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PRECIPITATED CALCIUM CARBONATE AS A SUSTAINABLE ALTERNATIVE TO CEMENT IN GEOTHERMAL WELL CEMENTING

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1 INTRODUCTION

Over the past decade, geothermal energy has been emerging as a vital renewable resource, contributing a significant role in electric power generation and heating application. Geothermal energy refers to the natural thermal energy stored beneath the Earth's surface. Unlike other renewable resources like solar, wind, and hydropower which are dependent on weather conditions, geothermal offers a predictable and reliable output, making it highly favorable for continuous power generation and heating applications (Shah et al. 2024). Geologic thermal energy storage system utilizes the earth's natural heat to generate and store thermal energy underground for long-term use. This stored energy can later be extracted and used for heating, electricity generation, or industrial processes, especially during peak demand times or when other energy sources are unavailable. It offers a highly efficient and sustainable method of long-term energy storage with minimal environmental impact.

This research focuses on two main categories of geologic thermal energy storage systems: Reservoir Thermal Energy Storage (RTES) and Borehole Thermal Energy Storage (BTES). Both approaches utilize well-engineered boreholes where cementing is essential to maintain structural integrity and prevent fluid migration. RTES involves injecting heat into underground reservoirs, typically aquifers or artificially created storage zones within geological formations to store thermal energy and retrieving it when needed (McLing et al. 2022; Dobson et al. 2025; Dobson et al. 2023, Atkinson et al. 2023). These systems often include three main components: a heat source, an underground reservoir that stores and circulates hot fluids, and a heat exchanger system that captures the heat and transfers it to the end user (Ginosar et al. 2023). In RTES, heat transfer fluids, usually water, are injected into reservoirs to store thermal energy during periods of low energy demand and extracted for use during periods of high demand (Bershaw et al. 2020). This method provides large-scale, long-term storage capabilities and is commonly employed for district heating and seasonal energy balancing. BTES, on the other hand, is a closed-loop thermal energy storage method that relies solely on subsurface thermal properties and does not require groundwater exchange or natural permeability, distinguishing it from Aquifer Thermal Energy Storage (ATES) and RTES (Mahon et al. 2022). BTES systems consist of clusters of shallow boreholes containing U-tube or similar heat-exchanger configurations. In summer, excess heat warms a circulating fluid, which transfers heat conductively to the surrounding formation for long-term storage, while cooler fluid from "cold" wells supports space conditioning. In winter, flow is reversed to extract the stored heat, and the cooled fluid is reinjected. Grouts incorporating phase-change materials are often used to enhance heat capture and transfer efficiency (J. L. Wang, Zhao, and Liu 2014).

Effective geothermal energy extraction and storage critically depend on the performance and integrity of geothermal wells, particularly regarding their construction and material durability under extreme subsurface conditions (Finger and Blankenship 2010). Geothermal well construction proceeds through the standard stages: surface casing, intermediate casing and production casing, and cementing the annular spaces fully, with each stage addressing thermal stress loadings and durability (Hole. H 2008; H. Wang et al. 2023; Marbun et al. 2020). Casing and cementing plays the critical role in the construction to ensure the stability, production capacity and the long-term performance of geothermal wells (Arbad, Emadi, and Watson 2022; Wu, Patel, and Salehi 2021). Cementing is a critical process in the construction of geothermal wells as it requires specialized cementing materials due to its high-temperature and aggressive chemical environments (Ostroot 1964; Lee 2025). Cementing in the geothermal wells ensures the zonal isolation, supports the casing, and protects the well from high temperatures, pressures, and chemically aggressive geothermal fluids (Rachimillah et al. 2021; Salim and Amani 2013; Wu, Patel, and Salehi 2020). See Figure 1 for schematic diagram of well cementing.

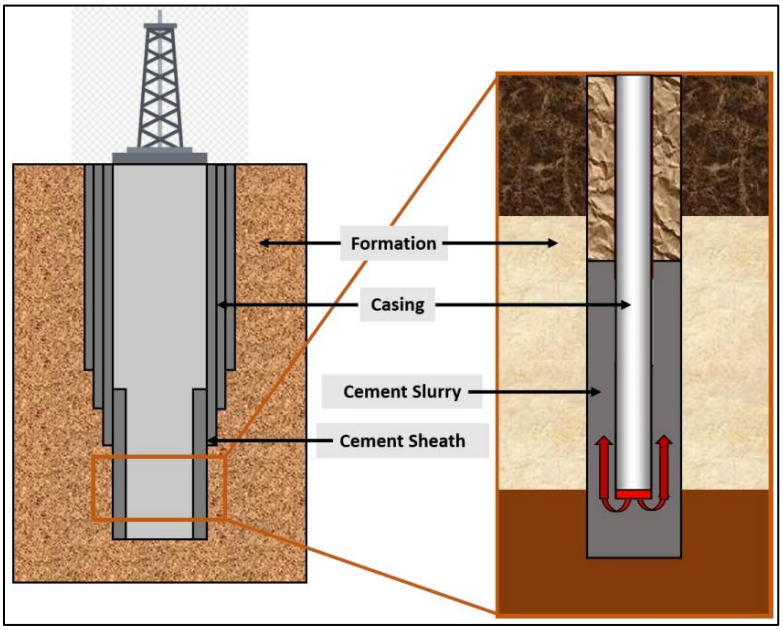


Figure 1. Schematic diagram of well cementing (Tao et al. 2019)

In recent studies, researchers have focused more on improving cementing methodology by developing geothermal cement systems that are high-strength, corrosion-resistant, self-healing, and resistant to high temperatures (Pyatina and Sugama 2020; Sugama and Brothers 2004). Pressure and temperature changes in geothermal wells cause increased mechanical stress in the cement (Kristinsdóttir 2022). Traditionally, Ordinary Portland Cement (OPC) has been the material of choice for geothermal well construction. However, its high cost, environmental impact, and limitations under extreme thermal conditions prompt the exploration of alternative cementitious materials. Precipitated Calcium Carbonate (PCC) is a by-product of the sugar beet industry and is primarily composed of fine, high-purity $CaCO_3$ particles. A study by (Phuyal et al. 2024) reported the presence of a higher concentration of calcium carbonate/calcite in PCC through the X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDX), showing that PCC contains calcium, oxygen, and carbon of 45.9%, 39.4%, and 9%, respectively, by weight. Another study by (Phuyal et al. 2023) has also concluded its potential on having sufficient strength and stiffness to satisfy the design requirements for concrete structures. Despite its potential, studies on PCC's use in high-temperature applications such as geothermal wells are limited, presenting an opportunity for further research.

2 METHODOLOGIES

This study was primarily divided into two phases: Phase I of the project was to determine the optimum matrix mix by incorporating the varying percentage of PCC as a partial replacement of cement. Phase II of the project was to identify the durability performance of the identified optimum matrix mix under the thermal cyclic test by subjecting it to repeated heating and cooling cycles commonly encountered in geothermal and high-temperature applications.

2.1 Materials

Ordinary Portland Cement (OPC) used in this research was Type- I/II Portland Cement. Fine and Coarse Aggregates were transported from a local concrete ready mix in Idaho. These aggregates are locally sourced from pits located within Southeast Idaho. PCC used in this research is a waste obtained from a sugar factory from Producer 'A' and was utilized in its original state as it is not subjected to any form of treatment and it was sourced directly from the sugar factory without any additional processing or modification. Class F fly ash was used in this research, with 15% replacement of cement by weight, maintaining the cement to fly ash replacement ratio of 1:1.

2.2 Concrete Design Mix

The mix design for this study was prepared using the absolute volume method, following the guidelines provided by (Mamlouk and Zaniewski 2018). The control mix used in this research is designed to achieve a compressive strength of 4500 psi or greater.

Concrete specimens were prepared at Engineering Research Complex (ERC), Idaho State University by following the procedure outlined in ASTM C192/C192M; Standard Practice for Making and Curing Concrete Test

Specimens in the Laboratory (ASTM C 192 2007). For the first phase of the research, six different batches of the mix were initially developed. The mixes contained 0% (conventional concrete mix), 5%, 10%, 15%, 20%, and 25% PCC mixes. The goal of this phase was to identify the optimum cement mix incorporating PCC. A total of 90 specimens were prepared to evaluate the mechanical properties of these mixes. In the second phase, the focus was on evaluating the thermal durability of selected mixes under conditions simulating geothermal environments with optimized mix of CM, 5-PCC, and 10-PCC mixes. Each of these mixes had nine specimens assigned for compressive strength testing and nine for split tensile strength testing, making a total of 54 specimens. These specimens were subjected to 10, 20, and 30 cycles of repeated heating and cooling, with three specimens tested after each cycle interval.

Table 1. Mix design.

Design Mix	Water, lbs.	Cement, lbs.	Fly Ash, lbs.	Coarse Aggregate, lbs.	Fine Aggregate, lbs.	PCC, lbs.
Control Mix (CM)	12.05	19.95	3.74	65.14	45.38	-
5-PCC	12.05	18.95	3.74	65.14	45.38	1.00
10-PCC	12.05	17.96	3.74	65.14	45.38	2.00
15-PCC	12.05	16.96	3.74	65.14	45.38	2.99
20-PCC	12.05	15.96	3.74	65.14	45.38	3.99
25-PCC	12.05	14.96	3.74	65.14	45.38	4.99

2.3 Unconfined Compressive Strength Test

The unconfined compression test on concrete was carried out by using the guidelines of ASTM C39/39M(C 39/C 39M 2021).The test was conducted using a UTEST compression testing machine as shown in Figure 2a, the machine is equipped with a hydraulically powered loading system, a digital control interface, and a high-strength loading frame with upper and lower platens that apply compressive force axially to the specimen. Concrete cylinders measuring 4 inches in diameter and 8 inches in height were placed centrally between the plates. The load was then applied at a controlled rate, in accordance with the recommended loading speed of 35 psi/s. Load was applied continuously and without shock until the specimen failed. The maximum load (P) and the compressive strength at failure were automatically recorded by the digital control unit.



(a) (b) (c)

Figure 2. UTEST material testing equipment test setup: (a) unconfined compressive strength, (b) split tensile strength, (c) modulus of elasticity.

2.4 Split Tensile Strength Test

Split tensile test (Figure 2b) was performed using a UTEST material testing machine, the same equipment used for compression testing. This method is the indirect method of measuring tensile strength of concrete by applying a compressive load along the diameter of a cylindrical specimen until failure occurs. The split tensile strength test was performed in the standard 6 in. diameters by 12 in. height concrete cylinders and the test was carried out by following the ASTM C496/C496M – Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens (ASTM C496 2008). Concrete cylinders were placed horizontally between the

plates, and two wooden bearing strips were placed along the length of the cylinder: one above and one below to ensure even distribution of the compressive load and proper load transfer to generate tensile stress across the vertical plane. The specimen was aligned horizontally on the lower platen of the testing machine, centered along its length. A uniform compressive load was applied through the wooden strips at a constant rate of 150 psi/min (2.5 psi/sec) until the specimen failed. Maximum applied load (P) at failure and the tensile strength was recorded automatically by the machine.

2.5 Modulus of Elasticity

The modulus of elasticity of concrete was carried out in accordance with ASTM C469/C469M, Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete (C469-14 2014). The test setup is shown in Figure 2c, where a standard concrete cylinder (4 in. diameter × 8 in. height) was positioned vertically in the UTEST material testing equipment. One axial and one vertical high accurate strain gauge-based displacement transducers were attached to the cylinder to record the longitudinal and lateral strain readings precisely. Before loading, the instrumentation was carefully tared. The cylinder was then subjected to a compressive axial load at a constant rate until the stress reached 40% of the ultimate compressive strength. Throughout the test, both stress and deformation were automatically recorded by the testing machine. The modulus of elasticity (E) was then calculated as the slope of the stress-strain curve.

2.6 Thermal Durability

The thermal durability test procedure involves subjecting concrete specimens, prepared using the optimum matrix mix determined from prior mechanical testing to repeated cycles of heating and cooling. Each cycle consists of heating the specimen to 250°C for up to 8 hrs. in a temperature-controlled oven, cooling it to room temperature (23°C) overnight for more than 8 hrs., further cooling to 10°C in a freeze/ thaw chamber for up to 4 hrs., and reheating it to 250°C. This process is designed to simulate the thermal stresses experienced in geothermal environments and to evaluate the concrete's ability to withstand repeated thermal loading without significant degradation, cracking, or loss of structural integrity.



(a) (b)

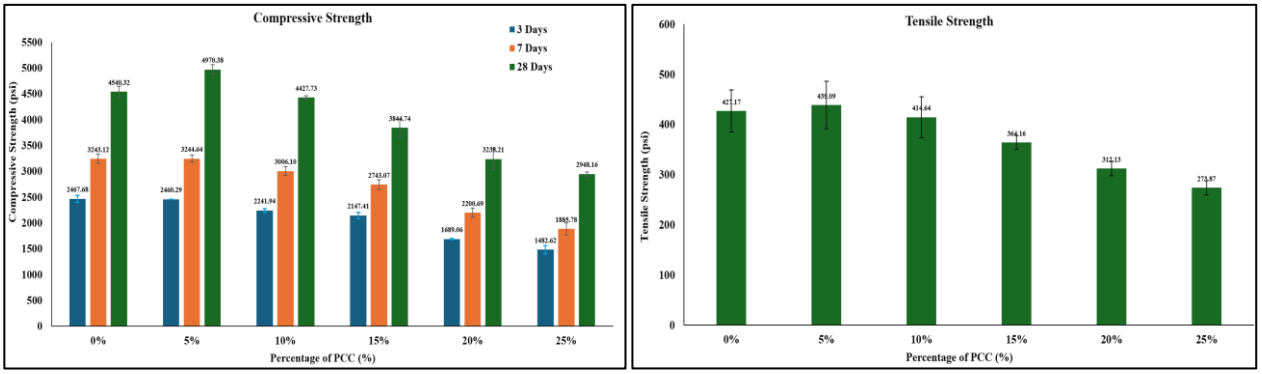
Figure 3: Heating and cooling test setup (a) samples in the freeze/thaw chamber for cooling, (b) samples on the oven for heating

3 RESULTS AND DISCUSSION

3.1 Compressive and Tensile Strength Test Result

Figure 4(a) shows the compressive strength test results at 3, 7, and 28 days for mixture incorporating 0-25% PCC. At early age of 3-days, the control mix containing 0% PCC achieved the highest strength of 2467.68 psi, with the 5% PCC mix closely achieving the strength of 2460.29 psi, a negligible reduction of approximately 0.3%. After 7-days, the control mix achieved a compressive strength of 3243.12 psi, which slightly increased to 3244.64 psi at 5% PCC, indicating no negative impact on early strength at this level, whereas, after 28-days the control mix achieved a compressive strength of 4540.32 psi, while the 5% PCC mix reached a peak strength of 4970.38 psi, representing an approximate 9.47% increase over the control. However, beyond 10% PCC replacement, a noticeable decline in compressive strength is observed at all curing ages. This indicates that a small replacement of cement with PCC has no adverse effect on early-age compressive strength development and can enhance long-term strength development, whereas the higher PCC content adversely affects the compressive strength development. Similarly, Figure 4(b) shows the split tensile test results after 28 days. Similar to the results achieved in compressive strength, the control mix (0% PCC) achieved a tensile strength of

427.17 psi. The mix with 5% PCC replacement achieved the highest tensile strength of 439.09 psi, an increase of approximately 2.9% compared to control mix. The 10% PCC mix also achieved a comparable tensile strength of 414.64 psi, remaining close to the control mix and the reduction in tensile strength was observed with higher PCC content.

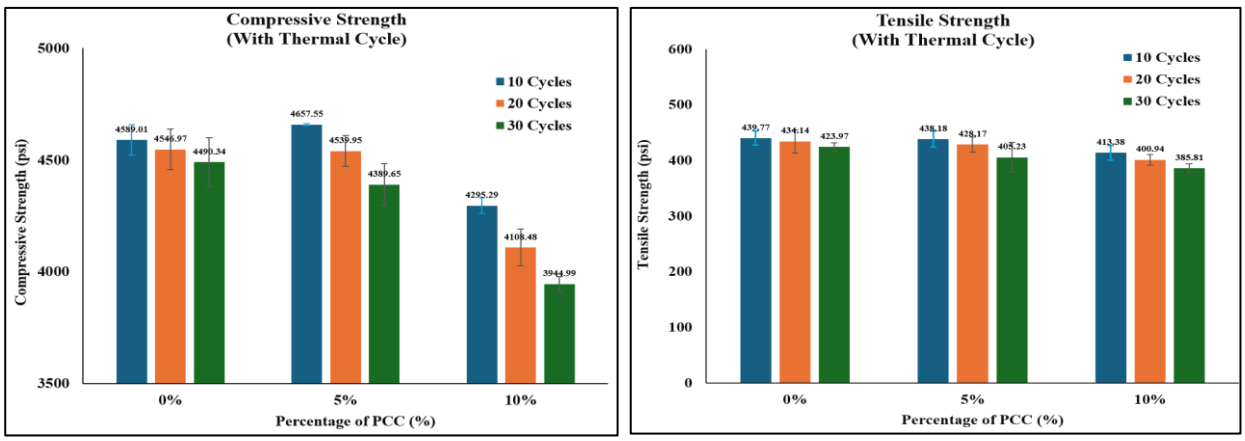


(a) (b)

Figure 4. Mechanical strength test results (a) 3/7/28-day compressive strength, (b) 28-day tensile strength.

3.2 Compressive and Tensile Strength Test Results with Thermal Cycle

Figure 5 shows compressive and tensile strength of concrete samples after 10, 20, and 30 cycles of repeated heating and cooling between 250°C and 10°C. After 10 cycles, the control mix achieved a compressive strength of 4589.01 psi, whereas the 5% PCC mix showed an average compressive strength of 4657.55 psi, an approximate 1.5% increase over the control. After 20 cycles, the control mix achieved an average compressive strength of 4546.97 psi, whereas 5% PCC mix maintained nearly identical performance to the control mix, averaging 4539.95 psi which is only 0.15% lower than that of control mix. After 30 cycles, the control mix achieved the highest average compressive strength of 4490.34 psi, followed by the 5% PCC mix at 4389.65 psi, showing only a 2.24% reduction. Similarly, the control mix achieved the tensile strength of 439.77 psi, 434.14 psi, 423.97 psi at 10, 20, and 30 cycles, followed closely by the 5% PCC mix at 438.18 psi, 428.17 psi, 423.97 psi showing 0.36%, 1.37%, and 4.4% reduction, respectively. This relatively small reduction in strength suggests that the 5% PCC mix maintains stable performance, compared to that of control mix, even after extended thermal exposure.



(a) (b)

Figure 5. 28-day test result with thermal cycle (a) compressive strength, (b) tensile strength.

3.3 Modulus of Elasticity Test Result

Figure 6 shows the average stress–strain curve of different PCC mixes. Both the control mix and the 5% PCC mix show similar and highest slopes, indicating the greatest stiffness. As the PCC replacement level increases, the slope becomes less steep, reflecting the reduction in stiffness. Overall, the graph clearly shows higher the PCC content, lower is the stiffness, while 5% PCC mix maintains performance nearly identical to the control, suggesting its potential as a sustainable and structurally effective cement replacement.

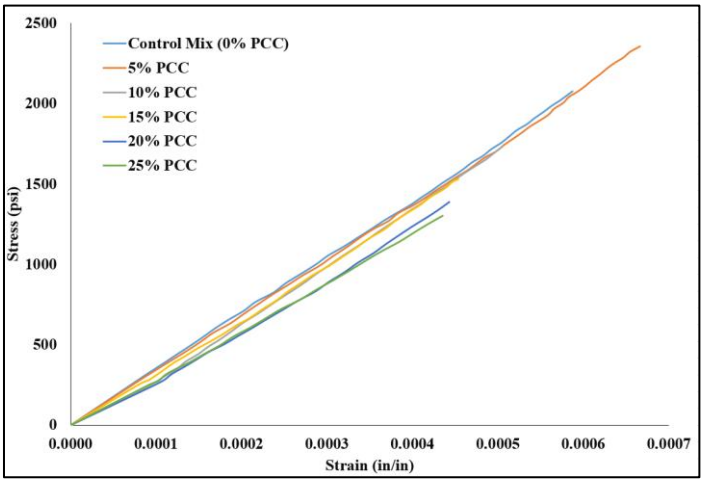


Figure 6. Stress vs Strain comparison of PCC mixes.

4 CONCLUSIONS

This study demonstrates that precipitated calcium carbonate (PCC), a waste byproduct from the sugar beet industry, holds strong potential as a sustainable alternative to conventional cement in the demanding environment of geothermal wells. As geothermal systems such as RTES and BTES continue to expand for long-duration energy storage and renewable power production, the need for durable, environmentally responsible cementing materials becomes increasingly critical. Within this context, the 5% PCC mix consistently delivered mechanical performance equal to or better than the control mix, including enhanced 28-day compressive and tensile strength, comparable stiffness, and stable behavior under up to 30 cycles of extreme thermal loading. While higher PCC replacement levels led to reductions in strength and modulus, the robust performance of the 5% PCC blend underscores its suitability for high-temperature geothermal infrastructure and highlights the promise of repurposing industrial waste streams to reduce the carbon footprint of well construction materials. Looking ahead, future research should explore long-term chemical durability under geothermal brine exposure, evaluate PCC-enhanced cement systems under in-situ wellbore pressure and stress conditions, and conduct field-scale demonstrations in both RTES and BTES environments. Additional investigations into microstructural evolution, optimization of PCC particle gradation, and integration with other supplementary cementitious materials could further advance PCC-based formulations as a reliable option for next-generation geothermal well cementing.

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