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3D CONSTRUCTION PRINTING OF COARSE AGGREGATE CEMENTITIOUS COMPOSITE

3D STAVEBNÍ TISK HRUBOZRNNÉHO CEMENTOVÉHO KOMPOZITU

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CONTENTS

1 INTRODUCTION

Currently, the construction industry is expanding rapidly, resulting in an overexploitation of limited natural resources and a massive emission of greenhouse gases [1]. According to the IEA (International Energy Agency), the construction industry will contribute 39% of the world's CO_2 emissions in 2019, a figure that is on the rise [2]. In the future, we will be confronted with inevitable climate changes that already pose a threat to the environment from a global scale.

Due to these realities, there will be a greater emphasis on reducing the production of greenhouse gas emissions and promoting sustainable economic development in relation to the circular economy, as highlighted by the efficient utilization of building materials. Since 1990s, an exponential increase (Fig. 1-1) in the number of research and development projects aimed at finding solutions for the sustainable production and design of buildings [3] has been observed in both the private and academic sectors of the construction industry. The use of additive manufacturing technology in the form of 3D printing is one solution.

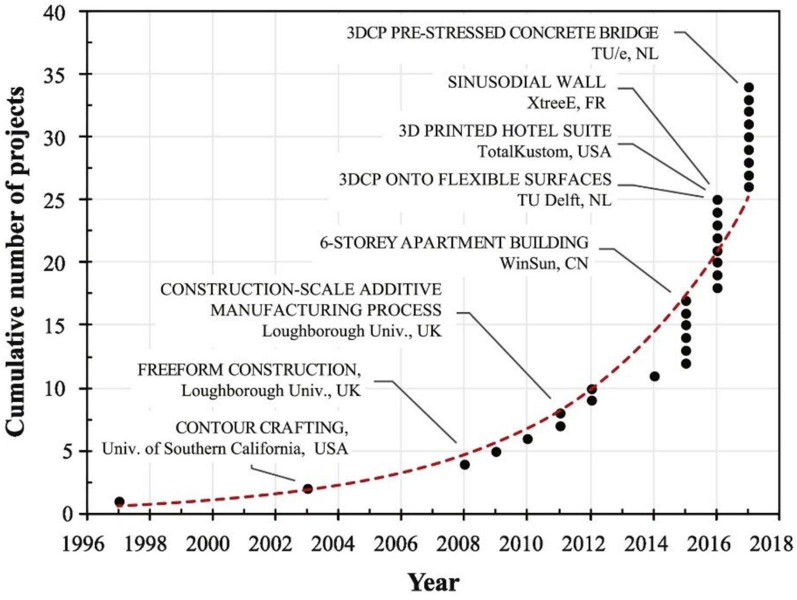


Figure 1-1 Additive manufacturing development in civil engineering [1]

In the 1930s, a primitive form of additive manufacturing existed, which consisted primarily of transporting building materials by pumping and pushing them to inaccessible construction site locations. Transport of the cementitious material was crucial and its main properties for this application were its easy workability and pumpability; these properties can be affected by the cementitious material's rheological properties [4].

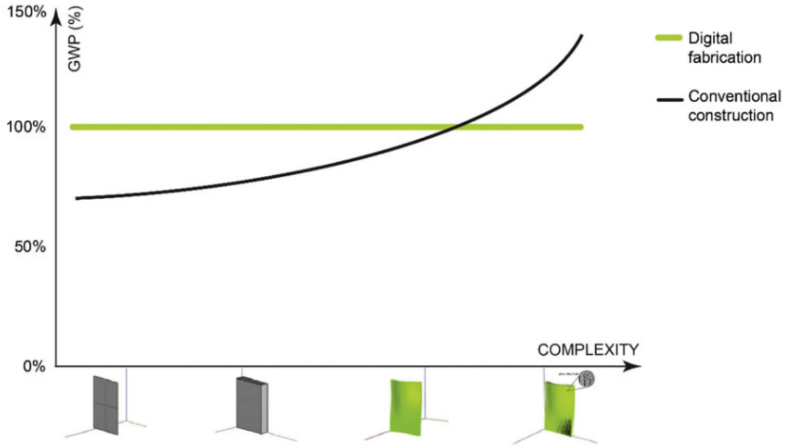


Figure 1-2 Relation between the additive and conventionally manufactured architecture according to GWP (Global Warming Potential). Kg CO2 per m2 [1]

In the vision of the 3D printing capabilities for freeform and complex structures that are virtually impossible to produce using conventional methods will transform the traditional form of construction (Fig. 1-2) [1, 5]. However, this technology introduces new challenges, opportunities and problems that must be identified and addressed [6]. Currently, additive manufacturing technology in architecture and construction utilizes costly, economically unfavourable and environmentally unfriendly cementitious mixtures with fine aggregate fraction [7, 8]. Despite the fact, that cement has a high environmental impact, there is currently no adequate substitute. This dissertation examines the process parameters of large-scale 3D printing of cementitious materials with a large aggregate fraction with an emphasis on application and technological advancements.

2 STATE OF THE ART

2.1 EVALUATION OF MATERIAL CHARACTERISTICS WHILE 3DCP

Since 2003, 3D printing technology has been known as C3DP/3DCPM (construction 3D print, 3D Construction Print - hereafter 3DCP) [9].

This technology is based on the extrusion of cementitious material, specifically on a system that shapes cementitious-based composites as they are expelled through the moving opening. This general definition encompasses a variety of methods such as the oldest dynamic casting process, known as Slip forming method or the newest Contour Crafting method (CC). The approach to extrusion scale differs between the two methodologies Charles F. Haglin, an engineer, invented the Slip forming in 1899 by the [10], and Lloret et al. used it in in 3DCP technology by extruding the entire cross-section of the geometry [7]. Professor Khoeshnevis introduced the CC method in 1995, which utilizes a surface shaping technology in the form of "squeegeeing" to create a smooth, relatively accurate edge surface or free surface geometry from extruded materials. Thus, the CC method provides shorter production times compared to the PEM method as well as greater precision in the shape of the extrusion geometry and required post-processing [11].

These printing methods were initially developed simultaneously with the printing material and equipment. Over time, more stringent requirements were placed on the print geometry in both its fresh and cured form. In order to maintain pumping simplicity and dimensional stability along the print path, increasing demands have been placed on the print's geometry in both its fresh and cured states[8]. These characteristics are highly sensitive to changes in printing compound composition, compound distribution, and printing device form. In general, fresh material specifications are divided into workability, pumpability/printability, buildability and yield time, with the most significant time intervals relating to mix production and lay-up. [5, 12]. Print track length and deposition time window (so-called open time) are key process parameters dependent on the print geometry include the. These factors then influence the overall geometry production time and the quality of the layer bond. Incorrect timing can lead to so-called cold joints, compromising the integrity of the print structure when transferring the load in the cured state [3, 13].

In order to respond to the response of the material, the design of the machines previously used to 3D print cement materials has been changed to use robotic arms that have up to ten times the speed of movement and six degrees of freedom compared to gantry machines [3].

Robotic arms are suitable for rapid production of thin-walled parts and complex spatial geometries and develop the full potential of 3D printing for printing complex and large structures in print space. A milestone has been the sub-additive manufacturing using the so-called CORBELLING method. This method is generally known in traditional architecture – it’s used to create a support structure by gradually stepping out layers of bricks or stones until they meet at an angle, allowing the weight of the structure above to be distributed more evenly. In the context of 3DCP corbeling is achieved by gradually printing each layer of the structure slightly further out than the previous layer, creating an overhanging structure that becomes increasingly self-supporting as it is built up. Corbeling is a useful technique in 3D printing as it allows for the creation of more complex geometries without the need for additional support structures, which can be time-consuming and difficult to remove.[14, 15].

The 3DCP technology area has three sub-areas (Figure 3-1), which are necessary for the specification of the main objective of the thesis and for the definition of the scientific questions and hypotheses. The current state of the art deals with studies dedicated to the manufacturing process using 3DCP technology with robotic arm and conventional machines. It also focuses on the parameters of the printing material and the behaviour of the printed and, marginally, cured geometry. The aim is to map the knowledge gained about the properties of the material in the 3D printing process and large-scale printed structured parts.

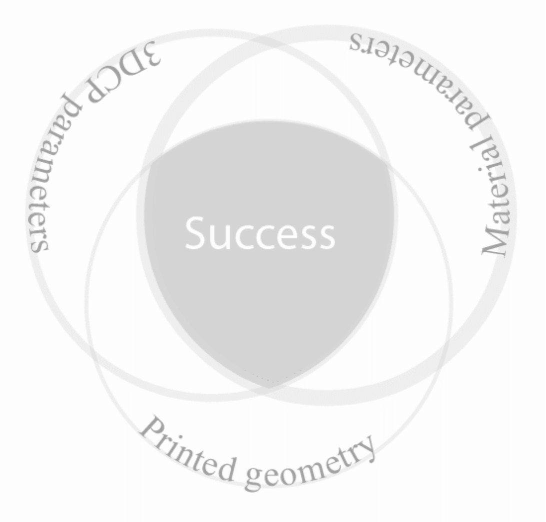


Figure 2-1 Set of fields of 3DCP leads to success.

2.2 MATERIAL AND PROCESS PARAMETERS OF 3D PRINTING

The mechanical properties and deformation characteristics of fresh cement mixture suitable for 3DCP has been analysed in the study [16]. Several approaches to ascertain the fresh behaviour of the mixture were investigated. The main goal of the study was to understand the principle of buildability of the 3D printed mixture and to improve it for printing large-sized parts without the use of chemical additives. Initially, the deformation interface and the collapse of test specimens of cylindrical geometry during the compression test were verified through the software. As a result, the correlation between the optical measurement and the measurement using a laboratory rheometer was confirmed. Furthermore, the upward tendency of the occurrence of elastic and plastic deformation of the yield when using the NC admixture was confirmed. The authors of study [16] recommend adding chemical accelerators to the fresh cement mixture to improve the mechanical properties and increase the exposure interval. Thus, minimizing the likelihood of plastic deformations causing the impression to collapse. The rheological parameters of the cement mixture suitable for 3DCP were investigated from the point of view: concrete flow, yield strength, viscosity, modulus of elasticity, critical deformation, structure growth rate and particle migration respectively. The authors of the many studies agree that the material must be pumped from the reservoir to the nozzle using a hose. This fact gives the requirements for initial liquidity (pumpability) [17]. From the point of view of the pumpability of the mixture, the yield strength and viscosity of the material must be as low as possible. Cementitious materials behave as Bingham fluids with thixotropic behaviour and thus begin to flow if they are subjected to a stress higher than the yield strength [18].

The flow of these liquids is accompanied by characteristic events, which include the migration of larger particles towards the central axis of the pipeline and the migration of smaller parts together with water towards the walls, where they form a so-called lubrication layer. The geometry of the pumping device (pipe, hose, transitions, nozzle...) is also important. Specific flow typologies can arise due to different geometries. Material slip occurs in a narrow zone at the interface with the pipe, hose or nozzle, while the volume of material does not slip and forms a so-called plug flow [19].

Only fine particles and water slide in the lubrication layer. It is reported that the ability to pump or extrude a given material depends more on its ability to form a lubrication layer than on its actual bulk rheology [17, 20].

For the evaluation of the material characteristics and deformation characteristics in terms of 3DCP technology, the conventionally known methodology has adopted and the mechanical properties and deformation characteristics of a fresh cement mix suitable for 3D printing technology has investigated firstly in the years 2018 [16]. A simple tensile test was used to determine the yield strength of the fresh cementitious material as in the previous study. The test bodies (TB) used for the tests were in the form of a cylinder with a diameter of 70 mm and a height of 140 mm. The size of the TB was chosen with respect to the maximum aggregate size so that diagonal shear would occur. The five test bodies were subjected to vibration immediately after casting and were tested at the time intervals shown in Figure 2-1 (b). Yield strength, viscosity and the ability to form a low-viscosity lubrication layer change drastically with the water content of the mixture. Mixtures with a low water content therefore exhibit a high yield strength and high plastic viscosity. They also show a low ability to form a lubricating layer. Even if this is the case, the local viscosity in this layer can be extremely high and can lead to high pumping pressures. However, if the nozzle is equipped with a screw pump or mixing screw in the nozzle, the laminar conditions for shear are not met. In the rectangular die, the shear stress is concentrated at the interface and thus a clean extrusion process occurs. So, the accumulated material does not slide onto the printing pad or the next layer. The extrusion of the material is in the form of a rigid and homogeneous trace and is not significantly deformed [26]. In contrast, with a nozzle of circular cross-section, shearing of the material occurs before deposition. Shear forces are transferred to the previous layer or printing pad. As the flow slows and material accumulates, the yield strength is exceeded. This results in plastic deformation until the shape is stabilized [21].

Shakor et al. were based on the findings of previous studies, where the authors agree on the dependence of the exit nozzle geometry and the rate of layer subsidence. The cause of subsidence is the effect of the weight of the material and the effect of the pressure of the extrusion of the applied layer. The characteristics of material extrusion depend on the geometry of the nozzle. In the case of nozzles with a rectangular cross-section, the pressure forces are evenly distributed over the entire contact surface of the layers. With circular nozzles, this contact area is smaller, resulting in greater deformation until the yield width and height limits stabilize. The rate of deposition of the layer with a rectangular cross-section has a linear character, whereas it does not with a nozzle with a circular cross-section. This can cause the Mohr-Coulomb criterion to be exceeded more quickly and the print collapses. The difference in width for nozzles of rectangular shapes was 1.15 to 2.28 mm greater than the reduced width, which approximately corresponds to the width of the nozzle and thus the required width of the printed track. For nozzles with a circular cross-section, this difference was 2.35 to 3.85 mm. For printing multiple layers, it is more appropriate to use a nozzle with a square or rectangular shape due to less deformation and change in the dimensions of the printed layers [22].

Perrot et al. published a study where specimens printed by a rectangular nozzle showed an order of magnitude lower incidence of voids and cracks due to less trace deformation at yield. This results in the formation of larger contact areas between the layers in the horizontal and vertical direction, while maintaining the laminar plug flow of the cement mixture and improving the overall stability of the printed track. Furthermore, hardened objects show higher compressive strength [23].The rheological properties of 3DCP can be summarized as followed paragraph. The output nozzle's shape has a direct impact on the extrusion's stability during 3D printing. In particular, a nozzle with a rectangular cross-section is preferred because it enables the printing of stable structures free of inappropriate deformations. The choice of cross-sectional shape is dependent on the maximum particle size of the printing material's aggregate. For optimal performance, the cross-section ratio of the nozzle is recommended to be either 1/3 or 2/3, depending on the predominant proportion of aggregate used in the mixture. In addition, the rheological criteria for attaining the ideal printed geometry are based on the Mohr-Coulomb criterion, which assists in determining the optimal printing conditions.

In the process of 3DCP of cement materials without reinforcement, undesirable phenomena always occur in the form of deformation of the printed geometry and its subsequent collapse. This phenomenon is caused by the weight of the material deposit and its rheological properties. There are several approaches to reinforce the fresh cement mixture during 3D printing [24]. Individual approaches are discussed in the following subsections.

2.3 STRATEGIES OF COMPLEX GEOMETRY PRINTING

During the 3D concrete printing process is the most crucial the interface bond strength, which is the most important due to homogeneous structural integrity.

Nerella et al. investigated the bonding behaviour of the printed layers with respect to the mechanical properties for two materials. The material labelled C1 contained only one binder, namely Portland cement. The binder of material C2 contained 2 components, pozzolan and fly ash. The layering was carried out at three-time intervals: 2 min, 10 min and 1 day. The first time defined the shortest mixture yield time, the second time demonstrated the standard layer extrusion time when printing large size parts, and the last time represented the print break. Both mixes were fine-grained concrete, where the maximum aggregate size was in the form of river sand: 2 mm (more about the mix in the study). The nozzle size was (30×18.72) mm, with extrusion dimensions ranging from 30-31 mm in height and 19-20 mm in width, and the printing speed was 75 mm/s. They used the destructive compression and three-point bending test method to determine the strength of the extrusion. The tests were performed on bodies where the layup was carried out at different time intervals. The aim was to determine the dependence of the layup strength on the deposition time of the cement mixture [25]. Mix C2 showed a relatively slight reduction in flexural strength of 9.9%, 14.1% and 23.1% for specimens produced at 2 min, 10 min and 1 day, respectively. The specimens were subjected to a simple tensile test. As a result, it was confirmed that the simple tensile test cannot adequately quantify the interlaminar strength. However, it can serve as an indicator of the stable anisotropy of the specimens when the tests are performed in different directions.

Le et al. investigated the hardened properties of a high-performance printing concrete, where the tensile bond strength has shown variable results with coefficient of variation 0.75. All the specimens fail at the interface area between older and younger concrete, when the delay time between layers was 15 min. With growing gap, the average bond strength decrease, where at the samples with time gap 30 min, the bond strength was 55% and in 7 day time gap 77% lower than control. However the values of interface bonding decrease in time, the time area of interest is in early ages, where the values exceeded the Concrete Society recommendation of a minimum bond strength 0.8 MPa [26].

Other authors focus on structures used in additive manufacturing, not only in the construction industry. The author looked at the reinforcement, but also at the structure of the individual elements of the structure. The advantages listed are time savings in construction, lower costs, higher worker safety, better quality and reliability, material savings and thus sustainability. With regard to material savings, recent studies have shown that digital fabrication is able to provide environmental benefits when applied to complex structures where the fabrication of secondary structures such as formwork can be eliminated [7, 27, 28].

Domenico et. al designed a hybrid structure for his experiment consisting of a main reinforcing structure and a support structure in the form of topologically optimized cells. The topological optimization was based on Finite element method (FEM) analysis, where the external forces on the beam structure were simulated [28].

Podroužek et. al in the first part of their study dealt with the current approaches and methods for modelling structured concrete columns. In the second phase, he describes the transition between traditional uniform shapes and organic structures with an example of a real structure. The paper also discusses the design and evaluation of structural members of organic forms, including the design of the actual structure of the structural member [27].

A beam loaded by linear forces was used for topological optimization. This beam was topologically optimized in IDEA StatiCa. The optimization was carried out at three levels, namely at the structural level, at the internal spatial structure, where the author proposes the use of surfaces with minimum surface area, and at the printed material. To design these structures, the additive manufacturing rules for 3D printing by FDM were used, where all walls must be at a maximum angle of 45°, so that they are printed without supports. For large-scale applications in the construction industry, concrete can be used as a printing material. For large-scale applications in the construction industry, concrete can be used as a printing material. However, the author also points out the limitations arising from the nature of the cementitious material itself.

It is also pointed out that for smaller structures it is possible to use unreinforced cementitious material, but for large structures reinforcement with, for example, steel or polymer fibres is necessary. In order to verify the properties of the minimum-surface areas, several test bodies were created in the form of cylinders filled with minimum-surface structures. These test bodies were then subjected to a destructive compression test, where the strain dependence on load was monitored by the optical DIC (Digital Image Corelation) method.

Gosselin et. al focused-on printing strategies for large-scale 3D printing in architecture, where the authors discuss in detail the differences of using the so-called tangential continuity layering method (TCM). This method is suitable for AM in the construction industry for printing large-scale parts. The print trajectories are in fact three-dimensional. The principle is therefore non-planar printing of layers with locally varying thicknesses. This strategy can better exploit the geometric possibilities and potential offered by 3D printing. The main advantage is keeping the contact of the surfaces at a constant distance. This approach avoids the formation of gaps between layers due to the FDM method, whose equivalent in the construction industry is the PEM method [29].

Layers obtained by TCM can therefore be mechanically loaded in the same way as conventional masonry arches, i.e., in compression, perpendicular to the plane of the layer interface. The FDM method maintains the height of the layers but the contact area of the layer changes (marked in red), whereas the TCM maintains the contact area of the layers and changes the height of the layers. From a structural point of view, TCM yields a more efficient force distribution.

Borg Costanzi and colleagues followed up the use of FDM (equivalent to PEM in the construction industry) and TCM printing methods, mainly focusing on hybrid curved surface production using PEM combined with curved surface casting. They first investigated the minimum radius of geometry allowed by 3DCM technology with the CC method. Thus, they investigated the process parameters of the print head as a function of material yield. Significantly, the maximum tilt of the print head and the curvature of the print trajectory limited by the minimum radius as a function of the stability of the printed trace were determined. The Rhinoceros software environment with the Grasshopper plugin was used to generate the geometry and prepare the print trajectories [30].

Maintaining the mechanical properties of the optimised design even at a lower weight. Mechanical properties are based on optimization at three levels: structural, internal spatial structure and material level. It is possible to apply 3DCP technology to produce topologically optimised parts based on environmental conditions (ultimate strength, direction of forces, temperature, airflow, location of utilities). The trend of printing structures and structured parts is beginning to emerge, and the authors recommend comparing standardized test bodies with bodies with internal structure.

The authors of the studies dealt with a combined form of production, using first subtractive and then additive manufacturing [14]. The authors followed the methodology of a previous study by Borg et al. For subtractive production, they used granular recycled concrete filled with aggregate as a substrate. This substrate was then rolled out to form a mould for the structure to be printed. For the 3DCP structure, a PEM method was used where the printed material was in the form of a cement paste with plastic fibres. The authors used software equipment in the form of Rhinoceros and Grasshopper plug-in.

The studies by Krejcik et al. and Lindmann et al. dealt with additive rules for 3D printing using FDM, TCM and spraying concrete using a robotic arm. The studies differ in the material used, in the case of the study by Petr Krejčiřík et al. it was thermoplastic printing where four experimental prints were made using a robotic arm. With samples I and II in the horizontal XY plane and with samples III and IV in the vertical XZ plane. In both planes, printing was tested with and without tilting the print head. Both samples printed without tilt failed to print with an offset of 40° and both tilted samples printed successfully. It can be concluded that tilting the print head in the direction of the weaving wall increases the possibility of printing larger overlaps of material without support [31]. The same methodological approach is presented in the study by Lindemann et al. This study represents the first experiments of an ongoing research in which the possibility of a gradual change of the printing plane is investigated, allowing a smooth transition from vertical to horizontal surfaces, thus making available a new technology for printing complex geometric shapes from cementitious mixtures [32].

In both studies, the authors agree that the TCM printing method in combination with the tilt of the print head provides the possibility of printing with a larger overhang. In both cases, they were able to print geometries at an angle of 60° from the vertical axis using different materials. In a study focusing on concrete (Lindemann), a structure up to 1 m high was printed in just 15 minutes, with the same 60° nozzle orientation deviated from the vertical axis and resulting in a horizontal overhang of 0.4 m. At this point, the two parts of the structure separated from the outer edge and the experiment was stopped. It should be emphasised that this was a 3DCP technique with concrete application by nozzle and compressed air. The authors state that this technology is capable of breaking down the cold joints of the layers, but there is a likelihood of higher porosity.

3 SUMMARY AND CONCLUSION OF STATE OF THE ART

3.1 EVALUATION OF MATERIAL CHARACTERISTICS WHILE 3DCP

Based on the 3D printing limits of cement-based materials declared by the study of Domenico Asprone and R.J.M. Wolf, it is generally necessary to modify any cement mixture to have the best possible rheological and mechanical properties without adding additives and reinforcing elements [33][28].

Thus, it is also possible to draw on the study of Yiwei Weng [34], which aims at good workability and load-bearing capacity of cementitious materials for 3D printing. The study generally addresses the parameters of the fresh cement mixture that significantly affect 3D printing. Particularly important are the buildability, rheological properties, and printability.

According to Perrot et al, the 3DCMP buildability is corelated with the static yield strength, with the individual quantities corresponding to Bingham's plasticity model. The Bingham plasticity model describes the rheological characteristics of cementitious materials [19].

The grain size has significant impact on the rheology of the mixture, which can be optimized using Fuller-Thompson theory. By applying this theory, a proportionate representation of sand grain size in the mixture can be attained when the contact surfaces of the individual grains interact. In other words, the optimal grain size ratio will maximise the utilisation inter-grain space. This is expressed by the compaction coefficient. The treatment result in a densification of the entire mixture, which improves shear stress transmission. When a certain threshold shear stress is exceeded (energy difference between static and dynamic shear stress = flow limit) and its duration is increased, the apparent viscosity of non-Newtonian fluid decreases, thereby allowing the fluid to flow [34].

The material's printability is a reflection of the working pressure during pumping, which is closely related to the parameters of the Bingham plastic model. Thus, for 3D printing of cementitious materials, a low plastic viscosity of the mixture on the pipe wall is generally required to achieve a lower working pressure, resulting in good extrudability, i.e., pumpability.

3.1.1 PUMPABILITY

Pumpability describes how easily the fresh cementitious composite is transported from the pump through the hose to the extrusion nozzle [35]. During this phase, numerous issues arise, one of which is segregation of particles in the hose, which causes clogging of the hose or the entire printing device, including the nozzle outlet. Particle segregation is influenced by the mixture's composition, its age, and homogenization during mixing process prior to pumping [36]. In 3DCP technology, various pumping machines and paste-containing mixtures are utilised to efficiently form a lubricating layer (LL) on the inner surface of a pipe or hose wall. The efficient formation of LL ensures good pumpability of a mixture without segregation at low pressure values [37].

3.1.2 WORKABILITY

The 3DCP process is sensitive to delays in the deposition of layers, which must form a homogeneous structure. There is a higher possibility of "cold joints" between layers during 3D printing, which is depended on the material’s solidification behaviour (Green-strength), specifically hydration process. Additives such as an accelerator, a solidification retarder, or plasticizers that modify the ductility and rigidity of a mixture can affect the workability, also known as open time, in 3DCP technology. Even with an optimised printing compound, deformation due to layering and gravity occurs in these processes [38]. This is essentially the interval of time when the cementitious composite initiates solidification and when the solidification process ends. Where Vicat's apparatus is used to measure the workability of fresh cement mixture [39]. In order to globally bond the layers, create a homogeneous joint and achieve the highest achievable yield strength (Green strength [40][16]) during layering and strength values during curing of the printed part, it is necessary to determine the open time of a mixture and narrow it to prevent cold joints [41]. Consequently, there is a nearly imperceptible gap at the layer interface.

3.1.3 BUILDABILITY

According to layering of fresh mixture, buildability investigates the post-deposition behaviour of print mixture and focuses on rheological parameters that are the inverse of pumpability/extrudability, where a static yield strength is required to resist flow [42]. It is generally defined as the resistance of deposited material during the dormant period against deformation when loaded by the mass of the previous layers [35][24]. As the height of building increases, so does the hydrostatic pressure increases, and the layers compress under their own weight [43]. There are two collapse modes to consider during printing. The plastic collapse of the first layer can be described as the global mass of the printed structure increasing linearly with printing time and the lower layers are subjected to gravity-induced stresses caused by the upper layers – plastic deformation can occur [44]. It relates to the so called “green strength” of the material, in which a high static yield strength to resist the flow of material is required after layer deposition is applied [42]. The mechanism of self-weight bearing after mixing or compaction is associated with a combination of inter-particle friction and cohesion, similar to the behaviour of soils, for which the Mohr-Coulomb yield criterion is used to characterise the such properties [40]. To determine the Mohr – Coulomb yield criterion, the Shear Box Test (SBT) is used, and to investigate the rigid behaviour (Young modulus) of fresh concrete the Unconfined Uniaxial Compression Test (UUCT) is used [45]. Early age mechanical testing of the mixtures reveals inherent variability, which can result in significant differences in buildability, where the sensitivity of buildability is dependent on material characterization (Mohr-Coulomb yield criterion, Youngs modulus). It leads to the use of simulation tools to define the mixture's boundaries prior to the real print in order to reduce the amount of waste that could occur [46].

3.1.4 LAYER ADHESION

The low strength between the printed layers is the weak point of any printed concrete structure. It is possible for defects to develop between the extruded layers, which act as stress concentrators. Moisture content of the concrete mixture affects the strength of joints between concrete layers during printing. In 3DCP, the layers are still in a fresh state, unlike when concrete is cast into a mould. Therefore, it is necessary to investigate the behaviour of the contacts between the layers. The strength between layers is affected by the adhesion of the materials between the extruded surfaces, so it is a time interval during the deposition of each layer. This duration is referred to as open time (in sec. Workability) [47].

Based on the research presented in the review, if no cold joints are formed during the layering process, then in destructive tests (three-point bending test, uniaxial tension test), that load the printed specimens according to the sense of orientation, the layers exhibit a similar trend even when using a different mixtures [48]. In studies, the uniaxial tension test is used to determine the adhesion of the layers.

Nevertheless, it is crucial to acknowledge that the accuracy of this test is contingent upon meticulous sample placement. Incorrect alignment can lead to 'interlocking', which can significantly distort the results. The adhesion of the layers is dependent on the accurate determination of the fresh cement mixture's workability time using the Vicat test. A significant influence on the adhesion of the layers is the so-called moisture effect related to the formation of pores, their size and migration in the layers and throughout the volume of the printed body. Through direct tensile stress the large variability of results can be occurred, where the acceptable bond strength of a print layer higher than 0.8 MPa is recommended [26].

3.1.5 PRINT STRATEGY

In general, the 3D printing strategy is based on the geometry and the generation of print trajectories in a programme that processes the input as modelled geometry. The generation of print trajectories is dependent on the printing strategy methods employed; for 3DCP technology utilising the CC method with a rectangular nozzle and robotic arm it is advantageous to use the TCM printing strategy method [29, 32, 49]. Notably, it is standard practise to maintain a constant layer height when 3D printing. As a result, the distance between the nozzle and the working surface increases, resulting in a change in the shape of the extruded layer, which may have an effect on its adhesion. This condition worsens with each successive layer, leading to inhomogeneous deposition of more mass (over-extrusion) and eventually to collapse of the printed structure [16, 33, 35]. This must be taken into account when creating trajectories. The generation of trajectories depends on the printing device used. As stated previously, the active printhead for processing the higher aggregate fraction is comprised of a screw extruder with a pull-in function. This feature is required for printing more complex parts and structures without continuous trajectory generation.

Thus, it is possible to print complex structures by varying the layer extrusion timing within the body volume [30, 48].

3.1.6 REINFORCEMENT

The after mentioned information’s leads to the solution of the cement mixture problem, but not to the enhancement of its mechanical properties and geometric stability during the 3D printing process. One of the disadvantages of 3DCP is the behavioural properties of the fresh mixture, which according to the majority of studies, makes it impossible to print spatially and shape-intensive structures or parts. It is desirable to reinforce this mixture with a suitable form of reinforcement in the form of fibres or additives and admixtures [16]. The choice of suitable reinforcement depends on the nature of the part to be printed, but for small structures it is advisable to choose additives in the form of admixtures and additives. For large structures subjected to bending stresses, it is advisable to choose geometric reinforcements in steel or fibre (glass, metal, plastic) [50][51].

In terms of pumpability, it is better to choose mineral admixtures that improve the viscosity of fresh cementitious material, where the scale of printed structure must be considered. For small construction print the large quantities of additive admixtures (plasticizers and hardening accelerators) and reinforcement fibres is needed. For larger structures, the large quantities of additive admixtures and fibres reinforcement (against the cracks during the hardening) is not needed, while the use of geometric elements in the form of steel or composite bars is needed to retain print stability.

3.2 EVALUATION OF PRINT GEOMETRY FORM

Additive manufacturing enables the production of previously unthinkable parts. Utilisation of topological optimization-based generative algorithms for conventional designs. The authors of studies on 3DCP technology highlight the obvious benefits of 3D printing manufacturing technology [50][27]. Printed structures are beginning to appear in the construction industry, but in most cases they serve only for demonstration purposes, which is due to the short development of this topic so far [6].

To investigate the material behaviour and determine its properties, its necessary to print simple bodies, especially cylinders, which are simple to simulate even for diagnosis of complex failure behaviour under layer loading [3][52]. The future of 3DCP technology is focused on two primary objectives. First is preserving the mechanical properties of the print geometry despite a reduction in weight. This depends on the shape form of the geometry, where complex structures based on topologically optimised geometry can be printed based on the experimental printing apparatus [53, 54]. The second objective is the purposeful design of structures for various environmental conditions.

Depending on the boundary conditions (ultimate strength, direction of forces, temperature, air flow and location of utilities), virtually any geometry of the printed structure can be designed [10].

4 AIM OF THE THESIS

4.1 THE ESSENCE OF THE THESIS

The essence of the dissertation is the adaptation of 3DCP technology for cement mixtures with aggregate fraction 8 mm. It is an applied research based on the results of the research project of the Technical Research Centre, solved with the industrial partner VIA ALTA s.r.o., and the Faculty of Civil Engineering of the Czech Technical University. The intended application is the additive manufacturing of high-dimensional, meter-scale, complex solids.

4.2 THE MAIN GOALS OF THE THESIS:

This dissertation seeks to clarify the behaviour of cementitious composites with a coarse aggregate fraction of 8 mm for additive manufacturing, specifically 3D printing by PME/CC methods, and to increase our understanding of this material for construction and architectural applications.

The objective of the doctoral thesis is based on three scientific questions, which are addressed in Chapters 2 and 3. For these scientific questions, working hypotheses to be tested during the course of the project were developed. To obtain adequate answers to the posed scientific questions and achieve the primary objective, the following sub-goals must be established:

- Research into the rheological properties of coarse aggregate concrete mixture.
- Determine the layer bonding of a printing mixture containing coarse aggregate up to 8 millimetres in size.
- Describe the layer bonding of print mixture containing coarse aggregate with size up to 8 mm.
- Determine the mechanical properties of print mixture containing coarse aggregate with a maximum size of 8 millimetres, based on its buildability, in its fresh state.
- Describe the mechanical properties in the fresh state of print mixture containing coarse aggregate with a maximum size of 8 millimetres in relation to its buildability.
- Determine the limits of print mixture with coarse aggregate with size up to 8 mm according to buildability.
- Define the limitations of print mixture with coarse aggregate up to 8 mm in size in terms of buildability. Development of experimental stand for UUCT (Unconfined Uniaxial Compression Test).
- Define a suitable combinations of process parameters for 3DCP technology.
- Development of the printhead for complex geometry printing from the mixture contains large aggregate up to 8mm.

4.3 HYPOTHESES AND SCIENTIFIC QUESTIONS

Q1 How do aggregate size fraction (8 mm), mix freshness, and application time affect the adhesion of the layer?

H1 The interface strength (adhesion) is related to the roughness of the surface, porosity, and evaporation of thin film of very fine particles on the upper surface of layer [55]*, in addition to interface roughness, it also can be depended on the aggregate.*

During the process of the deposition of a material with a higher fraction of coarse aggregate, there is a possibility that the roughness of the first-layer surface could cause air void locking due to the deposition of a second layer. The assumption is that with a large time gap, a large number of pores would be observed at the interface area and especially the larger voids occurrence close to the coarse aggregate grains is predicted. This would weaken the interface strength of a printed layers.

However the interface strength should follow the same trend as described by Le et al. [56] *and Sanjayan et al.* [47]*, where the strongest adhesion force for cementitious materials would be attained up to 15 minutes after the layer deposition.*

Q2 What effect does the coarse aggregate of 8 millimetres have on the development of green strength in comparison to the same material without coarse aggregate?

H2 The large aggregate fraction may be more resistant to compressive and shear forces, leading to prediction of an improved stability with a positive impact on buildability. In general, the presence of coarse aggregate in 3DCP is important because it increases the fracture mechanical properties of the hardening concrete and reduces the quantity of constituents that have a demonstrably high environmental impact and for which we have no appropriate substitute [2]*. In addition, coarse aggregate in fresh mixture can strengthen the mixture and increase its load capacity. The assumption from Mohr-Coulomb failure criterion is description of the failure boundaries of the isotropy material from the direct shear test (DST)* [57]*. Consequently, based on the response to normal and shear stresses, a linear development with an increasing tendency of cohesion can be anticipated for both materials, with coarse aggregate material exhibiting higher values. After evaluating the time evolution of compressive stress and Young's modulus. The same behaviour is predicted for the unconfined uniaxial compression test (UUCT),* *Q3 What is the impact of an optimized configuration of controllable parameters (print track dimension, print velocity) on the buildability of a cylindrical geometry printed using a cement mixture containing a larger aggregate fraction (8 mm) and waste reduction?*

H3 The buildability is an ability of a material to withstand its own collapse. There are two collapse modes to consider during the printing. The mechanism of elastic failure (Buckling failure) is characterised as the ability of a material to resist elastic deformation in the transverse and longitudinal directions, accompanied by a general instability of the geometry [24]. *The plastic collapse of the first layer can be described as the global mass of the printed structure increasing linearly with printing time and the lower layers are subjected to gravity-induced stresses caused by the upper layers, plastic deformation can occur* [44, 58].

The occurrence of these modes can be affected by controllable parameters – process parameters of 3D printing (print track geometry, print velocity) and by uncontrollable, difficult to modify and configure parameters – composition of material (material properties). The majority of studies have investigated the controllable parameters for circular (PEM print method) and rectangular (CC print method) cross-section nozzles. The use of a circular nozzle has proved to be unstable due to the higher level of requirements on structuration rate and elastic modulus from the buckling point [36].

The optimised configuration of controllable parameters should increase buildability while maintaining the uncontrollable parameters – material properties of a mixture with an 8 millimetres fraction of coarse aggregate. The majority of authors have observed this phenomenon when using cement pastes or mortars, but not when using a mixture with a larger aggregate fraction. Nevertheless, even with current 3DCP methods, a considerable quantity of waste is generated [52, 59]. *By adjusting the input parameters appropriately, the entire process can be streamlined and the waste associated with 3DCP can be minimised or eliminated* [60].

4.4 THESIS STRUCTURE

This thesis is composed of three articles in in journal with impact factor (Paper I, II, III) an in addition, one conference paper. The purpose of the first article [I] is to answer the first scientific question Q1: What is the effect of aggregate size fraction, freshness of the mix and application time on layer adhesion? Furthermore, the article examines the effect of moisture phenomenon between two layers of different concrete ages and investigate the open time of a mixture. The objective of the second and third articles is to respond to the second scientific question Q2, which asks what the effect is of using a rectangular nozzle (2:4 aspect ratio) in a cement mixture with a larger aggregate fraction (8 mm) has on the print stability of a simple geometry. The second article [II] addresses the characterization of the material in terms of processability, pumpability and buildability, resulting in an explanation of the material behaviour and its linear model, which serves as a foundation for the third article [III], which addresses the determination of process parameters in a digital environment. The thesis is linked to the research projects TH03010172, CK03000240 and FW06010034 which deal with additive manufacturing technology in construction.

I. VESPALEC, A.; NOVÁK, J.; KOHOUTKOVÁ, A.; VOSYNEK, P.; PODROUŽEK, J.; ŠKAROUPKA, D.; ZIKMUND, T.; KAISER, J.; PALOUŠEK, D. Interface Behavior and Interface Tensile Strength of a Hardened Concrete Mixture with a Coarse Aggregate for Additive Manufacturing. Materials 2020, 13, 5147.

   Journal impact factor: 3.4, Author's contribution 75%

II. VESPALEC, A.; PODROUŽEK, J.; BOŠTÍK, J.; MIČA, L.; KOUTNÝ, D. Experimental study on time dependent behaviour of coarse aggregate concrete mixture for 3D construction printing. Construction and Building Materials 2023, 376.

   Journal impact factor: 6, Author's contribution 80%

III. VESPALEC, A.; PODROUŽEK, J.; KOUTNÝ, D. DoE Approach to Setting Input Parameters for Digital 3D Printing of Concrete for Coarse Aggregates up to 8 mm. Materials 2023, 16, 3418.

   Journal impact factor: 3.4, Author's contribution 90%

5 MATERIALS AND METHODS

As stated in the preceding chapter, the focus of the PhD thesis is to fill a gap in the existing literature, referred to as a "white space," regarding the use of 3D printing technology with cement composite materials (as discussed in section 5.1). This entails the incorporation of large aggregates up to 8 mm in size to produce structures that resemble "real concrete." The identification of this white spot has led to the identification of several key challenges, which serve as the basis for the three scientific questions explored in the thesis. In an attempt, to answer these scientific questions, three hypotheses were examined. These hypotheses guided the development of the methods described in section 5.2.

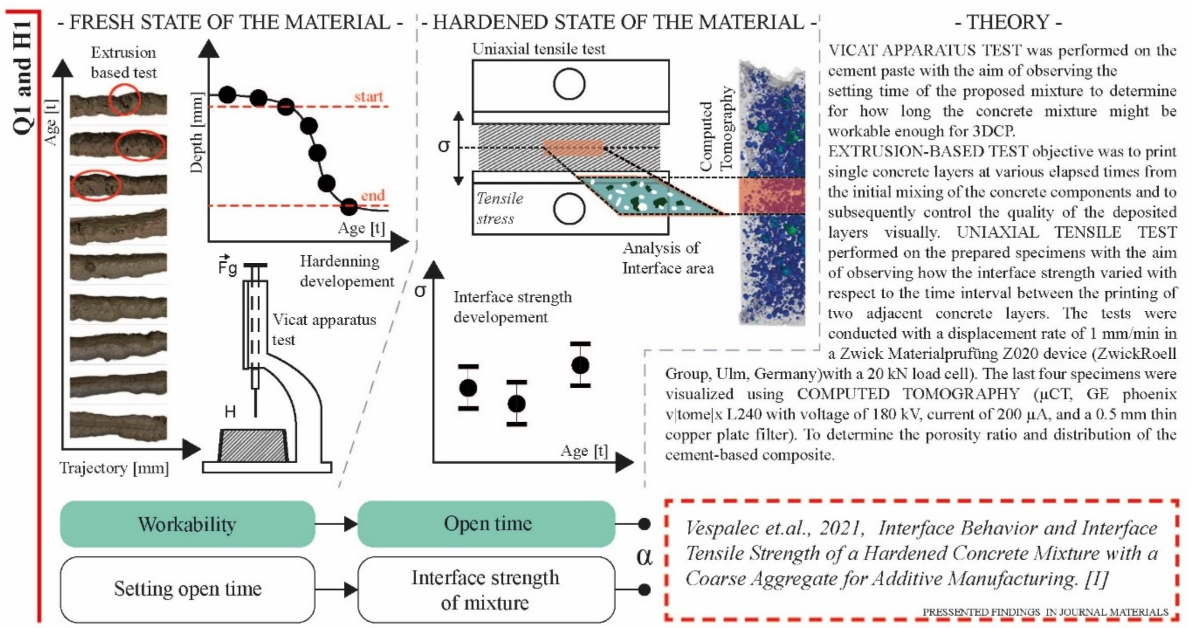
5.1 MATERIAL PROPERTIES

The doctoral dissertation uses material developed as a result of project TH03010172. Portland cement concrete was developed as a suitable additive manufacturing material and was shaped using 3DCP. The most important mechanical requirement for the cement-based composite was sufficient strength to withstand compressive stresses during early forming (cement grades according to European Standard-EN-197-1). The proposed concrete composition (in kilogrammes per cubic metre) was as follows:

- 400 kg Portland cement (OPC) conforming to the European standard, strength class 42.5 R.
- 1130 kg fine aggregate 0 – 4 mm.
- 300 kg coarse aggregate – crushed stone 4–8 mm.
- 100 kg Metakaolin, Mefisto L05, České Lupovské závody, Pecínov, CR , Czechia.
- 3 kg liquid solidification accelerator, Betodur A1, Stachema, Kolín, CR, Czechia.
- 285 kg of water.

5.2 MEASUREMENT METHODS

The methods of measurement used to test the hypotheses and scientific questions to be answered are described in detail in the three attached studies; however, to give the reader a sense of their general nature and application, a summary is provided within the context of the info-graphic workflow of the thesis.



- THEORY -

VICAT APPARATUS TEST was performed on the cement paste with the aim of observing the setting time of the proposed mixture to determine for how long the concrete mixture might be workable enough for 3DCP.

EXTRUSION-BASED TEST objective was to print single concrete layers at various elapsed times from the initial mixing of the concrete components and to subsequently control the quality of the deposited layers visually. UNIAXIAL TENSILE TEST performed on the prepared specimens with the aim of observing how the interface strength varied with respect to the time interval between the printing of two adjacent concrete layers. The tests were conducted with a displacement rate of 1 mm/min in a Zwick Materialprufüng Z020 device (ZwickRoell Group, Ulm, Germany)with a 20 kN load cell). The last four specimens were visualized using COMPUTED TOMOGRAPHY (μCT, GE phoenix v|tome|x L240 with voltage of 180 kV, current of 200 μA, and a 0.5 mm thin copper plate filter). To determine the porosity ratio and distribution of the cement-based composite.

Vespalec et.al., 2021, Interface Behavior and Interface Tensile Strength of a Hardened Concrete Mixture with a Coarse Aggregate for Additive Manufacturing. [I]

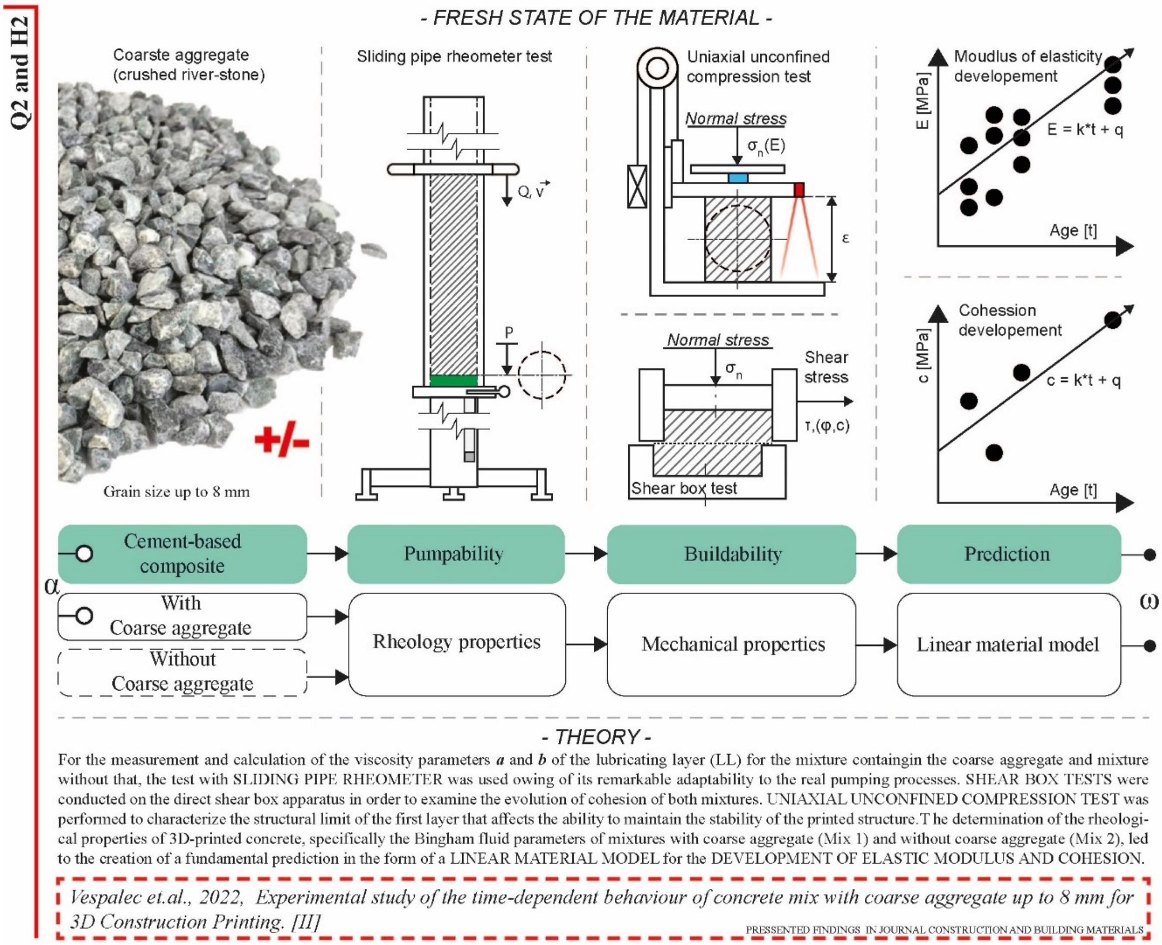
Figure 5-1 Infographic of research methodology leading to answering scientific questions Q1 [author].

5.2.1 Q1/H1 MEASUREMENT METHODS

Figure 5-1 depicts the group of methods used to determine the window of time during which a mixture is workable (open time) and the phenomenon of interface strength in deposited layers. The workability time is determined by the Vicat test in accordance with the European Standard on Test Methods for Cement (EN 196-3:2016) [39], in which a needle or roller is dropped into a sample of the material in the form of a cement slurry containing all of the mixture's components besides the coarse aggregate. By measuring the depth of penetration of the needle into the cement slurry test ring [25][44], this test establishes time of mixture setting initiation and completion. The extrusion-based test was designed to determine the workability of the mixture in terms of open 3DCP time, followed by a visual examination of the layer quality during the printing process. For further examination of the interlayer strength behaviour, the interface uniaxial tensile test, and CT scan analysis was performed in the Datos reconstruction software (GE Sensing & Inspection Technologies GmbH, Wunstorf, Germany).

All subsequent post-processing was performed in the software VGStudio MAX 3.3 (Volume Graphic GmbH, Heidelberg, Germany). In the authors' first study [I], these methods, data processing, and explanations are described in detail.

5.2.2 Q2/H2 MEASUREMENT METHODS



For the measurement and calculation of the viscosity parameters ***a*** and ***b*** of the lubricating layer (LL) for the mixture containgin the coarse aggregate and mixture without that, the test with SLIDING PIPE RHEOMETER was used owing of its remarkable adaptability to the real pumping processes. SHEAR BOX TESTS were conducted on the direct shear box apparatus in order to examine the evolution of cohesion of both mixtures. UNIAXIAL UNCONFINED COMPRESSION TEST was performed to characterize the structural limit of the first layer that affects the ability to maintain the stability of the printed structure.T he determination of the rheological properties of 3D-printed concrete, specifically the Bingham fluid parameters of mixtures with coarse aggregate (Mix 1) and without coarse aggregate (Mix 2), led to the creation of a fundamental prediction in the form of a LINEAR MATERIAL MODEL for the DEVELOPMENT OF ELASTIC MODULUS AND COHESION.

Vespalec et.al., 2022, Experimental study of the time-dependent behaviour of concrete mix with coarse aggregate up to 8 mm for 3D Construction Printing. [II]

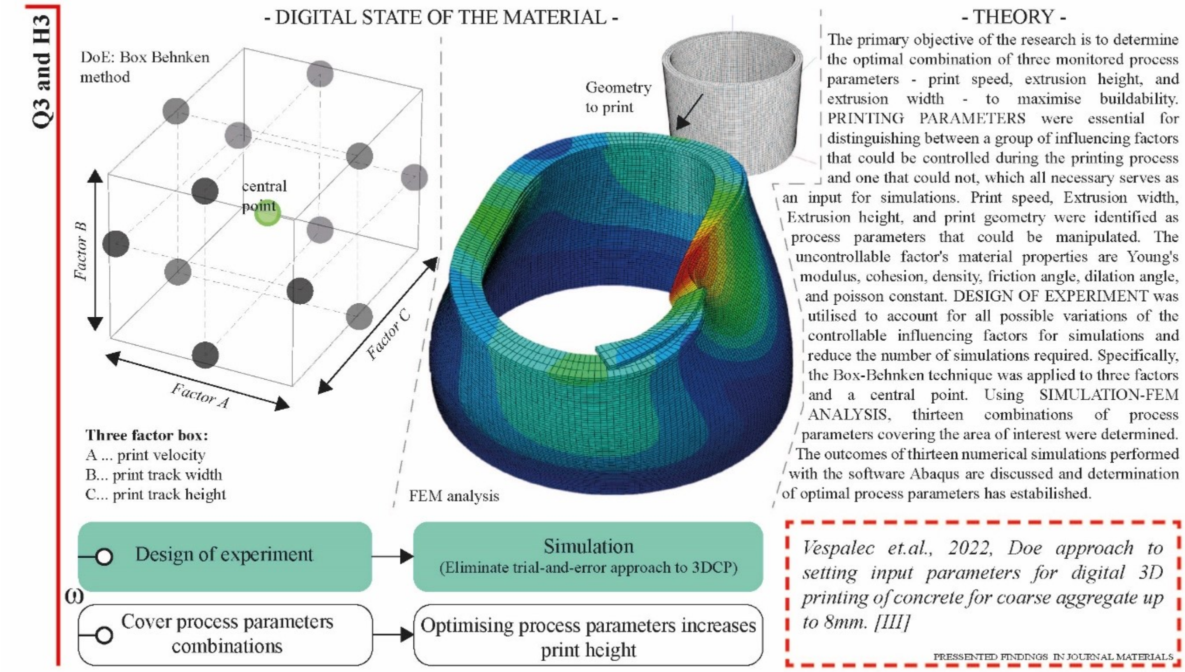
PRESSENTED FINDINGS IN JOURNAL CONSTRUCTION AND BUILDING MATERIALS

Figure 5-2 Infographic of research methodology leading to answering scientific questions Q2 [author].

Figure 5-2 depicted the group of methods used to determine the fundamental rheological and mechanical behavior of a material with and without coarse aggregate to derive material model equations and utilize the results of the author's previous research. The sliding pipe rheometer Schleibinger SLIPER (Schleibinger Geräte Teubert u. Greim GmbH) was utilized for the measurement and calculation of the viscosity parameters of a lubricating layer (LL) [37]. It related to the so-called "green strength" of the material, where a high static yield strength was required to resist the flow of material after layer deposition [42]. The mechanism of self-weight bearing after mixing or compaction was associated with a combination of inter-particle friction and cohesion, similar to the behavior of soils, where the Mohr-Coulomb yield criterion was used to characterize such properties [40].

The shear characterization of mixtures was carried out on a Direct Shear Test (DST) apparatus, following the standard of EN ISO/TS 17892-10. Uniaxial unconfined compression tests of mixtures were performed using an in-house-developed device, equipped with a Zemic L6D single-point load sensor, class: C3, and Baumer OADM 20U2472/S14C laser distance sensor. The signals from the sensors were connected to a DEWE-50-USB-8 processor unit. The acquired data were processed in DEWESoft 7.0 software. The evolution of mechanical behavior, particularly the development of Young's modulus, led to the formulation and generalization of fundamental equations for specific materials based on compressive strength. In the authors' second study [II], these methods, data processing, and explanations were described in detail.

5.2.3 Q3/H3 MEASUREMENT METHODS



The primary objective of the research is to determine the optimal combination of three monitored process parameters - print speed, extrusion height, and extrusion width - to maximise buildability. PRINTING PARAMETERS were essential for distinguishing between a group of influencing factors that could be controlled during the printing process and one that could not, which all necessary serves as an input for simulations. Print speed, Extrusion width, Extrusion height, and print geometry were identified as process parameters that could be manipulated. The uncontrollable factor's material properties are Young's modulus, cohesion, density, friction angle, dilation angle, and poisson constant. DESIGN OF EXPERIMENT was utilised to account for all possible variations of the controllable influencing factors for simulations and reduce the number of simulations required. Specifically, the Box-Behnken technique was applied to three factors and a central point. Using SIMULATION-FEM ANALYSIS, thirteen combinations of process parameters covering the area of interest were determined. The outcomes of thirteen numerical simulations performed with the software Abaqus are discussed and determination of optimal process parameters has estabilished.

Vespalec et.al., 2022, Doe approach to setting input parameters for digital 3D printing of concrete for coarse aggregate up to 8mm. [III]

Figure 5-3 Infographic of research methodology leading to answering scientific questions Q3 [author].

Figure 5-3 depicted a set of methods for inverse material characterization, with the primary objective of determining the optimal combination of three monitored process parameters—print speed, extrusion height, and extrusion width—to maximise buildability. Therefore, experimental planning methods, specifically the surface response design and Box Behnken methods, were utilised to reduce the number of possible process parameter combinations and the number of samples. Using the Minitab programme, the collected data were analysed. Utilising Abaqus simulation software, the variables were tested, resulting in the optimal configuration for the process parameters. These results were described in detail in the attached studies, particularly studies [II] and [III].

6 RESULTS AND DISCUSSION

The first experimental study [I] investigated the behaviour of a hardened concrete mixture containing coarse aggregates that were up to eight millimetres in size, which is somewhat unusual for 3DCP technology.

The resulting direct tensile strength at the interface of the layers was investigated for specimens produced within a specified time range at five-minute intervals from T0 to T20 settlement from the initial mixing of the concrete components. The interface strength was calculated using the engineering stress equation (Equation (1)). The interface tensile strength decreased gradually from 2.6 to 2.1 MPa as the time interval increased. This investigation also revealed that the time interval between the deposition of concrete layers influenced the mode of failure of the test specimens. The probability of specimen failure in the interface area was the most significant when using a delay time of 20 minutes with a 100% failure rate, then 15 min with an 80% failure rate, 10 minutes with a 40% failure rate, and 5 minutes with a 20% failure rate.

The size of coarse aggregates has no discernible effect on the uniaxial tension strength, but it can influence the propagation of cracks. The specimens failure areas were not smooth, as is typical for fine-grained concrete mixtures [47]. The fractured areas had rough surfaces, and visible coarse aggregate particles with sizes of 4 and 8 millimetres were fractured.

This indicates that the coarse aggregates penetrate the bottom layer, leading to in good layer connectivity. This is further supported by the two cracking patterns observed during specimens' failure. The first pattern of crack spread through a single surface due to a weaker interface strength, which required less energy compared to the second kind of pattern, in which the crack spread through multiple surfaces. This could be the result of a secondary flexure caused by a crack arrest by 4–8 mm coarse aggregates or local tension softening in the weakest part of the specimen [61].

The propagation of cracks proved to be related to the homogeneous arrangement of pores and aggregate (distribution and size) throughout the specimen, which was related to the effect of moisture and pore migration based on the setting stage of the concrete. Regarding the test specimens in which the material was layered 20 min after mixing, the layers did not bond perfectly due to solidification. This resulted in inhomogeneous distribution of pores throughout the specimen and an inhomogeneous distribution of overall hardness. These specimens fractured precisely at the layer interface during the Direct Tensile Test (DTT). The results of the extrusion-based test performed within the scope of the study [I] demonstrated that it was possible to print from the proposed mixture within 20 to 40 minutes of the initial mixing of concrete components, and the results obtained from uniaxial tension testing indicated that layer deposition was appropriate for 3DCP in terms of good adhesion between layers within a time interval from 5 to 10–15 minutes.

Follow-up second experimental study [II] focused on the evaluation of two mixtures without and with coarse aggregates with a size up to 8 millimetres. The primary objective was to investigate the evaluation of parameters such as pumpability/ extrudability and buildability and to develop the fundamental material model equations. This is the so-called Digital Concrete (DC), which consists of various time-dependent physical quantities, most notably modulus of elasticity (E) and cohesion (c). For the purpose of establishing these parameters, a Sliding test, Direct Shear Test (DST) and Unconfined Uniaxial Compression Test (UUCT) were conducted on the area of interest (open time of mixture) to establish these values.

The evaluation of pumpability for a both mixtures revealed the stable Lubricating Layer (LL) development between pipe and concrete mass at each age of the specimen, with the expectation of mixture with coarse aggregate at age T0. The LL does not develop properly as a result of the wet mixture, which causes the crushed coarse aggregate separation from the mortar and paste resulting in bleeding of the mixture [62], and exacerbated movement of the cement paste through the granular matrix [63]. This property causes a loss of LL and significant increase in plastic viscosity μ_i, leading to a higher effective viscosity at the interface layer, resulting in the lower pumping capability and an increase in the possibility of clogging the pipe.

At the same age, a similar effect was observed in mixture without coarse aggregate (Mix 2), whose plastic viscosity was lower due to absence of a crushed coarse aggregate. Between these two values is the area identified by the Sliper test as the region where Mixture with coarse aggregate (Mix1) clogging can be observed. On the basis of the literature, it can be concluded that a lower value of the parameter correlates with higher consistency classes [37], and mixture with coarse aggregate (Mix 1) at T0 can be classified as a higher consistency class with yield stress a = 150 Pa and plastic viscosity μ_i = 4,13 kPa at the interface of LL, which is not appropriate for the pumping process. The remaining ages of specimens of mixture with coarse aggregate have good profiles for pumping due to their lower $\mu_i$and higher a. At the same time, no clogging behaviour was observed in mixture without coarse aggregate that could cause problems during pumping. When comparing the results, mixture with coarse aggregate has a lower angle of each flow-rate curve, except at T0 age, where there is a higher risk of clogging due to the aforementioned inefficient LL formation causing a higher-pressure requirement to maintain a constant flow. For Mix 2, however, the P-Q curves exhibit similar characteristics at early ages, with LL efficiently forming. Thus, at early age T5, mixture without coarse aggregate is more resistant to clogging than mixture with coarse aggregate.

To evaluate buildability of a mixtures, its cohesiveness and compressive behaviour of need to be investigated. The cohesiveness behaviour was determined by evaluation of direct shear test, where the observation of different concrete ages revealed, that the friction angle values for each specimen age have a linear trend and a variable slope, resulting in a bi-linear cohesion behaviour. When comparing mixture with coarse aggregate and mixture without coarse aggregate, there are significant differences in slope, yield stress value, and cohesion, at the first four ages, with average deviation between slope of approximately 8°, yield stress value of 3.20 kPa and cohesion of 1.67 kPa, respectively. Mixture with coarse aggregate with coarse-aggregate exhibits an unanticipated behaviour, not yet described in the literature, in which the mixture with ages up to 60 min after wet mix shows a rapid decreasing trend in cohesion while the internal friction angle exhibits the opposite characteristics, and from 60 min onwards the opposite trend in cohesion and internal friction angle. The difference can be explained by a mobilisation of the reinforcement as in soils [64], whereas in our case the shear strength consists of two components: the shear strength of the cement and fine aggregate matrix and the tension mobilised within the coarse aggregate. The intrinsic mechanism of this rheological behaviour of the clay mineral (metakaolin) is dependent on the particle structure, where the lamellae of the clay minerals carry negative charges on their surfaces and positive charges on their edges, and thus a three-dimensional structure can be formed [65]. The viscosity of the structure increases due to the presence of flock, which locks suspended fluid in their structures, and the effective particle volume increases. When this fluid as a slurry is subjected to shearing, the three fundamental characteristics of shearing can emerge that depend on the specific surface area. Due to the above thixotropic characteristics with solid-like and liquid-like behaviour, this study is beyond the scope of research, but does inspire further investigation into this phenomenon in Bingham liquids.

The three experiments for each age range from T0 to T45 in 5 minutes intervals, provided sufficient data from the compression test to determine average stress-strain relationship of the mixtures. From the compression tests, the Young´s modulus of elasticity at 5% strain was determined for both mixtures and its limiting value for each age was within the linear range. This material characterization provides relatively accurate theoretical limits for deformations that could interfere with the printing process but are acceptable for 3DCP process.

The evolution of compressive strength in both mixtures revealed a significant difference between the values of maximum stress and its progression, which is known from the behaviour of bedding (stratification), where sedimentary rocks are composed of many layers (strata) consisting of different contents of soil, aggregate and water [66]. Both (mixture with coarse aggregate and mixture without coarse aggregate) stress-strain analyses revealed distinct stresses but comparable strain results. In general, mixture without coarse aggregate exhibited a transition from elastic to inelastic deformation development prior to specimen failure at strain rates around 0.2, which can be associated with the specimen's fragile failure. Mixture with coarse aggregate exhibited more ductile characteristics and deformed plastically in response to increasing stress, whereas the transition point between elastic and inelastic behaviour was less distinct but still evaluable.

The compressive strength and its average values for the younger samples (T0) of mixture with coarse aggregate are approximately equal to 8.15 kPa, whereas the strength linearly increases to 29.09 kPa for the older samples (T45). Mixture without coarse aggregate follows the same trend, with an initial average value starts at 36.16 kPa (T0) and an increase to 53.56 kPa (T45). The values of mixture with coarse aggregate fall within the same magnitude range as those reported by other researchers [38]. In the case of mixture without coarse aggregate, there are remarkable differences in the values. However, mixture with coarse aggregate was less rigid than mixture without coarse aggregate, and its values are still greater compared to other studies dealing with printable "concrete" at an early age [67–69]. The progression of the modulus has linear behaviour in both cases and the results are not disturbed by contact artefact or crack propagation. For mixture without coarse aggregate, the average value evolution begins at 0.24 MPa and increases to 0.70 MPa with a steeper slope compared to mixture with coarse aggregate, which begins at 0.0013 MPa and increases to 0.092 MPa [44, 70]. For these two mixtures a generalized equation for the time dependence of Young's modulus and, in particular, cohesion was determined.

The uncertainty and variability of the general quantification of basic mixture parameters based on experimental data prompted further study. The buildability can be significantly affected by the composition of the mixture and its measured material characteristics. There is a need to separate epistemic uncertainties from inherent uncertainties and to limit the trial-and-error procedure in 3DCP, which can be extremely sensitive to material and ambient properties. The use of a simulation tools is useful, but the proper material characterization is crucial.

The third [III] research study focuses on inverse material characterization, where the main objective is to determine the right combination of three monitored process parameters - print speed, print height and print width leading to maximization of buildability. Process parameters labelled as an influencing factor - controllable and their range were selected and numerically tested according to the literature review.

Utilising the Design of Experiment methodology, specifically the Box-Behnken method, all possible combinations of influencing factors, including printing speed, extrusion width, and extrusion height, were systematically investigated. This method effectively decreased the number of simulations to 13. The objective of the study was to improve the efficiency of the 3D printing process by predicting the compound's behaviour during printing using numerical simulations. The outcomes of these simulations enabled the calculated setting of controllable parameter values that, in theory, improve buildability. The investigation uncovered several significant findings. It highlighted the multidimensional obstacles faced by 3D printing of concrete, highlighting the need for practical solutions. The conventional trial-and-error method required significant amounts of energy, materials, time, and personnel. To address these obstacles, it was essential to reduce the number of simulations by implementing the Design of Experiment (DOE) method. Extrusion width emerged as a significant factor among the studied influencing factors, while other factors and their combinations were deemed statistically insignificant based on tests conducted.

At the = 0.1 significance level, the simulation input combinations produced combinations of process parameters that were correct from a theoretical standpoint.

In addition, the study revealed non-monotonic relationships between the printing process parameters, namely layer height, layer width, and printing speed. This finding highlighted the complexity of predicting the buildability of 3D-printed concrete, presenting a nontrivial problem. In addition, the majority of existing research studies lack a comprehensive material model that could serve as a new standard within the 3D concrete printing technology research community, as indicated by the study. The establishment of such a model would aid future research endeavours in conserving valuable human and material resources.

While it would be advantageous to include additional geometry and material parameters in the Design of Experiment, the large number of simulations that would result is currently infeasible. The ultimate objective is to precisely predict the behaviour of compounds and optimise the printing process.

Analysing the findings of the second research [II], it can be shown that when comparing mixtures with and without coarse aggregate, both composed in a volumetric unit of 1m3, the mixture including coarse aggregate exhibits a reduction of roughly 16% in the quantity of each material unit present in the mixture. The location of the most notable carbon dioxide emissions throughout the cement manufacturing process has been identified in previous research [71]. In this particular instance, the utilisation of coarse aggregate results in a reduction of about 62 kg of cement, so mitigating an equivalent of 52 kg of CO_2 emissions. By taking into account these global findings, the 3D printing of concrete can make significant strides towards more efficient and cost-effective processes.

7 CONCLUSIONS

The work presents novel findings that extend the knowledge of 3DCP technology to the use of a printing mixture containing large coarse aggregates up to eight millimetres in size. The results were presented to the global scientific community involved in 3DCP technology in the form of a publication that describes the anticipated applications, explanation of the behaviour and clearly defined printing parameters for a specific printing mixture. The principal contributions of the work can be summarized up as follows:

- CT analysis of porosity revealed the development of moisture effect phenomenon, which resulted in inhomogeneous distribution of pores throughout the entire volume, particularly at the layer interface areas.
- The extrusion-based test determined that the proposed mixture could be printed within 20 to 40 minutes of the initial mixing of concrete components.

- Based on the interface failure values and its evolution in correlation with the extrusion test led to the determination of the open time of the mixture from 5 to 15 minutes, where a decreasing trend of the interface strength from an average strength of 2.6 MPa to 2.2 MPa is evident.
- The presence of significant air voids or clusters of tiny pores in close proximity to the coarse aggregate grains may be attributed to the deposition and trowel operations. During these processes, the extended duration of layer deposition can lead to a greater occurrence of larger pores.
- Both mixtures can be pumped at any stage, except for the mixture containing coarse aggregate, which is not pumpable within the initial 5 minutes and has the potential to cause blockages in the hose.
- The cohesion of a mixture that includes coarse aggregate exhibits bi-linear behaviour, which is not anticipated.
- The Young's modulus of a mixture lacking coarse aggregate exhibits average values ranging from 0.24 MPa to 0.70 MPa, displaying a steeper slope in comparison to the mixture containing coarse aggregate, which ranges from 0.0013 MPa to 0.092 MPa.
- The material model for mixtures, both with and without coarse aggregate, has been established.
- The mixture containing coarse aggregate exhibited less rigidity compared to the mixture without coarse aggregate, and its values remain higher in comparison to previous studies investigating printable "concrete" during the early stages of development.
- The impact of material characterisation on buildability sensitivity is demonstrated by the variation in Young's modulus, as evidenced by a difference in print height of three layers within the range of measured standard deviation.
- The DOE – Box Behnken method was used to cover all the area of interest in terms of controllable parameters (print track dimensions, print velocity) with aim to find ideal set-up by using the numerical simulation of print process in Abaqus.
- Ideal set-up of controllable parameters (print track dimensions, print velocity) has found, that lead to larger stability when the collapse of geometry occurred due to elastic and plastic deformations. A correlation has been identified between the height of print and a controllable parameter, specifically the track width, denoted as factor B, which has shown a substantial influence.

7.1 HYPOTHESES EVALUATION

Q1 *Based on consideration of the hypothesis H1 the Deposition into Form method was developed to controllably produce layers of samples with precisely defined layer interface boundaries, further investigated by Computed Tomography. CT volumetric analysis showed sample heterogeneity caused by the layer deposition process, where the density of the top layer was lower than that of the bottom layer. Thus, the bottom layer was consolidated by the pressure exerted by the top layer. Large air pores were localised outside the layer bonding region and therefore have no direct effect on the interface strengths, as determined by an analysis of the pore size distribution and precise pore location. However, the occurrence of numerous large air pores in the interlayer area with increasing time has not been confirmed. However, the occurrence of the large air pores near the coarse aggregate developed by the entrapped air through the layering process has been confirmed. Thus, the localization of pores and large aggregate grains has significant effect on the development and propagation of crack in the specimen, where the crack spreading through single surface, especially at the specimens layered with time delay 20 min. In this specimen the lowest level of porosity at the interface area has recorded, which was not expected. It's evident, that in specimen, where the second layer was deposited in 20 min delay time the unexpected behaviour at the interface area is occurred and needs deeper investigation. The inhomogeneity with corelation of interface strength determine the open time of a mixture from 5 to 15 minutes, where decreasing trend of interface strength was evident from mean strength 2.6 MPa to 2.2 MPa.*

The hypothesis was not falsified.

Q2 Both mixtures in open time have proven to be pumpable. In the case of mixture with coarse aggregate, particularly at early ages T0, there is an increased risk of clogging of a pump pipe due to ineffective LL formation, as indicated by a significantly lower flow-rate curve angle. Significant differences have been observed in the cohesion of fresh concrete, with coarse aggregates resulting in negative cohesion slope in the early stage (up to 60 min.), and positive slope in the later stage; as a result, a bi-linear model was used to account for these findings. This phenomenon is unique as it has not yet been documented in the scientific literature. This behaviour necessitates more exploration into the underlying inherent mechanisms of shearing. The mixture without coarse aggregate exhibits a positive trend of cohesion development over time, which is in good agreement with the literature. Although the mix containing coarse aggregate exhibited a lower level of rigidity in comparison to the mix without coarse aggregate, the Young's modulus values obtained are similar to those reported in other research dealing with printable "concrete" at early mix ages. Mixture with coarse aggregate is more ductile than mixture without the coarse aggregate, which is more brittle, according to the fitted linear model, which also differs by approximately 15% in slope. Current simulation tools are limited to materials without coarse aggregates because they accept only positive trend in time dependent material characterization and cannot account for such behaviour. Despite the fact that the large coarse aggregate saves large amount of cementitious binder, the print mixture with coarse aggregate has a significantly worse development of Young´s modulus of elasticity compared to the mixture without coarse aggregate.

The hypothesis was falsified.

Q3 The theoretical buildability of a material with coarse aggregate was achieved during the 13 simulations of controllable process parameters (print track height, print track width and print velocity) with dependence on maximum print height of a simple cylindrical geometry.

To reduce the cost and time and to cover all the area of interest the design of experiment - Box Behnken method was used to reduce the possible combinations of variables. It resulted in a theoretically correct combination of process parameters leads to maximum print height 350.5 mm and based on the standardized effect at significance level $\alpha=0.1$ ($0.066 < 0.1$), the significant factor is the only extrusion width (factor B). Other factors and their combinations are statistically insignificant according to the tests. Digital twin concept for 3DCP is important as it eliminates the nowadays typical trial-and-error approach to 3DCP, which is prohibitive due to high number of parameters involved on the side of material, printing process and geometry.

The hypothesis was confirmed.

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9 AUTHOR'S PUBLICATIONS

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CONFERENCE PROCEEDINGS:

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CURRICULUM VITAE

Ing. Arnošt Vespalec

Education

- **2012 – 2017** Industrial Design, Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology
- **2017 – 2023** Doctoral study at Institute of Machine and Industrial Design, Faculty of Mechanical Engineering, Brno University of Technology.

Awards

- 2017 – A DESIGN AWARD – GOLD A DESIGN AWARD
- 2020 – A DESIGN AWARD – IRON A DESIGN AWARD
- 2020 – COMMEMORATIVE MEDAL FOR ACTIVITIES DURING THE COVID PANDEMIC

Teaching activities – seminars:

- YRP - Rapid Prototyping
- YA1 – Industrial Design 1
- YPA – Computer Modelling Alias
- ZM1 – CAD Modeling
- ZPP – Plastic Prototypes
- 3CD - CAD
- 1K, 2K – Engineering Drawing Fundamentals
- 4KC – Design and CAD
- VUC004 – Modeling and Visualization of 3D models
- BUA014 – Modeling of structures in 3D

Participations in scientific projects

- TAČR TREND: FW06010034 - Multi-component compound and application technology for 3D printing in the construction industry, Duration: 01.01.2023 — 31.12.2025

- SPECIFICKÝ PROJEKT FSI-S-23-8340 - Additive manufacturing of advanced materials and structures, Duration: 01.03.2023 - 28.02.2026

- SPECIFICKÝ PROJEKT: FAST-S-23-8318 - Computational support for process parameters of 3D printing and parameters of agent models of human movement, Duration: 01.03.2023 - 28.02.2024

- OP PIK APLIKACE: CZ.01.1.02/0.0/0.0/21_374/0026857 - Increasing the shear and bending strength of composite profiles by using 3D mat guiding and forming fixtures, Duration: 01.09.2021 - 31.05.2023

- SPECIFICKÝ PROJEKT: FSI-S-20-6296 - Research on mechanical and physical properties of structured material prepared by additive manufacturing, Duration: 01.03.2020 - 28.02.2023.

- FV 19 - 36 - Innovation of teaching of the subject Plastic Prototypes [ZPP] by continuity of production processes and technologies, Duration: 01.04.2019-31.12.2019

- FV 18 - 38 - Innovation of the Rapid Prototyping and 3D Digitalization [YRP] course to include robotic manufacturing in the form of robotic 3D printing, Duration: 01.04.2018 - 31.12.2018

- TAČR EPSILON: TH03010172 - Research and development of a 3D printer for use in the construction industry, Duration: 01.01.2018 - 30.06.2021

Patents

- VESPALEC, A.; DIAKOV, J.; Vysoké učení technické v Brně, Antonínská 548/1, 602 00 Brno, Veveří, Česká republika: *Tryska tiskové hlavy s nastavitelným obdélníkovým průřezem pro 3D tisk betonu*. 34622, užitný vzor. (2020) **Detail**

Products

- PŘIKRYL, R.; PALOUŠEK, D.; MENČÍK, P.; VESPALEC, A.; KRČMA, M.; ŠKAROUPKA, D.: Design obličeojvé polomasky pro výrobu termoformingem 01; *Obličejová polomaska realizovaná pomocí termoformingu*. FCH VUT v Brně, Purkyňova 464/118, Brno 612 00. URL: http://intranet.ustavkonstruovani.cz/project-documentations/edit/399. (funkční vzorek) http://intranet.ustavkonstruovani.cz/project-documentations/edit/399, **Detail**

- VESPALEC, A.; HURNÍK, J.; SLAVÍČEK, J.; KRČMA, M.; KOUTNÝ, D.; SIMON, P.; BARTÁK, L.; KREJČÍ, M.: Navaděč SQ50x50x5; *3D přípravek vyrobený technologií RPT určený k vedení rohože či tkaniny pro uzavřený profil SQ50x50x5*. GDP KORAL, s.r.o. Za mlýnem 5 666 01 Tišnov. URL:

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- VESPALEC, A.; HURNÍK, J.; SLAVÍČEK, J.; KRČMA, M.; KOUTNÝ, D.; SIMON, P.; BARTÁK, L.; KREJČÍ, M.: Sada navaděčů profilu V29; *3D přípravek vyrobený technologií RPT určený k vedení rohože či tkaniny pro otevřený profil V29*. GDP KORAL, s.r.o. Za mlýnem 5 666 01 Tišnov. URL: https://intranet.ustavkonstruovani.cz/file-download/get-project-pdf/463. (funkční vzorek) https://intranet.ustavkonstruovani.cz/file-download/get-project-pdf/463, **Detail**

- SIMON, P.; BARTÁK, L.; ŠKORPÍKOVÁ, Z.; KREJČÍ, M.; VESPALEC, A.; HURNÍK, J.; SLAVÍČEK, J.; KRČMA, M.; KOUTNÝ, D.: profil SQ50x50x5; *Profil uzavřeného průřezu vyrobený pomocí 3D naváděcích přípravků vedoucích rohože či tkaniny - SQ50x50x5*. GDP KORAL, s.r.o. Za mlýnem 5 666 01 Tišnov. URL: https://intranet.ustavkonstruovani.cz/FileDownload/getProjectPdf/464/. (prototyp) https://intranet.ustavkonstruovani.cz/FileDownload/getProjectPdf/464/, **Detail**

- SIMON, P.; BARTÁK, L.; ŠKORPÍKOVÁ, Z.; KREJČÍ, M.; VESPALEC, A.; HURNÍK, J.; SLAVÍČEK, J.; KRČMA, M.; KOUTNÝ, D.: profil - V29; *Profil otevřeného průřezu vyrobený pomocí 3D přípravků vedoucích rohože či tkaniny – V 29*. GDP KORAL, s.r.o. Za mlýnem 5 666 01 Tišnov. URL: https://intranet.ustavkonstruovani.cz/FileDownload/getProjectPdf/465/. (prototyp) https://intranet.ustavkonstruovani.cz/FileDownload/getProjectPdf/465/, **Detail**

- HURNÍK, J.; KRČMA, M.; VESPALEC, A.; SLAVÍČEK, J.; KOUTNÝ, D.; SIMON, P.: PAGNA-1.0; *Parametrický generátor naváděcích přípravků pro výrobu uzavřených kompozitních profilů*. Vysoké učení technické v Brně Fakulta strojního inženýrství Technická 2896/2 61669, Brno D5/463. URL: https://intranet.ustavkonstruovani.cz/FileDownload/getProjectPdf/466/. (software) https://intranet.ustavkonstruovani.cz/FileDownload/getProjectPdf/466/, **Detail**

Artistic outputs

- ŠKAROUPKA, D.; VESPALEC, A.: AUTOMATIC TRIMMER - XL. real: Stroje, nástroje a nářadí, Bez rozlišení státu, Bez rozlišení města, 01.08.2020 - 01.08.2020. (produktový a průmyslový design) **Detail**
- VESPALEC, A.: *Design krytu 3D tiskové hlavy na fillamentový tisk*. OPD ÚK FSI VUT v Brně, Česká republika, Brno, 01.02.2020 - 18.02.2021. (produktový a průmyslový design) **Detail**
- ŠKAROUPKA, D.; VESPALEC, A.: *Harvestor AUTOMATIC TRIMMER - L*. FSI VUT v Brně, Česká republika, Brno, 01.07.2019 - 01.07.2019. (produktový a průmyslový design) **Detail**
- ŠKAROUPKA, D.; VESPALEC, A.: *Adwitech WSM-2*. FSI VUT v Brně, Česká republika, Brno, 01.08.2018 - 01.08.2018. (produktový a průmyslový design) **Detail**
- VESPALEC, A.: *Termovizní Systém Workswell WIRIS*. real: Design spotřební elektroniky a strojů technické povahy, Bez rozlišení státu, Bez rozlišení města, 01.01.2017 - 01.01.2017. (produktový a průmyslový design) **Detail**

Language skills

Czech, English

Scientific activities

- Generative design
- Computational design
- Construction 3D printing

ABSTRACT

Today, the construction industry experiencing a period of rapid development. This is resulting in a massive production of greenhouse gas emissions (39% of global CO2 production) and an overexploitation of scarce natural resources leading to inevitable climate change. In this context, cement binders production represents one of the most significant environmental challenges. Despite extensive research being conducted on alternatives to cement, there remains considerable untapped potential in conventional building materials. The situation has led to a paradigm shift in the conventional construction sector, as inventive manufacturing techniques, including automation, are implemented. This predominantly involves additive manufacturing, particularly 3D printing in the construction industry, commonly referred to as 3DCP (3D Construction/ Concrete Print).

The dissertation examines the possibilities of using a mixture with coarse aggregate for 3DCP technology. This mixture has the potential to increase production efficiency and reduce the amount of other components, decreasing Portland cement usage and as a result, CO2. The thesis investigates a workability of a mixture containing 8 mm coarse aggregate and its effect on the printing parameters. Finding the optimal combination of process parameters for a mixture using simulation tools can improve its buildability, eliminate the need for a trial-and-error approach and thus rapidly reduce waste.

Analysis of the results demonstrates that the mixture containing coarse aggregate exhibits less buildability than the mixture without coarse aggregate. Although the mix containing coarse aggregate exhibited a lower level of rigidity in comparison to the mix without coarse aggregate, the Young's modulus values obtained are similar to those reported in other research dealing with printable "concrete" at early mixture ages. Further investigation using Design of Experiment (DOE) techniques resulted in a combination of 3D printing process parameters (print footprint dimensions, print speed) that were validated by the simulation software Abaqus. The utilisation of these process parameters has resulted in enhanced print stability, thereby improving the buildability of the printed object, and reducing the occurrence of deformation.

The mixture containing coarse aggregate effectively diminishes the requirement for additional mix material components by around 16%, resulting in decreased cement consumption and substantial CO2 emissions (equivalent to 52 kg per cubic metre of concrete). These factors, in conjunction with 3D printing technology in the construction industry, contribute to a sustainable approach to industrial production. This research contributes to a greater comprehension of the behaviour of cementitious composites with coarse aggregate sizes of up to 8 mm and their dependence on printing parameters.

The findings and outcomes are summarised in three peer-reviewed scientific articles.

ABSTRAKT

Stavební průmysl v současnosti prochází rychlým rozvojem. To vede k nadměrnému využívání omezených přírodních zdrojů a k vysoké produkci skleníkových plynů (až 39 % celosvětové produkce CO_2) vedoucí k nevyhnutelné změně klimatu. V tomto kontextu je jednou z hlavních environmentálních výzev výroba cementových pojiv. Přestože probíhá intenzivní výzkum alternativ k cementu, tradiční stavební materiály nabízejí mnoho nevyužitého potenciálu. Důsledkem situace je transformace tradičního stavebnictví v podobě využití inovativních metod výroby jako je automatizace. Jedná se především o aditivní výrobu, konkrétně 3D tisk ve stavebnictví, označovaný jako 3DCP (3D Construction/ Concrete Print).

Dizertační práce zkoumá možnosti využití směsi s hrubým kamenivem pro technologii 3DCP. Tato směs může přinést efektivnější výrobu, úsporu dalších komponent směsi, snížení množství používaného portlandského cementu a následné snížení emisí CO_2. Práce zkoumá zpracovatelnost směsi s hrubým kamenivem o velikosti 8 mm a její vliv na parametry tisku. Nalezení optimální kombinaci procesních parametrů směsi pomocí simulačních nástrojů může zlepšit její vystavitelnost, eliminovat potřebu přístupu pokus-omyl a tím rapidně redukovat množství odpadu.

Analýza výsledků ukázala, že směs s hrubým kamenivem vykazuje nižší vystavitelnost ve srovnání se směsí bez hrubého kameniva. I když směs s kamenivem nebyla tak rigidní jako směs bez kameniva, hodnoty Youngova modulu jsou srovnatelné s jinými studiemi zabývající se tisknutelným betonem v raném stáří směsi.

Vhodné kombinace parametrů procesu 3D tisku byly nalezeny metodou plánovaného experimentu a následně ověřeny simulačním nástrojem Abaqus. Tyto parametry vedou k minimalizaci deformací, vyšší stabilitě a vystavitelnosti tiskové geometrie. Směs s kamenivem tak snižuje potřebu ostatních složek materiálu směsi přibližně o 16 %, redukuje spotřebu cementu a dochází k významnému snížení emisí CO_2 – ekvivalent 52 kg na metr krychlový betonu. Tyto faktory v kombinaci s technologií 3D tisku společně podporují udržitelnější přístup k průmyslové výrobě ve stavebnictví. Tato práce přispívá k hlubšímu pochopení chování cementových kompozitů s hrubým kamenivem o velikosti až 8 mm a jeho závislosti na tiskových parametrech.

Získané poznatky a výsledky jsou shrnuty ve třech vědeckých článcích publikovaných v impaktovaných časopisech.