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Effect of recycled fine waste glass powder on workability performance in sustainable backfill

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ABSTRACT: One of the common problems in tunnel construction is ensuring efficient and low-cost backfilling of the void areas found behind the excavation contour. Paste backfill is a widely used backfill technique globally, which typically contains cementitious material, sand, and water. As per several reports, Australia consumes around 1.3 megatons of glass per annum, of which around 56% end up in landfills. Since glass has been successfully used as a sand replacement in pavement and concrete, the present study aims to substitute sand with fine waste glass powder to enhance sustainability in backfilling while reducing costs. The current study experimentally examines how the workability, yield stress, compressive strength, and tensile strength are impacted when sand is partially replaced with recycled waste glass powder. The obtained results indicate that 25% replacement improves the performance of the paste while increasing sustainability and reducing costs.

1 INTRODUCTION

Backfilling is the process of placing materials into an excavation to provide temporary or permanent support in order to help prevent ground subsidence and enhance strength and stability. It is widely used in both structural and non-structural civil and geotechnical engineering applications, including conduit bedding, mining, tunnelling, bridge abutments, and retaining walls, among others.

In the context of tunnel construction, we often encounter void areas located behind the excavation contour. These can arise from various causes, including the collapse of the overburden, large area overbreak, or due to the presence of karst caves within the geological formation (Zhang et al., 2022). If left unfilled, these voids can compromise the stability of the surrounding ground, pose safety risks, and significantly increase construction costs. Consequently, backfilling these voids is a critical and indispensable aspect of the overall tunnel engineering process. In particular, backfilling contributes to the stabilisation of soft soils near tunnel portals and facilitates the plugging of unused cross-passages or temporary connections, thereby preventing ground movement and mitigating potential hazards. Additionally, in tunnel boring machine (TBM) excavations, annular gap grouting requires the use of a self-levelling material that demands minimal compaction to ensure that the space between the excavated ground and the segmental linings is filled, which is essential for minimising settlement risks and maintaining the structural integrity of the tunnel lining (Das, 2021). Beyond TBM applications, backfilling also plays a vital role in redundant or abandoned tunnels, shafts, and utility trenches by providing long-term stabilisation and support. Moreover, it is an integral component in the design of tunnel foundation layers, where it ensures adequate support for the overlying structural courses, maintains overall stability, and facilitates efficient load transfer by being in direct contact with the rock base or with the permanent concrete lining, thereby enhancing both safety and durability of the tunnel structure (Riviera et al., 2019).

Cemented paste backfill (CPB) was proposed in the 1980s and is one of the most popularly used methods these days. Typically, the mix design consists of 70-80% solid content (sand), 1-

10% binder content by weight, and a 25-35% water-to-cement ratio (Behera et al., 2021, Sheshpari, 2015, Sivakugan et al., 2015), costing around 25-50 AUD/m^3.

1.1 *Recycled fine waste glass powder as a sand replacement*

Numerous reports suggest that Australia consumes around 1.3 million tonnes of glass annually (He et al., 2024, Kazmi et al., 2021, Kazmi et al., 2019, Serati et al., 2022, Serati et al., 2017). While efforts have been taken to reuse glass to manufacture other glass products, it is extremely challenging as glass pieces need to be separated based on their colour to maintain the quality of the manufactured products. Moreover, several sectors resort to crushing glass to minimise freight costs, thereby making recycling glass more challenging. As a result, around 56% of the consumed glass ends up in landfills, and since glass is an inert material, it remains in landfills for about 4,000 years. Figure 1 shows the glass waste flow in Australia as per the data from the report of the Department of Environment and Energy in 2019 (DEE, 2019).

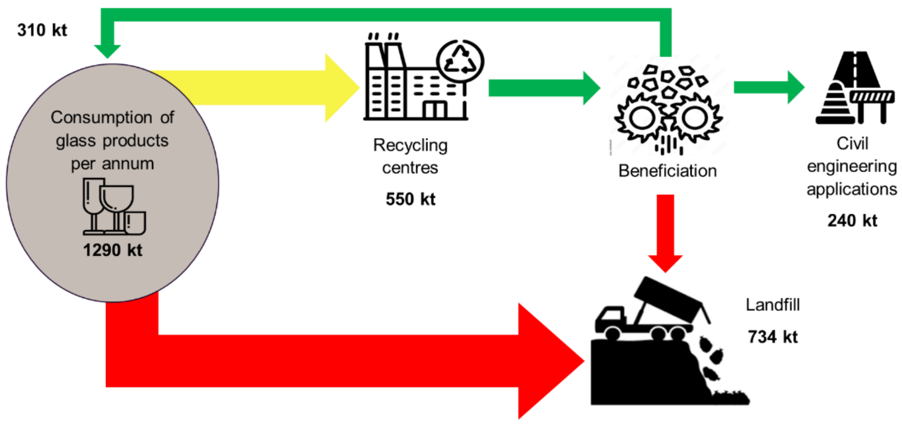

Figure 1. Glass waste flow diagram in Australia.

Recently, various studies have focused on reusing waste glass as a construction material in several civil engineering applications, such as pavement construction, drainage blankets, filter media, ultra-high-performance concrete, and mortar (Sankh et al., 2014, Tamanna et al., 2020). This study aims to partially replace sand with recycled fine waste glass powder in cement paste backfills and assess its impact on slurry and hardened-stage properties like yield stress, workability, compressive strength, and tensile strength. The potential advantages of using glass include reducing backfill costs, as sand costs around 55 AUD/tonne while fine glass costs 45 AUD/tonne. Additionally, it lessens the burden on landfills, decreases sand usage, and since glass is inert, it doesn't pollute the water table or release greenhouse gases (Disfani et al., 2011).

2 EXPERIMENTAL METHODS

The experimental program consists of slurry and hardened-stage testing of two mix designs, namely, the reference mix design and the 25% replacement mix design. The former tests include measuring the yield stress, slump, and spread, while the latter includes UCS and Brazilian tensile strength testing. The experimental set-up and methods followed are highlighted in the following section.

2.1 *Sample preparation*

The cement paste backfill (CPB) samples for the reference mix design were made by mixing general purpose portland cement conforming to AS 3972, mine tailings sourced from a mine in Australia as the solid material and tap water. For the 25% replacement mix, the same materials were used, except that 25% of the mine tails were replaced with recycled crushed waste glass sourced from a local supplier. The quantities of raw materials mixed for both the mix designs are shown in Table 1. Trials were conducted to optimise the water content in the 25% replacement mix design. Since glass doesn't absorb any water, the water content is reduced to regulate the segregation and bleed.

Table 1. Mix design details for the present study.

Raw materials	Reference mix design	25% replacement mix design
GP cement	98 kg/m^3	98 kg/m^3
Mine tailings	1530 kg/m^3	1,147.5 kg/m^3
Waste glass	0 kg/m^3	382.5 kg/m^3
Water	390 kg/m^3	385 kg/m^3

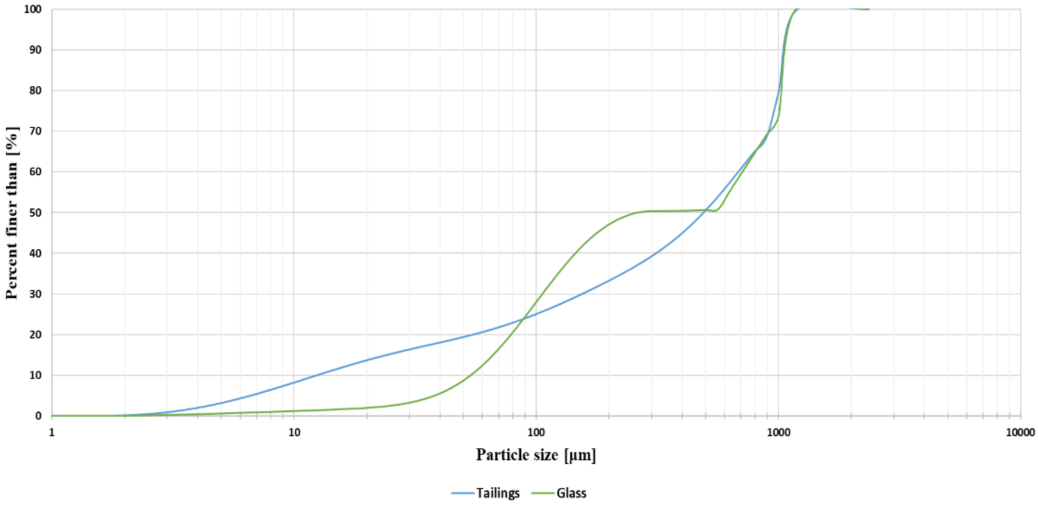

Figure 2. Particle size distribution of tails and glass used.

The mixing process involved dry mixing the solid materials for 3 minutes to break any lumps, post which cement was added and mixed for 1 minute. Lastly, water was added, and the mixture was mixed for 3 minutes (Sheshpari, 2015). The particle size distribution of the tailings and glass used is shown in Figure 2.

2.2 *Experimental set-up and methods*

Table 2 shows the list of tests conducted for both the mix designs, with their acceptable values and the test methods followed. In order to study the evolution of compressive strength with the curing duration, UCS testing was carried out on specimens with curing ages of day 1, 3, 7, and 28 on cylindrical samples with a diameter of 50 mm and a length of 100 mm. While the indirect Brazilian test was carried out for the curing age of 28 days to check the tensile strength on cylindrical samples with a diameter of 100 mm and a length of 200 mm. Since there are no standard procedures mentioned in the literature for the yield stress measurements, trials were conducted using the AntonPAAR MCR 102e rotational rheometer. The fluid was subjected to various low shear rate values for different durations to minimise the influence of instrument inertia and viscous resistance (Dzuy and Boger, 1985) and to check which speed gave the most suitable results. It was seen that subjecting the backfill slurry to a shear rate of $1s^{-1}$ for a duration of 150 seconds yielded the most appropriate results.

Table 2. Tests on CPB samples.

Tests	Acceptable results	Standards
Slump (Cao et al., 2021)	235 - 275 mm	AS 1012.3.5
Yield Stress (Li et al., 2020)	200 - 250 Pa	-
Compressive Strength (Feng et al., 2023)	0.4 - 4 MPa	AS 5101.4
Tensile Strength (Feng et al., 2023)	0.04 - 0.4 MPa	AS 1012.10

3 RESULTS AND DISCUSSION

3.1 *Workability*

Figure 3 (a) and (b) show the J-ring slump test results obtained for the reference mix design, measured immediately after mixing and after a one-hour retention period, respectively. Similarly, Figure 3 (c) and (d) show the results obtained for the 25% replacement mix design, measured immediately after mixing and after a one-hour retention period, respectively. It can be seen that the slump and spread results are comparable for both mixes when measured immediately. However, the reference mix design wasn't flowable after a one-hour retention period, while the 25% replacement mix design still flowed well. The values obtained for the slump, spread, J-ring passing ability difference, and flow rate are shown in Table 3. The J_r and T_{500} values are also similar for the mixes, indicating that they are flowable and resistant to segregation.

Table 3. Workability results for reference and 25% replacement mix design.

Values	Reference mix	25% replacement mix
T_{500} [s]	0.65	0.75
Jr [mm] – immediate	6	6
Slump [mm] – immediate	280	270
Spread [mm] – immediate	760	690
Jr [mm] – 1 hour	–	11
Slump [mm] – 1 hour	130	240
Spread [mm] – 1 hour	–	570

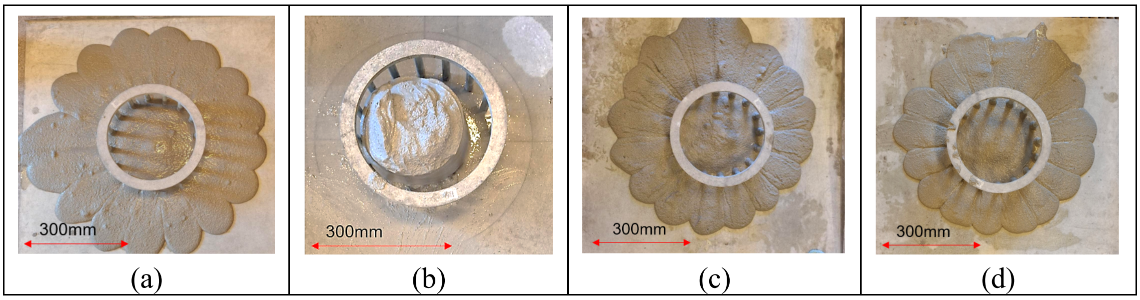

Figure 3. J-ring slump test results for reference mix (a) immediately, (b) 1 hour after mix and 25% replacement mix (c) immediately, (d) 1 hour after mix.

3.2 *Yield stress*

In order to determine the yield stress of the mixes, a vane rotor of diameter 14 mm and length 28 mm was used along with the cup holder with an inner diameter of 28.9 mm. All the tests performed on a sample were repeated at least two times to ensure repeatability and their average was taken. Figure 4 shows the yield stress of the reference and 25% replacement mix design. It can be seen that the yield stress of the reference mix design is 670 Pa, while that of the 25% replacement mix design is 175 Pa, which is significantly lower than the reference. A lower value of yield stress, despite a higher solid percentage and a lower water-to-cement ratio, is favourable since it ensures better filling of voids and reduces the risk of pipe blockages, which are often associated with significant financial consequences as the progress of the project gets delayed and the operating costs increase. Additionally, lower yield stress facilitates easier and more efficient pumping, which can lead to a reduction in the pumping costs (Haiqiang et al., 2016).

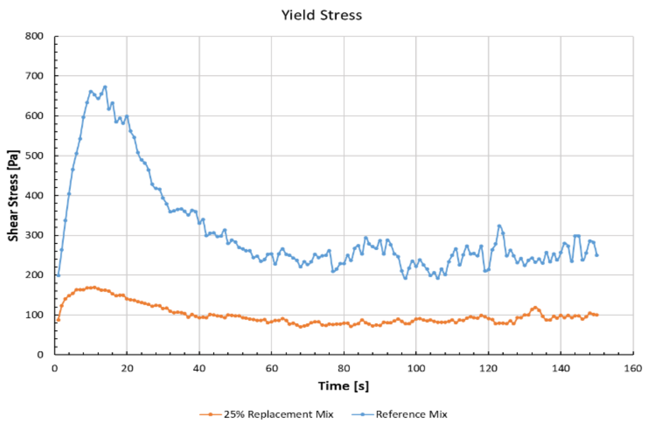

Figure 4. Yield stress results for the reference mix and the 25% replacement mix.

3.3 *Compressive strength*

Figure 5 (a) illustrates the UCS results obtained for the reference and 25% replacement mix for different curing ages of 1d, 3d, 7d, and 28d. It can be seen that the 25% replacement mix is overall stronger than the reference mix. The difference keeps getting more pronounced as the curing age increases, with the compressive strength of the 25% replacement mix samples on day 28 being around 1.5 times the strength of the reference mix sample. Figure 5 (b) and (c) present the photographs of the failure pattern observed in the 28-day samples for the reference and 25% replacement mix design, respectively.

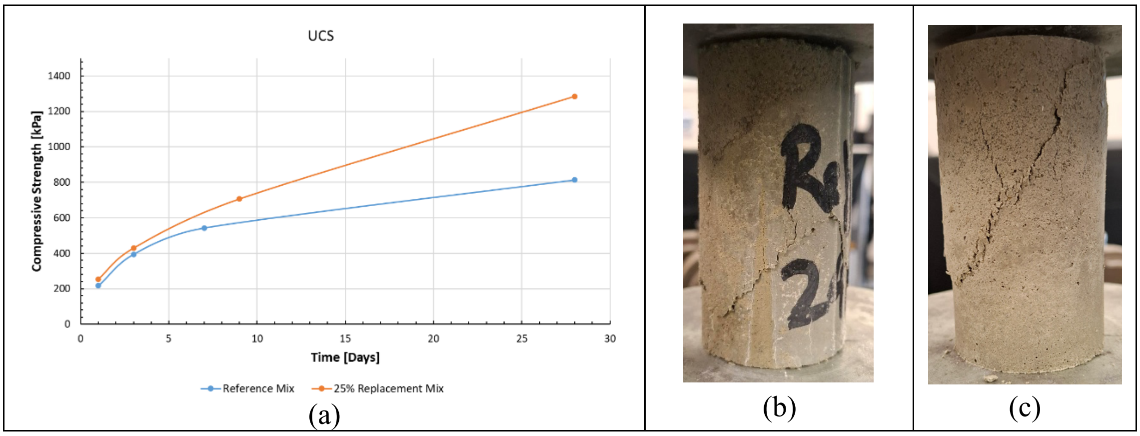

Figure 5. (a) Graph comparing UCS results for the reference mix and the 25% replacement mix (b) photograph of 28-day sample for the reference mix (c) photograph of 28-day sample for the 25% replacement mix.

3.4 *Tensile strength*

In addition to the assessment of the compressive strength, it is also essential to evaluate the tensile strength of CPB. As per several studies, typically, the tensile strength of a CPB sample is around 10% of its compressive strength (Behera et al., 2023). Using the indirect Brazilian test, the tensile strength of the reference mix was 175 kPa, while that of the 25% replacement mix was 235 kPa. Similar to the UCS, the replacement mix was significantly stronger in tension as well. Figure 6 (a) and (b) show the Brazilian test samples for the reference and replacement mix, respectively.

As expected, the failure plane is located along the vertical plane passing through the disk's centre, perpendicular to the applied load for both the samples.

(a) (b)

Figure 6. Brazilian test samples for (a) reference and (b) 25% replacement mix.

4 CONCLUSIONS

One of the most commonly encountered problems in tunnel construction is ensuring efficient and low-cost backfilling of the void areas found behind the excavation contour, which can be caused by the collapse of the overburden, large area overbreak, or by encountering karst caves. Paste backfilling is a widely used technique to overcome this problem, which typically consists of sand, cementitious material, and water. The present study studies how the partial replacement of sand with recycled crushed waste powdered glass impacts the strength parameters – UCS and tensile strength, and fluid behaviour parameters – workability and yield stress. To do so, two mix designs were prepared, namely, the reference mix design and the 25% replacement mix design and tested for the following properties.

The workability results were similar for both the mixes when tested immediately after mixing, however, the 25% replacement mix was flowable after one hour retention, while the reference mix design was not flowable. There was a significant reduction in the yield stress for the replacement mix design, which is favourable since it ensures better filling of voids and reduces the risk of pipe blockages, while facilitating easier and more efficient pumping, which can lead to a reduction in the pumping costs. The 25% replacement mix design exhibited higher compressive and tensile strengths compared to the reference mix, making it more favourable in terms of hardened stage properties as well. Hence, these results indicate that the partial replacement of sand with glass not only enhances the sustainability and cost-effectiveness of backfilling but also improves its fresh and hardened properties.

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