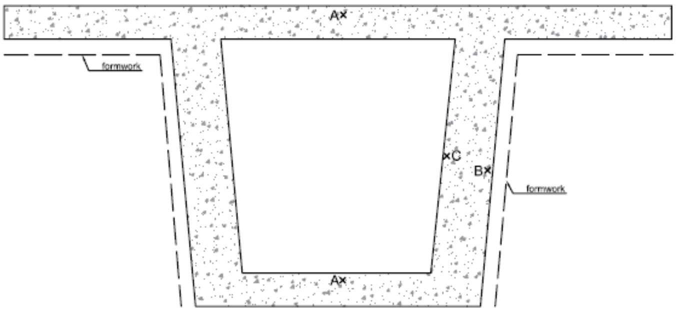
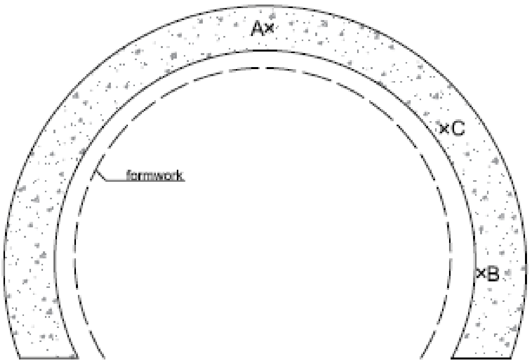


Figure 2. Indicative locations of temperature sensors (A, B and C) during execution of retaining wall construction. At one monitoring location, e.g. location B, should contain an additional sensor for redundancy

Table 2. Example of sensor location for different structural systems

Areas of use	Examples	Locations
Mass concrete structures		A – Measuring point in the structural surface member (within 50 mm) B, C – Measuring point in deeper section

Areas of use	Examples	Locations
Climbing formwork		A – measuring point installed at 50mm depth from surface (at 2/3 distance from bottom) B – measuring point installed at 50mm depth from surface (top ¼ of the wall)
Bridge formwork		A – measuring point at slab location B – Measuring point at wall location (installed 50mm depth from external surface) C – Measuring point at wall location (installed 50 mm depth from internal surface)

Areas of use	Examples	Locations
Tunnel Formwork		A – measuring point at crown location B – measuring location at wall section C – measuring location at mid-section

4.3 Equipment types

There are many types of equipment available as commercial products. In general, they have two components namely the temperature sensor (usually in the form of a cable with a temperature-sensing tip) and a maturity sensor. Temperature is recorded by the temperature sensor and data is sent to the maturity sensor. The maturity sensor records all the temperature data and exports it to the user by direct wiring, NFC or Bluetooth or sub-gigahertz channel.

Table 3. Summary of equipment types and measuring methodology

Type	Methodology
Direct wiring	Maturity sensor usually consists of a memory chip which can store temperature data for 28 days. Once the maturity sensor is connected to the data receiver device (PC/notebook/tablet/smart phone) by cable, data stored in the memory chip will be transferred to the receiver device.
NFC or Bluetooth	Maturity sensor has both a memory chip and a NFC or Bluetooth device embodied in it. When the maturity sensor is connected to a NFC or Bluetooh receiver, data will be transferred to the receiver. As Bluetooth can only cover a distance of not more than 10 meters, should continuous monitoring be required, the receiver must be installed close enough to the maturity sensor. The receiver could also be a signal transmitter which transmit the data into a cloud through WiFi or other means.
Sub-gigahertz Device	Instead of using NFC or Bluetooth, some maturity sensors use sub-gigahertz channels such as a LoRaWan system which can cover up to 3km in rural areas. With maturity sensor of this kind, a sim card is generally required. Some system requires a LoRaWan receiver to collect the data and then push it to a cloud. This

Type	Methodology
	means that the user can install many maturity sensors and sensors with just one LoRaWan receiver. The LoRaWan receiver will send the data through 3G/4G to a cloud in a 7-24 manner.

With reference to the above, the user should select the appropriate equipment for their application.

4.4 Equipment requirements

All the equipment necessary for application of the maturity method are commonly grouped together under the generic name of the maturity sensor and sometimes called sensors.

Today, maturity sensors have reached a more or less advanced degree of integration of the functions, including, but not limited to: measurements, data acquisition, calculations and visualization of the results in particular in the form of concrete resistance. All of these can be directly interpreted by the construction team.

Maturity sensor and its temperature sensor must have the required qualities (durability, robustness, waterproofing, autonomy, etc.) to be used under site conditions. Care must be taken in the field to ensure that over-exposure to the sun does not occur and prevent inspectors from reading the LCD display. Furthermore, to prevent theft of maturity sensors and associated instrumentation during the field-monitoring phase it is recommended that they be either secured or disguised.

Although the material quality of both the maturity sensor and temperature sensor is fundamental to the correct implementation of the method, this is not sufficient. *A priori* requirements involve the determinations of a certain number of parameters which are essential for the correct use of maturity method. In this sense, meters with programmable features such as variable datum temperatures and/or activation energies are preferred over simpler models because of the flexibility they offer.

As specified in the following section, any concrete intended to be monitored by the maturity method must be “calibrated”. This preliminary calibration consists in determining the apparent activation energy of the concrete (Ea or Ea/R in its reduced form) and the reference curve where the compressive strength is given as a function of its equivalent age [Rc = f (te)].

The maturity sensors are proprietary products essentially measuring temperature and time. The manufacturer is responsible for providing certifications of sensor soundness and calibration.

4.4.1 Equipment and methods

The equipment and methods necessary for use of the maturity method in construction projects must allow:

- measurement of the concrete temperature,
- storage of temperature measurements at an appropriate time frequency and easy to read time format
- calculation of the equivalent age and compressive strength associated with these measurements.

Miniaturization and evolution of wireless transmission methods made possible the introduction of new sensor technology that integrate temperature measurement with data acquisition and transmission in the same housing unit.

With regards to correct temperature measurement, this is performed using thermometers or other type of temperature probes. The most widely used are of two types:

- thermocouple cables (type T, type K, etc.)
- resistive probes (thermistors, platinum probes)

These probes are connected to a transducer which transforms the measured analogue quantity (voltage for thermocouples, electrical resistance for thermistors and platinum probe) into a physical quantity (degrees Celsius). A storage unit is required to record all measurements at a preestablished time frequency. These measurements are thus recorded in a system file for further download and processing. In the majority of the situations, the measurements can be automatically retrieved and processed by a calculation module resulting in the determination of the corresponding equivalent age.

4.4.2 Equipment acceptance

In the absence of any Hong Kong normative document, this Guideline offers recommendations on the characteristics that the equipment must have and on their uses. These recommendations should help in the qualification of equipment intended for maturity on construction sites. However, it is recommended to present the equipment envisaged for the approval of the client or Asset Owner, prior to use in any worksite.

4.4.3 Characteristics of the equipment

4.4.3.1 The temperature probe

Requirements

The temperature probe is an active measuring device which will be placed in contact with the concrete (either lost and directly embedded in the concrete, or recoverable and placed in a reserve tube in the concrete) and a connecting cable which will connect it to the acquisition unit or maturity sensor.

Regardless of the type of probe used, the connection cable will be shielded if certain electromagnetic disturbances may exist on the site or its direct environment. A priori, the cable length has no influence on the measurements, for a resistive probe connected in 4 wires, because the line resistance is compensated.

In practice, it is prudent to limit the single length of probe to 100 m. The length of the resistive probe cable connected in 3 wires must not exceed 50 m. In both cases, provision must be made not to expose the cables directly to sources of external heat. In addition, temperature-sensing tip should not be in contact with steel reinforcement.

Figure 3. Example of sensor installation with temperature sensor tip not in contact with reinforcement

With regards to utilization of wireless sensors or transmitting devices utilizing Bluetooth, mobile networks (e.g. LTE/3G/4G), Wi-Fi, or radio modems (UHF/VHF) there is the possibility of transmission interruption or fail (range shortage, path loss due to new obstructions, etc). To ensure that no data gathered by the sensors is lost, it is necessary to have a storage component so that data can be stored retrospectively and before the desired striking event.

Calibration of the temperature probes before use should be considered within the range of foreseeable temperature values and rate of temperature increase. In the absence of this calibration, the supplier or user of the probes must provide certificates of temperature calibration.

Thermocouple wire

Thermocouple wire is the most widely used type of temperature probe, but it is also the least precise. Special precautions apply before its use :

- the active section of the wire must be protected only in the case of reuse,
- the wire length must not exceed about 30 meters
- as it is expected that the concrete temperature exceeds 30 ˚C, the calibration curve may no longer be linear. In this case, it must ensure that the necessary corrections are adopted.

Note: Some manufacturers avoid the use of long cables and use the radio to transmit the temperature readings to the maturity sensor or data acquisition unit by radio. In this case, it should be checked that the temperature values transmitted by radio are indeed identical to those obtained by direct reading.

4.4.3.2 Specifications of the maturity sensor / data acquisition unit

Temperature measurement and recording

In the case that the supplier of the maturity sensor / data acquisition unit is not the supplier of the temperature probes, then he must clearly indicate the type (s) of probes to be used and how these may be connected to the device.

The temperature is measured by a transducer suitable for the type of probe connected. The precision of the temperature acquisition chain must be less than or equal to ± 1 ˚C in absolute.

The measurement acquisition frequency can be set using the internal clock indicating the date, the local time in hours, minutes and seconds. The acquisitions will be made either at time intervals not exceeding 20 minutes, or at temperature intervals not exceeding 2 ˚C, whichever is less.

The maturity sensor / reading unit can offer the possibility of connecting several probes. In this case, it is preferable that the user has the possibility of starting and stopping the measurement and the recording on each channel at a given or desired time.

The use of measurements: the calculation of the equivalent age

The only accepted method for this calculation is that using Arrhenius' law. For each probe and therefore each measurement channel, the calculation must take into account the thermal history of the concrete from mixing. If this thermal history is not known, it is possible to consider that the temperature is constant between the instant of mixing and the first measurement carried out, and equal to this value.

The calculation must be carried out by considering, over the chosen time interval, an average temperature equal to the arithmetic mean of the values measured at the start and at the end of the interval. For a temperature acquisition every 20 minutes, the calculation method must be as precise by considering an average temperature over each time interval. For example, if there are two readings of temperature during a time interval of one hour, the average of these two temperature readings should be used in the calculation of the equivalent age (or maturity) during this time interval.

The selected maturity sensor will offer the possibility of entering a value of the activity coefficient Ea/R and/or apparent activation energy Ea. Ea/R should be rounded to the nearest 50 K and apparent activation energy Ea rounded to the nearest 500 J/mol.

This apparent activation coefficient of the concrete must be determined at the end of the concrete calibration phase.

Strength estimate

If the maturity sensor has a function of estimating the compressive strengths of concrete at early-age, it must offer the possibility of entering a reference curve (compressive strength as a function of the equivalent age), obtained experimentally during calibration phase, either in the form of a parameterizable mathematical function, or in the form of a table of pairs of values (equivalent age / mechanical resistance).

Documentation and data files to be made available

Before any maturity operation, the user provides the concrete calibration file which specifies the apparent activation coefficient of the concrete and the reference curve, as well as the installation plan of the probes.

At the end of the maturity monitoring, the device must be able to provide, for each probe installed in the structure, the following elements:

- the evolution of the temperature of each probe, either in the form of a table or in the form of a graph [θ ° C = f (t)]
- Times expressed in local time, together with a time zone offset in hours and minutes. Local date format yyyy-mm-dd should be used.
- the calculation of the equivalent age for each probe,
- the reference curve used for the prediction of the resistance, if the device/platform estimates it.

This information can be furnished in paper or on computer.

4.5 Calibration

The determination of the apparent activation energy and of the reference curve can be the subject of preliminary tests in laboratory, for example during mix development stage.

With a view to maturity monitoring, it is recommended to initiate the implementation of this technique during these preliminary tests.

In all cases, validation tests are essential in industrial operation, on concrete produced in a ready-mix plant.

It is natural to schedule these tests in conjunction with other tests of convenience e.g. compressive strength of sister samples.

The principles of the different calibration steps are shown below.

4.5.1 Determination of apparent activation energy and calibration curve

The apparent activation energy describes the sensitivity of concrete to temperature and can be determined by verifying that a given concrete formula, subject to significantly different temperature histories, leads to the same equivalent age / strength correlation.

This differentiation is obtained, for example, by making two series of test specimens from the same load, one stored in an outdoor environment (or in a laboratory at 20 ˚C) and the other in quasi-adiabatic conditions (in insulated box). By crushing these specimens at different times while noting in parallel their maturity obtained from their temperature history, two curves are constructed which are adjusted by varying the apparent activation energy according to the superposition method (see Annex 1: Theoretical aspects).

The two curves obtained make possible to define a time zone whose lower envelope is considered as the calibration curve. The apparent activation energy obtained is only validated over the temperature range corresponding to the extreme histories tested.

Even if a first calibration has been carried out in the laboratory, it is necessary to carry out an on-site control calibration from the start of the site and to check the validity of the data obtained in the laboratory.

The preliminary calibration in the laboratory has the advantage of being able to test a temperature range wide enough to encompass the envelope of site conditions. It can also be based on heat release tests and not on mechanical tests (for the determination of Ea).

Annex 2 specifies the detailed procedures for laboratory and on-site calibration tests and for the use of the results. The different stages are presented on flowcharts. Examples of operations are given in Annex 4: Obtaining the apparent activation energy and the concrete calibration curve.

4.5.2 Validation

The calibration curve obtained by the superposition method should not be confused with the reference curve. It is necessary to consider a correction factor that accounts for variations in performance at a young age.

This correction factor is established from the data collected at the start of the construction site during an observation period. During this period, both the structure and test cubes are provided with temperature probes to regularly check the correlation maturity / resistance. The envelope obtained makes possible to establish the default reference curve. We recommend an observation period of at least three weeks and composed of at least 6 different concrete batches distributed over this period.

Refer to Annex 3: Conformity assessment for detailed procedures for initial compliance checks.

4.6 Conformity assessment

The original maturity/ strength relationship obtained shall be reviewed at each specific assessment period or when there are significant changes in the production conditions.

A distinction should be made between the initial set up and continuous production:

1. Initial set up: which involves the validation of the calibration and the establishment of the reference curve
2. Continuous production or during construction: to check the conformity.

It is necessary to carry out periodic compliance checks to verify or limit deviations in performance of concrete strength at early-age.

Typically, conformity assessment is carried out at least monthly.

Furthermore, if the temperature conditions deviate from the range corresponding to that of the calibration (5 °C deviation), it is necessary to verify the calibration results by a conformity check. This is necessary if the temperatures are lower than during calibration, during which time discrepancies are possible depending on the specifics of the admixtures in the concrete.

The regular control procedures during construction are also detailed in Annex 3: Conformity assessment.

5 Application examples

Not exhaustive, Table 4 lists some recent signature construction projects where the maturity method was used. Although, the maturity method of estimating strength is typically utilized to predict compressive strength, the same principles can be applied to estimate flexural and tensile strength. In mainland China, the same principles were employed to estimate the influence of temperature, age and curing conditions in the resulting fracture energy of concrete for super-high dams [21].

Table 4. Construction projects where the Maturity Method was used

Year	Project	Type of structure	Location	Reference
1989	Kwun Tong Bypass	Viaduct	Hong Kong, China	Arup [22]
1998	Vasco da Gama Bridge	Bridge	Portugal	Sensegreen Europe [23]
2000	Channel tunnel rail link Medway bridge	Bridge	UK	Waller et al [24]
2001	Rion–Antirion Bridge	Bridge	Greece	Sensegreen Europe [23]
2004	Millau Viaduct	Viaduct	France	Sensegreen Europe [23]
2008	Freedom Tower, World Trade Center	High Rise Building	USA	Wake Inc. [25]
2012	The Shard	High Rise Building	UK	Adrian Thomson, Don Houston, Bart Lemmens [26]
2012	Lee Tunnel	Tunnel	UK	John Greenhalgh [27]
2017	Chelsea Barracks	Residential Building	UK	Jacqui Royall [28]
2018	The Coastal Highway Route E39	Bridge	Norway	Maturix / Kruse-Smith [29]
2020	Karla Tower	High Rise Building	Sweden	Maturix / Serneke [30]
2020	Science & Technology Parks Corporation’s Advanced Manufacturing Centre (AMC)	Logistics/ Commercial Buidling	Hong Kong, China	World of Cement [31]

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A1 Annex 1: Theoretical aspects

A1.1 Maturity method

The maturity method is a method for in-situ strength estimation developed initially in the 1950s. Since then, it has been researched, analysed and improved considerably from different researchers and engineers. As the scope of the present document is on providing guidelines for the application of the maturity method in Hong Kong, it does not extensively cover the fundamental and advanced theoretical aspects of the maturity method. Therefore, the user is referred to [32] for more elaborated theoretical aspects of the maturity method.

A1.2 Calibration of current cases

The calibration of the current cases was conducted using a rigorous approach in order to reduce uncertainty over strength predictions from the maturity method. Appropriate calibration of the maturity model is of paramount importance so that the accuracy of the maturity method in predicting the in-situ strength development in concrete is maximised. The calibration of the considered maturity models in the current cases generally involved:

- Casting and curing concrete specimens at three different curing temperatures.
- Testing of concrete specimens for compressive strength at predefined time intervals.
- Identifying the Strength-Maturity (or Strength-Time) relationship to be used. For example, the FHP-TPE (exponential function) [33] [34] and ASTM C1074-19 (hyperbolic function) [4].
- Fitting the experimental results using the above-mentioned functions. This can be accomplished for example with regression analysis using specialized statistical software or through specially modified spreadsheets. The aim of this step is to determine the regression parameters at the reference temperature in order to facilitate a prediction of strength later on and the regression parameters at all other temperatures in order to calculate the apparent activation energy.
- Assessing the quality of the fit (e.g. through evaluating the R^2 figure from the regression analysis) before proceeding to the validation stage.
- Calculating the apparent activation energy of the concrete as described in Annex 4: Obtaining the apparent activation energy and the concrete calibration curve.

A1.3 Improvement for concretes with long dormant periods

In the particular case of concretes with a long dormant period (the case of concretes with high slump retention example) the calibration is slightly different from that of current cases by distinguishing the dormant period from the rest of the life of the concrete.

The instant at the end of the dormant period then corresponds to a "characteristic time" t*, beyond which the maturity sensor is applied in a conventional manner.

A1.3.1 Characteristic time

Definition

The characteristic time t* is used in the case of concretes with a long dormant period. This characteristic time marks approximately the end of the dormant period and the start of setting. The specifications that it must meet are as follows:

• t* must be "measurable": it must be able to be determined objectively, that is to say with satisfactory precision (repeatability).

• t* must be “significant” from the point of view of maturity: it must reflect a state of maturity (degree of hydration identified by a mechanical method, e.g. setting time test or strength test, or calorimetric method, e.g. heat of hydration test) constant whatever the history of temperatures followed by the material.

• t* must be "relevant": the possibility of applying the maturation conventionally beyond this moment should be verified.

Determination

There are three possibilities for determining the time t* in the structure:

1. The time t* can be measured directly in real time and in-situ by appropriate technical equipment, such as ASTM C 403 [35].
2. The time t* represents the workability time and is the time elapsed between mixing and the point in time by which the temperature has risen by +2 ºC over the initial temperature. It provides the basis for the assessment of workability time (Figure 4). At any rate, the permissible workability time is limited to a maximum of 3 hours, unless specialty admixtures such as hydration stabilizing admixtures are utilized. Construction-site influences (temperature, natural moisture of aggregates, cement temperature) have to be considered when assessing the actual workability time.
3. The change in t* with temperature can also be modelled on the basis of laboratory tests in which t* is measured by appropriate technical equipment. The Arrhenius's law can be applied during the dormant period by associating with the latter a particular apparent activation energy, a priori different from the apparent activation energy that is characteristic of early-age curing. From an engineering point of view, assuming zero strength up to the end of

the dormant period is deemed sufficient for the purpose of maturity estimation.

In this case, it is necessary to go through a calibration step before using the principle on site. This method is outside the scope of this guideline and is defined elsewhere [10].

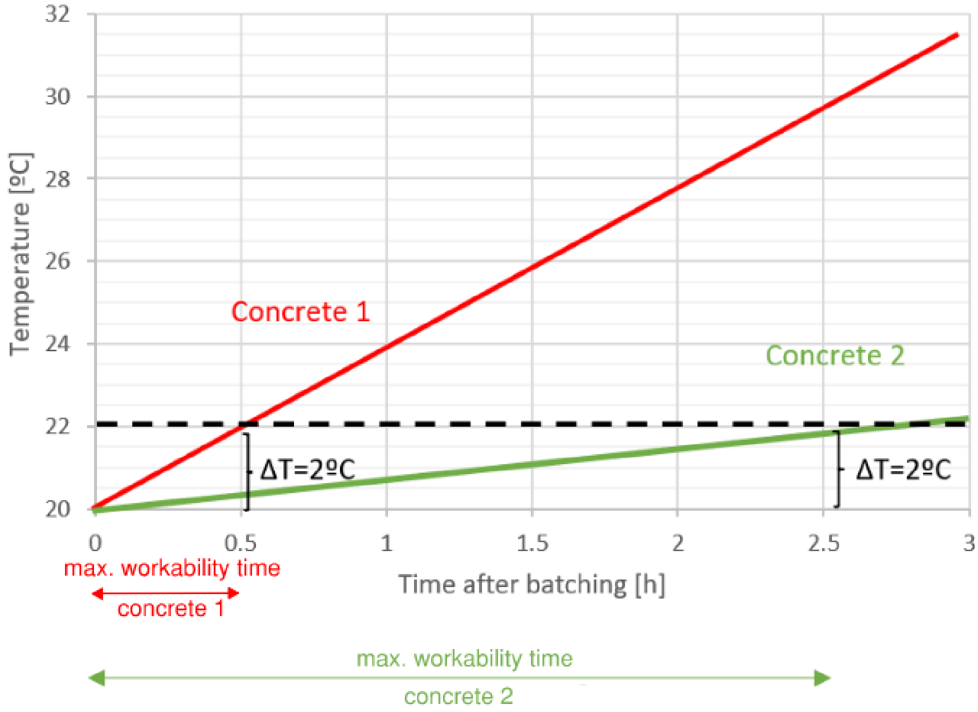


Figure 4. Principles for the assessment of workability time for concretes with long-dormant period

A2 Annex 2: Calibration procedures

The purpose of this annex is to describe the procedures for calibrating a concrete composition with a view to use the maturity method on site. Once the target strength range is defined, calibration procedure involves laboratory and on-site validation tests.

The result of the calibration consists of the calibration curve[3] of the concrete formula studied and its apparent activation energy. These results are only valid over limited temperature and resistance ranges.

The general objective of the maturity method aims to estimate the strength of concrete at certain so-called "critical" points of a structure. The minimum strength requirements are "target" values and are generally specified by the responsible engineer.

A2.1 Calibration procedure

This section describes the experimental methods used to determine the apparent activation energy and the calibration curve of the concrete.

The apparent activation energy can be determined using two methods:

1. Mechanical approach using compressive strength tests.
2. Heat of hydration approach using calorimeter tests.

This guideline proposes the determination of the apparent activation energy by measuring compressive strength development at 3 different temperature levels. Cube testing is executed at a pre-established time for each respective temperature level.

The heat of hydration approach is not described in this Guideline and found elsewhere [10].

It should be noted that as the apparent activation energy is deemed to be property specific, for compressive strength prediction purposes, the most appropriate method to determine the apparent activation energy should be based on compressive strength results, as noted elsewhere [33], [36], [37], [38].

[3] The concrete calibration curve will become the concrete reference curve once the initial compliance checks have been carried out (see Annex 1).

A2.1.1 Representativeness of the formula tested during calibration

The concrete tested during calibration must represent the concrete to be placed in the structure:

1. The mix design and mixing procedure must be the same and representing the volume of concrete to be placed during actual construction work.
2. The temperature range experienced during curing: the temperature profiles tested must correspond as closely as possible to the temperature range experienced during construction[4].

A2.1.2 Calibration testing plan

Derivation of the apparent activation energy is done utilizing compressive strength testing. The test plan and process is summarized in Table 5.

Table 5. Summary of testing requirements and process during calibration phase

Test phase	**Requirements**
Production of concrete	Concrete intended to be used on site. Concrete with production control certification e.g. QSPSCTM administered by HKQAA. Concrete to be manufactured by same production unit to be used during construction.
Test specimens: Calibration	Test specimens made in accordance with the standardization valid in Hong Kong. Appropriate test standards include CS1:2010 Section 7 Making test cubes from fresh concrete and CS1:2010 Section 12 Determination of compressive strength of concrete cubes. The type of test specimens, as well as the nature of the mould, must be the same as those used during QC activities. The number of specimens required depends on the number of specimens that constitute one strength determination and the number of temperature levels considered to measure strength development. As an absolute minimum: 1. 2 no. specimen to embed temperature sensor. 2. Three different temperature levels are proposed for Hong Kong climate (25 ºC, 40 ºC and 55 ºC) 3. 2 no. specimens for each pair temperature/age.

[4] These ranges can be estimated from thermal simulations using approximate values for the apparent activation energy

Test phase	Requirements
	4. Strength development to be measured exactly at the following time intervals: • 6 hours • 12 hours • 1 day • 3 days • 7 days • 14 days • 28 days Additional testing ages reflecting requirements of specific applications may be considered following agreement between associated parties. 5. The maximum temperature difference between two specimens placed in the same curing temperature should be around 1 to 2 ° C at most. 6. The test specimens must be stored in their moulds and wrapped with cling film or equivalent in order to prevent mortar washout (if water cured) or rapid water evaporation (if air cured). Apart from the specimens for 6 hours and 12 hours testing age, after 24 hours and provided that the specimens have gain adequate strength, the moulds may be removed whilst the specimens should be placed back into the curing chamber immediately after mould removal.
Calibration process steps	1. Determination of compressive strength development at 3 different temperatures. It is recommended that testing results are properly recorded and stored by concrete suppliers and associated parties to facilitate data analysis and later studies on the topic. 2. Obtaining model parameters for Arrhenius maturity law through regression analysis.
Selection of apparent activation energy	1. The concrete mix-specific apparent activation energy is appropriately calculated based on strength development results for at least three different curing temperatures as described in ASTM C1074 and Annex 4 of this guideline. Alternatively, the below process may be followed. 2. The apparent activation energy is first set at an initial value of 33,000 J/mol so that the equivalent age of the concrete can be calculated at each of the testing ages for each respective temperature level. 3. Different curves are plotted on the same graph. Each curve should represent strength development as a function of the equivalent age for each respective curing temperatures.

Test phase	Requirements
	4. Finally the apparent activation energy is adjusted to reduce the difference between these curves. 5. The desired value of the apparent activation energy is that which minimises the difference between the curves over the targeted resistance range (least squares method). The lower envelope curve of the experimental curve constitutes the desired estimate of the calibration curve. Examples of the use of results are given in Annex 4.

A2.2 Validation procedure

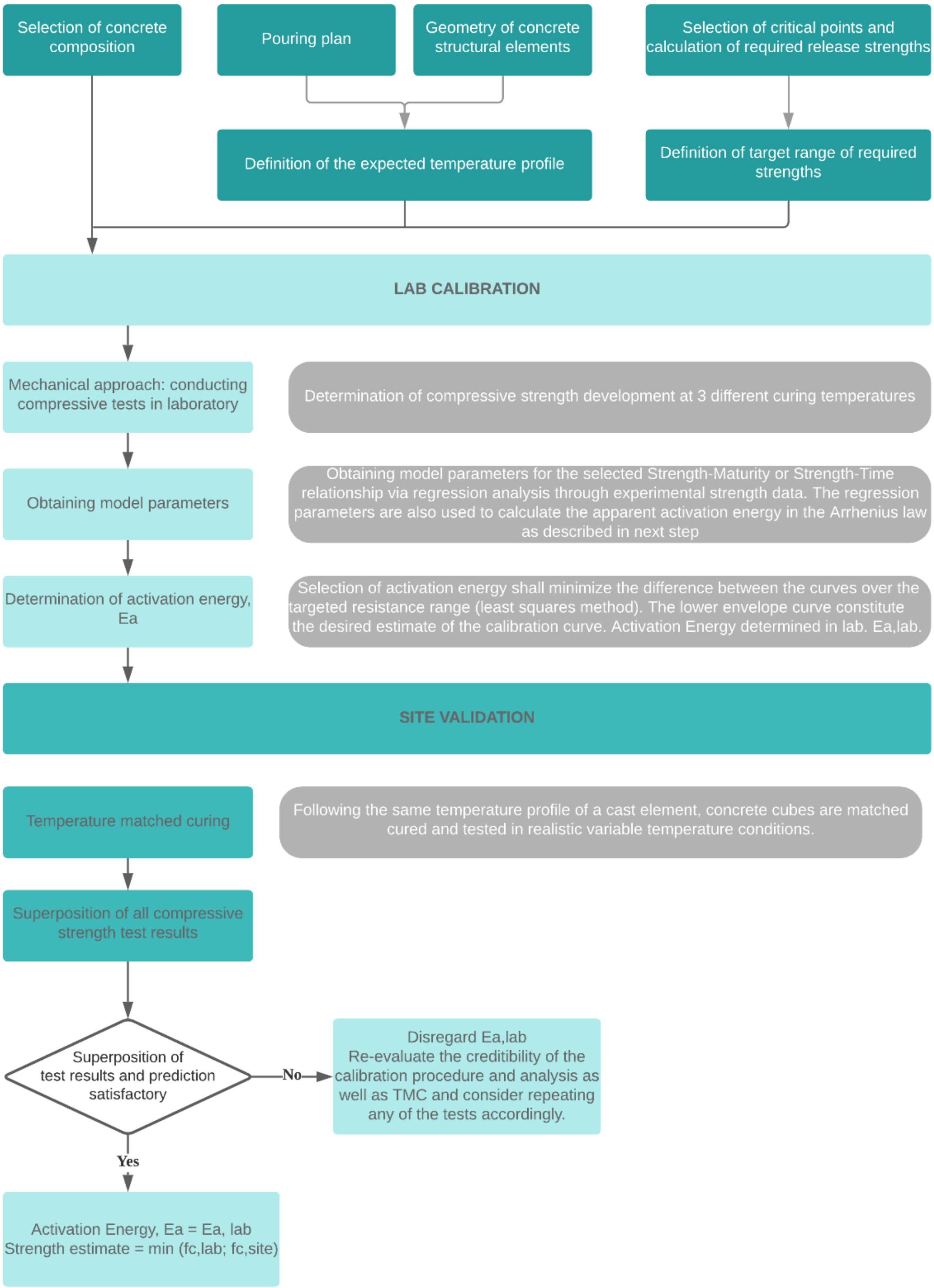
Temperature Matched Curing is implemented to validate the maturity models. The concrete cubes are cured and tested in realistic variable temperature conditions to ensure that the calibrated maturity method is being executed properly and accurate results are being obtained.

Table 6 summarizes the minimum number of test specimens to allow confirmation of the maturity/strength relationship.

Table 6. Minimum number of test specimens for validation of calibration relationship

Test phase	Testing age	No. of cubes
Performing Compressive Tests	6 hours	2
	12 hours	2
	1 day	2
	2 days	2
	3 days	2
	4 days	2
	7 days	2
	14 days (optional)	2
For embedding the maturity system sensor		2
For embedding thermocouple (Type-K or resistance detectors)		1
Spare samples for compressive tests		2
Total		**21**

A2.3 Flowchart of calibration and validation steps



A3 Annex 3: Conformity assessment

The purpose of this section is to describe the procedures to be implemented on site to ensure that, from a maturity point of view, the concrete used during construction does not present any significant difference with the concrete used during calibration (determination of Ea and the calibration curve).

A3.1 Conformity control

A3.1.1 Principle

The principle of conformity control consists in comparing, at the same time, the compressive strength measurements taken on test specimens (cubes) with the estimates indicated by the maturity sensor on a specimen (of the same type) kept under the same conditions. This approach is equivalent to temperature matched curing and is similar to the validation procedure discussed in section A2.2.

A3.1.2 Objective

For safe use of the method on site, with regard to the quality of the concrete, it is necessary to ensure that throughout the duration of the site:

1) neither the theoretical formulation of the concrete nor its actual composition during manufacture varies from the concrete used for calibration, even if the climatic conditions change;
2) the concrete production method does not change (mixing sequence, method of introducing admixtures, etc.).

However, like any industrial process, the production of concrete incorporates a number of variable elements. It is therefore necessary to ensure that the influence of these manufacturing variations remains minimal. With regard to production methods and concrete mixing, the maturity method cannot detect a possible change. Hence the commitment of the concrete producer to ensure consistent production process is then essential as well as exercising a systematic control of the batching tickets. On the other hand, with regard to the usual changes of production during construction, the initial conformity checks are precisely intended to assess its influence.

The initial compliance checks thus verify the calibration curve of the concrete to give the reference curve which will be used during the application of the maturity method. Compliance checks during the construction site then ensure that, over the entire duration of the construction site, variations in production do not lead to significant differences between the concrete used on the site and that used during calibration.

Note that the calibration of the concrete that led to the determination of the apparent activation energy and the calibration curve is only valid for thermal histories of the concrete included in the calibration zone. Compliance checks allow the apparent activation energy and / or the reference curve to be corrected in the event that the thermal histories of the compliance specimens fall outside the range of the thermal calibration histories.

A3.1.3 Conformity assessment

Initial conformity assessment is proposed for the first 3 distinct concrete placements over a minimum period of 3 weeks using temperature matched curing.

Note that in this phase, the maturity method cannot replace regular test cubes. However, strength predictions using temperature matched cured specimens is acceptable.

These are carried out at the frequency determined in agreement with the company, the contractor, the responsible engineer and the concrete supplier. After a minimum period of 3 weeks, maturity strength data can be used to replace the traditional test cubes for the purpose of early-age strength determination.

It is estimated that after at least 3 concrete placements and three weeks of production, future variations in concrete production should not exceed those already encountered. Nevertheless, monthly verifications should be performed (conformity checks during construction).

The conformity assessment during construction takes place through selected days of normal concrete production. The use of specific situations or alternative production considerations should not be considered to serve the purpose of conformity assessment.

The sampling and testing regime shall include:

- Initial production: during initial conformity verification at least 12 test specimens (cubes) are made for compressive strength determination. These specimens are subject to temperature matched curing with strengths determined at 6 different times e.g. 6 hours, 12 hours, 1 day, 2 days, 3 days and 7 days. Two specimens will be tested for compressive strength at each testing age. The testing ages provided are for reference only and can be adjusted to obtain in situ strength information of interest to the execution schedule. It is very important that an extra specimen is instrumented with a maturity sensor or thermoucouple wire or that a temperature record of the water bath or air-curing container is always provided.

- Continuous production: conformity evaluation during construction: at least 6 test specimens (cubes) are made for compressive strength determination. These specimens are subject to temperature matched curing with strengths determined at three different times e.g. 12 hours, 1 day and 3 days. Two specimens will be tested for compressive strength at each testing age. The testing ages provided are for reference only and can be adjusted to obtain in situ strength information of interest to the execution schedule. It is very important that an extra specimen is instrumented with a maturity sensor or thermoucouple wire or that a temperature record of the water bath or air-curing container is always provided.

The selection of the monitoring point used in the structure for temperature matched curing should coincide with one of the critical locations.

The crushing times should be chosen so that the measured compressive strength is distributed within the target range following the estimates provided by the maturity meter can be utilized.

For each conformity check, a signed report must be provided indicating:

- the references of the production weighing slip from which the sample was taken
- slump measurements carried out on fresh concrete
- the times of cube testing
- the actual ages of the concrete at each maturity
- the equivalent ages indicated by the maturity sensor at each maturity
- the compressive strength estimated by the maturity sensor at each age
- the 2 values of compressive strengths as well as their average at each age
- the difference in MPa between the average strengths measured through crushing and that indicated by the maturity at each age
- a graph showing the temperature curve of this control as well as the envelope curves of the thermal monitoring of the tests which enabled the establishment of the calibration and reference curve for the concrete.
- A copy of the batching ticket referenced in the document must be attached to this document, as well as a paper or computer backup of the thermal monitoring.

A3.2 Conformity assessment during initial and continuous production

A3.2.1 Initial production

Until three initial conformity verifications are completed, the concrete reference curve is not confirmed, therefore, maturity strength relationships cannot be used to determine when to remove formwork or to justify other temporary works measures. However, strength predictions using temperature matched cured (TMC) specimens is acceptable.

Once the 3 initial conformity verifications have been performed, these results are compared with the strength estimates obtained by the maturity method resulting, when applicable, in the derivation of correction factors.

Two situations are then possible:

1. Adequate Correlation: The results obtained using TMC are, generally, within the 80-120% range of the predicted compressive strength using maturity at all test ages up to 7 days.

   The compressive strength predicted $f_c(t)$ shall be the minimum obtained by the two methods:

   $$f_c(t) = min\{f_{c,mat}(t), f_{c,tmc}(t)\}$$

   where,

   $f_{c,mat}$ is the strength estimated by the maturity method at time t

   $f_{c,tmc}$ is the strength obtained using temperature matched cured specimens at time t

   Therefore, if the strengths predicted by the maturity method exceed those obtained during conformity assessment (match curing), determination of correction factors (CF) is required to update the quality of the prediction going forward. In order to determine representative CF, the following relationship applies

   $$CF_{t=i} = \frac{f_{c,mat}(t_i)}{f_{c,tmc}(t_i)}$$

   The global correction factor [5] selected shall be the maximum of all determinations executed during these three conformity verifications but should never exceed 1.20, unless a justification for a different approach is provided. The minimum correction factor is suggested to not drop below 1.10 regardless.

   With the determination of CF, the strength prediction using maturity-relationship can then be employed as shown below:

   $$f^*_{c,mat}(t) = \frac{f_{c,mat}}{CF}$$

2. Inadequate Correlation: The results obtained are outside the 80-120% range of the predicted compressive strength at all test ages up to 7 days.

   In this case, it must be determined whether the calibration of the apparent activation energy can be called into question or if the results reflect a production difference between the concretes tested during conformity assessment and during calibration. It is then necessary to react at the level of the production of concrete and to repeat new initial conformity checks.

   On the other hand, if the calibration curve does not contain the conformity check results, this difference can explain the poor quality of correlation. The apparent activation energy resulting from the calibration is then abandoned and a new apparent activation energy is inserted (empirically) to allow the results of the calibration and the initial compliance checks to be as closely

[5] Although the relationship is time-dependent in the sense that such correction factor changes with time, the intention is to obtain an average factor for the ages analyzed.

correlated as possible. The reference curve is then defined as the lower curve obtained from the spread of compressive strengths expressed as a function of the time equivalent to 25 ˚C calculated on the basis of this new apparent activation energy.

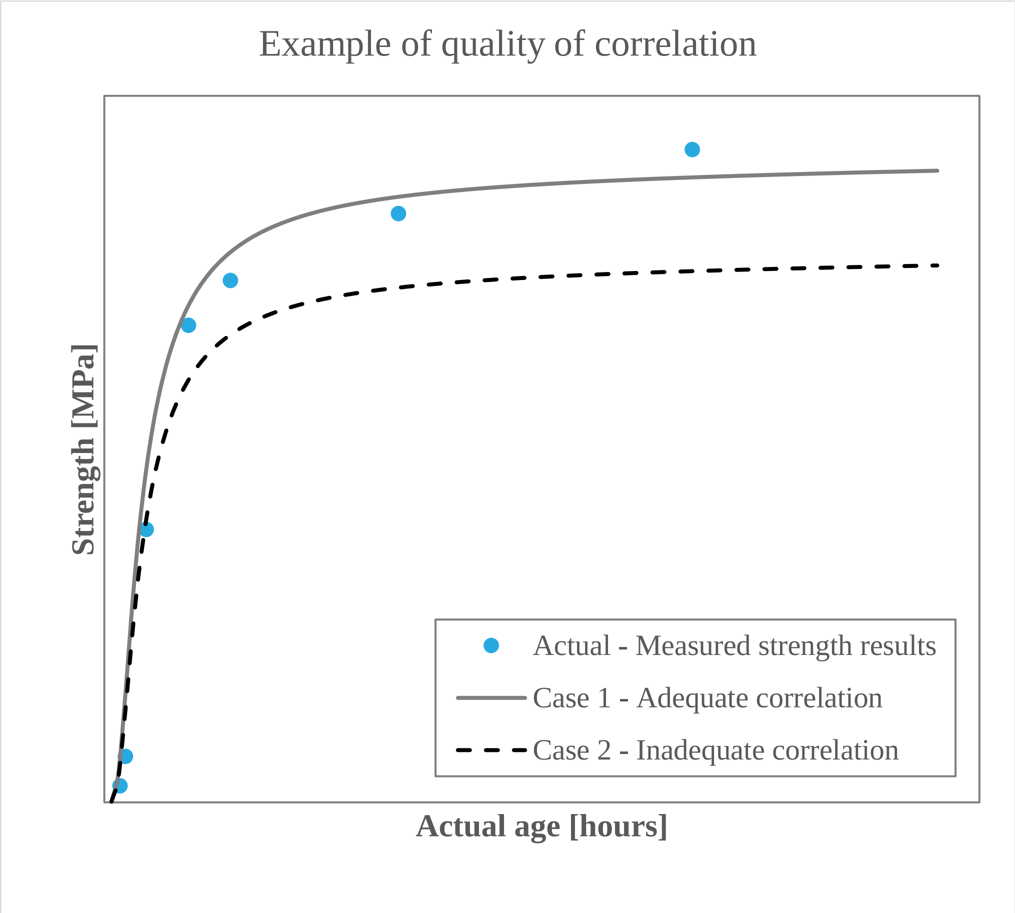


Figure 5 Example of quality of correlation/superposition

A3.2.2 Continuous production

Three scenarios are expected depending on the differences between the corrected maturity estimate ($f_{c,mat}^{*}$) and the results obtained from matched cube testing (average of two specimens) up to 7 days of age.

1. **Deviations between estimates ($f_{c,mat*}$) and measured values ($f_{c,tmc*}$) ≤ 2 MPa**

   It is then considered that the variations observed are acceptable and that the variations are "reduced" and consistent with the inherent variability of the testing methods.

2. **Maturity prediction $f_{c,mat*}$ underestimates the measured values > 2 MPa**

   The deviations are no longer considered to be marginal but in the sense of safety the reference curve should not be changed.

It can be of interest to identify the origin of these deviations. If this situation is to occur often, it may be advantageous that a new reference curve of the concrete is obtained thus better optimizing the formwork / striking cycle.

3. **The maturity $f_{c,mat*}$ overestimates the measured values ≥ 2 MPa**

The difference is no longer considered marginal and may lead to loss of safety. It is then necessary to determine whether the thermal monitoring is representative, or the reference curve and strength-maturity relationship is put into question (calibration and initial conformity checks).

It should be noted that the difference observed in the strength probably reflects the inherent production variability between the volume of concrete tested during this conformity check and the concrete used for the construction of the reference curve. It is then necessary to determine the origin of the change in the quality of the concrete, and whether this deviation is accidental or not. However, at this stage TMC results are accepted in lieu of maturity method estimates.

The aforementioned limit for over- and under-estimation are indicative and are relative to the strength of the concrete at the time of the strength prediction at a time instant. Generally, the above conditions are conservatively applicable to strengths above 15 MPa. The permitted deviation may be readjusted, e.g. relaxed, for a given scenario upon agreement with the company, the contractor, the responsible engineer and the concrete supplier and upon sufficient demonstration of substantiated information that safety and structural integrity are not going to be compromised in any way.

If a change is noted in the mix design or the production method:

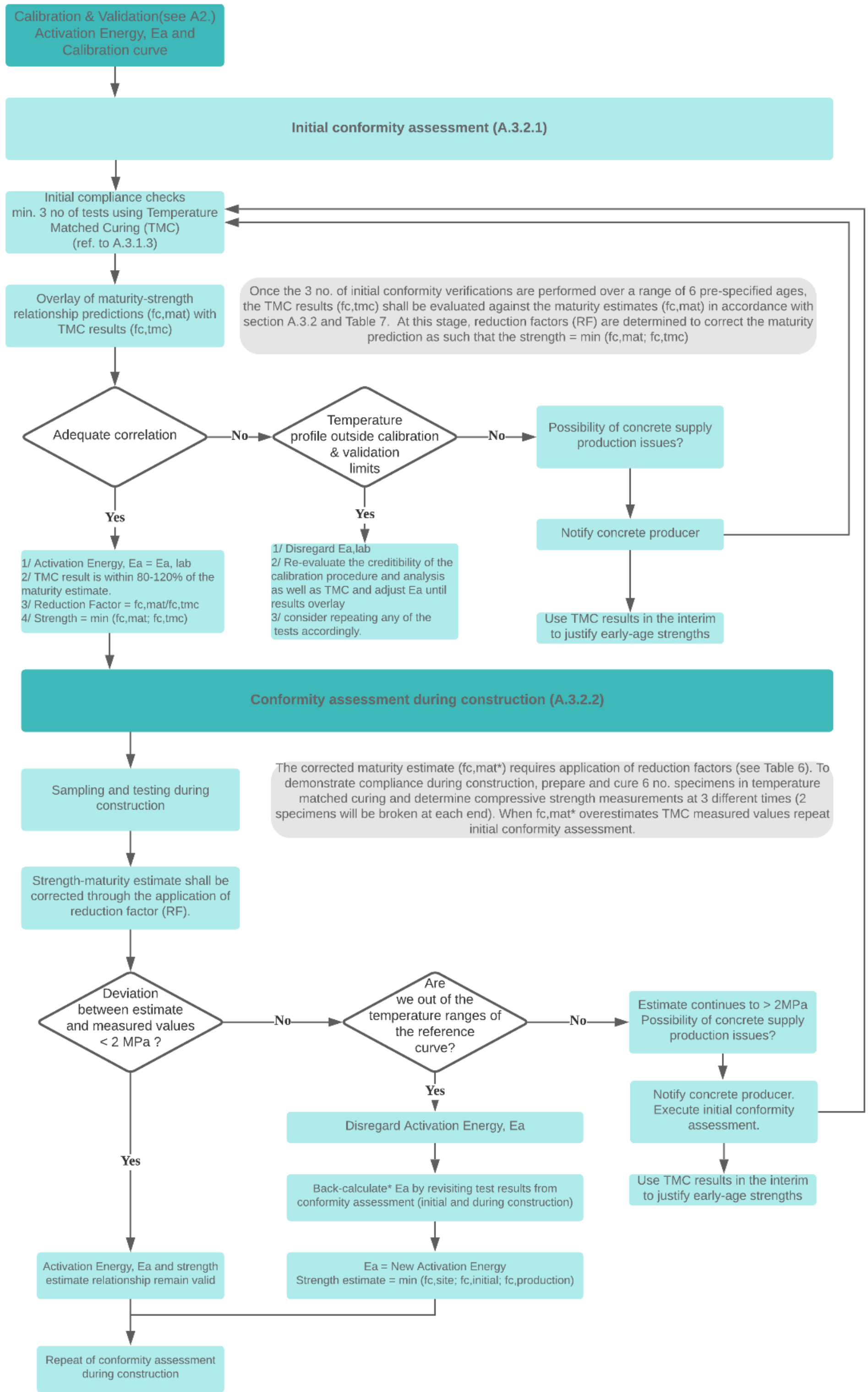
- This change is <u>accidental</u>. Conformity verification is repeated as of the next concreting, making sure that the error will no longer be made. At the same time, while awaiting the new results, the site formwork instructions are modified by increasing the target resistance by the average percentage deviation observed.
- This change is <u>not accidental</u> and will remain for the rest of the work. It is then necessary to determine the reference curve and the apparent activation energy of this new concrete.
- On the other hand, if *a priori* no change is observed in the formulation or the mode of production of the concrete, it is necessary to redo a conformity check from the next concreting to see if the deviations are repeated and to look elsewhere for the origin of the variations that may have influenced the quality of the concrete. While waiting for the results, the site instructions must be modified as previously and use of temperature matched curing is accepted.

Table 7. Sampling requirements, conformity criteria and recommended actions in case of non-conformity

Production	**Minimum rate of sampling for assessing conformity using temperature matched curing (TMC)**	**Conformity criteria**	**Observations**	**Recommended actions in case on non-conformity**
	Sampling rate	Mean of n results ($f_{c,tmc}$)		
Initial (until at least 3 verification results are obtained)	1 sample per week during first 3 weeks [Note 1]	$f_{c,mat} \leq 1.2x\ f_{c,tmc}$ and $f_{c,mat} \geq 0.8x\ f_{c,tmc}$	If $f_{c,mat} > f_{c,tmc.}$ determine correction factor, $CF = f_{c,mat}/f_{c,tmc}$	1. Adjust activation energy to obtain compliance. 2. Repeat initial conformity. 3. Redo calibration 4. TMC results are accepted in lieu of maturity method estimates.
Continuous	1 sample per month [Note 2]	$f_{c,mat}^* \geq f_{c,tmc} - 2$ MPa or $f_{c,mat}^* \leq f_{c,tmc} + 2$ MPa	$f_{c,mat}^* = f_{c,mat} / CF$	1. Repeat initial conformity assessment (12 specimens at 6 ages) until at least 3 verification results are obtained. 2. TMC results are accepted in lieu of maturity method estimates.

[Note 1] 12 no. specimens for testing at 6 ages
[Note 2] 6 no of specimens for testing at 3 ages

A3.3 Flowchart of the various stages of conformity assessment



*back-calculating is possible but preference should be given to experimentally determined Ea

A4 Annex 4: Obtaining the apparent activation energy and the concrete calibration curve

A4.1 Calculation approach

The apparent activation energy can be calculated using several different methods. The present guideline recommends that the apparent activation energy is calculated using:

1) The rate constant (k) inherent in the hyperbolic maturity function as recommended in ASTM C1074-19, and/or

2) The characteristic time constant (τ) inherent in the exponential maturity function developed by Freisleben Hansen and Pedersen which has become known as the Three Parameter Equation (TPE) [33] [34].

FHP-TPE (exponential equation) is as below:

$$S = S_u e^{-\left(\frac{\tau}{t}\right)^{\alpha}}$$

where:

S is compressive strength at age t (MPa)

Su is the ultimate compressive strength (MPa)

τ is the characteristic time constant

t is the test age (hours)

α is a shape parameter (-)

For (1), in order to calculate the apparent activation energy, Ea, the ASTM C1074-19 recommendation is to plot ln(k) against 1/Tabs (given in 1/Kelvin), where Tabs is the absolute curing temperature. The slope of the trend line is equal to −Q and the apparent activation energy (Ea) for the mixture will be equal to Q · R, where R is the universal gas constant equal to 8.31 J/K·mol.

For (2) the procedure for calculating the apparent activation energy, Ea, is to plot the natural logarithm of the characteristic time constant (τ), i.e. ln(τ), against 1/Tabs (given in 1/Kelvin). As previously, the slope of the trend line is equal to Q and the apparent activation energy (Ea) for the mixture will be equal to Q · R, where R is the universal gas constant equal to 8.31 J/K·mol.

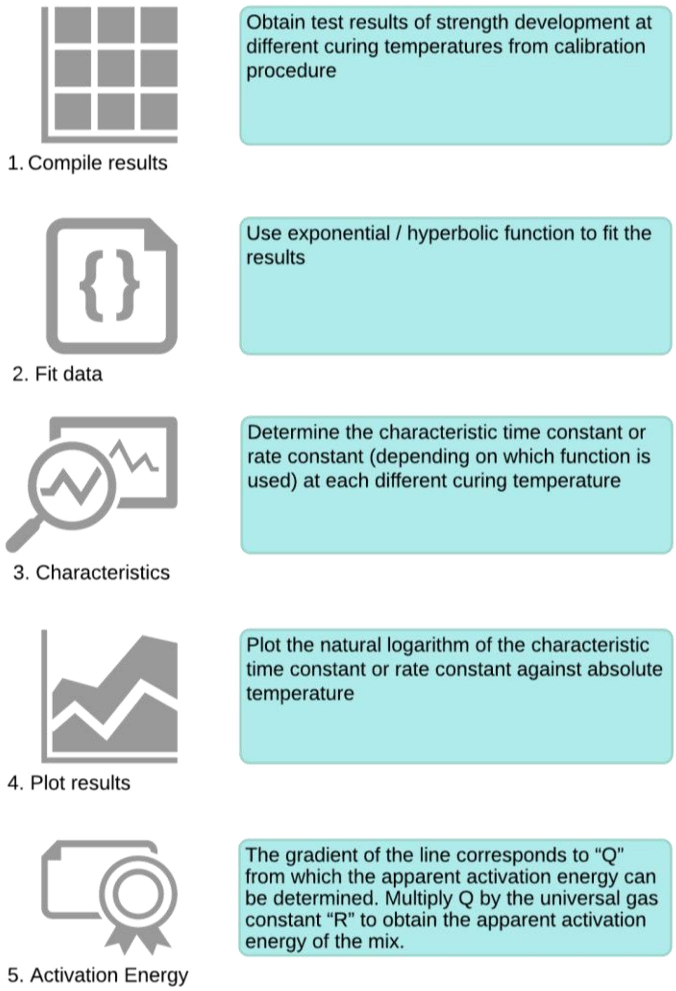


Figure 6. Steps involved in the determination of the Apparent Activation Energy

A4.1.1 Conventional concrete

The apparent activation energy of conventional concrete determined through compressive strength measurements generally varies between 25 and 65 kJ/ K·mol. The apparent activation energy of concrete largely depends on the supplementary cementitious material type incorporated into the concrete mix. Generally, for neat Portland cement concrete mixes, the apparent activation energy can normally be in the region of 30-40 kJ/ K·mol. Conversely, it has been observed that when fly ash in added in the mix, the apparent activation energy tends to decrease whilst with the addition of GGBS, the apparent activation energy usually increases. Guidance on indicative values of apparent activation energy of concrete mixes with and without supplementary cementitious materials and its method of determination is given in [33] [37] [38] [39].

A4.1.2 Concrete with long dormant period

Concretes with long dormant period may exhibit differences in the hydration kinetics when compared to ordinary ones. Usually, these types of concrete are characterised by longer setting times, owing to often a need for longer workability retention to facilitate casting after several hours since mixing. In the case where maturity measurement and determination of apparent activation energy of such concrete mixes is required, the recommendations outlined in A1.3 may be followed. With regards to the determination of apparent activation energy, this should be no different to the one described in A4.1 with the recommendation of A1.3 taken into account.

A5 Annex 5: HK Maturity Test Method

A5.1 Method for Estimation of Concrete Strength by the Maturity Method

Adapted from ODOT Test Method / Maturity Method Demonstration Final Report SRP 304-181.

A5.2 Scope

This method describes a procedure for estimating in real-time the in-situ strength of concrete. The method is applicable when strength-based actions such as removal of temporary works, striking formwork or tensioning strands for pre-stressing works can be performed and for quality assurance. It does not replace the need for testing cubes at 28 days for measuring the concrete compressive strength for acceptance.

A5.3 Background

The maturity method is based on the temperature history of hardening concrete. Conducting the maturity method consists of three steps:

1. Establish strength-maturity relationship

2. Estimate the strength of in-place concrete

3. Verify strength-maturity relationship

A separate strength-maturity relationship must be developed for each concrete mix design from each supplier. Furthermore, a new strength-maturity relationship must be established if the source of the concrete constituents' changes.

The limitations of the maturity method are:

1. It cannot account for errors in batching. Results are invalid if the field-placed concrete does not have the same constituents and proportions as the concrete used to establish the strength-maturity relationship. When variations in water dosage exceeding ±10 L/m^3 or water/cement ratios exceeding ±0.05 or ±0.02 for normal strength and high strength concrete, respectively, are identified the method is not applicable.

2. It cannot account for poor placement, compaction or curing.

3. The differences in early-age temperature histories will alter the strength-maturity relationship.

4. It is only valid if the concrete continuously hydrates during the time of testing.

5. It does not measure the strength of concrete but predicts it based on several assumptions. Results should be treated as such. The responsible engineer may choose to specify other forms of testing to verify the results from the maturity method.

6. It does not generally account for the detrimental effect of high early-age temperature on later age strength; a phenomenon known as “cross-over” effect. The “cross-over” effect may potentially lead to considerable overestimations of strength with the maturity method, especially if high early-age temperatures are observed in concrete elements. For these cases, more advanced maturity functions may be employed, such as those described in [40], [41]; however, as these are non-standardised methods, more careful calibration/validation may be required.

7. There are several strength-maturity relationships with varying accuracy and applicability depending on application and cementitious materials used. The effect of curing temperature and cementitious material type on the applicability/accuracy of maturity methods has been extensively examined in [33] [38] [39] [42] [43]. The user is referred to these studies for more explicit information and guidance on the peculiarities of the different maturity functions.

In this test method, the maturity to be calculated using the Arrhenius relationship for equivalent age:

$$t_e = \sum \left[e^{-Q\left(\frac{1}{T_a} - \frac{1}{T_s}\right)} \right] \Delta t$$

where:

t_e = equivalent age at a specified temperature T_s, in days or hours,
Q = apparent activation energy divided by the gas constant, in K,
T_a = average temperature of concrete during time interval Δt, in K,
T_s = specified temperature, in K, and
Δt = time interval, in days or hours

A5.4 Apparatus

Commercial, battery-powered maturity sensors that meet ASTM C 1074 specifications and are capable of computing Arrhenius equivalent age with variable apparent activation energy values shall be used.

A computer program for determining the best-fit, mathematical curve according to the strength-maturity model selected is required. If the temperature of concrete hydration is outside the range of 0ºC to 45°C, or if the apparent activation energy constant is determined without completing final set tests (as specified in ASTM C 1074), a computer program with capabilities for determining a best-fit, hyperbolic or exponential curve is required. The program must be capable of generating an equation and the corresponding regression coefficient.

A5.5 Apparatus preparation

Inspect, calibrate, and prepare the equipment as follows:

- Meters shall be inspected prior to each use to ensure sufficient battery power is available to complete testing.
- Meters shall be inspected prior to each use to ensure that proper apparent activation energy values indicative of the tested concrete are inputted.
- Meters shall be checked at least once every six months to ensure that the temperatures being outputted are correct. This can be done by inserting the sensors in a water bath of known temperature. If deviations greater than 1 ºC are noticed, the device shall be re-calibrated according to the manufacturer's instructions.
- Meters shall be protected from moisture, extreme heat, extreme cold, and theft when left in the field during testing. Each meter shall be maintained in a manner consistent with the manufacturer's instructions.
- If a maturity sensor that employs the use of thermocouples is used, then the wire tips at the temperature-sensing end of each thermocouple must be soldered or spot welded together.

A5.6 Correlation curves

Correlation curves shall be established for each concrete mix design that will be used in the project. The concrete production tolerances between the calibration concrete mix and field concrete mix shall be within 3 percent for all constituents. Air-entraining admixtures shall be proportioned so that both the calibration and field-delivered concrete mixes have the same design air content. The procedures for determining the curves are as follows:

1. Prepare at least 48 concrete cube specimens (150mm x 150 mm or 100mm x 100mm) from a batch of concrete that is approximately 3.5m^3 in size or larger. Record mixture proportions and constituents, slump, initial temperature, and mixture proportions. Embed temperature sensors into the centre of two of the cube specimens. Immediately connect the temperature sensors to the maturity sensor and begin data acquisition. Include a sensor to record the ambient temperature that the specimens are exposed to during the test. Ambient temperature can be measured simply through a thermocouple for cost efficiency. Data collection must continue uninterrupted for the duration of the test.
2. Moist-cure the specimens using at least three different temperature levels (25 ºC, 40 ºC and 55 ºC) for 28 days. Demould the cubes after 24 hours and return them to the prescribed conditions.
3. Perform compression tests at the ages of 6 hours, 12 hours, 1 day, 3 days, 7 days, 14 days and 28 days according to CS1:2010 Section 12 procedures [12], for each of the curing regime. At each age, test two specimens and record the individual and average compressive strengths. If the range of the

test results is greater than 10 percent of the average, test a third cube and average the strengths from all three specimens. If any specimen is obviously defective, discard it. The cubes with temperature sensors may be tested for the final two tests if required.

4. At the time of each test, record the two equivalent age values using the Arrhenius equivalent age formulation and the average value.

5. Use the curve-fitting computer program to plot the average strengths as a function of the average equivalent age values and draw the best-fit curve based on one of the following relationships:

Hyperbolic equation:

$$S = \frac{S_u \cdot K \cdot (t_e - t_{eo})}{1 + K(t_e - t_{eo})}$$

where:
S = average cube compressive strength (MPa)
S_u = limiting strength of the concrete (MPa)
t_e = equivalent age (C·hours)
t_{eo} = equivalent age when strength development begins (C·hours)
K = rate constant (-)

The computer program shall calculate S_u, t_{eo}, and K

Logarithmic equation:

$$S = A + B \cdot \log(t_e)$$

where:
A and B are constants calculated by the computer program

Exponential equation:

$$S = S_u e^{-\left(\frac{\tau}{t}\right)^{\alpha}}$$

where:
S is compressive strength at age t (MPa)
Su is the ultimate compressive strength (MPa)
τ is the characteristic time constant (-)
t is the test age (hours)
α is a shape parameter (-)

If the in-situ hydration temperature of the concrete structure is anticipated to be outside the range 0 to 45 ºC, then the hyperbolic or exponential strength-maturity relationship shall be used. If the in-situ hydration temperature of the concrete structure is anticipated to be within the range 0 to 45 °C, then either the logarithmic, exponential or the hyperbolic strength-maturity relationship can be used. Record the equation and R^2 value for the curve. For an R^2 value of 0.95 or greater, the strength-maturity curve and corresponding equation are considered valid. For an R^2 value less than 0.95, the responsible engineer shall determine the reason for the large variation. No points should be disregarded without a statistically valid reason (i.e.

faulty specimen). If removing outliers cannot be statistically justified, then the entire strength-maturity relationship must be redone.

6. Determine the apparent activation energy (Ea) or activation energy coefficient (Q) for the equivalent age equation using regression parameters as described in Annex 4: Obtaining the apparent activation energy and the concrete calibration curve of this guideline. The specified temperature, Ts, in the equation is 293.15 K.

A5.7 Validation for correlation curves

Use temperature matched curing to validate the maturity model.

Prepare concrete cubes that are cured and tested in realistic variable temperature conditions to ensure that the calibrated maturity method is being executed properly and accurate results are being obtained.

1. Prepare at least 14 cube concrete specimens (150mm x 150 mm or 100mm x 100mm) from a batch of concrete that is approximately 3.5m3 in size or larger. Record the concrete mix proportions and constituents, slump, initial temperature, and mixture proportions. Embed the temperature sensors into the centre of two extra cube specimens or obtain water bath or air curing temperature information continuously. Immediately connect the temperature sensors and begin data acquisition. Data collection must continue uninterrupted for the duration of the test.

2. Subject the cubes to temperature matched curing following the temperature profile of as placed concrete.

3. Compare the strength prediction against the results of the temperature matched cured specimens tested at ages of 6 hours, 12 hours, 1 day, 2 days, 3 days, 4 days, 7 days. Other ages that suit the construction schedule are acceptable.

4. The maturity model is validated if the deviation between the estimated and measured values is $\leqslant$ 2 MPa or if the maturity predictions underestimate the cube test results by more than 2 MPa.

A5.8 In-place concrete strength estimation

1. In the days prior to concrete placement, instrument the structure with temperature sensors compatible with the maturity sensor(s). The sensor wires shall be attached to reinforcing bars with ties and led out either through or underneath formwork. The wires shall be networked through the structure using the reinforcing bars. In instances when the wires are not tight against the reinforcement, sufficient slack shall be left so that the weight of concrete will not tear the wire. The exposed end of the sensors shall not touch the reinforcement. Label both ends of each sensor to avoid uncertainty in wire placement. It is advantageous to provide duplicate sensors in critical locations. More sensors than available maturity channels shall be placed in the structure so that if any sensor is destroyed during placement, the other leads can be used.

The ends of the wires to be placed into the maturity sensors shall be protected from any adverse weather conditions. In the unlikely event that the concrete element is not reinforced, thermocouples can be either connected to a steel bar placed into the sub-base, attached to formwork, or inserted directly into a fresh concrete surface.

2. The sensors shall be placed in the locations where strength estimation is required and/or in the positions that are anticipated to hydrate under the lowest temperatures or are placed last. In general, sensors for the latter purposes should commonly be placed within 50 mm from the exposed concrete surface. The responsible engineer shall be consulted for placement. Record the three-dimensional location of each sensor placed in the concrete structure and reference the location to the sensor label.

3. When the concrete arrives at the construction site, the batching slip shall be obtained and checked by the supervision staff assigned by the responsible engineer. If the concrete is not of the same composition as the correlation concrete mix, then the maturity method cannot be used to estimate strength.

4. If possible, connect the sensors to the meters prior to concrete placement. Otherwise, connect the sensors to the meters as soon after placement as possible. One sensor shall be located outside and near the structure so that ambient conditions can be monitored. As soon as possible after all of the sensors connected to an individual meter are covered with concrete, activate the maturity sensor. As concrete is placed, some of the sensors may break. If this occurs, replace the lead of the broken channels with the extra ones wired into the structure. Under no circumstances should wires be removed or switched for a specific sensor after half an hour past the time that the concrete was placed around that sensor. Maturity must be monitored in a continuous manner from time of placement. Do not disconnect the sensors or turn off the meters until the target maturity values are reached. The maturity value corresponding to the desired strength as provided by the calibration equation shall be recorded and made available to supervision personnel assigned by the responsible engineer and the QA/QC personnel. Correction factors should be applied depending on the conformity assessment results. A minimum correction factor of 1.1 applies (see section A5.9.2.).

5. When a channel displays the target maturity index, it is predicted that the concrete at that location has achieved the corresponding target strength. Data acquisition may be terminated once the desired strength has been estimated for all applicable channels. The wires may be cut flush with the concrete surface.

A5.9 Relationship verification

1. Verify the strength-maturity relationships during initial (once per week for the first 3 weeks) and continuous production (once per month).
2. During initial production, prepare 12 cube specimens to be subject to temperature matched curing according to the procedures outlined A5.7.
   a. Providing the maturity estimate does not exceed 80-120% range of strength obtained during match-curing ($f_{c,tmc}$), the calculation of correction factors (CF) is deemed as necessary to correct the maturity estimate $f_{c,mat}^*$ as follows:

$$f_{c,mat}^{*}(t) = \frac{f_{c,mat}}{CF}$$

Where:

$$CF_{t=i} = \frac{f_{c,mat}(t_i)}{f_{c,tmc}(t_i)}$$

$f_{c,mat}$ is the strength estimated by the maturity method at time t

$f_{c,tmc}$ is the strength obtained using temperature matched cured specimens at time t

   b. If maturity estimate exceeds 20% of the result obtained during match curing, repeat verification. If consecutive verification tests still exceeds results obtained during matched curing, the correlation curve is no longer valid and must be regenerated.
3. During continuous production, prepare six cubes for conformity evaluation during construction. These specimens shall be subject to temperature matched curing with strengths determined at three different times e.g. 12 hours, 1 day and 3 days. Two specimens will be tested for compressive strength at each testing age. The testing ages provided are for reference only and can be adjusted to obtain in situ strength information of interest to the execution schedule. It is very important that an extra specimen is instrumented with a maturity sensor or thermocouple wire or that a temperature record of the water bath or air-curing container is always provided.
   a. If the range of strength results is greater than 2 MPa of the corrected maturity estimate (fc,mat*), the maturity relationship and correlation curve is in doubt, relationship verification shall be repeated using the A.5.9.2.
   b. If the deviation between estimate (fc,mat*) and measured values (fc,tmc*) ⩽ 2 MPa the variation is consistent and consistent with the inherent variability of the testing method.
   c. If the maturity prediction fc,mat* underestimates the measured values > 2 MPa is still at least 80% of measured value, the

deviations are no longer considered to be marginal but in the sense of safety the reference curve should not be changed.

Correction factor

1. A correction factor (CF) shall be applied to the early-age strength estimate obtained from the maturity method.
2. The correction factor to be used depends on the confidence in the accuracy of the maturity function obtained during conformity assessment.
3. The application of an appropriate correction factor is necessary when the predicted strengths overestimate actual strengths (obtained by temperature matched curing) at the majority of testing ages.
4. A minimum correction factor of 1.1 shall be adopted regardless of the CF determined, i.e. to reduce the strength estimate by 10%. *(Note: Applicable to strength estimates up to 7 days from concrete casting)*.
5. If calibration, validation data suggest a poor strength - maturity correlation, or conformity during production is not met, correction factors up to 1.20 may be utilized. Correction factors in excess of 1.2 highlight that the maturity relationship and correlation curve is in doubt and should be re-calculated.
6. The above correction factors are predominately suggested for early-age strength estimates and up to 14 days since concrete casting. At elevated temperatures in the longer term, significant differences between actual and predicted strengths may be observed. Thus, at later ages e.g. 28 days, higher correction factors may be adopted to account for the “cross-over” effect.

A6 Annex 6: Sample Specification

The following sample specification is for reference only.

General Requirements	(1) If the Contractor wishes to use the maturity method for his application, he shall submit the following to the Architect/Engineer for approval at least xx weeks prior to concreting: (a) the planned application, (b) the date of concreting, (c) the method statement including the correction factor to be used, the name of the engineer responsible for the design and implementation, the decision making and the supervision of the application (the responsible engineer), (d) the names of the supervision personnel assigned by the responsible engineer to carry out the supervision of the implementation, their individual duties, and records of their training and competence assessment by the responsible engineer. (2) The Hong Kong maturity test method and the guidance given in the CIC Practical Guideline on Maturity Method for Estimation of Concrete Strength shall be adopted. (3) The Contractor shall provide all necessary access and support to the responsible engineer and his assigned supervision personnel in carrying out their duties effectively. (4) The Contractor shall give authority to the responsible engineer in decision making involving application of the maturity method including the determination of the quantity and locations of the sensors for each applications. (5) The responsible engineer shall provide necessary training to the assigned supervision personnel in carrying out their supervision duties in the implementation of the maturity method including the proper and robust installation of sensors and prevention of dislocation and damage to the equipment and installed sensors on site. (6) The Contractor shall bear all cost of the application including all equipment, sensors, calibrations, staff, precaution and protection works for equipment and installation of sensors on site and their replace if damaged etc.
Experience Requirements	(1) The responsible engineer nominated by the Contractor shall be a Registered Professional Engineer (Structural) who shall be supported by a concrete technologist with a degree in civil or

	structural engineering recognised by the Hong Kong Institution of Engineers. Both shall have at least 3 years of post-qualification practical experience in the design of temporary works and quality assurance and quality control of concrete production respectively. (2) The supervision personnel assigned shall meet the qualifications and experience requirements of a Technically Competent Person T3 or higher who shall have experience in supervision of works involving insitu construction of concrete structures.
Concrete Performance Assessment and Submission of Records	(1) The responsible engineer shall maintain all records, in a digital database format to be agreed with the Architect/ Engineer, related to the application of the maturity method, including records of equipment used, calibrations done/ calibration certificates from manufacturers, maturity-strength relationships obtained, verifications carried out, initial conformity assessment and compliance verifications completed, temperature measurements made and strength estimates obtained, etc., including all raw data supporting the calibrations, derivation of the maturity-strength relationship and all site measurements. (2) The responsible engineer shall submit the concrete temperature measurement records together with an assessment of the adequacy of development of concrete strength with time for the specified grade of concrete to the Contractor and the Architect/Engineer for the Contract within three days of obtaining the concrete temperature measurements. He shall highlight any anomaly in the concrete strength development observed. (3) The responsible engineer shall submit all records in digital form to the Contractor, the Architect/Engineer and the Project Client/ Employer for the Contract within one month of completion of the planned application.