Sustainable shotcrete production with waste glass aggregates

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Abstract

This study employs statistical and experimental procedures to assess the applicability of crushed waste glass to replace natural sand in shotcrete production for use in tunneling, mining and excavation industries as a support system. Mechanical strength under different uniaxial and biaxial load combinations, fracture properties, and ultra-high-speed photography of the crack growth mode in the newly developed shotcrete mixes were studied and compared against the control mix at 0% waste glass inclusion. Results suggest that shotcrete mixes containing synthetic glass aggregates exhibit similar or higher strength properties (compared with conventional shotcrete with natural aggregates) at early and late ages in both fresh and hardened shotcrete samples. Under biaxial stress conditions, in particular, the new glass shotcrete designs demonstrate a higher load-bearing capacity of up to 35% increase. Compared to conventional shotcrete, replacing sand with recycled glass aggregates further exhibited the need for less water and binder consumption owing to the glass water-reducing effect. This in return could leave more water available for improved workability in the mixture hence producing a more cost-effective and eco-friendly shotcrete product. From the results, no impairment of performance was recorded by substituting sand with crushed waste glass even at a high substitution percentage of up to 100%; suggesting high improvement potential of crushed waste glass re-use in the shotcrete industry.

Article highlights

- This study investigates sand replacement with glass aggregates in shotcrete production for use in excavation industry.
- Tested shotcrete mixes containing glass aggregates exhibited a similar or higher strength properties at both early and late ages.
- Results suggest that waste glass reuse as synthetic aggregates can reduce water and cement consumption to generate a low-cost and eco-friendly shotcrete.

Keywords Sustainability · Shotcrete · Sand depletion · Crushed waste glass · Mechanical properties

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1 Background and motivations

According to the International Tunnelling Association, the global demand for underground construction will boom in the coming years, with around AUD 42 billion of investment in the tunnelling sector in Australia alone. This trend, in fact, can be seen already with 9 out of the 12 current state and federal government infrastructure projects related to tunnelling in Australia [1]. With such an increased demand for tunnelling, shotcrete has also received increasing attention for ground support in tunnels and mines. In 2018, for instance, there was 800,000 m³ of shotcrete used in Australia of which 500,000 m³ was used in underground construction and 300,000 m³ in civil basements, swimming pools and embankments [2]. Table 1 provides a list of Australia's current and future major tunnelling projects with significant portions of shotcrete supported tunnelling. Shotcrete (aka Sprayed Concrete) is fundamentally concrete that is pneumatically projected onto the target surface from a nozzle at a high (typically 20–30 m/s) velocity to generate a dense homogeneous mass [2–4]. Given its unique placement method, shotcrete is also known as pneumatic concrete, guncrete, gunite when used as dry-mix, and fibre-crete if used in mining operations. The Australian and American concrete industries typically refer to shotcrete using the above terms where each guideline is named accordingly, i.e. ACI 506.4R-94 Guide for the Evaluation of Shotcrete [5] and the Recommended Practice - Shotcreting in Australia [2]. In Europe, the term sprayed concrete is used in the specifications produced by EFNARC [6] and also the British standard BS EN 14487-1 and 2 [7, 8].

The invention of shotcrete can be attributed to Carl Ethan Akeley, a famous hunter and professor, who trialled a dry mixed mortar on skeletal matrices for taxidermy purposes in 1907 [9]. He further refined his crude

original machine by adding a supplementary compression chamber and geared feed-wheels, and in 1911 patented his improved system that still resembles the dry-mix process used today [10, 11]. Dry-mix refers to the method by which the cement and the aggregates are blended and then placed into a special-purpose machine where the materials are then pneumatically conveyed to the nozzle where water is introduced to wet the mixture before it is pneumatically projected. The mix can also contain fibres and admixtures [2, 9, 10]. In contrast, in the wet-mix process, the cement, aggregate and water are batched and combined and the mix is then delivered to the site where the concrete is pumped to the nozzle. At the nozzle, compressed air is introduced and the mix is pneumatically projected—admixtures are normally used and may include fibres [2, 9, 10]. Where an accelerator is added at the nozzle, the mix is often referred to as nozzle accelerated shotcrete.

But, unlike conventional concrete (in which compaction is achieved by vibration to flush out air through a completely separate process after placement), shotcrete placement and compaction is done simultaneously as soon as it impacts the surface. Shotcrete also requires higher pumpability and workability properties than concrete as the site where shotcrete is needed and the location where shotcrete mixing is performed are often far away. Shotcrete needs to have a certain level of instance (i.e. early-age) strength within only a few hours after it is discharged, while in concrete design the 28-day strength is mainly the critical parameter. In addition, shotcrete requires little or no formwork, hence is highly preferred over concrete where (1) formwork cannot be placed, (2) access to the work is difficult, (3) normal casting techniques cannot be used, (4) a thin and/or various concrete thickness profile is needed, or (5) in situations where customisation in shape, depth and style is required. The main uses for shotcrete are varied in today's construction industry, but can be

Table 1 Infrastructure projects in Australia with significant shotcrete lined tunnelling

Name of Project	Location	Status	Comments
WestConnex 3A	Sydney	Under construction	Approx. 15 km of shotcrete-supported 3-lane road tunnels, ramps, Y-junctions
WestConnex 3B	Sydney	Under construction	Approx. 10 km of shotcrete-supported ramps and Y-junctions
M6	Sydney	In procurement process	Approx. 8 km of shotcrete-supported 3-lane road tunnels and ramps
Western Harbour Crossing and Beaches Link	Sydney	Future project	Approx. 30 km of shotcrete-supported 3-lane road tunnels, ramps, Y-junctions
Sydney Metro West	Sydney	In procurement process	Shotcreted caverns for stations and crossovers
Coffs Harbour Bypass	Coffs Harbour	Future project	Approx. 2 km shotcrete-supported tunnels
Melbourne Metro	Melbourne	Under construction	Shotcreted caverns for stations and crossovers
Cross River Rail	Brisbane	Under construction	Shotcreted caverns for stations and crossovers
Inland Rail	Brisbane	In procurement process	Approx. 2 km shotcrete-supported tunnels

summarised in the key categories of (1) support system in tunnels and underground excavations, (2) open pit mines, slopes and rock surface exposures against weathering and erosion, (3) fire protection of steelwork, (4) refractory linings, (5) concrete rehabilitation and repairs when major full-thickness repairs are uneconomical, and (6) rock and soil stabilisation.

For tunnel support applications, in particular, shotcrete is used in two slightly different ways. Where the ground is softer or where rockbolts are ineffective in reinforcing the ground, shotcrete is used in an arching action to assist the natural arching of the ground. In this type of ground support, the compressive stiffness and strength of the shotcrete is critical [2, 9, 12]. Where the ground can be reinforced by rockbolts, the shotcrete becomes a support for loose blocks between the rockbolts. Here, bending capacity becomes an important property in shotcrete design. Where bending strength is important, shotcrete can be reinforced conventionally by bars or mesh. However, the placing of bars and mesh overhead is undesirable in many ways, with issues of time, cost and safety. In Australia, the use of steel fibre reinforcement in lieu of mesh is often preferred. In deeper tunnels, the tendency for shotcrete to shrink and creep to relieve excessive ground deformations is a very useful property. However, in shallow tunnels where limiting deformations is important to avoid damage to surface facilities, shotcrete is reinforced with steel to reduce movement. Therefore, the important properties for shotcrete in tunnelling design include compressive strength, bending strength (which is related to tensile strength) and shrinkage. Moreover, since shotcrete is installed at the face and becomes loaded with face advance almost immediately, not just the hardened properties are important, but also the time-dependency of these properties.

To reduce rebound, shotcrete mixes usually use smaller aggregate. Additionally, to coat the surface, shotcrete mixes use an increased binder content compared to conventional concrete to improve the stickability and density. For these two reasons, shotcrete mixes tend to use a higher proportion of sand. In recent years, shotcrete supply has therefore suffered from a significant rise in the overall cost mainly due to steep hikes in the price of sand. This can be attributed to the widespread use of sand in today's blended aggregate industries (concrete, shotcrete, pavement, etc.) that has made sand the second-most consumed resource on earth (after freshwater) and the most important solid substance on the planet [13, 14]. It is expected that sand will become the commodity of the 21st century, like oil in the 20th century. According to the latest statistics, a staggering fifty billion tonnes of natural sand and aggregates is being consumed all over the world each year, which is equivalent to almost 18 kg per person

living on earth per day (or twice the amount of sand produced by every river in the world) [15]. Amongst many applications, the construction industry requires the highest volume of (a steady) sand supply. It is true to say that about 75% of construction material is concrete of which two-thirds is sand. This has made sand mining a highly-profitable 70 billion dollar industry, but at the expense of beaches losing their sand. Such unsustainable exhaustion of sand and natural aggregates has damaged aquatic habitats, caused beach erosion, made coastal communities vulnerable to floods, and has impacted biodiversity on land [15, 16]. For example, up to 90% of the world's beaches have shrunk by 40 m on average over the last 10 years only due to beach sand extraction. Recycling local wastes to replace the rapidly reducing natural and quarried sand is therefore becoming of urgent interest in Australia and worldwide.

Among multiple types of waste, glass is a perfect cost-effective candidate to replace sand, as glass (1) is theoretically 100% re-usable and can be infinitely recycled with no loss in performance or any reduction in quality, (2) is non-miscible, non-flammable, inert, non-biodegradable, and does not degrade, (3) is mainly composed of silica (SiO_2) which is a key mineral found in natural sand, and above all (4) has similar chemical compositions to that of natural sand [17]. There is an ever-increasing amount of waste glass generated worldwide that is currently sent to landfills while it has a high potential for re-use. Statistics show that waste glass accounted for 5% of all waste produced in the world globally in 2016, more than wood, rubber and leather waste combined [18, 19]. In Australia alone, annual consumption of glass is 1.36 million tonnes, with Queensland producing nearly 350,000 tonnes—second only to the state of New South Wales [20]. The same concerns are heard across Europe, Asia, and the US. In addition, China's waste import restrictions (i.e., National Sword and Blue Sky policies), and the imminent implementation of waste export bans, place Australia's and many other countries' waste and resource recovery sectors under tremendous pressure. Australia's states and territories have also recently agreed to ban the export of their waste glass by 2024, meaning that the states must find ways to deal with their glass waste disposal that would usually ship overseas. Due to the non-biodegradable nature of glass, it is one of the longest-lasting man-made materials. For example, a glass bottle needs to stay in landfills for up to one million years before it is fully decomposed. Traditional landfilling and stockpiling of waste glass are therefore not environment-friendly solutions, and thus the re-use of waste glass to replace sand has become an important research topic worldwide.

Over the past decades, recycling crushed waste glass (CWG or *cullet*) has grown significantly in a range of

applications including concrete production, tile and brick manufacturing, road pavement construction, water filtration, paint coatings and sealants, soil performance improvement, pipe bedding, sandblasting, glass wool insulation, and even plastics and paper production [15, 21–25]. But, large-volume CWG reuse has remained pitifully low in geotechnical domains and yet remains relatively under-investigated. This could be due to:

- access to yet cheaper (although not sustainable) natural aggregates in some places around the world;
- unrepresentative testing requirements for CWG reuse in geotechnical applications;
- lack of community-accepted and market-ready guidelines for the application of CWG in geotechnical fields;
- the perceived inferior quality of CWG as a reliable sand replacement;
- the hydrodynamical (HM), chemical (C), thermal (T) and particularly coupled HTCM engineering properties of CWG from granular (at individual particles) to macro levels (in-placed two/three-phase characteristics when placed within geo-structures) not yet being fully understood. While the short-term behaviour of a CWG placed material structure can be studied in the laboratory or by field measurements, long-term behaviour is largely under-studied;
- while it is known that particle shape, size and gradation of CWG affect its physical performance quite substantially, there is limited engineering (and scientific) knowledge of how these particle descriptors combined could trigger thermo-hydro-chemo-mechanical coupling effects in waste glass geo-structures;
- the perception that raw CWG and CWG-embedded products could have issues with consistency, hence the lack of confidence in and the perceived risk associated with CWG-embedded products;
- lack of certification of CWG-embedded products;
- lack of experience in geotechnical applications for CWG re-use and industry's strong preference to work with known materials which have proved their consistency and quality over the years;
- issues related to recycling waste glass in some geotechnical applications that may require colour sorting (mainly into clear, green and amber), as well as extraction of impurities, metal and contaminants leading to high costs of transportation and capital intensive processes which in return prohibit large-scale waste glass utilisation;
- the fact that the adoption of non-virgin materials through a circular economy is a political goal in many countries that requires government intervention to stimulate action; and

- the fact that many current industries, including the construction industry, are not yet fully prepared to embrace changes towards a circular economy. Changing the status quo will require a strong push from government and regulators through, for example, stream recycling at the kerbside, bottle bills that encourage consumers to bring back empties at high rates, introducing higher taxes for glass landfilling, and incentives to create glass recycling centres that can sort, clean, and process the material with better precision and cleanliness.

One of the geotechnical-related areas in which the utilisation of CWG yet remains largely under-studied is the production of shotcrete mixes. It is expected that using CWG in shotcrete production would offer the triple benefits of (1) addressing the global geo-environmental and financial challenges of natural and quarried sand depletion, (2) re-use of the ever-increasing waste glass worldwide, and (3) cutting construction costs and improving the sustainability of tunnelling and the mining sectors. With the above motivations in mind, this study assesses the applicability of cullet (CWG) in designing a sustainable shotcrete mix as sand replacement and investigates further how this replacement could affect shotcrete properties. Unconfined compressive strength (UCS), tensile strength, pumpability, workability, fracturing behaviour, early-age and long-term strength, drying shrinkage, and stiffness properties of several shotcrete mixes with glass aggregates were measured, and the results are discussed in this study and compared to those of the reference mixtures. In the following sections, experimental set up are first explained followed by results overview and discussion. Limitations of the study and future directions for research and recommendations are highlighted in the conclusion section.

2 Experimental set-up

Over 250 tests with five different mixes of shotcrete with waste glass aggregates replacing sand at proportions of 0%, 10%, 20%, 50% and 100% under constant water to binder ratio of 0.45, were carried out. The raw materials used in this research and their properties are summarised in Table 2. General-purpose (GP) cement was used, and fine river sand with a particle size of 0–0.425 mm, also medium and coarse break stone aggregates with particle size ranges of 0–4.75 mm and 1.18–9.5 mm, respectively, were adopted (see also Figs. 2 and 3). The crushed waste glass (sourced mainly from food containers and glass bottles) was provided by a local supplier in Brisbane (Enviro Sand, Australia), Flyash (Grade 1) was used as a Supplementary Cementitious Material (SCM), and steel fibres

(DRAMIX® 3D 65/35BG added at a target fibre content of 35 kg/m³) were added to all mixes to replicate real life mix conditions. In practice, steel fibres are mainly utilised to impart a high degree of ductility and enhance the bearing capacity of the shotcrete, while flyash improves the workability, pumping ability and ability to adhere to the surface. Flyash is further proven to be a cost-effective addition (also improving sustainability) as it reduces the amount of cement used in the shotcrete production. Tytro WR 174 and Tytro HC 270 admixtures - widely used by shotcrete practitioners and producers in Australia's mines and tunnels as high range water reducing (HRWR) and hydration-control chemicals, respectively—were added to all the mixes to enhance the workability and to stabilise hydration. Admixture rates were kept constant as a percentage of the cement weight in all the mixes for consistency. Table 3 shows the final proportions for the reference and the 100% sand-replaced design mixes.

The moisture content of each of the aggregates and admixtures was first measured (according to AS 1289.2.1.1 recommendations) to determine the volume of free-water in the mix and then to calculate the amount of water needed to reach the target w/c (water to cement) ratio of 0.45 in each mix. A carefully designed procedure (after several trials) was then followed to prepare the mixes in a consistent fashion. This included: (1) all the aggregates plus CWG and steel fibres were added and mixed in the mixer for three minutes, (2) the binder materials (cement and flyash) were then added and mixed for three more minutes to homogeneously combine the solid ingredients, (3) water and admixtures were finally added and mixed for another three minutes to achieve a uniform mixture, and (4) the mixture was allowed to rest for a further three minutes before actual testing of the batch. After testing for plastic properties (slump and reverse cone tests), shotcrete samples were cast into moulds and were allowed to rest for 24 h at room temperature. The samples were then de-moulded and stored in a lime saturated until removal for testing. The temperature of the curing bath was kept at 27 degrees $\pm$ 2 degrees at all times (see also Fig. 1). Cubed samples with 50 mm in dimension were further prepared to study the strength behaviour of shotcrete mixes under biaxial load combinations. The principal stresses and strains at failure were then recorded using a recently devolved true triaxial testing facility at the Geotechnical Engineering Centre (GEC) within the school of Civil engineering at the University of Queensland (Brisbane, Australia). The system is capable of performing true triaxial loading (up to 850 kN in each direction), permeability, hydraulic fracking, and thermo-mechanical coupled modelling at elevated temperature of up to 100 degrees [26]. The system is also designed to accommodate acoustic emission and ultrasonic monitoring instrumentations to

carefully monitor and assess the progressive damage in loaded samples. The mechanical properties, load-deflection curve, and fracture characteristics of the samples were finally investigated at curing periods of 7, 28 and 70 days. The test procedures and standard recommendations followed are listed in Table 4.

3 Results and discussion

It should be noted that the reverse cone test was conducted in a similar way to the slump test, but the slump cone was placed up-side-down (slight modification to BS EN 12350-8). Once the shotcrete was placed inside the inverted cone, it was then raised in a vertical direction for 2–4 s and the diameter of the spread shotcrete was measured (see Table 4). For practical purposes, the spread should be typically in the range of 500–600 mm within 1.5–2.5 s. The drying shrinkage (DS) specimens consisted of three embedded 75 $\times$ 75 $\times$ 285 mm bars with studs at each end. The drying shrinkage room was kept at 23 $\pm$ 2 degrees and 50 $\pm$ 5% relative humidity at all times. The airflow rate in the test room was measured as 12 $\pm$ 5 ml during the 8 weeks of testing. The two ends of UCS core samples were ground to ensure a uniform and evenly distributed stress was applied to the sample until failure. All the shotcrete mixes were designed to reach an early age strength of 1 MPa in 2 h and 2.5 MPa in 8 h as is often needed in practice. Also, apart from the slump test, shotcrete workability of the mixes was calculated by subtracting 100 from the sum of the slump and flow (reverse cone) tests. In addition, when preparing the final 100% mix, it was realised that the mixture has high workability and segregation was observed at the end of the batching process. It was therefore decided to add TYTRO RC 430 (which is a rheology-control admixture based on nanometric colloidal silica formulated) to pull the shotcrete back together. The admixture was added in three steps with 35 ml in the first step, 35 ml in the second step and 25 ml in the final step. All the results are summarised in Table 5 and Figs. 4 and 6. From the results, it can be seen that:

- The slump and reverse cone test results both show an increasing trend in the workability and pumpability indices with the addition of glass aggregate to the shotcrete mix. Apart from the 100% mix (being the only mix with Tytro RC 430 added), slump retention of no less than 140 mm was further confirmed up to 4 h after batching in all mixes.
- Density is increased slightly with increased amounts of CWG, but bleeding results have increased considerably which can be explained by the almost zero water absorption property of glass compared to sand. That

Fig. 1 Test results and the raw materials used in this research project, including **a** tested UCS samples at 0% and 50% sand replacement ratios, **b** installation of vertical and radial extensometers to measure the shotcrete stiffness and radial expansion, **c** aggregates and binders, **d** slump test to measure workability, **e** reverse cone test to measure pumpability, **f** end-beam test to assess shotcrete early-age strength, and **g** the experimental set-up for testing the samples under biaxial compression

is, bleeding is a phenomenon taking place due to self-weight consolidation of solids in a freshly-placed concrete/shotcrete (in the initial few hours after mixing) that forces the excess water in the mixture to the surface of the sample. The accumulated water (i.e. bleeding) represents the water percentage in the mixture not absorbed by the sand and cement. Therefore, at a constant w/c design (as adopted in this study), shotcrete mixtures with aggregates less prone to water absorption are expected to require less water (hence cement) to reach a similar workability index. Also, as explained above, it is worth re-mentioning that TYTRO RC 430 was used during the preparation of the 100% design

(with the highest initial bleed values) to bring the mixture bleed under 4 ml—see also Table 5.

- Air content decreased when more CWG is added which can be attributed to the higher mechanical interlocking of glass aggregates due to its higher angular nature, hence creating less void space in the mix to be filled with trapped air. This observation suggests that there would be an optimum percentage of CWG additive to minimise the air content of the shotcrete.
- The shotcrete early strength gain is typically associated with its water/cement ratio. Generally speaking, the lower the w/c ratio, the faster the early hydration rate, hence the greater the early strength of the shotcrete.

Table 2 Specification of the raw materials—see also [24, 27]

Material	Property	Standard
Cement	Fineness Index: 387 (m ² /kg)	AS/NZS 2350.8
	Normal Consistency: 27.50%	AS/NZS 2350.3
	Initial Setting Time: 135 min (Limit 45 mins. Min.)	AS/NZS 2350.4
	Final Setting Time: 190 min (Limit 360 mins. Max.)	AS/NZS 2350.4
	Soundness: 0 mm	AS/NZS 2350.5
	Mortar 3, 7 and 28-days Compressive Strength: 35.8 MPa, 47.9 MPa, and 66.8 MPa	AS/NZS 2350.11
Flyash	Specific Gravity: 2	AS 3583.5
	Fineness @ 45 micron: 86% (Limit 75% Minimum)	AS 3583.1
	Moisture Content: <0.1% (Limit 0.5% maximum)	AS 3583.2
Steel fibre	Length & Diameter: 35 mm & 0.55 mm	
	Aspect Ratio(l/d): 65	
	Young's modulus: 210 MPa	
	Strain at ultimate strength: 0.80% Nominal	
	Tensile Strength: 1.345 MPa	
	Made of cold-drawn wire with shape-hooked ends	
Sand	Apparent Particle Density: 2.65 (t/m ³)	AS 1141.5
	Particle Density-DRY: 2.62 (t/m ³)	AS 1141.5
	Particle Density-SSD: 2.63 (t/m ³)	AS 1141.5
	Water Absorption: 0.40%	AS 1141.5
	Clay and Fine Silt: 3%	AS 1141.33
	Particle Size Range: 0-0.425 mm	AS 1141.11.1
Medium Sand	Sample Source: Moreton Bay, QLD	
	Apparent Particle Density: 2.63 (t/m ³)	AS 1141.5
	Particle Density-Dry: 2.56 (t/m ³)	AS 1141.5
	Particle Density-SSD: 2.59 (t/m ³)	AS 1141.5
	Water Absorption: 1.00%	AS 1141.5
	Clay and Fine Silt: 8%	AS 1141.33
7 mm Aggregates	Particle Size Range: 0-4.75 mm	AS 1141.11.1
	Sample Source: Rockwell quarry, QLD	
	Apparent Particle Density: 2.97 (t/m ³)	AS 1141.6.1
	Particle Density-Dry: 2.92 (t/m ³)	AS 1141.6.1
	Particle Density-SSD: 2.94 (t/m ³)	AS 1141.6.1
	Water Absorption: 0.60%	AS 1141.6.1
Crushed Waste Glass (CWG)	Flakiness Index: 29%	AS 1141.6.1
	Particle Size Range: 1.18-9.5 mm	AS 1141.11.1
	Sample Source: Blue Rock Quarry, QLD	
	Specific Gravity: 2.5	ASTM D5550-14
	Particle Size Range: 1.25-4.30 (mm)	AS 1141.11.1
	Maximum Dry-Density: 1.82 (t/m ³)	AS1141.5
	Minimum Dry-Density: 1.39 (t/m ³)	AS1141.5
	Abrasion Loss: 2.40%	ASTM D7428
	Maximum Void Ratio: 0.79	—
	Minimum Void Ratio: 0.37	—
	Roundness index: 0.32	—
	SiO ₂ content using XRF spectroscopy: 72.07%	—
	Acid Solubility: <1%	—
	Crystalline Silica: <1%	—

Table 3 Mix design for the reference and the 100% sand-replaced mixes for preparing 85 litres of shotcrete

Material	Reference mix	100% CWG
7 mm aggregates	38.10 kg	38.10 kg
Sand	86.42 kg	–
Fine sand	13.01 kg	13.01 kg
CWG	–	85.00 kg
Cement	29.33 kg	29.33 kg
Flyash	9.78 kg	9.78 kg
Steel fibres	2.98 kg	2.98 kg
Added water	15.78 kg	17.15 kg

But, given this ratio was kept constant in all the mixes in this study, no apparent change in the shotcrete early-age strength was observed even at up to 100% sand replaced with glass aggregates (see Fig. 4a). However, after 5 h from batching, the highest shotcrete strength was reached with the 20% CWG mix at 2.25 MPa.

- Glass inclusion in concrete production has proven to introduce a water-reducing effect owing to the glass surface structure. This effect can also be seen readily in the results of drying shrinkage tests as illustrated in Fig. 4b. With reference to the figure, it is clear that the contraction of a hardened shotcrete mix (due to the loss of its capillary water) decreases with a higher

percentage of CWG inclusion. This observation is practically very important as the adverse effect of shotcrete shrinkage over time may lead to cracking, internal warping, and external deflection before the mixture is subjected to any kind of external loading. That is, the improved shrinkage characteristics in shotcrete mixes with sand replaced with higher percentages of glass aggregates would make the mix less susceptible to probable shrinkage movement and subsequent cracking in practice.

- There were hardly any differences observed in the stiffness and Poisson's ratio in all the mixes. This can be explained by the similar mechanical properties of CWG and sand at a particle scale (see also Figs. 4c and 4d). All mixes, however, demonstrated a steady increase of shotcrete stiffness over time.
- More interestingly, no significant change can be observed for the mechanical strengths up to 70-days between the control and all the new CWG mix designs. It can be seen that the tensile strength and UCS results only varied by around 10%, with the exemption of the 100% mix in which the combined PSD (particle size distribution) of the mix was found more coarse than the reference mix hence potentially not allowing a complete packing of the materials and the bonding interface with the steel fibres (see also Fig. 5). It was decided that additional mix design alterations need

Table 4 List of the tests conducted and their corresponding standards

Test type	Standards	Comments
Slump Test	AS 1012.3.1	To determine shotcrete workability. An initial Slump of 180–220 mm is often needed in practice
Slump Retention	AS 1012.3.1	To determine retention of the shotcrete workability by repeating the slump test at several time intervals of 1 h, 2 h, and 4 h after batching. Workability retention of 3 h minimum is often needed in practice
Reverse Cone	BS EN 12350-8	To measure shotcrete pumpability, flowability and its capacity to run freely down a slickline
Air content	AS 1012.4:2014	To measure the amount of air entrained in shotcrete. It can determine whether the mix is protected from freeze-thaw conditions or is prone to weathering, and can affect the finish and cosmetic look of the shotcrete. The mix should not contain air content greater than 3%
Density	AS 1012.5:2014	To gauge shotcrete solidity
Bleed Rate	AS 1012.6:2014	To describe the separation of water from a shotcrete mix due to the settlement of its solid materials
End Beam Test	AS 1012.3.1	To measure early-age strength of a shotcrete mix using a manually operated hydraulic ram as shown in Fig. 1
Compressive Strength	AS 1012.9:2014	To estimate the unconfined compressive strength (UCS) of shotcrete
Brazilian Test	AS 1012.8.1:2014	To indicate tensile strength of shotcrete and its cracking resistance under induced tensile stresses
Dry Shrinkage (DS)	AS 1012.13:2015	To gauge the contraction of shotcrete due to loss of water/moisture content by measuring the shortening of DS samples from a water-saturated condition at the age of 7-days for various periods of drying up to 8 weeks
High Speed Photography	–	To identify fracture patterns, cracking mode and crack growth mode in shotcrete mixes
Elastic Properties	AS 1012.17	To calculate the elastic properties of a shotcrete mix including stiffness modulus and Poisson's ratio

Fig. 2 Gradation curves of the materials used in this study. The uniformity coefficient (C_u) and the coefficient of gradation (C_c) are the measures of sand/CWG gradation defined as D_{60}/D_{10} and $D_{30}^2/(D_{60}D_{10})$, respectively. Also, D_x relates to the portion of particles with diameters smaller than $x\%$

to be considered other than the percentage of sand replacement. Nevertheless, the brittleness index, i.e. the ratio of UCS/tensile strength [28], is the same for different mixes despite glass being a relatively more brittle material than sand.

- It has been reported that the fracture mode in the Brazilian test is primarily controlled by the material's brittleness index. That is, in solids with a high brittleness index and a large tensile strength, it becomes more likely to observe an explosion-like failure in the form of multiple cracking and large secondary shear fractures during the Brazilian test [29]. However, given the

brittleness index in all the shotcrete mixes was similar (see the point above), further high-speed photography recordings (at 200 kHz and above) of the tensile cracking in CWG mixes didn't pick-up any significant changes in terms of the fracture mode and the cracking speed. However, image processing of the high speed video recordings identified three discrete fracturing patterns. These were (i) a single straight central crack initiated at the sample centre, (ii) a central tensile crack accompanied by small boundary cracks (mostly shear), and (iii) a fracture propagation mode where a central crack begins at one of the two loading points (instead of the sample's centre) and forms a straight fracture surface. While fracture type (i) above was the predominant failure mode observed in over 80% of all the Brazilian tests conducted, no direct link between the fracture mode and the shotcrete mix was verified after further careful investigations (see also Fig. 6a). A possible reason for this could be the existence of steel fibres in all the mixes that could have largely controlled the fracture propagation mode in the failed samples after the formation of initial cracks hence making the fracturing pattern independent of the mix design.

- The ultimate strength of all mixes under biaxial compression is always higher than under uniaxial compression. However, the control mix design with no waste glass aggregate shows the weakest shotcrete mix, meaning that the inclusion of CWG has a positive effect on the load bearing capacity of shotcrete under biaxial stress combinations. The maximum biaxial strength occurred with the 20% sand replacement mix at σ_2 equals to around 50% of the mixture UCS.

Fig. 3 Photographs of the aggregates' size and shape used in this study

Fig. 4 Influence of sand replacement with glass aggregates on shotcrete properties, including its **a** early-age strength, **b** drying shrinkage, **c** elastic properties, **d** stress–strain behaviour, **e** unconfined compressive strength, and **f** tensile strength

In order to evaluate if the replacement of sand with CWG makes a significant impact on shotcrete properties (i.e. to accept or reject this null hypothesis), a statistical methodology commonly referred to as the Analysis of Variance (ANOVA) was carried out. The ANOVA method

was developed in the early 1920s by Ronald Fisher, and is based on partitioning of the total variability in the response variable into components that are consistent with an underlying model for the experiment [30]. A typical model often used for a single-factor ANOVA test is in the form of Eq. 1, in which y_{ij} is the j^{th} observation of the

Table 5 Summary of the basic properties in all the tested shotcrete mixes

Test type	Reference mix	10%	20%	50%	100%
Slump (mm)	235	255	240	265	200
Slump (mm) after 1 h	200	250	225	225	165
Slump (mm) after 2 h	175	235	190	230	115
Slump (mm) after 3 h	160	220	165	220	–
Reverse Cone (mm)	460	560	475	600	–
Workability Index	595	715	615	765	–
Density (kg/m ³)	2663.09	2974.14	2985.27	2977.85	2874.01
Air content (%)	1.2	0.8	0.6	0.4	3.5
Bleed (ml)	0	4	4	12	3
Tensile crack speed (m/s)	1.23	0.92	1.56	1.37	0.67

Fig. 5 Analysis of thin sections obtained from shotcrete mixes with 0%, 10%, 15%, 20%, 50% and 100% sand replaced with glass aggregates from (a) to (f), respectively

i^{th} treatment, μ is the total average for all the observations in the experiment, τ_i is the effect of the i^{th} treatment, and

ϵ_{ij} is the random error term which is assumed to have a standard normal distribution with a constant variance of $0 < \sigma^2$. In other words, Eq. 1 assumes that a different mean

Fig. 6 **a** High-speed time-lapses of the fracture pattern observed in Brazilian shotcrete samples (captured at 120,000 frames per second) compressed between at horizontal platens according to ASTM recommendations, and **b** Biaxial strength results for different types of shotcrete mixes under biaxial compressions

for the i th treatment is not due to the treatments related to different populations but rather caused by a different treatment effect τ_i .

$$y_{ij} = \mu + \tau_i + \epsilon_{ij}$$

$i = 1, 2, 3, \dots, a$ number of treatments (1)

$j = 1, 2, 3, \dots, n$ number of observations per treatment

While other statistical testing methods exist, a one-way (single-factor) ANOVA test was referred since the only factor investigated in this study is the CWG ratio at different levels (treatments) of 0%, 10%, 20%, 50% and 100%. To minimise the probability of committing a Type II error, each factor level was designed to have equal sample sizes of a minimum of three (3) replications. Results of the ANOVA analysis with a small P-value (typically less than 5% significance level) reject the null hypothesis mentioned above. Alternatively, one can calculate the F-number in ANOVA defined as the ratio of the variation between a target property in all shotcrete mixes to the variation within each shotcrete mix. When the calculated F-statistic is less than the critical F-ratio (corresponding to the target P-value), it is concluded that there is not a significant amount of variation in the target shotcrete property caused by sand replacement with CWG. If the null

hypothesis is rejected, however, the alternative hypothesis is considered that at least one shotcrete mix has a significantly different variance. In this case, a Tukey comparison can be conducted further to determine which of the sample means (shotcrete mixes) are different. A detailed discussion of the ANOVA and Tukey test is beyond the scope of this paper and interested readers are referred to [30]. To perform the ANOVA test, SAS JMP program was utilised. The results are shown in Tables 6, 7 and 8 for the UCS and Brazilian tensile strength data points. A significance level of 0.05 was considered and equal variances were assumed, given ANOVA becomes insensitive to departures from the assumption of equal variances if the sample size for factor levers are equal. Nevertheless, to test for homogeneity of variances and to check normality of residuals as the two key assumptions in ANOVA, further quantile plots of residuals and Bartlett tests were performed before each ANOVA analysis.

According to Tables 6–8, it can be seen that there are statistically significant differences (where P-value is less than 0.05) between the 100% mix design and the reference (control) mixture in both the UCS and Brazilian tests results. However, up to 50% sand replacement with glass waste produces approximately similar tensile and compressive strength in all other shotcrete mix designs. The

Table 6 ANOVA Test Results for the Brazilian tests

	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_o	fP value
7-days	CWG Ratio	2.5763111	4	0.644078	8.8113	0.0174
	Error	0.3654830	5	0.073097		
	Total	2.9417941	9			
28-days	CWG Ratio	5.6569727	4	1.41424	3.5358	0.0993
	Error	1.9998936	5	0.39998		
	Total	7.6568663	9			
70-days	CWG Ratio	6.7955513	4	1.69889	19.8796	0.0029
	Error	0.4272945	5	0.08546		
	Total	7.2228458	9			

Table 7 ANOVA Test Results for the UCS tests

	Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F_0	P value
7-days	CWG Ratio	229.53121	4	57.3828	15.3186	0.0003
	Error	37.45951	10	3.7460		
	Total	266.99072	14			
28-days	CWG Ratio	380.25358	4	95.0634	37.6926	< 0.0001
	Error	25.22073	10	2.5221		
	Total	405.47431	14			
70-days	CWG Ratio	629.01072	4	157.253	71.3217	< 0.0001
	Error	15.43385	10	2.205		
	Total	644.44457	14			

Table 8 Tukey comparisons for the UCS and Brazilian test results

Level	Level	P value for the Brazilian tests			P value for the UCS tests		
		7-days	28-days	70-days	7-days	28-days	70-days
Reference Mix	100% CWG	0.0180	0.4875	0.0078	0.0002	< 0.0001	< 0.0001
20% CWG	100% CWG	0.0319	0.2972	0.6091	0.0011	< 0.0001	< 0.0001
10% CWG	100% CWG	0.0333	0.3922	0.0502	0.0176	0.0017	< 0.0001
50% CWG	100% CWG	0.0350	0.0658	0.0036	0.0465	0.0114	< 0.0001
Reference Mix	50% CWG	0.9256	0.3872	0.7572	0.0186	0.0010	0.0077
Reference Mix	10% CWG	0.9414	0.9992	0.2811	0.0494	0.0065	0.0928
Reference Mix	20% CWG	0.9530	0.9836	0.0244	0.6542	1.0000	0.0235
20% CWG	50% CWG	1.0000	0.6129	0.0096	0.1542	0.0009	0.8857
10% CWG	50% CWG	1.0000	0.4816	0.0826	0.9666	0.6914	0.2102
20% CWG	10% CWG	1.0000	0.9983	0.2229	0.3657	0.0055	0.6232

promising results discussed above and depicted in Fig. 4 suggest high applicability of cullet re-use in sustainable shotcrete design. It can therefore be concluded that glass utilisation to replace sand not only can improve shotcrete workability and pumpability (without negatively impacting shotcrete mechanical strength properties), but also reduces the amount of cement (and water) needed at a constant w/c design; mainly owing to the water-reducing effect and glass surface properties that don't attract water in fresh shotcrete. Further large-scale field testing, which is underway by the authors, is needed to develop specifications for the manufacture of recycled crushed waste glass as an engineering material for use in shotcrete production in large volumes.

4 Conclusions

The increasing price and diminishing reserves of natural sand and aggregates signify the urgency to develop a cost-effective and eco-friendly alternative. The ever-increasing amounts of waste glass stockpiled worldwide could offer a potential solution to this dilemma. In this study, crushed waste glass was used in shotcrete

production to replace sand at varying percentages up to 100%. According to the experimental results, no impairment of performance was recorded by substituting sand with CWG. Utilisation of glass aggregates in shotcrete mixes could, therefore, not only help to conserve precious sand resources and promote closed-loop recycling of waste glass, but will also produce a cheaper product (without negatively impacting shotcrete mechanical strength properties), provide energy savings, and reduce the carbon footprint in the excavation industry by cutting back on the consumption of natural and quarried sand and cement. However, despite the very promising outcomes, further research is needed to understand how glass aggregate inclusion can impact Alkali-Silica Reaction (ASR) property of shotcrete mixes, their thermomechanical strength under coupled biaxial and true triaxial field stresses, and their fire-induced spalling strength under external heat sources, e.g. when there is a fire in tunnel. Extension of the results to large scale and field trials are also needed; which is currently underway by the author group. Such further studies and analyses would provide a more fundamental understanding of CWG inclusion in shotcrete mixtures under real field conditions.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors have no competing interests to declare that are relevant to the content of this article

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