RILEM Recommendation from TC 289-DCM:
Guideline for designing and operating long-term marine exposure sites

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Abstract:
This guideline prescribes the technical requirements for the design and operation of long-term exposure sites in marine environments. The technical content includes the design of exposure site, the monitoring of environmental conditions, the monitoring of exposed specimens, the data management and the maintenance of exposure facilities. The design of exposure site covers the choice of exposure sites, the exposure infrastructure and facilities, exposure specimens and their placing and protection. Then, the guideline defines the environmental factors to be monitored and the corresponding monitoring methods. For the exposed specimens, the guideline specifies the target performance to monitor, the sampling, the testing and the reporting of exposure results. The data management deals with such aspects as the data storage, data transmission and the data sharing. At the end, the guideline gives the principles for the maintenance of the exposure facilities. This guideline summarizes the best practice of long-term exposure in marine environments, and it is expected to support the normalization of exposure practice and to generate more added values from this practice.

Keywords:
Exposure site, Marine environment, Concrete, Specimens, Environmental factor, Target performance

1. Introduction

The long-term exposure practice of concrete materials in marine environments provides a unique source for durability mechanism investigation and durability model validation [1]. The scope of this guideline covers the main features of design and operation aspects of exposure sites of concrete materials in marine environments. The principles stated in this guideline can, with careful examination, be applied to the long-term exposure practice of other engineering materials and other natural environments. This guideline aims to optimize the design and the operation of exposure sites, and help to generate more added values from long-term exposure practice.

Typically, the exposure sites or stations can be divided into two categories: exposure sites for general use [2-4] and those for specific projects [5-7]. The former is established to support investigating the durability mechanisms and performance of concrete materials while the latter is conceived to verify the durability performance of concrete materials in given projects. Accordingly, the general exposure sites are usually chosen to represent the environmental conditions of a given region. The project-based sites are normally built into the projects to use the environmental conditions identical to projects for exposure. Both categories of exposure sites are covered by this guideline.

The practice of long-term exposure sites in marine environments begins with the design of exposure sites, involving the choice of sites, design of exposure facilities and exposed specimens, placing and protection of exposed specimens. Then, the monitoring of exposure sites consists of monitoring of environmental conditions and the performance of exposed specimens. The environmental conditions refer to the meteorological parameters, such as the temperature and the relative humidity, and the local contact conditions of specimens, such as the chloride accumulation rate. The monitoring of durability performance pertains to the continuous measurement of target performance parameters of exposure specimens, and the associated sampling and test methods. Both monitoring operations need to set up protocols for data management. Finally, systematic inspection and maintenance schemes are needed for the exposure facilities to maintain the operation.

Following this logic line, this recommendation is organized as follows: the design of exposure sites is described in Section 2, the monitoring of environmental conditions is provided in Section 3, the monitoring of durability performance of exposed specimens is clarified in Section 4, the data management is covered in Section 5, and the maintenance of exposure facilities is specified in Section 6. This recommendation is expected to help the engineers and the structure owners to rationalize and optimize their design and operation of the long-term exposure sites. The researchers can also benefit from this recommendation for a clearer vision on the long-term exposure practice in view of better interpretation and exploitation of exposure data.

2 Design of exposure site

2.1 Choice of exposure site

The exposure sites (stations) in marine environments refer to sheltered or open-air areas, exposed in coastal areas, with infrastructure and facilities allowing for engineering materials, such as concrete and reinforced concrete, to be investigated for their performance under the environmental actions. The design of the exposure sites begins with the choice of site (siting). The siting should consider, but not limited to, the environmental conditions, infrastructure for exposure, accessibility to transport and to power, safety, security and costs. In addition, the duration of exposure and the severity of the environment can be factors for siting.

Environmental conditions
The environmental conditions refer to the local meteorology (temperature, humidity, precipitation, wind direction and speed, atmospheric CO_2 concentration and air-borne chlorides), and the seawater hydrology (sea levels, wave heights, salinity, sediment flushing). The environmental conditions of the chosen site should meet the needs of long-term exposure study. For general use sites, the environmental conditions should be representative of the defined region. For project-based sites, they should represent the exposure conditions of the projects or the defined parts of project.

Infrastructure for exposure
The exposure site should be situated in locations where the exposure infrastructure can be easily and conveniently constructed. Reuse of existing structures and facilities is recommended. If construction works will be involved, the entailed environmental and ecological impact, if any, should be minimized.

Accessibility
The chosen site should be accessible to transport (roadway or waterway), fresh water and electric power. Also, the site should be convenient for specimen placement and retrieval.

Safety
Extreme climates and environmental actions such as typhoons and earthquakes should be considered during site choice. Normally, the site choice should avoid these extreme conditions to protect the exposed infrastructure and specimens. If these climates cannot be avoided, e.g. sites set up in open seas, special measures should be taken to assure the safety of personnel, infrastructure and specimens.

Cost considerations
The choice of exposure site should consider the entailed costs related to the construction of infrastructure, if any, the operation and the maintenance of the exposure site. It is a good practice to

combine exposure sites with existing or planned constructions, or to reuse decommissioned structures and facilities for exposure.

Figure 1: Austefjord field station supported by an existing quay, Norway (left) and HongKong-Zhuhai-Macau Bridge exposure site built into the project, China (right). The exposure sites may be built on some existing structures, such as wharves in service, or designed and built as new structure. In either case, the service life of the structures should cover the expected operation duration of the exposure site. Courtesy of Dr. Karla Hornbostel (Norwegian public roads administration) and Mr. Yan Yu (HZMBA).

2.2 Exposure infrastructure and facilities

The exposure infrastructure can be newly built for exposure purpose, or reuse existing structures and facilities, cf. Figure 1. The service life of these structures should meet the requirement of exposure study, normally not less than 50 years. In marine environments, anti-corrosion measures are recommended to maintain and extend the service life of these structures.

The exposure infrastructure should allow for the placement and retrieval of specimens, the works of on-site testing and the maintenance activities. The exposure infrastructure should also provide the required exposure conditions for the exposure study. The marine exposure conditions are classified as submerged, tidal, splash and atmospheric zones [8]. The correct design of these exposure zones within the exposure infrastructure needs the long-term recording of the seawater hydrology, and, if any, the shielding effect of the exposure infrastructure against the seawater flow.

The selected space for the submerged zone should ensure the specimens to be kept immersed in seawater permanently. The space for tidal zone should subject the specimens to periodic seawater tidal actions, whilst the space for splash zone should put specimens to the drying-wetting actions of the waves. Finally, the space for atmospheric zone should expose the specimens to marine saline atmosphere, cf. Figure 2. The atmospheric zone may be further designed as heavy/light exposure zones depending on deposition rates of airborne chlorides and the shelter conditions. The detailed definition of different zones is provided in Appendix A.

In addition to the main exposure structures, the safety facilities, such as stairs, guardrails, fences, and fastening chains, need to be designed properly according to their functions. Indicating and warning signs should be installed for spaces of different exposure zones.

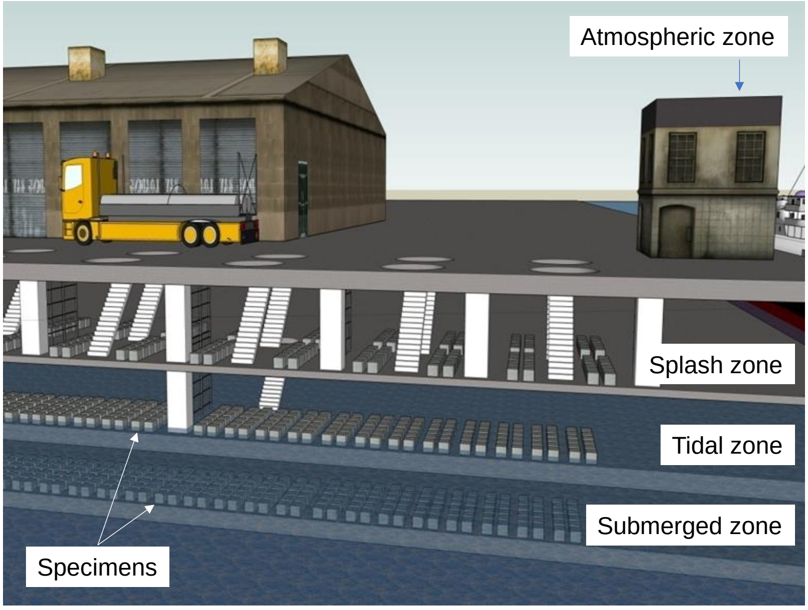

Figure 2: Illustration of the spaces designed for different exposure zones in Zhanjiang exposure site, China. The exposure site is situated in existing marine wharfs, using the existing structures to provide submerged, tidal, splash and atmospheric exposure conditions for concrete and reinforced concrete specimens. Due to the shielding effect of wharf structures, the local wave splashing is more relevant to this arrangement, and will be different from the splash actions in open sea.

Figure 3: Large-sized specimens (0.2mx1mx2m) from exposure site at Rødbyhavn, Denmark (left) and small-sized specimens (100mm cubes) in Zhanjiang exposure site, China (upper right), and a label tag on exposed specimen (down right). Courtesy of Dr. Henrik Erndahl Sørensen and Dr. Xiong Jianbo (CCCC).

2.3 Exposed specimens

The design of specimens should meet the requirements of the long-term exposure study, considering their geometry, numbers, exposure conditions, raw materials, curing and manufacture, labelling, sampling frequency and testing.

The geometry of specimens is determined by the study purpose. Specimens of large size are recommended when continuous sampling or coring are needed for the exposure study, or when structural effects such as cracking also constitute part of the investigation. Specimens of small size can be used for single-property monitoring. For small-sized specimens, attention should be paid to the concrete homogeneity, and the minimum size of the specimen should be larger than 5 times the maximum size of aggregates used in concrete.

The number of specimens is determined upon the study purpose and the storage capacity of exposure site. Since large-size specimens can support multiple sampling, the required number of large-sized specimens can be less than that of small-sized specimens when continuous sampling or coring is needed. Duplicate specimens are recommended when the same parameter is to be checked for a same exposure age.

The raw materials and proportioning of concrete should conform to the requirements of the exposure study. Prior to transport to the exposure site, the concrete specimens should be subject to specific and well-defined procedures of curing. For general studies, standard curing to a maturity of 28d or 56d is recommended. If any specific curing condition is intentionally simulated, the concrete specimens should be cured under this specific scheme before exposure. It is recommended to characterize the concrete properties of fresh state and at standard curing ages in the laboratory.

When the specimens are ready for exposure, surface treatments are necessary for the study of ionic transport into concrete. All surfaces except the exposed one should be sealed. For specimens in submerged and tidal zones, epoxy-resin is recommended for sealing while, for splash and atmospheric zones, coatings with aging-resistance, such as acrylic- and silicone-based coatings, are recommended. For cubic specimens, the casting top and bottom surfaces are not recommended as the exposed surface.

The specimens placed in the exposure site should be labelled clearly and each specimen should bear a unique label. The label information should include the responsible institution, exposure zone, concrete mixture, casting date and study purpose. The label tag should be protected by sealing materials or made from resistant materials as the specimens are in direct contact with seawater. If necessary, the label tag can also include a QR code with more information available, cf. Figure 3.

It is a good practice to establish a primitive mapping of the exposure site, containing the crude drawing of exposure site and the labelled positions of exposed specimens. Also, the photographic documentation of specimens is recommended. Both measures help to minimize the possible loss of data due to missing of labels.

2.4 Placing and protection of exposed specimens

Exposed specimens from the same batch of concrete mixture or for the same study purpose, should be arranged and placed in the same unit of space (possibly covering different exposure zones) to facilitate their transport, placing and retrieving.

Necessary measures should be taken to protect the exposed specimens from extreme climates and vandalism. The fixation facilities, such as cages made from steel wires together and their anchorage, are recommended for small-sized specimens. These fixation facilities are better made with corrosion-resistant materials such as stainless steel, titanium alloy and galvanized steel. Special shielding and protecting measures should be taken if other disturbing factors arise, such as stray current or polluting agents in seawater.

3 Monitoring of environmental conditions

The aim of recording environmental conditions is to describe accurately the environmental envelope of the exposed specimens. The surface environment of concrete specimens includes also the interference effects of exposure infrastructure, even the concrete specimens themselves, in the local meteorology and hydrology. These conditions are crucial for characterizing the performance of concrete specimens in exposure and conducting supplementary experiments and modeling in laboratory [9,10]. Further, if the exposure data are to be compared among different exposure sites, accurate recording of relevant environmental conditions becomes indispensable [11,12]. In addition, extreme climate events should be recorded separately. The exposure zonation in marine environments is adopted as follows (altitude from low to high) [8]: the submerged zone (SUB), the tidal zone (TID), the splash zone (SPL), and the atmospheric zone (ATM). This zonation is detailed in Appendix A, and the involved durability processes can be referred to [1,11].

3.1 Environmental conditions

The environmental conditions are represented by the following factors with their relevance, if any, to the exposure zones.

<u>Temperature</u>
The temperature refers to both the atmosphere and the seawater enveloping the exposure specimens. Since both temperatures can have important temporal and spatial variations, it is recommended to monitor the temperature locally near the exposed specimens.

The temperature is related to exposure zones. In the SUB zone, the specimen temperature is equal to that of seawater; both the air and seawater temperatures are relevant to specimens exposed in TID and SPL zones; the temperature in ATM zone follows the air temperature. For accurate analysis of temperature, the thermal interaction between the environment and the concrete surface may be necessary, e.g. through an equivalent surface temperature [11].

<u>Sea (water) levels</u>
The water levels refer to the high tide and low tide levels from the seawater hydrology recordings. Together with the wave height, the water levels help to determine the ranges for TID and SUB zones for shielded and unshielded conditions [13,14]. Note that the water levels are not constant values but related to the return period of hydrology observation.

<u>Wave height</u>
The wave height refers to the distance between the crest and the trough of a wave, affected by local hydrology factors such as water depth. The wave height assumes also statistical properties from the recording of hydrology, and its value depends on the wave height-occurrence distribution. The wave height will largely determine the ranges of ATM and SPL. Note that in exposure sites with shielded conditions provided by the exposure infrastructure, the wave height can be largely different from the

seawater hydrology, and its determination needs supplementary local recordings for the exposure infrastructure.

Precipitation
Precipitation refers to the duration and amount of atmospheric precipitation from the meteorology recordings. Its value is highly correlated to the relative humidity in marine atmosphere. The precipitation is relevant to the humidity conditions for ATM zone and SPL zone.

Time of Wetness (ToW)
The time of wetness pertains to the total time of the concrete surface wetting due to rain, surface condensation and water flowing from higher parts of the structure. This factor helps to quantify the effective wetting time after wetting events, a typical quantity for environment-material interaction [15]. A quantitative method has been proposed to evaluate ToW for concrete surface [16]. The factor is primarily relevant to ATM zone, and also relevant to SPL zone.

Relative humidity
The relative humidity depicts the relative vapor content in the ambient atmosphere, available from the local meteorology recordings. Note that for the exposure infrastructure with shielding effect, e.g. from atmosphere precipitation, the relative humidity may be different from the local meteorology recordings. This factor is relevant to ATM zone, and also to SPL zone because it scales to what extent the air is wet during the period without seawater contact.

Wind direction and speed
The wind direction and speed refer to the wind characteristics from meteorology recordings. Again, for exposure infrastructure with shielding effects, the impact of wind speed and direction should be studied locally. The wind factors are relevant to ATM and SPL zones: the wind direction can determine the preferred directions of the airborne chloride deposition and the seawater splashing; the wind speed will determine the reach of airborne chlorides and the range of splashing action [17,18].

Salinity (concentrations of chlorides, sulfates)
The salinity refers to the total amount of dissolved salts present in seawater, defined as the mass of salts, in grams, dissolved in 1 kg seawater and expressed in parts per thousand (‰). The sodium (Na^+) and chloride (Cl^-) ions are the predominant ionic species in seawater, followed by magnesium (Mg^{2+}) and sulfate (SO_4^{2-}) ions. The last three species bear aggressive nature for concrete materials. The concentrations of chlorides and sulfates can be obtained through chemical analysis in laboratory from seawater samples. The salinity varies in terms of the water depth and coastal distance: higher salinity value is found in deep water and salinity becomes lower as one approaches the coast. Since the marine environment relates closely to seawater, the salinity of seawater is relevant for all exposure zones.

CO_2 in air
The CO_2 in air refers to the concentration of CO_2 present in the marine atmosphere, also available from the meteorology recordings. The CO_2 concentration value is usually noted in parts per million (ppm). This factor is important for the correct interpretation of chloride ingress in ATM and SPL zones because during the "dry" period the carbonation of surface layer will alter the chloride binding and transport in concrete [19].

Air-borne chlorides
The airborne chlorides refer to the quantity of chlorides contained in the tiny seawater droplets sprayed into the atmosphere by the aerodynamics of marine air. This is the key source for the chlorides of ATM zone, and its quantity depends much on the wind direction and speed. Normally the

measurement of airborne chlorides should be arranged close to the exposure site (specimens) and needs special experimental setups [20].

Biological growth
The biological growth refers to the marine colonizing organisms depositing on the concrete surface, usually by calcium carbonate formation [21]. The influence of biological growth on the durability of concrete is not yet well understood, but it seems to change the microclimate at the concrete surface, e.g. the growth of mussels and barnacles can coat the concrete surface and thus impede the chloride penetration. The biological growth occurs mainly in SUB zone, also possible in tidal and SPL zones.

3.2 Monitoring methods

The environmental conditions for exposure site are represented by the factors in the previous section. For a specific exposure site, these factors can either be obtained from local meteorological and hydrological recordings if these recordings represent the exposure site conditions, or from the monitoring on the exposure site. Table 1 summarizes the available monitoring methods, monitoring sensors and devices for these factors, together with the recommended data collection frequency. The relevance to the different exposure zones is also given in the table.

Table 1: Monitoring methods for environmental factors in marine exposure sites.

Environmental factor	Method	Device/Sensor	Exposure zone	Recommended frequency
Temperature (air, seawater)	Sensor	Thermocouple Resistance thermal detector Thermistor Semiconductor	All	1/hour
Sea level	Sensor	Pressure sensor Ultrasonic sensor	SUB, TID	1/hour
Wave height	Sensor	Microwave radar Laser sensor MEMS sensor	SPL, ATM	1/hour
Precipitation	Sensor	Radar precipitation sensor Laser weather sensor Weighing precipitation gauge	SPL, ATM	1/hour
Time of Wetness (ToW)	Sensor	Resistivity sensor WETCORR sensor Leaf Wetness sensor	SPL, ATM	1/hour
Relative humidity	Sensor	Capacitive sensor Resistivity sensor	SPL, ATM	1/hour
Wind direction	Sensor	Wind vane sensor	SPL, ATM	1/hour
Wind speed	Sensor	Anemometer	SPL, ATM	1/hour
Salinity	Sensor	Conductivity sensor [22]	All	1/day
Chloride/Sulfate	Device	Chemical analysis	SUB	1/year
CO_2 concentration in air	Sensor	PAS sensor, NDIR sensor	SPL, ATM	1/month
Air-borne chlorides	Device	Wet candle method [23], Custom made device [24-26]	ATM	1/month (first year), followed by 1/quarter
Biological growth	Visual	Colorimetric measurement [27], Scraping and weighing [28]	SUB, TID, SPL	1/year

The monitoring methods in Table 1 are detailed in the following. The measurement of seawater salinity is based on the electrical conductivity measurement [22], deduced from an established relationship between the electrical conductivity and the salinity under given temperature and pressure. For the air-borne chlorides, the wet-candle method collects aerosols and particles retained on a wet wick, expressing the chloride deposition rate in mg/day·m^2 [23]. A salt-laden mist sensor was developed to adapt the measurement in cold climate [24], the mortar disc method was used to simulate better the microclimate on concrete surface [25], and the capture tank method was conceived to collect the total load of air-borne chlorides [26]. The monitoring of biological growth can be performed through colorimetric measurements for short-term growth [27], and scraping and weighing methods for long-term growth [28]. The living lives of all sensors should be determined before their installation, allowing for a timely replacement.

4 Monitoring of exposed specimens

4.1 Target performance for exposed specimens

The performance of exposed specimens in marine environments refers to the resistance to different environmental actions, including chloride ingress, carbonation, freeze-thaw, sulfate attack, drying-wetting cycles, erosion, and the internal expansion reactions such as alkali-aggregate reaction and delayed ettringite formation. Some processes deteriorate the concrete materials while the others lead to the corrosion of embedded steel reinforcement. Since the processes deteriorating the concrete cover will also accelerate the steel corrosion, these processes are usually also regarded as the indirect causes for steel corrosion.

The resistance to chloride ingress is usually characterized by the chloride diffusivity of the concrete cover and the chloride ingress profiles. At given exposure ages, the chloride diffusivity scales how easily the chlorides can diffuse into concrete while the chloride ingress profile shows to what extent the chlorides have penetrated concrete. In practice, the chloride diffusivity has been found well correlated to the electrical resistivity (conductivity) [29], and thus electrical resistivity can be an alternative parameter for chloride diffusivity.

The resistance to concrete deteriorating processes is first characterized by the affected concrete properties such as strength, elastic modulus, and permeability. Other measurable parameters at macroscopic level include the volume change, the surface cracking and internal damage of specimens. For the drying-wetting and erosion actions, the chemical analysis of mineral composition in concrete cover is pertinent. The internal expansion reactions would need further petrography, microscopic, computerized tomography and chemical analyses.

The steel corrosion is characterized by the electrochemical stability of the embedded steel bars. The relevant parameters can include the half-cell potential and the polarization resistance of steel bars, and the electrical resistance of concrete cover. The carbonation changes the pore solution chemistry of concrete cover, and thus promotes the chloride ingress and the subsequent steel corrosion [30]. The parameter pertinent to carbonation is the carbonation depth into concrete cover. The distribution of mineral composition would also be pertinent to the carbonation resistance.

4.2 Sampling and testing

Continuous sampling and testing are necessary to monitor the performance parameters of exposure specimens. A detailed study plan should be set up for the specimen sampling, retrieving and testing. Since most processes are diffusion-related, the observation frequency can scale to the square-root of exposure age. On the basis of 100a exposure duration, the sampling ages are recommended to follow 0.5a, 1a, 2a, 5a, 10a, 20a, 35a, 50a, 75a and 100a, and the sampling ages of 35a, 50a, 75a and 100a can be optional if the double number of specimens are available during the sampling ages between 0.5a-20a.

Sampling

The specimen sampling, by coring or cutting, should be conducted in a homogeneous way. The sampling operation should first record accurately the sampling position, the exposure condition (zone) of specimen and the specimen label. The number of samples should be enough to fulfil the required procedures for the target measurements, and avoid the local heterogeneity of concrete materials. The size of sampling surface depends on the study purpose and the drilling capacity as well. Special care should be taken when wet-saw coring or cutting is used in sampling for chloride profile measurement because the water jet in sampling operation can dissolve chlorides [31]. After a drilling or coring operation in large-sized specimens, the drilling holes should be re-filled and sealed.

Testing

The obtained samples can either be tested on-site or transported to laboratory for testing. For laboratory testing, the samples should be kept in sealable plastic bags, protected from physical and chemical disturbance. Then, the tests on retrieved specimens and samples should be conducted in short delay to avoid the physical or chemical alteration. The measurable parameters and the corresponding test methods are provided in Table 2.

The chloride diffusivity cannot be measured directly by laboratory methods such as rapid chloride permeability test (RCPT) [32], rapid migration test (RCM) [33], or Ponding methods [34,35] because the exposed specimens contain already chlorides and these chlorides can affect the results. In this case, the rapid iodide migration (RIM) method may be suitable for testing ionic diffusivity in chloride contaminated specimens. [36,37]. The electrical resistivity of concrete is proposed as the alternative parameter to characterize the chloride diffusivity in Table 2.

Apart from the methods in Tables 2, sensors can be placed in the specimens to monitor the steel corrosion using open circuit sensors, wireless sensors, or optic fibers [38,39]. In marine environments, the sensors and corresponding equipment should be robust enough to survive the marine conditions and the possible contact with seawater. Moreover, these sensors should be sufficiently powered to be functional over long durations.

Table 2: Measurable parameters and testing methods for the target performance

Performance	Parameter	Testing method	Scope
Chloride ingress	Concrete resistivity (conductivity)	Bulk method [40-42]	Laboratory
		Surface/Wenner probe [43]	In-situ
	Chloride profile	Grinding method, cutting and crushing method, dry drilling method [44]	Laboratory
	Ionic diffusivity	RIM [36, 37]	Laboratory
Carbonation	Carbonation depth	phenolphthalein solution spray, or other reagents [45]	In-situ/laboratory
Steel corrosion	Half-cell potential	ASTM C876 [46]	In-situ/Laboratory
	Polarization resistance	ASTM C876 [46]	In-situ/Laboratory
		GECOR [47], GalvaPulse [48], RapiCorr [49]	In situ, portable
	Concrete resistivity	See above	See above
Concrete property and damage	Compressive strength	ASTM C39 [50]	Laboratory
	Elastic modulus	ASTM C469 [51], UPV method [52] Fundamental frequency [53]	Laboratory
	Surface damage and cracking, discoloration	Visual, microscopy	In-situ/Laboratory
	Change in volume	(Vernier) callipers	In-situ/Laboratory
	Surface absorption rate	ASTM C1585 [54]	Laboratory
	Air permeability	Torrent device [55]	In-situ
	Moisture content	Tremax [56], Embedded probes [57]	In-situ

<u>Reporting</u>

The reporting of exposure results may contain, but not limited to, the information in Table 3. The data of recordings and measurements should be formatted in such a way that can be opened by commonly used software, such as text editors and spreadsheets. In addition, it is of great help to provide an authorized contact person, of long-term availability, along with the information in Table 3.

Table 3: Reporting of long-term exposure results

Type	Item	Information	Nature
Environment	Exposure site	station owner/operator (ID), exposure location (ID), opening year, status of station, exposure conditions provided, capacity of exposure station	Description
	Environmental factors	Height from the average level of seawater, and distance from the coastline	Description
		Specified exposure zone (ATM, SPL, TID or SUB)	Description
		Exposure duration (in years and months)	Digital
		Average temperature and relative humidity of atmosphere surrounding the exposure specimens	Digital
		Average temperature of seawater, and temperature of seawater at sampling	Digital
		Salinity, or preferably chloride and sulfate concentrations, of the seawater	Digital
		Other factors such as seawater chemistry, seawater hydrology, air-borne chlorides, CO2 concentration in air, precipitation, wind speed and direction, and biological growth at concrete surface.	Digital /Description
Materials	Concrete specimen label	specimen ID, mix ID, specimen geometry, casting date, exposure date, exposure location/station (ID)	Digital /Description
	Concrete mix proportioning and properties	mix proportion, air content and chloride content of the fresh concrete, density and slump of fresh concrete, laboratory production and curing, compressive strength of concrete at 28d	Digital /Description
	Raw materials and other properties	type, chemical composition and physical properties of cement and mineral admixtures; type, maximum size and grade curve of aggregates; specimen surface cracking (if apply)	Digital /Description
Performance	Basic properties (if apply)	Method for sampling; Size and geometry of sampled specimens; Method employed to assess the basic properties such as compressive strength and elastic modulus, and the obtained values	Digital /Description
	Chloride ingress profiles	Date and Method for sampling; Size and geometry of sampled specimens; Method for analysis of chloride content, and Chloride content at any given sampling depth	Digital /Description
	Corrosion conditions of reinforcement	Type of reinforcement; Thickness of cover; Method for corrosion assessment, and Values and/or indexes from the measurements	Digital /Description
	External/internal damages (if apply)	Date and Method for sampling; Size and geometry of sampled specimens; Method employed to assess the damage, and Values and/or indexes from the measurements	Digital /Description
	Other properties (if apply)	Date and Method for sampling; Size and geometry of sampled specimens; Method employed to assess the properties, and Values and/or indexes from the measurements	Digital /Description

* The contact of an authorized person of long-term availability is recommended to be provided along with this table.

5 Data management

The data management of long-term exposure is to collect, store, publish and reuse the data generated during the exposure practice. A successful data management can materialize the research efforts and generate the added value. Some recent concepts for data management, such as FAIR data principles [58], provide a sound framework for data management. A data management system should consider the following elements: data and storage media, data transmission, data accessibility and sharing. Recommendations are given to these aspects on the basis of return of experiences from some major exposure sites.

5.1 Data storage

The data generated from the long-term exposure practice include the recordings on the environmental conditions, the information on concrete materials, and the testing results on the exposed specimens. The environmental data can be referred to the factors in Table 1, the information on concrete materials can be referred to the descriptions in Section 2.3, and the testing results can follow the description in Section 4.2. A standard presentation for exposure data can be referred to Table 3 and [1, Table 2].

The data storage modes include the local storage and the centralized storage. The local storage refers to the data collected directly from the exposure sites through sensors or recordings, or the data and results from on-site or and off-site (laboratory) tests. The centralized storage refers to the systematic storage of the whole exposure datasets for a given exposure site. The data storage should be adapted to the change of storage technology. The electronic format is recommended for both modes of storage, and the data storage formats should be approved among the concerned parties. The data storages, local or centralized, should observe a pre-agreed protocol for data backup. In extreme cases where the electronic format storage is not available, recordings and results in paper forms can be used, but special guideline should be set up for the storage of these documents.

5.2 Data transmission

The transmission of data is necessary when consolidating the data stored locally to the centralized storage. As the data transmission media are available and functional, the collected data, from on-site sensors or off-site laboratory tests, can be transmitted automatically as long as the sensors or the local storage media are connected to the centralized storage media through the same network. For in-site sensors, modulators are sometimes needed to convert the analogue signals to digital ones. If no transmission medium is available, the data transmission can only be done manually using movable storage media.

The transmission media for digital data can include wired transmission such as coaxial cables or optical fibre cables, and wireless transmission through microwaves (mobile phone) or radio waves (low power wide area networks, LPWAN). The cable transmission offers high transmission speeds, high security and reliability, but requires high power consumption and local access to a wired network. The mobile phone technology offers high transmission speeds, high security and reliability, but has high power consumption and requires local access to a mobile network. The LPWAN offers low power consumption, does not need access to wired or mobile network, but has a limited transmission speed and is not available in all countries [59].

5.3 Data access and sharing

For the centralized data storage, a systematic data management regulation should be established, clearly defining the data access and operation rights for the concerned persons. It is a good practice to carefully distribute different access rights of reading, copying, writing and deleting, especially to restrict the authorized persons with rights of writing and deleting. If some parts of data are confidential, they should be marked as such and only authorized persons should have access. For local data storage, the responsible institutions should apply a systematic data management and appoint authorized persons to record, maintain and transmit the local data. And the contact of these authorized persons is recommended to be included into the data reporting in Table 3.

A sharing policy should be agreed in advance among partners and investigators. The sharing of exposure data should comply with the active policies on intellectual property. A data sharing interface will be helpful with the main information of exposure data arranged into readable format.

6 Maintenance for facilities of exposure site

6.1 General management requirements

For an exposure site, specific logos are recommended to be set up in an easily visible location. The entrance into the exposure site should be approved by the operator, and the works in the exposure site should be registered and recorded. The works should be carried out according to the pre-determined plan which has been approved by the operator. No works should be performed during the extreme climates.

The works in exposure site should respect the safety regulations. The personnel should be trained prior to the works according to relevant safety standards and maintaining operations. The safety equipment and items such as helmet, safety belt and life jacket should be worn properly. When electricity is used, special measures should be taken against the electricity leakage. The site should be recovered after works and all litters should be taken away and disposed. If chemicals are used during the works, ecological regulations should be followed.

6.2 Routine and regular inspection

<u>Routine inspection</u>
Routine inspection is recommended to be performed on a yearly basis to check the appearance of the exposure facilities and specimens. It can be combined with the placing or retrieving of specimens. The routine inspection checks the following items and involves also the relevant maintenance if necessary.

The surface state of metal structures and facilities and their surface coatings, if any, need to be checked. The severely corroded parts should be replaced by new ones and the broken coatings should be repaired. The specimens and their fixation facilities are to be checked. If the specimens are lost, new specimens should be prepared for substitution or the retrieval plan should be amended. If the fixation is failed, the facilities should be replaced.

The surface of exposure specimens is to be checked. In cases where the biological growth is deemed unacceptable, cleaning operations should be organized. In cases where the surface sealing and coating lose their integrity due to unexpected actions, repair works should be conducted immediately. For specimens with accessories such as loading devices and corrosion monitoring devices, these devices should be checked and any abnormality should be reported to the operator or the responsible institution.

When reinforced concretes are used as main exposure support, a monitoring system is recommended to be set up for these structures during their service life. Both video monitoring and photo monitoring are possible choices to transfer the images of the exposure site to remote terminals.

Regular inspection

Regular inspection is to check the integrity and the functionality of the exposure infrastructure and facilities. The frequency of regular inspection can be determined on the basis of the operation state of exposure site, normally no longer than 10 years. The regular inspection checks the following items and involves the relevant maintenance.

For reinforced concrete and steel structures to support the exposure practice, the regular inspection checks the structural integrity, loading resistance, structural displacement and deformation, and durability performance. If anti-corrosion protection and materials are used, they should be checked for their functionality. On the basis of the inspection results, a comprehensive assessment is to be conducted for the safety, serviceability and durability, and the corresponding maintenance works should be organized if necessary.

6.3 Special inspection

The special inspection of exposure sites should be carried out after special events such as ship collision, typhoon and earthquake. If the specimens are exposed in open air, they should be withdrawn before the passage of a hurricane to avoid their loss. The inspection should be done by a professional team. First, the access to power and water should be checked. Then, the safety of the main support structures should be assessed, and the relevant maintenance works should be performed if necessary. Lastly, the facilities and exposed specimens should be checked for their functionality and integrity. Any abnormality should be alerted to the operator and the responsible institution.

The special inspection occurs also for an exposure site approaching its design life or the end of exposure mission. The same items will be checked for the exposure site and the assessment should provide a basis for the continuation of the exposure site.

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Appendix A: Marine exposure zones

The definition of exposure zones in marine environments is essential for the exposure practice. The exposure zones are the results of the interaction between the seawater, the aerodynamics of marine air and the structure in question. Thus, the position of these zones depends on the seawater hydrology, the location of the exposure infrastructure and the placement of specimens. The definition of these exposure zones is summarized in the following.

The SUB zone

The submerged zone refers to the condition permanently exposed to seawater. The exposure environment follows mainly the characteristics of the seawater, including its temperature and chemical composition. Also, marine biological growth can occur on the surface of concrete structures and specimens. The upper limit for SUB zone is related to the lowest astronomical tide level and wave height [13] for unshielded marine environment, and to the design low water level for shielded marine environment [14].

The TID zone

The tidal zone refers to the condition of concrete subject to alternating immersion by tidal water and atmospheric exposure to marine air. The seawater tide follows approximately 12-hour cycles. The exposure environment in TID zone relates to the characteristics of both seawater and marine air. Accordingly, the durability degradation includes both seawater-induced ones and the marine air induced ones, and the surface biological growth can also occur. The lower limit of TID zone is the upper limit of SUB zone. The extended range (upper limit) of TID zone considers mainly the highest astronomical tide and effective wave height for unshielded marine environment, and the design high water level for shielded marine environment [14]. In some cases, the TID zone is combined into the SPL zone.

The SPL zone

The splash zone refers to the exposure of concrete surface to both the splashing actions of seawater waves and the marine air. The splashing actions are created by the collision between the seawater waves and the concrete surface, and thus they are highly dependent on the local arrangement of exposure structures and specimens. The concrete surface in SPL zone will be subject to actions from both the seawater splashing and the marine air. The chloride accumulation and the subsequent steel corrosion are substantially promoted by the drying-wetting cycles and the alternative availability of moisture and oxygen in air [8]. For unshielded marine environments, the upper limit of SPL zone is related to the highest astronomical tide and wave height [13], and to design high water level for shielded marine environment [14]. As the exposure site is arranged into a shielded structure, the splashing actions will be specific to the arrangement of the exposure spaces, and the appropriate placing of concrete specimens should resort to the local observation and recordings of the water movement.

The ATM zone

The atmospheric zone refers to the exposure of concrete surface to marine air only. The exposure environment of concrete surface is the marine atmosphere, and the main environmental actions include the temperature, the airborne chlorides, the CO_2 and the natural precipitation. The lower limit of ATM zone is the upper limit of SPL zone, and the intensity of the airborne chlorides depends much on the local aerodynamics and the height/distance from the sea level and the coastline [11]. For concrete specimens exposed in ATM zone, the chloride deposition rate is one of the environmental factors to be recorded.

Compliance with Ethical Standards

Conflict of Interest: The authors declare that they have no conflict of interest.

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