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Opening Letter of RILEM TC QPA - Quality and Performance Assurance of Additively Manufactured Cementitious Composites by Advanced Non-Invasive Techniques

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Abstract

This Opening Letter outlines the objectives and scope of the newly developed RILEM Technical Committee QPA "Quality and Performance Assurance of Additively Manufactured Cementitious Composites by Advanced Non-Invasive Techniques". The letter also provides quick overview of the current state-of-the-art on 3D concrete printing (3DCP) technology, and highlight key issues with regards to sustaining quality of the additive manufacturing process and the corresponding performance of the printed materials and structures. These are followed by discussion on prospect of developing and rationalising suitable non-destructive testing and evaluation methodologies to improve efficiency and quality of 3DCP through review of some previous studies. The letter also identifies potential achievements that can be obtained, and discusses key challenges and strategies in running the TC.

Keywords: Non-destructive testing and evaluation; Quality assurance; Performance evaluation; Cementitious composites; 3D printing.

1 Introduction

Technology that involves additive manufacturing or contour crafting of concrete structures, which is also particularly associated with implementation of 3D printing procedure, has the potential to revolutionize the traditional construction methods by permitting the creation of complex architectural designs, reducing material wastage, and speeding up construction processes. The 3D concrete printing technology has quickly become, over the last couple of decades, one of the leading digital fabrication technologies [1]. The technology has been versatile to adapt to various application needs that range from factory-controlled manufacturing of pre-fabricated concrete members to constructions of buildings onsite [2].

Significant aspects of the state-of-the-art studies have been found for 3D concrete printing technology, covering developments in materials, printing process, material workability, mechanical and durability properties, and design technique [3-9]. For studies on materials, discussions have been revolving around the types of cementitious materials suitable for 3D printing, including high performance cement-based mixes and advanced additives for improving workability and strength, and the utilization of environmentally sustainable alternatives including recycled cement/aggregates and geopolymers [10–12]. In the case for printing technologies, reports are found detailing development of various printing techniques such as extrusion-based methods, powder-based methods, and binder jetting, which focus on discussing advantages, limitations, and applications of the respective methods in real-world construction [13–15]. Research has also been focused on optimizing the structural integrity and durability of 3D printed structures with cementitious composites. This includes exploring reinforcement strategies, curing methods, and post-processing treatments to enhance structural performance and longevity of different structural systems printed with cementitious composites. [16–22]. In terms of studies for design technique, the ability to create complex geometries and custom designs has been a major focus [23]. Numerous reports have showcased examples of architectural innovations that leverage 3D printing of cementitious composites, including enabling intricate shapes and structures that were previously challenging or impossible to construct using traditional methods [24, 25].

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As aforementioned, over the last couple of decades, studies on 3D printing of concrete or cementitious composite materials have been focused on addressing the fundamental but essential aspects such as materials, mix design, printing process and design technique. In situations where it is possible to realise a perfectly designed and executed 3D printing process, supplemented by well-controlled auxiliary operations, the optimally designed-and-built structure would demand very little labour time and budget compared to the one constructed with the "conventional" practice. Also, high-precision printing process helps prevent unnecessary material wastage, leading to contributing towards sustainable and environmental-friendly concrete constructions. However, in cases where construction (printing) quality is not met, structural performance levels may not sustain over the intended service life of structure as a result of the presence of preliminary defects that trigger unexpected degradation process, e.g. voids in printed concrete that attract moisture and accelerate material deterioration; inconsistent quality of extruded mixture that causes uneven stress distribution and unanticipated cracking behaviour under loading. The said defects may have been induced during the construction phase in initiating premature failure with eventual disastrous consequences to lives and properties, the process of which cannot be deliberately accounted for at the design stage. In order to mitigate the unanticipated failures caused by inherent structural faults of 3D printed concrete structures, and to ensure their long-term performance and safety, quality assurance of additively manufactured materials at the initial phase of casting (printing) and setting forms the principal scope of study of this current TC. It is to be noted that 3D printed concretes normally differ from the conventional cementitious composites in certain key properties, demonstrating some distinct physical, mechanical and structural behaviours than the conventional cementitious composites. Also, the concrete structures built using the most standard type of printing techniques are most often associated with layered deposition of materials that exhibit strong anisotropy or controlled inhomogeneity, all of which have the potential of introducing additional complexity and challenges to understanding the "real" structural behaviour, performance and integrity in long term. Therefore, implementation of robust inspection and evaluation methods to facilitate initial quality control of 3D-printed concrete should form a crucial part of the construction process. Furthermore, methods that allow continuous assessment and assurance of the long-term service performance of the printed structures are equally essential.

Developing a systematic framework is of paramount importance if the 3D-printed concrete technology is to further advance and justify as a sustainable, cost-effective approach in modern-day, large-scale construction that is conveniently available and widely applicable. The framework should address critically the measurement and quantification of evolution (EV), process variation (PV) and processing conditions (PC), spanning over all aspects of the digital fabrication (including 3D printing of concrete and cementitious composites) to allow quality control of fresh state mechanical performance [26]. The assessment scheme, as suggested by [26], would require integration of off-line, on-line, in-line and in-situ protocols to ensure attainment of the required printing quality, involving a diverse range of techniques to assess pressure, temperature, flow etc.

The deployment of non-destructive testing (NDT) methods in civil engineering is becoming increasingly important due to rising numbers of aging and deteriorating infrastructure including reinforced concrete structures. Different types of NDT methods have been used to assess the integrity of in-service reinforced concrete structures which are approaching their design life as a basis for safety considerations and maintenance strategy. Some of the methods are utilized as an effective means to survey feasibility of existing structures to undergo refurbishment, expansion or significant alteration (e.g. removal of load bearing members, local change of structural system) whereby no design document is available as reference. In addition, some NDT methods have also been used in the protocol of quality control for new constructions, in locating and rectifying defects, such as voids and pre-matured cracks attributed to events including poor concrete compaction and unexpected load transfer during construction [27]. The typical NDT methods that have been successfully used for assessing reinforced concrete structures on-site include: rebound hammer testing (for assessment of concrete compressive strength), ultrasonic testing (for assessment of cracks and internal defects), impact echo testing (for assessment of cracks and internal defects), impulse response testing (for assessment of internal defects), ground penetrating radar scanning (for assessment of sub-surface defects, cover thickness, and rebar position), and half-cell potentiometer testing (for assessment of rebar corrosion). To enable relatively quick but less indicative condition assessments, methods such as thermography, acoustic emission monitoring and elastic wave tomography are becoming increasingly popular (e.g. [28-32])., which are used to detect and locate defects at surface/subsurface or internal of structural elements.

In the past RILEM TC activities, damage identification methods for concrete structures have successfully been studied and proposed through TC 212-ACD (*Acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete*). Following that, in TC 239-MCM committee (*On-site measurement of concrete and masonry structures by visualized NDT*), on-site NDT-utilized damage visualization techniques have been studied comprehensively, focusing on establishment of reliable interpretation procedure of the results measured by non-destructive testing (NDT), which has been summarized as a state-of-the-art report at present. The resultant three RILEM recommendations from this TC led to establishments of three ISO standards, namely ISO 16836, ISO 16837, and ISO 16838 in 2019. In the follow up technical committee TC 269-IAM (*Damage assessment in consideration of repair/ retrofit-recovery in concrete and masonry structures by means of innovative NDT*), a state-of-the-art report has been issued, with two RILEM recommendations published on the use of active and passive elastic wave measurement techniques for infrastructure assessment [33, 34]. With reference to the extensive outcomes yielded from the past three TC activities, important contributions have been made in qualifying and quantifying damage in concrete and masonry structures capitalising on innovations realised for the various advanced NDT techniques that are applicable onsite.

The prospect of developing and rationalising suitable NDT methodologies to meet assessment needs of 3D printed cementitious composites structures is huge due to the potential widespread application of the 3D printing technology. In the case of 3D printed concrete, research studies on the use of NDT methods for quality assurance and performance evaluation are relatively recent, and there are still numerous challenges that needs to be addressed in order for the 3D-printed concrete to achieve industry scale implementation. It has been indicated that NDT techniques are generally useful to provide off-line or in-situ assessment of EV, as well as in-line and initial in-situ measurement during PV [26]. Among the studies found, ultrasonic pulse velocity testing has been utilised to monitor real time stiffness change of concrete during the printing process, in evaluating its setting behaviour [35]. The presence of layered structure which is inherent with the printing process may introduce anomalies and complexities, which implications on mechanical, durability and structural performance of the concrete and the corresponding printed structure are not well understood. In another study, different NDT tests were carried out, namely x-ray radiography, ultrasonic pulse velocity test, vibration resonance test and multi-element array ultrasonic test, to characterize interlayer bonds of idealized concrete additive manufacturing products [36]. It has been widely agreed by the industry and various research that layer interfaces in a hardened printed concrete structure are weak stress transfer locations, and effective examination is often required to prevent occurrence of cold joints or layer delamination which can cause deleterious impacts to overall structural integrity. Besides, there has been study on developing correlations compression test results with ultrasonic pulse velocity test results of early age 3D printed concrete, which also discussed the prospect of developing an online ultrasonic-based monitoring process for examining uniformity of the concrete strength during extrusion process [37].

The above-outlined preliminary survey on the state-of-the-art of 3D printing technology for cementitious composites (concrete), its common issues, and on the use of NDT methods for evaluating quality of printed structures offer an exciting avenue for this technical committee to be established, as an important attempt to address the development and adaptation of some of the most practical NDT methodologies that will be effective and crucial for incorporation into the construction process to ensure quality of the 3D printing process and long-term performance of the printed structures. It is considered that successful development and implementation of evaluation methodologies based on the above-mentioned advanced NDT techniques would help accelerate, rationalise and increased applicability 3D printing technology to accommodate various construction needs, which would include printing of functionally graded cementitious materials and low carbon mixtures such as geopolymer concrete and those derived from construction demolition wastes such as recycled concrete, as well as composites obtained from earthen materials to help realise sustainable digital construction practice.

2 Overall objectives

Building upon the successes of the past TCs (TC 212-ACD, TC 239-MC and TC 269-IAM), this new TC aims at developing and proposing rationalised NDT methods for inspecting and evaluating casting (printing) quality of cementitious composites, especially on ensuring soundness and homogeneity of the layered materials, and long-term service performance of the printed structures. In this regard it has been established that suitable existing NDT methods can be modified and adapted in accounting for the needs to assess different characteristics of laminar or layers and the forming of bulk materials, and to enable effective characterization of the manufacturing quality, which subsequently lead towards ensuring long-term performance of the printed structure. In addition, the aforementioned past TCs, which activities addressed the use of cutting-edge NDT methods to evaluate concrete and masonry (rocks and bricks) structures will lay the foundations for this new TC. The outcome of this new TC will be timely and positively impactful not only to the concrete design and construction communities, but will initiate significant revolution in the sector for sensing and health monitoring of buildings and infrastructure in the near future. Under this new TC, suitable NDT methodologies will be developed and proposed for testing, inspection and evaluation of additively manufactured structures using cementitious composites, suitable for both laboratory investigation settings and in-situ application phases. In synchronising with the previous outcomes generated from past TCs, several RILEM recommendations, aiming at future adaptation to ISO standards, will be made based on the findings of this new TC.

The following achievements are promisingly expected, which can be attained based on our immense experience from the past closely related TC activities:

- RILEM recommendations and recommended practices for quality assurance and performance assessment of 3D printed cementitious composites using innovative NDT instrumentation and data analysis;
- Dataset obtained from independent and collaborative (with other TCs) laboratory testing and onsite measurements;
- Workshop proceedings, possibly published as special issues of Materials & Structures journal;
- State-of-the-art report for assuring initial quality and long-term performance of 3D printed structures using different types of cementitious composites based on application of innovative NDT methodologies;
- Pre-standards for the relevant assessment methods and data analysis schemes to be submitted to ISO.

In addition, it is envisioned that this new TC will help achieve a significant step towards accelerating widespread adoption of 3D printing technology for cementitious composite construction, which shall bring forth significant impacts in various economic aspects: 1) Reduced Labour Costs: One of the primary advantages of 3D printing in construction is the potential for reduced labour costs. Automation through 3D printing minimizes the need for manual labour in certain construction tasks, leading to savings in wages and related expenses; 2) Higher Construction Speed: 3D printing technology has the potential to significantly accelerate the construction process. Complex structures that might traditionally take months to build could be completed in a fraction of the time. This speed could lead to cost savings due to shorter project durations and reduced overheads; 3) Material Saving: compared to traditional construction methods, 3D printing of cementitious composites can achieve precise control of material consumption, minimizes waste output. The higher efficiency in material usage can lead to cost savings in the long term, especially considering the rising costs of raw materials. This also helps enable the reduction of carbon emission and energy consumption associated with raw material production and construction, contributing towards achieving net-zero practices; 4) Design Flexibility and Customizability: The flexibility of 3D printing allows for intricate and customized designs that would have been challenging or impossible to achieve with the traditional construction methods. The versatility can lead to fulfilment of stringent needs imposed by bespoke architectural designs that emphasise on both aesthetic and structural efficiency aspects; 5) Highly skilled Job Creation and Development: While communizing 3D printing technology might reduce the need for traditional construction jobs, it will create new roles that require specialized skills related to programming, operating and maintaining 3D printing facility. This offers new opportunities for skill development in the relevant areas of emerging technologies.

An outline of our TC proposed working program is given in Figure 1. The working program showcases our initial thinking and plan on the scope of activities that is required to fulfill the TC objectives. Essentially, the activities are classified under three main pillars; the first one covers information collection, idea exchange and discussion held during meetings, the activities of which will form a feedback loop with the proposed activities in the second pillar to encapsulate laboratory experimentation, numerical and theoretical modelling, data analysis and in-situ trials; the third pillar includes activities that are targeted at generating impacts of the TC outcomes, which cover outreach activities for the wider research community and general public, and reporting activities in providing outcome dissemination and practical guidance of the development by the TC, as well as facilitating opportunities for future collaborative works to address the next stage of development.

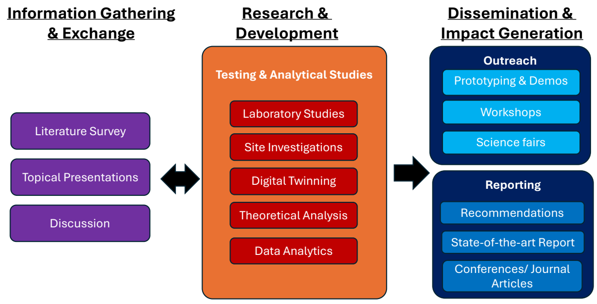

Figure 1. Outline of TC Work Program.

3 Challenges and strategies

We identified some potential key challenges in the running of this TC, which will need to be overcome to ensure successful delivery of the objectives set forth. The challenges and strategies are described as follows:

1. Maturity of Technology

   Whilst we have identified some potentially useful existing NDT techniques for assessing 3D printed cementitious composite structures to evaluate printing quality and long-term performance, case studies on successful applications of these techniques, seem to be scarce or not available at all. Hence, we anticipate some significant research and development activities from our members over the TC active period to address adaptation of these techniques to serve the various purposes, which would encompass assessments for early age strength development of printed materials, material distribution state, density and anisotropy characteristic, interlayer bond and joint condition, and long-term structural performance and degradation possibility. At the time of writing this technical letter, we plan to develop and propose a series of NDT methodologies building upon the basis of ultrasonics and elastic waves principles. With carefully planned assignments to TC members (based on the current member composition), we will focus on the development of ultrasonic pulse velocity and echo methods, acoustic emission methods and elastic wave tomography at the initial stage of the TC. Some challenges associated with effective deployment of these methods are identified, which are largely linked with instrumentation (sensor mounting, data acquisition configurations, duration of testing) and data processing and analysis, knowing that assessments need to be carried out in majority of cases where the printed material is still relatively "fresh" and "soft", imposing very different circumstances on how sensors could be coupled as well as sensitivity and relevance of the data collected, and on how to not intervene construction process if online monitoring becomes necessary. For now, we think the said problems can be resolved by developing contactless measurement using air-coupled sensor (potentially with wireless connection capability) and the corresponding sensing/ data analysis principles. Also, the TC intends to explore integration of different NDT methods for a more comprehensive assessment that entails quick scanning to detailed characterisation, and in this regard adaptation of more techniques, including visual based methods such as real-time photo image processing and thermography becomes attractive.

2. Corporate members and authority

The current member composition of this TC is biased towards experts from academia. Whilst we also have a few members who represent the industry, it is thought that we would still require more participants from the industry, especially from companies and businesses that specialise in material supply, printer manufacturing, construction and design, so that the TC is able to utilise industry data and insights more directly, in developing NDT methodologies and guidance that are readily applicable to resolve issues within the industry. We expect our industry-based members to provide convenience in facility and data sharing, in improving the scope of TC activities on prototype testing and onsite assessments. Besides industry, we are also aiming to have TC members representing the authorities, who have influence on policy making and execution, and whose high-level insights on standardisation of 3D concrete printing process incorporated with the quality and performance assessment technology would be valuable for the TC to identify any pertinent key issues and formulate suitable strategy of overcoming the problems. With the support from all other members, we will exert effort in recruiting more members from industry and authority through active promotion of the TC in events including symposium, conferences, workshops and seminars. We will also encourage existing members to provide introduction or recommendation to experts and practitioners who would be interested in joining the TC. Whenever possible, we also plan to populate the TC page on RILEM website with up-to-date information of our TC activities as a way to attract participation by RILEM members.

3. Expertise diversification

We are aware that, at the time of writing this letter, our TC members are in majority experts in NDT, who collectively have very solid skillsets and experience in developing and using different types of NDT methods on concrete materials and structures. We also have a few members who specialise in concrete materials development and structural testing. Allowing a more diverse expertise to exist within the TC will enable us to address a wider subset of problems towards realising the use of NDT methods for 3D printed cementitious composite structures. In this regard, we will strive to attract participations from a more diverge research background to help increase the scope comprehensiveness of the TC activities, making the outcomes more encompassing towards resolving the most imminent issues faced in the industry practice. To achieve this, we will adopt similar approaches as described in 3. above. Ideally, we are keen to have a good mix of experimentalists, theorists and analysists within our TC to tackle the various initiatives for innovation and standardisation. Furthermore, it is our motivation to have some of our members representing us in other RILEM TCs of cross-cutting interests, including TC 303-PFC "*Performance requirements and testing of fresh printable cement-based materials*" and TC 304-ADC "*Assessment of Additively Manufactured Concrete Materials and Structures*" to facilitate direct information exchange, data and knowledge sharing and encourage joint-research investigations of 3D printing process and quality assurance. We think that the members of these TCs would be distinctly different from our TC's in terms of expertise and technical background, hence mutual engagements among the connected TCs' members would be invaluable towards generating impactful innovations and technical guidance for practical implementation.

4. Dispersion of geographical locations of members

Our TC members are based in different continents, from Asia to Europe and North/South America. Whilst it is our plan to organise TC meetings in conjunction to international symposium or conference held in locations that would attract as many participations as possible, with option of attending online, it will always be challenging to find a meeting time that suit everyone who wants to attend online, because of time zone difference. The issue with time zone difference will cause delay in conveyance of meeting discussion outcome, and make it rather inconvenient for some members to provide timely and effective contribution in the meetings and any associated activities. The difference in geographical locations of the members will also pose difficulties to close collaborations among certain members, in not just in communication but also in conducting joint laboratory activities and sharing of resources. To overcome these issues, the TC management team aspires to always ensure that meeting records would be available to all members as quickly as possible after each meeting. A cloud-based shared folder will be created to keep all documentations and data of the TC activities that can be shared. The management team will also take the lead in frequent communication (via email primarily) to update progress and share information, in encouraging more active interactions among all members.

Authorship statement (CRediT)

Hwa Kian Chai: Conceptualization, Writing – Original Draft, Writing – Review & Editing. **Tomoki Shiotani:** Conceptualization, Writing – Review & Editing.

References

[1] RA. Buswell, WR. Leal da Silva, FP. Bos, HR. Schipper, D. Lowke, N. Hack, H. Kloft, V. Mechtcherine, T. Wangler, N. Roussel, A process classification framework for defining and describing Digital Fabrication with Concrete. Cem Concr Res (2020) 134: 106068. https://doi.org/10.1016/j.cemconres.2020.106068

[2] IO. Demirel, A. Yakut, B. Binici, Seismic performance of mid-rise reinforced concrete buildings in Izmir Bayrakli after the 2020 Samos earthquake. Eng Fail Anal (2022) 137: 106277. https://doi.org/10.1016/j.engfailanal.2022.106277
[3] D. Falliano, G. Crupi, D. De Domenico, G. Ricciardi, L. Restuccia, G. Ferro, E. Guliandolo, Investigation on the rheological behavior of lightweight foamed concrete for 3D printing applications. In: 2nd RILEM Int Conf on Con Dig Fab. DC 2020. FP. Bos, SS. Lucas, RJM. Wolfs, TAM. Salet (Eds.) 6-9 July 2020, RILEM Book Series 28, Springer, Cham. https://doi.org/10.1007/978-3-030-49916-7_25
[4] VN. Nerella, M. Näther, A. Iqbal, M. Butler, V. Mechtcherine, Inline quantification of extrudability of cementitious materials for digital construction. Cem Concr Compos (2019) 95: 260-270. https://doi.org/10.1016/j.cemconcomp.2018.09.015
[5] VN. Nerella, S. Hempel, V. Mechtcherine, Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion-based 3D-printing. Construct Build Mater (2019) 205: 586-601. https://doi.org/10.1016/j.conbuildmat.2019.01.235
[6] A. Anton, L. Reiter, T. Wangler, V. Frangez, RJ. Flatt, B. Dillenburger, A 3D concrete printing prefabrication platform for bespoke columns. Autom Construct (2021) 122: 103467. https://doi.org/10.1016/j.autcon.2020.103467
[7] GM. Moelich, J. Kruger, R. Combrinck, Plastic shrinkage cracking in 3D printed concrete. Compos B Eng (2020) 200: 108313. https://doi.org/10.1016/j.compositesb.2020.108313
[8] V. Mechtcherine, R. Buswell, H. Kloft, FP. Bos, N. Hack, R. Wolfs, J. Sanjayan, B. Nematollahi, E. Ivaniuk, T. Neef, Integrating reinforcement in digital fabrication with concrete: a review and classification framework. Cem Concr Compos (2021) 119: 103964. https://doi.org/10.1016/j.cemconcomp.2021.103964
[9] Y. Chen, S. Chaves Figueiredo, Ç. Yalçinkaya, O. Çopuroğlu, F. Veer, E. Schlangen, The effect of viscosity-modifying admixture on the extrudability of limestone and calcined clay-based cementitious material for extrusion-based 3D concrete printing. Mater (2019) 12(9): 1374. https://doi.org/10.3390/ma12091374
[10] MS. Khan, F. Sanchez, H. Zhou, 3-D printing of concrete: beyond horizons. Cem Concr Res (2020) 133, 106070. https://doi.org/10.1016/j.cemconres.2020.106070
[11] A. Lu, M. Li, TN. Wong, S. Qian, Effect of printing parameters on material distribution in spray-based 3D concrete printing (S-3DCP). Autom Construct (2021) 124: 103570. https://doi.org/10.1016/j.autcon.2021.103570
[12] GHA. Ting, YWD. Tay, MJ. Tan, Experimental measurement on the effects of recycled glass cullets as aggregates for construction 3D printing. J Clean Prod (2021) 300: 126919. https://doi.org/10.1016/j.jclepro.2021.126919
[13] M. Krause, J. Otto, A. Bulgakov, D. Seyfeddine, Strategic optimization of 3D concrete printing using the method of CONPrint3D®. In: ISARC. Proc Int Symp Autom Rob Construc, Berlin, IAARC Publications, 2018, 9-15 https://doi.org/10.22260/ISARC2018/0002
[14] SC. Figueiredo, CR. Rodríguez, ZY. Ahmed, DH. Bos, Y. Xu, TM. Salet, O. Çopuroğlu, E. Schlangen, FP. Bos, An approach to develop printable strain hardening cementitious composites. Mater Des (2019) 169, 107651. https://doi.org/10.1016/j.matdes.2019.107651
[15] V. Mechtcherine, FP. Bos, A. Perrot, WR. Leal da Silva, VN. Nerella, S. Fataei, R.J.M. Wolfs, M. Sonebi, N. Roussel, Extrusion-based additive manufacturing with cement-based materials-production steps, processes, and their underlying physics: a review. (2020) Cem Concr Res 132: 106037. https://doi.org/10.1016/j.cemconres.2020.106037
[16] AV. Rahul, M. Santhanam, H. Meena, Z. Ghani, Mechanical characterization of 3D printable concrete. Construct Build Mater (2019) 227: 116710. https://doi.org/10.1016/j.conbuildmat.2019.116710
[17] JG. Sanjayan, B. Nematollahi, M. Xia, T. Marchment, Effect of surface moisture on inter-layer strength of 3D printed concrete. Construct Build Mater (2018) 172: 468-475. https://doi.org/10.1016/j.conbuildmat.2018.03.232
[18] J. Van Der Putten, G. De Schutter, K. Van Tittelboom, Surface modification as a technique to improve inter-layer bonding strength in 3D printed cementitious materials. RILEM Tech Lett (2019) 4: 33-38. https://doi.org/10.21809/rilemtechlett.2019.84
[19] J. Van Der Putten, D. Snoeck, G. De Schutter, 3D Printing of Cementitious Materials with Superabsorbent Polymers: A Durable Solution?" 4th Int RILEM Conf Microstruc Rel Dura Cement Comp: Microdurability 2020, Delft University of Technology - Southeast University, 2021, 603-10. https://doi.org/10.1016/j.jobe.2020.102059
[20] RJM. Wolfs, FP Bos, TAM Salet, Hardened properties of 3D printed concrete: the influence of process parameters on interlayer adhesion. Cement Concr Res. (2019) 119: 132-140. https://doi.org/10.1016/j.cemconres.2019.02.017
[21] FP. Bos, ZY. Ahmed, ER. Jutinov, TAM. Salet, Experimental exploration of metal cable as reinforcement in 3D printed concrete. Materials (2017) 10(11): 1314. https://doi.org/10.3390/ma10111314
[22] FP. Bos, ZY. Ahmed, RJM. Wolfs, TAM. Salet, 3D Printing Concrete with Reinforcement. In: Hordijk, D., Luković, M. (eds.) High Tech Concrete: Where Technology and Engineering Meet. Springer, Cham, 2017, 2482-2493. https://doi.org/10.1007/978-3-319-59471-2_283
[23] A. du Plessis, AJ. Babafemi, SC. Paul, B. Panda, JP. Tran, C. Broeckhoven, Biomimicry for 3D concrete printing: a review and perspective. Addit Manuf (2021) 38: 101823. https://doi.org/10.1016/j.addma.2020.101823
[24] L. Breseghello, R. Naboni, Toolpath-based design for 3D concrete printing of carbon-efficient architectural structures. Addit Manuf (2022) 56: 102872. https://doi.org/10.1016/j.addma.2022.102872
[25] J. Kietzmann, L. Pitt, P. Berthon, Disruptions, decisions, and destinations: enter the age of 3-D printing and additive manufacturing. Bus Horiz (2015) 58(2): 209-215. https://doi.org/10.1016/j.bushor.2014.11.005
[26] F. Bos and R. Wolfs, A quality control framework for digital fabrication with concrete. RILEM Tech Lett, (2023) 8: 106-112. https://doi.org/10.21809/rilemtechlett.2023.181
[27] C. Lang, M. Willmes, Non-destructive testing of reinforced concrete sturctures. Proc of Int Symp Struct Health Monit Nondestruct Test, 4-5 Oct, Saarbruecken, 2018, 23(12).
[28] C. Cheng, T. Cheng, C. Chiang, Defect detection of concrete structures using both infrared thermography and elastic waves, Autom Construct, (2008) 18(1): 87-92. https://doi.org/10.1016/j.autcon.2008.05.004
[29] A. Behnia, HK. Chai, T. Shiotani, Advanced structural health monitoring of concrete structures with the aid of acoustic emission, Construct Build Mater, (2014) 65:282-302. https://doi.org/10.1016/j.conbuildmat.2014.04.103
[30] A. Behnia, HK. Chai, M. Yorikawa, S. Momoki, M. Terazawa, Integrated non-destructive assessment of concrete structures under flexure by acoustic emission and travel time tomography, Construct Build Mater, (2014) 67: 202-215. https://doi.org/10.1016/j.conbuildmat.2014.05.011
[31] Y. Gao, B. Suryanto, HK. Chai, MC. Forde, Evaluating the effect of corrosion on shear-critical RC beams by integrated NDT, Dev Built Env, (2021) 7: 100050. https://doi.org/10.1016/j.dibe.2021.100050
[32] T. Shiotani, N. Ogura, N. Okude, K. Watabe, C. Van Steen, E. Tsangouri, G. Lacidogna, S. Czarnecki, HK. Chai, Y. Yang, E. Verstrynge, D.G. Aggelis, Non-destructive inspection technologies for repair assessment in materials and structures, Dev Built Env, (2024) 18: 100443 https://doi.org/10.1016/j.dibe.2024.100443
[33] T. Shiotani, K. Watabe, RILEM Technical Committee. Recommendation of RILEM TC 269-IAM: damage assessment in consideration of repair/retrofit-recovery in concrete and masonry structures by means of innovative NDT. Mater Struct 58, 45 (2025). https://doi.org/10.1617/s11527-024-02525-5
[34] T. Shiotani, K. Watabe, RILEM Technical Committee. Recommendation of RILEM TC 269-IAM: damage assessment in consideration of repair/retrofit-recovery in concrete and masonry structures by means of innovative NDT. Mater Struct 58, 69 (2025). https://doi.org/10.1617/s11527-024-02525-5
[35] HJ. Yim, JH. Kim, SP. Shah, Ultrasonic monitoring of the setting of cement-based materials: frequency dependence. Construct Build Mater (2014) 65: 518-525. https://doi.org/10.1016/j.conbuildmat.2014.04.128

[36] RJM. Wolfs, FP. Bos, TAM. Salet, Correlation between destructive compression tests and non-destructive ultrasonic measurements on early age 3D printed concrete. Construct Build Mater (2018) 181: 447-454.
https://doi.org/10.1016/j.conbuildmat.2018.06.060

[37] MA. Helsel, JS. Popovics JS, PB. Stynoski, E. Kreiger, Non-destructive testing to characterize interlayer bonds of idealized concrete additive manufacturing products. NDT & E Inter, (2021) 121: 102443.
https://doi.org/10.1016/j.ndteint.2021.102443