Adoption of New and Green Construction Materials in the Landslip Prevention and Mitigation Programme

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ABSTRACT

As technology advances, the Geotechnical Engineering Office of the Civil Engineering and Development Department has endeavoured to take every opportunity to improve our geotechnical standards and services through technical development and innovation. It is also our policy to seek continuous improvement in the Landslip Prevention and Mitigation Programme, our long-term rolling programme in reducing systematically the landslide risks of man-made slopes and natural hillsides affecting existing facilities. One of the key areas of technical development is the adoption of new and green construction materials for use in the design and construction of our landslip prevention and mitigation works. This paper summarises our work on the technical development and application of self-compacting backfill material and ground granulated blastfurnace slag grout mixes as part of our contribution in shaping a safe, green and sustainable city.

Keywords: Construction Materials, Self-Compacting Backfill, GGBS-Cement Grout

1 Introduction

The Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) has devoted its effort to tackle landslide problems in Hong Kong. One of the key elements of the Hong Kong Slope Safety System is the implementation of the Landslip Prevention and Mitigation Programme (LPMitP) with a view to reducing systematically the landslide risks in Hong Kong. The Programme has also provided ample opportunities for technical development and innovation in the slope engineering field, as well as in geotechnical engineering from a wider perspective.

Recently, we have explored the use of self-compacting backfill material (SCM) in slope works with a view to improving productivity and enhancing site safety. The trials completed at selected sites under the LPMitP revealed that the use of SCM had resulted in notable improvement in site progress and significant reduction in manual handling required for the backfilling operations when compared with conventional fill replacement methods. Following the successful pilot applications, we have documented the relevant findings in the GEO Technical Note No. 1/2023 (Chan & Ip, 2023) and issued a standard material specification with a view to promoting a wider use of the material in slope and retaining wall works.

In addition, noting the continuous improvement in quality control and supply of ground granulated blastfurnace slag (GGBS), a by-product of the iron manufacturing industry, for concrete production in the past few years, we have explored the use of GGBS for partial replacement of Ordinary Portland Cement (OPC) in grout mixes for soil nailing works with a view to reducing the carbon footprint of LPMit works. GGBS is a supplementary cementitious material, of which its production requires less additional energy as compared to the production of OPC, and thus a relatively green construction material. We have arranged laboratory testing at the Public Works Central Laboratory (PWCL) for identifying possible grout mixes which satisfy the relevant technical requirements. Field trials of the

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preferred GGBS-cement grout mixes are being arranged. Upon successful laboratory and field trials, a standard material specification will be prepared to promote the use of GGBS-cement grout in LPMit works.

2 Use Of Self-Compacting Backfill Material

2.1 Background

In Hong Kong, the stabilisation of loose fill slopes is usually challenging in terms of constructability and construction time. The replacement or re-compaction of the top 3 m layer of loose fill is one of the options for the slope upgrading works. The current practice for the replacement of loose fill typically involves re-compaction of the existing fill, replacement by cement-soil, replacement by no-fines concrete or replacement by mass concrete. To address the concern on slope stability during the construction stage and for preservation of existing trees on the slopes, the fill replacement is usually undertaken by pit-by-pit construction method. However, it is usually difficult and time consuming to carry out fill replacement and the necessary quality assurance test with such limited working space at steep terrain, not to mention the site safety hazards in connection with manual handling and working in those pits.

With this background, the GEO has identified the opportunity of using a SCM developed by Nano and Advanced Materials Institute Ltd. (NAMI) in lieu of the conventional soil backfill materials in slope and retaining wall works with a view to enhancing constructability and site safety. A pilot study with site trials for use of the SCM was launched in late 2020 as a continuous improvement initiative under the LPMitP.

2.2 The self-compacting backfill material

The SCM developed by NAMI (SCM-NAMI), with a material formulation named as “NAMI DM-4” as referred to by NAMI, is originally designed for trench backfilling for the Highways Department (HyD) (HyD, 2022; Kwong *et al.*, 2022; Nissinen, 2021). SCM-NAMI is a mix of (i) cementitious material; (ii) fine aggregate; (iii) crushed rock fines; (iv) water; and (v) admixtures, with necessary optimisation in the mix formula to achieve a balance between workability and strength, while maintaining homogeneity. As the SCM-NAMI was originally developed for its intended use in backfilling of trenches and voids in road works, the mix was designed for a target maximum compressive strength of less than 1 MPa to allow future re-excavation while achieving high flowability, as well as self-levelling and self-consolidating properties.

Considering the composition and properties of the SCM-NAMI, it could be categorised as a kind of “Controlled Low-Strength Material (CLSM)” (ACI, 2013; ASTM, 1998; Hitch & Howard, 1998), which is a collective term to describe a family of mixtures that compose of a self-consolidating cementitious material used primarily as a backfill as an alternative to compacted fill. The SCM-NAMI with a target maximum compressive strength of less than 1 MPa is classified as a lower-strength CLSM mix. Typical lower-strength CLSM mixes exhibits soil-like performance with negligible liquefaction potential. As the SCM-NAMI exhibits self-compacting properties, the conventional compaction control requirements for fill material as laid down in Section 6 of the General Specification for Civil Engineering Works (GS) (HKSAR Government, 2020) are not applicable.

2.3 Site trials and key findings

After a preliminary review on the feasibility of using SCM-NAMI in LPMit works including initial laboratory tests conducted by the PWCL to verify the properties and suitability of SCM-NAMI for slope

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applications, a series of site trials was arranged. Pilot applications, involving the use of over 1,300 m^3 of SCM-NAMI, had been carried out at a total of eight trial sites. The pilot applications involved the replacement of about top 3 m of existing loose fill on slope or behind retaining wall by SCM-NAMI as part of the slope upgrading works under the LPMitP. Both ready-mixed SCM-NAMI produced by concrete batching plants and mixed-on-site SCM-NAMI using pre-packed materials by adding water and admixture, were under trial. A list of the pilot sites is shown in Table 1.

Table 1: *List of pilot sites*

Feature no.	Location	Type of mix	Volume applied (m^3)
7SW-D/C454	Lei Uk Tsuen, Sha Tin	Ready-mixed	166
15NE-A/F116	Tai Tam Road, Southern	Ready-mixed	22
7SE-C/F110	Sha Tin Road, Sha Tin	Ready-mixed	179
6NE-C/R45	Shug Shan New Village, Yuen Long	Ready-mixed	50
8SW-A/R16	Tso Wo Hang, Sai Kung	Mixed on site	50
14NW-D/FR53	Kwun Yam Wan Road, Cheung Chau	Mixed on site	30
14NW-D/FR54	Kwun Yam Wan Road, Cheung Chau	Mixed on site	10
11NW-D/FR141	King's Park, Yau Ma Tei	Ready-mixed	855

The key findings from the site trials are summarised below:

(a) General - The SCM-NAMI produced by the concrete batching plant or by mixing on site has demonstrated self-compacting properties, and the respective material properties, including wet density and flowability, were largely consistent among the samples collected from the trial sites. In general, the ready-mixed SCM-NAMI demonstrates better consistency in material properties than SCM-NAMI mixed on site as expected. After placement and setting of the SCM-NAMI, no noticeable ground subsidence was observed.

(b) Strength - The SCM-NAMI at 28 days achieved an unconfined compressive strength of at least 0.2 MPa consistently.

(c) Flowability and density - The fresh SCM-NAMI exhibited high flowability (i.e. slump greater than 200 mm) consistently at the trial sites. The self-levelling, self-consolidating and void-fillable characteristics enhanced the efficiency of the fill replacement operations significantly. The wet density of the fresh SCM-NAMI ranges from 1.9 Mg/m^3 to 2.3 Mg/m^3. The bulk density of hardened SCM-NAMI is about 1.8 Mg/m^3 to 2.2 Mg/m^3.

(d) Constructability - The SCM-NAMI allows horizontal pumping of over 250 m and vertical pumping of over 30 m by using typical concrete pumps, thus facilitating placement of the SCM-NAMI at sites with difficult access. There was also no observable excessive ingress of the SCM-NAMI into the surrounding loose fill materials. The setting time of SCM-NAMI was about 8 hours. The key quality control tests, i.e. checking of wet density and flowability, to be carried out on site are simple and straight-forward. The ease in placement and simple quality control of the material also led to a remarkable shortening of construction duration.

(e) Permeability - The SCM-NAMI is relatively impermeable, with a mass permeability between 5.2 x 10^{-6} m/s and 7.4 x 10^{-9} m/s, which is close to the lower bound value of the compacted soil fill.

According to the pilot study (Chan & Ip, 2023), the SCM-NAMI or equivalent is found to be a feasible alternative to compacted fill (or other typical backfill material such as cement-soil, no-fines concrete, and mass concrete) for backfilling of pits, trenches and voids in slope and retaining wall works. Photographs of the site trials are presented in Figures 1 to 4.

(a)Delivery of ready-mixed SCM by concrete truck

(b) Discharge of ready-mixed SCM to concrete pump

(c)Use of pipelines for transportation of SCM within the site

(d)Placement of SCM by chutes

Figure 1: *Delivery and placement of ready-mixed self-compacting backfill material*

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(a)Production of SCM using screw mixer on site *(b)SCM discharged from the screw mixer*

Figure 2: *Production of self-compacting backfill material mixed on site*

(a)Placement of SCM for fill replacement in a pit (b)Loose fill replaced by SCM

Figure 3: *Application of self-compacting backfill material on site*

(a) Flowability test in accordance with ASTM D6103-17

(b) Sampling and preparation of cylindrical sample for laboratory testing

Figure 4: *Field testing and sampling of self-compacting backfill material on site*

2.4 Benefits and limitations

The most significant benefits about the use of SCM are the major reduction of manual handling and the remarkable shortening of construction duration due to the elimination of compaction operations. As compared with conventional soil re-compaction or replacement by cement-soil, the use of SCM, which exhibits self-levelling, self-consolidating and void-filling properties, eliminates the need for compaction operations and necessary compaction tests required. The use of SCM is also less affected by inclement weather, bringing further improvement of the overall site progress. As compared with replacement of loose fill by no-fines concrete or mass concrete, the use of high pumpability of SCM without the need of in-situ vibration during placement can minimise the manual operations in connection with the transportation and placement of replacement material. It expedites the backfilling process and helps to overcome access constraints. Besides, on some special occasions, e.g. maintenance of underground utilities is required, use of SCM with limited strength would facilitate future excavation. Overall speaking, the site trials completed revealed that the use of the ready-mixed SCM had resulted in a notable improvement in site progress, with over 75% time saving and 50% labour reduction for the backfilling operation as compared with the conventional fill replacement methods. The use of SCM to be mixed on site provide similar benefits on labour reduction but with less time saving as production rate of SCM on site is limited. Last but not least, the use of SCM in fill replacement operations was also observed to have enhanced the overall constructability and minimised the construction operations at the congested environment on steep slopes, which improved construction site safety as a whole.

Currently, the material cost of SCM in Hong Kong is higher than that of re-compaction of the existing fill or replacement by cement-soil, no-fines concrete or mass concrete, likely due to limited demand at the current stage. At the time being, the SCM developed by NAMI has been licensed to four companies for commercial scale production and supply locally. It is believed that the cost of SCM-NAMI or equivalent can be reduced through market competition among suppliers and with wider application of the material in the future.

2.5 Wider uses in slope and retaining wall works

With the observations and findings of the site trials, a set of particular specification (PS) for the use of SCM-NAMI or equivalent in slope and retaining wall works was prepared with a view to facilitating the wider use of the material. The PS sets out the quality requirements, standards of workmanship, testing methods and acceptance criteria of using SCM for backfilling of pits, trenches and voids in slopes and retaining walls. The PS supplements Section 7 – Geotechnical Works of the GS (HKSAR Government, 2020). The GEO issued the PS to government departments and geotechnical practitioners in September 2022 to facilitate the general use of the SCM in backfilling of pits, trenches and voids in slope and retaining wall works (GEO, 2022).

For quality control requirements of the SCM, the key tests rest on the field checking of flowability and wet density to verify the consistency of the SCM mix without segregation. For the compliance test of minimum strength level, UCS tests for cylindrical specimens has been specified with due consideration on the use of the SCM for geotechnical works. The method of testing shall be in accordance with Appendix B of the “Interim Guidelines on Testing of Unconfined Compressive Strength of Cement Stabilised Soil Cores in Hong Kong” published by Geotechnical Division of The Hong Kong Institution of Engineers in October 2017 (HKIE, 2017). In the PS, the flowability of the SCM is specified to be at least 200 mm without segregation according to ASTM D6103-17 (ASTM, 2017). The minimum compressive strength of the SCM at 28 days is specified to be 0.2 MPa.

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The SCM, which has been demonstrated as a feasible alternative in fill replacement operations, provides opportunities for streamlining site operations in suitable projects in enhancing the project performance in terms of productivity, safety and sustainability.

3 Use of Ground Granulated Blastfurnace Slag in Cement Grout

3.1 Background

Cement-based grout is widely used in slope engineering works in particular for grouting of soil nails, rock bolts and rock dowels. Traditionally, a simple and standardised cement grout mix, involving OPC and water with a water cement ratio not exceeding 0.45 has been referred to in standard specifications in the past decades. To promote a green and sustainable slope engineering practice and to support the carbon neutrality initiative, the potential incorporation of supplementary cementitious material for partial replacement of OPC in grout mixes has been explored. In addition to the reduction of carbon footprint, the use of supplementary cementitious material, such as pulverised fuel ash (PFA) and GGBS, usually means the incorporation of potential waste for production use.

PFA, which is the ash resulting from the burning of pulverised coal in coal-fired electricity power stations, has been widely used as supplementary cementitious material locally. However, there may be a shortage of supply of PFA in the near future due to the reduced use of coal for power generation locally. GGBS, which is a by-product of the iron manufacturing industry, is another supplementary cementitious material which may be used for replacement of OPC in concrete production. Granulated blastfurnace slag is obtained by quenching molten iron slag from a blastfurnace in water to produce a granular product, which is then dried and ground to become GGBS.

For concrete, Section 16 the General Specification for Civil Engineering Works (HKSAR, 2006) was amended in 2012 to allow the general use of GGBS as supplementary cementitious material. For cement grout in geotechnical works, there are provisions for the use of PFA in cement grout in Section 7 of the GS but not GGBS. In view of the foreseeable decline of local PFA supply and the continuous improvement in quality control and supply of GGBS for concrete production in the past few years, we have launched a study to review the use of GGBS for partial replacement of OPC in grout mixes for soil nailing works under the LPMitP.

3.2 Key issues on the use of GGBS in cement grout and past experience

With due consideration on the material properties and supply of GGBS, as well as the past experience of the GEO on the use of GGBS in concrete and in cement grout (Wong & Chi, 2016), key issues on the use of GGBS in cement grout are summarised below:

(a) Sustainability - The production of one tonne of GGBS would generate about 0.083 tonne of CO_2 equivalent, as compared to 0.95 tonne for cement and the energy consumption for one tone of GGBS and cement are 1,600 MJ and 5,500 MJ respectively (Hammond *et al.*, 2011). Therefore, using GGBS as a partial replacement of cement can significantly reduce the carbon footprint in concrete and cement grout production.

(b) Physical and chemical properties - Section 16 of the GS (HKSAR Government, 2020) requires that the GGBS should comply with BS EN 15167-1 (BSI, 2006). Generally speaking, the physical and chemical properties of GGBS are similar to those of OPC, and this makes partial replacement of cement with GGBS technically feasible. Notwithstanding this, the fineness of GGBS typically adopted in concrete production is higher than that of OPC.

(c) Setting time and strength development - Generally speaking, since the hydration property of GGBS is latent when compared to that of OPC, GGBS-cement grout requires more time for setting than conventional cement grout. Moreover, the GGBS-cement grout may have a slower early strength development as compared with that of conventional cement grout.

(d) Workability and bleeding - Due to the higher fineness of GGBS as compared with OPC, the replacement of OPC by GGBS may reduce the workability of the cement grout. In theory, the bleeding of GGBS-cement grout is related to the fineness of GGBS, the water to cementitious materials ratio and the amount of any admixture used.

(e) Quality control and supply - There are continuous improvement in the quality control and supply of GGBS for concrete production. In particular, GGBS produced by plants with internationally recognised quality assurance system which fulfils BS EN 15167-1 are available locally. The material cost of GGBS is in the same order of OPC.

In view of the above, we have arranged laboratory testing at the PWCL for identifying possible grout mixes which satisfy the relevant technical requirements with a view to seeking considerable replacement of OPC by GGBS with an optimal addition of admixtures. Particular attention is given to the use of admixture and the performance of GGBS-cement grout mixes in terms of workability and bleeding.

3.3 Laboratory trials

With the technical support of GGBS / cement / concrete suppliers, a series of laboratory trial mixing using different grout formulas, cementitious materials and admixtures was arranged. In addition, four control mixes with GGBS replacement ratio of 50% and one control mix using pure OPC were arranged. No admixtures were used in the control mixes. A list of the grout mix formulas is shown in Table 2.

Table 2: *List of grout mix formulas*

Mix ID.	Cementitious content (kg/m^3)	GGBS replacement ratio	w/c ratio	Admixture	Cement brand	GGBS manufacturer	Mixing sequence
E1AA	1420	65%	0.36	Retarder + Superplasticiser + Water retaining agent	A	A	Adding water to dry cement and GGBS
E1AB						B	
E1BA					B	A	
E1BB						B	
E2AA	1365	50%	0.39		A	A	
E2AB						B	
E2BA					B	A	
E2BB						B	
G1AA	1305	69%	0.41	Superplasticiser + Retarder and expansion agent	A	A	Adding cement to water first and then adding GGBS to the grout mix
G1AB						B	
G1BA					B	A	
G1BB						B	
G2AA	1320	73%	0.40		A	A	
G2AB						B	
G2BA					B	A	
G2BB						B	
CMAA	1365	50%	0.40	-	A	A	
CMAB						B	
CMBA					B	A	
CMBB						B	
CMA	1365	-	0.40		A	-	

A number of compliance tests were carried out on the trial mixes in accordance with the GS:

(a) Flow cone test in accordance with ASTM C939;

(b) Bleeding tests in accordance with ASTM C940; and

(c) Compressive strength tests on grout cubes at 3, 7, 14 and 28 days in accordance with Construction Standard CS1:2010 Testing Concrete (HKSAR Government, 2010).

3.4 Observations from laboratory test results

The test results of the compliance tests on the trial mixes are summarised below:

(a) General and workability - The GGBS-cement grout mixes with various replacement ratios ranging from 50% to 73%, using different brands of raw materials and with the addition of admixtures (i.e. mixes under E1, E2, G1 and G2 series) meet flow cone efflux time requirement of not less than 15 seconds as stipulated in the GS as shown in Figure 5 and the limiting maximum time of 35 seconds as recommended in the relevant testing standard. The four control mixes using 50% GGBS replacement but without the use of admixtures demonstrated poor workabilility as expected.

(b) Bleeding - For all mixes, the 3-hour bleeding results are the same as the final bleeding results. The mixes under the E1 series, which have the lowest w/c ratio of 0.36, as well as the control mixes under the CM series satisfy the 3-hour bleeding requirement (< 0.5%) as specified in the GS. All the mixes under E2, G1 and G2 series with a higher w/c ratio of 0.39 to 0.41, except the G2AB mix, demonstrated 3-hour bleeding results of 0.5% to 1%. All mixes satisfy the maximum bleeding requirement (< 1%). The test results are summarised in Figure 6. In addition, all mixes were observed to have absorbed the bled water within 24 hours.

(c) Strength - All samples achieved the compressive strength requirement of 30 MPa as stipulated in the GS. Mixes under the E1 and E2 series exhibited higher compressive strengths when compared to mixes under the G1 and G2 series as shown in Figures 7 and 8 and this may be due to the lower w/c ratios (0.36 & 0.39) adopted in the former series. In addition, it is observed that for the E2AA mix, the 28-day compressive strength result is lower than the 14-day compressive strength result as shown in Figure 7(b). This may be due to the poor uniformity of the mix as observed inside the crushed sample. Such uniformity of the mix may be attributed to the adopted method of mixing as listed in Table 2.

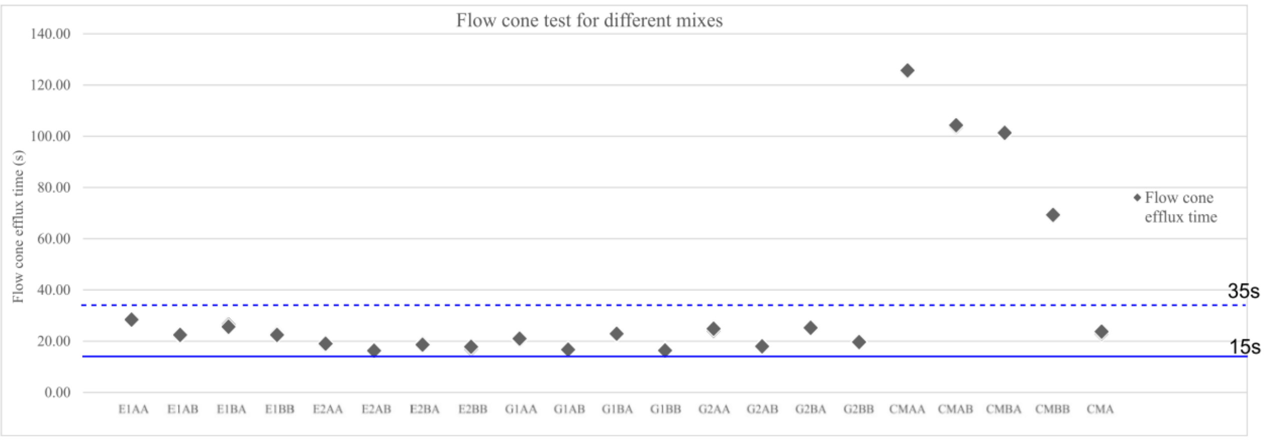

Figure 5: *Flow cone test results*

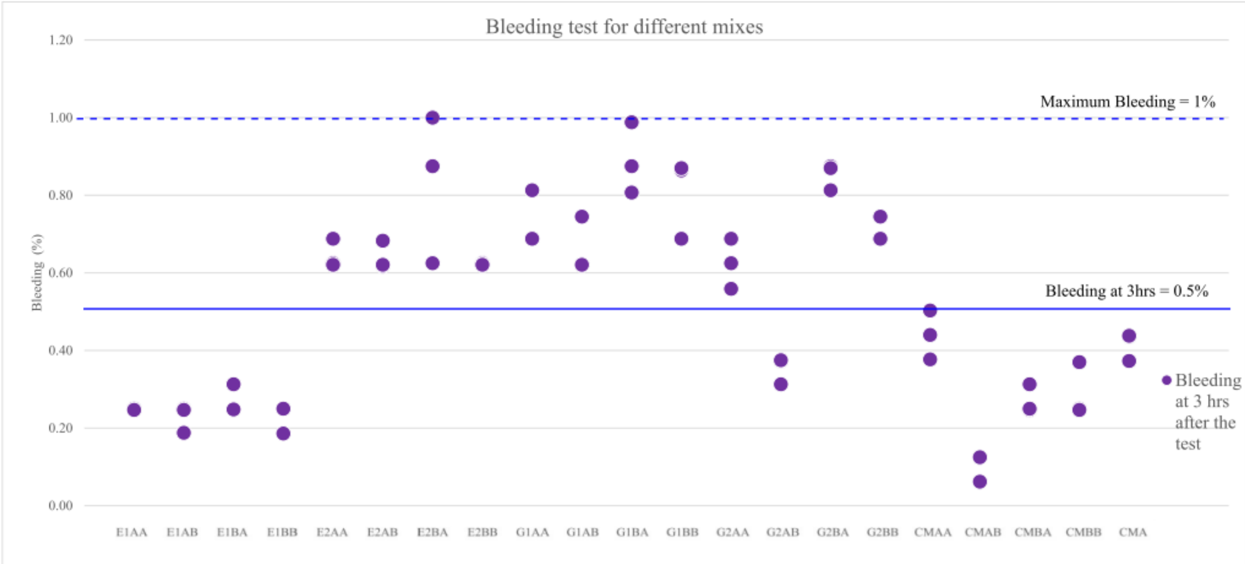

Figure 6: *Bleeding test results*

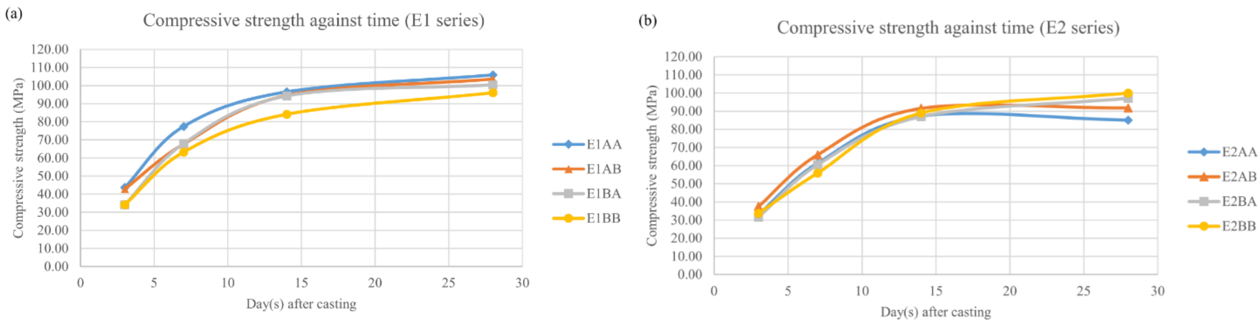

Figure 7(a) and (b): *Compressive test results for E1 and E2 series grout mixes*

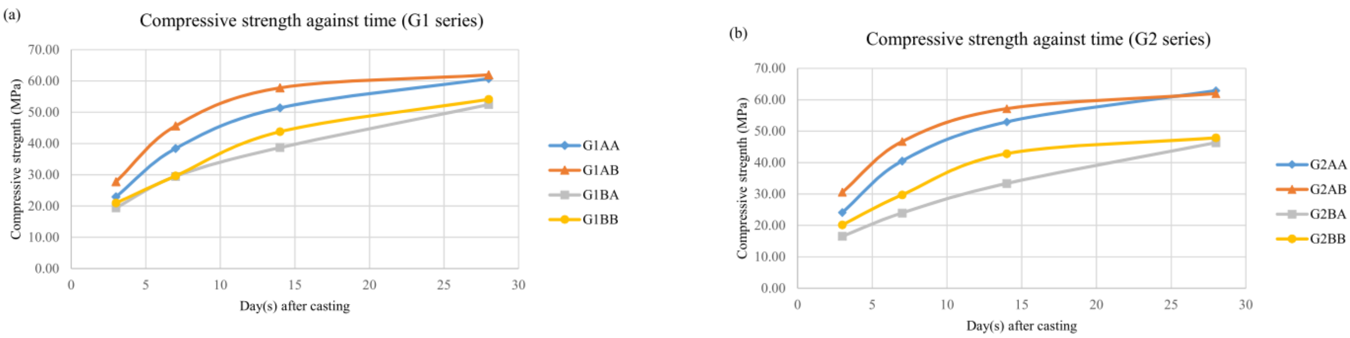

Figure 8(a) and (b): *Compressive test results for G1 and G2 series grout mixes*

With due consideration of the test results, further trials are being undertaken to review the potential use of mixes with different w/c ratio and the respective bleeding performance and the recommended grout mixing sequence.

3.5 Further work

The GEO are now arranging field trials of the preferred GGBS-cement grout mixes at sites under the LPMitP. The findings from the initial field trial conducted in March 2023 are also promising. Specific review shall be carried out on the field mixing operations of the GGBS-cement grout mixes. In parallel, the GEO and the consultants are reviewing the anticipated order of overall OPC replacement by GGBS in slope engineering works, with an intention to encourage supply of pre-packed GGBS in bags to facilitate storage, transportation and field mixing of GGBS-cement grout. Upon successful laboratory and field trials, a standard material specification will be prepared to promote the use of GGBS-cement in LPMit works.

4 Conclusion

While the ongoing LPMitP has brought about major improvement to slope safety in Hong Kong, it is necessary to seek continuous improvement in the LPMitP in overcoming the challenge of potentially increasing landslide risks due to climate change and in decarbonising our LPMit works. Technical development and innovation in the slope engineering field in the past decades have also led to advances in knowledge and technology in reducing landslide risks. The recent work of the GEO in the two pilot projects involving the adoption of new and green construction materials in the LPMitP has been highlighted in this paper. Further technical development and innovation as part of the ongoing LPMitP will continue, which can open up more opportunities for practical applications and advances in geotechnical engineering practice, for the development of a safer, greener and sustainable city.

5 Declarations

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5.2 Publisher's Note

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