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# Correlation between destructive compression tests and non-destructive ultrasonic measurements on early age 3D printed concrete

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## HIGHLIGHTS

- Non-destructive ultrasonic tests were performed on early age 3D printed concrete.
- Results of the ultrasonic tests were compared with uniaxial compression tests.
- A linear correlation was found between pulse velocity, strength, and stiffness.
- The study stimulates development of online ultrasonic methods for 3D printing.

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## ABSTRACT

3D printing of concrete and related digital fabrication techniques are enjoying rapid growth. For these technologies to be broadly accepted in structural applications and to be economically competitive, quality control methods of the process will be required. Additive concrete manufacturing processes are sensitive to process settings and conditions, which calls not only for preprint structural modelling to establish printability, but also for in-print monitoring to ensure expected properties are indeed achieved. Non-destructive test methods are highly suitable for this aspect of quality control, as they usually allow efficient, high frequent digital measurements that require relatively little effort. However, as they generally do not directly measure the appropriate parameter(s), correlations between non-destructive and destructive testing have to be established. The preprint structural modelling is based on a number of time-dependent mechanical properties, including the compressive strength and the Young's modulus. If concrete is still in the dormant state, as it often is in 3D concrete printing, these properties require difficult, time consuming destructive tests to establish. In the present work, the correlation between these two mechanical properties on the one hand, and the pulse velocity on the other, was studied. A (destructive) unconfined uniaxial compression test was applied to determine the former, while a (non-destructive) ultrasonic wave transmission test was used for the latter. As expected from previous research on a similar mortar, both the compressive strength and the Young's modulus were found to increase linearly in a time frame of 5–90 min after extrusion. This is attributed to thixotropic build-up. Within that time frame, the pulse velocity also grew in a linear fashion. Thus, a simple linear correlation between the destructive and non-destructive test results could be established. For now, this allows continuous quality control on simply obtainable control batches. Furthermore, it stimulates the development of ultrasonic online monitoring methods for the objects during printing.

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## 1. Introduction

Presently, a rapidly growing number of innovative case-study structures is being presented that have been realized through various forms of additive manufacturing methods of concrete and cementitious materials. It is increasingly recognized by industry and clients that these technologies present a serious potential in terms of optimized material use, reduced labour, and form freedom. The focus, by and large, is on delivering proofs of concept which show the aesthetical and economical potential. In most cases, extrusion-type methods with a nozzle attached to various types of moving robots are applied [1–5]. These layer-wise extrusion processes are commonly referred to as (3D) concrete printing.

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Some associated technologies are simultaneously under development, such as D-Shape (based on binder jetting) [6], Mesh Mould [7], and Smart Dynamic Casting [8,9]. Digitally Fabricated Concrete (DFC) is used as a generic term to refer to these innovations. Their common denominator is the perspective to move towards largely automated production. The study presented in this paper relates to 3D Concrete Printing (3DCP) technology under development at the Eindhoven University of Technology [10].

Owing to the novelty of concrete printing, the structural properties of the fabricated object, both during and after printing, are often only globally understood. Significant knowledge gaps still exists concerning the specific relations between the design, material, system, and product. It is known from other 3D printing industries, these parameters interact heavily and significantly influence the quality of the fabricated product [11]. Structural collapse during printing and layer delamination afterwards are common failures associated with insufficiently attuned processes. To avoid such failures to occur, and to prove that the manufactured object is equal to the design, quality control procedures should be introduced to DFC. As such, the authors suggest a development towards a system in which:

(1) the manufacturing process is monitored continuously,
(2) the acquired data is used for real-time quality control, and
(3) a closed feedback loop reacts upon the quality control when required.

Primarily, this concerns a measuring method in line with the digital nature of the manufacturing process. In conventional concrete construction, type testing (e.g. cube compression tests, slump-flow tests) is a commonly applied instrument to prove certification compliance and thus to show sufficient quality has been obtained. However, the continuous nature of the printing process and the presence of interacting parameters, make such isolated and destructive tests unsuitable. Instead, an online non-destructive monitoring system is required, which can measure properties on every position and moment in the process.

To assess the quality, or structural integrity, of the printed object based on the online measurements, initial steps towards the structural analytical and numerical modelling of the 3DCP process have been presented [12,13]. These modelling methods aim to predict the structural performance and possible failure modes of objects during printing, based on mechanical properties as defined by the printing process. Further development of modelling methods will be required to predict other crucial properties, such as the interface adhesion, which depends on interval time and application pressure among others.

Likewise, early examples of online monitoring and feedback systems were introduced. Lloret et al. adopted a method of simultaneous penetrometer tests during extrusion to record the concrete strength evolution [8], and formwork pressure and friction measurements [9], to adjust the robot speed accordingly. Neudecker et al. [14] proposed a feedback loop for robotic spraying of concrete, where 3D scanners measure the surface finish of the sprayed concrete parts. Wolfs et al. [15] presented a continuous measurement and real-time adjustment of print height nozzle relative to the print surface (or previous layer) for the 3DCP system.

This study takes a first step in connecting the structural modelling on 3DCP objects during printing as introduced by the authors [12] with continuous monitoring of the mechanical properties that are used in such modelling. In particular, the correlation of parameters from a non-destructive test method with potential for online monitoring, to mechanical properties determined from an appropriate destructive test for concrete in the dormant state is established.

## 2. Theoretical framework

### 2.1. Concrete hydration and the 3DCP process

Concrete goes through several stages during 3D printing that can be organized by its hydration processes and relative to the printing process. The four stages of hydration are: (1) the initial hydration directly after mixing, when the cement first comes in contact with water, (2) the dormant stage in which the cementing reactions are delayed, and the mechanical properties are mainly determined by thixotropic build-up attributed to both interparticle forces and low-rate hydration reactions [16], (3) the setting stage when cementing reactions accelerate and the materials hardens, (4) the hardened stage when the cementing reactions decelerate. On the other hand, 3 stages can be distinguished relative to the print process: (1) pre-deposition, when the concrete is still in the print system, (2) post-deposition/in-print, when the concrete is being printed, (3) after printing, when the print process is finished. The hydration and print process stages do not necessarily develop in parallel, rather the extent of that alignment depends heavily on the particular print material, print system and object design. Moreover, competing requirements may be found in the required performance in each stage.

The pre-deposition stage concerns the material in a fluid, moving state, while being transported through a system of pump, hose and nozzle. In this phase, a high workability is desirable to minimize friction, prevent blockage or fracture in the system and guarantee extrusion of the desired cross section [17–19]. Furthermore, considering recent developments in the field of (fibre) reinforcement of 3D printed concrete [20,21], the material should be fluid enough to compact around such reinforcement and realize proper bond.

The in-print stage concerns the material in an intermediate and static state. Here, the extruded concrete should be shape-stable with a sufficient strength and stiffness development to sustain the subsequent deposited layers and guarantee stability of the printed geometry [17,22,23]. Generally, the strength and stiffness in the dormant phase fulfils this requirement up to a certain object height, after which the setting stage should initiate to maintain the desired building rate.

Finally, the concrete is in a solid, hardened state, where sufficient bond strength between the layers is required. If the hydration process during printing is too quick, or the printing speed too low, the layers may not longer bond properly, resulting in poor structural integrity of the printed product [24–26]. Thus, understanding the transition between stages and the properties of concrete within each stage is critical to guarantee a robust printing process and a structurally safe end product.

### 2.2. Monitoring mechanical properties of early age concrete

A typical print duration in 3DCP is several minutes up to two hours. With the print materials that are currently being used in the process, the critical stage during printing is when the concrete is in the dormant stage. As the structural integrity during printing can be predicted through analytical and numerical modelling that have shown it to be highly sensitive to the early age mechanical properties, monitoring these properties is of particular interest for quality control. Due to thixotropic build-up in static conditions, they are time-dependent and develop significantly within the time-span of a typical printing process (as has been shown by the authors [12]), but are also expected to rely on a number of other variables in the print process that are difficult to predict or control (e.g. induced energy through pumping and system friction, compaction/density, temperature).

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