

Compressive Strength of Cement Stabilized Cold In-Place Recycling Pavement Base Course with Ground Coal Bottom Ash and Calcium Chloride

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ABSTRACT

Pavement degradation throughout its design life requires rehabilitation to maintain its functionality. Conventional repair methods, such as ‘remove and replace,’ are costly and environmentally unfriendly. Cold in-place recycling (CIPR) has emerged as an eco-friendly alternative for addressing severe pavement damage. CIPR involves recycling the existing pavement and part of the base layer, which are then compacted to form a new base layer with the addition of a stabilizing agent. In Malaysia, cement is a commonly used stabilizing agent. However, the extensive use of cement raises environmental concerns, as its production contributes between 5-9% of global CO₂ emissions. This study explores partially replacing ordinary Portland cement (OPC) with ground coal bottom ash (GCBA) and using calcium chloride (CaCl₂) as an accelerator to address this issue. The study varied OPC content from 1-4%, with GCBA and CaCl₂ ranging from 0-3%. An unconfined compressive strength (UCS) test was conducted to analyze the effects on compressive strength and strength development over time. Results indicated that the optimal GCBA percentage for cement replacement is 1%, while the optimal CaCl₂ content is between 1% and 2%. Overall, compressive strength increased with curing time, highlighting the potential of this innovative approach to pavement rehabilitation.

Keywords: Cold in-place recycling (CIPR); stabilizing agent; ordinary Portland cement (OPC); ground coal bottom ash (GCBA); calcium chloride (CaCl₂); unconfined compressive strength

INTRODUCTION

Pavement is an infrastructure subjected to non-stop traffic loadings and stresses, gradually deteriorating, and reducing serviceability. Pavement maintenance and rehabilitation are required to restore its serviceability. However, there is a condition when the rehabilitation process cannot be executed when the damage on the base layer of the pavement becomes severe and beyond repair. At this point, the reconstruction of the pavement structure is necessary where the process of ‘remove and replace’ is implemented. The pavement layers, which include the surface and base layer, are removed. These layers are frequently replaced

with virgin materials. The process requires extensive effort in purchasing and transporting new materials to the site, which costs money, time, and energy (Association of Asphalt Paving Technology 1992). Additionally, the old materials will become waste, harming the environment, and increasing disposal costs (Kang-Won et al. 2014).

Cold in-place recycling (CIPR) is a cost-effective and environmentally friendly pavement rehabilitation technique generally used in road construction and maintenance. It is a technique available apart from the conventional way of ‘remove and replace’. CIPR offers a possibility to reduce the amount of such excessive waste materials as recycled old asphalt is used back in the rehabilitation process. The

analysis of the life cycle of construction and maintenance practices revealed that this technique is the least costly, reducing the overall cost of maintaining the road pavement during its lifetime (Santos et al. 2017). Furthermore, the construction cost can be reduced by 40% compared to the conventional technique since fewer new materials are used in the process (Sufian et al. 2009).

The process of CIPR involves recycling deteriorated existing asphalt materials on-site, known as RAP (recycled asphalt pavement), with some portion of the aggregate base layer using the CIPR machine and compacted to create a new base layer without a heating mechanism. The base layer is then paved over with fresh premix asphalt. In order to enhance the load-carrying qualities of the recycled base layer, a stabilizing agent is added to the process. In general, there are many choices of stabilizing agents available depending upon the condition of the pavement, required strength and the cost of materials. These vary from mechanical, chemical, or bituminous additives, which are all introduced during the recycling process to boost the load-carrying capability of the reclaimed materials.

In Malaysia, the CIPR was first introduced in the mid-80s as one of the alternatives to road rehabilitation. Since then, the technique has been employed throughout the country to rehabilitate tolled expressways, major highways, and rural and village roads with various traffic volumes (Sufian et al. 2009). Cement is the most common type of chemical stabilizing agent that is used in Malaysia (Tan & Chan 2021). However, global cement production has increased dramatically in recent years, overtaking fossil fuels and changing land use as the third-largest source of anthropogenic carbon dioxide emissions (Andrew, 2019). According to Liu et al. (2022), the production of cement generates between 5–9% of total global CO₂ emissions. The major impact on the environment has prompted an increasing number of research on the use of pozzolanic supplementary cementitious materials (SCMs) as partial replacements for cement (Kopić et al. 2022). Therefore, a study is needed to identify other possible chemical stabilizing agents as an alternative.

In this study, Ground Coal Bottom Ash (GCBA) is used as a partial replacement for Ordinary Portland Cement (OPC) and as a stabilizing agent, while CaCl₂ serves as an accelerator to enhance the early strength of the design mix. In producing GCBA, coal bottom ash (CBA) is mechanically grounded (Poudel et al. 2024). This process transforms the coarse ash particles into a very fine powder. GCBA exhibits good pozzolanic properties with the increase of its fineness (Arun et al. 2020).

This study aims to analyze the effects of the proposed stabilizing agent on compressive strength through an unconfined compressive strength (UCS) test, which measures the material's ability to withstand compressive loads. By evaluating compressive strength, the study seeks to determine how the stabilizing agent enhances the mechanical properties of the proposed design mix, contributing to its structural integrity and durability. Additionally, the study investigates the compressive strength development pattern over time, providing insights into the curing process and long-term performance of the material. Understanding these effects is crucial for optimizing the design mix, ensuring that the rehabilitated pavement meets required performance standards and exhibits improved resistance to traffic loads and environmental stresses.

MATERIALS

The proposed design mix incorporates two key materials for the primary structure, which are crushed aggregate (CA) and recycled asphalt pavement (RAP). CA is sourced from the Kajang rock quarry, while RAP is derived from the milling waste of a pavement construction project in Putrajaya. These materials form the fundamental components, contributing to the overall composition and structural integrity of the mix.

The stabilizing agents chosen for this study are OPC, specifically CEM type I, raw CBA from Jana Manjung Power Plant, and industrial-grade CaCl₂. While OPC is carefully produced to ensure a specific and consistent particle size distribution, raw CBA is typically unsuitable due to its broad and uncontrolled size distribution. To overcome this limitation, the raw CBA undergoes a physical treatment process, being ground down to a finer size range, resulting in ground coal bottom ash (GCBA) with particles passing 45µm. This treatment aligns the particle size distribution of GCBA with that of OPC, ensuring uniformity crucial for achieving the desired workability and strength properties in the mix.

The meticulous selection and treatment of these materials highlight the importance of precision in mix design, addressing both the structural requirements and the need for consistent properties in the stabilizing agents. The combination of the main structure and the stabilizing agent represents a strategic approach towards developing a resilient and sustainable mix for pavement rehabilitation, with each component contributing to the overall performance and longevity of the final product. The physical properties of each material used for the design mix are shown in Table 1.

TABLE 1. Physical properties of CIPR materials

Materials	Properties
RAP	Specific gravity: 2.00
CA	Specific gravity: 2.43
GCBA	Specific gravity: 2.56, Size: passing 45 μ m
OPC	Specific gravity: 2.96
CaCl ₂	74% flakes, soluble in water

The ratio for CA-RAP used is 50:50. This equal distribution ensures a harmonized blend of materials, with 50% of the total dry weight allocated to each component. In terms of stabilizing agents, the OPC ranges from 1-4% of the total dry weight, offering flexibility in adjusting the cement content based on performance requirements.

Simultaneously, both GCBA and CaCl₂ are varied between 0-3%, allowing for a nuanced exploration of their effects on the mix properties. The total percentage of stabilizing agents, limited to 4%, represents the optimum value employed in the practical field which striking a balance between achieving desired properties and practical considerations.

A control specimen serves as a benchmark, featuring 4% OPC without any other stabilizing agents. This reference point helps assess the impact of additional stabilizing agents and the accelerator on the mix's performance. Three specimens are prepared for each design mix set to ensure reliable findings, enabling a thorough evaluation of consistency and reliability.

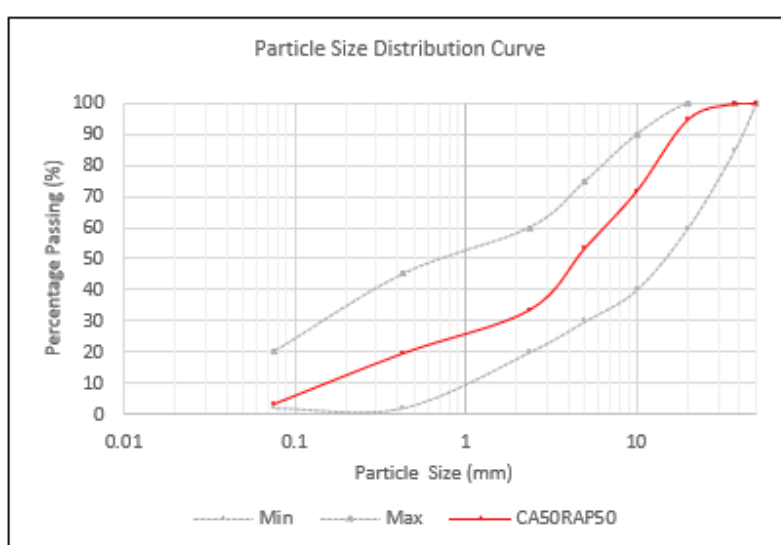


FIGURE 1. Particle size distribution of CA-RAP

Table 2 provides percentages of stabilizing agents and accelerator employed in this study, while Figure 1 visually

captures the particle size distribution for the 50:50 ratio CA-RAP design mix.

TABLE 2. Percentage of stabilizing agent and accelerator

Total percentage of stabilizing agent (%)	Stabilizing agent (%)		Accelerator (%)
	OPC	GCBA	CaCl ₂
4	1	3	0,1,2,3
	2	2	0,1,2,3
	3	1	0,1,2,3
	4	0	0,1,2,3

TESTING METHOD

During the preparation phase, specimens featuring various percentages of stabilizing agent and accelerator are prepared, aligning with the optimum moisture content

(OMC) and maximum dry density (MDD) for a 50:50 ratio of CA-RAP design mix. Subsequently, these specimens undergo curing at 25°C for the designated period before undergoing the unconfined compressive strength (UCS) test. Table 3 provides a summary of the OMC and MDD values acquired in preparation for the UCS test.

TABLE 3. OMC and MDD of the specimen

CA-RAP ratio	50:50
OMC (%)	5.60
MDD (Mg/m ³)	1.93

The unconfined compression test is one of the tests required by the Malaysia Public Works Department (JKR Malaysia) to determine the compressive strength of cement

stabilized CIPR layer under unconfined conditions. This test is crucial to ensure that the material proposed can bear the loads and stresses experienced in service, conducted in accordance with B.S. 1881, part 116. A 100 mm diameter cylindrical specimen made of proposed design mix materials is put through an axial compressive load at the rate of 153 kN/min until the maximum load is reached.



(a)



(b)

FIGURE 2. Specimen (a) before and (b) after the UCS test

RESULTS AND DISCUSSION

EFFECT OF STABILIZING AGENT ON THE COMPRESSIVE STRENGTH

The initial phase of the analysis focused on assessing the influence of OPC, GCBA and CaCl₂ on compressive strength from day 1 to day 28 of the curing period, in accordance with the specifications outlined in the Standard Specification for Road Works Section 4: Flexible Pavement. The stipulated requirement is a minimum strength of 2 MPa. The graphical representation in Figure 3 (a) – (d) illustrates the outcomes for various proportions of stabilizing agents and accelerators integrated into the proposed design mix.

It can be seen that all proposed design mixes successfully fulfilled the specified minimum requirement of 2 MPa from the first day. The mix containing 4% OPC and 1% CaCl₂ exhibited the highest compressive strength on day 1, reaching 3.86 MPa. This trend persisted on day

3, with the same mixed composition recorded a strength of 4.19 MPa. However, on day 7, a mix comprising 3% OPC, 1% GCBA, and CaCl₂ achieved the highest value at 4.59 MPa. Moving to days 14 and 28, once again, a design mix featuring 4% OPC and 1% CaCl₂ demonstrated the highest strengths at 4.86 MPa and 5.93 MPa, respectively.

Generally, OPC reacts with water to form hydration products that contribute to the strength of concrete material. GCBA with its pozzolanic properties, reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel, improving both strength and durability. Moreover, the presence of CaCl₂ accelerates the hydration process which improve early strength and reducing the setting time. However, excessive replacement of OPC with GCBA did not enhance compressive strength effectively. This is evident as the design mix with 1% OPC and 3% GCBA consistently exhibited the lowest compressive strength throughout the curing period. Therefore, 1% GCBA appears to be the optimal replacement level for OPC. The findings of this study are contrasted with those of Kurama et al. (2008), who discovered that adding GCBA

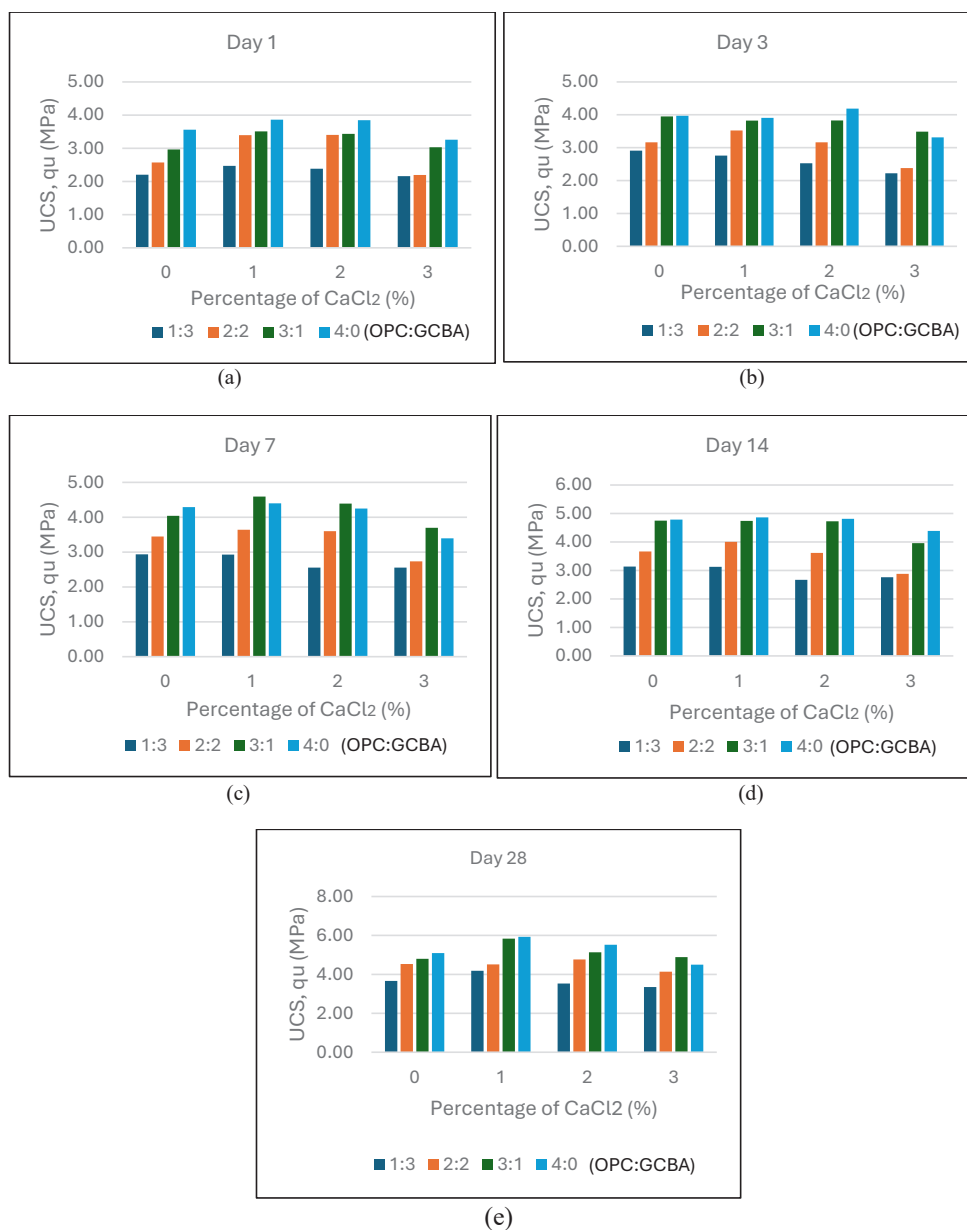


FIGURE 3. Effect of stabilizing agent on the compressive strength at (a) day 1, (b) day 3, (c) day 7, (d) day 14 and (e) day 28

up to 10% in replacement of OPC improved the compressive strength of concrete. On the other hand, a high replacement GCBA percentage was found to decrease compressive strength by Kim et al. (2011). The results of this investigation are consistent with those of Kim et al. (2011).

In terms of $CaCl_2$ contains, according to Occidental Chemical Corporation (2006), the presence of $CaCl_2$ in the range of 1-2% plays a pivotal role in facilitating early strength development by expediting the cement hydration process. Beyond this range it might affect the hydration process. This insight highlights the efficacy of a relatively small amount of $CaCl_2$ in enhancing the overall strength of the mix. From the analysis done, the results further

indicate that exceeding 1% $CaCl_2$ content results in a slight reduction in compressive strength. The results are in line with those of William et al. (2020), who discovered that adding high $CaCl_2$ percentages caused a decrease in compressive strength.

Therefore, the optimal GCBA percentage for cement replacement is identified as 1% while $CaCl_2$ falls between 1% and 2%. This range is deemed ideal for achieving the desired compressive strength while minimizing the impact of GCBA and $CaCl_2$ content on the overall mix performance.

COMPRESSIVE STRENGTH OVER CURING TIME

The second phase of the study focuses on the analysis of

compressive strength development over time, a critical aspect in understanding the long-term performance of the proposed mix designs. Curing periods of 1, 3, 7, 14, and 28 days are employed to systematically observe the evolution of compressive strength. This approach allows for a comprehensive examination of the material’s response to varying curing durations, providing valuable insights into its strength characteristics at different stages of maturity. Figure 4 (a) – (d) visually presents the results for compressive strength over curing time for all the design mix composition.

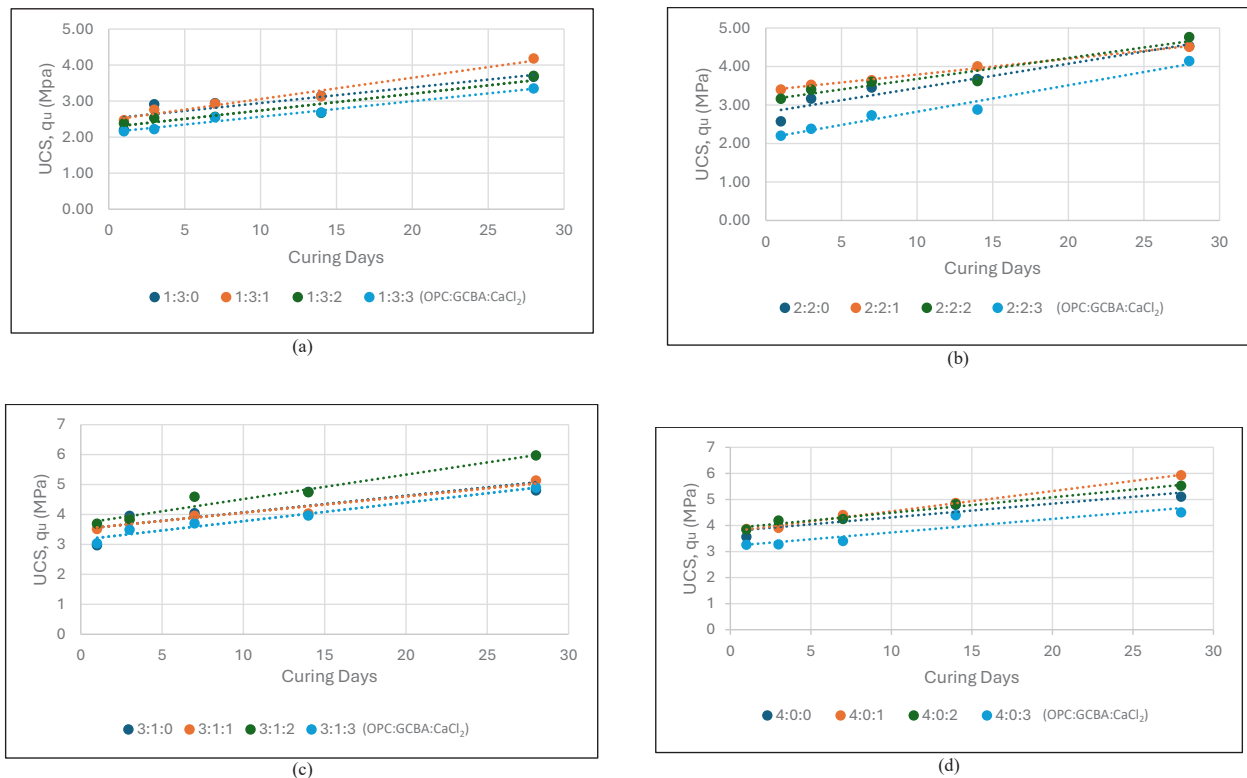


FIGURE 4. Strength development over time for (a) 1% OPC + 3% GCBA, (b) 2% OPC + 2% GCBA, (c) 3% OPC + 1% GCBA, and (d) 4% OPC with various $CaCl_2$ percentages

The analysis of the results reveals a clear pattern where the compressive strength of all design mixes, characterized by varying material compositions, shows a direct proportionality to curing time. The trend indicates that as the curing time extends, there is a corresponding increase in compressive strength across all design mix variations. A similar trend was observed in previous studies conducted by Sufian et al. (2009) and Tan & Chan (2021), though different stabilizing agents were used.

The observed phenomenon is likely due to the time-dependent nature of the hydration process, which persists as long as there is sufficient supply of water or moisture. The sustained presence of adequate moisture, facilitated by the addition of $CaCl_2$, consistently promotes and sustains the ongoing hydration reactions. As the curing time extends, this prolonged exposure to moisture creates favorable conditions for a greater number of cement particles to engage in the hydration process. Consequently,

an increased formation of strength-contributing compounds, such as calcium silicate hydrate (C-S-H) gel and calcium hydroxide, occurs.

The relationship between the UCS and the curing days was established using a multiple regression analysis, which produced the regression model for the proposed mix design. The final form of the regression model proposed in this study is defined in Equation (1).

$$Y = b_0 + b_1X_1 + b_2X_2 + \dots + b_nX_n \tag{1}$$

Where;

b_0 = intercept

b_1, b_2, \dots, b_n = coefficient associated with X (curing days)

Y = unconfined compressive strength (q_u)

The equation also demonstrated the significant

relationship between the number of curing days and compressive strength. In particular, the majority of the proposed mix designs exhibit coefficients of determination (R-squared values) ranging from 0.82 to 0.99. These high R-squared values indicate a strong and nearly perfect fit

of the generated regression models to the observed data which could be utilized to predict the compressive strength for each curing period on any specific day, assuming all other variables remain constant. Table 3 summarizes the regression model for all of the proposed mix designs.

TABLE 3. Regression model of proposed mix designs

Mix design ratio OPC: GCBA: CaCl ₂	Regression model	Coefficient, R ²
1:3:0	$q_u = 0.0381CD + 2.6207$	0.9097
1:3:1	$q_u = 0.0649CD + 2.3378$	0.9474
1:3:2	$q_u = 0.0465CD + 2.2756$	0.9122
1:3:3	$q_u = 0.0432CD + 2.1341$	0.9795
2:2:0	$q_u = 0.0622CD + 2.7584$	0.9127
2:2:1	$q_u = 0.0408CD + 3.3875$	0.9962
2:2:2	$q_u = 0.1217CD + 2.7925$	0.8557
2:2:3	$q_u = 0.0687CD + 2.1376$	0.9707
3:1:0	$q_u = 0.0487CD + 3.7140$	0.4815
3:1:1	$q_u = 0.0544CD + 3.5138$	0.9346
3:1:2	$q_u = 0.1046CD + 3.5169$	0.9705
3:1:3	$q_u = 0.0621CD + 3.1561$	0.9616
4:0:0	$q_u = 0.0450CD + 3.9569$	0.9108
4:0:1	$q_u = 0.0696CD + 3.6897$	0.9566
4:0:2	$q_u = 0.0992CD + 3.8484$	0.9670
4:0:3	$q_u = 0.0520CD + 3.2123$	0.8265

CONCLUSION

The experimental study was performed to analyze the effect of the proposed stabilizing agent and accelerator on compressive strength of CIPR base course from day 1 to day 28 of curing process, and regression models were established for every proposed mix design between compressive strength and curing period. The findings have led to the following conclusions;

1. The proposed design mix demonstrates improved compressive strength compared to the control mix containing 4% OPC. Specifically, a design mix containing 4% OPC with the addition of 1-2% CaCl₂ achieved the highest compressive strength over the entire 28-day curing period.
2. In terms of OPC replacement, only mix with 1% GCBA replacing OPC (3% OPC + 1% GCBA) and the addition of 1-2% CaCl₂ shows significant strength improvements compared to the control mix.
3. The production of different silicate hydrates during the hydration process in OPC, GCBA and CaCl₂ may have contributed to the improvement in compressive strength.

4. A longer curing period provides better compressive strength for all the proposed design mix. However, the minimum requirement of 2 MPa was already achieved as early as day 1 of the curing period, with all the proposed design mix surpassing the minimum requirement. This indicates that the proposed stabilizing agent and accelerator have the potential to be alternatives for OPC partial replacement.
5. The established regression models could be applied to predict the compressive strength of the proposed stabilized CIPR base course when various curing times are taken into consideration.

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DECLARATION OF COMPETING INTEREST

None.

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