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Evaluating the setting behaviour of shotcrete with crushed waste glass as sand replacement

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ABSTRACT: The increasing demand for shotcrete, driven by the expansion of underground construction, has intensified concerns on its supply chain over natural sand depletion. This issue is particularly pressing as shotcrete typically requires an over-sanded mix, further straining finite resources and posing environmental and economic challenges. To address this, a novel approach was proposed using crushed waste glass (CWG) as a partial replacement for natural sand. Given the importance of early-age strength in shotcrete, especially when used with accelerators, this study focused on the influence of CWG on setting behaviour. A series of tests using thermocouple-embedded cube moulds were conducted across CWG replacement levels from 0% to 50%. Findings revealed the overall comparable setting dynamics across different mixes, while it was observed that CWG inclusion caused a slight increase in peak temperature and a minor delay in setting initiation, which requires careful consideration in developing shotcrete mix design.

1 INTRODUCTION

With rapid urbanisation and growing demand for construction, tunnelling has become essential not only for transportation, but also for resource and energy sectors, including shaft construction and pumped hydro for sustainable energy storage (Blakers et al., 2021). As the tunnelling projects increase, so does the demand for shotcrete. It is a specialised form of concrete applied pneumatically through a nozzle, offering notable advantages in flexibility and efficiency (Australian Shotcrete Society, 2020). Shotcrete application provides immediate support to the rock mass after excavation, making it especially valuable in most tunnelling methods, such as drill and blast. It can serve as both a temporary and final rock support system. Unlike conventional concrete, shotcrete does not require traditional formwork, thereby reducing both construction time and cost.

To meet application demands, shotcrete must exhibit high flowability in its base mix (without accelerator) and minimise rebound during application (Armelin & Banthia, 1998). Achieving these properties requires modifications to conventional concrete mix designs. In addition to chemical admixtures such as accelerators, superplasticisers and retarders, shotcrete uses smaller aggregates, typically up to 10 mm, and a significantly higher proportion of fine aggregates. Natural sand is the most commonly used fine aggregate due to its wide availability and reliable performance history.

However, natural sand is now the second most consumable resource globally. Its annual consumption exceeds 50 billion tons, with a growth rate of 5% per year (Kazmi et al., 2020). Despite the economic impact of the increasing market price, over-excavation of natural sand has also led to environmental degradation, such as deforestation and riverbank corrosion. Given the over-sanded mix design of shotcrete, such depletion presents a critical supply chain concern for the shotcrete industry.

In response, the industry is actively seeking alternatives to natural sand. The author group has explored the use of synthetic fine aggregates derived from solid waste for shotcrete production, with crushed waste glass (CWG) emerging as a promising option (Kazmi et al., 2021; Kazmi et al., 2020; Zhu et al., 2025; Zhu et al., 2023). As a material originally manufactured from natural sand, CWG shares a similar chemical composition, primarily composed of silica (SiO_2). It is also advantageous due to its non-biodegradability and inert nature.

The reuse of waste glass, particularly from packaging such as bottles and jars, which are difficult to recycle due to variations in colour and composition, also addresses landfill reduction and sustainability goals. Industrial glass (e.g., windows) is more easily recycled, while packaging glass often ends up as waste due to the higher energy cost of sorting and reprocessing (Costa & Meillon, 2022).

To advance sustainable practices in shotcrete production, the author group has conducted a series of investigations on CWG at multiple scales, ranging from grain-level characterisation to laboratory batch testing and progressing toward field trials. In the first laboratory-scale study, the incorporation of CWG as a partial replacement for natural sand (up to 50%) was shown to maintain comparable mechanical strength and fresh properties, demonstrating its feasibility for structural applications (Serati et al., 2022). Recognising the critical role of early-age strength in ensuring safe site access after shotcrete application, a subsequent study focused specifically on the interaction between CWG content and accelerator dosage, which is currently under publication process (Zhu et al., 2025). This second investigation examined the early-age strength development of shotcrete mixes with varying CWG replacement levels (0%, 10%, 25%, and 50%) while maintaining a constant accelerator dosage of 3%. The results, summarised in a forthcoming conference proceeding, revealed that CWG-containing mixes exhibited reduced strength at 3 hours based on end-beam tests. However, as hydration progressed, strength levels improved and approached those of conventional mixes, indicating a distinct early-age behaviour influenced by the presence of CWG.

These findings align with previous literatures working on CWG replacing natural sand in concrete materials, where unconfined compressive strength (UCS) demonstrated similar trends, with initial strength reductions attributed to weaker interfacial transition zone (ITZ) (Shao et al., 2000; Tamanna et al., 2020; Tan & Du, 2013). However, the presence of amorphous silica in fine glass particles can lead to pozzolanic activity, enhancing strength at later ages. In accelerated shotcrete, though, pozzolanic reactions are unlikely to significantly contribute within short timeframes. Instead, the early-age strength reduction may be linked to delayed cement hydration caused by the glass aggregates, which is an area requiring further research.

This gap in understanding underscores the need for deeper investigation into the setting behaviour of shotcrete containing CWG. One effective method for evaluating setting behaviour is thermal characterisation. Cement hydration is an exothermic process, and temperature monitoring provides insight into setting dynamics. While prior studies have used isothermal calorimetry to evaluate hydration rates in glass-containing cementitious materials, such tests are limited to small samples (e.g., pastes or mortars) and do not fully represent shotcrete behaviour (Jochem et al., 2021; Liu et al., 2015; Mirzahosseini & Riding, 2014).

To address this, Poutos et al. (2008) have measured temperature changes using thermocouples embedded in a 200 mm concrete cube with 100% aggregate replacement by various types of crushed glass. The study revealed significant differences in temperature profiles, indicating variations in setting behaviour. Building on this foundation, the present study improves upon previous studies by accounting for practical shotcrete mix conditions, including chemical admixtures, adjusted water-to-cement ratios and increased thermocouple distribution to capture localised effects on cement hydration.

This study investigates four shotcrete mixes with 0%, 10%, 25%, and 50% replacement of natural sand by CWG, with a focus on early-age setting behaviour. By adopting the same mix design as previous studies, this work aims to provide deeper insight into the influence of CWG on early hydration and setting dynamics.

2 EXPERIMENTAL PROGRAM

2.1 *Materials*

The shotcrete mix used in this study was specifically designed for tunnelling applications and has been successfully implemented in actual tunnel construction projects. The constituent materials, including fine sand, medium sand, coarse aggregates, cement, fly ash, and the reference mix design, were supplied by Wagners, a collaborating concrete supplier, with raw materials sourced from local quarries and cement plants. Chemical admixtures were provided by GCP Applied Technologies and included Tytro WR172 (water reducer), Tytro HC270 (hydration stabiliser), and ALSET 13 (accelerator).

The crushed waste glass originated from landfilled glass waste, primarily consisting of beverage bottles in various colours. The raw glass underwent heat treatment to remove paper labels and contaminants, followed by crushing into multiple size fractions. For this study, different CWG sizes were blended to closely match the particle size distribution of the medium sand they replaced. This approach ensured that the combined aggregate gradation remained consistent across all CWG-containing mixes.

Table 1. Shotcrete mix design per m^3 with different CWG replacement ratios.

Materials	0%	10%	25%	50%
7mm Aggregate (kg)	450	450	450	450
Medium Sand (kg)	1,016	914	762	508
Crushed Waste Glass (kg)	0	102	254	508
Fine Sand (kg)	153	153	153	153
Cement (kg)	345	345	345	345
Fly Ash (kg)	115	115	115	115
Tytro WR172 (kg)	3.71	3.64	3.64	3.49
Tytro HC270 (kg)	1.1	1.1	1.1	1.1
Water (L)	245	245	245	245

The mix designs, summarised in Table 1, were developed through iterative adjustments to the water reducer (Tytro WR172) and water content, with the goal of achieving slump values comparable to the reference mix. Optimised shotcrete mixes reached target slump values in the range of 230–250 mm. Notably, mixes incorporating CWG required reduced dosages of both water and water reducer, likely due to the hydrophobic nature of glass. This observation aligns with findings reported by Serati et al. (2022) and Zhu et al. (2023).

2.2 *Experimental Process*

The experimental tests were performed using 200 mm concrete cube moulds as shown in Figure 1a. Each mould was instrumented with five thermocouples, positioned vertically and equally spaced, with the alignment displayed in Figures 1b and 1h. Type T thermocouples with 0.5 mm diameter, supplied by TC Measurement & Control, were used in the setup. The thermocouple used in this study is made from copper, allowing measurement up to 125°C with a tolerance of +/- 0.5°C. Thermocouple junctions were formed by twisting and connecting both wires, and the extension cables were made from the same thermocouple wire, fitted with thermocouple connectors (both socket and plug in Figs 1d, e). Data acquisition was managed using a Keysight 34980A system, which supports up to 40 simultaneous inputs and operates within the environmental parameters specified for the test.

The experimental process was divided into two phases: mixing (in Fig. 1f) and conditioning (in Fig. 1g), with temperature continuously recorded throughout by the data logger. All four mixes were prepared on the same day. Aggregates and binders were pre-weighed, dried, and dry-mixed before adding water and admixtures. Each batch was mixed for no longer than 10 minutes and immediately cast into moulds. Since mixed order can influence temperature development, two separate trials were conducted to account for this variable. In Trial 1, mixes were prepared in the order of 50%, 25%, 10%, and 0% CWG replacement; in Trial 2, the order was reversed. This allowed for normalisation of temperature profiles by averaging the data from both trials to establish a consistent baseline.

To ensure consistent curing conditions, the conditioning phase was conducted in the Concrete Creep Room at the University of Queensland's Civil Engineering Laboratory. This facility maintains a stable environment of 23.5°C and 50% relative humidity, minimising the influence of external temperature fluctuations. The transition from mixing to conditioning took approximately one minute, during which data logging was temporarily paused.

Temperature was recorded continuously at a frequency of 1 Hz throughout the test. For post-processing and analysis, the data were averaged at 15-minute intervals to reduce noise and improve clarity of the temperature profiles.

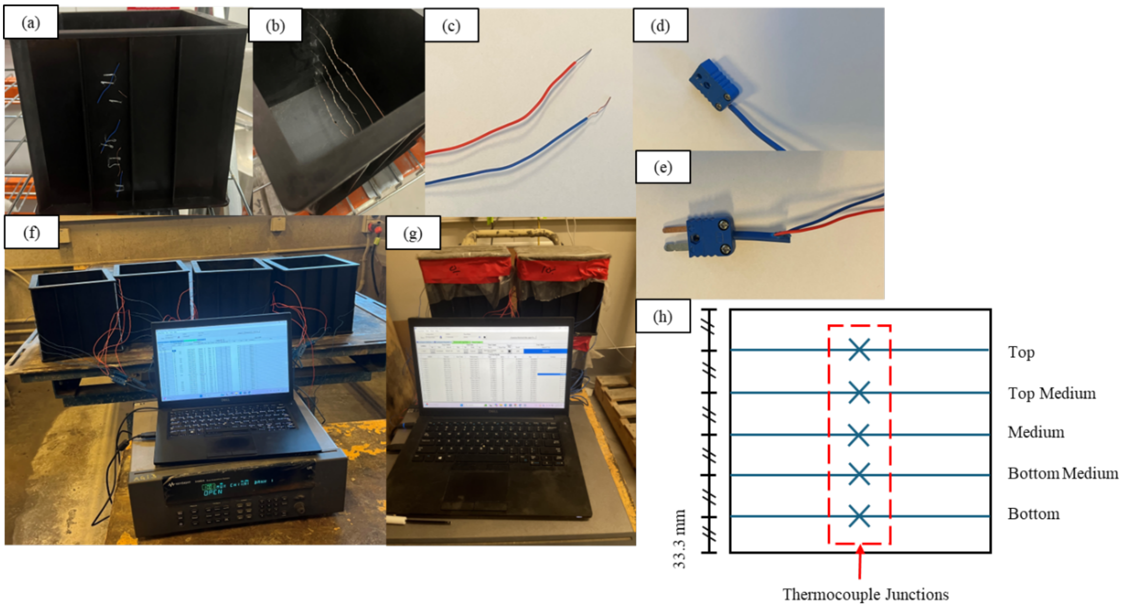


Figure 1. Experimental test setup: (a) 200 mm cube mould, (b) thermocouples installed in mould, (c) Type T thermocouples, (d) thermocouple socket connector, (e) thermocouple plug connector, (f) measurement setup in mixing phase, (g) measurement setup in conditioning phase and (h) thermocouple installation alignment.

3 RESULT DISCUSSION

Figure 2 presents the averaged temperature profiles of all four shotcrete mixes, compiled from both experimental trials. The results demonstrated minimal variation among thermocouple positions. While the bottom thermocouple occasionally displayed slight deviations from the general trend, which is likely due to proximity to the mould boundary and heightened sensitivity to ambient temperature, these differences were minor and did not significantly affect the overall analysis. The consistency across thermocouple readings indicates that cement hydration occurred uniformly throughout the shotcrete matrix, with no evidence of localised hotspots. This spatial uniformity enabled the use of averaged temperature values across all ten thermocouples (two trials, five per mould) for each mix.

These average profiles are plotted in Figure 3a. To further interpret the hydration kinetics, the rate of temperature change was analysed and presented in Figure 3b. This was calculated as the slope between successive 15-minute intervals, providing an estimate of the instantaneous rate of temperature increase or decrease.

In the first 7 hours following mixing, temperature variation largely reflected external influences - namely, the transition from ambient mixing conditions to the controlled environment of

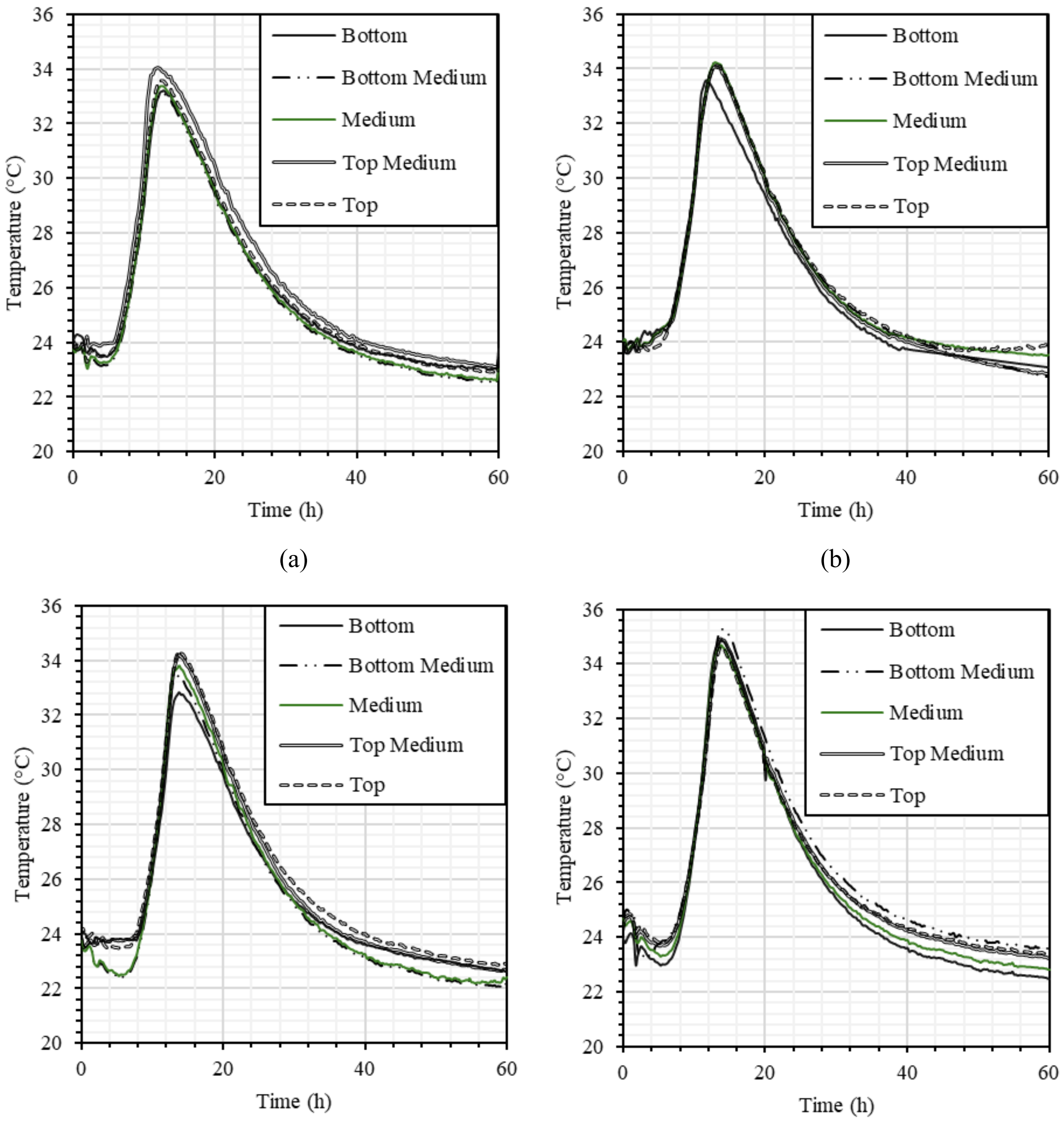
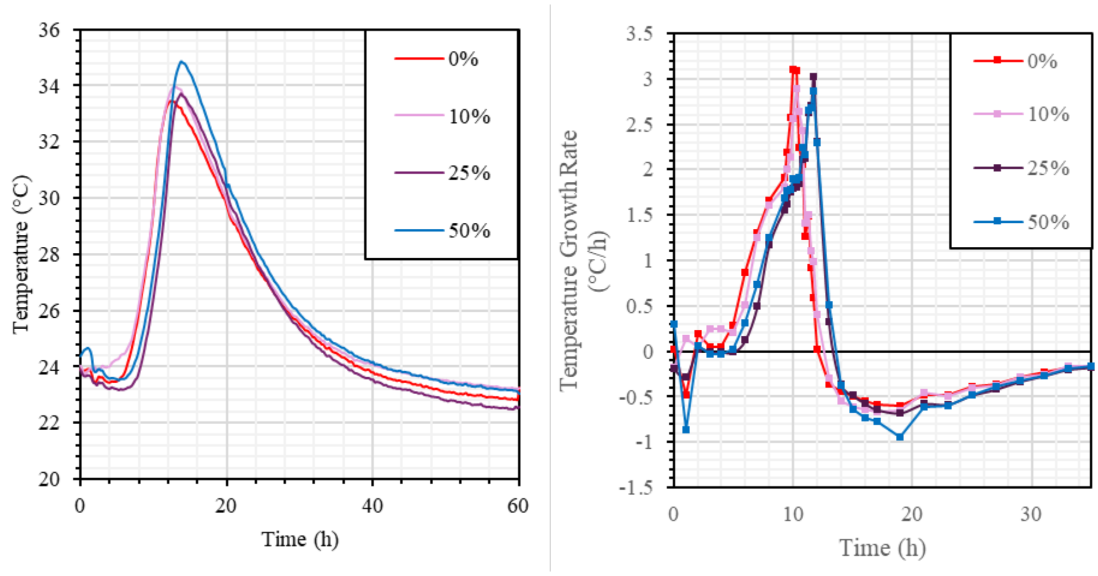


Figure 2. Average temperature profile from shotcrete mixes based on two trials: (a) 0% CWG mix, (b) 10% CWG mix, (c) 25% CWG mix and (d) 50% CWG mix.

the conditioning room. Additionally, the mixing process itself may have slightly elevated temperatures due to mechanical energy input; however, given the controlled slump across all mixes, flow-related differences were considered negligible.

Overall, the inclusion of CWG did not significantly alter the thermal profile of cement hydration. Maximum recorded temperatures ranged from 34°C to 36°C, comparable reported temperature rise in the literature for cementitious materials due to cement hydration (Poutos et al., 2008; Schackow et al., 2016; Wade et al., 2010). Figure 3a shows a slight increasing trend in peak temperature with higher CWG replacement. Notably, the mix with 50% CWG exhibited a temperature approximately 2°C higher than the reference mix. An additional observation was a modest delay in setting initiation for mixes with higher CWG content, with onset delayed by approximately 1 hour. To address the key findings from this study, the outcomes may be explained by the following mechanisms related to CWG properties:

- Unlike natural sand, which is predominantly composed of crystalline silica, glass is made of amorphous silica. The disordered atomic structure of amorphous silica results in lower thermal conductivity, slowing heat transfer (Zhou et al., 2020). Consequently, heat generated during hydration is retained longer, potentially elevating peak temperatures.



(a) (b)

Figure 3. Analysed temperature profiles for four mixes: (a) temperature variation and (b) temperature growth rate.

- Fine CWG particles with high specific surface area can act as pozzolanic reactants. The reaction between amorphous silica in glass and calcium hydroxide (portlandite), a hydration by-product, forms secondary C-S-H gel (Shao et al., 2000; Tamanna et al., 2020). Although pozzolanic reactions typically occur after initial cement hydration, their exothermic nature may contribute to slightly higher temperatures observed at later stages.
- Glass particles are smoother and more hydrophobic than natural sand, as confirmed in Zhu et al. (2023). This can hinder water absorption, reduce paste-aggregate bonding, and slow hydration. Despite the consistent dosage of hydration stabiliser, the hydrophobic nature of CWG may contribute to delayed setting through retention of free water in the mix.
- The CWG used in this study was sourced from recycled beverage containers. The treatment process involved only thermal cleaning without washing, likely leaving residual sugar from contents such as honey and soft drinks. Previous research has proven that sugar contamination can retard the setting of cementitious materials, which may further explain the observed delay in hydration onset (Khan & Baradan, 2002; Wang et al., 2022).

4 CONCLUSION

This study explored the influence of crushed waste glass (CWG) as a partial replacement for natural sand in shotcrete applications, with a focus on its effects on early-age temperature development and setting behaviour. The experimental approach involved full-scale batching of shotcrete mixes incorporating CWG at varying replacement levels (0%, 10%, 25%, and 50%), followed by detailed thermal monitoring using embedded thermocouples under controlled environmental conditions. Key findings are as follows:

- Temperature profiles obtained from multiple thermocouple positions confirmed that cement hydration occurred uniformly throughout the shotcrete matrix, allowing reliable analysis based on averaged temperature data.
- Across all mixes, peak hydration temperatures ranged from 34°C to 36°C, with a slight upward trend observed as CWG content increased. The increase, although modest, suggests that the presence of CWG may contribute to improved thermal retention within the matrix.
- Higher CWG replacement ratios were associated with a delay in the initiation of cement setting by approximately one hour. This delay is attributed to several interrelated factors, including thermal conductivity, potential pozzolanic activity, unique surface characteristics and sugar contamination.

Overall, the inclusion of CWG up to 50% did not negatively impact the thermal signature of cement hydration, and in fact, exhibited slightly elevated peak temperatures with minimal disruption to setting kinetics. These findings support the feasibility of CWG as a sustainable alternative to natural sand in shotcrete, with manageable effects on early-age behaviour. The study also provided an explanation for previous findings in the early-age strength pattern of CWG-incorporated shotcrete with accelerator dosage. This finding suggested the potential to adjust the accelerator dosage or reduce the retarder content to enhance the early-age performance of shotcrete with high CWG replacement ratios.

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