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UTILIZATION OF RECYCLED GLASS FOR 3D CONCRETE PRINTING: RHEOLOGICAL AND MECHANICAL PROPERTIES

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Abstract

The disposal of post-consumer glass has been a major issue due to its inert properties that may cause environmental effects. While recycling of these glass is only feasible if the waste glass recovered is sorted into its different colour to prevent chemical incompatibility in the manufacturing process. 3D printing in building and construction have gain increasing attention in the past decade and provide a potential to sustainably utilize the recycled unsorted glasses. This paper examines the use of recycled glass as the fine aggregates for 3D concrete printing applications. Despite the several studies done on the use of recycled glass in concrete, there is a lack of focus on the rheology of the material which is essential to the performance of the material in 3D concrete printing. Although results have shown that the mechanical strength for the recycled glass concrete is lower than the sand aggregates concrete, yet the flow properties of the former is better than the latter. Nonetheless, a balance between the mechanical strength and flowability of the mix design should be studied. The future work revolves around the optimization of the mix design using a combination of sand and recycled glass, adjusting the gradation of recycled glass particles and addition of accelerators to improve its buildability and mechanical strengths.

Keywords: Recycled glass; 3D concrete printing; sand gradation; rheology; mechanical strength.

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1. Introduction

With the growth in the applications of glass, the rate of waste glass generation have escalated significantly [1]. The disposal of post-consumer glass has therefore become a major issue worldwide due to the increase in demand for landfill space, a becoming scarce resource [1, 2]. Furthermore, glass being a non-biodegradable material due to its inert nature is not suitable for landfill and can cause severe environmental effects [1]. Hence, waste glass needs to be recovered from waste destined for landfill and recycled to reduce such harmful effects. Nonetheless, glass materials which can be recycled without changing its chemical composition, is often recovered for manufacturing new glass products [1, 2]. The above way of glass recycling however, is only feasible if the glass is recovered and sorted into different colors to prevent chemical incompatibility in the manufacturing processes[1, 2]. Whilst such method exists, it is often challenging to sort the glass into different colors as most waste glass is co-mingled [2]; thus, an alternative measure is required to utilize this mixed colour recycled glass. Moreover, despite various methods of recycling the waste glass, the rate of recycling is still considerably low [1, 3].

Over the past 70 years, research has been conducted to incorporate crushed recycled glass into construction materials [1]. Crushed recycled glass had been used as fine aggregates for cementitious materials while fine glass powder is also used as supplementary cementitious material (SCM) in concrete. The use of recycled glass as fine aggregates in concrete creates another channel for mixed color recycled glass and reduces the demand for sand which is a finite natural resource [4]. Application of fine glass powder as SCM reduces the usage of cement and thus, reduces the environmental pollution and energy consumption for cement production [5]. However, one major problem in the use of recycled glass aggregates in concrete is the effect of alkali-silica reaction (ASR) which can cause cracks and harm the structural integrity of concrete [1, 2, 4].

Three-Dimensional Concrete Printing (3DCP), also known as additive manufacturing in building and construction, is the combination of cementitious material extrusion with robotic motion control to build structures through a layering operation [6]. A rise in interest towards the 3DCP technology in the past few decades can be observed both in academia and the industry[7-9]. This can be mainly attributed to the advantages that it provides; no formwork requirement and human intervention due to the integration of automation which largely reduces the time to build a structure. Moreover, this technology also permits design for structural optimization because of its ability to create complex structures [5, 9-11].

In most of the existing 3DCP literature, only fine aggregates were used [10, 12, 13]. The size of the aggregate is limited by the material delivery system. Common material in 3DCP utilizes river sand as the aggregates [5, 6]. The replacement of river sand by recycled glass in the material creates a new avenue for waste glass and reduces the demand for river sand, a depleting resource. This paper explores the potential of incorporating recycled glass aggregates into cementitious material that is used for 3D concrete printing.

2. Related works/background

2.1 Existing 3D concrete printing (3DCP) materials

Many existing literatures have examined the properties of materials for 3DCP. Generally, some fresh characteristics that the materials should possess are, high extrudability and flowability for conveying the material, high shape retention of material upon extrusion and high buildability to support the weight of the subsequent layers being deposited above [5, 10, 12, 13]. Several researches have used different cementitious material mix design to achieve such requirements for 3DCP [14]. Other than the common cement and water mixture, researchers have also added various SCM and admixtures into their mix design to alter the properties of the materials for use in 3DCP applications. Table 1 shows the summary of materials used by various researchers. Tay et al. [5] uses a low-cost material with good extrudability and buildability and added superplasticizer at 1.05% of water weight to improve the flowability [5].

Le et al. identified an optimum mix design with sand/binder ratio at 1.5 and with a water/binder ratio of 0.26. To obtain a high-performance printable concrete, superplasticizer and retarder at 1% and 0.5% by weight of binder was also added. F. bos et al. [9] customized a cementitious material with siliceous aggregates that have an optimized particle size distribution with maximum particle size of 1 mm. Other additives were also added to achieve various properties; improving the material pumpability, obtaining thixotropic behavior and reducing crack formation due to early drying.

C. Gosselin et al. [12] designed a novel premix with a low water/(cement +sand) ratio of 0.1, resulting in an ultra-high performance self-placing mortar. Polymer-based resin are added to enhance quality of interface between layers while accelerating and thresholding agents are added to obtain rheological properties required for 3DCP. On the other hand, Panda et al. [15] developed a green construction material to be used for 3DCP based on industrial by-products such as fly ash

and ground granulated blast furnace slag (GGBS) [15]. An alkaline reagent (potassium silicate) was added to activate the cementitious properties of the material.

In general, various materials have been developed in application to 3DCP and discussed in this section. Such materials are flowable enough to be conveyed through the delivery system and stiff enough upon extrusion to hold its shape as well as the weight of subsequent layers relating to the thixotropic properties of the material [16, 17]. Hence, to understand the materials behavior, it is essential to study its rheological properties and the factors affecting it. However, due to the number of factors governing the fresh properties of the concrete, the control of rheology can be a complex area of study.

Most cementitious materials used for 3DCP in various studies utilizes sand as the aggregates. In this study, the possibility of using recycled glass as the aggregates is explored and the effect on the properties related to 3DCP with comparison to the sand aggregates is investigated. It is well understood that the various factors such as the binder mix design, gradation of aggregates and addition of admixtures plays a major role in affecting the properties of cementitious materials. Nonetheless, this study aims to compare the effect of different types of aggregates, hence, other factors such as gradation, volume fraction of aggregates and binder composition are kept constant in order to minimize any variance. To the best of the author's knowledge, no previous research has been conducted on the application of concrete with recycled glass aggregates or fine glass powder as cement replacement in 3DCP.

2.2 Recycled glass aggregates concrete

The research of using recycled glass aggregates in concrete has been going on for many decades. However, various researchers have observed conflicting results between the properties of the concrete incorporating recycled glass aggregates and sand. The concrete properties commonly examined and compared are compressive strength, flexural strength and splitting tensile strength.

Generally, research using glass as aggregates in concretes obtained an increase in compressive strength as compared to the sand aggregates [18-21]. Some researchers attributed such observations to the strength and surface texture of the glass aggregates, [1, 20] while others state that the larger surface area of glass particles enables greater bonding surface with the cement matrix and subsequently improving the compressive strength [1, 22]. Moreover, the compressive strength of the concrete is improved by the pozzolanic reactions caused by glass particles[1, 23].

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4 93 However, some researchers have also observed contradictory results, obtaining a decrease in
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6 94 compressive strength when compared to sand aggregates [3, 24, 25]. The reduction in compressive
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10 96 aggregates[1, 3, 24, 26-30]. Malik et al. [31] and Adaway and Wang [22] studied the various
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12 97 percentage of recycled glass aggregates replacement and obtained compressive strengths higher
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14 98 than the control at 7 and 28 days with replacement levels up to 30% and a decrease with further
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16 99 replacement of recycled glass aggregates while Limbachiya. [32] found the optimum replacement
17 100 level for compressive strength to be up to 20% and a decrease thereafter.

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19 101 Similar to the studies conducted on the compressive strength, some researchers obtained
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21 102 results with higher flexural strength in concrete with recycled glass aggregates as compared to the
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23 103 sand aggregates [19, 20, 23, 27]. In contrast, numerous studies have observed a decrease in flexural
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25 104 strength in the concrete with sand aggregates when compared with the concrete with recycled glass
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27 105 aggregates [3, 24, 25, 33, 34]. Tan and Du [3] and Lin et al. [33] attributed such observation to the
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29 106 decrease in bonding strength between the cement and the glass particles. Taha and Nounu [34],
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31 107 Ali and Al-Tersawy [24], Ismail and Al-Hashimi [27] and Park et al. [25] also observed that
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33 108 increasing the percentage of recycled glass replacement in concrete decreases the flexural strength.
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35 109 Batayneh et al. [20] and Abdallah and Fan [23] on the other hand, observed the opposite and found
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37 110 that increasing the percentage of recycled glass results in a higher flexural strength.

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39 111 In contrast to compressive and flexural strength, results have shown that the replacement of
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41 112 recycled glass aggregates in concrete has achieved a lower splitting tensile strength than the
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43 113 concrete with sand aggregates [24, 25, 31]. However, other researchers also obtained results
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45 114 indicating an increase in splitting tensile strength as compared to the control [19]. Various
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47 115 researchers have also observed that increasing the percentage of recycled glass replacement causes
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49 116 a decrease in splitting tensile strength [20, 24, 25, 31, 34]. Tan and Du [3] reported an increase in
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51 117 splitting tensile strength up to 25% replacement level of recycled glass aggregates and decreases
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55 119 Although there is a significant amount of research done on the replacement of aggregates in
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57 120 concrete by recycled glass, to the best knowledge of the authors, there is no existing literature that
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59 121 is targeted at 3DCP applications. It is essential to study the rheological properties of cementitious
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61 122 materials in order to understand the material performance in 3DCP since the materials is in the
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63 123 fresh state during the deposition process [16]. Previous researches conducted on recycled glass
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concrete focused on hardened properties and often neglect the rheological properties which is essential in understanding the performance of the material in 3DCP [9, 13, 35, 36]. This study investigates the rheological properties of recycled glass aggregates concrete in comparison to river sand aggregates in a printable cementitious material and examines its mechanical properties.

3 Methods

3.1 Material preparation

The raw materials used for the binder in this study were Ordinary Portland cement (OPC, ASTM Type 1, Grade 42.5), silica fume (Undensified, Elkem), fly ash (Class F). Table 2 shows the chemical composition of the components in the binder. Fly ash and silica fume was used to increase the workability of the binder paste. Two different types of aggregates used were fine river sand and recycled glass. The recycled glass was supplied by Envirosand Pty Ltd at five different gradings; coarse, medium, fine, super fine and moondust gradings, out of which three of the gradings, medium, fine and super fine were used for this study and the grading curves are shown in Figure 1. Table 2 shows the particle size range of each grading of recycled glass being used in this study. The recycled glass used in this study was extracted from co-mingled waste and crushed into fine glass particles using a vertical shaft impactor crusher.

The purpose of this paper is to examine the effect of replacing sand with recycled glass. To compare fairly with the sand aggregate bearing samples, the three gradings of recycled glass is proportioned to mimic the aggregate grading of the river sand as shown in Table 3. The gradation curve of the fine river sand is shown in Figure 1. The mix design of both mixtures was kept constant (See Table 4).

A Hobart mixer was used to prepare the material. Dry components were dry-mixed at 59rpm for 5 minutes. Water is then added to the dry mixture for mixing at slow-speed (59rpm) for 1-minute, followed by 7-minutes of high-speed mixing (198rpm). After which, the material is deposited in the delivery system for printing.

3.2 Rheology measurements

The rheological properties of the fresh mixtures are measured using the Anton Paar Modular Compact Rheometer 102 (MCR 102). The protocols are designed to examine the static yield stress as well as dynamic yield stress of the fresh mixtures. A four-blade stirrer probe with a diameter of

30mm and a height of 40 mm was used to apply a torque to the specimen. The construction cell has a diameter of 70 mm.

After mixing, the fresh mortars are poured into the construction cell. Before each test, the material is hand tampered for 1 minute using a small whisk. Then the vane is quickly put in position and lowered to the designated position. The shearing protocol used in this study is shown in Figure 2. A pre-shear at 100 rpm for 30 s was applied. The material is allowed to rest for 20 s follow by a constant angular velocity at 1 rpm for 20 s. The constant shear rate at 1 rpm is used to measure the static yield stress [37]. A decreasing step-wise rheological protocol was used to measure the dynamic yield stress and plastic viscosity measuring from 100rpm to 20 rpm (at 20 rpm interval with 20 s at each interval). The torque is recorded at 4 data points per second. It is noted that for mortars, sand migration might occur at high shear rate [38]; thus, shear rates below 100 rpm are used for rheological measurement.

3.3 Printing investigation

Printing investigation was conducted on both mixtures to determine the feasibility of the recycled glass as aggregates in materials for 3DCP. A structure as shown in Figure 3 was printed using each mixture to test the extrudability of both materials. The printed samples were examined to evaluate the printing performance of the materials. The 3D printer used to print the samples is a four degree-of-freedom gantry robot printer with a rectangular nozzle orifice of 15mm by 30mm. The printing parameters such as print path, printing speed and flow rate is the same for both different aggregates mixtures. The printing speed was fixed at 100 mm/s while the material flow rate was fixed at 0.037 l/s. Table 4 shows the printing parameters that were used in the printing investigation process.

3.4 Mechanical properties

The samples were tested for their harden properties such as compressive testing, flexural testing and inter-layer bond strength via the splitting tensile test. The samples used for testing of the materials were extracted from printed structures. Figure 4 shows the cut surface of the cross-section of the recycled glass and river sand specimens. The printed structures were left to cure in a lab environment at 25°C and covered with plastic sheets to prevent any loss of moisture for 7

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4 185 days. The 7-day strength was obtained for each material since early age strength is more concerned
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8 187 For the compressive testing, 30mm cube samples (2 layers) were extracted corresponding to
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10 188 the width of the nozzle opening which is limited by the process. The samples were tested using the
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12 189 ALPHA 3-2000A model tester and the applied load rate to the samples is set at 0.6 MPa/s in the
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14 190 negative z-direction according to the cartesian coordinates.

15 191 For the flexural testing, samples with dimensions of 150 x 30 x 60 mm was extracted from
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17 192 the printed structure using a diamond cutter. The Instron 5969 Dual Column Tabletop Universal
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19 193 Testing System is used to apply the load and measure the maximum applied load. The load rate of
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21 194 the system was set at 0.1 mm/min and the span length were set at 120 mm.

22 195 For the splitting tensile test, samples were cut into 50 mm of length with a height of 2 printed
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24 196 layers with a diamond cutter. Wooden sticks of about 40 mm are stuck on both sides of the layer
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26 197 interface as shown in Figure 5(a) [39]. The Instron 5969 Dual Column Tabletop Universal Testing
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28 198 System is used to apply the load and measure the maximum applied load. The load rate of the
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30 199 system was set at 0.8 mm/min. The loading point is concentrated on the layer interface through the
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32 200 wooden sticks to ensure that the failure occurs at the interface. The test set up is shown in Figure
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34 201 5(b). The interlayer tensile bond strength can then be computed using equation (2).

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$$\sigma = \frac{2P}{\pi A} \quad (2)$$

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38 203 where σ is the interlayer tensile bond strength, P is the maximum load applied and A is the interface
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40 204 area.

41 205 42 206 **4 Results**

43 207 **4.1 Rheological properties**

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45 208 Preshear at 100 rpm for 30 s and resting for 20 s is applied before each step. The samples
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47 209 are then sheared at 100, 80, 60, 40 and 20 rpm for 20 s each. The equilibrium flow curve is thus
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49 210 obtained as the equilibrium torque vs. angular velocity, as shown in Figure 6. Torque (mNm) and
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51 211 angular velocity (rad/s) are measured by the rheometer. They are commonly transferred to shear
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53 212 stress and shear rate, respectively. In this study, the Reiner-Riwlin equation assuming Bingham
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55 213 behavior for flow is used to obtain the equilibrium shear stresses and shear rates [40]. It could be
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57 214 seen that the equilibrium flow curves are quite linear and could fit well in Bingham model, as
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59 215 shown in Equation 3.

$$\tau = \tau_y + \mu\dot{\gamma} \quad (3)$$

where τ and $\dot{\gamma}$ are shear stress and shear rate, respectively; τ_y is the yield stress; μ is the plastic viscosity.

Under constant shear rate, the torque/shear stress increases to a peak value, then decay to an equilibrium value [41], as shown in Figure 7. The peak value is assumed to be the static yield stress [37]. It has been shown in many 3D printing papers that dynamic yield stress and plastic viscosity is related to pumpability; while static yield stress is related to buildability [36].

The dynamic yield stress and plastic viscosity obtained from the flow curve model fitting, together with static yield stress are shown in Figure 8. It could be seen that the mixture with recycled glass has lower dynamic yield stress and plastic viscosity than with river sand. It indicates that the mixture with recycled glass has better flowing properties. In the meanwhile, the static yield stress is much lower for mixtures with recycled glass than with river sand which might induce weaker buildability for using recycled glass in 3D printing.

4.2 Mechanical properties

The replacement of river sand in the material for 3DCP have reduced the mechanical properties. Figure 9 shows the mechanical properties of both materials. The compressive strength, flexural strength and tensile strength of the recycled glass concrete is 50%, 30% and 80% lower than the sand aggregates samples respectively. The difference for the compressive strength and flexural strength agrees with the results obtained by Tan and Du [3]. The difference in compressive and flexural strength can most likely be attributed to the weak adhesive strength between the recycled glass particles and the cement matrix as compared to the river sand concrete [1, 3, 24, 26-30].

In contrast, the reduction in splitting tensile strength was much higher than previous research [3]. The large decrease in interlayer bond strength can be mainly contributed by the weak adhesive strength between the recycled glass particles [1, 3, 24, 26-30] as well as the anisotropic characteristic of 3D printed concrete [6, 10]. Nonetheless, the overall mechanical strength of the material can be improved by adjusting the gradation of recycled glass aggregates to achieve a higher particle packing density [42, 43].

4.3 Optical microscopy analysis

Optical microscope was used to conduct the analysis on the dry particles of both river sand as well as recycled glass. Figure 10(a) and Figure 10(b) shows the microscopy images obtained for the river sand particles and recycled glass particles respectively. As shown in Figure 10, both particles have irregular and angular shapes. However, the recycled glass particles have a much smoother surface and sharper edges than the river sand particles which could have caused the weaker bond between the particle and the cement matrix at the Interfacial Transition Zone (ITZ), causing the decrease in the mechanical strength of the hardened concrete [3].

The shape of the particles also have an effect on the difference in the rheology of the concrete mixtures [44]. The rough surface of the river sand shown in Figure 10(a) restricts the flow in the mortar and results in a higher yield stress and viscosity [45, 46]. Rougher surface increases the specific surface area and reduce the free water content [46]. On the other hand, the smooth surface of the recycled glass particles as shown in Figure 10(b) induces better flow properties of the materials. Nonetheless, the angular shapes of the particles increases the inter-particle friction resistance [46].

5. Discussion

River sand and recycled glass aggregates mortar were printed and compared in this study. Rheological testing and mechanical characterizations were conducted on the mixtures to compare the effects of the different aggregates. The rheology results have shown the advantage of incorporating recycled glass into concrete for 3DCP. The lower plastic viscosity and dynamic yield stress of the fresh material indicated that the recycled glass mixture have better flowing properties than the river sand mixture. This observation can be attributed to the availability of excess water in the recycled glass mixture due to the lower water absorption capacity of the recycled glass particles as compared to the river sand observed in previous researches [3]. Other reasons could be due to the smooth surface of the recycled glass particles as compared to the river sand particles [46]. Since the recycled glass are processed materials which are graded into different size ranges, the fines are possibly removed which could have contributed to the higher flowability. On the other hand, the presence of fines in the unprocessed natural river sand could also result in the lower flowability of the mortar. More fines meant a higher specific surface area and thus, more cement paste would be required to lubricate the surface and lesser to provide the flowing properties of the

mortar. The increase in specific area could also cause more water to be absorbed and resulting in a lower apparent water-cement ratio, thus reducing flowability [47].

In the contrast, the lower static yield stress of the recycled glass mixture also meant a lower buildability. Nonetheless, the deficiency in static yield stress can be corrected with the right quantity of admixtures added to the fresh material during the printing process to attain the characteristics necessary for 3DCP [44]. Panda et al. [48] improved the static yield stress of his cementitious material for 3DCP by the addition of nano-attapulgite clay, as nano-clay increases thixotropy [49]. Accelerator has been reported in previous publications to improve the buildability of material during the printing process [50].

In the meanwhile, the compressive strength, flexural strength and splitting tensile strength of the recycled glass samples was found to be significantly lower than the river sand samples. The reduction in mechanical strength was also observed in bulk materials based on literatures [3, 24, 25, 31, 33, 34]. The reduction in compressive strength and flexural strength was similar to previous researches despite the samples used in the experiments were printed instead of casted [3]. Many literatures have attributed such observations to the weak adhesive strength between the recycled glass particles and the cement matrix at the ITZ [1, 3, 24, 26-30]. Literatures have shown that the gradation of the recycled glass particles has an influence on the mechanical strength of the materials due to the particles packing density [43]. Another observation was the use of finer recycled glass particles causes pozzolanic reaction which further improve the strength of the concrete material [1, 23].

The decrease in splitting tensile test results of the printed samples is much higher from the control as compared to the casted samples in the literatures. This observation can also be attributed to the weaker bond strength at the ITZ [1, 3, 24, 26-30] yet another factor that might have contributed to the further reduction in strength is the anisotropic characteristic of the 3D printed samples [6, 10].

Although the mechanical properties of the recycled glass specimen are significantly lower than the river sand specimen, the improvement of flowability of the recycled glass specimen cannot be neglected. The buildability, flowability and the mechanical strength of the mix design should be optimized to achieve a good 3DCP material.

Future work focuses on the optimization of the recycled glass cementitious materials to achieve high buildability, flowability and mechanical strength. The combination of the two aggregates in the mixture will be examined at varying ratios. In order to better understand the role of fine particles in the materials, the investigation on its effect on the rheological properties will be carried out further. The gradation of recycled glass aggregates will also be studied to achieve higher particle packing density. The particle packing density is critical in governing the rheological as well as the mechanical properties of cementitious materials [42]. Additionally, the addition of accelerator and fillers such as clay to help improve the buildability will be explored. Apart from the material performance in 3D printing, the alkali-silica reaction (ASR) between the recycled glass aggregates and the cement paste of the printed specimen will be studied. The expansion cause by the ASR gel can significantly threaten the structural integrity of the hardened material and reduce the durability of the material [1, 2, 4, 30]. The durability of the materials such as ASR testing is not included here but will be examined in another study.

6. Conclusion

This paper demonstrated the feasibility of the utilization of recycled glass as fine aggregates in 3DCP. Generally, the utilization of recycled glass as aggregates in the material for 3DCP could potentially create a new channel for the waste glass in addition to the current recycling processes. With the rapidly increasing popularity of 3DCP technology, the broad use of recycled glass as a raw material for such application can be promising. As such, the considerably low recycling rate of waste glass can be increased, reducing the need for landfill space.

This study makes a comparison between two materials consisting of fine river sand and recycled glass aggregates. The gradation of the recycled glass was controlled to match that of the river sand. The rheological and mechanical properties of both materials were examined. The material with recycled glass aggregates demonstrated better flow properties as compared to the material with fine river sand. However, the buildability and mechanical properties are lower for the recycled glass material as compared to the river sand material. Nonetheless, further studies will be conducted to improve and develop an optimized material with recycled glass with the aim for 3DCP applications.

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Compliance with ethical standards

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Conflict of interest

The authors declare that they have no conflict of interest.

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Figure 1: Gradation of river sand and recycled glass

Figure 2: Protocol for rheology measurement

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Table 1: Summary of material composition used by researcher in various publication [5, 9, 12, 13, 15].

Author	Material	Material Composition	Institute/ Organization	Maximum Aggregate Particle Size
Tay et al.	High flow- low slump concrete	Cement Fly ash Silica fume Sand Water	Nanyang Technological University	2 mm
Le et al.	High performance concrete	Cement Fly ash Silica fume Sand Water	Loughborough University	2 mm
F. bos et al.	Customized Cementitious Material	Portland cement (CEM I 52,5 R) Siliceous aggregate Limestone filler Polypropylene fibers Other additives Water	Eindhoven University of Technology	1 mm
C. Gosselin et al.	Ultra-High Performance Concrete	Portland cement CEM I 52.5N Crystalline silica Silica fume Limestone filler Sand Water	XtreeE SAS	-
Panda et al.	Geopolymer	Fly ash Ground granulated blast furnace slag Silica fume Sand Potassium silicate Thixotropic additives Water	Nanyang Technological University	2 mm

Table 2: Chemical composition (%) of binder materials

Elements	OPC	Fly ash	Silica fume
SiO ₂	19.70	51.10	98.37
CaO	63.10	5.80	0.35
Al ₂ O ₃	4.80	28.80	0.19
Fe ₂ O ₃	3.20	6.40	0.08
SO ₃	2.50	1.00	0.19
MgO	2.10	1.10	0.15
Na ₂ O	0.20	0.30	0.20
K ₂ O	0.40	1.20	0.28
TiO ₂	0.10	2.50	-
P ₂ O ₅	-	-	0.04
SrO	-	-	0.01
ZnO	-	-	0.04

Table 3: Recycled glass gradings particle size range and proportion

Recycled glass grading	Particle size range (μm)	Proportioning river sand grading (%)
Medium	1000-1700	24.4
Fine	500-1000	1.0
Super Fine	150-710	74.6

Table 4: Mix design of both mixtures

Cement to binder ratio	Fly ash to binder ratio	Silica fume to binder ratio	Aggregate to binder ratio	Water to binder ratio
0.7	0.2	0.1	1.2	0.46

Table 5: Printing parameters used in 3D printing investigation

Nozzle Travelling Speed	Material Flow Rate	Layer Height	Nozzle Orifice Area
100 mm/s	0.037 l/s	15 mm	450mm ²