Review Article ISSN 2832-9384

Journal of Materials and Polymer Science

A New Approach for Durable and Sustainable Infrastructure Concrete

C. Paglia[1*], C. di Bella[2], M. Brugin[3] and M. Caroselli[1]

[1]*Institute of Materials and Construction, Supsi, V. Flora Ruchat 15, CH-6850 Mendrisio, Switzerland.*

[2]*Jura-Cement-Fabriken AG, Talstrasse 13, CH-5103 Switzerland.*

[3]*Lombardi SA, CH-6512 Giubiasco, Switzerland.*

***Corresponding author**

C. Paglia,
Institute of Materials and Construction,
Supsi, V. Flora Ruchat 15,
CH-6850 Mendrisio,
Switzerland.

Submitted : 21 Dec 2023 ; Published : 27 Jan 2024

Citation: Paglia, C. et al., (2024). A New Approach for Durable and Sustainable Infrastructure Concrete. J mate poly sci, 4(1):1-12.
DOI : DOI : https://doi.org/10.47485/2832-9384.1045

Abstract
The durability of reinforced concrete infrastructures is a major concern related to several aspects of the sustainability. The actual concrete design is still largely based on prescriptive indications, such as the cement content and the water cement ratio, while the durability investigation started to be oriented towards a more performance-based concept. The actual laboratory durability tests depend on the environmental exposure classes. Nonetheless, the actual stringent durability limits force to produce concrete with a too rapid strength development. This fact adversely affects the rigidity of the infrastructure and reduce the durability. Furthermore, the actual concrete requirement concepts partially inhibit the use of more sustainable concrete. This work proposes a new approach and a new concrete framework to produce more eco-efficient and more durable concrete. This will be attained by introducing a better laboratory-field relationship with respect to the durability by means of combined laboratory environmental attacks, which better simulate the real infrastructure site condition.

Keywords: eco-concrete, infrastructure, durability, sustainability.

Introduction

The quality and durability of concrete in Europe are currently regulated by a standard with some local adaptations as for Switzerland (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021), which are based on a prescriptive approach. At the same time, the concept of guaranteed performance concrete depends on environmental exposure classes.

The choice and requirements of concrete are left to the customer. The critical exposure classes are frost, the penetration of soluble salts, such as chlorides and carbonation. The current standard is in use for over 20 years and contributed to simplify the production and use of concrete. Nevertheless, this partial prescriptive approach is not sufficient to control the real durability of the infrastructure concrete in the field.

The minimum requirements for the concrete composition are mentioned in the standard, based on experience and accepted practice. Limits for the concrete composition depend on environmental exposition, minimum cement content, compressive strength and maximum water-cement ratio. Concretes with standardized minimum requirements meet the main properties. The minimum cement content satisfies the strength requirements, but there is no consensus on the minimum cement dosage in relation to durability (Bentur et al., 1997; Damineli et al., 2010).

Indeed, to comply with the strict durability limits (Standard SIA 262/1 Concrete construction, complimentary specifications, 2019, 2019), there is a tendency to reduce the porosity by lowering water content and w/c ratio. This results in an excessive increase in early strength that leads to over strength and stiffness of concrete. Increasing the cement content provides higher strength and high modulus of elasticity, but results in an increased shrinkage and premature cracking. The load-bearing capacity, load frequency and environmental conditions on infrastructures also contribute to a reduction in durability. Consequently, a more controlled strength development and concretes adapted to specific requirements of the infrastructure would help to increase the long-term life.

In addition, concretes with high cement content lead to unnecessarily high energy consumption and CO_2 emissions. Although some reductions in the environmental burden as for the Swiss cement industry was achieved in the carbon footprint, by reducing the emission from 813 kg CO_2 /*t* in 1990 to 570 kg CO_2 /*t* in 2021, there are still several challenges to overcome to further minimize the carbon emissions. Greenhouse gas emissions (GHG) from concrete are still too high, as is the amount of waste from the demolition of structures. According to Cemsuisse and the latest estimates, 4.1 million tons and 15 million m^3 of concrete were produced in Switzerland in 2021, respectively (Report Cement Suisse, 2022).

The current standard provisions (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021) only partially make use of today's knowledge of concrete technology and make it increasingly difficult to exploit the existing potential of eco-concretes.

Thus, it is necessary to develop a new performance-based worldwide concrete concept that considers the technological implementation in the sustainable concretes, the reduction of cement content as well as the knowledge gathered for decades concerning the real site durability of specific infrastructures (Paglia et al., 2022; Paglia et al., 2021; Paglia & Antonietti, 2022; Paglia, 2022; Paglia & Antonietti, 2021; Paglia& Mosca, 2023; Paglia & Jornet, 2022; Paglia et al., 2022). Furthermore, more reliable laboratory testing methods must be thought to simulate the real exposure conditions in the field and achieve more durable infrastructures.

Research state of the art and needs

Swiss state of the Research

In Switzerland, the design of concrete is adapted to the European standard (Wikipedia, 1992), which is based on prescriptive provisions deemed to satisfy (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021), with minimum cement content and the maximum w/c ratio. Exposure classes, strength and performance requirements are also defined. These were validated by several years of laboratory and field experience by using prescriptive provisions.

However, national annexes were added to the EN standard (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021), with the concept of guaranteed performance. The w/c ratio and the minimum cement content remain indicative parameters, since they cannot be measured once the concrete is used.

As in other European countries (Linger & Cussigh, 2018), interests in performance-based approaches also grew in Switzerland. Tests were adopted for each exposure class as a durability performance indicator: accelerated carbonation tests, water absorption by capillarity, chloride migration for wet / dry cycles (Standard SIA 262/1 Concrete construction, complimentary specifications, 2019). The standards specify limits for the test results in each exposure class.

The transition from a prescriptive to a performance-based approach should be made without compromising concrete performance and without confusing the producers. The reduction of the clinker content in cement is a way of reducing the CO_2 emissions. On the other hand, an excessive clinker substitution and lower cement content in concretes may push the system to its limits and compromise durability requirements. While the use of k-values belongs to the obsolete parameters. The introduction of the performance concrete concept should consider the limited experience with this approach to reduce the premature deterioration of the material. To avoid this, the concrete mixes should be subjected to more appropriate laboratory testing. In fact, the energy and CO_2 emission saving benefits of a concrete mix can easily be negated if durability is adversely affected and the combined effects of multiple degradation mechanisms in the field are not considered. These latter are largely underestimated in the actual laboratory tests (Wittmann et al., 2010; Kuosa et al., 2014; Jhatial et al., 2020). An adequate assessment of the combined deterioration effects in concrete allows the implementation of the performance concrete concept and the mix designs with adequate strength, durability and sustainability.

Fresh state properties are important factors. The problems of manual casting and vibration still need to be addressed. A significant correlation exists between concrete segregation and bleeding with time and vibration, type of mix, aggregate size, fine particle content, type of superplasticizers. The increase in fluidity may be accompanied by an increase in compressive strength up to the optimum level. However, excessive use of superplasticizers or air carrier can lead to bleeding and segregation and reduce compressive strength (Alsadey, 2012; Antoni et al., 2017). Since decades, the concept of robustness of a mixture is a widely known topic, that can affect mechanical performance and durability (Neville, 1996). Grain size curves extensively studied the packing and fine content, while the mix design rather than vibration, tends to avoid segregation (Navarrete & Lopez, 2016). The interaction between aggregate surface area and the density differences of the components also play a significant role (Navarrete & Lopez, 2016; Navarrete & Lopez, 2017). The accumulation of fine particles on the surface, can affect the performance. Appropriate classification, type and content of fillers and hydraulic fine particles help to control segregation. On the other hand, the conventional measures of consistency (Standard SN EN 12350-2: 2019, Testing fresh concrete - part 2, 2019; Standard SN EN 12350-4: 2019, Testing fresh concrete, part 4, 2019; Standard SN EN 12350-5: 2019, Testing fresh concrete, part 5, 2019) are not suitable for determining the tendency to segregate.

The propensity to segregation can be measured with more reliable methods (Olbrecht & Moser, 2004; ASTM, 2009), although active rheological control mechanisms are also investigated (Geert & Karel, 2023). Nevertheless, some methods are not simple to be applied.

Concrete and Specific Requirements

Concrete is one of the preferred materials for civil works due to its strength and low cost compared to other materials. Historically, the need to meet high durability and construction standard specifications caused concrete mix overdesign, resulting in an increase of the cement content. This situation, underestimated for a long time, caused an over strength in concrete and a simultaneous decrease in durability due to induced cracking (Antunes, 2022).

In order to control cracking, a minimal reinforcement content must be guaranteed. Since this parameter is often linearly dependent on the concrete strength, increasing the concrete compression resistance also increases the minimum required reinforcement.

The elements of a structure exhibit differing needs in material characteristics. A bridge pier foundation usually shows a very basic need in terms of elastic modulus and chloride penetration resistance, while the deck requires a high modulus of elasticity and a low chloride penetration. Therefore, project specifications depend on the type of structure, but are also influenced by parameters, such as sustainability, location, and production method. In addition, the digitalization of the construction process, new techniques and life cycle optimization may improve efficiency, reduce errors and costs.

Global Research and Tests

There is a worldwide interest in innovative solutions to reduce the carbon footprint of the cement industry. The performance approach aims at achieving durability without specifying how it should be achieved, leaving flexibility for experimentation and innovation.

Many countries that adopted the perspective recommendations of the standard EN 206 added changes to the limits of the w/c ratio and minimum cement content depending on the exposure class. The minimum depth of cover, maximum w/c ratio, minimum binder content and minimum strength classes, depending on the binder, were modified (Laborat´orio Nacional de Engenharia Civil, Concrete. Prescriptive Methodology for a Design Working Life of 50 Years under the Environmental Exposure, LNEC E 464, 2007). Similarly, it was proposed to set limits for chloride migration for the exposure classes and binders (Polder et al., 2006) or a parameter that considers the environmental conditions calibrated for each specific environment (El Farissi et al., 2018).

Two main design (Associaç˜ao Brasileira de Normas T´ecnicas, Design of Concrete Structures – Procedure, vol. 6118, NBR, 2014) and construction codes (Associaç˜ao Brasileira de Normas T´ecnicas, NBR, Portland Cement Concrete - Preparation, Control, Receipt, and Acceptance - Procedure, vol. 12655, 2015) are prescriptive and indicate limits for w/c ratio, compressive strength, cement content and depth of cover for each exposure class. In addition, performance requirements for the construction sector, specify a minimum service life (Associaç˜ao Brasileira de Normas T´ecnicas, Residential Buildings — Performance Part 1: General Requirements, NBR 15575-1, 2013). Durability indicators were also suggested (Associaç˜ao Brasileira de Normas T´ecnicas, Residential Buildings — Performance Part 2: Requirements for Structural Systems, NBR 15575-2, 2013), without clarifying the test methods and reference values for the validation. Performance requirements are also measured in situ, so that the concrete producers and designers must work to meet the specification (CSA, Canadian Standard A23.1/A23.2., Concrete materials and methods of concrete construction/Methods of test and standard practices for concrete. Canadian Standards Association, 2004). Prescriptive specifications are also part of the North American Standard for Concrete, which is based on durability indicators, such as concrete strength class and w/c ratio, but does not include a minimum cement content (American Concrete Institute (ACI), 2011).

The Laboratory-field Relationship

The simulation of the field environmental conditions in laboratory is a challenging task. During the years, the main deterioration phenomena were partially understood (Tang et al., 2015). Alkali-aggregate reactions, sulphate attacks, carbonation, chloride migration, steel rebar corrosion, critical chloride thresholds (Angst et al., 2009), resistance to frost, shrinkage and the mechanical actions, all exhibit damages. Most of these phenomena were clarified by isolating the deterioration mechanisms and testing the susceptibility of concrete exposed to a few single environmental parameters.

However, the durability of infrastructures is asymmetrical (Paglia, 2022). Bridges, tunnels, walls and geotechnical elements are directly or indirectly exposed to water splashing, chlorides, rainfall, sun irradiation, air and humidity. The entrance of tunnels may exhibit different chloride and freeze / thaw exposition as in the middle. Long tunnels may show an asymmetrical leaching of tunnel walls across the lanes (Paglia, 2022). The South side of a bridge directly exposed to the sun irradiation, is subjected to wide thermal and humidity excursions and shows a higher carbonation depth as compared to the North side. The alpine infrastructures appear to exhibit only a slight correlation between high chloride content and low carbonation. This correlation is more present in a marine environment. On the other hand, it is not possible to plan a different type of concrete for each part of an infrastructure. Nonetheless, this asymmetrical deterioration of infrastructures and the surrounding micro climates help to define four main environmental exposition fields, where to focus new performance-based durability laboratory tests.

Furthermore, the deterioration of infrastructures is a combination of several environmental factors (Wang et al., 2022; AL-Ameeri et al., 2021; Malheiro et al., 2014; Tumidajski & Chan, 1996; Alava, 2017; Fan et al., 2019; Ndahirwa et al., 2018; Rao et al., 2017), that the laboratory tests must consider. In some cases, field application techniques may differ from those in the laboratory and this fact must also be taken into account (Paglia et al., 2002).

Summary of the Research Needs

The concrete framework must be modified by considering new sustainable cements and recycled components. A special attention is focused on the propensity of fresh concrete to segregate. The compressive strength should attain the actual classes C25/30 and C30/37, avoiding over strength. The modulus of elasticity, i.e. the stiffness, must be kept under control. On the contrary, the w/c ratio and the minimum cement content can be eliminated. The new concrete concepts need to give a sufficient degree of freedom on mix designs to better allow the use of sustainable materials. On the other hand, the concrete framework needs to remain simple and with clearly defined parameters.

The durability of infrastructures contributes to sustainability. The deterioration depends on environmental conditions, which need to be classified and tested according to the real exposure conditions of an infrastructure and not solely on a single deterioration mechanism. New performance-based combined durability tests will allow to increase the relationship between laboratory and field behaviour. Each micro climate along infrastructures may be simulated in laboratory by alternatively combining the environmental expositions and by accelerating the testing methods. However, the tests must avoid artificial damaging mechanisms. New clear and measurable parameters and limits need to be determined after the durability tests. The severity of the combined environmental laboratory tests will maintain a high level of concrete quality. In the meantime, tests on site are also required to confirm the laboratory behaviour.

All these tasks facilitate the use of sustainable materials, produce more reliable laboratory results and maintain a simple concrete framework, where producers and engineers will be able to cast in place durable concrete in the interests of the specific infrastructure type and owner.

Limitations

Cement and concrete producers try to reduce the clinker in the cement manufacture and the cement in the concrete. The development of sustainable products may increase the risks related to the quality and durability of concrete. This fact may hinder the use of sustainable cements. Therefore, the cementitious binders need to be certified or controlled with respect to detrimental pollutants. The use of sustainable cements produced on a local scale, including the recycled components must be promoted. This fact helps to partially replace the natural aggregates and reduces the exploitation of natural resources, while maintaining the performance, sustainability and durability.

The behaviour of materials and construction systems is controlled by environmental and mechanical factors and predicting the service life of a structure is still a matter of debate. The laboratory simplification and the isolation of factors, such as the carbonation or the diffusion of chlorides, gave helpful indications on the degradation mechanisms over time. However, the combined field actions of carbonation, chloride penetration, water leaching, drying, temperature variation and freeze / thaw actions, make prediction difficult for infrastructures.

Nonetheless, to increase the relationship between laboratory tests and real field behaviour, it is necessary to combine the alternate action of the several environmental effects on the laboratory specimens. This will lead to more performance-oriented durability tests and give more reliable behaviour on site. On the other hand, the interpretation of the results and the contribution to the damage of the single components may become more difficult. However, this is a unique way to simulate in laboratory the exposure conditions on site. Thus, long-term durability results in the field will need to be done to clarify the laboratory-field relationship.

The New Approach

Two Main Objectives

It is necessary to develop new concrete concepts based on the performance and the sustainability of the materials. Furthermore, durability performance-based laboratory tests derived from on-site exposure conditions to produce robust and durable infrastructure concrete are required.

Sustainable cements and concretes must increasingly be used by testing their durability performance on the new real exposure conditions. A revision of some durability specifications for performance-based concretes is necessary. The EN 206/1 can be used as a background, but the main exposition classes are re-arranged to better simulate the field conditions. A focus must be given to sustainable concretes with low clinker, inert and / or reactive mineral additions as well as recycled cementitious aggregates. These latter components can no longer be disregarded on a long-term basis.

Material and Construction Systems Sustainability

The local availability of resources is a fundamental aspect that needs to be taken into account to get a sustainable concrete infrastructure. Some of the most used composite cements with a reduced clinker amount contain a carbonate mineral addition. This latter is one of the main Swiss available constituents, except for CEM III/B (Bundesamt für Landestopografie swisstopo, 2020). Nevertheless, the cement choice may be done according to the international raw and supplementary cementitious material availability.

Binder type	Clinker replacement (range)	Application
CEM II/B-LL 32.5 R	21 - 35 %	Building construction and civil engineering
CEM II/B-M (S-LL) 42.5 N-HS-CH	21 - 35 %	Building construction and civil engineering
CEM II/C-M (Q-LL) 42.5 N (LC3)	36 - 50 %	Building construction; (potential use to be extended in the civil engineering)
CEM III/B 42.5 L-LH/SR	66-80%	Building construction and civil engineering

Table 1: Some binder type, clinker replacement and carbonate addition containing cements used for the Swiss local market.

Sorting and preparation of the recycled concrete components needs to be done along with the characterization of the recycled concrete aggregates (RCA). A fundamental division will be the separation of the high-quality infrastructure concrete from the rest of the concrete structures, with lower mechanical and durability properties. It will also be necessary to set the maximum dosages of recycled components to attain the durability of the recycled concrete and to optimize the eco-mix designs. Performing of a CO_2 equivalent evaluation to investigate the CO_2 potential sink would also be a useful indication for the type of blend used. These actions will allow to characterize the sustainable concrete components. Finally, the mechanical and the new durability performance tests of the sustainable concretes will enable their use or rejection.

Infrastructure requirements and environmental exposition

The infrastructures are subjected to several types of environmental exposition that largely affect their durability. Usually, durability of more than 100 years are required for tunnels and bridges. The cementitious materials used for the tunnel service life are mainly composed of the shotcrete, basement and pre-cast linings elements. All these type of structures are differently exposed to environmental condition, water infiltration, humidity, CO_2-rich water, leaching, chloride exposure, sulphate attack, salt crystallization and mechanical damage.

Bridges are partially differently exposed to the deterioration agents. Carbonation, chloride contamination of reinforced concrete, freeze and thaw degradation are the main environmental damages to face off. In this concern, a large asymmetrical behaviour with respect to the durability is seen between the directly and indirectly atmospheric exposed parts. The buried parts also exhibit slightly different requirements and are subjected to aggressive waters, but exhibit a significantly lower carbonation and only a partial presence of chlorides. At depth below two meters, the freeze and thaw degradation is less of an issue.

Concrete framework procedure and concepts re-assessment

The compressive strength classes C25/30 and C 30/37 and the modulus of elasticity remain the main mechanical parameters to achieve performance related concretes. On the other hand, in order to increase the use of more sustainable cementitious binders, the concrete parameters such as the cement type, the clinker component, the SCM's type and the recycled concrete content should be indicated. Conventional mechanical and durability tests (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021; Standard SIA 262/1 Concrete construction, complimentary specifications, 2019) may be taken as a baseline and may serve as a comparison with the new durability performance tests. In order not to completely change the actual normative framework, the sulphate and the alkali-aggregate resistance may be tested with conventional susceptibility methods.

On the contrary, new performance durability classes for the new eco-concretes based on the microclimates along the infrastructures must be specified and can be compared with the actual exposition classes (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021; Standard SIA 262/1 Concrete construction, complimentary specifications, 2019). Consequently, new ranges and limits must be set to allow the production of more durable and sustainable infrastructure concretes.

Tests	Standard / test environment	Explanation
Concrete tests (actual normatives)		
Consistency class	SN EN 12350-2 SN EN 12350-4 SN EN 12350-5	Workability of the fresh mixture
Segregation propensity	Degree of segregation / Bauer Filter press	Segregation / bleeding tendency of the fresh mixture
Compressive strength	EN 12390-3	Main concrete mechanical performance
Modulus of elasticity	SN EN 12390-13	Material stiffness
Chloride migration tests	Sia 262/1 appendix B	Resistance to chloride penetration detrimental to rebar corrosion
Accelerated carbonation	Sia 262/1 appendix I	Propensity of rebar corrosion induced by carbonation
Sulphate resistance	Sia 262/1 appendix D	Chemical attack from chemical-enriched aqueous solutions
Alkali-aggregate susceptibility Performance test	SIA 2042 AFNOR NF P18-454 SIA 262/1 Appendix G	AAR susceptibility (alkali content of cementitious binders and Si-rich aggregates)
Chemical degradation	Aggressive ions [1]	Exposure class severity based on concentrations
Concrete tests according to the new environmental combined exposition		
MCIAE	Mild Clima Indirect Atmospheric Exposition	Exposure condition for tunnels, lower parts of bridges, piles, underpasses covered or partially protected from the direct atmospheric agents
CCIAE	Cold Clima Indirect Atmospheric Exposition	Exposure condition for tunnel entrances, upper parts of bridges partially sheltered, piles, underpasses in cold regions

MCDAE	Mild Clima Direct Atmospheric Exposition	Exposure condition for upper parts of bridges and geotechnical support walls
CCDAE	Cold Clima Direct Atmospheric Exposition	Exposure conditions for tunnel entrances, upper parts of bridges and geotechnical support walls in cold regions.
UG (underground)	Concrete slabs exposed to continuous water leaching (flow rate 300-500 l /h)	Simulation of groundwater and infiltration water leaching
Recycled concrete aggregates (RCA)		
Water adsorption	EN 1097-6	RCA water adsorption
Chemical characterization	Waste pollutants limits guidelines	Chemical analysis. Concentration to be checked according to the dosage and leaching tests.
Cement binders		
Composite cements	Tests according to the 197-1 or Certified materials	Cementitious binder capacity to be documented
Steel rebar / mesh		
Visual inspection	EN ISO 8501-1	Determination of the corrosion intensity
Electrochemical potential monitoring	Recommendation SIA N° 2006, 2013	Corrosion evolution susceptibility during the environmental combined attacks
Microstructure		
Optical / SEM microscopy		Clarification of the main degradation issues / mechanisms and extent

Table 2: Old and new laboratory tests and environmental exposition.

Implementation of the laboratory-site relationship on the durability

Laboratory tests on concrete are a crucial factor to assess a reliable infrastructure field durability on site. The main fresh state properties of the new blends will need to be characterized with respect to the workability and the segregation propensity. The hardened state will be investigated by means of the determination of the compressive strength and modulus of elasticity.

The different real exposure conditions to which the infrastructures are subjected are characterized as follows:

Mild Climate Indirect Atmospheric Exposition (MCIAE). Mild climate: average annual temperature 10-20oC. Test combinations and alternate environmental exposure. Part of the infrastructure exposed to such conditions are tunnels, lower parts of bridges, piles, underpasses covered or partially protected from the direct atmospheric agents.

Tests Proposal: combined cyclic temperature excursions, cyclic immersion / spraying with water-rich chlorides, cyclic relative humidity, accelerated carbonation. Re-exposure to previous cyclic conditions.

Cold Climate Indirect Atmospheric Exposition (CCIAE). Cold climate: average annual temperature range –20°C to 10°C. Cyclic and combined environmental exposure to assess the concrete durability in tunnel entrances, upper parts of bridges partially sheltered, piles, underpasses in cold regions.

Test Proposal: combined cyclic temperature excursions, cyclic immersion / spraying with water-rich chlorides, cyclic relative humidity, accelerated carbonation and freeze / thaw resistance. Re-exposure to previous cyclic conditions.

Mild Climate Direct Atmospheric Exposition (MCDAE). Combined cyclic environmental exposure to determine the concrete durability for upper parts of bridges and geotechnical support walls.

Test Proposal: combined cyclic water leaching exposition to a water flow / rainfall, temperature excursions, cyclic immersion / spraying with water-rich chlorides, cyclic relative humidity, accelerated carbonation. Re-exposure to previous cyclic conditions.

Cold Climate Direct Atmospheric Exposition (CCDAE). Combined cyclic environmental exposure to determine the concrete durability in tunnel entrances, upper parts of bridges and geotechnical support walls in cold regions.

Test Proposal: combined cyclic water leaching exposition to a water flow / rainfall, freeze / thaw resistance, temperature excursions, cyclic immersion / spraying with water-rich chlorides, cyclic relative humidity, accelerated carbonation. Re-exposure to previous cyclic conditions.

Whole reinforced concrete system exposition (WSE). Considering the use of composite cements and their chemical-electrochemical interaction with the rebars during the hydration process, but especially during the combined attacks, hydrated composite cement paste-rebar systems and the overall chemical susceptibility of the systems must be studied.

Tests Proposal: Tests of composite cement paste-rebar specimens. The maximum hydrated cement paste cover on all sites of the steel rebar mesh may be max. 10 mm. The specimens are exposed to combined cyclic exposure as described above (four conditions MCIAE, CCIAE, MCDAE, CCDAE). Measurable parameters, such as cracking, scaling, weight lost, visual rebar corrosion state similarly as for metallic surfaces (Standard EN ISO 8501-1 Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings, 2007) and corrosion electrochemical potentials during time and damage / corrosion evolution are observed.

The long-term atmospheric temperature increase prediction may cause a very limited or the absence of freeze / thaw phenomena. This fact needs to be considered in the detail design and the development of laboratory of the new performance-based combined durability tests.

Laboratory tests, measurable outputs and limits

The main objective of the new tests will be to set measurable parameters and limits for the new concretes and the whole reinforced concrete systems (Table 3). The actual compressive strength classes can be maintained to keep a clear existing measurable parameter, while it would be useful to set modulus of elasticity ranges at 28 days hydration for the new sustainable concretes. This will allow to limit a too rapid early stage stiffness development of the infrastructure material.

The measurements can be done with some of the existing devices (Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021, 2021; Standard SIA 262/1 Concrete construction, complimentary specifications, 2019), while instrumentation adaptations will be required to produce the combined cyclic actions for the chloride immersion / spraying / wetting / drying / temperature cycles and alternate leaching.

The main measurement outputs can be the scaling mass loss, carbonation and chloride penetration depth, cracking pattern and width, surface microstructure, rebar corrosion state visual inspection / electrochemical potential measurements.

The new durability combined tests will identify the durability limits for the new cyclic combined tests (MCIAE, CCIAE, MCDAE, CCDAE, WSE). In an initial stage of the tests, the behaviour of the mixes after the new durability tests can be compared with the actual exposition classes resistance XC-XD-XF-XA. This fact will help, at least at this early stage of the tests, to better clarify the possible new limits to be set. Limits for the clinker range and the recycled components contents are also to identified, at least on a broad range, in order to target durable eco-concretes.

Main parameters	**Concrete NPK MCIAE** Mild Climate Indirect Atmospheric Exposition	**Concrete NPK CCIAE** Cold Climate Indirect Atmospheric Exposition	**Concrete NPK MCDAE** Mild Climate Direct Atmospheric Exposition	**Concrete NPK CCDAE** Cold Climate Direct Atmospheric Exposition	**Concrete NPK UG** (underground)
Fresh state Consistency class Segregation	 1) C3 2)	 1) C3 2)	 1) C3 2)	 1) C3 2)	 1) C3 2)
Hardened state					
Compressive strength class [MPa] Modulus of elasticity [MPa]	1) C25/30 2)	1) C25/30 2)	1) C 30/37 2)	1) C 30/37 2)	1) C25/30 2)

Cement type / clinker replacement range [%] (dosage range) CEM II/B-LL 32.5 R (21 – 35) CEM II/B-M (S-LL) 42.5 N-HS-CH (21 – 35) CEM II/C-M (Q-LL) 42.5 N (36-50) CEM III/B 42.5 L-LH/SR (20-34) CEM ZN-D CEM type to be indicated by producers and subjected to all performance tests 4)	2) 2) 2) 2) 2) 2)	2) 2) 2) 2) 2) 2)	2) 2) 2) 2) 2) 2)	2) 2) 2) 2) 2) 2)	2) 2) 2) 2) not allowed 2) 2)
Recycled concrete aggregates RCA (0-32 mm) [% tot. aggregate weight] RCA water adsorption weight [%] 3)	1) ≤ 50 % 2)	1) ≤ 50 % 2)	2) 2)	2) 2)	not allowed not allowed
Performance durability class	MCIAE	CCIAE	MCDAE	CCDAE	UG (underground)
Concrete specimens	2)	2)	2)	2)	2)
Sample mass loss [%]	2)	2)	2)	2)	2)
Carbonation depth [1/10 mm]	2)	2)	2)	2)	2)
Chloride penetration depth [1/10 mm]	2)	2)	2)	2)	2)
Surface microstructural features	2)	2)	2)	2)	2)
Cracking pattern and width	2)	2)	2)	2)	2)
Environmental exposition class (SN EN 206, SIA 262/1)	XC1-XC4 XD1 2)	XC1-XC4 XD1-XD2 XF1-XF2 2)	XC1-XC3 XD1-XD3 2)	XC1-XC3 XD1-XD3 XF1-XF4 2)	XC1 XD1-XD2 XA1-XA3 2)
Leaching tests Hardened state (mass loss, chemical analysis of the leachate)	Not necessary	Not necessary	2)	2)	2)
Reinforced concrete specimens Whole system exposition (WSE)					
Cracking nr. of cracks mean width [1/10 mm] scaling mass [%]	2) 2) 2)	2) 2) 2)	2) 2) 2)	2) 2) 2)	2) 2) 2)
Rebar corrosion state visual inspection electrochemical potential monitoring	2) 2)	2) 2)	2) 2)	2) 2)	2) 2)

Table 3: New main concrete parameters and new environmental exposure classes outputs.

The values can be treated as allowed target intervals. The evaluation, the values, classes and the allowed use will be determined after the tests. Standards as the SIA 2030 does not allow the use of recycled components for infrastructure concrete, although by using high quality concrete or infrastructure recycled concrete aggregates it is possible to attain the actual durability parameters [55, 56, 57]. This will be further clarified in the present tests.

New cements and mineral additives must respect the actual standards [58, 59] or demonstrate not to release pollutants in the environment.

Durability monitoring on site

The observation of the field durability of specific infrastructures and for the main type of mixtures is essential to assess the laboratory-field correlation. This fact is often underestimated and a lot of the long-term behaviour experience is lost. There is a general lack of data analysis between the original laboratory investigations during the placing of the concrete and the long-term behaviour of the infrastructure. Therefore, it is necessary to conduct field trials for the new sustainable concretes tested in laboratory. The infrastructure should be monitored within the first 1-5 years from the casting on site. Periodical sampling and site-laboratory investigation should be done each year until 5 years. During this time lapse it will be possible to gather the initial reaction of the material with respect to the degradation agents and will allow an initial correlation with the new performance-based laboratory environmental combined exposure tests. On a long-term basis, an inspection after 20 years would give additional information on the ageing process.

Benefits and Impact

The new concrete concept framework and the elimination of a minimum cement content and maximum water / cement ratio contribute to the reduction of CO_2 and give a higher freedom to producers and engineers, by maintaining performance-based measurable parameters to avoid complications in the concrete production context. The new environmental durability combined performance laboratory tests enable to use new sustainable and durable concretes. A reduction of roadways maintenance is expected. In addition, the use of locally available composite cements, mineral additives and recycled high quality infrastructure crushed concrete aggregates contribute to sustainability. The new durability-performance tests maintain the high quality of the durable eco-concrete for infrastructures.

The increase in the durability significantly contribute to sustainability. The reduction of clinker and the cement content and type in concrete lower the CO_2 emissions (Figure 1).

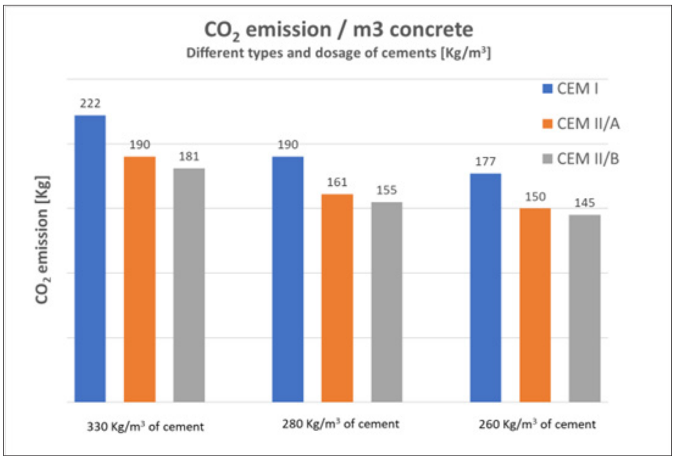

Figure 1: CO_2 emission reduction for carbonate containing cement type and dosage for each m^3 of concrete (Source: Cemsuisse).

Conclusions

The overview of the state of the art of concrete concept planning requires a new framework for infrastructure concrete by substituing the minimal cement content and the water /cement ratio with measurable parameters to produce new sustainable eco-concretes more durable on site. The development of performance-combined laboratory tests is the best way to simulate the microclimates to which the infrastructures are subjected and to assess a more reliable durability on site. In this concern, a revision of the old concrete concept parameters and durability limits with respect to the new performance-based combined laboratory tests (MCIAE, CCIAE, MCDAE, CCDAE) will be required. Indications on the durability of reinforced concrete systems based on chemical / electrochemical susceptibility during the degradation process (WSE tests) will provide a more reliable behaviour on site. The new approach will also enable an increased use of products with lower clinker and higher recycled components. An updating or a revision as well as a guideline for some actual standards (EN 206/1; SIA 262/1) standards with the main concrete parameters and new environmental exposure classes may be required in order to get more durable infrastructure eco-concretes.

References

1. Standard Concrete - Specification, performance, production and conformity, SN EN 206: 2021.
2. Bentur, A., Diamond, S. & Berke, N. S. (1997). Steel corrosion in concrete. *Fundamentals and civil engineering practice* (1st ed.). London, CRC Press. DOI: https://doi.org/10.1201/9781482271898
3. Damineli, B. L., Kemeid, F. M., Aguiar, P. S. & John, V. M. (2010). Measuring the ecoefficiency of cement use. *Cement Concr. Compos, 32*(8), 555-562. DOI: http://dx.doi.org/10.1016/j.cemconcomp.2010.07.009
4. Standard SIA 262/1 Concrete construction, complimentary specifications, 2019.
5. Report Cement Suisse, 2022.
6. Paglia, C., Antonietti, S. & Corredig, G. (2022). The environmental degradation of cement-based materials due to alcali-silica reaction: case studies. *The Second International Conference on Construction Materials and Structures*, (ICCMS-2022). Retrieved from https://www.researchgate.net/publication/366399644_The_environmental_degradation_of_cement-based_materials_due_to_alcali-silica_reaction_case_studies
7. Paglia, C., Antonietti, S. & Mosca, C. (2021). The Degradation of Reinforced Concrete Bridge Elements. The 5th International Conference on Building Materials and Materials Engineering, Barcelona, Spain, 24-26 September, 2021, 1-9.
8. Paglia, C. & Antonietti, S. (2022). The carbonation and chloride penetration along highway concrete structures in a South alpine space. The 8th International Conference on Concrete Technology, Concrete Solutions Leeds, UK, 2022. *MATEC Web of Conferences, 361*(2), 01003. DOI: http://dx.doi.org/10.1051/matecconf/202236101003
9. Paglia, C. (2022). The degradation of concrete tunnel wall panels. The 7th International Conference on Durability

of Concrete Structures, University of Jinan, Shandong, China, Mai 20-22, 2022.
10. Paglia, C. & Antonietti, S. (2021). The Air Permeability, Carbonation and Chloride Content along a Concrete Highway Underpass. The 4th International Rilem Conference on Microstructure Related Durability of Cementitious Composites, Micro durability, *The Hague*, The Netherlands, Mai 2021.
11. Paglia, C. & Mosca, C. (2023). The concrete road pavement durability: a study of over 50 years old concrete structures in a South alpine space. The 14th International Symposium on Concrete Roads, Krakow, Poland, 25-29 June 2023. Retrieved from https://doi.org/10.14359/1341
12. Paglia, C. & Jornet, A. (2022). The Conservation State of Highway Foundation Bridge Piles. The 15th International Conference on Recent Advances in Concrete Technology and Sustainability Issues Milan (Italy), July 13-15, 2022, 1-7.
13. Paglia, C., Antonietti S. & Mosca, C. (2022). The Relationship between Compressive Strength and Carbonation for in Service Concrete Elements. The 8th International conference on advanced engineering and technology, Incheon National University South Korea, online, 21 Mai 2022. Retrieved from https://www.researchgate.net/publication/360756587_The_relationship_between_compressive_strength_and_carbonation_for_in_service_concrete_elements_The_8_th_International_conference_on_advanced_engineering_and_technology
14. Wikipedia. (1992). Eurocode 2: Design of concrete structures. Retrieved from https://en.wikipedia.org/wiki/Eurocode_2:_Design_of_concrete_structures#:~:text=In%20the%20Eurocode%20series%20of,the%20limit%20state%20design%20philosophy.
15. Linger, L. & Cussigh, F. (2018). PERFDUB: A New French Research Project on Performance-Based Approach for Justifying Concrete Structures Durability. Proceedings of the 2017 fib Symposium, Maastricht, The Netherlands, 2017 (pp. 2266-2274). Springer International Publishing, 2018. Retrieved from https://link.springer.com/chapter/10.1007/978-3-319-59471-2_258
16. Cemsuisse. (2021). Cemsuisse Roadmap 2050 Klimaneutraler Zement als Ziel, April 2021, 1-13. Retrieved from https://www.cemsuisse.ch/app/uploads/2021/04/Cemsuisse_Roadmap_210422.pdf
17. Wittmann, F. H., Zhao, T., Zhang, P. & Jiang, F., (2010). Service life of reinforced concrete structures under combined mechanical and environmental loads. The 2nd International Symposium on Service Life Design for Infrastructures (pp. 91-98). RILEM Publications SARL. Retrieved from https://www.rilem.net/images/publis/pro070-011.pdf
18. Kuosa, H., Ferreira, R. M., Holt, E., Leivo, M. and Vesikari, E., (2014). Effect of coupled deterioration by freeze–thaw, carbonation and chlorides on concrete service life. Cement and Concrete Composites, 47, 32-40. DOI: https://doi.org/10.1016/j.cemconcomp.2013.10.008
19. Jhatial, A. A., Serdar, M., and Ye, G., (2020). Review on concrete under combined environmental actions and possibilities for application to alkali activated materials. The 6th Symposium on Doctoral Studies in Civil Engineering, University of Zagreb, Croatia, pp. 7-8. DOI: http://dx.doi.org/10.5592/CO/PhDSym.2020.09
20. Alsadey, S. (2012). Influence of superplasticizer on strength of concrete. Int. *Journal of Research in Engineering and Technology, 1*(3), pp. 164-166. Retrieved from https://www.researchgate.net/publication/285816594_Influence_of_superplasticizer_on_strength_of_concrete
21. Antoni, A., Halim, J. G., Kusuma, O. C. & Hardjito, D. (2017). Optimizing polycarboxylate based superplasticizer dosage with different cement type. Procedia engineering, 171, 752-759. DOI: http://dx.doi.org/10.1016/j.proeng.2017.01.442
22. Neville, A. M. (1996). Properties of concrete, 4th edition, Paperbacks. Retrieved from https://books.google.co.in/books/about/Properties_of_Concrete.html?id=mKEeAQAAIAAJ&redir_esc=y
23. Navarrete, I. & Lopez, M., (2016). Estimating the segregation of concrete based on mixture design and vibratory energy. Construction and building materials, 122, 384-390. DOI: https://doi.org/10.1016/j.conbuildmat.2016.06.066
24. Navarrete, I. & Lopez, M., (2017). Understanding the relationship between the segregation of concrete and coarse aggregate density and size. Construction and Building Materials, 149, 741-748. DOI: https://doi.org/10.1016/j.conbuildmat.2017.05.185
25. Standard SN EN 12350-2: 2019, Testing fresh concrete - part 2, 2019. Retrieved from https://standards.iteh.ai/catalog/standards/cen/cf0e0511-2176-454c-948d-9e515f3a03f1/en-12350-2-2019#:~:text=This%20document%20specifies%20a%20method,10%20mm%20and%20210%20mm.
26. Standard SN EN 12350-4: 2019, Testing fresh concrete, part 4, 2019. Retrieved from https://standards.iteh.ai/catalog/standards/cen/31623d05-be61-4781-84e7-5ae820b6c8b7/en-12350-4-2019#:~:text=Testing%20fresh%20concrete%20%2D%20Part%204%3A%20Degree%20of%20compactability,-This%20document%20specifies&text=The%20test%20is%20suitable%20for,not%20greater%20than%2063%20mm.
27. Standard SN EN 12350-5: 2019, Testing fresh concrete, part 5, 2019. Retrieved from https://standards.iteh.ai/catalog/standards/cen/f2803e56-a027-49b8-8ce7-30bca7ca224e/en-12350-5-2019
28. Olbrecht, H., & Moser, K. (2004). Entmischung von Beton durch Überverdichtung. *Tec21, 130*(44), 13-16. DOI: https://doi.org/10.5169/seals-108461
29. ASTM Visual Index. (2009). Standard Test Method for Static Segregation of Self-Consolidating Concrete Using Column Technique1. Designation: C 1610/C 1610M – 06a. Retrieved from https://cdn.standards.iteh.ai/samples/48227/3b5504bdd84145e49293b62c531827bd/ASTM-C1610-C1610M-06.pdf
30. Geert, D-S. & Karel, L. (2023). Active rheology control of cementitious materials. Modern concrete technology, 23, CRC Press. Retrieved from https://library.oapen.org/handle/20.500.12657/76023

31. Antunes, R. (2022). Concrete Overstrength: Assessment of Field Strength Seeking Insights for Overdesign Optimization. *Civil Eng., 3*(1), 51-65. DOI: https://doi.org/10.3390/civileng3010004
32. Laborat´orio Nacional de Engenharia Civil, Concrete. Prescriptive Methodology for a Design Working Life of 50 Years under the Environmental Exposure, *LNEC E* 464, 2007.
33. Polder, R. B., van der Wegen, G. K. & Boutz, M. (2006). Performance based guidelines for service life design of concrete for civil engineering structures – proposal discussed in the Netherlands. International RILEM Workshop on Performance based evaluation and indicators for concrete durability, pp. 31–39. Madrid. Retrieved from https://www.rilem.net/publication/publication/52?id_papier=9893
34. El Farissi, A., P. Turcry, A. Younsi, A. Aït-Mokhtar, A. Aït-Alaïwa, P. (2018). Gotteland, Analysis of the influence of chloride exposure conditions and concrete properties on the convection zone depth and the corresponding chloride content. The 12th Fib International PhD Symposium in Civil Engineering, Prague, pp. 1–7. Retrieved from https://www.researchgate.net/publication/330244802_Analysis_of_the_influence_of_chloride_exposure_conditions_and_concrete_properties_on_the_convection_zone_depth_and_the_corresponding_chloride_content
35. Associaç˜ao Brasileira de Normas T´ecnicas, Design of Concrete Structures – Procedure, vol. 6, 118, NBR, 2014.
36. Associaç˜ao Brasileira de Normas T´ecnicas, NBR, Portland Cement Concrete - Preparation, Control, Receipt, and Acceptance - Procedure, vol. 12655, 2015. Retrieved from https://professor.pucgoias.edu.br/SiteDocente/admin/arquivosUpload/17831/material/NBR%20 12655%20-%202015.pdf
37. Associaç˜ao Brasileira de Normas T´ecnicas, Residential Buildings — Performance Part 1: General Requirements, NBR 15575-1, 2013.
38. Associaç˜ao Brasileira de Normas T´ecnicas, Residential Buildings — Performance Part 2: Requirements for Structural Systems, NBR 15575-2, 2013.
39. CSA, Canadian Standard A23.1/A23.2., Concrete materials and methods of concrete construction/Methods of test and standard practices for concrete. Canadian Standards Association, 2004.
40. American Concrete Institute, (ACI). (2011). ACI-318-11, Building Code Requirements for Structural Concrete (ACI-318-11) and Commentary, American Concrete Institute, Farmington Hills, MI, ACI, 2011. Retrieved from https://www.concrete.org/Portals/0/Files/PDF/Previews/318-11_preview.pdf
41. Tang, S. W., Yao, Y., Andrade, C. & Li, Z. J. (2015). Recent durability studies on concrete structure. Cement and concrete research, 78, 143-154. DOI: https://doi.org/10.1016/j.cemconres.2015.05.021
42. Angst U., Elsener, B., Larsen, C. K. & Vennesland, Ø. (2009). Critical chloride content in reinforced concrete — A review. Cement and Concrete Research, 39(12), 1122-1138. DOI: http://dx.doi.org/10.1016/j.cemconres.2009.08.006
43. Paglia, C. (2022). The Deterioration Asymmetry of Engineering Structures. Case Studies in Construction Materials, 16, e00980. DOI: https://doi.org/10.1016/j.cscm.2022.e00980
44. Wang, R., Zhang, Q. & Li, Y. (2022). Deterioration of concrete under the coupling effects of freeze–thaw cycles and other actions: A review. *Construction and Building Materials*, 319, 126045. DOI: https://doi.org/10.1016/j.conbuildmat.2021.126045
45. AL-Ameeri, A. S., Rafiq, M. I. & Tsioulou, O. (2021). Combined impact of carbonation and crack width on the Chloride Penetration and Corrosion Resistance of Concrete Structures. *Cement and Concrete Composites*, 115, 103819. DOI: https://doi.org/10.1016/j.cemconcomp.2020.103819
46. Malheiro, R., Camões, A., Ferreira, R. M., Meira, G. & Amorim, T. (2014). Effect of carbonation on the chloride diffusion of mortar specimens exposed to cyclic Wetting and Drying. XIII International Conference on Durability of Building Materials and Components, Sao Paulo, Brazil. DOI: http://dx.doi.org/10.13140/2.1.1251.7768
47. Tumidajski, P. J. & Chan, G. W. (1996). Effect of sulfate and carbon dioxide on chloride diffusivity. *Cement and Concrete Research, 26*(4), pp. 551-556. DOI: https://doi.org/10.1016/0008-8846(96)00019-1
48. Alava, E. H. (2017). Durability of Concrete under Combined Attack. Frost Salt Scaling in Carbonated Concrete and Chloride Ingress in Mechanically Loaded Concrete. Ph. Thesis, Magnel Laboratory for Concrete Research Department of Structural Engineering Faculty of Engineering and Architecture Ghent University, Belgium. Retrieved from https://www.researchgate.net/profile/Hugo-Eguez/publication/320194748_Durability_of_Concrete_under_Combined_Attack_Frost_Salt_Scaling_in_Carbonated_Concrete_and_Chloride_Ingress_in_Mechanically_Loaded_Concrete/links/5a8eead7a6fdccecffffcc4b/Durability-of-Concrete-under-Combined-Attack-Frost-Salt-Scaling-in-Carbonated-Concrete-and-Chloride-Ingress-in-Mechanically-Loaded-Concrete.pdf
49. Fan, J., Zhu, H., Yi, C. & Li, Z. (2019). Research on durability evaluation of concrete in complex attack environment. *AIP Advances, 9*(11), 115019. DOI: https://doi.org/10.1063/1.5128461
50. Ndahirwa, D., Qiao, H. & Mahame, C. (2018). Effect of carbonation, chloride and sulphate attacks on reinforced concrete: a review. *International Journal of Civil Engineering, Construction and Estate Management, l6*(2), pp. 59-64. Retrieved from https://www.researchgate.net/publication/327561096_Effect_of_Carbonation_Chloride_and_Sulphate_Attacks_on_Reinforced_Concrete_A_Review
51. Rao, M. J., Dong, Y., Yang, H. Q., Li, M. X. & Yu, Z. (2017). Influence of carbonation and freeze-thaw on macro-properties of concrete. The 5th Global Conference on Materials Science and Engineering, IOP Conf. Series: *Materials Science and Engineering, 164*(1). Retrieved from https://iopscience.iop.org/article/10.1088/1757-899X/164/1/012005

52. Paglia, C., Wombacher, S., F., Boehni, H. & Sommer, M. (2002). An Evaluation of the Sulfate Resistance of Cementitious Material Accelerated with Alkali-free and Alkaline Admixtures: Laboratory vs. Field. Cem. and Concr. Res., 32(4), pp. 665-671.
DOI: http://dx.doi.org/10.1016/S0008-8846(01)00739-6
53. Bundesamt für Landestopografie swisstopo. (2020). Rohstoffe zur Herstellung von Zement – Bedarf und Versorgungssituation in der Schweiz. Reports of the Swiss Geological Survey, CH-3084 Wabern. Retrieved from https://neros.ch/upload/projects/64560_ZementRohstoffeSchweiz.pdf
54. Standard EN ISO 8501-1 Preparation of steel substrates before application of paints and related products — Visual assessment of surface cleanliness — Part 1: Rust grades and preparation grades of uncoated steel substrates and of steel substrates after overall removal of previous coatings. 2007. Retrieved from https://www.iso.org/standard/43426.html
55. Antonietti, S., Mosca, C. & Paglia, C. (2024). Concrete Recycling Aggregates to Produce Durable Concrete. 12th ACI/RILEM International Conference on Cementitious Materials and Alternative Binders for Sustainable Concrete, ICCM2024, Toulouse, France.
56. Paglia, C., Paderi, M., Mosca, C. & Antonietti, S. (2022). The recycling of a concrete with known properties to reproduce a durable material for the civil engineering infrastructure, International meet on civil, structural and environmental engineering, 23-26 Mai, Munich, Germany, Civilmeet 2022. Retrieved from https://www.researchgate.net/publication/360868711_International_meet_on_civil_structural_and_environmental_engineering_23-26_Mai
57. Paglia, C., Antonietti, S. & Mosca, C. (2022). The Known Quality of Concrete to Produce high Quality Recycled Cementitious Material for buildings Supsi. The 15th International Conference on Recent Advances in Concrete Technology and Sustainability Issues Milan (Italy). Retrieved from https://www.researchgate.net/publication/362066611_THE_KNOWN_QUALITY_OF_CONCRETE_TO_PRODUCE_HIGH_QUALITY_RECYCLED_CEMENTITOUS_MATERIAL_FOR_BUILDINGS_SUPSI
58. Standard SIA 215/1 -Requirements on new cements, 2022.
59. Standard SIA 215/2 - Requirements on new additives, 2022.