

Trial Piles with High Percentage GGBS

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doi: <https://doi.org/10.21467/proceedings.171.4>

ABSTRACT

With a view to reducing carbon emissions, there is a pressing need to promote wider application of low-carbon concrete in construction works. The use of Ground Granulated Blastfurnace Slag (GGBS) as a supplementary cementitious material has been proven effective in reducing the total carbon emission of the concrete production process. While the application of GGBS concrete is not uncommon in the construction of superstructure and precast facades, it is rare to see the use of GGBS concrete in piling works nowadays in Hong Kong. Recent communications with relevant stakeholders revealed a general lack of knowledge of the effects of using GGBS concrete, especially those with high percentage of GGBS, in the construction operation and quality control of piling works. In order to collect more field data and site operation observations in respect of adopting high percentage GGBS in piling works, two full-scale trial piles were constructed with over 75% GGBS replacement level. The entire construction process was carefully monitored and recorded, together with a well-designed testing and monitoring plan, to identify any potential issues during site operation and quality control, and to gain better understanding of the performance of GGBS concrete in-situ. The successful completion of these trial piles would provide technical evidence to support a wider application of GGBS concrete in piling works, thus contributing to the achievement of carbon neutrality in Hong Kong.

1 INTRODUCTION

The use of Ground Granulated Blastfurnace Slag (GGBS), a by-product of the iron manufacturing industry, as a supplementary cementitious material (SCM) has been proven effective in reducing the total carbon emission of the concrete production process by lowering the use of Ordinary Portland Cement (OPC). Taking cognisance of the goal to achieve carbon neutrality under the Hong Kong's Climate Action Plan 2050, there is a pressing need to promote a wider application of low-carbon concrete in construction works.

Since 2012, the General Specification for Civil Engineering Works (GS) published by the Government of the HKSAR has allowed the use of GGBS as SCM in concrete production for public works projects, with a replacement level between 35% and 75% for normal concrete. Since then, GGBS concrete has been used, albeit not very common, in the construction of superstructure and precast facades, etc. The durability aspects of GGBS concrete were studied by Leung & Wong (2011). Kwok & Leung (2023) evaluated the performance of GGBS concrete mixes, which were found generally on-par with OPC concrete mixes and were considered suitable for general civil and geotechnical engineering works.

Despite the proven performance of GGBS concrete, its use is rarely seen in the construction of piles in Hong Kong. Recently, Chu (2023) reported the trial use of GGBS concrete with a replacement level of 50% in deep foundation works under an urban renewal project. Recent communications with relevant stakeholders, including piling contractors and concrete suppliers, etc., have revealed various practical concerns of adopting GGBS concrete with a high replacement level (i.e. more than 50%) in piling works. For example, the potential high adhesiveness of the concrete due to the fineness of GGBS could pose challenges to the tremie concreting process and the pile casing extraction process. Other hesitations include workability, retention of slump, temperature evolution in the pile, and the long-term strength development have also been discussed.



In view of the general lack of understanding of the effects of using GGBS concrete in the construction operation and quality control of piling works on site, the Geotechnical Engineering Office (GEO) of Civil Engineering and Development Department (CEDD) initiated a series of full-scale trial piling works in 2023 to examine this matter in a systematic manner. The first two trial piles with different GGBS replacement levels were successfully constructed in early 2024. While monitoring work and data interpretation are still in progress, this paper presents some of the key observations made during the construction operation and discusses the preliminary results regarding the performance of GGBS concrete used in these trial piles.

2 TECHNICAL DETAILS OF TRIAL PILES

2.1 The Trial Piles

With the support of the West Development Office of the CEDD, two trial bored piles of 3 m in diameter and 63 m and 52 m in length respectively, namely GGBS-YLS-P1 and GGBS-YLS-P2, with different replacement levels of GGBS were constructed at a site near Lam Tai West Road at Yuen Long South, New Territories. In order to mimic the actual situation of large concreting volume and long concreting time, full-scale trial on concreting of bored piles was proposed. The replacement level of GGBS for GGBS-YLS-P1 was 75%, which is the ceiling of the allowable portion of the total cementitious content in the GS. For GGBS-YLS-P2, in view of the success of the first trial pile, a slightly higher replacement level of 80% was adopted in the second pile. Construction of the two trial piles was completed in February and March 2024 respectively. The technical details of these two trial piles are summarised in Table 2.1. Figure 2.1(a) gives an overview of the trial piling works.

Table 2.1: Technical details of GGBS-YLS-P1 and GGBS-YLS-P2

	GGBS-YLS-P1	GGBS-YLS-P2
Pile shaft diameter	3.0 m (2.85 m in rock)	3.0 m (2.85 m in rock)
Pile shaft length	63 m (300 mm toe-in into rock)	52 m (300 mm toe-in into rock)
Steel reinforcement ratio	1.8% to 2.6%	1.8% to 2.6%
Proportion of GGBS to total cementitious content in concrete	75%	80%
Concrete grade strength	60D/20	60D/20
Designed slump value	200 mm	200 mm

2.2 Testing and monitoring

To properly identify any potential construction issues during site operation and quality control, the entire construction process, including tremie concreting and pile casing extraction, was carefully monitored and recorded. The conventional construction, testing and monitoring procedures of a typical bored pile apply to the two trial piles, which include slump test, cubes for 28-day compressive strength tests, sonic logging test, interface core drilling, full-length core drilling and associated unconfined compressive strength tests of concrete cores. The following additional testing and monitoring were also proposed to better understand the performance of tremie concrete with high percentage GGBS:

- slump retention tests at every 2 hours for a period of 10 hours after the commencement of concreting works for the retention of workability;
- extra concrete cubes for 3-, 7-, 10-, 14-, 56- and 90-day compressive strength tests for capturing the strength development from early age to long term;
- additional full-length core drilling for unconfined compressive strength (UCS) test at 56th and 90th day;
- Temperature Rise Evaluation Test (TRET) for evaluating the heat development properties; and
- temperature evolution monitoring along pile shaft and across pile diameter using thermal couples and fiber optics (see Figure 2.1(b)).

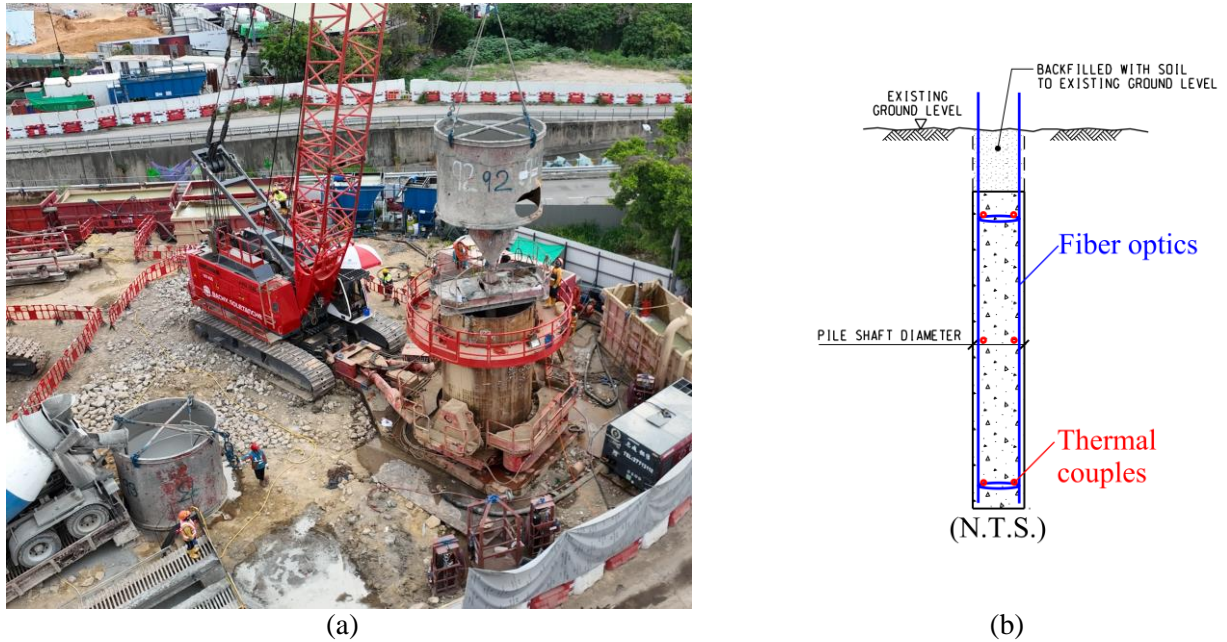


Figure 2.1: (a) Overview of the trial piling works; (b) Instrumentation arrangement within the trial pile

3 RESULTS AND DISCUSSIONS

3.1 Laboratory trials and plant trials

To provide basis for selection of suitable concrete mixes for the trial piles, laboratory trials were conducted for mixes with GGBS content ranging from 65% to 85% (see Table 3.1). Compressive cube strength tests and slump tests were conducted, and the results of which met the acceptance criteria (i.e. 60 MPa and 200 mm respectively). For control, concrete mix with 25% Pulverised Fly Ash (PFA) content was also tested.

Table 3.1: Summary of concrete mixes tested in laboratory trials

Concrete Grade [Design Slump]	GGBS Content (SCM %)	Water-Cement Ratio	Aggregate-Cement Ratio	Average Cube Strength [Average Slump value]	Selected for Plant Trials	Trial Pile ID
Grade 60D/20 [200 mm]	65%	0.34	2.99	81 MPa [220 mm]	-	-
	70%	0.34	2.98	68 MPa [210 mm]	-	-
	75%	0.34	2.98	69 MPa [220 mm]	Yes*	GGBS-YLS-P1*
	80%	0.35	2.98	66 MPa [235 mm]	Yes**	GGBS-YLS-P2**
	85%	0.34	2.98	70 MPa [235 mm]	-	-
	25% PFA	0.35	2.96	84 MPa [200 mm]	-	-

* The plant trial of 75% GGBS concrete was normal and the same mix was applied to the trial pile GGBS-YLS-P1.

** During the plant trial of 80% GGBS concrete, a premature stiffening of the concrete (“false set”) was observed which occurred within a short period after mixing (about 5 to 15 minutes). As a result, a new concrete mix with another set-retarding admixture was adopted, which was also applied to the trial pile GGBS-YLS-P2.

3.2 Tremie concreting and pile casing extraction

One of the major concerns of using GGBS concrete in piling works is the high adhesiveness of the GGBS concrete with a high replacement level (i.e. $\geq 50\%$). This issue poses significant challenge to the tremie concreting process (e.g. longer concrete pouring, clogging of tremie pipe) as well as the pile casing extraction process (e.g. difficulty in casing extraction, up-dragging of steel cage). Therefore, these processes were carefully examined during the construction of trial piles.

Figure 3.1 compares the observed different degrees of adhesiveness of the concrete mixes with and without GGBS. While PFA concrete could slide down the plate relatively smoothly when the plate was placed upright, GGBS concrete appeared more adhesive to the plate.



Figure 3.1: Different degrees of adhesiveness of concrete observed during slump tests: (a) 80% GGBS (GGBS-YLS-P2); (b) PFA concrete (observed at another site)

Comparing with the typical concreting time of a bored pile with PFA concrete (observed at another site), a longer pouring time of concrete from the concrete bucket to the tremie pipe was observed when a high percentage of GGBS was adopted (see Figure 3.2). This is particularly notable for 75% GGBS concrete. The reduced concrete pouring time observed in 80% GGBS was probably due to the use of a different set-retarding admixture (see Section 3.1), which could have made the concrete less adhesive.



Figure 3.2: Pouring of concrete from concrete bucket to tremie pipe and the approximate observed pouring time: (a) 75% GGBS (GGBS-YLS-P1); (b) 80% GGBS (GGBS-YLS-P2)

As reflected by the contractors and the concrete supplier, other concreting stages (e.g. concrete pouring from the mixing plant to the agitator of trucks at the plant, and the transfer from the agitator of trucks to the

concrete bucket at the site) could have also taken a slightly longer time due to the adhesiveness of GGBS concrete, especially at the early stage of the construction works due to a lack of experience with the new concrete mix. As experience accrued, the situation was found to be improved.

Other aspects of the construction process for both trial piles were found to be normal. Despite the relatively higher adhesiveness of the GGBS concrete, no clogging of the tremie pipe was observed. There was also no difficulty during pile casing extraction. As reported by the piling contractor, comparing with the typical operation when OPC or PFA concrete was used, no extra power was required to extract the casing, and no up-dragging of the steel cage was observed throughout the process.

The construction process was reviewed among different parties, including resident site supervision staff, contractors and concrete supplier. In hindsight, there are various measures to mitigate the prolonged concrete pouring time when a high percentage of GGBS is used. For examples, the construction site arrangement can be suitably adjusted to tighten the loading/unloading cycle of the concrete trucks, more manpower for field concrete testing and more machinery / equipment (e.g. additional crane, concrete bucket, ramp for concrete trucks to unload) could be deployed on-site (subject to site availability). From the material point of view, further study to tackle the increased adhesiveness of GGBS concrete could be explored. In this study, the observed improved performance of 80% GGBS concrete could be attributed to the use of a different set-retarding admixture. With the developing concrete admixture technology, there is room for further alleviating the adhesiveness issue of GGBS concrete. Despite the above-mentioned issues, for sites where the concreting volume is less (e.g. smaller pile diameter, shorter pile depth), such added concrete pouring time should not be critical to the construction process.

3.3 Testing and monitoring

For workability, apart from carrying out slump tests for each truck of concrete, slump retention test was also carried out every 2 hours for a period of 10 hours due to the typically long concreting time for bored pile construction. To summarise, the measured average slumps for both trial piles fulfilled the design requirements. The slump for 75% GGBS concrete dropped from 250 mm to 240 mm at the 10th hour (of a 4% decrease), while that for 80% GGBS concrete remains at 250 mm after 10 hours. This may probably be due to the use of a different set-retarding admixture for 80% GGBS concrete (see Section 3.1).

For strength, by the time of preparing this paper, only the concrete cube compressive strength test results for GGBS-YLS-P1 up to the 28-day were available (as shown in Figure 3.3).

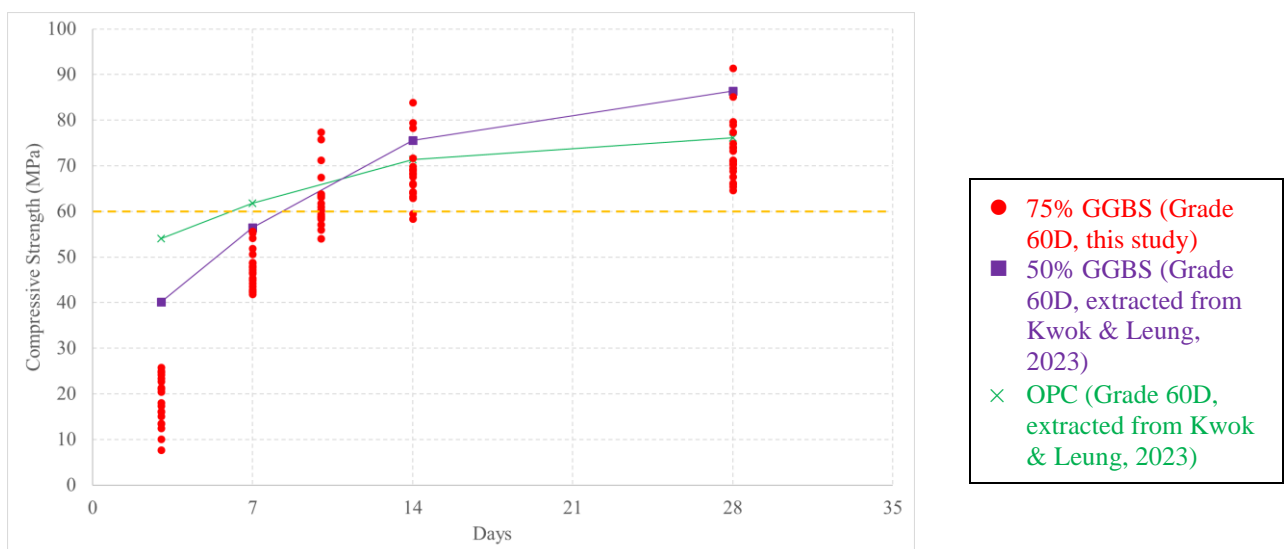


Figure 3.3: Compressive strength test results (up to 28-day) for 75% GGBS content (GGBS-YLS-P1 of this study) in comparison with 50% GGBS concrete and OPC concrete (both results extracted from Kwok & Leung, 2023)

For early strengths, the measured 3-day early age compressive strengths of 75% GGBS concrete were found to be about 11% to 36% of the measured mean 28-day strength. In comparison, those of 50% GGBS concrete

and OPC concrete were found to be 47% and 71% respectively (results presented by Kwok & Leung (2023), which are also plotted in Figure 3.3). This indicates a slower strength development at the early age for 75% GGBS concrete as compared with 50% GGBS concrete and OPC concrete. It should, however, be remarked that the GGBS concrete mix used in this study was specifically designed for a slower initial setting time (for tremie concrete in bored pile construction) as compared with the concrete tested in Kwok & Leung (2023). The strength gain for GGBS concrete and OPC concrete became more comparable at 7th day and after.

As can be seen from the test results of 75% GGBS concrete, there were some variations among the measured concrete cube strengths at different ages. For 3-day strength, the variation is not unexpected as the effect of workmanship on preparing, dismantling and testing the cubes became more prominent when the cubes were still at a very low strength. For 28-day strength, the calculated standard deviation was within the tolerance specified in the GS. Further work will be carried out to evaluate the strength variations when more test data (e.g. further concrete cube tests, UCS tests of full-length concrete cores) become available later.

To verify the concrete cube strengths and supplement the strength evolution with time, especially for longer term, full-length core drilling will be carried out for the trial piles at 28th, 56th and 90th day for core strength testing. For viewing the concrete core quality, Figure 3.4 shows the concrete cores extracted from GGBS-YLS-P1 after 28 days of concreting. Further results will be studied and presented later.



Figure 3.4: Full-length concrete core drilled from GGBS-YLS-P1 after 28 days of concreting

For temperature, in-situ measurements of the concrete in the constructed trial piles using both thermal couples and fiber optics (see Figure 2.1(b)) are still on-going by the time of preparing this paper. Preliminary results indicate that the measured temperature rise was up to about 30°C and the peak temperature of about 75°C was reached on the 3rd day after concreting. More monitoring results would be collected and analysed for better understanding the temperature evolution of in-situ GGBS concrete along the pile shaft and across the pile diameter in future.

4 CONCLUDING REMARKS AND WAY FORWARD

4.1 Key observations

Two full-scale trial piles (3 m diameter, over 50 m long) using tremie concrete with high percentage GGBS (75% and 80% GGBS replacement levels respectively) were successfully constructed in Hong Kong. The construction works, including the tremie concreting process and the pile casing extraction process, were carefully monitored. These trial piles were also systematically tested and monitored with a view to better understanding the performance using GGBS concrete in piling works. While some monitoring work and data interpretation are still in progress, key observations from the preliminary results of this study are summarised below:

- (a) The cube compressive strength, workability and its retention of both 75% and 80% GGBS concrete met the design requirements of tremie concrete for trial piles (Grade 60, 200 mm slump). Longer-term strength of in-situ concrete cores up to 90 days is being monitored and will be reported in the future.
- (b) Compared with PFA concrete, higher adhesiveness was observed in GGBS concrete rendering a generally longer pouring time during the concreting process. Different means to alleviate this issue has been discussed in the paper.
- (c) Other aspects of the construction process for both trial piles were found to be normal, e.g. no clogging of the tremie pipe, no difficulty in pile casing extraction and no up-dragging of the steel cage was observed throughout the process.
- (d) Temperature evolution along the pile shaft and across the pile diameter is being monitored using both thermal couples and fiber optics, and the results will be reported in the future.

4.2 Way forward

The trial piles presented in this paper form part of the trial pile study programme of the GEO in the Northern New Territories of Hong Kong. To facilitate the design and construction of pile foundation works in meta-sedimentary rocks, which are commonly found in the Northern Metropolis, another series of trial piles are being undertaken at various sites. Full-scale loading tests using bi-directional loading equipment installed at the pile base will be carried out for these trial piles. The test results will be studied with a view to enhancing the foundation design guideline for meta-sedimentary rocks. The study findings once available will be reported in the future.

ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering and Development, the Government of the Hong Kong Special Administrative Region of the People's Republic of China. The support from the West Development Office of the CEDD in undertaking the trial piling works is appreciated. The authors would like to thank the Public Works Central Laboratory and Housing Department for the technical advice and support.

PUBLISHER'S NOTE

AIJR remains neutral with regard to jurisdictional claims in published maps & institutional affiliations.

HOW TO CITE

Kian Y.K. Chiu & Eric H.Y. Sze (2024). Trial Piles with High Percentage GGBS. *AIJR Proceedings*, 35-41. <https://doi.org/10.21467/proceedings.171.4>

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