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Standardization Aspects of Concrete 3D Printing

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Abstract

Digital fabrication with concrete has the potential to contribute to sustainability as a resource-efficient construction method. However, the absence of standardized testing, processing and approval procedures hinders the widespread adoption of 3D printing in concrete construction. The need for uniform testing procedures and processing requirements is crucial to overcome the complexities, lengthiness, and costliness of current construction processes, ultimately promoting the quality and reliability of 3D printed structures. This paper examines the current state of development, identifies gaps in existing standards, and proposes initial steps towards European-level standardization.

Keywords: Concrete; Additive manufacturing; 3D printing; Standardization; Codes; Guidelines.

1 Introduction

Digital fabrication with concrete (DFC) has witnessed exponential growth over the past decade, with a primary focus on Additive Manufacturing (AM) and, more specifically, 3D printing with concrete [1]. Currently, various digital fabrication technologies for cementitious materials are being developed worldwide. Their classification can be found in [2]. The AM technologies can be classified into extrusion [3-5], selective binding [6] and material jetting [7, 8] based technologies. Some of these technologies have already reached a high level of development. As shown in [9, 10] certain technologies have achieved a Technology Readiness Level (TRL) [11] of 8, indicating demonstrated functionality within their application domain and paving the way for practical implementation in real-world projects. Consequently, the number of 3D printed buildings is also increasing, resulting in numerous printed structures worldwide [12].

When realising 3D-printed buildings, the engineers have to apply for project-related approvals and/or project-related construction technique approvals [13, 14]. As there are no established product and testing standards for 3D printed concrete, existing regulations have to be applied for concrete testing in approval procedures [13, 14]. However, 3D-printed concrete differs significantly from conventional concrete, as it is anisotropic (layered), not compacted, and produced without formwork, whereas the existing standards are designed for isotropic, vibrated, and formwork-based materials (see Chapter 4 for further details). Thus, due to the differences between conventional and printed concrete, the existing regulations can only be partially applied. This leads to complex approval procedures, where additional testing and expertise are necessary, making the construction process time-consuming, complicated and cost intensive. This makes 3D printing currently uneconomical and shows that without a normative framework and standardised testing principles, 3D printing will not be widely adopted. Therefore, at this stage in the development of 3D printing technologies, standardization efforts are needed to define uniform material testing procedures and processing requirements. Uniform testing procedures and standards can improve the quality and reliability of 3D printed structures and thus increase the acceptance of the technology.

This paper provides a concise overview of the current state of the art with regard to the normative aspects of 3D printing with cement-based materials. In this context, the testing principles and current publications are also mentioned. The paper analyses why and in which aspects the current standards are not applicable to 3D printing and identifies the gaps in current standards. Additionally, it serves as a preliminary draft of standardization requirements, which can serve as a basis for initiating further standardization activities. Finally, the paper proposes concrete initial steps towards standardization at the European level.

2 Motivation

With its initiatives focused on climate protection, the German Society for Concrete and Construction Technology (DBV) aims

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to works towards "climate-neutral concrete construction site" by 2045 and advance the principles of the circular economy. This objective encompasses not only the reduction of greenhouse gas emissions but also the minimization of resource consumption. Digital fabrication and in particular 3D printing with concrete has the potential to contribute to sustainability as a resource-efficient construction method. Moreover, the automated processes like 3D printing not only enhances productivity but also mitigates skills shortages within the construction sector. Thus, the introduction of digital technologies in construction is becoming essential as one of the keys to increasing sustainability and productivity. To enable the implementation of 3D printing in construction, standards must be developed and integrated into the existing regulatory framework. As a result, the normative framework for concrete 3D printing can indirectly contribute to creating a more sustainable concrete construction method and getting closer to the above goals. For this reason, the DBV and its working group 'Digital Fabrication with Concrete' (AK DigFab) focused on standardization aspects of 3D printing, deliberating the concrete requirements for normative activities. This paper partially draws upon the outcomes of these activities.

3 State of the art

3.1 Quality control and testing principles

Currently, there are no uniformly defined testing principles for concrete 3D printing. To obtain project-related approvals for 3D printed structures, adapted test methods from concrete and masonry construction were used (as for instance in [13, 14]). In [14], project-related approval for a 3D-printed house involved tests on fresh and hardened properties as well as large scale tests. Tests specific to 3D-printed concrete, tests on hardened properties included 3-directional testing an evaluation of interlayer adhesion. Large-scale tests focused on load-bearing and non-load-bearing walls, assessing flexural strength, impact resistance, and the performance of 3D-printed lost formwork under concrete pressure. In [13] project-specific approval for a 3D-printed bridge was obtained by following the "design by testing" principle, based on Eurocode 0. This concept involves four sequential steps: material testing on printed specimens in three directions, structural calculations based on EN 1992-1-1, and laboratory bending tests of the model bridge, and field testing of the printed bridge. Both examples demonstrated that, the standard EN 206-1 tests, tailored for vibrated concrete in cylinders, proved unsuitable for non-vibrated printed materials, necessitating additional testing protocols. Therefore, in addition to assessing fresh concrete properties and hardened concrete properties in three directions, tests on a larger scale were necessary.

In DFC, processing differs significantly from conventional concrete casting, requiring concretes to meet new printability criteria: pumpability, extrudability, and buildability [9]. This necessitates controlling rheology, hydration, and hardening during the whole process. Thus, the quality control of concrete properties both before and during the process is essential [9]. A quality control framework for DFC was recently discussed by Bos and Wolfs in [15]. In this paper, the authors point out that quality control in DFC is more demanding than in traditional casting. Without formwork, concrete is exposed to external factors, increasing risks of deformation or collapse and requiring close monitoring of evolution of concrete properties during the process. In addition, manufacturing systems and printed objects are also highly sensitive to dosage variations, requiring finer control of process variations during printing. The authors propose a framework of destructive and non-destructive tests, conducted on-line, off-line, in-line, and in-situ, to monitor property development and ensure quality under representative conditions [15].

The testing of fresh and hardened concrete properties is initially discussed in [9]. More recently, Mechtcherine et al. [16] have published a guide for planning and implementing additive manufacturing projects, covering legal aspects and explaining the approval process. A list of testing methods for fresh and hardened concrete properties that are optimally suited for 3D printing, along with the corresponding standards that can be utilised for these tests, have been published in [9] and an extended list most recently in [16].

The testing principles for 3D-printed components are currently the subject of the activities of certain technical committees, such as RILEM TC PFC [17] and RILEM TC ADC [18]. The aim of these committees is to publish protocols and recommendations for industrial quality control of the requirements for fresh concrete properties [19], as well as recommendations for the testing of printable and printed concrete [20]. The first considerations on the assessment of concrete's fresh and hardened properties (such as mechanical and durability) are published in [19] and [20] respectively. The database of the RILEM TC 304-ADC interlaboratory study on mechanical properties of 3D printed concrete is recently made available in [21]. However, the full protocols are yet to be developed.

3.2 Standards and regulations

Currently no specific product or process standards for 3D printing with concrete. However, Initial efforts towards standards for AM in construction in the standardization bodies have already begun [22-25].

Based on ISO/ASTM initiative [22] a draft standard DIN EN ISO/ASTM 52939 "Additive Manufacturing for Construction - Principles of Qualification - Structural and Infrastructure Elements" [26] was published. It describes the necessary requirements as a basis for the production and delivery of additively manufactured structures (residential or infrastructure) in the construction sector. The requirements should apply regardless of the material used and to all additive manufacturing technologies in the construction industry [26]. However, this document is not specific for concrete neither it defines testing procedures, material properties or process specifics. Hence, there remains a need to develop tailored standards for DFC across planning, design, materials, and execution.

The Chinese standard T/CECS 786-2020 "Technical Specification for 3D Printing Concrete Structures" [25] covers the technical requirements for concrete 3D printing and applies to buildings, structures, components, etc. constructed using concrete 3D printing. It covers material requirements, structural design, construction processes, and quality control to ensure safety and reliability. The standard specifies printable concrete properties, design principles, equipment, process requirements and inspection methods.

3D printing is also addressed in the new revised Construction Products Regulation (EU) 305/2011 [27], that will presumably come into force at the end of 2024. The new regulation also covers 3D printing, including related products and services. The regulation outlines the obligations of 3D printing service providers, as well as providers of 3D printing data sets and materials. Furthermore, the new regulation introduces the Digital Product Passport (DPP), a set of digital documents containing technical and environmental information (governed by Ecodesign legislation) about a construction product throughout its lifecycle. DPP will become mandatory for construction products (including 3D-printed ones) starting from 2028-2030.

3.3 Publications

At the recent RILEM conference 'Digital Concrete 2024' [28, 29], the importance of standardization was recognised by many speakers. It was pointed out that standards and codes are the barriers to implementation, highlighting them as a crucial next step for 3D printing.

To the authors' knowledge, the standardization of digital manufacturing in concrete construction has only been addressed in a few publications [9, 30, 31]. A first overview of standardization aspects and the need for standardization for digital fabrication with concrete was provided in [9], and will be reflected in the following section. In [30] the authors focused on the mix composition and analysed the constraints imposed by the current standards on concrete mix design (in particular EN 206, EN 197-1 and EN 197-5). They pointed out, that the binder composition must be limited to standard cement types and the fines content must be limited. Finally, they successfully tested the 3D-printable concrete, which complies with all the standard specifications applicable in Germany. In [31], the authors addressed the path to standardization for 3DCP structures. They discussed the structural components designed according to the 'Design by Testing' principle (see above) and gave a brief outlook on legislation and standardization. Once the Design by Testing protocol is approved, empirical data can be compiled into standardised technical recommendations. It's important to distinguish between material, design and execution categories, and to specify generic or specific levels of abstraction.

In construction, design and testing rely on acceptance criteria (standards, certifications, and guidelines) and regulatory language (codes) [32]. Kreiger et al. [32] recently reviewed acceptance criteria for additive construction, building on Bos et al. [12] by addressing gaps and highlighting U.S. developments. Initiatives by NIST, USACE-ERDC, ASTM, and ACI focus on developing criteria, guidelines, and future code language. Acceptance criteria are essential for quality and practicality but must address challenges like print path consistency and sample handling. The case studies presented in the paper provide takeaways that can be used as recommendations for project timelines, quality control, etc.

4 Problem definition and need for standardization

The main differences between printed and conventional concrete are that the former is produced in layers without formwork or vibrating in a digital process. As a result, adapting current standards and regulations for 3D printing is necessary due to following reasons [9]:

- In most 3D printing processes, the concrete is printed in layers. Consequently, the properties of the concrete vary in different directions, resulting in the concrete being anisotropic. Therefore, the 3D printed concrete samples need to be tested in different directions (see [33] for details). On the other hand, conventional concrete has no layers and is in principle isotropic. As a result, existing testing methods developed for quality control of conventionally produced isotropic concrete are not suitable for anisotropic 3D-printed concrete and need to be adapted.
- Testing methods for vibrated concrete are not applicable to 3D-printed concrete as it is not vibrated during the printing process. As mentioned in section 3.1, produced without vibration, 3D printed concrete must maintain its shape and stability after extrusion. This presents unique challenges, such as controlling rheological properties, and addressing buildability and time-dependent behaviour, ensuring proper interlayer bonding, which are not addressed by traditional vibration-based methods and standards. Regulations suitable for self-compacting concrete or shotcrete also have to be adjusted, to include additional requirements.
- In 3D printing processes, concrete is produced without formwork. Since formwork is typically absent, the material is exposed to external influences that can result in deformations, collapse, or deterioration [15]. Therefore, the evolution of properties during the process must be controlled, which requires a new set of quality control regulations and standards. In addition, 3D printed concrete has been used in many pilot projects as unreinforced concrete (for example, as "lost formwork). However, the production of unreinforced structural elements is currently only permitted with the use of compaction and formwork. This will therefore need to be addressed in the future regulatory framework.
- In conventional concrete, standardized test specimens are produced by pouring the concrete into a mould. In DFC, concrete is deposited layer-by-layer, and the resulting anisotropy and heterogeneity cannot be captured by cast specimens. Preparing test specimens for 3D-printed concrete is thus challenging, and the specimen production methods proposed in [20] should be used. These include specimens produced before or during printing, as well as samples extracted from full-size printed elements, which must be representative in size,

include layer interfaces, and account for different orientations relative to the printing direction.

- Digital fabrication with concrete is a mechanized process, in contrast to traditional concrete construction. The choice of the printing technology influences all project aspects, including material, machinery and process engineering. Therefore, it is imperative to articulate these automatised processes in established standards.

The test methods requirements for fresh concrete properties from EN 12350 and EN 14488 can be partially used for extrusion processes. The test methods for hardened concrete properties are partly listed in e.g. EN 12390, EN 14488 or ASTM D2166. For the shotcrete processes, in addition, e.g. EN 14487-1, EN 14487-2 can be employed. However, to fully suit the specific requirements of 3D-printed buildings the existing standards have to be modified and extended. Figure 1 shows the main modules of European standards as a basis for the design, execution and choice of building materials for concrete structures [34, 35]. This figure also shows the relationship between EN 206 and standards for design and execution, as well as standards for starting materials and test standards. Framed in red are the fields that cannot be transferred directly to the digitally produced concrete structures and thus require adaptation or expansion. An extract from the standardization Framework for the Sustainability Assessment of Construction Works, relevant for DFC [36], is also shown in the figure (marked green).

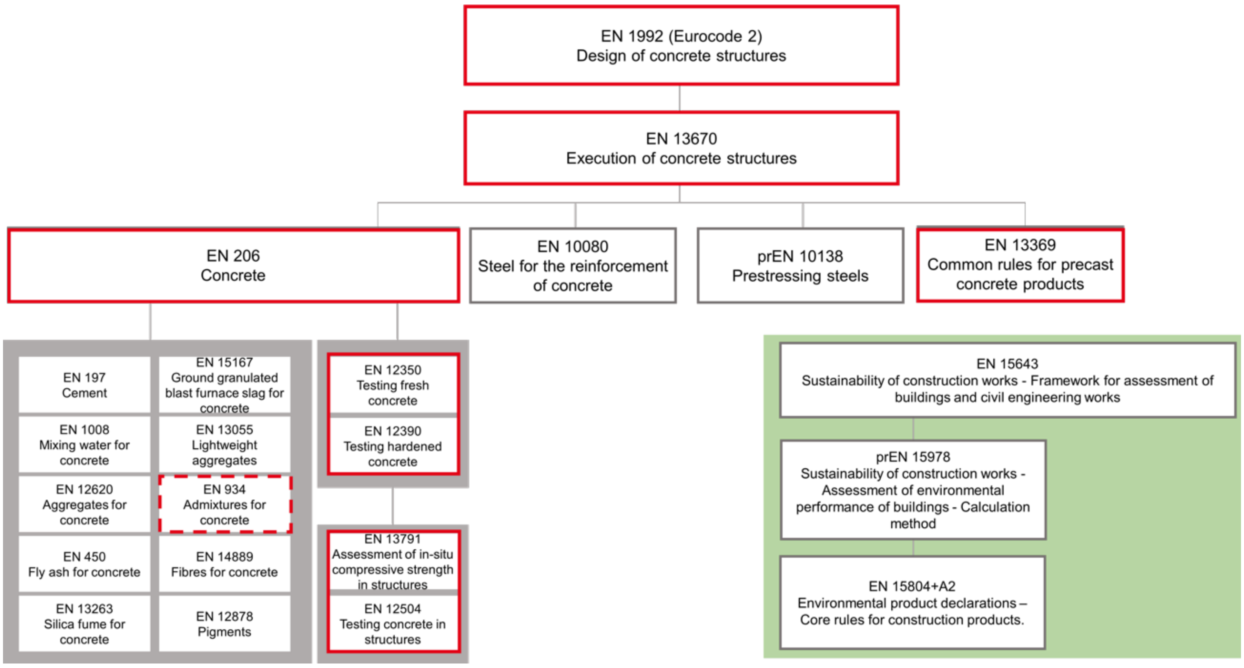

Figure 1. A scheme of European standards as a basis for the design, execution and choice of building materials for concrete structures (adapted from [34, 35]) and the standards for sustainability assessment of construction works (adapted from [36]). © Ksenija Vasilic, DBV.

However, the concrete standardization requirements vary greatly depending on the chosen process and material. Examples of the need for standardization in various areas, such as planning, dimensioning, materials, and execution, are provided below [9].

- In the field of planning (BIM) [37]
    - Extension for machine control programs (e.g. G-code),
    - IFC extension for automated construction,
    - Real-time capability of information provision.
- In the area of design:
    - Closing of regulatory gaps that arise in design and construction, new or adapted design approaches for load-bearing capacity and serviceability, durability, adapted design rules, etc.,
    - Design in case of fire.
- In the area of materials and finishes:
    - Requirements for fresh concrete and verification methods,
    - Testing of fresh concrete,
    - Technology of test specimen production,
    - Requirements for hardened concrete and verification methods (test principles of hardened concrete properties different from conventional concrete),
    - Verification of concrete strength in buildings,
    - Production control (incl. inline control of fresh concrete properties).
    - Reinforcing steel and reinforcement (integration of reinforcement into 3D printed structures),
    - Curing,
    - Prefabricated concrete components.

5 Boundary conditions and further steps

AK DigFab conducted an analysis of the existing standardization framework and its relevance to DFC. The objective was to identify the deficiencies in the standardization framework and determine the concrete requirements as well as order in which standards should be developed. The outcomes of these studies are summarized in the open questions and the boundary conditions critical for further developments, outlined below.

- At the process level, there is a need to differentiate between digital process (i.e. use of digital technologies in sub-processes) and fully automated production processes. Due to the differences in production processes and associated quality assessment, control and factory production control (FPC), a further distinction should be made at the process level between prefabrication and in-situ manufacturing.
- The process chain for digital manufacturing processes differs from the conventional one, incorporating automation, enhanced process control, and advanced machinery. Consequently, there's a need to describe these processes, delineate interfaces, and establish protocols for data exchange.
- Digital manufacturing processes for cement-based materials are very different. The above-mentioned additive manufacturing processes based on extrusion [3-5], selective binding [6] and material jetting [7, 8] differ in terms of basic principles, machinery, material used as well as size, quality and resolution of the printed products. In the production process, the processes and quality assessment during the printing process are different for the above AM subcategories [38]. As a result, the standardization requirements vary across different technologies, making it unrealistic to expect uniform test procedures, acceptance criteria, or a single standard to address all these technologies. Therefore, the standardization requirements of the different DFC technologies need to be defined more precisely.
- There is the question of whether the existing construction standards can be transferred to DFC (for instance [20]), or whether standards from other fields can be used as a basis (e.g. standards from aeronautics for the design of composites).
- A set of rules must be developed that covers both printable mortar and concrete. It is necessary to specify limits that reflect the current state of experience in terms of maximum grain size, strength, and other relevant factors.
- When designing, it is important to consider load-bearing capacity while taking into account tolerances and geometric precision. The design process should also include determining the layer bond and examining the durability parameters, shrinkage, and modulus of elasticity of concrete, especially with regard to exposure classes. This may require adjusting the safety coefficients.
- The first step towards quality assurance in concrete 3D printing can be found in the "design by testing" principle [31], which is set out in DIN EN 1990 (Eurocode 0) and has already been applied to 3D printed objects [13]. This method prescribes a sophisticated determination of various material properties, based on standardized tests, followed by various test programs to map the structural parameters and a simulation of the real conditions and behavior of the structure. In this context, the building regulations regarding experiment-controlled design must also be taken into account.
- At the moment, the composition of 3D-printed concretes is usually still different from that of conventional concrete. These contain more fine particles and more cement than conventional concrete. Therefore, for 3D printable concretes, the limitations of fine particle content are crucial [7]. The current standards limit the absolute fines depending on the cement content, the grain size, the compressive strength to be achieved and the exposure classes.
- Printable concretes have to meet new complex requirements, which are summarized under the term printability. Digital tools (e.g. numerical simulations, AI-based prediction tools) can be used to optimize the material and predict properties. For this so-called predictive quality control, normative descriptions are also required.
- In a digital manufacturing process, the properties of the material should be fully controlled in real time throughout the printing process. During the printing process, fresh concrete properties are measured digitally inline (e.g. by sensors) and the material properties and process parameters are automatically adjusted during the printing process. These digital measurement methods and control processes will also be described.

The above-mentioned boundary conditions and open questions illustrate the complexity and diversity of standardization requirements for different manufacturing processes. Figure 2 shows a possible structure of a standardization program for the DFC as suggested by AK DigFab. Based on the above-mentioned standardization needs, the structure of the divided into the areas of planning, concrete and execution, delineating the necessary descriptions for each segment.

To enable a prompt initiation of standardization work and rapid implementation in concrete construction, prioritization is required. Therefore, as a first step, the focus of standardization activities shall be limited to those procedures with a high (Technology Readiness Level (TRL), where the lack of standardization is the only obstacle to practical implementation.

The first important step towards standards for the requirements and quality control of concrete for 3D printing has been taken within the CEN committee dealing with the further development of the EN 206 standard. It has recently been proposed by CEN/TC 104/SC 1 to provide additional requirements for specification and conformity of concrete for digital fabrication as a new amendment to the EN 206 [24]. Figure 3 shows the proposed, new structure of the EN 206. The new parts that are to be added is shown in blue.

The Part 4 "Additional requirements for specification and conformity of concrete for digital fabrication" is intended to support the implementation of 3D printing in the concrete sector. It will focus on fresh and hardened properties of concrete and mortar for digital fabrication. Additionally, it will provide fundamental guidelines for factory production control and assessment procedures of inline control for different DFC technologies. These guidelines encompass property definitions, test method definitions, and verification criteria. The need for real time information (inline control) will be considered. The focus is on additive manufacturing and 3D printing with cementitious building materials, with priority given to digital manufacturing processes with a high technology readiness level (TRL > 6). For this purpose, a new working group "Digital Fabrication" is established within the committee CEN/TC 104/SC 1 and the work is supposed to be initiated in 2025. The development of the EN 206-4 standard should consider the protocols and recommendations for quality control of fresh concrete as well as the recommendations for testing printable and printed concrete developed by RILEM TC PFC and RILEM TC ADC.

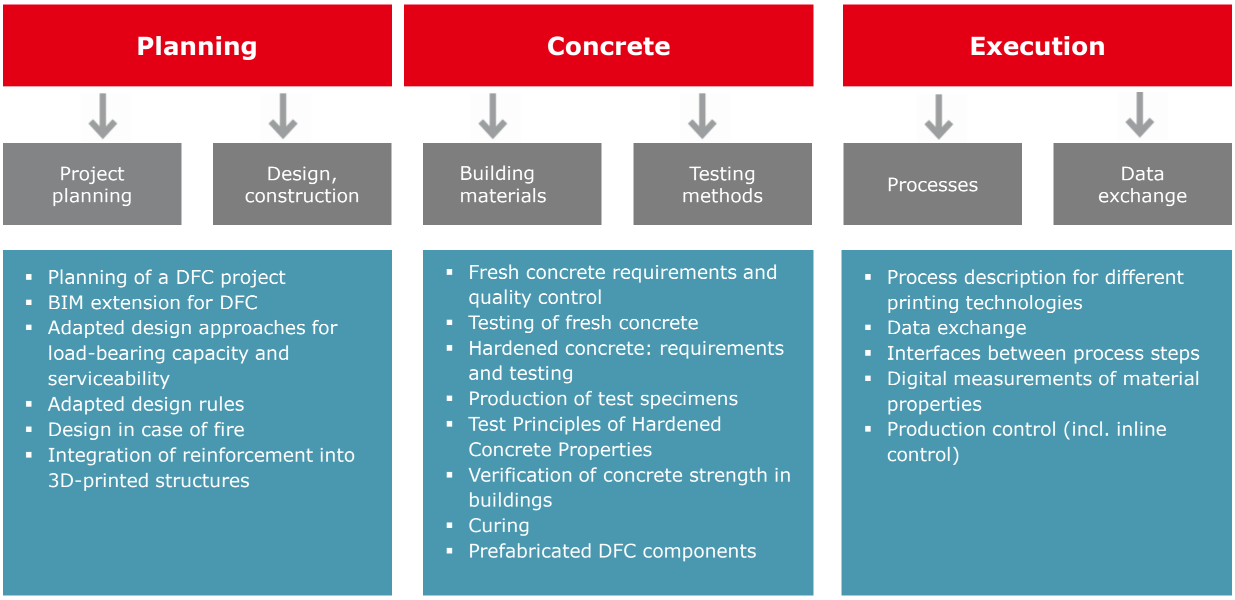

Figure 2. Standardization needs and possible structure for a DFC standardization program. © Ksenija Vasilic, DBV.

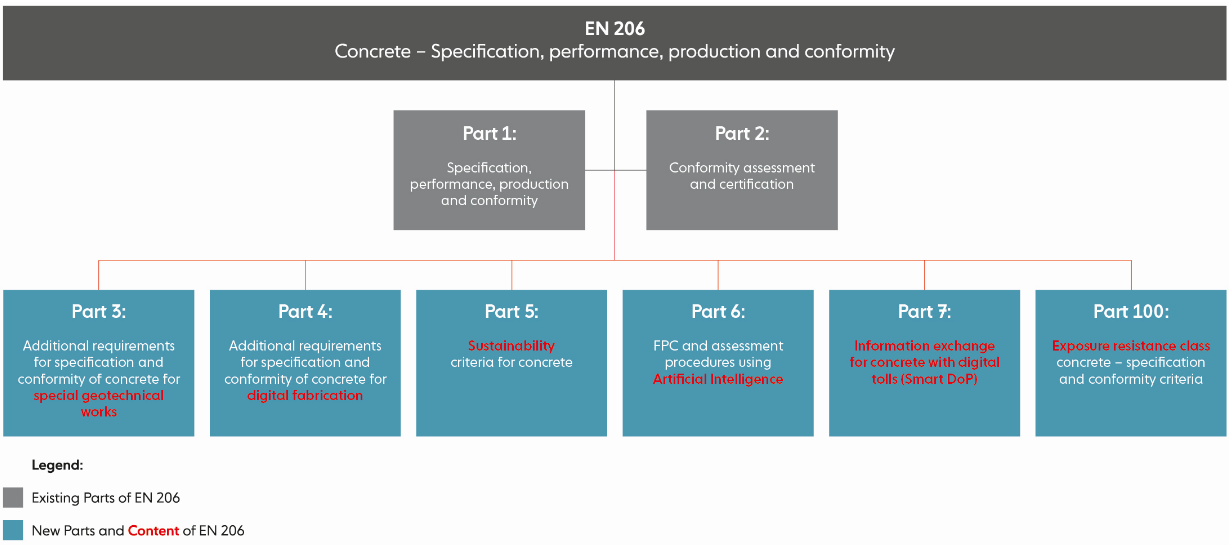

Figure 3. Proposed structure of EN 206 [24]. © Lars Meyer, DBV.

During the printing process, digital tools (such as sensors, ultrasound, etc.) are used for the purpose of in-line and online quality assessment and control [38]. Moreover, digital methods (such as numerical [39-41] or AI-based methods [42, 43]) are utilised to predicting material properties and behaviour in the printing process. Therefore, the proposed EN 206 Part 6 (see Figure 3), which focuses on predictive quality assurance using digital tools and AI, is also highly relevant to the DFC and will support its implementation.

It is also very important to define a common language for the standards in this fields. Thus, the classification of digital fabrication technologies for cementitious materials given by RILEM in [2] should be adopted in further standardisation activities. The terminology and definitions for digital fabrication with concrete are defined in DBV-Heft 53 [9]. When developing standards regarding execution of DFC projects, the general rules for the additive construction projects in DIN EN ISO/ASTM 52939 can be used as a basis and analysed for their applicability to DFC.

6 Concluding remarks

The development of digital fabrication with concrete has already reached a mature stage of technology readiness for several 3D printing technologies. It was successfully used to print buildings, yet the lack of standards complicates approval processes, hindering economic viability and widespread adoption. For these technologies, the lack of standardization is the main obstacle to wide practical implementation. Thus, a suitable set of standards would enable the widespread implementation of these technologies. To the authors opinion, the next step should be to develop a superordinate document within the framework of EN 206, with clear recommendations, in which digital fabrication is defined separately for design, concrete and execution. This document shall also establish cross-references to the above-mentioned recommendations developed by RILEM and DBV.

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K. Vasilić: Conceptualization, Writing – Original Draft, Writing – Review & Editing.

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