

Article

Preliminary Assessment of Ultrasonic Pulse Velocity for Quality Control of Shotcrete 3D-Printed Concrete

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Abstract

Digital fabrication with concrete enables manufacturing of geometrically complex and individualized elements, increasing the need for scalable non-destructive quality-control methods. This study is a preliminary investigation of the ultrasonic pulse velocity (UPV) use for shotcrete 3D-printed (SC3DP) concrete, with a particular focus on material variability caused by changes in the key manufacturing parameters, i.e., nozzle traverse speed and distance, as well as air volume flow and concrete pump speed. A series of small SC3DP specimens was produced using different manufacturing parameters settings. UPV was first measured transversely, across a single layer. Cores were then extracted, and UPV was measured axially through multiple layers before compression testing. The results showed a good correlation between UPV and bulk density but only a weak relationship between UPV and compressive strength. Pulse velocities measured across a single layer were lower than those measured through multiple layers, indicating direction-dependent wave propagation different to what is known from extrusion-based concrete 3D printing. Subsequently, UPV measurements were performed on two full-scale wall elements. The wall elements exhibited very low spatial variability in UPV, although their absolute velocities were lower than those measured for the small specimens. Overall, UPV appears promising for relative quality and homogeneity assessment of SC3DP elements, but further systematic research is required to clarify its relationships with microstructure and mechanical properties imposed by variation of manufacturing parameters.

Keywords: shotcrete 3D printing; concrete additive manufacturing; concrete 3D printing; NDT; quality assessment; compressive strength; additive manufacturing in construction



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1. Introduction

Additive manufacturing in construction (AMC) allows for unprecedented freedom of form and material, promising the possibility of structural optimization [1]. The serial production of unique elements requires, however, development of a new approach to quality control, where each element is individually checked after fabrication. The non-destructive testing (NDT) methods seem suitable for this task and, among them, an Ultrasonic Pulse Velocity (UPV) in particular. This method is easily scalable and applicable from range of centimeters to meters.

While UPV has been investigated for conventional concrete, extrusion-based 3D-printed concrete (3DPC) and conventional shotcrete, its application to hardened shotcrete 3D-printed (SC3DP) concrete remains largely unexplored. To verify applicability of UPV to SC3DP, especially with respect to change of material's microstructure during fabrication,

an experimental approach was taken. First, the relationship between UPV, compressive strength, and material density was tested on a material scale, including the influence of the layer orientation on the achieved wave velocity. The fabrication parameters were used to induce variability as semi-controlled variables. Subsequently, UPV was applied to two walls of meter scale, in order to analyze the variation of velocity within an element, and between the elements, to investigate its variability with stable manufacturing parameters. The main goal was to verify whether a density–strength–UPV relation exists in SC3DP produced with the same fresh material.

2. State of the Art

2.1. Ultrasonic Pulse Velocity

Ultrasonic Pulse Velocity (UPV) is a non-destructive testing method based on measuring the travel time of an ultrasonic pulse through a concrete element [2]. The pulse velocity is calculated from the known path length and the measured time of flight between the transducer and receiver, which can be attached to two opposite faces (direct transmission) or in other settings. In hardened concrete, UPV is commonly used to assess material uniformity, relative quality, cracking, voids, discontinuities, and changes in material condition. As such, the contours of equal velocity can give significant information regarding the quality of a concrete unit [2]. Since pulse velocity depends on density and elastic properties, it can also correlate with compressive strength or modulus of elasticity but only after material-specific calibration. It must also be considered that the correlation between UPV and compressive strength can be affected by factors such as the humidity of the concrete or the presence of reinforcement, which in both cases increase the velocity of the wave [2].

2.1.1. UPV for 3DPC

In 3D-printed concrete (3DPC), UPV has recently been explored mainly for three purposes: fresh-state monitoring, assessment of structural build-up, and evaluation of anisotropy of the interlayer zone. In extrusion-based 3DPC, the layer-wise deposition process introduces interfaces, interlayer pores, and directional material structure. Therefore, UPV may vary depending on whether the pulse travels along the printed filament, across adjacent filaments, or normal to the layer interfaces. The highest velocity is noted in the direction of the printing path (*u* direction [3]). In the studies where a volumetric shape is printed with interfaces in both transverse and vertical directions (*v* and *w* directions, respectively), the UPV is lower than in the *u* direction; however, while some results show that in the *w* direction the velocity is lower than in *v* direction [4,5], other results present an inverse relation [6,7]. As such, it can be stated that the velocity of UPV is highly affected by the interlayer interface between concrete layers, and in volumetric elements the velocity relation in *v* and *w* orientations depends on many parameters defining the properties of interfaces in these two directions, such as printing delay, rheology of fresh material, composition of material, and many others. Nevertheless, UPV is a good indicator especially regarding the quality and homogeneity of the interlayer zone, which in turn often guide the element strength [8]. However, some research indicated that the direct P-wave velocity measurements might not be sufficiently sensitive to identify localized faults in the interlayer zone, and more advanced methods such as ultrasonic arrays should be used [9].

Despite established research on use of UPV for early-age strength gain of 3D-printed concrete [10,11] and attempts to establish similar correlation between UPV and dynamic compressive strength [6], to date there have been only limited attempts to use UPV for the assessment of the 28-day compressive strength of the 3D-printed cementitious materials [7].

2.1.2. UPV for Shotcrete

There were several attempts reported in the literature to track various parameters of traditional shotcrete through measurement of UPV, including density and compressive strength.

Hubáček et al. tracked hardening of shotcrete of medium age, i.e., 3, 7, and 28 days, with various dosages of accelerator. They suggested a polynomial relation between compressive strength and UPV and suggested that the relation established for cast concrete can underestimate the compressive strength [12]. In turn, Polat and Özel varied the aggregate in the shotcrete. They obtained an excellent and linear relation between UPV and the density of shotcrete. Furthermore, they suggested a relation between UPV and compressive strength; however, the curve they fitted was non-monotonic and based on a low number of points [13], indicating potential overfitting of the model and hence low translational reliability from the statistical point of view. Likewise, the reduction in the water-to-cement ratio in shotcrete seem to increase both UPV and compressive strength, but no direct relation was established [14]. Liang et al. used UPV to track corrosion damage of shotcrete; they investigated the relation between UPV and compressive strength, obtaining what they called a moderate positive correlation with a correlation coefficient of 0.667, i.e., an R^2 of around 0.45 [15].

There were, furthermore, several attempts to use UPV for the assessment of the physical characteristics of shotcrete with various fiber types and dosage, focused, however, mostly on compactness and internal quality. There seem to be very strong correlations between UPV and density [16] and moderate relations between UPV and compressive strength [17]. The authors did not find, however, a study focused on the influence of variation of shotcrete parameters on UPV and other material characteristics.

2.2. Shotcrete 3D Printing (SC3DP)

Shotcrete 3D printing (SC3DP) is an additive manufacturing technology for large-scale structural concrete components that overcomes the key limitations of conventional extrusion-based methods [18–20]. The fundamental principle of the SC3DP process is based on pneumatically sprayed material which is applied in layers along a robotic path. Unlike extrusion, the high kinetic energy impact of the sprayed concrete yields an inherently denser interfacial microstructure, which significantly improves interlayer bond strength and mitigates the classic ‘cold joint’ phenomenon [21]. Crucial process parameters are concrete and air volume flow, accelerator dosage, nozzle traverse speed, and nozzle distance [22], as schematically presented in Figure 1. These core process parameters are broadly classified into kinematic variables (nozzle distance and traverse speed) and pneumatic variables (concrete volume flow rate and air volume flow) as well as additives (accelerator dosage). The strand geometry, specifically the width, height, and surface profile, are directly governed by the interaction of these parameters [22]. Beyond geometry, these parameters dictate critical material–process interactions.

The quality of the produced element, understood as the uniformity of the material after application within layers and between them, can change radically depending on the used parameters of the application despite using the same material mix. Accelerator dosage, understood here as a process parameter as it can be varied over the printing path, influences interlayer strength and tortuosity [23]. The interlayer time affects, especially, the tensile interlayer properties [21]. The nozzle shape predominately influences the distribution of the aggregate and the density in the strand, as well as the flexural strength [24]; interestingly, no strong correlation between a change in flexural strength and compressive strength of SC3DP concrete exists, i.e., an increase in one characteristic does not determine whether the other one increases or decreases, as they may result from different micro- and

mesomaterial phenomena [25]. Finally, parameters such as accelerator dosage, air volume flow, and concrete volume flow predominately influence global density, local density, and tensile interlayer strength [26,27]. Overall, the available research suggests that while a relation between bulk density and interlayer tensile strength of SC3DP exists [27], as well as a relation between the bulk density and the compressive strength of extruded 3DPC concrete [28,29], the bulk density and compressive strength may not correlate for the SC3DP [21]. Nevertheless, as process parameters guide both geometry and material properties of SC3DP, it is crucial to establish non-destructive testing procedures to verify the quality of produced elements [30].

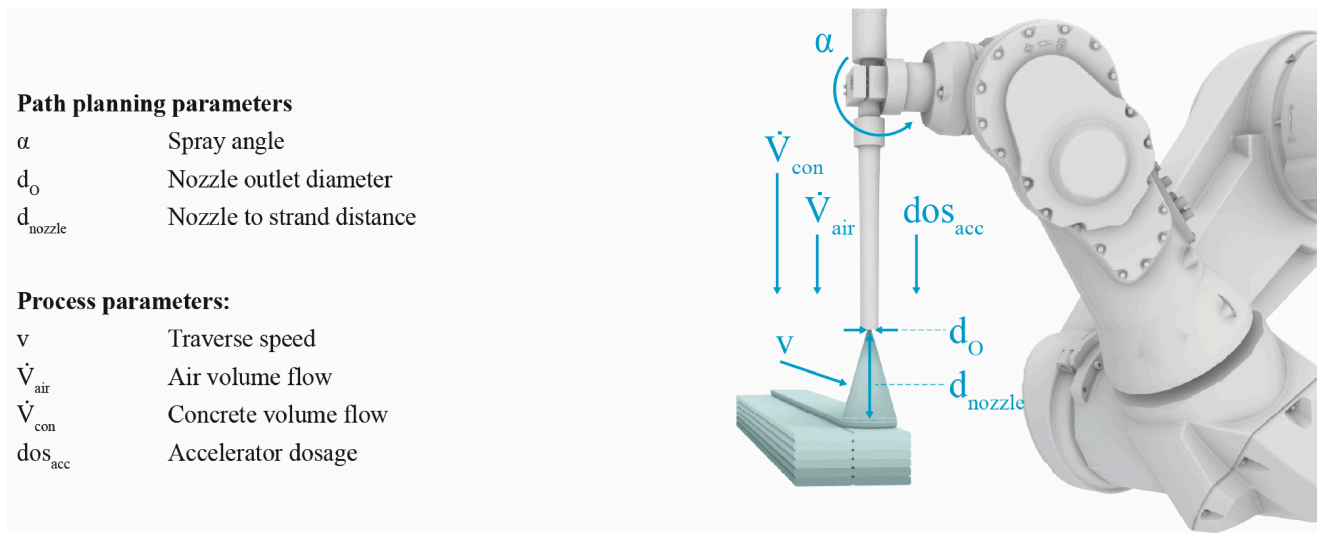


Figure 1. Scheme of shotcrete 3D printing (SC3DP) process parameters affecting as-manufactured material properties, adapted from [22].

To date, to the knowledge of the authors, there was no reported attempt to use UPV as a non-destructive testing method for hardened SC3DP. On the basis of experience with other 3D-printing concrete methods, it can be expected that the poor bond caused by porosity and voids in the interlayer zone would reduce the velocity, as well as impair the mechanical properties. Likewise, on the basis of experience with classical shotcrete, it seems that a change in material mix would be reflected in both UPV and compressive strength change. Nevertheless, it is uncertain whether material variation of the same fresh mix due to difference in process parameters would affect UPV. These hypotheses should be verified by experimental research.

3. Relation Between UPV and Compressive Strength

3.1. Materials and Methods

In order to analyze the relation between compressive strength and UPV of SC3DP, a series of specimens was prepared. All were prepared with the same material, Nafufill RM 40 (MC Bauchemie, Bottrop, Germany), with a maximum aggregate diameter of 4 mm and declared mean compressive strength when applied by spraying of 52.4 MPa [31]. The preparation and processing sequence is schematically outlined in Figure 2.

To impose the variation of microstructure and hence potentially of the compressive strength and the UPV without changing the composition of material, specimens were produced under various process parameter sets. The used values are presented in Table 1. While traverse speed, nozzle distance, and air volume flow are digitally controlled in a feedback loop and represent stable and reliable values [32], the concrete pump speed was set manually. The obtained concrete volume flow is therefore a resultant of pump

setting, material rheology, and concrete–air interaction in the nozzle [33], and obtaining the exact value is nontrivial. The experiment measurement with the bucket was conducted for some settings, but no relation between the concrete pump setting and the volume flow of concrete at the nozzle could be reliably established; nevertheless, it varied in the range of around $0.5 \text{ m}^3/\text{h}$ to $1 \text{ m}^3/\text{h}$. Due to low certainty regarding the factual concrete flow, the statistical relation between the SC3DP parameters and the obtained concrete strength as well as the ultrasonic pulse velocity are not analyzed here in terms of analysis of variance (ANOVA). Only the relationships between UPV, compressive strength, and density are further discussed, while the parameter variation is treated as a measure to purposely induce the variation in the material.

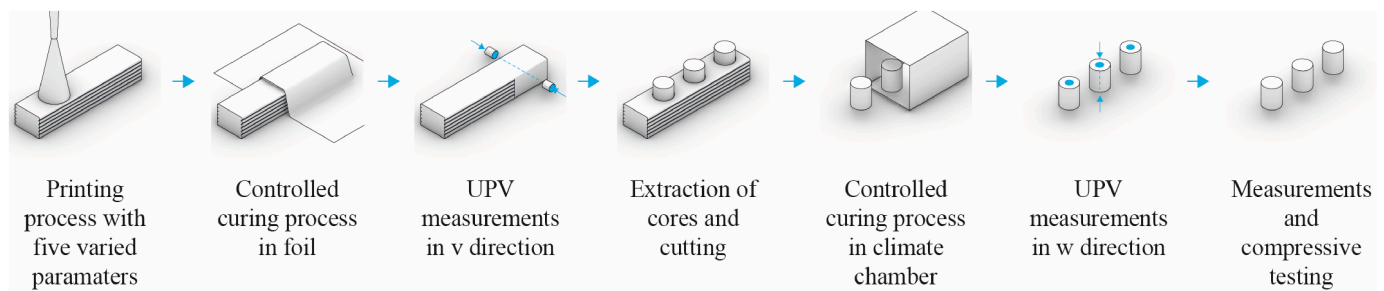


Figure 2. Scheme of specimen preparation and testing to investigate the relation between UPV and compressive strength.

Table 1. Spraying parameters used for compressive strength variation.

Normalized Value [–]	Traverse Speed [mm/min]	Nozzle Distance [mm]	Air Volume Flow [m ³ /h]	Concrete Pump Speed [%] ¹
–1	3000	100	20	40
0	4500	200	35	60
1	6000	300	50	80

¹ Concrete pump speed set manually.

In total, 19 one-meter prisms were produced with different combinations of the parameters. The prisms measured between around 7 cm and 15 cm in width and around 16 cm and 20 cm in height, encompassing between 6 and 15 layers of material, depending on the spraying parameters. The prisms were cured while tightly wrapped in foil for one week.

The lateral surfaces of some prisms were manually smoothed in a green state at an area of around 20 cm by 20 cm to assure good contact with UPV transducers, and the UPV was measured in the transverse direction across the concrete layer, i.e., in the *v* direction [3]. The UPV was measured in 3 randomly selected points of the area. The measurements in the lateral direction took place at an age of around 20 days, when the prisms were still curing and wrapped in foil. In total, 9 randomly selected prisms were measured.

Subsequently, at an age of around 21 days, three concrete cores were extracted from each prism in the *w* direction [3], i.e., parallel to the spraying direction across multiple layers. In most cases cores with a diameter of 72 mm were extracted, except for the prisms with a width lower than 80 mm, where cores of 50 mm diameter were extracted. The cores were subsequently cut and polished to a height-to-diameter ratio $l/d = 2$. Afterwards, the cores were stored in the standard conditions of a curing chamber, i.e., around 20 °C and relative humidity around 95%. During the curing time, the UPV was measured in the axial direction of cores, i.e., in the *w* direction parallel to the spraying direction during fabrication. The measurements were taken directly in the curing chamber, i.e., no drying of concrete

specimens took place. For each core, measurements at three points were taken, in order to account for potential variation in material [27]. All cores were measured accordingly.

The cores were tested for axial compression strength at an age of 28 days, according to European standards [34]. A Walter + Bai (Löhningen, Switzerland) 600 kN hydraulic machine was used, with a load rate of around 0.5 MPa/s. Only the maximum force indicating compressive strength was registered.

For the UPV measurements the BP 700 Pro Ultrasonic Tester (UltraTest GmbH, Achim, Germany) was used. The S-70 transducers from the same producer were used, with a diameter of 30 mm and a frequency of around 45 kHz. It must be noted that for such a transducer and concrete material, the minimum recommended measurement path is 100 mm [2]; therefore, the cylinders satisfy this requirement, including the smallest cores with $d = 50$ mm and $l/d = 2$. In turn, the minimum recommended lateral dimension is around 100 mm [2], which is violated by all cores and can potentially result in a slower measured UPV.

In all cases petroleum jelly was used as coupling agent, and the UPV was measured in the direct transmission. The approximately axially aligned points were first marked on the two opposite faces of a cylinder, and the direct distance between them was measured by the measurement caliper with a precision of 0.1 mm. This distance was then registered in a device, and the measured wave velocity was taken as a result. The transducers were pressed with approximately constant pressure, and measurements were taken automatically each second. The speed after stabilizing the read-out was noted, indicating that no more air was present in the coupling material.

3.2. Results

For measurements in the w direction, it was verified according to the norm for UPV testing [2] whether the variation in wave speed does not exceed 1% between the three measurements points. In total 49 out of 57 cores passed this verification. However, since for the remaining eight cores this variation did not exceed 1.5%, all the results were taken into consideration. Furthermore, certain cores were rejected after compressive testing as outliers according to the relevant standard [34], or due to other faults during testing; for these cores, all the data is neglected, including UPV. In total, the data from 53 cores is presented in Table 2 as mean values for each combination. The detailed results are available in the Supplementary Materials.

The obtained data indicates the importance of spraying parameters on the obtained mechanical properties of the hardened material. The special case is of specimen 13, where local accumulations of material instead of uniform deposition were observed, resulting in pronounced irregularities of the prism. It also exhibited a density (2.12 g/cm^3) and compressive strength (20.1 MPa) radically lower than for other specimens. This indicates that a combination of low traverse speed and low distance of the nozzle (both normalized parameters -1), with a large air volume flow and concrete flow (both $+1$), violated the allowable process parameter range. Contrarily, for specimen 19, where the same concrete pump speed and air flow were used but with a greater nozzle traverse speed and nozzle distance ($+1$), the resulting compressive strength (55.2 MPa) is in the higher ranges of all the specimens. Such an anomaly as in the case of specimen 13 would be detected during fabrication. Importantly, the measured UPV in both directions demonstrated lower values than for any other specimen. After a sensitivity study, it was found that specimen 13 largely skews the regressions; as such, it was decided to neglect the specimen in the further analysis and interpretation presented below, unless explicitly mentioned.

Table 2. Fabrication parameters and testing results for small specimens.

Specimen Number	Process Parameters				Geometric Properties			Physical Properties				Mechanical Properties	
	Normalized Traverse Speed [-]	Normalized Nozzle Distance [-]	Normalized Air Volume Flow [-]	Normalized Concrete Pump Speed [-]	Layer Width [mm]	Layer Height [mm]	Number of Layers [-]	Mean Core Density [g/cm ³]	Mean UPV in v Direction [m/s]	Mean UPV in w Direction [m/s]	Std Deviation UPV in w Direction [m/s]	Mean Concrete Core Strength [MPa]	Std Deviation Core Strength [MPa]
1	0	0	0	0	73	1.7	12	2.26 ³	— ¹	4365 ³	37 ³	58.2 ³	1.5 ³
2	0	0	0	0	72	1.7	13	2.25 _{2,3}	— ¹	4305 _{2,3}	43 ^{2,3}	49.3 _{2,3}	3.7 ^{2,3}
3	−1	0	0	0	71	4.8	4	2.23 ³	— ¹	4196 ³	32 ³	51.9 ³	2.1 ³
4	0	−1	0	0	78	3.6	6	2.21 ³	— ¹	4176 ³	47 ³	45.6 ³	2.2 ³
5	0	0	−1	0	107	2.8	7	2.21	— ¹	4222	32	58.5	2.0
6	0	0	0	−1	100	1.5	11	2.27	— ¹	4353	58	58.7	2.7
7	+1	0	0	0	100	1.9	10	2.27	— ¹	4302	58	57.7	1.9
8	0	+1	0	0	119	1.7	10	2.28	— ¹	4292	27	53.5	4.6
9	0	0	+1	0	109	2.1	9	2.25	— ¹	4310	34	53.5	1.2
10	0	0	0	+1	136	2.5	8	2.23	— ¹	4268	31	51.1	0.6
11	−1	−1	−1	−1	92	1.5	13	2.20 ²	4049	4154	40	52.4 ²	0.7 ²
12	0	0	0	0	85	1.5	12	2.24 ²	4161	4268	14	54.3 ²	1.0 ²
13	−1	−1	+1	+1	126	1.8	10	2.12 ²	3886	4130 ²	37 ²	21.0 ²	7.3 ²
14	+1	+1	−1	+1	151	1.8	11	2.19	— ¹	4144	31	45.1	5.5
15	+1	+1	+1	−1	147	2.3	8	2.29	4072	4346	29	51.7	1.2
16	−1	−1	−1	+1	138	2.0	8	2.21	4003	4188	33	44.8	4.0
17	−1	−1	+1	−1	121	1.2	15	2.25	— ¹	4316	29	48.1	4.1
18	+1	+1	−1	−1	131	2.8	6	2.22	4112	4207	16	52.6	0.5
19	+1	+1	+1	+1	152	2.7	7	2.27	4129	4327	31	55.2	0.6

¹ Not measured; ² only two cores considered; ³ cores 50 mm diameter, 1/d = 2.

Overall, all specimens reached the mean compressive strength in the range of 44.8 MPa to 58.7 MPa. The mean compressive strength declared by the producer is 52.4 MPa, correlating exceptionally well with the mean value of all accepted concrete cores, equal to 52.3 MPa. As such, it can be stated that the producer accordingly considered the possible variation in application parameters in their declaration of performance [31].

Interestingly, for specimens where it was measured, the UPV in a single layer (v direction) indicated consistent velocity around 3–6% lower than across layers (w direction). In the literature for extrusion-based 3DPC, usually the velocity across multiple strands in both the v and w directions are compared, with varying relations between them [4–7]; however, where the velocity is measured withing one strand, i.e., along the printing path u, the velocities are consistently higher than in the w direction. This suggests that the microstructure variation in SC3DP is of a different character than in extrusion-based C3DP. The measurements were taken at a different time instance and curing regime, which could affect humidity and hence the variation in the UPV. Another reason could be manual smoothening of surface in the green state to provide a surface for UPV measurement; this post-processing definitely influences microstructure and potentially the UPV as well. This phenomenon should be investigated in more detail including separation of the effects of curing age, humidity, and surface processing to explain the apparent directional difference in UPV in SC3DP.

The use of two core diameters, i.e., 72 mm for the majority of specimens and 50 mm for the narrowest ones, may introduce some size-related variability in both compressive strength and UPV. According to the European standard for assessment of in situ compressive strength [35], smaller diameter cores generally exhibit higher scatter and may give lower strength, although the magnitude depends strongly on aggregate size [36]. Considering the maximum aggregate size in the current study of 4 mm, which is much smaller than in regular concrete and much smaller than both core diameters, it can be assumed that the effect of core size on the compressive strength can be neglected. For UPV, European standard [2] indicates a possible reduction in measured velocity for smaller cores; the experimental results show a decrease of a few percent which is neglectable in the discussed case [37,38]. Therefore, in order to investigate the relation between UPV, density, and strength in the *w* direction, their relations are plotted without any size-related corrections for the 18 data points, i.e., mean values for each combination. Furthermore, least-square fitting of the linear function, as well as a 95% confidence band, fitted function, and the R^2 of the fitting are presented.

For the direct relation between UPV and compressive strength (Figure 3), a relatively weak correlation can be observed ($R^2 = 0.31$, $p = 0.0175$). The UPV seems to be, however, strongly correlated with the density (Figure 4), with $R^2 = 0.80$, $p < 0.0001$, and a comparatively narrow confidence band. This is consistent with the sensitivity of UPV to the porosity and density of the medium. The low correlation between UPV and compressive strength is therefore caused by the weak correlation between density and compressive strength (Figure 5) with $R^2 = 0.25$, albeit with a statistically significant positive slope $p = 0.0333$. Thus, within the investigated range, variations in density explain only a limited part of the observed variation in compressive strength. This suggests that additional microstructural characteristics of the sprayed material need to be considered to better explain its compressive strength variation.

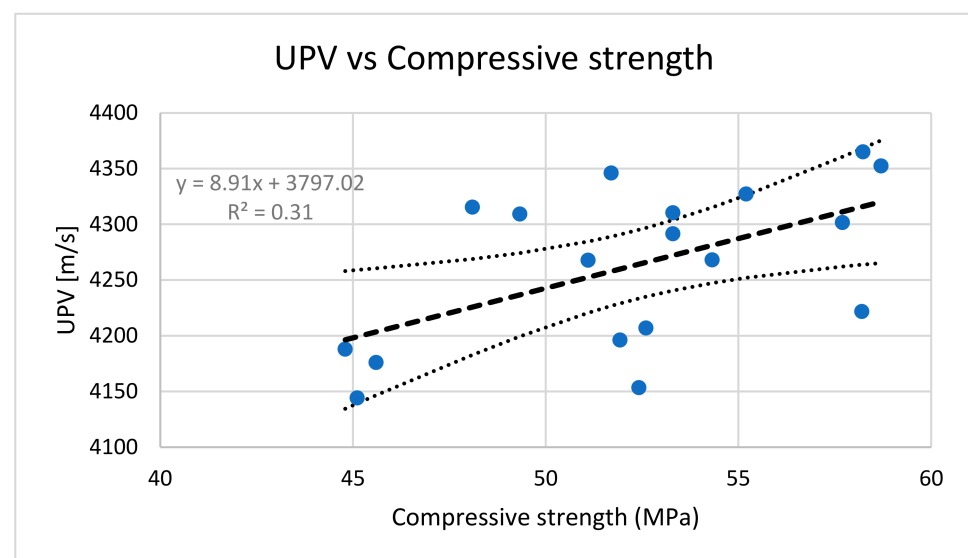


Figure 3. Relationship between UPV and compressive strength with the least-squares linear regression line and its 95% confidence band.

The above regressions were also performed for all $n = 19$ data points, including specimen 13. The slopes (a) and coefficients of determination (R^2) were strongly affected in all the cases: UPV-strength ($a = 5.35$; $R^2 = 0.36$), UPV-density ($a = 1657.80$; $R^2 = 0.77$), and density-strength ($a = 0.00$; $R^2 = 0.59$), proving that specimen 13 introduces the statistical distortion and should be excluded.

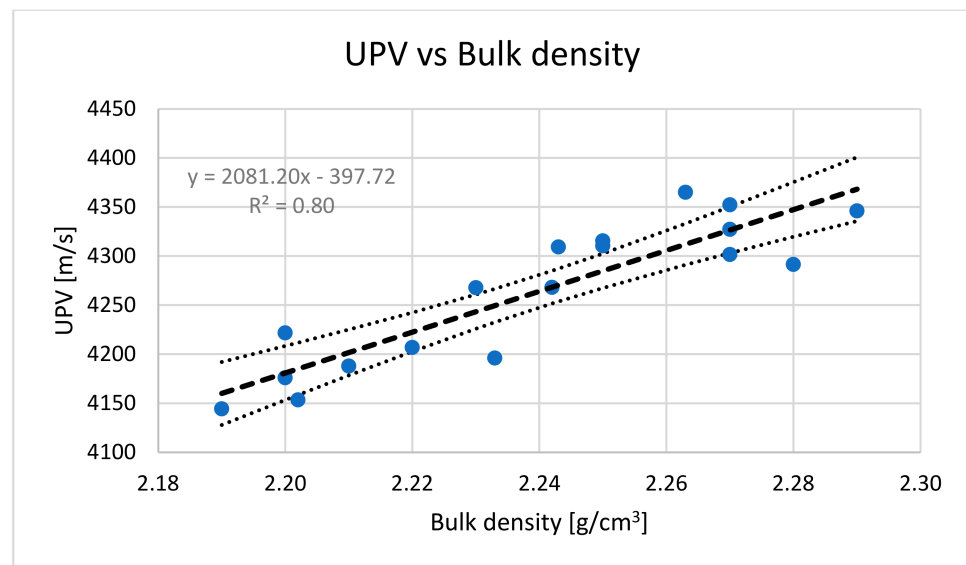


Figure 4. Relationship between UPV and bulk density with the least-squares linear regression line and its 95% confidence band.

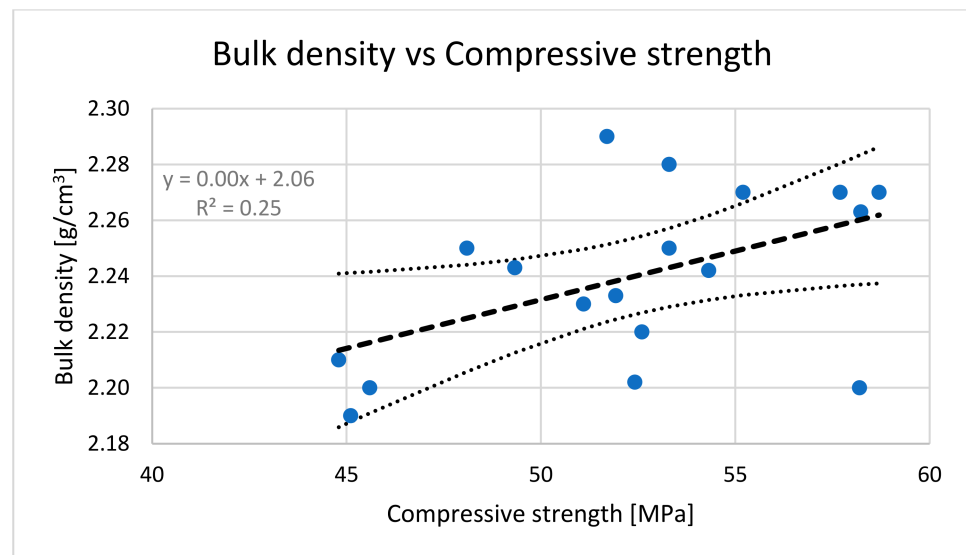


Figure 5. Relationship between bulk density and compressive strength with the least-squares linear regression line and its 95% confidence band.

3.3. Discussion

It is established that in cast concrete, the relation between UPV and compressive strength is dependent on the type of aggregate, amount of cement paste, their proportion, and their physical properties. On the other hand, the strength of concrete is more related to the water/cement ratio than to the aggregate type and the proportions of aggregate and paste. Thus, correlations between the pulse velocity and strength of concrete are physically indirect and have to be established for the specific concrete mix [2]. This is in contrast with the current research, where the variation in strength was induced by a change in the SC3DP process parameters, without altering the fresh material composition.

The obtained results suggest a quite strong correlation between UPV and density, which was also observed for the traditional shotcrete [13,16]. In the traditional shotcrete, however, a clearer UPV–strength relationship was established, when the material properties were varied through age, accelerator dosage, mixture composition, or deterioration [12–17], than in the current study. It can be thus reasoned that the compressive strength of SC3DP

likely reflects process-induced variability, including differences in compaction, pore structure, local material distribution, and directional wave propagation caused by changes in spraying parameters, which was not fully reflected by the bulk density change detectable by the UPV. This suggests that the UPV-based strength estimation of compressive strength in SC3DP may require process-specific calibration rather than only mix-specific calibration, or additional methods to characterize the microstructure of the material are required. Further research in this direction should hence consider how the density, density distribution, and other microstructure characteristics of as-built SC3DP material influences its performance.

4. UPV as a Quality Control for Large-Scale Element

4.1. Materials and Methods

Despite a lack of a strong correlation between the UPV and compressive strength as a function of changing spraying parameters as concluded above, there exists a strong correlation between UPV and density of material. Therefore, UPV is potentially useful for quality control in terms of air pockets, voids, and other similar faults in larger elements. Hence, it was decided to apply UPV to two fabricated walls.

Two wall elements were produced as part of a larger structure, which is not discussed here. The first wall had an S-shape with a developed length of 2350 mm and a height of 1034.5 mm. The second wall element was curved in both the horizontal and vertical directions, resulting in a slightly double curved geometry. The developed length of the second element was 3680 mm with 1085 mm height.

During the manufacturing, the process parameters were set as constant and as presented in Table 3. Only the print speed was adaptively adjusted to ensure a stable application rate and constant nozzle-to-strand distance [39]. The same material Nafufill RM40 by MC Bauchemie was utilized for printing the wall elements as in the case of the previously described parametric study; however, an accelerator was introduced to stabilize the print and increase the possible print height, thus increasing yield strength and minimizing the risk for buckling failure during printing.

Table 3. Process parameters during fabrication of both wall elements.

Process Parameters During Wall Fabrication	
Spray angle α	90° (vertical)
Nozzle outlet diameter d_0	15 mm
Nozzle outlet distance d_{nozzle}	200 mm
Traverse speed v	4500 mm/min $\pm$ 25% ¹
Air volume flow V_{air}	50 m ³ /h
Concrete volume flow V_{con}	0.5 m ³ /h
Accelerator dosage dos_{acc}	1.50%

¹ Automatically adjusted in feedback loop.

During the fabrication process, concrete deposition was carried out in horizontal, planar layers with a strand geometry of 125 mm width and targeted 17 mm height per layer. To enhance the structure's capacity, a bidirectional reinforcement system consisting of horizontal and vertical steel bars was integrated into the printing process. The horizontal interlayer reinforcement [40] used pre-bent 8 mm steel bars which were placed manually between successive layers during print breaks at approximately 200 mm intervals. Concurrently, vertical reinforcement was integrated at three discrete locations in the first wall and five discrete locations along the length of the second wall element [41]. These 900 mm long bars were integrated using a vibration-assisted insertion method to ensure deep penetration and a robust bond within the fresh concrete [42]. Together, these methods successfully

established a continuous two-directional internal reinforcement network. The walls were cured under waterproof tarp for 14 days and subsequently stored at room temperature in a shaded place.

Since the bottom of each wall was produced on a flat surface, while the top was milled for a further assembly and joining, these surfaces provided a precise setup for the UPV measurements through the wall elements along their height, i.e., in the w direction. This correlates also with the previous experiments on the cylinders. The same procedure and device were utilized in the measurements, with five measurements at each point. The UPV was measured at an age of around 90 days from fabrication.

4.2. Results

The measured UPV for wall one and two are presented in Figures 6 and 7, with a mean velocity of 4020 m/s and 3877 m/s, respectively. Overall, they show very good coherence for each wall separately, with a Coefficient of Variation (CoV), respectively, of 0.7% and 1.1% for all measurements on a given wall. The largest difference between extreme measured values for each wall is, respectively, 2.0% and 2.4%. As such, no slow traverse velocity region was clearly identified in the measurements. As no coring was possible, so as to not damage the walls, the UPVs cannot be compared against any other indicator characterizing the as-built material.

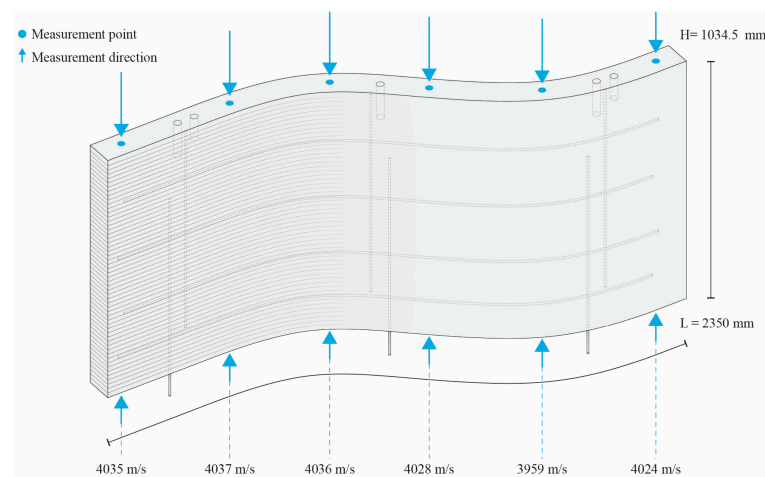


Figure 6. Sketch of wall no. 1, with reinforcement outlines, UPV measurement points, and obtained results.

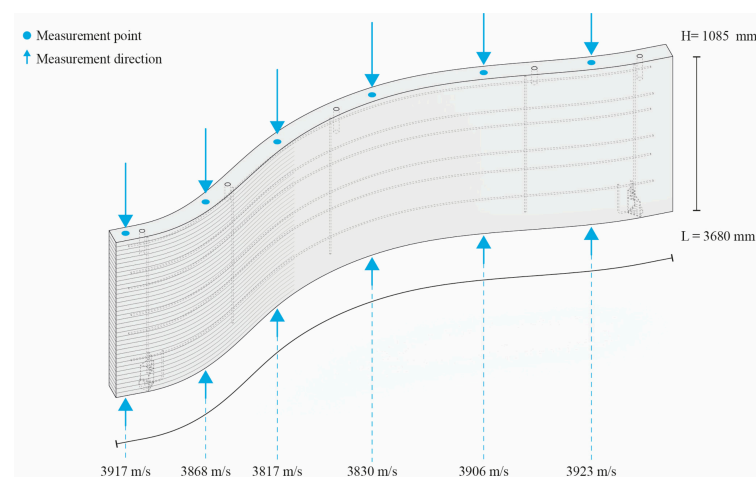


Figure 7. Sketch of wall no. 2, with reinforcement outlines, UPV measurement points, and obtained results.

4.3. Discussion

The European standard for UPV measurement [2] does not indicate what the acceptance criteria are for an element. In contrast, the national standards of the Czech Republic [43] and Vietnam [44] provide such an indication in their informative annexes. According to the Czech standard, for concrete class C30/37–C50/60, to which range the concrete used here can be roughly qualified, the acceptable uniformity of an element is indicated by a UPV CoV $\leq 3\%$, and $\Delta \leq 7.5\%$, where Δ is the maximum relative difference between neighboring measurements. Both wall elements easily satisfy these requirements: wall one with CoV = 0.7% and $\Delta = 1.7\%$ and wall two with CoV = 1.1% and $\Delta = 1.9\%$. These values are also in the range indicated by the Vietnam standard, which states that the CoV in the range of 2–3% demonstrates good uniformity. Such variation is also well below what is reported in the literature for cast reinforced concrete [45] and extrusion-based 3D-printed concrete [46]. This uniformity was, however, not cross-verified with other methods, in particular those allowing for the identification of small-sized voids and local defects. It remains unclear whether the rules applicable to cast concrete can be successfully applied to SC3DP.

Interestingly, while each wall demonstrates internal coherence of results, the difference between mean values for each wall of 3.6% is relatively high in the view of low variability within each of them. It is, however, impossible to quantify the importance of this difference without further research. Furthermore, both of them demonstrate velocities lower than that measured for small specimens with the same material. The lower absolute UPV of the wall elements should not be interpreted directly as lower compressive strength, particularly in view of the weak UPV–strength relationship established for the small specimens. Moreover, the wall measurements were performed over a substantially longer propagation path and on elements with different curing history, at significantly different ages and fabricated with an accelerator. These differences prevent a direct quantitative transfer of the laboratory correlation to the wall-scale measurements. While both the geometric effects [47] and increased tortuosity of the interlayer zone provoked by use of an accelerator which in turn could increase interlayer porosity [23] would reduce the pulse velocity, the older age of the wall at testing could potentially increase the velocity [12]. Additional research separating the potential causes would be needed to clearly identify the reasons and quantify the importance of the reduced velocity.

5. Conclusions

This study assessed in an experimental manner the applicability of Ultrasonic Pulse Velocity (UPV) non-destructive testing (NDT) as a quality assessment tool for shotcrete 3D-printed (SC3DP) elements. Particular attention was given to the identification of as-built material variation due to a change in manufacturing parameters. First, small elements with a range of parameters were produced, where UPV was measured across a single layer (v direction) and through multiple layers (w direction); subsequently, the extracted cores were tested in compression. Next, UPV was applied to two large-scale wall elements. The same base concrete mixture was used throughout, while an accelerator was additionally applied in the wall-scale elements.

The main findings were as follows:

- Variation in SC3DP fabrication parameters induced considerable change in the compressive strength of as-built material; as such, they should be considered together with the material composition for strength assessment;
- UPV correlated well with bulk density for the process-induced variations investigated;

- Bulk density showed only a weak relationship with compressive strength; consequently, the sole use of UPV was not a reliable indicator of compressive strength variation within the investigated parameter range;
- UPV measured through multiple layers was higher than that measured across a single layer, suggesting a directional response different from that commonly reported for extrusion-based 3D-printed concrete; the source of this behavior is uncertain and could be related with the surface processing or different age at measurement in each direction;
- Spatial UPV variability in each wall-scale element based on measurement points was low, indicating a uniform ultrasonic response; however, their absolute UPV values were lower than those measured in the small specimens which should be explained by additional research.

Overall, UPV appears promising for the assessment and homogeneity control of SC3DP elements. The main limitation of the current study stems from the use of fabrication parameters as semi-controllable variables to induce the material changes; as such, no sensitivity of UPV, density, and strength to variation parameters is studied. Further systematic research is needed to clarify the effects of microstructure, accelerator use, interlayer conditions, material composition, and element scale on UPV. It should be also investigated whether process-specific relationships with mechanical properties can be developed.

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Abbreviations

The following abbreviations are used in this manuscript:

UPV	Ultrasonic Pulse Velocity
SC3DP	Shotcrete 3D Printing
NDT	Non-destructive Testing
3DPC	3D-Printed Concrete

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