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3D Concrete Printing with Industrial Waste: Effects of GGBS and Spent Catalyst on Fresh and Hardened Properties

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Abstract

3D concrete printing (3DCP) is a revolutionary technology in construction that deposits concrete layers in a controlled way, reducing formwork, labour, and material waste. However, its heavy reliance on Portland cement and natural sand raises sustainability and performance challenges. This study determines the incorporation of Ground Granulated Blast Furnace Slag (GGBS) and spent catalyst (SC)—two industrial by-products—as partial replacements for cement (20–40% of GGBS) and sand (10–20% of SC) in 3DCP mixtures. The objective is to assess how these substitutions affect fresh properties (flowability, extrudability, buildability) and hardened performance (compressive and flexural strength at 7 and 28 days). Sixteen mix designs were cast with a water-to-cement ratio of 0.5 and 0.5% superplasticiser. Fresh-state tests included flow table measurements, manual extrusion through a 15 mm × 40 mm nozzle, and five-layer stacking trials. 100 × 100 × 100 mm cubes and 100 × 100 × 400 mm prisms were used to assess the hardened properties. Results indicate that GGBS enhances flowability and long-term strength, while SC accelerates early strength gain; all mixes exhibited acceptable printability. The optimum mix—30% GGBS and 20% SC—achieved the highest 28-day compressive strength (50.61 MPa) and flexural strength (6.73 MPa). These findings demonstrate that GGBS and SC are viable sustainable alternatives in 3DCP, improving environmental impact and structural performance without compromising printability.

1. Introduction

A recently developed innovative technique called 3D concrete printing has a lot of potential for improving construction site productivity and safety [1], [2]. Construction time, cost, labour, material consumption, and waste production can all be significantly decreased by fabricating 3D structures layer by layer without the need for formwork [3]. The major issue that arises from this innovative technique lies in the preparation and optimisation of concrete materials, which must possess favourable printable properties that are compatible with the 3D print concrete.

This paper displays mechanical properties (compressive and flexural strength) and printable concrete, which need to have good buildability when many layers are placed from the bottom layer, while also having good flowability and extrudability qualities. Intensive studies from different researchers stated that cement, fine aggregate, and water comprise most of the 3D printing concrete combinations that are nowadays accessible in the literature and construction industry. To meet the requirements for 3D printed concrete's pumpability, printable concrete currently uses a substantially higher proportion of cement than mould-cast concrete (3DCP) [4]. Apart from that, this research shows the possibility of achieving printability characteristics, in comparison to traditional concrete, the mixture uses a significantly higher cement-to-sand ratio. To overcome the high use of natural resources (cement and sand), this paper will briefly study the use of industrial waste, which is ground granulated blast furnace slag (GGBS), to partially replace the cement, while spent catalyst (SC) will be used to partially replace the sand.

GGBS can be replaced with up to 80% Ordinary Portland Cement (OPC), according to previously conducted research, which also explains a lower amount of carbon dioxide gas if GGBS were implemented in the mixtures [5]. The most common type of cement used in concrete mixtures is Portland cement. Regardless of the usage of 3D concrete printing techniques, GGBS waste material will be incorporated into the concrete mixture in this research. Apart from GGBS, this study looks into the involvement of several research institutes and experts on the use of spent catalysts and properties, which are also waste from industrial processes, specifically from the petrochemical and petroleum refining sectors. After fulfilling their original purpose, these catalysts are frequently thrown away, which presents environmental issues. On the other hand, new research has shown that it is feasible to reuse these materials in building applications by investigating the possibility of employing wasted catalysts as a partial replacement for sand in concrete [6].

This study evaluated the compressive and flexural strength of 3DCP mixtures and fresh properties of concrete that are produced by partially replacing cement and sand with ground granulated blast furnace slag (GGBS) and spent catalysts through 3D printing. The consequences of properties on flowability, extrudability, and buildability of concrete mixes from intensive research will be evaluated in addition to their effects on the structural performance and durability of concrete.

2. Material Preparation and Method

2.1 Material Preparation

Cement, sand, coarse aggregate, water, superplasticiser, spent catalyst, and Ground Granulated Blast Furnace Slag (GGBS) are the materials utilised in this study to 3D print concrete. OPC, or ordinary Portland cement, was used as the main binder. The sand was sieved in compliance with BS EN 993-1:2012 [7], which stipulates that particles must be retained by a 0.075 mm sieve and pass through a 5 mm sieve. Particle sizes of the coarse aggregate utilised in the mix ranged from 5 mm to 10 mm. Tap water was utilized to mix the concrete in accordance with BS EN 1008 [8] standards. A superplasticiser of 0.5% by weight of cement was added to improve the mix's workability and flowability. Sand was partially replaced with a spent catalyst in 10% to 20% with 5% increments. The catalyst's particle sizes were similar to fine aggregate that could pass through a 5 mm sieve. Furthermore, because of the favourable effects of GGBS on the characteristics of concrete, it was utilised to partially replace cement in 10% increments of 20% to 40%. Fig. 1 shows the waste materials used in this study as partial replacement for cement and sand, which are Ground Granulated Blast Furnace Slag (GGBS) and Spent Catalyst.

(a) (b)

Fig. 1 *(a) Ground granulated blast furnace slag (GGBS); and (b) Spent catalyst*

2.2 Concrete Mix Design

This study used 0.5% superplasticiser and a water-to-cement ratio of 0.5. Table 1 lists the various mix proportions along with the corresponding test specimens. The mix design ratio of 1:3:1 (cement: sand: coarse aggregate) was used for this study's 3D concrete printing (3DCP) because it offered a reasonable level of resistance during extrusion, necessitating a controlled amount of effort to force the mixtures through the extruder [9]. Cement used in the mixtures had a density of 1440 kg/m^3, sand had a density of 1600 kg/m^3, and coarse aggregate had a density of 1500 kg/m^3. Superplasticisers were added in fixed amounts to improve the mix design's performance. The mix design of 3D printing concrete with various mix ratios of GGBS, ranging from 20% to 40% in increments of 10%, and spent catalyst from 10% to 20% in 5% increments, was cast. Three cube specimens were tested for 7 and 28 days, and their compressive strength was evaluated. Based on the outcomes of the three specimens in each experiment, an average compressive strength was determined. The specimen's cube dimensions were 100 x 100 x 100 mm. Three prisms measuring 100 x 100 x 400 mm were cast and left to cure for 28 days before being tested to measure their flexural strength. Adding 50% more to the specimen's total volume will make up for any volume loss that may occur from some mixes sticking to the tray during mixing and the buildability test carried out with the manual cement pump.

Table 1 *Mix design ratio of specimens*

Specimen	Cement (%)	GGBS (%)	Sand (%)	Spent Catalyst (%)
0G-0S	100	0	100	0
20G-0S	80	20	100	0
30G-0S	70	30	100	0
40G-0S	60	40	100	0
0G-10S	100	0	90	10
0G-15S	100	0	85	15
0G-20S	100	0	80	20
20G-10S	80	20	90	10
30G-10S	70	30	90	10
40G-10S	60	40	90	10
20G-15S	80	20	85	15
30G-15S	70	30	85	15
40G-15S	60	40	85	15
20G-20S	80	20	80	20
30G-20S	70	30	80	20
40G-20S	60	40	80	20

G – Percentage of GGBS used in the mix
S – Percentage of spent catalyst used in the mix

2.3 Fresh Properties Tests

In utilising concrete mixtures, it's significant to provide consideration to several types of essential characteristics, including the water-to-cement ratio, the type of aggregates used, the ease of extrusion and flow, and the strength between layers. When stacked, the concrete layers need to adhere to one another firmly for the structure to be stable. In order to ensure the hydration process may continue, it should not be completely hardened when extruding the following layer. In 3DCP applications, this parameter is essential for the workability of concrete. To preserve the strength of the structure and provide adequate adhesion between layers, each mortar layer's shape must also be thoroughly investigated [10].

2.3.1 Flowability Test

In order to evaluate the fresh concrete's flow consistency in the pumping system, flow table tests have been carried out. The flowability indicates that the flowability rises in parallel with an increase in the GGBS percentage [11]. Colyn et al. [12] reported that the ASTM C230/230 M guidelines were followed in conducting a small slump cone flow table test. The test involved using a conical bronze mould that was precisely 50 mm high, 70 mm top diameter, and 100 mm bottom diameter. The mould was placed carefully on a 255 mm diameter, 4.08 kg sturdy flow table, as shown in Fig. 2. After filling the mould with the fresh concrete mix, any excess air was taken out with the use of a tamping rod. To ensure that the sample was not disturbed, the mould was then carefully elevated and dropped 15 times. Cho et al. [13] describe how this procedure conveyed an impact load to the concrete mix. According to Cho et al. [13], the permissible flow diameter for 3D printing concrete should be between 150 and 165 mm for it to be considered acceptable for pumping and construction uses. On the other hand, 150–190 cm was suggested by Tay et al. [14].

(a) **(b)**

Fig. 2 *(a) Slump flow table test apparatus; and (b) Specimen flowability*

2.3.2 Extrudability Test

The term "extrudability" describes a mixture's capacity to be extruded as a single, consistent, dimension-controlled filament through a nozzle. Although extrudability was also found to be influenced by the size and shape of the nozzle used in the extrusion process, these two factors were discovered to be closely related to the rheology properties (e.g., yield stress) of a combination [15]. Le et al. [16] examined five mixes with varying ratios of sand to binder, including GGBS, and discovered a correlation between a mixture's pumpability and extrudability and the total particle size distribution of its component elements. In order to determine whether concrete combinations might be successfully extruded through a 15 mm × 40 mm nozzle, the extrudability test was conducted. Using a grouting pump, the mixtures were filled into the nozzle and extruded to produce 150mm of filament. The evaluation was based on whether the extrusion process was successful or not.

2.3.3 Buildability Test

Buildability is the potential of the print material to continue emerging from the nozzle via extrusion in the form of connected layers and withstand the weight of the next layers that are collected as a result of the printing phenomena. In order to achieve great buildability, the extruded filament must first maintain a stable form [17]. In the meantime, the printing mix needs to have sufficient early "green" strength so that the top layer won't fail or deform too much under the weight of the layers below it [12]. Most models that forecast a material's buildability performance in 3D printed construction are based on the material's mechanical properties in its fresh condition. The buildability test specimen is shown in Fig. 3, and Table 2 lists the necessity for designating a concrete mixture as printable.

Fig. 3 *Specimen of buildability test*

Table 2 *The prerequisites for determining if a concrete mixture can be printed [18]*

Aspect of 3DCP	Accepted	Not Accepted
Printability	1. Extrusion of the mixture from the nozzle was successful. 2. Printed mixture is consistent, which means the extruded material has no voids or dimensional deviations.	If none of the statements apply
Buildability	1. Printing material can stack in five layers without collapsing. 2. The difference in height between the first and fifth layers.	If none of the statements apply

2.4 Compressive and Flexural Strength

The aim of this test is to determine the flexural and compressive strengths of the hardened concrete. Cubic moulds measuring 100 mm x 100 mm x 100 mm were tested and cured after 7 and 28 days, while prism moulds measuring 100 mm x 100 mm x 400 mm were examined for flexural strength after 28 days of curing.

3. Results and Discussions

3.1 Flowability Test

Flowability, a critical measure of the workability of fresh mortar or paste, was assessed using the flow table test by averaging two perpendicular spread diameters as shown in Eq. (1), after applying standard drops. The results of the flowability measurement with a w/c ratio of 0.5 are presented in Table 3. The value of the diameter spread is in the range of 180 to 230mm. Specimen 30G-20S recorded the highest flowability of 230mm while Specimen 0G-20S had the lowest flowability of 180mm. The control mix (0G-0S) exhibited a flowability of 197 mm. Incorporating Ground Granulated Blast Furnace Slag (GGBS) alone maintained or slightly improved flowability, with the highest value of 215 mm observed at 30% GGBS. In contrast, the addition of Spent Catalyst (SC) alone led to a reduction in flowability, likely due to its high surface area and water demand. However, mixes combining GGBS and SC, such as 30G-20S, demonstrated enhanced flowability, achieving a maximum of 230 mm. This suggests that GGBS can counteract the stiffening effect of SC by improving particle packing and reducing water demand. Nonetheless, mixes with higher levels of GGBS or SC, such as 40G-10S or 20G-15S, showed diminished flowability, indicating a threshold beyond which the benefits declined. Overall, the results highlight that a well-balanced combination of GGBS and SC can significantly enhance flowability without increasing water or admixture usage. The researchers reported that the acceptable flow table value was between 150 mm to 230 mm [14], [19]. Therefore, the flow table readings obtained for all the mixtures were within the acceptable range of flowability.

$$f = \frac{D_1 + D_2}{2} \tag{1}$$

3.2 Extrudability Test

An extrudability test was performed to evaluate the ability of concrete mixtures to be smoothly extruded through a 15 mm × 40 mm rectangular nozzle using a manual pump setup. Since no standard currently exists for this test, visual assessment was used to determine print quality. A mixture was deemed successfully extruded if it maintained continuous flow without blockages or fractures. The results showed that all mixtures as shown in Table 3, including those with varying amounts of Ground Granulated Blast Furnace Slag (GGBS) and spent catalyst (SC), exhibited good extrudability. Even at high replacement levels (up to 60%), no clogging or interruptions occurred, indicating strong rheological compatibility among OPC, GGBS, and SC. These outcomes support the viability of using such industrial by-products in sustainable concrete formulations for 3D concrete printing, demonstrating that functional performance can be retained while reducing cement content.

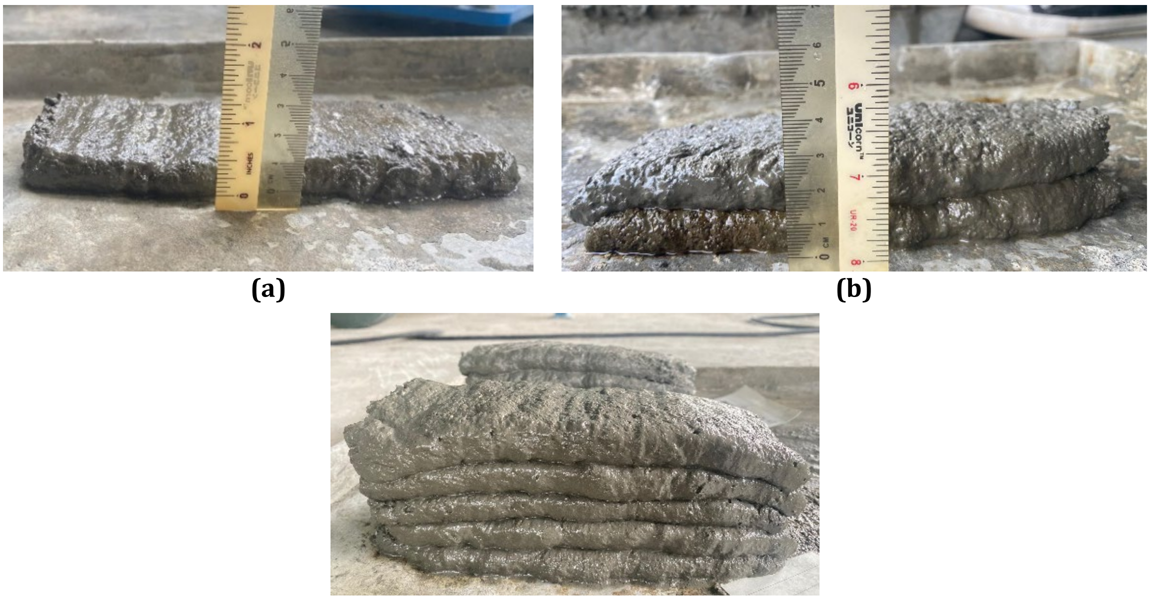
3.3 Buildability Test

Buildability, which reflects the ability of freshly extruded concrete to retain its shape and support successive layers, was assessed for all tested mixtures in a 3D concrete printing (3DCP) context. Each mixture successfully supported the stacking of five layers without exhibiting slumping, lateral spreading, or instability (see Fig. 4). This indicates that the inclusion of Ground Granulated Blast Furnace Slag (GGBS) and spent catalyst (SC), even at higher replacement levels (e.g., 40% GGBS and 20% SC), does not negatively impact the structural buildability of the mix. The consistent performance across all mixtures suggests good shape retention and early-age strength, essential for achieving print accuracy and minimising the need for external formwork. These findings complement the extrudability results, confirming that GGBS and SC are compatible with 3DCP requirements and are suitable as sustainable supplementary materials in printable concrete formulations. The layers are easily connected to one another; however, when the bottom layer supports the weight of the top layer, its thickness diminishes.

Table 3 *Flowability of different mixtures*

Specimen	D_1 (mm)	D_2 (mm)	Flowability (mm)	Extrudability
0G-0S	197	198	197	Yes
20G-0S	200	200	200	Yes
30G-0S	200	230	215	Yes
40G-0S	200	200	200	Yes
0G-10S	200	200	200	Yes
0G-15S	190	190	190	Yes
0G-20S	190	180	180	Yes
20G-10S	220	220	220	Yes
30G-10S	210	200	205	Yes
40G-10S	190	180	185	Yes
20G-15S	190	180	185	Yes
30G-15S	200	180	190	Yes
40G-15S	200	200	200	Yes
20G-20S	210	200	205	Yes
30G-20S	230	230	230	Yes
40G-20S	200	190	195	Yes

G – Percentage of GGBS used in the mix
S – Percentage of Spent Catalyst used in the mix



(a) (b) (c)

Fig. 4 *Buildability test: (a) First layer; (b) Second layer; and (c) Fifth layer*

3.4 Compressive and Flexural Strength Test

The control mix achieved a 28-day compressive strength of 35.49 MPa and a flexural strength of 4.43 MPa. GGBS alone led to moderate strength gains, while SC had a more substantial impact, with the 0G-15S mix reaching 44.22 MPa compressive and 6.76 MPa flexural strength. The combination of GGBS and SC produced the best results, with 30G-20S and 40G-20S achieving the highest compressive strength (50.61 MPa) at 28 days and 30G-10S reaching the highest flexural strength (8.03 MPa). These findings indicate that GGBS improves long-term strength [20], while SC enhances early age and overall performance due to its high reactivity. The results confirm that using these cementitious materials not only preserves printability but also significantly boosts mechanical strength, supporting their suitability for sustainable and high-performance 3D concrete printing applications. Compressive and flexural strength results reveal clear trends in both early-age (7-day) and long-term (28-day) performance (Table 4) and Fig. 5 and Fig. 6.

Table 4 *Compressive and flexural strength of 3DCP mixtures*

Specimen	Compressive Strength (MPa)		Flexural Strength (MPa)
	7 Days	28 Days	
0G-0S	30.40	35.49	4.43
20G-0S	31.64	39.19	4.20
30G-0S	31.24	37.60	7.56
40G-0S	30.07	36.50	7.82
0G-10S	35.83	37.23	5.61
0G-15S	43.86	44.22	6.76
0G-20S	33.00	38.05	4.58
20G-10S	41.67	45.24	7.18
30G-10S	42.67	45.30	8.03
40G-10S	34.29	47.53	6.74
20G-15S	31.87	43.52	7.04
30G-15S	25.51	44.64	6.82
40G-15S	33.41	48.83	6.86
20G-20S	33.40	46.23	6.87
30G-20S	38.50	50.61	6.73
40G-20S	36.62	50.61	6.25

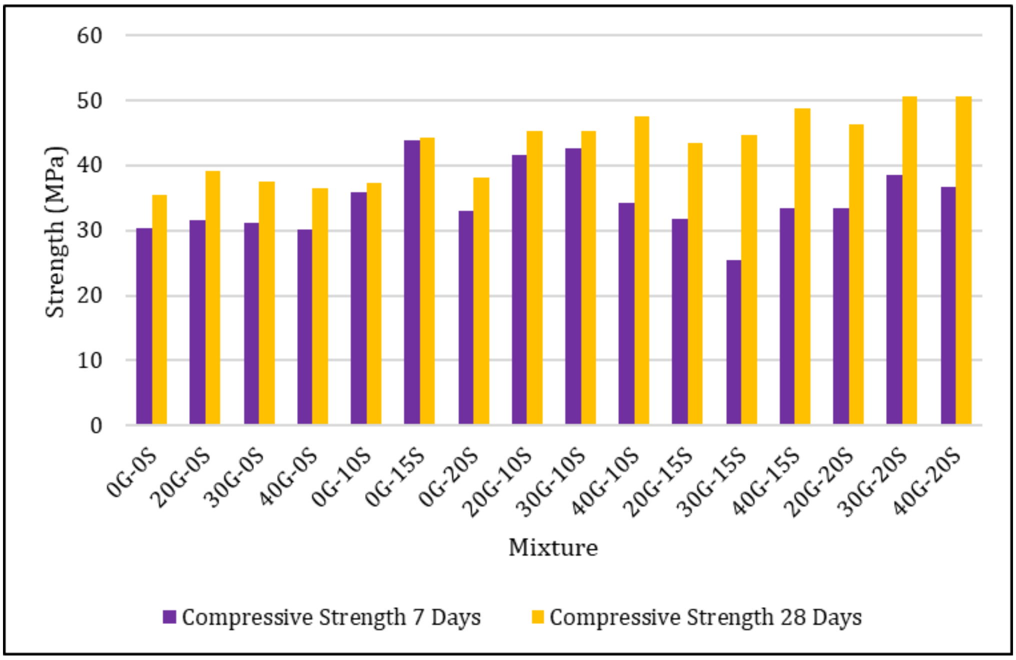


Fig. 5 *Compressive strength of 3DCP for 7 and 28 days*

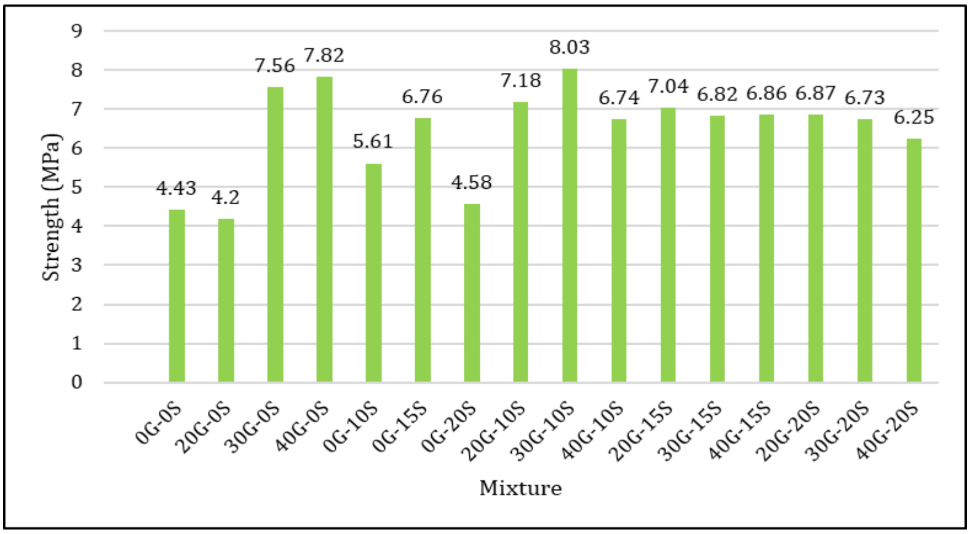


Fig. 6 *Flexural strength of 3DCP for 28 days*

4. Conclusion

This study begins with the 3D printing concrete technologies that are used with waste materials, such as spent catalysts and ground granulated blast furnace slag (GGBS), through a case study. The 3D concrete printing mix design appears to use 10%–20% spent catalyst as a substitute for partial sand, and 20%–40% GGBS in replacement of Portland cement. The reason for this is that a lot of studies usually use the concrete mixture's workability and compressive strength in 3D-printed structures. This study explores the use of Ground Granulated Blast Furnace Slag (GGBS) and Spent Catalyst (SC) as sustainable substitutes for cement and sand in 3D concrete printing (3DCP). Testing of fresh and hardened properties—including flowability, extrudability, buildability, compressive, and flexural strength—demonstrated that incorporating these industrial by-products enhances 3DCP performance while reducing environmental impact. Flowability improved with higher GGBS content, and all mixes showed smooth extrusion and maintained structural stability up to five layers. SC accelerated early strength gain, and the combined use of 30% GGBS and 20% SC yielded the highest 28-day compressive strength (50.61 MPa), the early strength at 38.50 MPa in 7 days, and flexural strength (6.73 MPa). These results confirm the potential of GGBS and SC as effective supplementary materials in 3DCP, with 30% GGBS identified as the optimal replacement level for balancing fresh and mechanical properties. The study advances sustainable construction by promoting industrial waste reuse in high-performance 3D printable concrete.

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Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *N. Ali, B. Zulkifli, S. R. Abdullah, M Ibrahim;* ***Data collection:*** *B. Zulkifli;* ***Analysis and interpretation of results:*** *B. Zulkifli, N. Ali, N. Salleh, N. A. Abdul Hamid;* ***Draft manuscript preparation:*** *B. Zulkifli, N. Ali. All authors reviewed the results and approved the final version of the manuscript.*

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