Sustainable Shotcrete with Crushed Waste Glass

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Abstract. There is an ever-increasing amount of waste glass generated worldwide that is currently sent to landfill, and has a high potential for re-use. In Australia alone, the consumption of glass is 1.36 million tonnes, with the state of New South Wales producing the highest amount. Traditional landflling and stockpiling of waste glass are not an environment-friendly solution, and the re-use of waste glass has become an important research topic in Australia and worldwide. This Project employs an experimental study to estimate waste glass re-cycling in shotcrete production. Mechanical strength and fracture properties of the new mix designs are compared against the controlled mixes at 0% waste glass inclusions. From the results, no impaired performance was recorded by substituting sand with crushed waste glass even at a high percentage ratio of up to 100%. While further research is needed, the promising early results highly encourage the applicability of crushed waste glass for sustainable shotcrete design, a topic that is yet relatively under-researched.

1. Introduction

Estimates show that a staggering fifty billion metric tonnes of natural sand and aggregates is being consumed all over the world every year [1]. Such unsustainable exhaustion of natural aggregates has damaged aquatic habitats, endangered animal species, and have caused beach erosion, making coastal communities vulnerable to floods and other natural disasters. If immediate actions are not taken to address the huge indiscriminate mining of non-renewable sources of beach and quarry sands, it is estimated that around 67% of southern California beaches, for instance, will disappear by the year 2100 [2]. The depletion of sand reserves has also resulted in a dramatic increase in its international trade value, and the sand price has increased almost six-fold just over the last 25 years [3, 4, 5, 6]. As a result, the emerging paradigm shift taking place is to replace natural and quarried sand with sustainable and cost-effective alternatives, like crushed waste glass through circular economy, to mitigate the environmental degradation caused by sand overexploitation at a global scale.

Waste glass (also known as cullet) is theoretically 100% re-usable. It does not degrade and can be recycled over and over without any reduction in quality. It is mainly composed of silica (SiO₂), a key mineral found in natural sand, and shares similar chemical composition to that of natural sand [7, 8, 9]. However, although the use of crushed waste glass (CWG) has grown in the last few years in a range of applications (e.g., concrete production, road pavement construction, tile and brick manufacturing, water filtration, and sandblasting), its wider use remains relatively under-investigated in geotechnical domains. Some potential reasons could
be the perceived inferior quality of CWG as a reliable sand replacement, lack of community-accepted and market-ready guidelines, unrepresentative testing requirements for CWG re-use, and the fact that the construction industry is not yet fully prepared to embrace change towards a circular economy [10, 11, 12]. One of the geotechnical-related areas in which the utilisation of CWG yet remains largely under-studied is the production of shotcrete mixes.

According to the International Tunnelling Society (ATS), the demand for tunnelling and underground constructions will boom in the next coming years. In Australia, the peak is expected in 2022/23 with around $42 billion of investment in the tunnelling sector. With such an increased demand for tunnelling, shotcrete has also received increasing attention for ground support, repairs, and final linings in underground excavation industries. Shotcrete (also known as sprayed concrete or gunite) thus play a vital role in today’s modern construction, civil, mining and excavation projects. In tunnelling applications, in particular, shotcrete is commonly used as a temporary support system (or permanent if applied in several layers), encasing structural steel for fireproofing, deterioration, and in the final lining. Compared to concrete, shotcrete mixes are rich in sand; hence require an increased binder content to coat the surface. Despite shotcrete wide range of applications and its huge global consumption demands, shotcrete industries have suffered from a significant rise in the overall cost in recent years, mainly due to steep hikes in the price of sand. While the availability of desert sand is abundant, it is often not suitable for construction purposes. Sand for shotcrete production is, therefore, sourced mainly from beaches and quarries. This work aims to assess the applicability of CWG to replace sand in shotcrete mix design and investigates further how sand replacement with CWG could affect shotcrete properties. Unconfined compressive (UCS) and tensile strength of different shotcrete mixes were measured using high-speed photography techniques, and the results are discussed and reported in this study.

2. Experimental Results

This study was aimed at partial to full replacement of sand with CWG in shotcrete production with up to 100%. Experiments were conducted at the Geotechnical Engineering Centre (GEC) within the School of Civil Engineering at the University of Queensland, Australia [13]. Five different mixes of shotcrete were produced with CWG replacing sand at proportions of 0%, 10%, 15%, 20%, and 50% under constant water to binder ratio of 0.45. Crushed waste glass in coarse sizes (1.7 – 3.35 mm) was obtained from a commercial supplier, Enviro Sand, in Brisbane, utilising 100% recycled glass, and milling it using a mining crusher under near-dry conditions with less than 2% moisture content (see Fig.1b). To replicate field conditions and to provide post-crack reinforcement, steel fibres (DRAMIX-3D 65/35BG) were added in all shotcrete designs at 35 kg/m$^3$. Flyash was also used as supplementary cementitious material (SCM) to improve shotcrete mixes performance in their fresh and hardened state. In addition, TYTRO WR 174 (water-reducing) and TYTRO HC 270 (hydration-stabilizer) chemical admixtures were added to achieve better workability and to stabilise hydration, respectively. Tytro RC 430 is a high performance and liquid rheology-control admixture formulated based on nanometric colloidal silica to improve cohesion, adhesion and early strength development to shotcrete. It is added when shotcrete shows signs of segregating during batching to pull it back together.

For each mix design, typical shotcrete tests including slump, slump retention, air content, density, as well as UCS and Brazilian tests, were conducted for each mix design. The UCS and Brazilian samples were prepared and cured at 22-24 °C for 7 and 28 days before testing [14]. The samples were stored in a lime saturated bath at 1 day of age until removal for testing. The temperature of the baths was 27 degrees ± 2 degrees at all times. Using ultra-high-speed photography technique and optical methods at 130 kHz and above, the fracture propagation mode and crack speed in the shotcrete samples were then inspected. To record the fracture pattern, a Phantom v2012 camera was utilised. The camera system is capable of recording
at up to 1,000,000 frames per second (fps) at reduced resolution or 22.5 kHz at a maximum resolution of 1 megapixel. By identifying the exact frame where the crack initiated and the frame at which the fracture was fully propagated through the test specimen, an average tensile crack propagation speed for each sample was obtained. A suitable camera speed was carefully selected to ensure the full crack propagation process can be captured over at least 10 frames. Figures 1 & 2 and Tables 2 & 1 illustrate the raw materials used in this project and some of the early test data. Figure 3 further shows high-speed recordings of crack propagation in a shotcrete mix with 50% sand replacement.

Figure 1. Test results and raw materials used in this research project, including (a) tested UCS samples at 0% and 100% sand replacement ratio, (b) aggerates, binders and steel fibres, (c) Brazilian test results to measure shotcrete’s tensile strength indirectly.

3. Discussion
The slump and reverse cone tests are commonly adopted in practice in shotcrete and concrete industries to specify the mix workability and pumpability. Yet another useful index to determine shotcrete workability can be determined by subtracting 100 from the sum of slump and flow (reverse cone) test results, as shown in Tables 2. With reference to results obtained, it can be concluded that:

- the slump and reverse cone test results both show an increasing trend in the workability index with the addition of CWG. This trend, however, is not followed by the 100% mix. A potential reason could be the addition of Tytro RC 430 during batching since this mix was recognised very wet and runny during mixing. That is, the addition of admixture TYTRO RC 430 to the 100% CWG mix hindered workability when compared to other mixes. It is worth mentioning that Tytro RC 430 was not used in any other mix designs.
Density, air content and bleeding results are only changing slightly by higher additions of CWG, which can be explained by almost zero water absorption property of glass compared to natural aggregates and sand.

Up to 50% sand replacement with CWG, no significant change was observed in 7-days and 28-days mechanical strength results between the control and new mix designs. The 100%, however, mix shows a significant reduction in its strength properties; but it could be related to the addition of Tytro RC 430 during batching and not due to the replacement of sand with glass waste.

As expected, both UCS and Brazilian tensile strength of all mixes increase over time. The rate of mechanical strength increase between 7-days and 28-days is very similar in all mixes regardless of the CWG replacement ratio. However, the 20% mix design shows the highest improvement with around 37%.

The value of the brittleness index, defined as the ratio of UCS/tensile strength [14, 15], shows a slight increase from 7-days to 28-days post-curing. This can be explained by noting that glass is a relatively more brittle material than sand. That is, the higher the glass content, the more brittle the mix. It can also be seen more clearly by assessing the fracture pattern on the face of Brazilian test samples between different mixes as shown in Fig.1c.

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**Figure 2.** Compressive and indirect tensile strength test results for various shotcrete mixes at different sand replacement ratio.

**Figure 3.** High-speed time-lapses of the fracture pattern observed in shotcrete samples compressed between flat horizontal platens according to ASTM recommendations.
Serati et al. (2021) reported that the fracture mode in the Brazilian test (from a single crack to multiple cracking) is preliminarily governed by the material’s brittleness index. It means, a single crack in Brazilian testing of a brittle solid is mostly recorded in specimens with a low brittleness index and tensile strength (usually less than 5 MPa), also shown in Fig.4a. For medium tensile strength materials, the dominant fracture pattern becomes a single crack accompanied by moderate-sized inverse shear conical plugs in the vicinity of contacts (see Fig.4b). For high tensile strength materials (e.g. granite, ceramic and basalt), the most commonly observed fracture pattern always involves breaking up samples into many fragments due to unstable multiple cracking, unwanted shear fractures at contacts.
Table 2. Summary of the test results

| Test Type             | Reference Mix | 10%   | 15%   | 20%   | 50%   | 100%  |
|-----------------------|---------------|-------|-------|-------|-------|-------|
| Slump (mm)            | 235           | 255   | 250   | 240   | 265   | 200   |
| Reverse Cone (mm)     | 460           | 560   | 475   | 475   | 600   | -     |
| Workability index     | 595           | 715   | 625   | 615   | 765   | -     |
| Density (kg/m³)       | 2663.09       | 2974.14 | 2990.85 | 2985.27 | 2977.85 | 2874.01 |
| Air Content (%)       | 1.2           | 0.8   | 1.30  | 0.6   | 0.4   | 3.5   |
| Tensile Crack Speed (m/s) | 1.03       | 1.08  | 1.06  | 1.21  | 1.19  | -     |

Figure 4. Typical fracture modes observed in Brazilian tensile strength testing of geomaterials [16, 17, 18]

and a dominant central crack (see also Fig.4c). As illustrated in 1c, the reference mix with 0% CWG exhibits a single straight crack. As the ratio of CWG in the mix design increases, the tensile crack becomes more violent with several fragments generated on the fracture surface, e.g. the reference mix against the 100% sand replacement with CWG mix design.

- However, the effect of increased brittleness index on the tensile cracking speed in mixes with higher CWG is less pronounced. A possible explanation for this observation could be the existence of steel fibres in all mixes which control fracture propagation and crack speed in failed samples under induced stresses. More research is needed to verify the fracturing speed results over a longer time period, which is underway by the authors.

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4. Conclusions

Sand, being one of the most valuable non-fuel mineral commodity, is being mined at an alarming 50 billion tonnes every year globally, equivalent to almost 18 kg per person per day. Such an ever-increasing use and diminishing reserves of natural and quarried sand, and hence its price, has highlighted the urgent need for a cost-effective replacement, embracing the circular economy. Waste glass is perceived to be relatively ‘inert’ and potentially offers opportunities for recycling...
as a substitute for diminishing and increasingly expensive sand supplies. This study assesses the applicability of large-scale waste glass re-use in shotcrete production. The promising results confirm the applicability of waste glass in shotcrete mixes, but also highlight the necessity of further research with more experimental testing (including early age strength test, the alkali-silica reaction, creep, biaxial and true triaxial testing of mix designs), which are underway with the authors’ group.

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