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The Potential of Glass Waste as Sand Replacement in Concrete Mix for 3DCP Technology

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Abstract

The global population generates millions of metric tons of glass waste annually, with only a small fraction being recycled, leaving the rest to accumulate in stockpiles. This underutilization of glass waste poses environmental concerns and a tremendous need to increase recycling efforts to address sustainability concerns in the construction industry. The construction industry has seen the emergence of 3D Construction Printing (3DCP) technology for innovative opportunities. However, current research in 3DCP predominantly focuses on conventional methods, which are not environmentally sustainable practices in concrete production. Therefore, the objectives of the study are to determine the optimal proportion of glass waste to be used as a sand replacement in 3DCP, to assess the resulting concrete's strength, and to seek the acceptance of glass waste as a viable sand replacement in 3DCP. The research conducts a quantitative approach by varying test levels of glass wase (0%, 10%, 15%, 20%, and 25%) as a partial substitute for sand in concrete mixtures. In addition, this study employs qualitative methods to gain the acceptance of construction industry players about glass waste as a sand replacement in 3DCP. The findings show the potential of glass waste as a sustainable material, reducing waste disposal costs, mitigating environmental pollution risks, and conserving valuable landfill space. In conclusion, this study contributes to the promotion of green concrete practices and aligns with the Sustainable Development Goals (SDG).

1. Introduction

Concrete production relies heavily on natural aggregates, particularly sand, which is depleting rapidly (Sharma & Sangamnerkar, 2015). Substituting sand with Glass waste (GW) at a precise ratio of 2 can mitigate the environmental impact of sand depletion, making the concrete industry more sustainable (Ahmad *et al.*, 2022). The increasing production of GW, driven by growing glass product demand, presents an opportunity to reduce concrete costs and landfill usage (Chandrappa & Biligiri, 2016). Glass is an ideal material for recycling, offering energy savings and sustainability benefits in concrete production (Gowtham *et al.*, 2021). Despite its advantages, GW usage in concrete remains limited due to the alkali-silica reaction (ASR), which reduces concrete durability and strength (Seddik Medah, 2019). Glass aggregates have distinct characteristics, including hardness, angular shape, low shrinkage, and good wear resistance (Dhir *et al.*, 2018). However, the interaction between alkalis in cement and silica in glass produces a silica gel that can swell upon absorbing water, leading to internal stresses and crack formation. Research indicates that the strength of GW concrete decreases with increasing GW ratio, but up to 30% glass powder can be incorporated without long-term negative effects (Park *et al.*, 2004).

The construction industry is transforming, embracing cutting-edge technologies such as 3D concrete printing, which holds the potential for fully automated building construction (Lin *et al.*, 2011). Concrete printing, a prominent construction-scale 3D printing technique, emerged in 2010 and is being explored by various businesses, including KA Bina in Malaysia, which aims to address housing ownership challenges among the B40 population (KA Bina, 2022). Simultaneously, the issue of glass waste has gained significance, with Malaysia generating one million tons of glass waste annually, most of which ends up in landfills due to the absence of a recycling system (Seddik Medah, 2019). Glass materials come in different forms, such as soda-lime glass for window glass and glass bottles, and boron-silicate glasses known for their resistance to corrosive substances and high-temperature tolerance. Silicon dioxide (SiO_2), primarily found in sand, has been the most effective glass-forming component, with potential applications in concrete production (Seddik Medah, 2019). Considering the environmental impact of glass waste disposal and the resource-intensive nature of concrete production, the research explores the utilization of glass waste as a sand substitute in 3D construction printing (3DCP), contributing to both waste reduction and sustainable construction practices.

The problem statement for the application of glass waste in concrete mix design is to address the environmental impact of glass waste by incorporating it into concrete production. Glass waste can be used as a partial replacement for cement or natural sand in concrete, leading to potential benefits such as improved tensile and flexural strength, workability, sulfate, and chloride resistance, and reduced drying shrinkage. However, challenges such as variations in the melting points of mixed glass and potential reduction in bonding strength between glass waste and the cement matrix have been identified. Ongoing research aims to optimize the use of glass waste in concrete production. Because of this, the construction industry was highly interested in using alternative resources such as recovered glass waste as a replacement for natural sand in concrete. In Australia, one million metric tons of used glass are gathered every year to be sorted and recycled (Arulrajah *et al.*, 2017).

3D concrete printing (3DCP) encompasses several challenges that hinder its widespread adoption. These challenges include reinforcing methods, sustainable processes, lack of technology, and material variability. Additionally, there is a need for a more holistic approach to assessing the environmental impacts of 3DCP, particularly in terms of sustainability considerations. The development of 3DCP is influenced by various research areas, such as material science, computational design, and structure and performance, and it is essential to address the interdisciplinary nature of 3DCP research. Furthermore, while proponents argue that 3DCP can reduce material usage and waste, as well as increase productivity, there is a need to carefully evaluate the sustainability tradeoffs associated with its adoption. Therefore, the problem statement for 3DCP revolves around overcoming these challenges and ensuring that its adoption is sustainable, efficient, and technologically viable. 3DCP was the new technology that was implemented in the construction sector. As of then, in the 3DCP sector, there was no research about the replacement of concrete to make it sustainable to achieve the SDG goals. Most of the studies focused on the conventional method without allocating some research for the good of the environment in 3DCP. Therefore, this study aimed to identify the optimum amount of glass waste, and the strength of concrete mixed with glass as a sand replacement in 3DCP. Furthermore, this study investigated the acceptance of glass waste as a cement replacement for concrete mix in 3D construction printing (3DCP).

The global production of glass waste is substantial, with only a fraction being recycled, posing environmental challenges (Kaza *et al.*, 2018). Concurrently, the construction industry is witnessing a surge in demand for concrete due to expanding infrastructure needs, leading to extensive extraction of natural resources like sand and gravel (Torres *et al.*, 2017). However, the overexploitation of natural sand reserves has far-reaching environmental consequences, including habitat disruption, water supply issues, and increased greenhouse gas emissions (Torres *et al.*, 2017). In response to these challenges, there is a growing interest in utilizing recovered glass waste as a sustainable alternative to natural sand in concrete production (Arulrajah *et al.*, 2017). While glass recycling rates vary globally, the substantial volume of single-use glass items, such as beverage bottles, contributes significantly to solid waste (Kaza *et al.*, 2018). By repurposing crushed glass as a sand substitute in concrete, not only can the demand for natural sand be reduced, but also the volume of glass waste sent to landfills can be minimized. This study seeks to determine the compressive strength of concrete mix, to identify the optimum percentage, and to investigate the acceptance of glass waste as sand replacement for concrete mix in 3D construction printing (3DCP).

2. Experimental Procedure

2.1 Concrete Mix Design

In this study, the concrete mix design is based on the design mix of KA Bina, which is a company that provides a printer of 3DCP and the first company 3DCP in Malaysia with specific material quantities required for different concrete compositions. The study focuses on achieving a target strength of 30 MPa (M30) concrete, with a recommended density range of 2200 to 2400 kg/m^3. To account for potential errors or spills during the mixing process, the volume of the concrete cube moulds is increased by 10% using the DOE approach. While the quantities of water, cement, and sand remain constant across all samples, the amounts of aggregates vary for different samples. This variation is due to the inclusion of glass waste, with samples containing 10%, 15%, 20%, and 25% by weight of glass waste, as outlined in Table 1, which summarizes the concrete mix design parameters.

Table 1 *Research concrete mix design*

Concrete mix design	Value
Characteristic strength	30 N/mm^2 at 28 Days
Target mean strength	30-38.25 N/mm^2
Water cement ratio	0.45
Slump	30-50 mm

2.2 Preparation of Materials

This section discusses the materials necessary for this experiment, which include glass waste (GW), cement, natural fine aggregate (NFA), coarse aggregate, and water. In this study, glass aggregate (a combination of colors crushed to small particles) is utilized. Glass waste with a maximum size of 4.75 mm is used as a partial replacement of fine aggregates in the concrete mixture. The glass waste was collected at SWM Recycle Centre, Sri Gading, Johor. Before it is used, it will go through the sieving process by BS EN 12620:2013. Fig. 1(a) shows the glass waste bottle before it was crushed, and Fig. 1(b) shows the glass waste bottle after crushing.


(a) (b)

Fig. 1 *(a) Glass waste before crush; (b) Glass waster after crush*

2.3 Sieve Analysis

The purpose of this study was to conduct a sieve analysis to determine the particle size distribution and assess the acceptability of fine and coarse aggregate for concrete mixing. Furthermore, the laboratory testing was carried out in compliance with BS EN 12620:2013. The maximum size for fine aggregate in aggregate is 4.75 mm, whereas for coarse aggregate it is 10 mm.

2.4 Concrete Mix Process

Each sample has 3 specimens to record the average of their maximum result of each strength. In this study, the GW indicates the abbreviation glass waste aggregate, and the number that follows indicates the percentage of replacement of fine aggregate. 30 samples are prepared. The volume of each cube-shaped sample of concrete is 3.375 m^3 (150 mm x 150 mm x 150 mm). Slump testing is an also adopted method to assess the workability of fresh concrete due to its simplicity and practicality. The test involves using a cylindrical mold with dimensions of 200 mm at the base, 100 mm at the top, and a height of 300 mm. A 16 mm diameter tamping rod and measuring tape are used for the testing, adhering to the guidelines specified in BS EN 12350-2:2019 for standardized and accurate evaluations. Quantities of raw material preparation per trial mix of 3.375 m^3 including increased by 10% of wastage as shown in Table 2.

Table 2 *Quantities of ingredients per 3.375 m^3 of concrete*

Ingredient	% of GW in concrete (by weight)				
	GW-0	GW-10	GW-15	GW-20	GW-25
Water-cement ratio	0.45	0.45	0.45	0.45	0.45
Water (kg)	4.25	4.25	4.25	4.25	4.25
Cement (kg)	13.3	13.3	13.3	13.3	13.3
Coarse aggregate (kg)	19.42	19.42	19.42	19.42	19.42
Admixture (ml)	0.43	0.43	0.43	0.43	0.43
Fine aggregate (kg)	21.15	19.04	17.98	16.92	15.86
Glass waste (kg)	-	2.1	3.2	4.2	5.3

2.5 Slump Test

Slump testing is a widely used method for evaluating the workability of fresh concrete due to its simplicity and practicality. The inside dimensions of the test mold are as follows: a diameter of 200 mm at the base, 100 mm at the top, and a height of 300 mm. This test utilized a tamping rod measuring 16 mm in diameter and 600 mm in height, together with a measuring tape. The laboratory will conduct the testing according to the specifications outlined in BS EN 12350-2:2019. Fig. 2 shows the activity of the slump test.

Fig. 2 *Slump test*

2.6 Curing Process

According to the British Standard BS EN 13670:2009, curing of concrete typically spans a duration of 7 to 28 days. Proper curing is essential for achieving high-quality concrete by facilitating the initial phases of hardening. The primary goal of the curing process is to enhance cement hydration, thereby strengthening and prolonging the life of the concrete. Moreover, it plays a crucial role in regulating thermal and hygroscopic interactions between the concrete and its environment. Essentially, the objective of curing is to maintain adequate moisture in the concrete for 7 and 28 days, allowing the chemical reactions between cement and water to fill the voids in the fresh cement paste to the desired extent. Fig. 3 shows the concrete curing process.

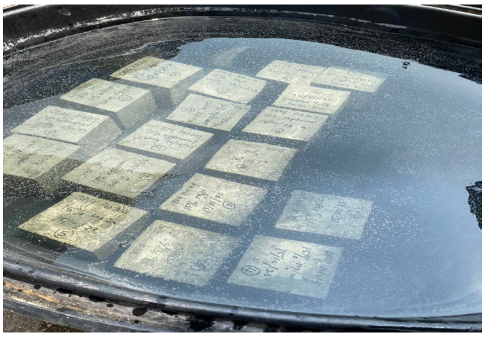


Fig. 3 *Concrete curing process*

2.7 Compressive Strength

This test method determines the compressive strength of a concrete cube sample of 150 mm x 150 mm x 150 mm by BS EN 12390-3:2019. The compression strength of the cube test is widely used to determine the strength of concrete all over the world. Fig. 4 shows the concrete cube sample before the compressive strength is made. Apply the load gradually, without shock, at a rate of 140 kg/cm^2/min until the specimen fails as shown in Fig. 4. Maximum load has been recorded and take note of any unusual failure characteristics.

Fig. 4 *Compressive test*

2.8 Qualitative Method

To fulfill the third aim of the study, qualitative interview sessions were conducted. An interview was conducted to obtain information immediately. The qualitative method is used to gain an understanding of underlying reasons and motivations. It focuses on groups, individual in-depth interviews, or group discussions. Besides, it is used to uncover prevalent trends in thought and opinion (Moser & Korstjens, 2017). For this research, this method is used using interview sessions with consultants and developers on how their opinions about the acceptance of the implementation of glass waste in concrete for 3DCP in Malaysia. Table 3 shows the respondent's background.

Table 3 *Respondent background*

Question	R1	R2	R3
Organization	Consultant	Consultant	Consultant
Position	Co-founder	Senior engineer	Project manager
Work experience 3D printing construction 3DCP	> 10 years	> 10 years	5 years

3. Results and Discussion

3.1 Sieve Distribution on Natural Fine Aggregate (NFA) and Glass Waste (GW)

The grading curve for NFA & GW, which represents the size distribution of aggregate particles in the sample, is determined through dry sieve analysis. Also, to ascertain certifications and compliance with design and production control specifications in terms of specifications. The obtained results are then compared to the BS 12620: 2013 standard for concrete components derived from natural sources for both specimens. Table 4 and Table 5 show the sieve analysis data for NFA and sieve analysis data for GW. Fig. 5 shows a semi-log graph for NFA and GW.

Table 4 *Sieve analysis of NFA*

Sieve Size	Mass of Sieve (g)	Mass of Sieve & NFA (g)	NFA Retained (g)	NFA Retained (%)	Passing of Cumulative Percentage (%)
5mm	400.24	400.24	0.0	0.0	100.0
2mm	400.2	423.0	21.0	4.2	95.8
1.18mm	356.2	417.21	61.0	12.2	83.6
600 µm	334.01	598.36	264.4	52.9	30.7
300 µm	290.69	388.13	97.4	19.5	11.2
150 µm	360.67	406.1	45.4	9.1	2.2
Pan	400.24	400.24	0.0	0.0	0
		Total	500.0	100.0	

Table 5 *Sieve analysis for GW*

Sieve Size	Mass of Sieve (g)	Mass of Sieve & GW (g)	GW Retained (g)	WG Retained (%)	Passing of Cumulative Percentage (%)
5mm	400.24	400.24	0.0	0.0	100.0
2mm	402.0	598.3	196.30	39.26	60.74
1.18mm	356.2	450.63	94.43	18.89	41.85
600 µm	334.01	450.4	116.39	23.28	18.58
300 µm	290.69	358.48	67.79	13.56	5.02
150 µm	360.67	376.35	15.68	3.14	1.88
Pan	400.24	359.12	9.38	1.88	0.01
		Total	500.0	100.0	

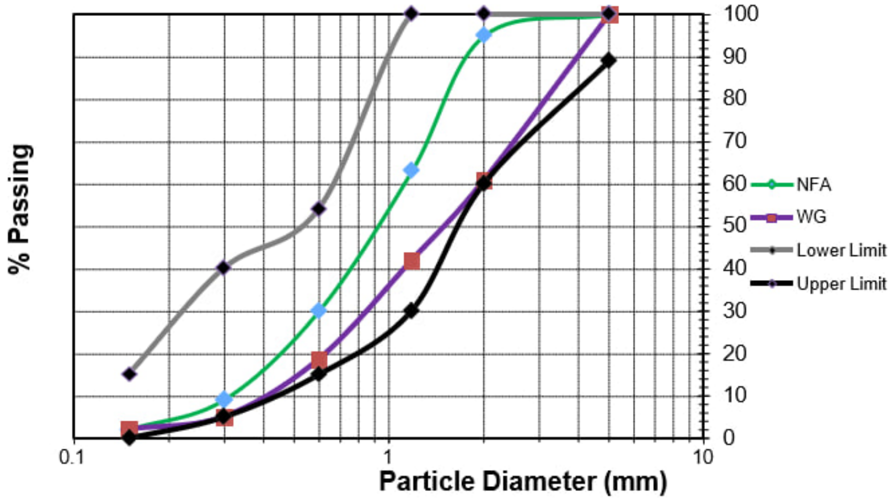
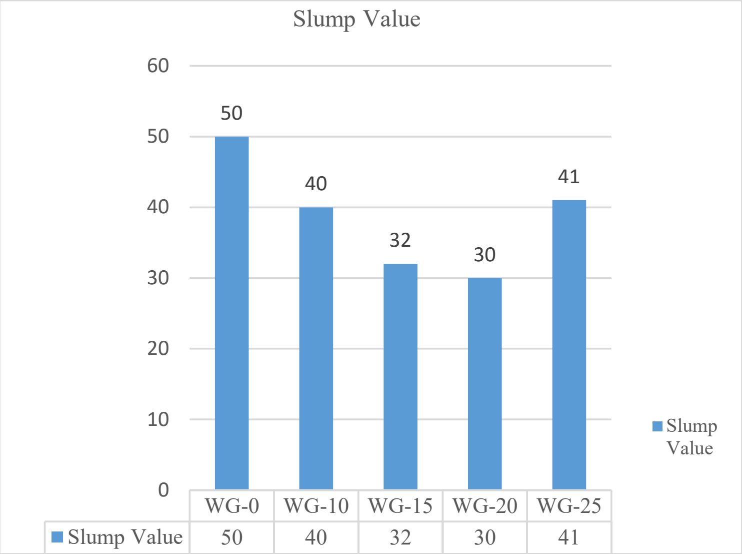


Fig. 5 *Semi-log graph for NFA and GW*

3.2 Slump Test

To evaluate the consistency or workability of the utilized concrete, the slump test is required. Concrete that contains an inordinate amount of water will become brittle. In the context of concrete mix design, the target droop ranges from 30 mm to 50 mm. This value is commonly employed to ascertain the suitability of concrete for use in the construction of structures. A slump test was conducted on each quantity of concrete mixture to ensure that the final product was of consistent quality throughout the preparation process. In this test, every decline that was measured was an authentic slump. The clear graphic in Fig. 6 illustrates the trend of the decline effect of GW replacement. The findings presented in Fig. 6 demonstrate a clear correlation between depression values and the proportion of Glass waste (GW). There is a consistent downward trend in drop as the percentage of GW increases, which signifies a decline in workability. Notwithstanding increased levels of GW replacement, the decline values persist within the designated range of 30 to 50 mm.

The decrease in drop can be ascribed to Glass waste's comparatively elevated water absorption properties in contrast to conventional aggregates. Nevertheless, efforts have been made to mitigate this consequence by modifying the proportion of fine to coarse aggregate throughout the blending procedure. This study establishes connections with previous investigations, including the one conducted by Sharifi *et al.* (2013), which documented that substituting glass for natural fine aggregate results in a reduction in the unit weight of concrete. The clear graphic in Fig. 6 illustrates the trend of the decline effect of GW replacement.



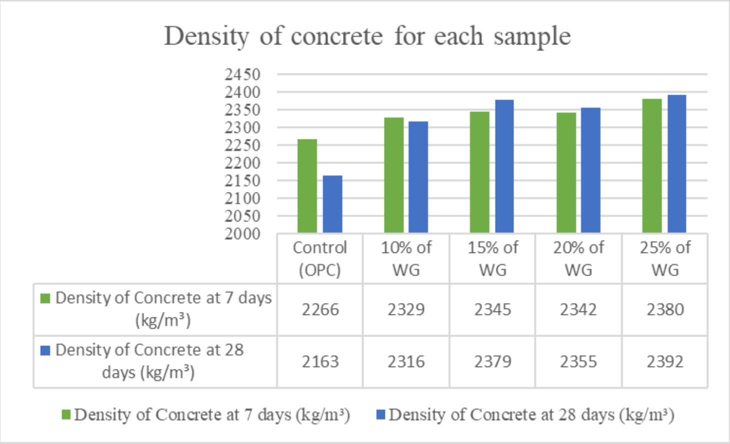
	WG-0	WG-10	WG-15	WG-20	WG-25
🟦 Slump Value	50	40	32	30	41

Fig. 6 *The variation of the slump with the replacement of GW*

3.3 Concrete Density

Normal-weight concrete ranges between 2200 and 2400 kg/m^3 (Ouda, 2015). The density of concrete is subject to variation based on factors such as the quantity and density of aggregate and additional GW, as well as the concentrations of entrained air, water, and cement (Ouda, 2015). As expressed in Fig. 7, the increase in density of the concrete from day 7 to day 28 is due to its hydration process. The constituents of the concrete mixture undergo a chemical reaction with water throughout this procedure, resulting in the creation of novel compounds that contribute to the density and composition of the solidified concrete. As the hydration process progresses, the density and strength of the concrete increase.

Adding the GW component to the concrete mixture in varying proportions is presumed to influence the hydration process and the overall density of the concrete in particular ways. The potential uses of GW in concrete are diverse, including serving as a binder, infill, or material that facilitates further chemical reactions that gradually increase the density. Fig. 7 illustrates the impact of GW on the density of concrete at two distinct curing periods. It demonstrates that irrespective of the proportion of GW incorporated, all samples exhibit a consistent upward trajectory in density over time. This property is highly valued in the construction industry due to its association with enhanced structural stability and durability. The chart functions as a graphical depiction of empirical data, providing insights that can be utilized to refine concrete mixture formulations for engineering purposes. Fig. 7 illustrates the density outcome of the examined GW sample.



	Control (OPC)	10% of WG	15% of WG	20% of WG	25% of WG
🟩 Density of Concrete at 7 days (kg/m^3)	2266	2329	2345	2342	2380
🟦 Density of Concrete at 28 days (kg/m^3)	2163	2316	2379	2355	2392

Fig. 7 *Density of concrete for each sample*

3.4 Compressive Strength

Fig. 8 shows the compressive strengths of the NFA and GW specimens at the 7-day and 28-day time points. An upward trend in compressive strength was noted as age increased. This is a strong indication that stamina is being developed because of the hydration of cement. The inclusion of glass waste particles in concrete can result in increased porosity due to their irregular shape and surface characteristics. This elevated porosity can weaken the structural integrity of the concrete by creating pathways for moisture ingress and reducing its ability to withstand compressive forces. In contrast, conventional sand, which packs more densely, leads to lower porosity and, consequently, higher compressive strength. Research by Seddik Meddah (2019) indicated that a 20% replacement of glass resulted in a compressive strength of 31.5 MPa at 28 days. Additionally, variations in the pozzolanic reactivity of glass waste, influenced by factors such as composition and thermal history, can contribute to differences in compressive strength. Pozzolanic materials, when activated by calcium hydroxide produced during cement hydration, participate in the formation of additional binding materials within the concrete, thereby enhancing its strength. However, the pozzolanic reactivity of glass waste can vary between different batches or sources, potentially impacting the overall strength of the concrete.

The concrete mix design and the inclusion of specific admixtures are critical considerations that influence compressive strength. Such as KA Bina (2022) in their test with additive for 3DCP recorded 40.1 MPa on the control which is GW-0%. Variations in the proportions of cement, water, admixtures, and glass waste can lead to differences in the hydration process, curing conditions, and consequently, the compressive strength of the concrete. As can be seen in Fig. 8, at GW-20% it achieved 44.3MPa more strength than KA Bina (2022) and previous research. In conclusion, these multifaceted factors collectively contribute to the compressive strength disparity between concrete mixes with and without glass waste replacement. Therefore, comprehending and optimizing these factors is pivotal when incorporating glass waste into concrete mixtures, ensuring that resultant structures meet the necessary standards for strength and durability. The relationship between the slump value and compressive strength utilized in this study is presented in Fig. 9.

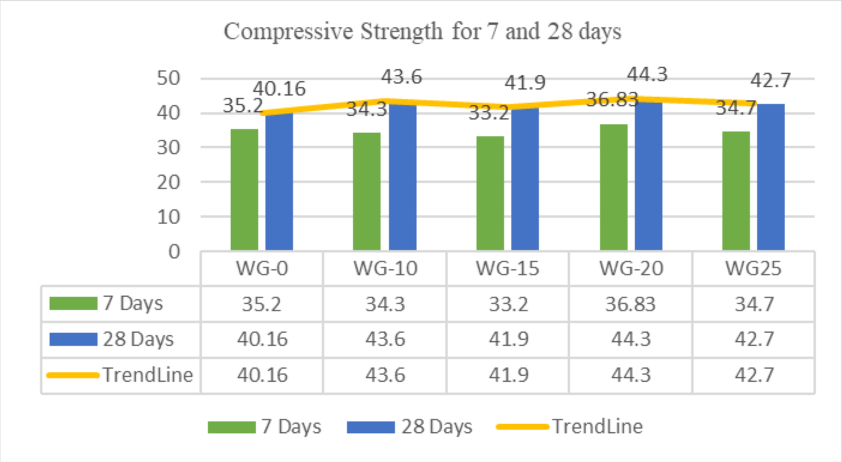


Fig. 8 *Compressive strength for 7 and 28 days*

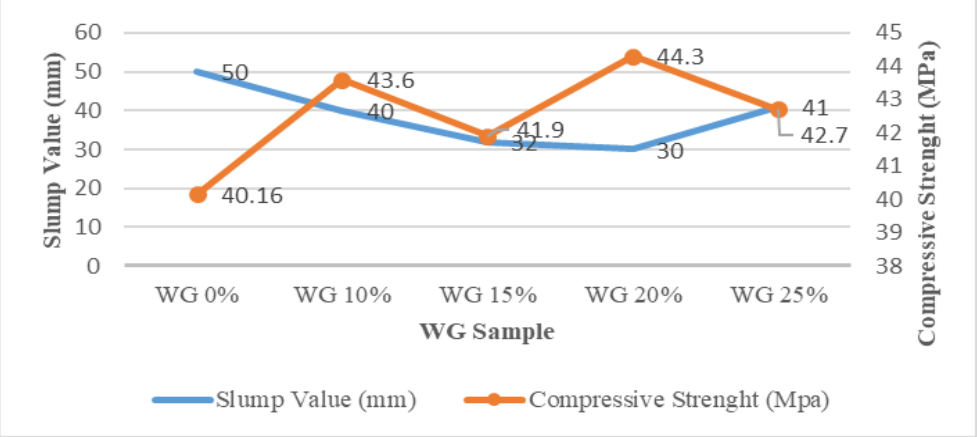


Fig. 9 *Relationship between the slump value and compressive strength*

3.5 Optimum Percentage of Glass Waste as Sand Replacement for Concrete Mix in 3D Construction Printing (3DCP)

The optimal quantity of glass waste to be used as a substitute for sand in the concrete mixture for 3DCP has been established at 4.2 kg, equivalent to a 20% substitution of the sand ingredient. The specific proportion has been meticulously computed and chosen for a variety of persuasive justifications. First and foremost, sustainability is of utmost importance. The 20% replacement rate perfectly corresponds with sustainable construction techniques by significantly lowering the use of limited natural resources, such as sand, while simultaneously recycling waste materials.

Furthermore, thorough testing and analysis have conclusively proven that this 4.2 kg substitute successfully upholds the necessary strength and long-lasting quality of the 3D-printed concrete, guaranteeing adherence to strict construction regulations. The precision of this % guarantees that the structural performance remains intact. Moreover, practicality is crucial in this decision-making process. An increase in replacement percentages could potentially impede the extrusion and printing process. However, when the replacement percentage is set at 20%, an ideal equilibrium is reached in terms of both workability and performance in 3DCP. Cost-effectiveness is an important consideration. This amount is inexpensive since it decreases waste disposal expenses and keeps the entire cost of the concrete mix fair.

Lastly, and equally importantly, this 20% substitution considerably adds to the reduction of the environmental impact of construction. Through the recycling of 4.2 kg of discarded glass, 3DCP projects can reduce CO_2 emissions, preserve natural resources, and achieve their environmental obligations. The decision to choose 4.2 kg as the appropriate amount of glass waste for replacing sand in 3D Construction Printing is based on solid reasoning. This choice considers sustainability, structural strength, practicality, cost-effectiveness, and environmental impact factors. Table 6 shows the optimum percentage of glass waste. Fig. 10 illustrates the concrete mixture subjected to compressive strength testing.

Table 6 *Optimum percentage of glass waste*

% of GW in concrete (by weight)	Ingredient		
	Compressive Strength at 28 Days (MPa)	Fine aggregate (kg)	Glass waste (kg)
GW 0%	40.16	21.15	-
GW 10%	43.6	19.04	2.1
GW 15%	41.9	17.98	3.2
GW 20%	44.3	16.92	4.2
GW 25%	42.7	15.86	5.3

Fig. 10 *Concrete mixture after compressive strength*

Based on this research presents a notable improvement compared to Seddik Meddah's (2019) research, where it is reported to achieve a compressive strength of only 31.5 MPa by replacing 20% of sand with a significantly larger quantity of waste glass, totaling 146 kg. In contrast, this research utilized a much smaller quantity of waste glass, just 4.2 kg, as a 20% replacement for sand and achieved an impressive compressive strength of 44.3 MPa within the same 28-day curing period. This stark contrast underscores the superior performance of this concrete mixture, which not only used less waste glass but also yielded significantly higher compressive strength, demonstrating its potential for more efficient and sustainable construction practices.

Furthermore, the results also surpass the typical compressive strength achieved by industries engaged in 3D Construction Printing (3DCP). In the 3DCP industry, concrete mixtures typically attain a compressive strength of around 40.1 MPa at the control level within the same 28-day timeframe (KA Bina, 2022). The fact that these findings achieved a compressive strength of 44.3 MPa with the incorporation of waste glass highlights the advantages of this innovative approach, as it not only outperforms industry standards but also offers an environmentally friendly solution for enhancing the strength and durability of 3D-printed structures.

In summary, this research's remarkable achievement of 44.3 MPa compressive strength with just 20% waste glass replacement (equivalent to 4.2 kg) not only surpasses Seddik Meddah (2019) study but also exceeds the typical results observed in 3DCP industries. These findings underscore the tremendous potential of waste glass as a sustainable and high-performance material in concrete mixtures, offering a promising avenue for advancing the efficiency and quality of construction practices.

3.6 Qualitative Method

Every interview session that the researcher conducted was meticulously recorded, down to the last detail, to verify the accuracy of the data obtained from the respondents. The interview questions consisted of two parts which are Part A (Respondent Background) and Part B (Stakeholders feedback regarding the viability of glass waste in concrete design for 3DCP). In summary, the industries accepted the new technology that can be implemented into industries used. The interview highlighted the promising potential of glass waste in 3D concrete printing, driven by the industry's commitment to sustainability and eco-friendly practices. It underscored the importance of research, innovative design, and collaborative efforts between stakeholders to harness the full benefits of glass waste in the construction sector while addressing structural, economic, and environmental considerations (KA Bina, 2022). Table 7 shows the table of the summary interview.

Table 7 *Summary for qualitative method findings*

Question	R1	R2	R3
Comments about glass waste in concrete design for 3D Printing (3DCP). Is it possible in your view?	Sustainable 3D printing supports goals. Cost competitiveness is vital for sustainability.	Glass waste: sustainable construction option. Engineers embrace eco-friendly glass alternatives.	Glass waste in 3DCP: research needed. Transforming glass waste into resources.
What are the specific challenges that the construction industry may face when integrating glass waste into 3D-printed concrete projects, and how can these challenges be addressed?	Concern: consistent glass waste supply. Government incentives for sustainable adoption.	Challenge: matching glass to sand. Government involvement for effective solutions.	Integrating glass waste: a comprehensive approach. Challenges and solutions in construction.
Are there any emerging trends or innovations in the construction industry related to glass waste utilization in 3D printed concrete, such as new printing technologies or design approaches?	Glass waste benefits Sustainable Development. Construction adoption aligns with trends.	Construction industry, SDGs, and glass. Glass waste aids sustainability goals. clearance.	Emerging trends: 3D printing, glass. Eco-friendly construction and innovation.

4. Conclusion

In the analysis of the experimental data, various compositions of concrete incorporating different percentages of glass waste, ranging from 0% to 25%, were thoroughly examined. However, it was determined that the composition containing 20% glass waste emerged as the optimum choice This specific composition demonstrated significantly higher strength compared to the others, underscoring its potential to strike a balance between sustainability and structural performance, making it a promising option for eco-friendly construction practices. The strength analysis of the various concrete mixtures produced using 3DCP yielded valuable insights. Notably, the control mix with 0% glass waste exhibited the smallest difference in compressive strength, with only a 4.96 MPa variation. Conversely, the mix containing 25% glass waste demonstrated the largest difference of 10 MPa. Ultimately, the conclusion drawn from these findings underscores the optimal balance achieved with a 20% glass waste composition, which boasted a remarkable compressive strength of 44.3 MPa as an environmentally friendly and structurally sound construction material. This study project has effectively shown that it is possible to use glass waste in 3D concrete printing technology. The project followed a systematic strategy that involved analyzing the materials, designing the mixture, conducting printing experiments, testing the mechanical properties, and assessing the environmental impact. This accomplishment demonstrates that glass waste can fulfill the necessary performance standards while also decreasing the environmental impact. As a result, it not only enhances the effectiveness and sustainability of construction methods but also tackles the urgent issue of glass waste management. The results of this inquiry establish the groundwork for the extensive implementation of an environmentally benign and economically efficient solution, advancing a more sustainable future for the construction sector.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhamad Aniq Haziq Zaidi, Narimah Kasim;* ***data collection:*** *Muhamad Aniq Haziq Zaidi;* ***analysis and interpretation of results:*** *Muhamad Aniq Haziq Zaidi, Narimah Kasim;* ***draft manuscript preparation:*** *Muhamad Aniq Haziq Zaidi, Narimah Kasim, Idi Namara. All authors reviewed the results and approved the final version of the manuscript.*

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