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Research Article

Future of Sustainable Construction Industry: A Review of Research, Practice and Applications of 3D Concrete Printing

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ISSN: 2639-0574

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Submission: February 13, 2023

Published: March 01, 2023

Volume 5 - Issue 4

How to cite this article: Mohamed Gamal Aboelhassan. Future of Sustainable Construction Industry: A Review of Research, Practice and Applications of 3D Concrete Printing. Adv Civil Eng Tech. 5(4). ACET.000616. 2023. DOI: 10.31031/ACET.2023.05.000616

Abstract

3D concrete printing (3DCP) is a new technique in the construction sector that allows the printing of concrete structures of various sizes and shapes. This article aims to present the evolution of 3DCP technology as well as the various concrete mixtures and materials that are used in 3DCP. In addition, it describes the necessary tests to determine the mechanical properties of 3DCP. There are mainly two techniques of 3DCP which are laying down concrete layer by layer or using shotcrete 3D printing. The characteristics of concrete mixtures are conducted by compression, flexural, tensile, and shear tests to determine the strength, pumpability, printability, durability, and workability of 3DCP. Furthermore, the slump flow is used to determine the flowability of concrete that passes through the printer's nozzle. Superplasticizers, silica fume, fly ash, geopolymer and fibers such as steel, polypropylene, and glass are commonly used in mixtures to increase the strength of 3DCP and control the formation of the drying shrinkage cracking.

Keywords: 3D concrete printing; 3D printing techniques; Cementitious materials; Concrete structures; Cementitious composites

Abbreviations: 3DCP: 3D Concrete Printing; 3DPT: 3D Printing Technique; $\tau_{D,i}$: Initial Dynamic Yield Shear Stress of the Material; Measured from the First Rheological Test (Pa); $\tau_{S,i}$: Initial Static Yield Shear Stress of the Material; Measured from the First Rheological Test (Pa); $\tau_S(t)$: Static or Apparent Yield Shear Stress of the Material at Time t After Agitation (Pa); AM: Additive Manufacturing; Athix: Structuration Rate (Pa/sec); Rthix: Short-term Re-flocculation Rate (Pa/sec); trf: Time Period Over which the Re-flocculation Occurs and the Dominant Shear Stress Increase (sec); t: Time Since the Cessation of Agitation (sec)

Introduction

3D printing technique (3DPT) is the transformation of 3D digital drawings into 3D shapes using a 3D printer. Previously, 3DPT was used in industrial design and manufacturing, now it includes different sectors such as biomedical, food, construction, and aerospace [1]. A well-detailed review of the 3D-printed polymers and their applications is presented by Ramadan [2]. Also, Dey et al. [3] introduced a useful review of the use of industrial wastes in 3D concrete printing, which is useful for the industry to introduce sustainable buildings. The main advantage of using the 3DCP technique is that it can print different types and shapes of concrete elements or structures without the need for formwork. Furthermore, when using 3DCP instead of traditional concrete construction, the time and cost of construction are reduced because the 3DCP technique reduces the manpower and material resources which decreases CO_2 emissions [4-6]. On the other hand, there is no code standards developed for the 3DCP which is the main disadvantage [7]. The main objective of this research is to discuss the development statutes of the 3DCP technology and the 3D concrete mixtures and materials. Also, it has been described the 3DCP mechanical properties and the required laboratory tests to obtain these properties.

3D Concrete Printing Technology and Applications

In the mid of 1990s, Khoshnevis and Dutton [8] introduced the counter-crafting method using a computer-controlled robot to develop 3DPC at the University of South California, USA. In recent years, fast development has occurred by researchers, and the first commercial 3DCP building was developed in 2014. Figure 1 presents the 3DCP facility at the Eindhoven University of Technology (TU/e). A research team at Loughborough University developed a concrete printing system that had a 3D steel frame, a printing head that moves in the x-direction located on a movable beam in the vertical direction (y) and the out-of-plane direction (z) [9,10] as shown in Figure 2a. Currently, more different institutes and commercial companies are working on the development of 3DCP [11-17]. Furthermore, there are different companies are manufacturing and supply 3D concrete printers to the construction market such as Xtreee (France), Cybe Construction (Netherlands), and COBOD International (Denmark) [11].

Figure 1: 3D Concrete Printing Station at TU/e [6].

Two types of printers are commonly used in the construction market which is the four-axes gantry printers used for large-scale structures and on-site, and the six-axes robotic arm printers used for more complex component and small-scale units, as shown in Figure 2. The concrete printer includes three main parts which are the material hopper and mixer, pump, and nozzle, as shown in Figure 3. The commonly available techniques of 3DCP are laying down concrete layer by layer or using shotcrete 3D printing.

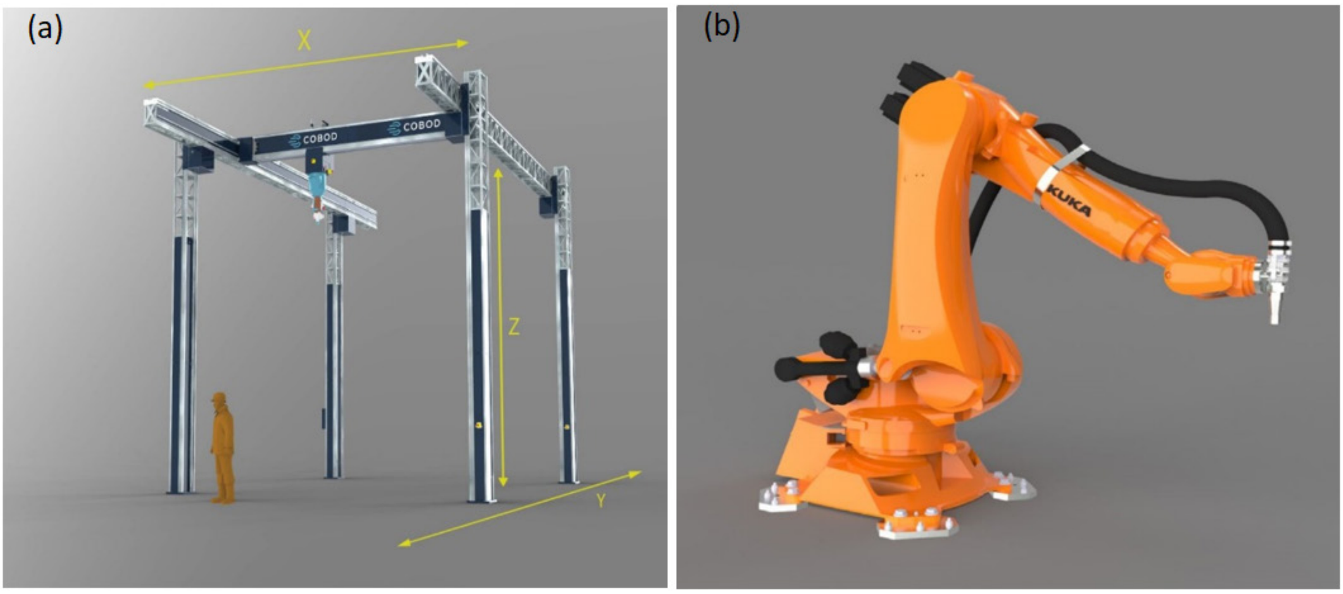

Figure 2: Types of 3D Concrete Printing used in the construction market [11]: (a) Four-axes gantry printers; (b) Six-axes robotic arm printers.

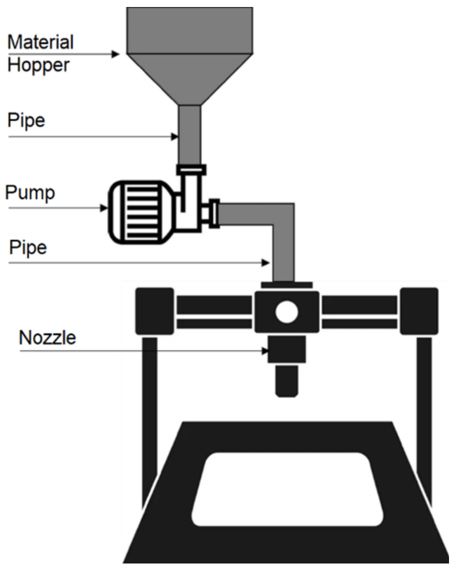

Figure 3: Components of the 3D concrete printer [23].

Heidarnezhad and Zhang [18] reviewed the past work conducted on shotcrete 3D printing and discussed the existing challenges in this field. Menna et al. [1] presented an overview of various structural projects conducted using the 3DCP technique and discussed the structural details of these projects. Table 1 shows different types of 3DCP projects. On the other hand, a state for additive manufacturing technology (AM) was introduced by Paolini et al. [19]. This review included the AM systems and processes of the 3DCP. Also, the applications and methods of digital planning were described. Asprone et al. [20] developed a novel method based on additive manufacturing for the design and fabrication of 3DCP structures. This method consisted of 3DCP members printed separately, which assembled into the required structure using a reinforcing steel system. Experimental and numerical investigations were implemented to check the efficiency of this system. The TU/e conducted a research program to increase the ductility of 3DCP. A new technique to place reinforcement during 3DCP was investigated and developed [5,6].

Table 1: Applications for Structural Projects Constructed using 3D Concrete Printing Techniques [1].

Project name	Type	Location	3DCP conductor
3D concrete printed castle	HB	USA	Total Kustom
Leward Grand Hotel	HB	Philippines	Total Kustom
Office Building	OB	UAE	Winsun
Krypton post	SE	France	XtreeE
USH sinusoidal wall	SE	France	XtreeE
R&Drone Laboratory	HB	UAE	CyBe
Pedestrian bridge	B	Spain	Acciona Spain and D-Shape
Bicycle bridge	B	Netherlands	TU/e
Apis Cor printed house, Russia	HB	Russia	Apis Cor
Maison Concept YRYS	HB	France	XtreeE
Stormwater Collector	SE	France	XtreeE
3D Housing 05	HB	Italy	Italcementi and CyBe
The BOD	HB	Denmark	COBOD
KnitCandela	SE	Mexico	NCCR Digital Fabrication
3D-Printed Concrete Pedestrian Bridge	B	China	Tsinghua University
Future Tree	SE	Switzerland	NCCR Digital Fabrication
Building Apis Cor, Dubai	OB	UAE	Apis Cor
3D-printed post-tensioned concrete girder	B	Belgium	Ghent University and Vertico
B is a bridge, HB is a house building, OB is an office building and SE is a structural element			

The effect of different reinforcement techniques on the structural performance of 3DCP beams was experimentally tested by Gebhard et al. [21]. Based on the obtained results from these experiments, a simple model was developed for the mechanical behavior and design of the required interlayer shear reinforcement. Also, Kloft et al. [22] introduced different strategies to install the steel reinforcement used in the 3DCP structures. These strategies are valid for laying down concrete layer by layer or using shotcrete 3D printing.

In the research conducted by Jo et al. [23], a 3D concrete printer in a suitable scale to the lab size was developed using laying down concrete layer by layer. This printer proved the possibility to develop 3DCP structures. However, Hack et al. [24] developed a dynamic robot-based manufacturing process for FRP concrete reinforcement which allows for increasing the efficiency of 3DCP structures with different sizes and shapes using shotcrete 3D printing.

3D Concrete Printing Mixtures and Mechanical Properties

The material selection is one of the important parameters to provide the required strength and properties of 3DCP mixtures. Usually, the aggregate size used in the 3DCP mixtures is too small to pass through the nozzle. Superplasticizers and accelerator admixtures are commonly used in the 3DCP mixtures to increase workability and accelerate the initial setting time. Silica fume, fly ash, Limestone powder, geopolymer and fibers are used to increase the strength of the concrete mixture and control the formation of the drying shrinkage cracking [25].

Liu et al. [26] conducted a review of the 3DCP development of 3D in the construction industry, which included the requirements of 3DCP materials. Also, Khan [27] presented a review of the suitable mixtures commonly used in the 3DCP using for the fiber-reinforced and Geopolymer mixes. This research focused on both the fresh and hardened properties of the 3DCP mixtures. Another review of the 3DCP was introduced by Krishnaraja and Guru [28]. This review summarized 48 concrete mixtures developed by other researchers that could be used for the 3DCP. On the other hand, Buswell et al. [29] conducted a road map for using concrete extrusion to draw the technical issues that affect the extrusion of 3D concrete printing and to disentangle the critical interdependencies between the materials, manufacturing, and design processes. This study introduced solutions to some of these issues, and research areas had been identified.

Jo et al. [23] conducted an experimental investigation to develop a suitable 3D concrete mixture. This material investigation succeeded in introducing the best mixing ratio of cementitious materials used in 3D concrete printing for laying down concrete layer by layer. Şahin [30] investigated the different materials used in the 3DCP mixtures and their effect on the printability of these mixtures using experimental studies conducted by other researchers. In addition, an experimental investigation of the effect of synthetic microfiber addition for 3DCP in the 3DCP mixtures was developed by Antoni et al. [25]. Also, this research discussed the effect of the ratio between cement and sand in addition to the practical size of sand. The experimental results showed that the workability and strength of the concrete mix decreased with adding the synthetic microfiber. However, synthetic microfiber reduces the cracking possibility and the initial setting time was increased while using a smaller particle size of sand. Chen et al. [31] studied the feasibility of using supplementary cementitious materials in 3D concrete printing instead of the high volume of ordinary portland cement. This study found that up to 45% of cement can be replaced by a blend of fly ash and silica fume. Also, calcined clay is one potential alternative for developing sustainable 3D printable concrete in areas that are in short supply of fly ash and silica fume. Zhu et al. [32] conducted an experimental study to develop a cementitious concrete mixture using the ordinary Portland cement, mineral powder, the accelerating agent. In order to reach the acceptable values of workability, viscosity, and plasticity of the concrete mixtures, different trials of the kind and amount of accelerating agent and the dosage were conducted. Results proved that the performance for all different mixtures were good. The initial and final setting time was 10-40 minutes and 15-80 minutes, respectively. Also, results showed that the speed was so far and controlled, the appearance looked knitted and layered.

To develop a framework for laboratory testing and the mechanical properties of 3DCP mixtures, Kazemian et al. [33] conducted an experimental test program. This experimental program included all details of two test methods to evaluate the shape stability, and four 3DCP mixtures using Nano clay or silica-fume. The developed framework is considered a basis for the guidelines and specifications of 3DCP. This shape stability test is similar to the concept introduced by Perrot et al. [34] to develop the plastic deformation over time for a fresh concrete cylinder. In the experimental study of Perrot et al. [34], the role of structural build-up properties of cement-based materials in such a layer-by-layer construction technique was experimentally validated in a layer-wise built column. The results of this study developed a theoretical framework to propose a building rate optimization method. Tay et al. [35] implemented an experimental test to determine the pumpability index, quality of surface, and the maximum height of 3DCP layers using the results from the slump test and the slump flow test. Zareiyana [36] investigated experimentally the effect of interlocking between 3DCP layers and the bond strength between these layers using the splitting test. The experimental results showed the sensitivity of the bonding strengths between layers due to the layer's interlocking. Xu et al. [37] presented a new volume and forming of a 3DCP technique using a square nozzle. This experimental study focused on the effect of the size and speed of the nozzle size, and the extrusion rate of materials. The experimental results showed the accuracy of architectural ornament printing using this technique. The experimental study conducted by Tay et al. [35] used standardized field-friendly protocols to measure the slump and slump flow of the cenemtious mortar mixtures. In this study, the pumpability and buildability were evaluated in terms of the pumpability index and maximum height printed before collapsing. These results together with the slump and slump-flow values were used to define the printable region.

Results and Discussion

Based on the previous experimental studies conducted by other researchers, the mechanical properties of 3D concrete printing mixtures can be obtained by various laboratory tests considering different aspects such as the material aspect, the control aspect, and the open time aspect [23]. The characteristics of 3DCP mixtures are conducted by compression, flexural, tensile, and shear tests to determine the strength, pumpability, printability, durability, and workability.

Strength

3DCP mixtures require a high compression strength as well as a good performance for the shear and crack resistance by increasing the tensile and shear properties to decrease the brittle failure. The strength of concrete increases with addition of superplasticizers, silica fume, fly ash, geopolymer, and fibers such as steel, polypropylene, and glass. Also, these additions control the formation of the drying shrinkage cracking and increase the tensile and shear properties. To determine the strength of 3DCP mixtures, different tests are usually conducted such as the compressive strength test, flexural strength and tensile strength test, and direct shear test [33].

Pumpability

Pumpability is to print concrete constantly and stably while maintaining the initial properties of the concrete mixture under the pump pressure such as concrete densities, shape, and size. Both concrete and cementitious mixtures are used in 3D concrete printing, but it is preferred to use soft materials to decrease the friction while pumping the process into the nozzles. The pumpability of concrete could be measured using the rheometer [28] and/or the pumpability index developed by Tay et al. [35]. The pumpability index is the ratio between the flow rate of the concrete mixture and that of water. The flow rate is the volume of concrete mixtures per second, which is calculated by measuring the weight of each mixture being pumped for 30 seconds at a constant speed of 2890 rpm.

Printability

Printability refers to the extrudability of concrete mixtures which tests the flowability of the 3DCP mixtures by the timespan during which the 3DCP mixtures could be extruded from the nozzle with an acceptable quality [33]. The concrete penetrometer method introduced by ASTM C403 [38] can be used to measure the initial setting time of the concrete mixtures to define the printability of 3DCP mixtures.

Durability

The durability in 3DCP structures refers to the quality of the printing layers to maximize the safety and service life of these 3DCP structures. The printing quality includes surface layer quality, sizes, and materials. The slump and slump flow tests using a flow table defined by ASTM C1437-15 [39], could be used to determine the surface quality [35]. In addition, Kruger et al. [40] developed an analytical model that can measure the durability of concrete using the yield stress of concrete mixture considering time as shown in Equations (1) to (3) and Figure 4.

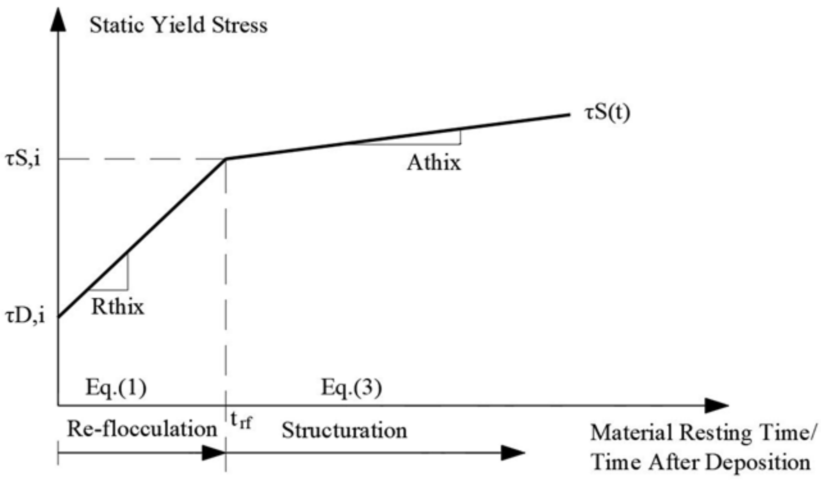

Figure 4: Static yield shear stress evolution as a function of resting time [40].

$$\tau S(t) = \tau D,i + Rthix * t \quad (1)$$

$$t_{rf} = (\tau S,i - \tau D,i) / Rthix \quad (2)$$

$$\tau S(t) = \tau S,i + Athix(t - t_{rf}) \quad (3)$$

Where, τS(t) is the static or apparent yield shear stress of the material at the time (t) after agitation (Pa), τD,i is the initial dynamic yield shear stress of the material; measured from the first rheological test (Pa), τS,i is the initial static yield shear stress of the material; measured from the first rheological test (Pa), trf is the time period over which the re-flocculation occurs and the dominates shear stress increase (sec), Rthix is the short-term re-flocculation rate (Pa/sec), Athix is the structuration rate (Pa/sec), and t is the time since cessation of agitation (sec), as shown in Figure 3. It should be noted that prerequisite (t ≤ trf) for Equation (1).

Workability

Concrete workability depends on several parameters. The water-cement ratio is the main parameter that has a big impact on the workability of the concrete and cementitious mixtures. The workability of concrete enhances by increasing the water-cement ratio. However, 3DCP mixtures should be solidified in a shorter time than normal concrete during the printing process due to the short time of construction and the effect of the weight of the upper layer on the underlying one. To ensure the quality and the requirements of the 3DCP mixtures, accelerator and polycarboxylate-based water-reducing admixtures are usually used in the mixtures, which accelerate the cement hydration process and increase the flowability. The workability can be conducted using the slump flow test defined by ASTM C1437-15 [39]. According to Tay et al. [35] the slump flow diameter should be between 130 and 210 mm.

On the other hand, the shape stability of the fresh 3DCP layers is an important parameter and should be considered. The shape stability can be determined using the layer settlement test and the cylinder stability test, which were developed by Kazemian et al. [33]. In the layer settlement test, two concrete layers are printed with a specific time gap and a ruler is placed as a scale. In addition, a camera is placed to take photos before and after the concrete printing of the second layer. The layer settlement is obtained by analyzing the photos using a computer program. Figure 5 presents the cylinder stability test components, which include a plastic frame, a cylinder with a height of 80mm, a tamping rod, two loading guides and a cylinder container to apply a uniform load. In the cylinder stability test, the plastic cylinder is fixed in its place, and filled by the first concrete layer of 40mm height. This first layer is consolidated by rodding 15 times using the tamping rod. Then, the second concrete layer is applied with the same procedure and any excessive concrete is removed from the top surface of the cylinder. After that, the plastic cylinder is removed carefully. Any settlement in the concrete cylinder is measured. Finally, a stress of 44.70 kPa is applied using the cylinder container and the resulting settlement is recorded [33].

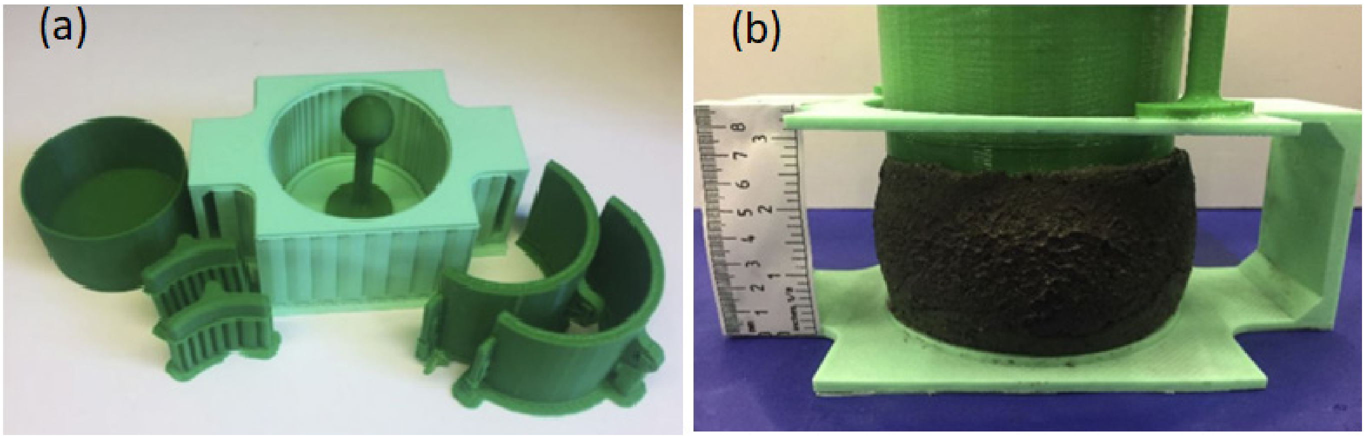

Figure 5: Cylinder stability test [33].

Conclusion

This paper has collected and discussed the development statutes of the 3DCP technology and the 3D concrete materials and mixtures. In addition, it has been described the 3DCP mechanical properties and the required laboratory tests to obtain these properties. These are as follows:

A. The pumpability of 3DCP could be measured using the rheometer and/or the pumpability index.

B. The printability of 3DCP is developed using the concrete penetrometer method introduced by ASTM C403, in which the initial setting time of the concrete mixtures is measured.

C. The durability of 3DCP can be conducted using the analytical model introduced by Kruger et al. [40] which focused on the yield stress of concrete mixture considering time. Also, the slump and slump flow tests may be used to determine the surface quality of 3DCP.

D. The workability of 3DCP can be obtained from the shape stability through the layer settlement test and the cylinder stability test.

Declarations

Availability of data and material. All data used or analyzed during this study are included in this article.

Competing of Interest

The author declares no competing interest.

Funding

No funding was obtained for this study.

Authors' Contributions

As the single author of this paper, Aboelhassan has been part of every single activity involving conceptualization, collection of data, literature review, writing, and revising.

Acknowledgment

The author would like to thank Tesserian Tech for their support.

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