# Sustainable Pavement Solutions: Geopolymer Concrete from Laboratory Design to Full-Scale Trial

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## ABSTRACT

This study evaluates the performance of geopolymer concrete (GPC) in pavement applications, focusing on the outcomes from a laboratory and full-scale trial. A fly ash (FA)-ground granulated blast furnace slag (GGBFS) GPC was designed to meet pavement requirements of relevant TfNSW specifications. Laboratory tests assessed its fresh and hardened properties, including compressive and flexural strength, and volume stability properties including drying shrinkage, as well as durability aspects such as alkali-silica reactivity and chloride migration and diffusion. The laboratory results show that the developed GPC mix has an adequate retention time and meets TfNSW R53 and R83 specification requirements for strength development and drying shrinkage. The trial demonstrated that GPC could be effectively hand-placed and finished using conventional paving equipment. Laboratory and field performance data indicate that the material successfully transitions from lab-scale to large-scale applications, meeting the critical benchmarks for pavement applications. By advancing the technology readiness level (TRL) of GPC for pavement use from TRL 1–3 to TRL 4-6, this study offers a solid foundation for the adoption of GPC in pavement construction. The findings offer valuable insights into the scalability and effectiveness of GPC, guiding engineers toward sustainable, high-performance pavement alternatives.

# INTRODUCTION

The production of ordinary Portland cement (OPC) for conventional concrete systems is a major contributor to global $CO_2$ emissions and climate change, highlighting the urgent need for more sustainable alternatives. Geopolymer (GP) technology offers a promising solution, with comparable durability, high early strength, lower environmental impact, and strong potential for applications in infrastructure and pavement constructions. The technology uses aluminosilicate precursors such as fly ash (FA) and ground granulated blast furnace slag (GGBFS), "activated" by alkali-metal solutions of sodium or potassium.

In FA-based geopolymer concrete (GPC), the primary reaction product is typically a sodium-aluminosilicate-hydrate (N-A-S-H) gel, with activation often requiring elevated temperatures. However, when calcium is introduced through the incorporation of GGBFS, the gel chemistry shifts towards a composite matrix of calcium-aluminosilicate-hydrate (C-A-S-H) and N-A-S-H gels. This synergistic gel formation enhances mechanical performance and durability, enabling the development of a denser and more homogeneous microstructure under ambient curing conditions [1-3].

GPC can be produced through the activation of aluminosilicate precursor materials using concentrated alkaline activators, which may be supplied in either liquid or powder form. On this basis, two main production routes are typically employed: liquid-activated (two-part) and powder-activated (one-part) systems [4]. Liquid-activated GPC systems are well established and widely adopted in research, offering proven performance and flexibility in mix design[5]. However, they generally require careful handling and precise batching of alkaline solutions, which may introduce logistical and safety considerations, particularly for in-situ construction [6, 7]. In contrast, powder-activated GPC systems simplify these aspects by integrating the activator in solid form, enabling easier transport, storage, and on-site mixing. This approach supports more straightforward implementation in pavement construction, enhancing practicality while maintaining the benefits of geopolymer (GP) technology.

GPC, particularly the mixes incorporating GGBFS as a binding agent, offers promising opportunities for transportation infrastructure, particularly rigid pavements and precast elements, due to its ambient curing capability and quick traffic reopening. While global interest is growing, practical applications remain limited [8]. Key challenges include achieving sufficient workability retention and controlled setting behaviour, meeting prescriptive requirements such as Transport for New South Wales (TfNSW) R53 and R83 specifications, and demonstrating consistent field performance under real-world conditions. Addressing these challenges is essential to advancing the broader adoption of GPC as a sustainable pavement material. This study contributes to this effort by evaluating an optimised GPC mix through detailed laboratory testing and a full-scale field trial, focusing on workability, mechanical performance, drying shrinkage, durability and constructability. The findings aim to inform practical implementation and support wider use of GPC in road infrastructure.

# METHODOLOGY

This study was structured in three main phases, as illustrated in Figure 1. The first phase focused on binder optimisation through a series of mortar trials under ambient laboratory conditions. Various mortar mix designs were evaluated by adjusting fly ash-to-GGBFS ratios, total binder contents, and alkali activator dosages to study workability retention and early compressive strength. Mortar flow tests were performed in accordance with AS 2701-2001, while mortar compressive strength was measured following AS/NZS 2350.11. The mortar specimens were sealed and cured at 23±2 °C and relative humidity (RH) of greater than 95%. In the second phase, the optimised binder system was scaled to concrete and tested to verify compliance with TfNSW R53 and R83 specifications for pavement applications. Laboratory evaluations covered compressive strength in accordance with AS 1012.9, and flexural strength following AS 1012.11. For these mechanical tests, all specimens were sealed and cured at 23 ± 2 °C with RH more than 95% until the time of testing. Drying shrinkage was assessed on prisms prepared and initially cured in line with AS 1012.8.4, stored in a temperature and humidity control cabinet at 23 ± 2 °C and ≥95% RH for seven days before baseline measurements. They were then transferred to a controlled environment at 23 ± 1 °C and 50 ± 5% RH with appropriate air circulation, with shrinkage readings recorded at multiple intervals.

Durability assessments included chloride migration testing based on NT Build 492, chloride diffusion following NT Build 443, and alkali-silica reactivity using AS 1141.60.1 accelerated mortar bar test (AMBT). For the chloride tests, specimens were cured under the same conditions as the mechanical tests up to 28 days. NT Build 492 was then conducted directly, whereas specimens, coated on all sides except the exposed face, for NT Build 443 were immersed in sodium chloride solution for 35 days prior to testing. For the AMBT, specimens were demoulded and initially cured in water at 80 °C for 24 hours, after which zero-length measurements were recorded. They were then immersed in a 1 molar sodium hydroxide solution at 80 °C, with length changes monitored at specified intervals to determine expansion.

The third phase involved a full-scale field trial in West Melbourne to validate the practical application of the developed powder-activated GPC mix. Cylinders were cast on site according to AS 1012.8.1 to confirm strength development under field conditions.

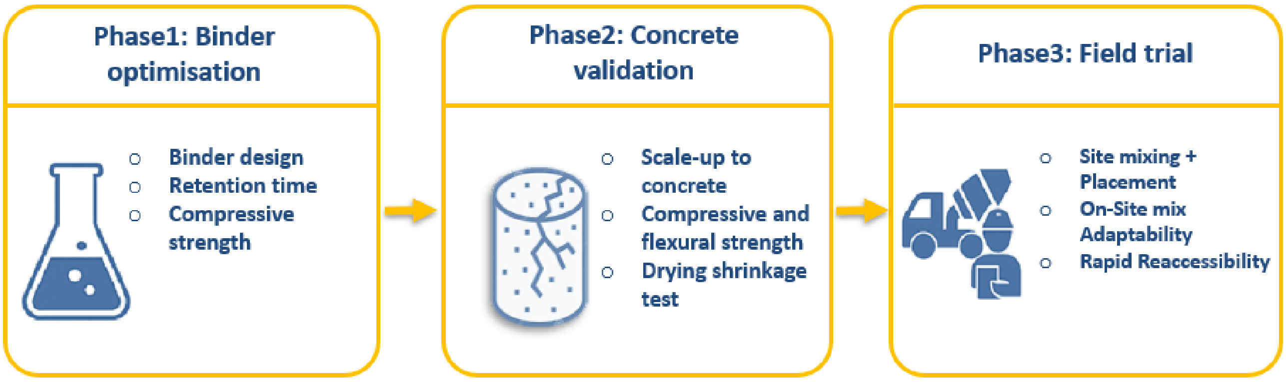

*Figure 1 Overview of the three-phase methodology: mortar optimisation, lab-scale concrete validation, and field trial execution for powder-activated GPC development.*

# RAW MATERIALS

The binders used in this study comprised Eraring FA, Port Kembla GGBFS and powder activator. *Table 1* presents the physical and chemical properties of the precursor materials. To ensure compliance with TfNSW QA Specification R83 requirements, this study adopted a blended aggregate grading approach. Coarse aggregates with nominal sizes of 10 mm and 20 mm were selected and proportioned to develop a continuous gradation within the specified limits. The fine aggregate blend consisted of Dunmore sand and Peppertree manufactured sand. Mapetard was introduced as a retarder in field mixes to extend the setting time to allow for proper placing, compaction, and broom-finishing.

| Properties | Fly ash | GGBFS | Reference test method |
|---|---|---|---|
| **$SiO_2$ (%)** | 64.7 | 36.2 | AS 2350.2 |
| **$Al_2O_3$ (%)** | 23.0 | 13.1 | AS 2350.2 |
| **$Fe_2O_3$ / FeO (%)** | 3.0 | 0.4 | AS 2350.2 |
| **CaO (%)** | 1.58 | 43.1 | AS 2350.2 |
| **Fineness (45 micron % passing)** | 88 | 99 | AS 3583.1 |
| **Loss on ignition (%)** | 1.2 | -1 | AS 3583.3 |
| **Strength index 7 day (%)** | 95 | 108 | AS 3583.6 |
| **Relative density** | 2.13 | 2.94 | AS3583.5 |

*Table 1 – Physical and chemical properties of FA and GGBFS*

# LABORATORY INVESTIGATIONS

## GP MORTAR MIXES

The GP system examined in this study was designed to cure under ambient laboratory conditions for lab-scale trials and under natural outdoor conditions during field testing. Mortar mixes (nine in total) were prepared using varying precursor contents and FA-to-GGBFS ratios. These trials served as a foundation for scaling up to concrete, where further tests were conducted to evaluate performance and strength development.

Laboratory investigations began with a series of mortar trials aimed at identifying the most effective binder combination. Three control mixes were prepared within an OPC-based system, with the 100% OPC mix containing only general-purpose cement (hereafter referred to simply as cement in this paper) as the standard control mix, the 75% OPC mix incorporating 75% cement and 25% FA as a research control mix, and the 50% OPC mix comprising 50% cement, 25% FA, and 25% GGBFS as a low carbon concrete mix, alongside several GP mortar mixes considered for further investigation. The OPC-based control mixes were prepared with the same water-to-binder ratio and total binder and aggregate contents as the GP P9 mix.

As shown in Table 2, flow retention over a 120-minute period was assessed alongside compressive strength at 1, 3, and 7 days. The results indicate an inverse correlation between reactivity and flow retention, where highly reactive systems, particularly those with higher GGBFS content, reduced workable time. This trend highlights the importance of achieving sufficient workability for practical applications. Additionally, a clear correlation was observed between increased GGBFS/FA ratios and enhanced early-age strength, attributed to the higher calcium content and reactivity of GGBFS. This strength gain was further accelerated by elevated $Na_2O$/precursor ratios, promoting faster geopolymerisation. These findings underscore the need to balance precursor composition and activator dosage to optimise both workability and strength development in GPC mixes.

The experiment indicated that GP mortars have potential to achieve a suitable workable time under ambient conditions, with no signs of quick hardening. Based on visual observation, the mixes maintained a consistent appearance with no visible bleeding, even at relatively high water-to-binder ratios. This behaviour is largely attributed to the naturally more viscous and cohesive character of GP systems, which helps keep particles well suspended and minimises segregation. By testing different binder combinations, the study aimed to find a balance between workability and early strength. Based on these results, mix P9 was selected for more detailed testing, as it demonstrated excellent flow retention along with appropriate 1-day compressive strength and favourable strength development.

| Mix ID | Sand/Precursor ratio | GGBFS/FA ratio | W/B ratio | $Na_2O$/precursor | Flow(%) | | | Compressive strength (MPa) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Initial | 60 mins | 120 mins | 1-day | 3-day | 7-day |
| **P1** | 1.6 | 1.25 | 0.43 | 4.91 | 140 | 115 | 105 | 0.9 | 28.5 | 37.5 |
| **P2** | 1.6 | 1.6 | 0.43 | 4.91 | 140 | 110 | 105 | 1.0 | 30.0 | 40.0 |
| **P3** | 1.6 | 2 | 0.43 | 4.91 | 140 | 110 | 105 | 1.6 | 29.0 | 40.0 |
| **P4** | 1.6 | 2.6 | 0.43 | 4.91 | 130 | 100 | 95 | 2.5 | 35.5 | 44.5 |
| **P5** | 1.6 | 2 | 0.43 | 4.53 | 110 | 85 | 80 | 7.0 | 42.0 | 49.0 |
| **P6** | 1.6 | 2 | 0.42 | 4.79 | 105 | 80 | 75 | 11.0 | 42.5 | 50.5 |
| **P7** | 1.6 | 2 | 0.42 | 5.18 | 90 | 75 | 65 | 15.0 | 45.5 | 52.5 |
| **P8** | 1.45 | 1.2 | 0.42 | 4.42 | 135 | 105 | 105 | 0.4 | 24.0 | 34.0 |
| **P9** | 1.45 | 1.9 | 0.46 | 4.42 | 140 | 135 | 130 | 11.5 | 32.5 | 41.0 |

*Table 2 – Precursor composition, flow retention, and early-age compressive strength of geopolymer mortar mixes.*

Recognising practical challenges associated with GP systems, such as potential cement contamination, the selected binder (mix P9) was subjected to further testing. As shown in Figure 2, even with 5% cement contamination by precursor mass, there was no significant impact on flow retention. The cement-contaminated mix exhibited improved early strength while maintaining comparable 7-day strength. A comparison of strength development highlights the rapid strength gain potential of the GP system. The 3-day strength of the GP mix reached 79% of its 7-day strength, whereas the corresponding ratios for the OPC control mixes were lower, averaging at approximately 63%.

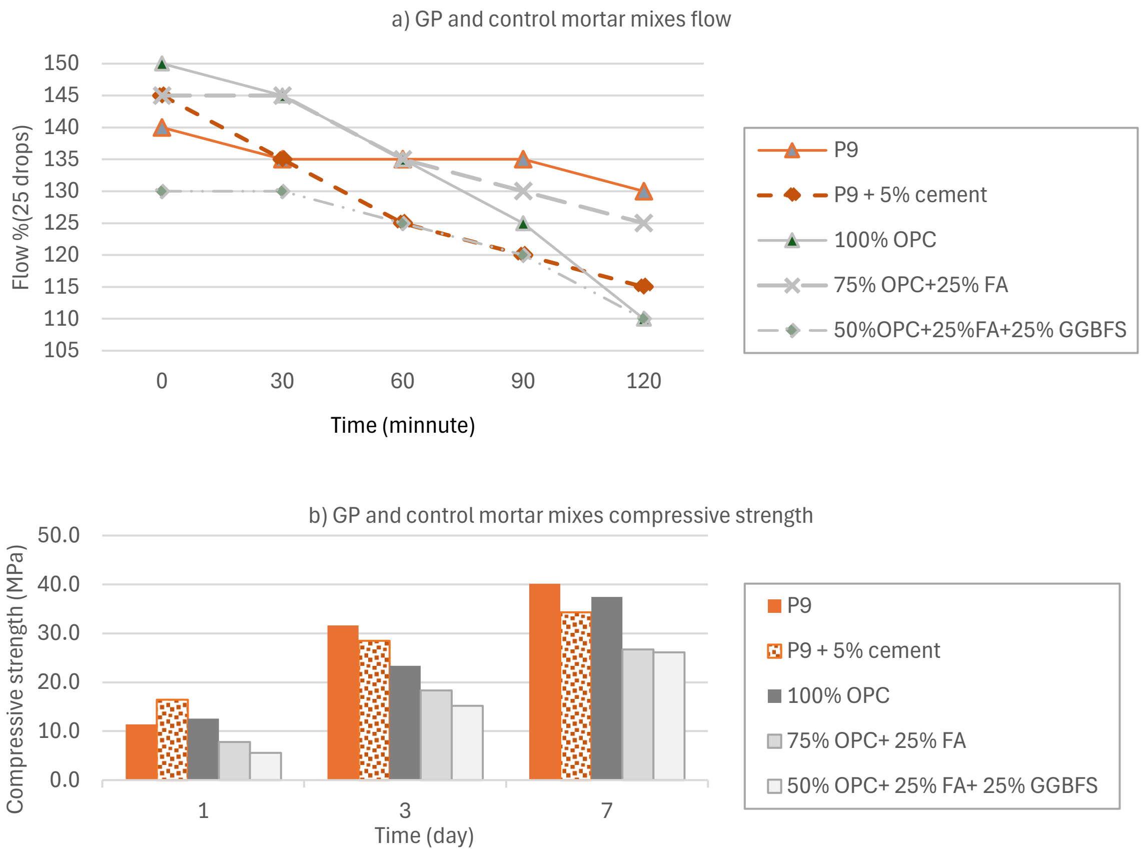

*Figure 2 Comparison of GP and control mortar mixes: (a) flow retention and (b) compressive strength development.*

# GPC MIXES

Scaling up mortar systems to concrete mixes can be achieved by considering the intended application and performance requirements. In this study, as discussed P9 mix showed strong potential for upscaling. The GPC mix was further tested to verify its compliance with TfNSW R53 and R83 specifications. As outlined in Table 3, the testing program covered compressive strength, flexural strength, and drying shrinkage. Results confirmed that the mix met all performance criteria. These outcomes demonstrate the concrete's suitability for structural and pavement applications in the transport sector.

The developed GPC mix exhibited excellent mechanical properties, satisfying both industry requirements and the specifications set out in TfNSW R83. Early-age strength development was also notable, with compressive strengths of 28 MPa at 3 days and 35 MPa at 7 days, supporting the suitability of this mix for applications requiring early opening to traffic.

The mix showed excellent volume stability, with shrinkage well below R83 limits, confirming that the optimised GPC binder effectively controls shrinkage and reduces cracking risk. The chloride migration coefficient, determined under an imposed electrical field (NT Build 492), was measured at $1.49\times10^{-12}$ m$^2$/s, while the diffusion coefficient (NT Build 443) was found to be $0.55\times10^{-12}$ m$^2$/s. These extremely low values indicate a dense matrix with limited ionic permeability, which translates into a high resistance to chloride ingress and thus a reduced risk of reinforcement corrosion over the service life of the infrastructure. Alkali-silica reactivity was evaluated using AMBT method, primarily intended to classify aggregate reactivity. A known reactive aggregate source, which exhibited expansions exceeding 0.3% at 10 days when tested with the general-purpose cement, was employed to ensure the sensitivity of the method. The expansion observed with the GP binder was less than 0.10% at 21 days, indicating that the binder effectively mitigates deleterious ASR-related expansion.

| Properties | GPC mix results (mean ± SD[1]) | Test standard | R83 specifications |
|---|---|---|---|
| 3-day compressive strength (MPa) | 28 ± 0.5 | AS 1012.9 | 20 (based on industry needs) |
| 7-day compressive strength (MPa) | 35 ± 1.0 | AS 1012.9 | Min 20 |
| 28-day compressive strength (MPa) | 45 ± 1.5 | AS 1012.9 | Min 40 |
| 28-day flexural strength (MPa) | 6.0 ± 0.1 | AS 1012.11 | 4.8 to 6.5 |
| Drying shrinkage (µm) | 250 (21 days), 360 (56 days) | AS 1012.13 | 580 (21 days), 680 (56 days) |
| Chloride migration coefficient (m$^2$/s) | $1.49\times10^{-12}$ | NT Build 492 | - |
| Chloride diffusion coefficient (m$^2$/s) | $0.55\times10^{-12}$ | NT Build 443 | - |
| ASR (%) – AMBT method | E < 0.10 (21 days) | AS 1141.60.1 | - |

*1:SD= standard deviation*

*Table 3 Evaluation of GPC mix properties in accordance with R83 specifications*

# FIELD TRIAL IMPLEMENTATION

A full-scale off-site yard trial was conducted in West Melbourne to assess the practical application of powder-activated GPC under real site conditions. As part of this trial, a footpath section was laid with GPC, primarily to monitor the handling, compaction, and finishing behaviour of the mix. The trial was designed to target a 25 MPa compressive strength, informed by laboratory-scale investigations, with precursor modifications including the use of 360 kg/m³ of GGBFS to accommodate site-specific constraints such as raw material availability, cost considerations, and the requirement for early reopening of the pavement. The overall approach was guided by key insights obtained from earlier mortar and concrete-scale studies.

The trial site was located approximately 350 metres from the batching plant, enabling concrete delivery via mini truck agitators. Four batches, each with a volume of 1.7 m³, were prepared to capture a range of site-relevant conditions and operational variations. Batches 1 and 2 experienced issues related to suboptimal water dosing, which resulted in either excessive or insufficient workability and setting times that deviated from expectations. However, Batches 3 and 4 were optimised through the incorporation of upfront water addition and the use of a chemical retarder (Mapetard), which enhanced slump retention and placement performance. The concrete reached sufficient strength to allow foot traffic within two hours of placement.

All processes, from mixing to casting and finishing, were carried out using conventional equipment typically employed for hand-placed concrete pavement works. As illustrated in Figure 3, careful attention was given to the sequencing of placement and finishing operations to ensure satisfactory outcomes. The footpath casting was executed in a controlled sequence, section by section, progressing through completed, finishing, spreading, and concrete pouring stages.

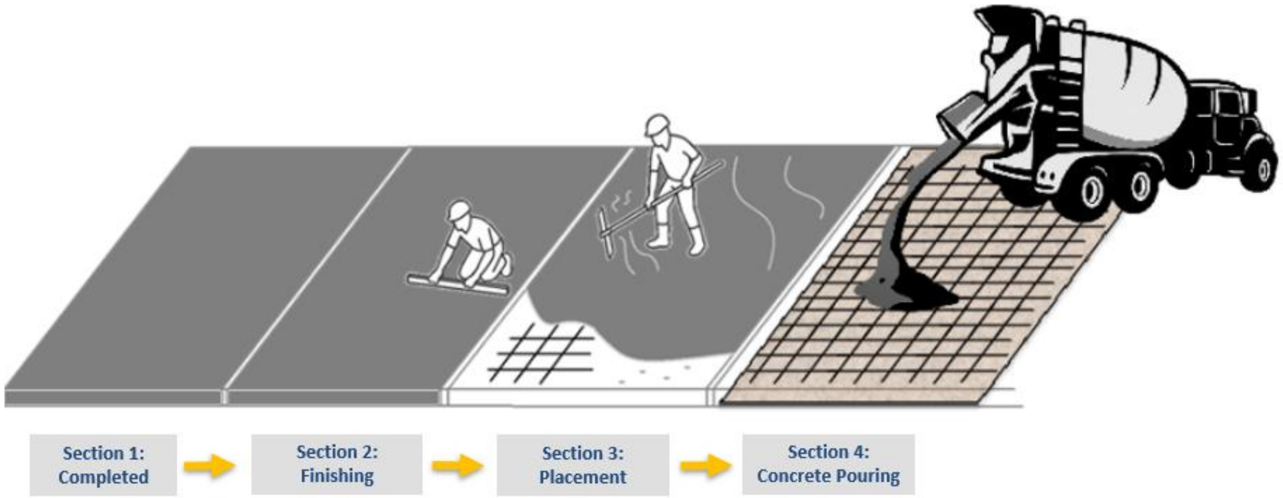

*Figure 3 Section-by-section casting sequence adopted for the GPC footpath trial*

Following the use of bull floats on compacted concrete, a broom finish was employed and the final surface finish across the trial section was uniform and consistent. As illustrated in Figure 4, the trial demonstrated the constructability of GPC under field conditions, highlighted the importance and feasibility of applying field-specific adjustments, and confirmed its potential for broader use in footpath and pavement construction.

*Figure 4 GPC footpath placement and finished surface texture*

Cylinder specimens were cast on site following AS 1012.8.1 specifications during the field trial to allow further evaluation of the concrete's mechanical performance under field conditions. The results of the field tests are presented in Table 4.

| Mix ID | Slump (mm) | compressive strength (MPa) | | |
|---|---|---|---|---|
| | | 1-day | 7-day | 28-day |
| **Field trial GPC mix** | 200 | 8.5 | 19 | 25 |

*Table 4 Fresh properties and compressive strength of the field trial GPC mix*

# CONCLUSIONS

This study demonstrates that powder-activated GPC mixes can successfully transition from laboratory optimisation to practical field application. Laboratory results showed strong compliance with key performance specifications of R53 and R83 in terms of strength development and drying shrinkage, while the field trial provided valuable insights into constructability, adaptability, and implementation practices. Critical to the success of the trial was a clear understanding of the mix behaviour and deliberate selection and adjustment of the mix to suit project-specific requirements, including a staged, section-by-section footpath construction approach.

The combined outcomes from laboratory testing and field validation confirm that powder-activated GPC is a technically and operationally viable alternative to OPC concrete for footpath and pavement applications. The material met performance targets for strength and shrinkage and proved reliable under real-world construction conditions when supported by appropriate handling and placement practices. This case study highlights the potential for broader adoption of GPC in infrastructure projects, provided that careful mix calibration and adequate training of site personnel are ensured.

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