MULTI OBJECTIVE PARAMETERS OPTIMISATION OF KENAF CEMENTITIOUS COMPOSITES MATERIAL FOR 3D PRINTING APPLICATIONS

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ٱلْحَمْدُ لِلَّٰهِ رَبِّ ٱلْعَالَمِينَ

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ABSTRACT

3D Concrete Printing (3DCP) is an innovative technology that fabricates structures without the need for conventional formwork. The growing interest lies in formulating cement mixtures that integrate natural organic fibres. Kenaf, an abundant resource in Malaysia, emerges as a promising candidate. The essence of successful 3DCP lies in the mix's dual characteristics, it must exhibit both flowability during extrusion and stability upon deposition, ensuring effective layering. The cyclical nature of 3D printing, involving intermittent pauses and resumptions, underscores the importance of maintaining workability. The efficacy of this process is profoundly influenced by parameters such as speed and accuracy, which are particularly significant when working with natural fibres. This investigation specifically focuses on the influence of Kenaf fibre on cement mixtures for 3DCP. Concurrently, it explores the optimal ratios of additives and binders, and examines the requisite parameter configurations such as nozzle size and shape to enable successful printing. Leveraging insights from prior research and adhering to pertinent American Standards (ASTM), various tests including slump tests, slump flow tests, extrusion tests, and visual inspections were conducted to evaluate fresh properties. The optimal proportions, deduced from experimentation, comprise 30 grams of Kenaf fiber and 14 grams of plasticizer per 100 grams of cementitious mixture. The study investigated ten distinct parameter settings, ultimately revealing that a circular nozzle with a 7mm diameter and a printing speed of 10 Millimetres per second (mm/s) resulted in superior layer adhesion and structural integrity. By comparing the printed model with its digital design using Cura slicer software, it was discerned that a minimal height shrinkage of 4% occurred. This shrinkage is deemed acceptable within the context of 3DCP. Consequently, this research attests to the practicality of integrating Kenaf-concrete in 3DCP.

ABSTRAK

Pencetakan Konkrit 3D (3DCP) adalah teknologi inovatif yang membina struktur tanpa memerlukan borang konvensional. Minat yang berkembang adalah dalam merumuskan campuran simen yang mengintegrasikan serat organik semula jadi. Kenaf, sumber yang melimpah di Malaysia. Kunci keberhasilan 3DCP terletak pada ciri ganda campuran ini, ia harus menunjukkan kelalaiannya semasa pengekstrakan dan kestabilan semasa pengekalan, memastikan lapisan yang efektif. Sifat berulang-alik pencetakan 3D, melibatkan hentian sementara dan sambungan semula, menekankan kepentingan menjaga kelengkapan kerja. Keberkesanan proses ini sangat dipengaruhi oleh parameter seperti kelajuan dan ketepatan, yang sangat signifikan apabila bekerja dengan serat semula jadi. Penyelidikan ini secara khusus memberi tumpuan kepada pengaruh serat Kenaf ke atas campuran simen untuk 3DCP. Pada masa yang sama, ia meneroka nisbah optimal bahan tambahan dan perekat, dan mengkaji konfigurasi parameter yang diperlukan seperti saiz dan bentuk nozel untuk membolehkan pencetakan yang berjaya. Dengan memanfaatkan wawasan dari penyelidikan sebelumnya dan mematuhi piawaian (ASTM), pelbagai ujian termasuk ujian kemerosotan, ujian aliran kemerosotan, ujian pengekstrakan, dan pemeriksaan visual telah dijalankan untuk menilai sifat-sifat segar. 30 gram serat Kenaf dan 14 gram plastikiser setiap 100 gram campuran simen. Kajian ini mengkaji sepuluh tetapan parameter yang berbeza, akhirnya mendedahkan bahawa nozel bulat dengan diameter 7mm dan kelajuan pencetakan 10(mm/s) menghasilkan lekatan lapisan yang lebih baik dan integriti struktur yang lebih baik. Dengan membandingkan model yang dicetak dengan reka bentuk digitalnya menggunakan perisian Cura slicer, didapati bahawa terdapat pengecutan ketinggian minimal sebanyak 4%. Pengecutan ini dianggap dapat diterima dalam konteks 3DCP. Oleh itu, penyelidikan ini mengesahkan kesesuaian penggabungan Kenaf-konkrit dalam 3DCP.

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LIST OF SYMBOLS AND ABBREVIATIONS

KPa	-	Kilo Pascal
UTHM	-	Universiti Tun Hussein Onn Malaysia
ASTM	-	American Society for Testing and Materials
FDM	-	Fused Deposition Modelling
MPa	-	Mega Pascal
mm	-	Millimetre
3D	-	3 Dimensional
2D	-	2 Dimensional
3DCP	-	3 Dimensional Concrete Printing
CC	-	Contour Crafting
KCC	-	Kenaf Concrete Composite
GDP	-	Growth Domestic Product
AM	-	Additive Manufacturing
RP	-	Rapid Prototyping
STL	-	Stereolithography
R & D	-	Research and Development
USA	-	United State of America
w/b	-	Water to binder
w/c	-	Water to cement

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CHAPTER 1

INTRODUCTION

In the modern era, both industries and society have heavily relied on concrete, envisioning a built environment that predominantly utilizes this widely employed construction material. Nevertheless, this reliance has brought forth various challenges encompassing both the concrete material itself and the structures it supports. A significant challenge lies in the maintenance of existing infrastructure, often designed according to older paradigms. Comparatively, the traditional concrete exhibits distinct advantages when juxtaposed with contemporary formulations. Nonetheless, it's important to note that traditional concrete often compromises numerous sustainability considerations. Amidst these challenges, the emergence of 3D concrete printing introduces a revolutionary construction technique with the potential to yield substantial benefits across various construction aspects. These advantages encompass the optimization of construction timelines, cost-efficiency, enhanced design adaptability, error mitigation, and an improved environmental profile. At its core, 3D concrete printing is a construction approach that entails fabricating predetermined building components through a layer-by-layer deposition method. The cumulative stacking of these layers ultimately culminates in the formation of a fully realized 3D structure.

1.1 Background Study

Additive manufacturing (AM) or also known as “three-dimensional (3D) printing”, is a process of printing material to form a 3D model. Most of the common process is done by layer. AM offers a lot of advantages over other manufacturing process. Complex shape parts can be easily produced. Besides that, AM also helps reduce in material waste, time and manufacturing costs. Recently, a 3D printing process, or additive manufacturing (AM), has been introduced into the construction industry to increase productivity. To apply this technology to construction, concrete, one of the most representative construction materials, must be used as the 3D printing material. Concrete or cementitious material is one of the key elements associated with 3D printing in construction. There are many applications for 3D printing concrete. These could include printing walls, columns, precast elements, architectural structures, stand-alone elements, panels, garden chairs, roofs and others.

However, the research on concrete that considers the unique characteristics of 3D printing technology needs to be improved. The basic concrete components are cement, aggregates, sand and water. The 3DCP is normally known for self-compacting concrete as it does not require vibration for compaction. The basic principle of self-compacting concrete is that the aggregate particles form a smooth grading with a minimum void content and a considerable volume of cementitious paste with a plasticizer, which fill the gap between aggregate particles. In contrast, plasticizers increase the workability of the concrete mix and allow for better flowability and extrudability (Costanzi, 2016).

Natural plant fibres represent a sustainable alternative to conventional fibre reinforcement materials in cementitious materials due to their suitable mechanical properties, cost-effective availability and the principle of carbon neutrality (Bittner & Oettel, 2022). A study address using Kenaf-concrete composite as a concrete material in construction (Elsaid et al., 2011). This regular fibre included the fortified solid section to improve the structural quality and ductility (Shadheer et al., 2021).

Kenaf fibre can enhance the homogeneity of the concrete mixture. The fibers help to disperse evenly throughout the mix, improving the distribution of reinforcement and ensuring uniform properties in the final product and kenaf fibre can aid in the dispersion of chemical admixtures in the concrete mix. The fibres act as carriers, helping to disperse the admixtures evenly throughout the mixture and improving their effectiveness(Makar et al., 2004).

The addition kenaf fibre can help reduce the risk of segregation in the concrete mixture during mixing and transportation. The fibres act as a binder, enhancing the cohesion of the mix and minimizing the separation of aggregates and water as well as Kenaf fiber can influence the rheological properties of the concrete mix, such as workability and viscosity. The addition of fibers can modify the flow behavior and consistency of the mix, leading to improved handling and placing characteristics(Jianzhuang et al., 2018).

Many issues need to be clarified before implementing or industrializing these 3D printing of Kenaf-concrete composite. Some of them are their fresh state, hardened state, geometry conformity and printing control or parameter settings.

This research undertakes a comprehensive investigation into the viability of employing Kenaf fiber as a material for 3D concrete printing. The study involves meticulous observation, analysis, and experimentation to assess the feasibility of incorporating Kenaf fiber into the 3D printing process. Various aspects, including workability and printability of 3D printed concrete, are thoroughly examined. Furthermore, the research delves into the potential sustainability advantages associated with the utilization of Kenaf fiber in 3D concrete printing. Rigorous testing methods, such as printability assessments, are employed to discern the performance capabilities and limitations of Kenaf fiber in the context of 3D printed concrete.

1.2 Problem Statement

Customer requirement, needs and time-saving have generated a new interest in AM technology. Concrete Printing or 3D Concrete Printing, has been identified as the focus of this research because of its potential in the construction industry.

Studies and development of new materials for 3D printing would benefit many industries, such as construction and real estate. The big challenge with 3DCP is the material itself which is concrete or mortar. Concrete itself is a complex material to handle. Its setting time is affected by many changeable factors, including temperature, humidity, parameter settings and machinery components. If the concrete mix is perfect, the structure will be more robust, and it could succeed.

Firstly, the major issues in 3D concrete printing are flowability and stability (Buswell et al., 2018; Owen-Hill, 2019). 3D Concrete Printing needs to exist in two states with completely opposite properties. Before it is being extruded, the concrete must be easy to pump and achieve a consistent flow. After extrusion, the concrete needs to be stable and strong enough to support further layers of material. It involved the method of mixing and pumping.

Secondly, to produce a good shape and decent final product, the structure must maintain its workability as the process is layer by layer (Papachristoforou et al., 2018). The workability of the wet concrete is the key to good printing. Although concrete takes an extensive time to harden, it quickly loses workability as soon as it is mixed and lightweight kenaf fibres may settle over time, leading to uneven distribution within the printed structure and potentially compromising its properties. Additives like water-reducing admixtures or plasticiser must be added to the mix to maintain workability. The continuous good bonding between layers would increase the buildability.

Thirdly, speed and accuracy are significant issues in layered manufacturing (Kruger et al., 2020). It is vital that the speed of the 3D printer match precisely with the concrete's behaviour and reach a good parametric setting. The mechanisms need to move the printing nozzle at a precise speed, while the nozzle plays a significant role in accuracy, and presences of kenaf fibre might cause clogging. Addressing nozzle clogging issues requires careful consideration of fibre length, content, and nozzle design. It needs to move fast enough that the layer below does not set too much, which would jeopardize the structure's stability, but slow enough that the lower levels can hold the new concrete's weight without collapsing.

Further study and research are required to explore the potential of KCC for 3D printing. As the field is still in its early stages, this research holds promise for introducing a novel composite material suitable for freeform construction and 3D printing applications.

1.3 Aim

The objective of this study is to produce a 3D printed model using KCC through a 3D printer. The research investigates the feasibility of the composite mixture, printing processes, machine settings, parameter configurations, and the resulting 3D printed models. To enhance flowability and buildability, an appropriate plasticizer and binder have been incorporated into the composite material. The study establishes a series of mixing designs and parameter settings specifically tailored for printing KCC.

1.4 Objectives

Generally, the main objective of this study is to evaluate the Kenaf-Concrete composite and its properties that influence the parameter setting of the 3D printer machine. Below are the detailed objectives that have to be achieved, which are:

i. To study and investigate the effect of Kenaf Concrete Composite(KCC) on 3D Concrete Printing (3DCP).
ii. To set a suitable ratio for plasticizer and binder to ease the printing process of KCC on a laboratory scale.
iii. To explore the impact of different parameter configurations and nozzle types on the outcomes of 3D Concrete Printing (3DCP).

1.5 Scope of Study

The studies focused on the following scopes:

i. Various materials were utilized in this research, including Kenaf fiber, Kaolin, Ball Clay, Bentonite, Plasticizer, Water, and Ordinary Portland Cement (OPC)
ii. A specific formulation was devised for the plasticizer and binder to facilitate the printing process.
iii. The 3D printing procedure involved the utilization of Kenaf Concrete Composite (KCC) as the printing material, incorporating different mixing designs, varying parameter settings, and employing distinct nozzle sizes.
iv. The printing procedure was executed employing a Cerambot 3D printer situated within the laboratory setting.
v. The dimensions of the 3D printed model were meticulously planned to manifest as a 50 mm X 50 mm X 50 mm hollow cube.

vi. The mixture's traits, encompassing workability, flowability, and extrudability, were subjected to rigorous evaluation.

vii. The printed model underwent a comprehensive analysis to assess its buildability and capacity to retain shape.

1.6 Significant of study

The study's findings are redounding to the construction industry and society, considering that concrete plays a significant role in daily life. After water, concrete is the most material that been used in our daily life. The greater the demand for concrete, the greater waste produced. Therefore, composite or fibre materials are used in concrete admixture as it can improve the mixture properties such homogeneity and reduce segregations. The study also provides further knowledge on KCC with a brighter future in freeform construction. It also develops a set of the guideline on mixing design and parameter settings for the new KCC. The study proved and justified the best composition for the composite to produce a 3D-printed model that can sustain and longstanding structure. The most notable contribution is the new KCC developed as an alternative in layered manufacturing or 3D concrete printing.

1.7 Organization of Thesis

The comprehensive content of the thesis in five (5) chapters is included in this section. The introduction of the additive manufacturing process, the problem statement, the objectives, the scope and the significance of the study are presented in Chapter One.

Chapter Two presents an overview of materials and processes in additive manufacturing, materials issue in mixing and compounding, machine design, and the fresh properties. On the other hand, various data and suggestions are being collected from various researchers on the machine's mixture properties, mixing design and parameters.

Chapter Three presents the development of a new Kenaf-concrete admixture, the selection of materials, including plasticiser and retarder and its proportion or percentage. Machine parameters are also stated and discussed. Few types of testing on the feasibility study, mixture properties and experimental setup are being discussed.

In Chapter Four, this study presents the results and data obtained from the experiments. Some data are presented as a table and some as a graph. The results include material selection, mixing, preliminary testing and parameter settings.

Lastly is Chapter Five, which contains conclusions summarising the entire study and recommendations for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Additive Manufacturing (AM) is based on the notion of adding material in two dimensional (2D) to create a complete three-dimensional (3D) model. Almost every major industry, except construction, has already adopted AM. Aerospace, automobile, retail, and manufacturing are examples of these industries that have reaped AM's benefits over the past few decades. The construction industry could be described as the last frontier for AM.

Construction is one of the largest sectors of the global economy. with construction-related spending at $10 trillion globally, equivalent to 13% of world GDP, however the construction has shown inferior productivity gains relative to other sectors and under these conditions, the global infrastructure and housing construction industry will need to catch up and meet the global demand(Kinsey, 2017).

This section has been discussed in the research review from previous researchers regarding material issues, technical issues and research direction in 3D Concrete Printing (3DCP). However, varieties of material used in 3DCP, such as polymer, reinforced polymer, wood, ceramic, composite, biomaterial and sustainable material, were beyond our research direction. Therefore, some findings need to be reviewed in this chapter.

2.2 Addictive Manufacturing (AM)) and 3D Printing

AM technology been widely used in the automotive, manufacturing and construction industries. The word additive refers to a substance added to something in some quantities to improve or preserve it and the combination would give an additive effect. Additive manufacturing is the official industry standard (ASTM, 2013) for all technology application. It is defined as the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies. Applying AM technology in the construction industry is a chance for significant improvement and advancement in construction processes. Figure 2.1 shows Fused Deposition Modelling (FDM) is printing plastic parts.

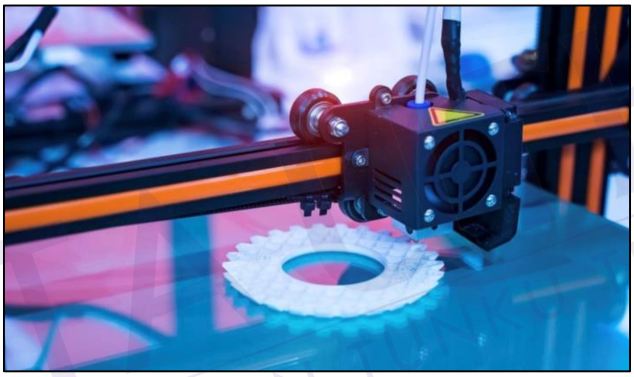

Figure 2.1 The FDM printing machine (Geeks, 2019)

AM consists of building layer by layer of slices to print 3-dimensional (3D) construction parts. AM technology is based on adding material in-two dimensional (2D) layers to build a complete 3D model. (Chen et al., 2019) classified AM into three (3) types of material such as liquid-based, powder-based and solid-based, with distinct sorts of melting technologies such as drop-on-demand binder in powder-based, laser tracer in liquid-based and heated liquefied head by solid-based material (Gao et al., 2015).

There are several names for AM, such as Rapid prototyping (RP), 3D-printing, solid freeform fabrication (SFF), freeform fabrication (FF) and additive manufacturing (Ligon et al., 2017). In the United State of America (USA), solid freeform fabrication is the preferred term for Rapid Prototyping or Rapid Manufacturing (Buswell et al., 2007). Figure 2.2 shows a variety of 3D printers available in the market.

Traditionally, AM technology systems have been able to fabricate parts from solid, liquids or powder material. Nowadays, each AM method uses a different material, such as plastic, wax, metal, metal matrix composite (MMC), polymer matrix composite (PMC) and ceramic matrix composite (CMC) material. Material is vital in producing a cost-effective part or component using AM techniques.

The application of composite material in AM is mainly for the inter-discipline area in optical and electronic and those areas still need to be extensively explored and investigated (Kumar & Kruth, 2010).

2.3 Overview of AM Process

This technology, also known as rapid prototyping (RP) is a new technique for part fabrication in a layer-by-layer process (Petrovic et al., 2011). Typically, it would be focused on preliminary stages such as research and development (R & D), fitting and testing. Customer needs for the end user product and continued demand for low-cost and time-saving have generated a renewed interest in AM. A shift from prototyping to manufacturing the final product will give an alternative selection with different material choices, low-cost part fabrication and achieving the necessary mechanical properties. Figure 2.2 shows a typical schematic diagram of a 3D printer.

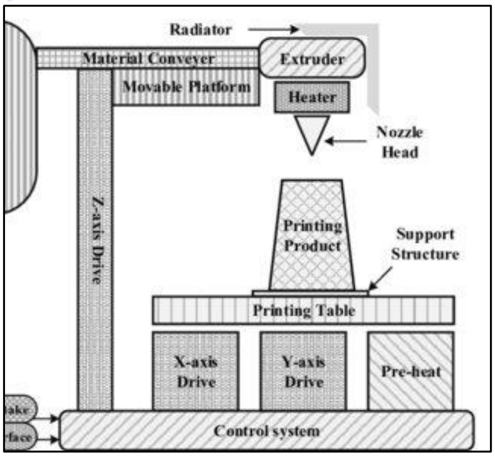

Figure 2.2 The schematic diagram of a 3D printer (Peng, 2016)

The most famous RP technology widely used is Fused Deposition Modelling (FDM). The material used is thermoplastic, which is heated by a heater and extruded through a nozzle. AM techniques have been confined to high-value-adding sectors

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