INFLUENCE OF ADMIXTURES ON THE PROPERTIES OF EXTRUDABLE CONCRETE FOR 3D PRINTING

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SCHOOL OF CIVIL ENGINEERING
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INFLUENCE OF ADMIXTURES ON THE PROPERTIES OF EXTRUDABLE CONCRETE FOR 3D PRINTING

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ABSTRAK

Kejayaan perindustrian pesat di banyak tempat di dunia mungkin disebabkan oleh teknik automasi yang menghasilkan proses pengeluaran yang lebih cepat dan lebih murah. Namun, dibandingkan dengan sektor perindustrian lain, industri bangunan konkrit tidak pada tahap yang sama. Untuk mengatasi masalah ini, percetakan tiga dimensi (3DP) mula diperkenalkan pada tahun 1987. Konkrit bercetak 3D adalah teknologi fabrikasi yang menggunakan teknik pembuatan berasaskan lapisan tambahan untuk mencipta komponen konkrit yang memerlukan kurang masa dan tenaga kerja tanpa menggunakan acuan. Walau bagaimanapun, konkrit bercetak 3D dalam industri pembinaan Malaysia dianggap sebagai teknologi baru. Oleh itu, kajian eksperimen ini akan memberi tumpuan kepada tingkah laku mekanikal konkrit bercetak 3D dan mencadangkan bahagian campuran yang sesuai untuk konkrit bercetak 3D. Dalam kajian ini, dua objektif utama disiasat; (a) Pengaruh campuran terhadap sifat mekanikal konkrit bercetak 3D, (b) bahagian campuran optimum konkrit bercetak 3D. Lima campuran konkrit telah disediakan dan diuji berdasarkan kebolehkerjaan, ketumpatan, kekuatan mampatan, kekuatan lenturan dan kekuatan tegangan berpecah. Kajian perbandingan sifat mekanikal 3DPC telah dilakukan. Manakala ramalan bahagian campuran optimum untuk 3DPC diperiksa berdasarkan sifat konkrit. Hasilnya menunjukkan bahawa sifat mekanikal 3DPC bertambah baik dengan penggabungan wasap silika tanpa melebihi keperluan. Bahagian campuran optimum untuk 3DPC ditentukan sebagai 3DPCS10 di mana jumlah wasap silika yang ditambah adalah 10%.

ABSTRACT

The success of rapid industrialization in many parts of the world may be ascribed to automation techniques that resulted in a faster and less expensive production process. However, compared to other industrial sectors, the concrete building industry has not been as mechanised or to the same degree. In order to overcome this problem, three-dimensional printing (3DP) was first introduced in 1987. 3D printed concrete is a fabrication technology that uses an additive, layer-based manufacturing technique to create concrete components which requires less time and labour without the use of formwork. However, 3D printed concrete in construction industry of Malaysia is considered as a new technology. Thus, this experimental study will focus on the mechanical behaviour of 3D printed concrete and proposed a suitable mix proportion for 3D printed concrete. In this study, two main objectives were investigated: (a) Influence of admixtures toward the mechanical properties of 3D printed concrete, (b) the optimum mix proportion of 3D printed concrete. Five concrete mixes were prepared and tested based on workability, density, compressive strength, flexural strength and splitting tensile strength. Comparative study of mechanical properties of the 3DPC was done. Whereas prediction of optimum mix proportion for 3DPC was examined based on the properties of concrete. The results revealed that the mechanical properties of 3DPC improves with incorporation of silica fume without excessing the requirement. The optimum mix proportion for 3DPC was determined to be 3DPCS10 where the amount of the silica fume added was 10%.

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LIST OF ABBREVIATIONS

BS	British Standard
3DP	Three Dimension Printing
3DPC	Three Dimension Printing Concrete
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
ALM	Additive Layer Manufacturing

CHAPTER 1

INTRODUCTION

1.1 Overview

The success of rapid industrialization in various regions of the world can be attributed to automation procedures that resulted in a faster and less expensive manufacturing process. However, the concrete construction sector has not been automated in the same manner and to the same extent as other industrial sectors. In numerous industrialized and newly industrialized countries, the conventional method of mixing and casting concrete in-situ has been largely superseded by pre-cast or prefabrication of building components in the previous two decades. However, greater automation in the construction industry may dramatically cut labour requirement and cost, construction time, improve quality, and reduce environmental effect. Therefore, three-dimensional printing (3DP) was first introduced in 1987 as a mean of rapid prototyping (Chua and Leong, 2014).

3D printing can be known as additive manufacturing (AM) or additive layer manufacturing (ALM) which is defined as "creation of items through the deposition of a material utilising a print head, nozzle, or other printer technology." It has been successfully used in a wide range of industries, including aerospace, automotive, biomedical, energy, and food (Wong et al., 2012). Generally, 3D-printing technologies used in the construction industry can be roughly classified into two major groups: powder-based and extrusion-based printing (Sanjayan et al., 2018). Despite its advantages of high printing resolution and geometric freedom, the powder-based technique builds each layer at a relatively slow printing speed, making it better suited to off-site and small-scale manufacturing, such as panel fabrication, permanent formworks, interior structures, and other building components.

Since the printing process requires a continuous, high degree of control of the material during printing, high performance building materials are preferred (Lim et al., 2011). Low to zero slump concrete is necessary to ensure little or no deformation in the bedding layers. Low viscosity concrete can be adopted for ease of pumping, but it will need to be treated with a chemical accelerator at the nozzle to set quickly once printed. Thixotropic behaviours are desired, material with a high static viscosity can undergo microstructural changes to become less viscous through de-flocculation, but once extruded and at rest, it rebuilds or re-flocculates to become highly viscous (Zhen et al., 2011). Therefore, the study focuses on studying the effect of different admixtures to the mixtures and obtaining optimal mix proportions to evaluate the printability of the concrete for 3D printing.

1.2 Problem Statement

Concrete is the most significant and popular human-made construction material globally in terms of volume. The use of concrete in the construction of buildings and other structures has various benefits. Concrete is frequently chosen because its low price, high strength, great durability, and high fire resistance. Nearly 25 gigatons of concrete are consumed annually across the world. It means that each person uses more than 3.8 tonnes of concrete annually on a worldwide scale. Concrete will remain in high demand as a main building material in the future. To ensure that concrete remains as a competitive building material, it is necessary to increase the sustainability of concrete structures.

According to the ASTM [2018], additive manufacturing (AM) is defined as: "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies". Additive manufacturing has been applied widely during the past three decades in a variety of industries, including aerospace and medicine. 3D printed concrete is a fabrication technology that uses an additive, layer-based manufacturing technique to create concrete components without the use of formwork. Concrete printing requires less time and labour to create than it does with formwork. Furthermore, 3D printed concrete is a sustainable building method with minimal environmental effect.

However, 3D printed concrete in construction industry of Malaysia is considered as a new technology. The influence of combination of admixtures on the properties of extrudable concrete for 3D printing has not been extensively explored. Thus, this experimental study will focus on the mechanical behaviour of 3D printed concrete and proposed a suitable mix proportion for 3D printed concrete.

1.3 Objectives

The objectives of this experimental study are:

1. To investigate the suitability of the admixtures for the 3D printed concrete.
2. To develop a printable and functional 3D printed concrete mixture.
3. To determine influence of admixture on the mechanical properties of 3D printed concrete.

1.4 Scope of Work

The scope of this study included the determination of mechanical properties of 3D printed concrete with different mix design. A comparison study was carried out for 3D printed concrete with different proportion of admixtures to evaluate the influence of the admixtures toward the concrete based on the mechanical properties. The produced 3D printed concretes were evaluated based on slump test, compressive test, splitting tensile test and also flexural test. As such, the influenced of the admixtures toward the concrete could be determined. Whereas to obtain optimum mix proportion for 3D printed concrete, five batches of mixes with different percentage of silica fumes (0%, 5%, 10% and 15%) were studied to produce 3D printed concrete.

1.5 Dissertation Outline

This dissertation consists of five chapters and is organized as follows.

Chapter 1: Introduction

This chapter describes the general overview of the research which provides a foundation and background to the subject along with problem statement and scope of the study.

Chapter 2: Literature Review

This chapter covers the previous research work on 3D printed concrete and their mechanical properties. Furthermore, studies of the main performed requirement for 3D printed concrete were discuss in this chapter.

Chapter 3: Methodology

This chapter describes the outline of the research work. Each procedure to derive the research program is explained accordingly. In addition, methodology of study and the technique used in the specimen testing are addressed in this chapter.

Chapter 4: Results and Discussion

The results and data obtained from the tests performed on the specimens are analysed and discussed in this chapter. The results are analysed and illustrated in the form of tables as well as graphs for comparison and interpretation to facilitate discussion.

Chapter 5: Conclusions and Recommendations

This chapter summarizes the key results and reviews the study objectives. Suggestions for future work are also presented.

CHAPTER 2

Literature Review

2.1 Introduction

Concrete, one of the most widely used commercial materials, which is made by combining cement, water, and aggregate in certain proportion. Portland cement is the most crucial element of concrete, which has undergone a tremendous revolution in the past century. About 4.4 billion tons of cement were produced worldwide in 2021. Comparing the current situation to the previous one, it can be seen that over 30 billion tons of concrete were utilized in 2021, along with 27 billion tons of aggregate and 2.8 billion tons of water. Concrete is widely used in the construction industry such as in the construction of roads, bridges, tunnels, dams, power plants, airports, electricity networks, ditches, sea barriers, as well as wastewater and freshwater treatment plants. Concrete will become more and more in demand as a result of changes in the energy industry and ongoing climate change. For now, 3D printing technology is used in many fields with different usage in our daily life such as industrial manufacturing, medicine, aerospace and also construction. Among all these areas, the construction industry is rather left behind in 3D printing technology. The usage of 3D printed concrete is still very limited in the construction industry. The benefits of 3D printing for the construction sector should not be underestimated because it will cut down on the different project factors, including construction, materials, expenses or cost, and time. Rapid prototyping creates object made from concrete by discharging or laying it layer by layer via 3D printing. Since 3-D printing technology only needs a minimal quantity of material, it adds lightness to the products and enables the creation of components with many functions.

2.2 History and Background of 3DP Concrete

3D-printed concrete is a new technique based on 3D printing that is used in the manufacturing of concrete. The 3D software controls it while the designed concrete slurry is delivered through the extrusion mechanism in accordance with predetermined specifications. The specified concrete component is eventually produced once a proper printing programs is executed, and the concrete is extruded via a nozzle. When used to create complicated structures, 3D-printing concrete technology uses less energy than conventional building construction methods and may customize the structure to suit the needs of the project. With the large-scale application and promotion of 3D-printing concrete technology, it can effectively reduce the input of materials, personnel, and machinery in the building construction process, and promote the development of digital and intelligent building construction technology (Bock et al, 2015). 3D printed concrete was originated from the Rensselaer Polytechnic Institute in New York, USA. In 1997, Pegna conducted the first investigation into the viability and potential of 3D printing technology in the construction industry (Pegna, 1997). Contour crafting, which uses computer exact control to automatically finish the pouring process and accomplish the smooth contour surface and complicated feature model pouring by manipulating the nozzle, was invented at the University of Southern California in 1998 (Khoshnevis et al, 2001). In addition, Lim et al (2009) introduced their D-shape technology in 2009. The bottom of the printing equipment has hundreds of nozzles that are used in the D-shape technology and may spray magnesia binders. The binders are covered with fine sand that has been mixed with magnesia powder, which progressively harden to produce a solid stone. In the end, a stone structure is created by cementing the sand layers together. The mesh mould project was started at ETH Zurich in 2012 to investigate the feasibility of producing very complex geometric concrete structures digitally (Hack et al, 2014). This innovation creates a polymer network via 3D printing. A project to print "In-situ 3D-printing double-layer demonstration buildings" was established by China Construction Second Bureau South China Company and China Construction Industrial Technology Research Institute Co., Ltd. in 2019 (Lim et al, 2019). This project represents a breakthrough for in-situ 3D printing technology in the construction industry.

2.3 Performance Requirement for 3DP Concrete

3D Concrete printing technology differs from traditional concrete moulding technology, and 3D printing concrete technology has more stringent material requirements. In order to achieve smooth material pumping and continuous extrusion from the nozzle, the printing material must also be sufficiently fluid. It also needs sufficient hardening speed to ensure the steady accumulation of subsequent layers to grow, as well as strong water retention to prevent material segregation from blocking the pumping tube. As a result, fluidity, extrudability, setting time and strength are the primary factors that determine a material's printability.

2.3.1 Rheological properties of 3DP Concrete

Shear stress, viscosity, open time, and green strength of concrete material are critical because they affect pumpability, extrudability, buildability, and interlayer adhesion. Concrete's "open time" refers to how flowability changes over time, allowing printing to proceed without compromising the print's quality or hardened qualities. By determining the initial setting time and (final) setting time, a Vicat device is commonly used to determine the concrete open time (Le et al., 2012). The period of time between the end of mixing and the beginning of setting is known as open time. On the other hand, shear stress and viscosity, which are typically evaluated using a rheometer, have a direct impact on the pumpability and extrudability (Liu et al., 2018).

2.3.2 Fluidity

Fluidity is the ability of concrete materials to be smoothly extruded from the print head's discharge port, readily pumped, and transported. It is a crucial factor to consider when assessing printability. Small fluidity will probably result in high mechanical wear rates and equipment blockages. The printed components are prone to collapsing if the fluidity is too high. Water content is the main variable that affects fluidity. The mixture will become dry and hard and be unable to flow smoothly through the conveying pipeline if the water content is too low. An excessive water content will result in many damaging pores in the printed sample, which will have an impact on the final strength. Perrot et al (2016) produced a 3D-printable combination that has a water-cement ratio of 0.41 and polycarboxylate polymer powder that makes up 0.3% of the cement mass. The best construction speed achieved in the study was 1.1 m/h. By enhancing the particle size gradation with mineral admixtures, the fluidity may also be increased. A combination is more likely to develop in a densely packed condition, which improves fluidity, with the more continuous particle gradation.

2.3.3 Extrudability

Extrudability is a term used to describe the difficulty of 3D printing concrete as well as the consistency and surface quality of the material following the extrusion. Extrudability research can make sure that the mixture can be smoothly deposited through the print head's nozzle and delivered continuously through the feed pipe. It can guarantee the structural integrity of the printed building and is a guarantee for continuous printing during construction. The proportion of aggregate particle size to extrusion nozzle diameter has a significant impact on the extrudability of the printed concrete. The extrusion nozzle will become blocked if the aggregate particle size is too big. Conversely, if the aggregate particle size is too tiny, the aggregate's surface area will rise and more slurry will be needed to cover its surface, which will make the concrete more brittle and susceptible to cracking. Liu et al (2018) discovered that using fine aggregate can guarantee good extrudability and successfully avoid concrete materials from clogging the printing pipes and nozzles. Furthermore, Khalil et al (2017) discovered that the printing material won't be extruded when the mixture's maximum sand particle size is 2 mm, the weight ratio of the cement is 2, and the ratio of the nozzle diameter to the maximum aggregate particle size is larger than 5. According to Hambach et al (2019), the printing nozzle will become blocked when the amount of fiber in cement-based materials surpasses 1.5%.

2.3.4 Setting Time

Setting time refers to the period of time when the mixture is mixed with water and maintained its performance. An essential component of the performance indicators for 3D printing materials is setting time. Good fluidity and extrudability can be attained with a longer setting time, while enough early strength can be attained with a shorter setting time. Due to the various sizes of buildings, it is necessary to modify the setting time of materials to suit the printed structure's scale. As a result, the range of the setting time of 3D printed concrete should be flexible. Coagulant, retarder, or a different gelling substance can change the setting time. Previous study has discovered that mixing the cementitious material might lengthen the time taken for the mixture to set (Le et al., 2012). Figure

2.1 illustrates the effects of addition of superplasticizer on the setting time, where it is clear that the setting time (open time) increases with greater dosage of superplasticizer used.

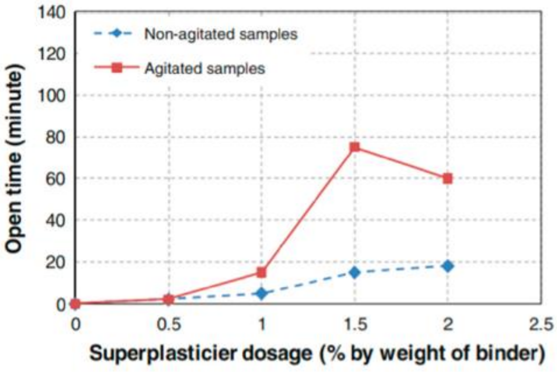

Figure 2.1: Superplasticizer dosage versus open time (Le et al., 2012)

The researchers' tools and procedures were not the same, and the setting time test is based on distinct criteria. Chen et al (2020) began printing an 800 mm x 40 mm strip every 10 minutes after a static period of 30 minutes and noted the rupture time as the setting time. Kazemian et al (2017)'s penetration resistance meter test revealed that the first setting time of the combination containing 3% of calcium chloride was 163 min. Aqel et al (2016) measured the initial setting time of cement slurry including limestone fillers using a Vicat tester and discovered that the initial setting time of the mixture decreased as limestone content and fineness increased. Through the Vicat tester, Khalil et al (2017) were able to acquire the setting times of 99 min for the combination to satisfy the needs of 3D printing.

2.4 Mechanical properties of 3DP Concrete

2.4.1 Compressive and Flexural Strength of 3DP Concrete

Although the w/c ratio dominates in determining the strength of concrete, it is well established that air entrainment greatly lowers strength. Curing, test direction in relation to interlayer joints, and, in the case of fibre reinforcement, fibre orientation, all affect strength. According to Table 2.1, these characteristics are considered when interpreting the compressive and flexural test findings on 3DPC specimens and control specimens made by conventional casting and curing, as reported by various studies.

In comparison to cast examples, Nerella et al (2016) observed that 3DPC specimens had higher compressive and flexural strengths. They removed specimens from 3DPC elements by cutting and coring them in the various orientations depicted in Figure 2.1. However, Le et al (2012) discovered that specimens taken from the 3DPC specimens had lower compressive strengths than the cast specimens, as indicated in Table 2. These contradictory results might have been caused by a number of reasons, such as decreased air content, segregation by printing of non-optimized material, and curing conditions. Lesser air content may have contributed to the strengthening in the Nerella et al (2016) and Le et al (2012) wet cured printed specimens under damp hessian, whereas the cast specimens were cured at 20^{o}C after stripping at the age of 1 day, until the test age of 28 days, which may explain lower strength development in printed specimens. However, segregation-related faults in the specimens might also be to blame for the printed specimens' reduced strength.

Table 2.1: Comparison of mechanical properties of cast and printed object

Authors	Specimens retrieved from	Type of test	Testing direction	Testing time				
				Printed specimens			Cast specimens	
				3 days	21 days	28 days	21 days	28 days
Nerella et al, 2016	1000x300x35 mm wall	Compressive strength (MPa) (size: 35 mm cube)	I	45.9	83.5	-	73.4	-
			II	49.7	80.6	-		-
		Flexural strength (MPa) (size: 160x35x35 mm)	I	4.8	5.8	-	5.1	-
			II	4.3	5.9	-		-
Le et al, 2012	350x350x120 mm slab	Compressive strength (MPa) (size: 100 mm cube)	I	-	-	96	-	107
			II			93		
			III			93		
	500x350x120 mm slab		I	-	-	102		
			II			102		
			III			91		
	Curvy bench	Compressive strength (MPa) (size: 63 mm cube)	I	-	-	74		
			II			82		
			III			76		
	500x350x120 mm slab	Flexural strength (MPa) (size: 400x100x100 mm)	I	-	-	16.5	-	11
			II			13		
			III			6.5		
	Curvy bench	Flexural strength (MPa) (size: 220x63x50 mm)	I	-	-	12		
			II			13		
Feng et al, 2015	70.7 mm cube	Compressive strength (MPa)	Testing time 3 hours after casting					
			I	11.2 (3.6)*			-	-
			II	7.23 (1.9)*				
	50 mm cube	Compressive strength (MPa)	I	16.8 (7.1)*				
			II	13.2 (4.9)*				
			III	11.6 (5.8)*				

* Note that the values in the brackets are E-modulus and unit in GPa

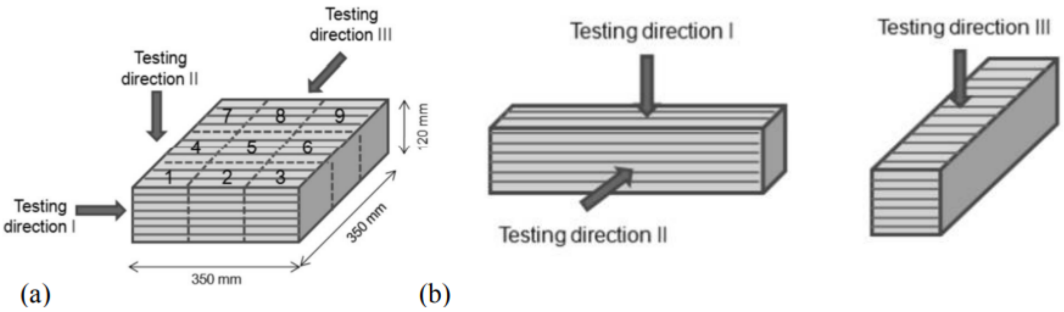

Figure 2.2: Collection of 3DPC specimen for (a)compressive strength and (b) flexural strength (Le et al, 2012; Feng et al, 2015 and Nerella et al, 2016)

According to Table 2.1 and Figure 2.2, the direction of loading the printed specimen has an impact on its strength characteristics. Feng et al (2015) discovered more compressive strength when testing parallel to the layer depositions than when testing perpendicular to the layer depositions, as illustrated in Figure 2.3. It is difficult to explain this occurrence. It is notable that they evaluated their specimens after only three hours of heat curing. Feng et al (2015) also looked into the mechanism of printed cube failure after compression testing. The failure patterns for specimen loaded in the X, Y, and Z directions as depicted in Figure 2.2 were quite comparable. In every instance, the specimens showed diagonal failure, with two sets of triangular fractures meeting in the middle and forming an hourglass shape on the two opposite sides. In the findings of Nerella et al (2016) and Feng et al (2015), the impact of joint location is more obvious. Compressive and flexural strengths were constantly the lowest in testing direction III (Figure 2.3), which is when loads are applied parallel to joints, in the findings of both groups. Under compressive and flexural stress in this orientation, weak joints in 3DPC specimens may experience compressive and flexural splitting. For the samples examined by Feng et al (2015), the Young's modulus (E-mod) value is further provided in Table 2.1. Similar to compressive strength, distinct E-mod were discovered for various loading directions in relation to the direction of printing.

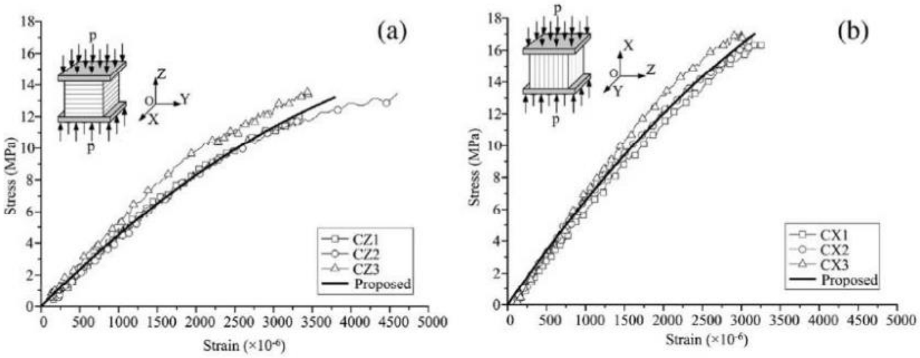

Figure 2.3: Early age (3 hours heat cured) compressive response of 3DPC specimens loaded (a) perpendicular to the layer and (b) parallel to the layer direction (Feng, et al 2015)

The speed and calibre of the printing might be influencing elements that significantly affect the outcomes. A 3DPC wall built from a single batch of concrete and measuring 500 mm × 300 mm and 50 mm thick is used as an example in Figure 2.4. The printing quality is thought to be decent at first, but as time goes on, the hydration process speeds up and the matrix hardens. Additionally, if moisture is lost from the mixture, the printing quality will suffer. As a result, lower-quality concrete interfaces and layers may have formed in the top levels. The specimens derived from samples 1, 2, and 3 will all have distinct mechanical characteristics as shown in Figure 2.4, and as a result, there may be variations in the findings, which might account for Le et al (2012)’s stated scatter.

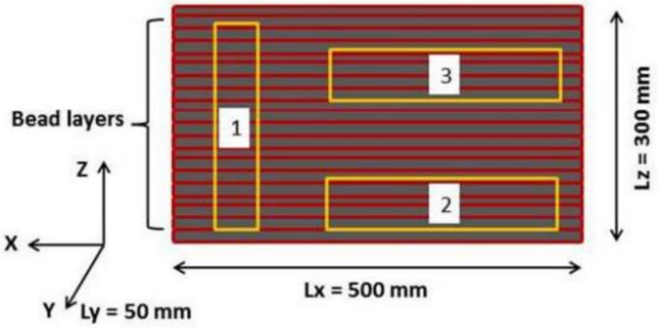

Figure 2.4: Collection of specimens for mechanical tests from different orientations in a printed wall (Le et al, 2012)

According to the explanation above, the overall load bearing capability of the produced items in 3D printing is significantly influenced by the printing direction and time. This suggests that while developing the structures, it is important to consider the anisotropic characteristics of 3D printed items as well as the appropriate printing speed.

2.4.2 Splitting Tensile Strength of 3DP Concrete

Wolf et al (2019) utilised a split tensile test to assess the interlayer bond strength using 40 mm 40 mm 40 mm samples in accordance to NEN-NE 12390 standard. The test sample utilised by Wolf et al (2019) comprised up to five layers, in contrast to past investigations. In order to verify the strength of the direct tensile connection, Ma et al (2020) also employed samples with many layers, as shown in Figure 12.5. The applied interlayer mortar with calcium sulphoaluminate cement, cellulose fibre, and limestone filler that was the subject of the investigation was intended to increase bonding. This study investigated at least six replicate samples.

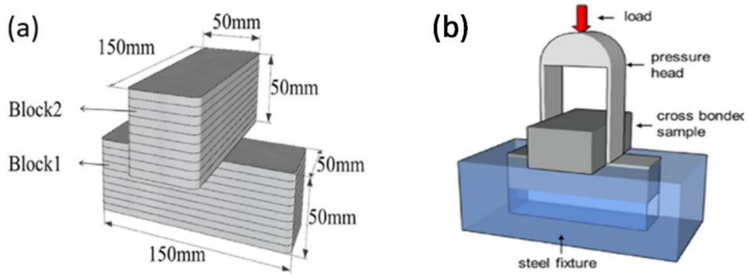

Figure 2.5: (a) Sample geometry and (b) tensile test set (Ma et al, 2020)

In contrast to past designs, Lee et al (2019) employed cylindrical cores for the BS EN 14488-4 direct tensile test of 3D printed concrete at 28 days. The shape was intentionally utilized following X-ray computed microscopy (XCT) scans, and the findings point to the possibility that the pore volume at the interlayer had no effect on the mortar's failure. This is consistent with the findings of Chen et al (2020), where the authors utilised notches to guarantee that the plane of failure occurs at the interlayer. It also suggests that the point of greater pore is not always the plane of debonding or fracture. Similar to this, Zareiyan et al (2017)'s early research discovered that uniaxial tensile tests occasionally resulted in failures outside of the bond region and misalignment, which can lead to a significant amount of result dispersion. The authors used two-layer 100 mm cube specimens in a splitting tensile test. This size is larger than the cubes which Wolf et al (2019) used for the splitting tensile test, which were 40 mm in size. For a direct tensile test after 28 days of curing, Panda et al (2019) utilised sliced 40 mm cubes of two layers. Panda et al (2019) conducted a direct tensile test on 50 mm cube pieces in a different investigation. To assess bond strength at 7, 14, and 28 days, Lee et al (2019) utilised four-layer 3DPC cylindrical samples that were 50 mm in diameter and 140 mm high. As may be seen from the foregoing and the next sections, some writers employed two-layer samples while others permitted multilayer samples for the interlayer bond test. Zareiyan et al (2017) examined the impacts of single and four-layer splitting tensile samples across time periods of 75 minutes, 3, 7, and 28 days. They discovered that employing multilayer samples can boost interlayer bond strength by 10–30%. This affects how findings from the selection of the sample geometry should be interpreted. The discussion above, as well as the usage of diverse concrete ages and several replicate test samples by different authors, highlight the need for standardisation in sample processing and test techniques in order to achieve uniformity and consistency for digital concrete production. It might be argued that methods of material preparation for strong bonds should resemble those of 3D printed parts.

2.4.3 Bond Strength of 3DP Concrete

As a primary need to withstand operations on the structure, the interface between concrete layers with varying ages must ensure sufficiently strong shear and tensile strength. The methods for transferring shear and tensile stress between two concrete layers are complicated, nevertheless. The amount of reinforcement (if any) crossing the interface, the concrete's compressive resistance, the roughness of the interface, the presence of cracking, or the stress brought on by normal forces across the interface are a few parameters that affect the transmission process and are involved in these interactions. Figure 2.6 displays the findings of Le et al (2012)'s investigation on the interlayer bond strength of 3DPC with varied time gaps between printing following layers. Direct tensile testing was done on cylindrical specimens cored from 3DPC components to measure bond strength. The printing time interval between layers was changed from 0 seconds to 7 days, and the outcomes were compared to cast specimens devoid of interfacial joints. Figure 2.6 makes it very evident that the bond strength is significantly impacted by the printing time gap.

However, neither the authors nor their research focused on the primary processes of bond strength. It is still unclear whether the bond strength variation with the interlayer printing time difference in their data was primarily caused by chemical or mechanical interfacial bonding processes. The creation of a crystalline structure which strengthens the link between the two layers may be caused by hydration or chemical interaction of binders in the fresh concrete layers for narrower interlayer gaps. It is hypothesized that when the bottom layer sets, hardens, and cures with more interlayer time, the chemical link weakens. The ultimate interlayer bond strength may also be greatly impacted by variable interlayer drying shrinkage. Therefore, the printing time needs to be reduced for layer concrete to have greater bond strength.

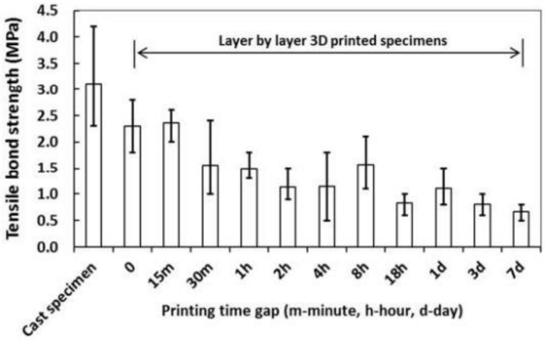

Figure 2.6: Influence of bond strength with printing time gap (Le et al, 2012)

2.5 Factors Affecting the Interlayer Bond Strength of 3DP Concrete

According to the literature, the interlayer bond strength in 3DCP depends on a variety of variables, including the "time gap between the layers," "surface wetness," "structuration rate," and "printing speed." The research on the impact of these factors on the bond strength of 3D printed concrete is summarised in this section.

2.5.1 Effect of Time Interval between the Two Successive Layers

Time has a significant role in cementitious materials because different stages of the hydration process, or concrete maturity, are reached at different times. The time elapsed in 3DPC between two subsequent layers results in a loss of surface moisture, which may weaken the binding. However, the amount of moisture present on the deposited layers is significantly influenced by temperature and humidity. Figure 2.7 summarises and exemplifies the impact of the printing time gap on the uniaxial tensile strength of 3D printed materials as described in previous works.

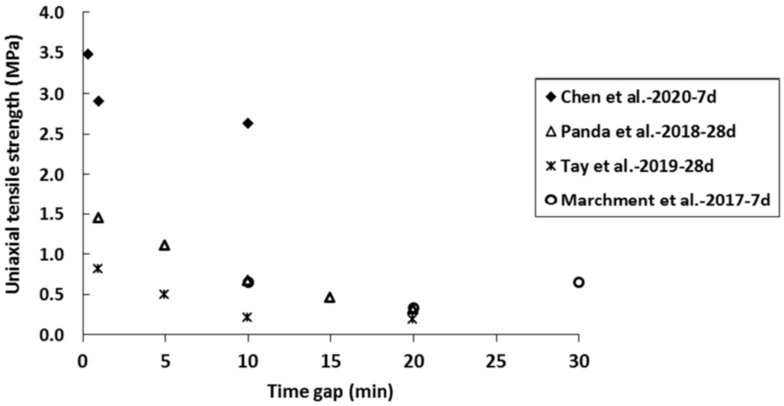

Figure 2.7: Effect of printing time gap in uniaxial tensile strength of 3DP Concrete from several authors

Chen et al (2020) studied the relationship between the binding strength of 3D printed concrete and the time interval (20 s, 1 min, 10 min). With the exception of the 20 s time gap, strength drop of 4% and 13%, when compared to cast samples, was seen for printed samples with time gaps of one minute and ten minutes, respectively. Wolf et al (2019) found a similar (strength reduction) pattern for time intervals of 15 s, 4 hours, and 24 hours, while Sanjayan et al (2019) reported a similar trend for time gaps of 10 and 20 minutes. Panda et al (2019) used two layers of extruded filament to investigate the effects of various time intervals (1, 5, 10, 15, and 20 min) on the binding strength of samples of 3D-printed geopolymer cement. Bond strength was observed to decrease for time intervals greater than one minute. It was discovered that the strength loss was 23%, 55%, 67%, and 76%, respectively, for time intervals of 5, 10, 15, and 20 min. This behavior was linked to the geopolymer's increased rate of structuration, which led to poor interlayer bonding and decreased tensile bond strength.

Figure 2.8 graphically illustrates the impact of the printing time gap on the extruded layers' interface state (Tay et al, 2019). Cavities and voids are created in the filament layer and interface with a greater printing time gap. It should be noticed that the arrows in Figure 2.8 indicate where the two-track layers' interface is located. When the printing time gap widens, it is obvious that holes and voids predominate in the contact. This is a result of the fresh material's setting period, during which the hydration processes of the binders devour the combined water and harden the composite, reducing the amount of moisture that is available for evaporation onto the printed layers' surfaces. Dry cementitious materials typically create a weak zone at the junction, which dramatically lowers the bond strength. It's important to note that after the material has been deposited, unlike traditional concrete, no external force or vibration is used to compact the substance. This is yet another factor that contributes to the formation of a weak zone between the printed layer joints.

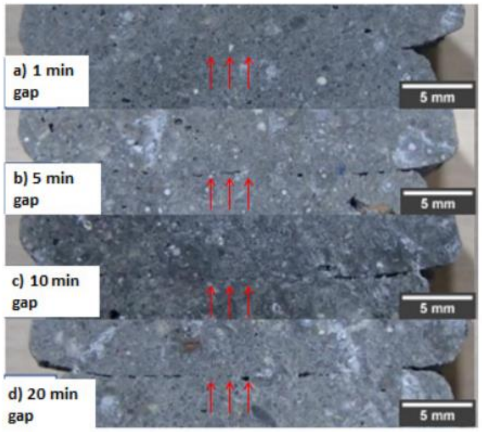

Figure 2.8: Effect of printing time gap on the interface of the two layers of 3D printed samples (Tay et al, 2019)

2.5.2 Effect of Nozzle Stand-Off Distance

The binding strength of 3DPC can also be significantly influenced by nozzle stand-off distance. Higher stand-off distances might result in lower bond strengths. The printed samples' bond strength decreased between 23 and 35 percent when the stand-off distance was raised from 0 to 2 and 4 mm, respectively (Panda et al, 2018). Large cavities may develop in the contact as the stand-off distance grows, which will affect the mechanical and durability qualities. The impact of nozzle standoff distance on the uniaxial tensile strength as reported by different researchers is shown in Figure 2.9.

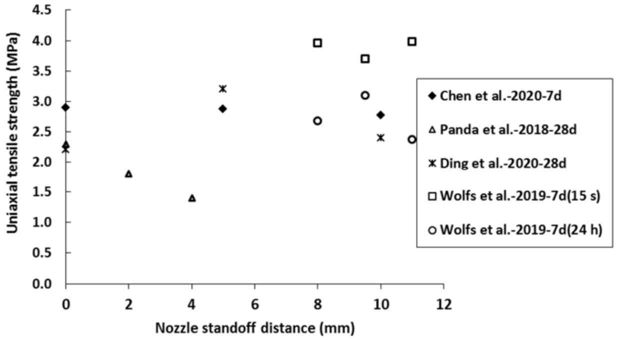

Figure 2.9: Impact of nozzle standoff distance in uniaxial tensile strength of 3D printed objects from researchers

Ding et al (2020) concluded that a standoff distance of around 5 mm is optimal. The loss in bond strength for nozzle heights of 0 mm and 10 mm was approximately 31.1 % and 24.2 %, respectively. In research by Wolf et al (2019), however, there was no discernible variation in the strength for three different nozzle heights (8 mm, 9.5 mm, and 11 mm) at two different printing time intervals (15 s and 24 h). It was determined that materials with higher starting yield strengths and structuration rates are more affected by nozzle height and interlayer strength. More research is required since the physics underlying this strength loss owing to nozzle stand-off height are not yet obvious and have not been thoroughly explained by the researchers.

2.5.3 Effect of Printing Speed

The success of 3D printing is also greatly influenced by printing speed. An ideal printing speed is necessary for a certain 3D printable mix design in order to print it successfully. Due to the fact that the rheological characteristics of cementitious mixes can vary greatly depending on the source materials, mix formulas, and mix designs, this optimal speed may change.

The effect of printing speed on the bond strength was studied by Wang et al (2020). The bond strength of the samples printed at time intervals of 10 minutes and 60 minutes lost strength as compared to 0 minute by about 58 % and %, respectively, at a printing speed of 1.7 cm/s. These reductions were 89% and 97%, respectively, at a printing speed of 3 cm/s. There was no discernible change in the average bond strength of 3D printed samples created at various speeds with a brief printing time gap (1 minute). The printing speed affects the layer's roughness as well. Higher speeds often result in smoother layer surfaces and might reduce binding strength. Higher printing speeds also result in printed materials with more porosity and larger voids, which may impact the structure's mechanical and durability attributes. In general, a faster printing speed may result in inconsistencies in the track form that compromise structural integrity and cause bonding issues for the same material and nozzle size.

2.5.4 Effect of Mix Design and Curing Conditions

A high-performance cementitious mix with regulated material properties is necessary for 3DCP to succeed, especially in its early stages. As there is no formwork involved in 3DCP, a material with the right yield stress and viscosity is needed to guarantee that the present layer won't deform once a subsequent layer is deposited over it. A material must have a high initial static viscosity for greater printability so that it may undergo microstructural changes to become less viscous via deflocculation when applied force is applied yet rebuild or re-flocculate to become extremely viscous after being extruded and coming to rest. This behavior is known as thixotropy. Weng et al (2021) recently tried to alter the material's thixotropy index by adding superplasticizer, however this had an impact on the surface moisture content of the printed specimens. It was