International Society for Rock Mechanics and Rock Engineering
Norwegian Group for Rock Mechanics

ISRM International Symposium
Eurock 2025 – Expanding the Underground Space
Trondheim, Norway, 16-20 June
ISBN 978-82-8208-079-8

Early-Age Strength Performance of Shotcrete Mix with Crushed Waste Glass as Replacement for Natural Sand

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Abstract

Shotcrete, or sprayed concrete, is a key component of rock support, preventing rock falling in various geotechnical engineering projects. Due to the specific requirement of spraying process, shotcrete mix needs to consider obtaining higher flowability and reducing the unwanted rebound, which necessitates a higher sand content in mix design than traditional concrete. However, sand is becoming the second-most consumable resource on earth. The current high consumption of sand is leading to depletion, resulting in price increase and negative environmental impacts. A sustainable solution is using synthetic aggregates produced from solid waste to replace sand in shotcrete mix. Given that glass contributes to a high percentage in solid waste stream in recent years, utilizing crushed waste glass (CWG) as a partial replacement for natural sand in shotcrete production has emerged as a sustainable solution.

To develop a sustainable shotcrete mix with CWG, the early-age strength performance effected by glass inclusion with different replacement ratios (0%, 10%, 25% and 50%) to natural sand was investigated in this study using with the dosage of accelerator. The research outcome has indicated comparable early-age shotcrete strength with glass inclusion, with increase in later age strength.

Keywords

Shotcrete, Crushed waste glass (CWG), early-age strength, accelerator, strength development

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1 Introduction

Shotcrete, which is a specialised form of concrete applied through high-pressure spraying, is commonly used in tunnel linings, retaining walls and slope stabilization, among other applications, making it an essential material for rock support (Hemphill, 2012; Thomas, 2008; Wang et al., 2015). It offers distinct advantages over traditional concrete by eliminating the need of formwork and enabling application on complex geometries, vertical and overhead surfaces (Bernard, 2008). This versatility makes shotcrete especially ideal either temporary or permanent rock support in tunnelling projects. One notable application is the WestConnex M4-M5 link tunnels in Sydney, an approximately 7.5km long tunnel, with four lanes in each direction, where over 250,000 m^3 shotcrete sprayed (Acciona, 2022). Given the scale of such large infrastructure projects, the demand for shotcrete has surged, especially in the face of rapid construction growth, highlighting the importance of optimizing shotcrete's performance for effective rock stabilization.

As the need for shotcrete continues to rise, it is crucial to address the unique performance characteristics required for its effective application. However, the differing application method of shotcrete necessitate distinct performance requirements compared to conventional concrete. These include greater workability, extended consistency, enhanced flowability, increased early-age strength, improved long-term durability, and most critically, reduced rebound (Jolin & Beaupre, 2003). Rebound, the portion of the shotcrete mix that bounces off the surface during spraying, results in material wastage and diminished performance (Armelin & Banthia, 1998; Pan et al., 2019). To meet the performance requirements of shotcrete, one of the key differences in shotcrete mix design is the inclusion of higher sand content. The finer particle size of natural sand, compared to coarse aggregates, offers three main advantages: (i) it reduces momentum during spraying, thereby lowering the rebound rate; (ii) it creates a more cohesive mix with its higher specific area, improving both flowability and pumpability; and (iii) it provides a smoother, more uniform surface finish, minimising the need for additional surface treatment (Chan, 1998).

However, the increasing reliance on sand as a vital component in shotcrete also raises concerns about sustainability. Sand is now the second-most consumable natural resource on earth. Sand depletion, the excessive extraction and consumption of sand from natural ecosystems, is resulting in a global shortage of this vital resource (Ludacer, 2018). This depletion is driven by a combination of factors, including population growth, urbanization, construction boom and limited availability of construction-grade sands, etc (Kelly, 2020). The consequence of sand depletion extended beyond the rising market price of construction-grade sands, leading to severe environmental impacts. These include river and coastal erosion, loss of biodiversity, increased flooding and ground water depletion (de Leeuw et al., 2010).

Given these pressing challenges, the shotcrete industry must seek alternatives to natural sand to ensure sustainability and resilience in its supply chain. One promising solution is to explore synthetic aggregates made from solid waste as substitute for natural sands in shotcrete mixtures. Despite of reducing negative impacts from sand depletion, it offers dual benefit by enhancing effective solid waste management. By repurposing materials that would otherwise contribute to landfill overflow, such as crushed glass, recycled plastics and other forms of construction and demolition waste, the industry can reduce its environmental footprint significantly (Batayneh et al., 2007; Tang et al., 2019).

Among the different solid wastes, waste glass contributes to a substantial portion of solid waste generation. In Australia alone, nearly 850,000 tonnes of glass are consumed each year, yet only 350,000 tonnes are recovered for recycling (Kazmi et al., 2020). Glass is often discarded in mixed waste stream, complicating its recovery and recycling. The challenges associated with glass waste management stem from its non-biodegradable nature and the high energy costs associated with recycling.

However, by crushing waste glass into smaller particle sizes, crushed waste glass (CWG) has emerged as a viable synthetic aggregate in concrete and shotcrete production. As a manufactured product derived from natural sand, CWG shares similar chemical properties, primarily composed silica (SiO_2), the major chemical compounds found in natural sand. In addition to its chemical similarity, CWG offers several advantages, including 100% recyclability, high corrosion resistance and thermal stability (Serati et al., 2022). Recent studies have also indicated that CWG possessed comparable geotechnical and mechanical parameters to both natural and manufactured fine aggregates (Kazmi et al., 2021; Zhu et al., 2023).

Widespread studies on CWG as a synthetic aggregate in construction have been conducted for decades, with numerous research highlighting the potential (Gautam et al., 2012; Park et al., 2004; Rashad, 2014). However, the research in shotcrete applicability with utilizing CWG as fine aggregates has only gained recent attention (Serati et al., 2022; Serati et al., 2021). Despite the current achievements, the early-age strength characterisation of shotcrete remains underexplore, concerning accelerator dosage. Hence, this study addresses this gap by investigating the shotcrete early-age strength performance with varying CWG replacement ratios (0%, 10%, 25% and 50%) for medium sand, using consistent accelerator dosage.

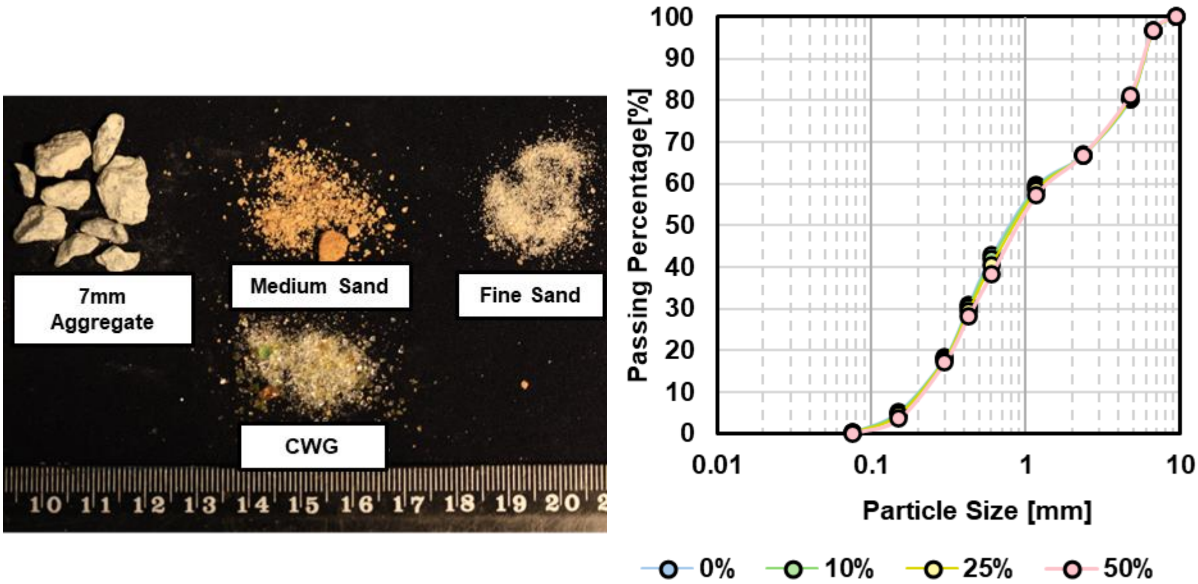
The experimental program involves in this study involves beam-end tests at 3-hour and 8-hour intervals, as well as 14-day core strength tests with accelerator, to evaluate the early-age strength performance, together with 28-day unconfined strength (UCS) on shotcrete without accelerator as a benchmark for comparison.

2 Experimental Procedure

2.1 Raw Materials and Optimised Mix Design

In this test, the mix design used is specifically tailored for shotcrete, which has been successfully applied in actual tunnelling projects. The materials, including fine sand, medium sand, coarse aggregates, cement, fly ash, as well as the reference mix design were provided by a collaborating concrete supplier, Wagners, sourced from the local quarries and cement plants. The chemical admixtures used in the study were supplied by GCP applied technology, including Tytro WR172 (water reducer), Tytro HC270 (hydration stabiliser) and ALSET 13 (accelerator).

Fig. 1 a) combines different types of aggregates used in this study, including the crushed waste glass. Crushed waste glass was supplied by a local supplier, Abrasive Media Supplies. The glass was originated from the landfills and primarily consisted of the bottle containers, such as wine and drink bottles, in a variety of colours. The raw glass underwent heat treatment to remove any paper labels and other contaminant, followed by a crushing process into different sizes products. For this study, the different sizes of CWG were blended to achieve a similar particle size distribution to that of medium sand being replaced. The objective was to maintain consistent gradation curves for the combined aggregates across all mixes incorporating CWG. The result gradation curves are depicted in Fig. 1 b).



a) b)

Fig. 1 Information of raw materials in this project, including a) different types of coarse and fine aggregates and b) particle gradation of blended aggregates for different mixes

Table 1 Optimised mix designs for shotcrete with different CWG percentages inclusion

Materials and Properties	0% CWG	10% CWG	25% CWG	50% CWG
7mm Aggregate (kg)	450	450	450	450
Medium Sand (kg)	1016	914	762	508
Fine Sand (kg)	153	153	153	153
Crushed Waste Glass (kg)	0	102	254	508
Cement (kg)	345	345	345	345
Fly Ash (kg)	115	115	115	115
Tytro WR 172 (g)	3706	3636	3636	3485
Tytro HC 270 (g)	1100	1100	1100	1100
Water (L)	209	208	203	192
Water-to-binder ratio	0.45	0.45	0.44	0.42
Slump (mm)	245	250	230	235

Note: the slump test was carried out according to test standard AS1012.3.1.

Laboratory batches were prepared within a pan mixer, following a consistent process for the base mix (without accelerator dosage) across different mixes. The batching process was divided into the following steps: (1) blended all aggregates, including CWG, for 3 minutes; (2) added cement and fly ash into the blended aggregates and mix for additional 3 minutes; (3) added water and admixture into the mixer without pausing from previous step and mixed for another 3 minutes; (4) Allowed the mix to rest for a final 3 minutes before further testing.

Before proceeding with the actual batches, optimisation batches were carried out to determine the necessary adjustments in the water-to-cement ratios and water reducer (Tytro WR172) dosage to accommodate the differing behaviour between CWG and natural sands. The aim of these optimisation batches was to achieve similar slump value comparable to the reference mix design. The optimised shotcrete mix designs, with results summarised in **Error! Reference source not found.**, achieved target slump values ranged around 230-250mm. An interesting finding was a noticeable reduction in the required water and water reducer dosages for mixes containing CWG. This trend is likely contributed by the hydrophobic nature of CWG, a characteristics aligns well with findings from previous studies (Serati et al., 2022; Zhu et al., 2023).

2.2 Accelerator Mixing and Strength Testing

In this test, both beam-end tests and 14-day core strength tests were performed on shotcrete specimens mixed with accelerator. Since the mixing process was conducted at the laboratory batch scale without access to spraying equipment, all mixing activities with accelerator was conducted inside 20L buckets with a hand-held mixer. To ensure sufficient flowability during mixing, the accelerator dosage was controlled at 3% of binder mass, which differs from the typical 7-8% accelerator dosage applied on-site through nozzle to enhance early-age strength. Each mix was performed for approximately 1 minute, until the mixture lost its flowability.

The end-beam test is a widely used method to assess the early-age strength of shotcrete, typically within a few hours, ensuring the construction safety and structural stability at spraying sites (Bernard, 2008). The test measures the compressive strength at the ends of a shotcrete beam with a square cross section of 75 x 75 mm. In this study, the test setup consisted of a CONTROLS point load tester, modified with fixed test platens on both ends as illustrated in Fig. 2. 75x75mm loading plates were used to ensure uniform load distribution across the targeting test areas. After completion of accelerator mixing, the mix was then scooped into the mould. Each mould allowed for the preparation of three test specimens, with a dimension of 75 x 75 x 285 mm. To eliminate the air pockets and achieve uniform density, vibration and mechanical compaction were applied in two stages: once after filling half the mould with first layer, and again after the mould fully filled. After compaction process, the specimens were covered with plastic to minimize evaporation and cured until the designated testing time. During the test, the first end of each specimen was tested for compressive strength at 3 hours and followed by 8h test at the opposite end of the same specimen, allowing the sufficient use of the material. It should be notable that since the loading is controlled manually with the mechanical pump, the loading rate is not able to be controlled precisely. To minimise variations, all tests were conducted by a single operator to ensure consistency int the test conditions.

The preparation of 14-day core strength specimens followed a similar procedure to the beam-end specimens, with compaction and vibration performed directly inside the bucket. The buckets were then covered with air-tight lids to prevent moisture content change until the testing age. On the testing date, the samples were demoulded from the bucket and cored with diameter around 70mm and trimmed to provide smooth loading surface. Sulphur capping was applied to further smooth the surface and ensure both surfaces of the core are parallel to each other.

For the preparation of UCS specimens, the procedure strictly adheres to AS 1012.8.1 standards. The specimens were cured in a water tank at a constant 25 °C for 28 days. Both the core strengths and UCS tests were performed using the Tecnotest compression tester, with a load capacity of 3000 kN. The loading rate was controlled as 0.33 MPa/s.

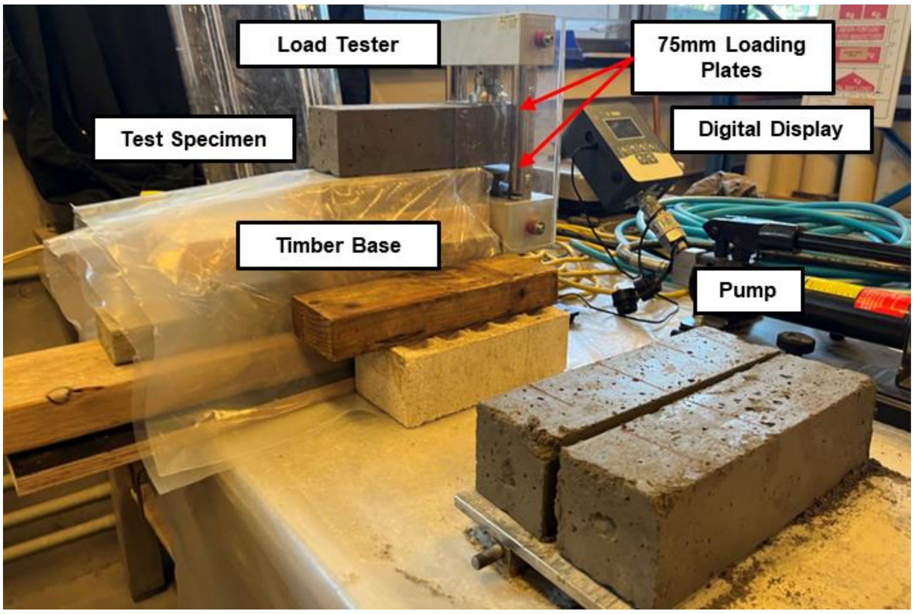


Fig. 2 Beam-end test setup

Table 2 Correction factor for core strengths (after AS 1012.9)

Diameter-to-Height Ratios	Correction Factor
2	1
1.75	0.98
1.5	0.96
1.25	0.93
1	0.87

3 Results and Discussion

For all three tests, the compressive strength was calculated based on the applied force and the loading areas. Yet it is noted that since 14-day core specimens had differed in their diameter-to-height ratios, a correction factor was applied according to AS 1012.9 as displayed in Table 2. The test results are summarized in Fig. 3, which represents independent trails. The strength development over 28 days from batching was analyzed and plotted on a logarithm scale in Fig. 4. Overall, a positive outcome has been demonstrated across the tests, highlighting comparable early-age mechanical response of shotcrete with glass inclusion. The key findings from this experimental program are listed and discussed below:

- Given the zero-water absorption of crushed waste glass, the shotcrete mix with CWG inclusion has a water-reducing effect as well as reduction in the dosage of water-reducer to achieve similar fresh properties.
- The beam-end test results in Fig. 3 a) showed a significant decrease in the 3-hour strength with CWG inclusion. This phenomenon can be attributed by the smooth surface and angular shape of CWG. The smooth surface reduces the friction to the cement paste, thus the entire strength in interfacial transition zone (ITZ) is weakened, which affects early-age strength (Tan & Du, 2013). While the high angularity of CWG improves bulk interlocking, its irregular nature also increases void ratios. particularly since the hydration process was not completed at 3-hour age (Kwan & Mora, 2001). Additionally, the hydrophobic nature of CWG compared to natural aggregates as noted by Zhu et al. (2023), leads to excess water in the test specimens, as

excessive water was observed on the surface of the test specimens. The high moisture content may lubricate the CWG surface, further weakening bond strength between ITZ.

- A contrasting trend was observed on 8-hour test specimens. The 25% CWG mix outperformed the others, and both 10% and 50% CWG mix also exhibited comparable or even higher strength than the mix without CWG in this study. At this stage, the shotcrete has fully hardened, and any excess water has been either absorbed into hydration, or evaporated, eliminating moisture-related concern.
- A similar trend was observed in the 14-day core strength with the same accelerator dosage in Fig. 3 b). The three mixes containing CWG showed comparable strength, with both 10% and 25% CWG mixes outperforming. The variation in strength across these mixes also decreases as the CWG content increases, suggesting that the accelerator mixing process was more effective with better flowability, aided by unique shape and hydrophobic nature of CWG.
- The UCS test results after 28-day standard moist curing suggested comparable strengths across different base mixes (without accelerator), shown in Fig. 3 c). This is the strength expected from the shotcrete mix with accelerator. However, due to the limitations of using hand-held mixer, the mixing was less efficient than in a field spray process, as well as the mechanical compaction and vibration was insufficient compared to the spray process.
- The average strengths obtained from all three tests on are plotted in Fig. 4, comparing the strength development curves over time. A significant increase in early-age strength was observed within the first 14 days with the accelerator. This is attributed to the difference in the grain-scale properties of aggregates, which have both physical and chemical impacts. While the physical properties (shape and surface condition) of the aggregates affect the performance, the chemical properties also play a role. Despite both glass and sand being primarily composed of silica, they differ in the crystalline structures. Glass is made of amorphous silica, while sand typically consists of crystalline silica. Amorphous silica is more reactive than crystalline silica, and when finely ground, it exhibits pozzolanic behavior (Shao et al., 2000). The reactivity contributes to a chemical reaction with calcium hydroxide (from unhydrated cement), leading to a strength growth at later age. This explains why strength increase with glass is generally faster and higher at later ages.

4 Conclusions

This study focused on the shotcrete strength characterisation with different testing methods at the early ages. Overall, a positive outcome was observed in the accelerated shotcrete early-age performance with up to 50% CWG inclusion, where comparable strength achieved within the first 14 days, similar to the base mix. Notably, a higher strength development at “later” ages (after 3 hours). However, the 3-hour end beam test results indicated a need for adjustment on the mix design to enhance early-age strength post-setting. This may involve modifying the water-to-cement (w/c) ratio to reduce the excess water repelled by the glass nature or increasing the accelerator dosage. Further studies should focus on shotcrete performance at field scale with spraying process and actual accelerator dosage is controlled at least 7% by binder mass. Additionally, an in-depth investigation into the impact of CWG on the hydration rate in shotcrete is recommended.

Acknowledgements

The project team wishes to acknowledge the financial support from the Queensland Government (Australia) under the Advanced Queensland Industry Research Fellowships program (No. CTS 20355/21) and the support from industry partners Aurecon, Hanson, GCP Applied Technology, and GHD. The project team also thanks Mr Shane Walker, Ms Sumedha Koul, Ms Dorna Emami, Mr Reza Mottaghi and Dr Xiaohan Yang for their in-kind support, assistance and input.

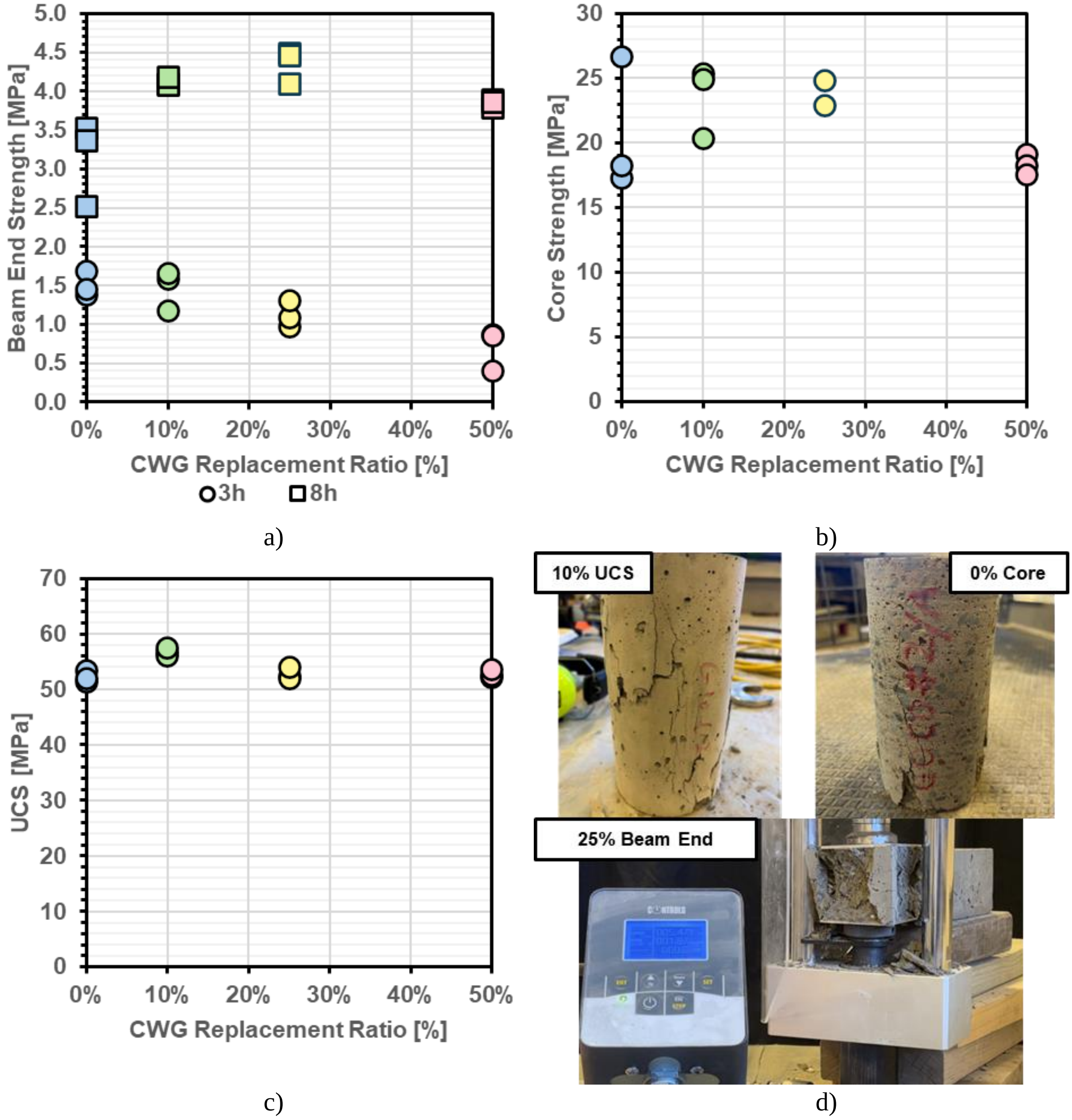


Fig. 3 Test outcomes: a) beam end test results at 3h and 8h age, b) 14-day core strength with accelerator, c) 28-day base mix UCS and d) tested specimens

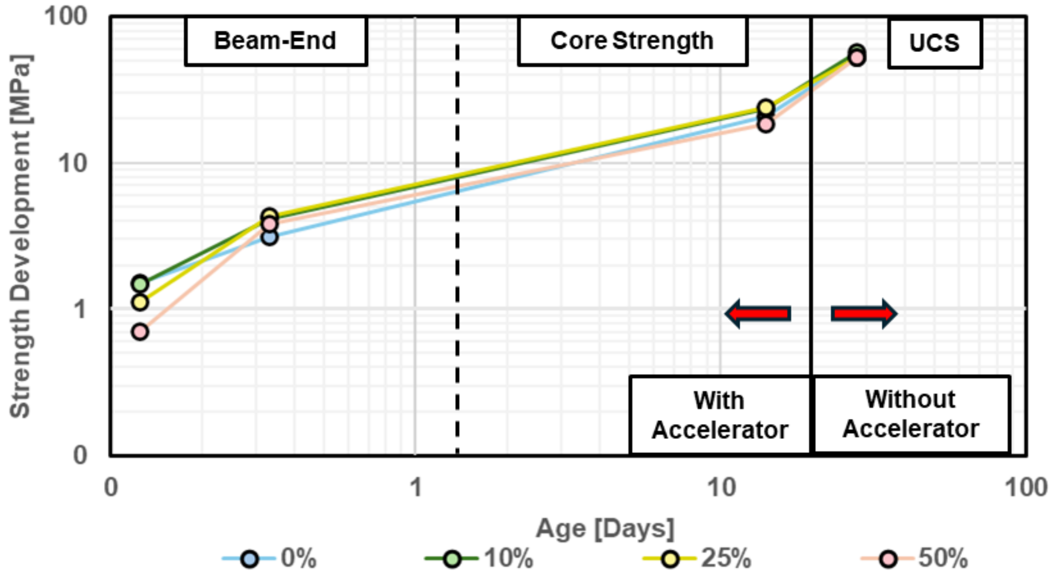


Fig. 4 Strength development of shotcrete mixes with different CWG replacement ratios

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