Novel Cementitious Materials for Geotechnical Applications - Vibration Resistant Sprayed Concrete for Rock Tunnel Lining and Self compacting Backfill for Slope Upgrading Works

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ABSTRACT

Innovations in material sciences create new opportunities to enhance the ways of construction in the geotechnical field. By streamlining the conventional construction procedures with the application of new materials, more efficient, more cost-effective and safer construction could be achieved. Two material development projects have been launched by the Geotechnical Engineering Office (GEO), Civil Engineering and Development Department, the Government of the Hong Kong Special Administrative Region, China, and the Nano and Advanced Materials Institute (NAMI) was commissioned to develop the vibration resistant sprayed concrete (VRSC) and the self-compacting backfilling material. This paper presents the development of the two novel materials with particular highlights on the benefits of their applications in rock tunnels and slope upgrading works respectively and addresses the potential development in further applications of the novel materials in the fields.

Keywords: Shotcrete, Backfill, Materials

1 Introduction

Cementitious materials has a wide range of applications in geotechnical engineering, from structural support of tunnels, ground improvement to backfilling. Traditional concrete materials exhibit high compressive strength and stiffness. In combination with the use of steel reinforcements, reinforced concrete become an excellent material for many engineering applications. However, in order to meet the specific needs for applications in drill and blast rock tunnel lining support and fill replacement of slope upgrading works, extra performance in certain cementitious materials is required.

In drill and blast rock tunnelling, a two-pass concrete lining system, comprising one layer of sacrificial temporary sprayed concrete lining and another layer of permanent lining, is commonly adopted in Hong Kong for rock support. The first-pass lining (the temporary lining) is not considered as part of the permanent works as it could be damaged by blasting vibration in the tunnelling process. Potential damage of the fresh sprayed concrete is assumed in case when the allowable vibration limits, in terms of Peak Particle Velocity (PPV) based on the GEO Report No. 102, are exceeded. Experimental data and recommended limits in this report, however, were based on plain concrete and hence may not be directly applicable to fibre-reinforced sprayed concrete. Overseas examples from field and laboratory testing have demonstrated that sprayed concrete lining could sustain a PPV beyond 500 mm/s (Ansell, 2007; ITA Working Group n°12 & ITAtech, 2020), while the recommended PPV limit in the GEO Report No. 102 is only 70 mm/s at 24-hour after casting. This apparently conservative approach has added constraints to the optimisation of a drill and blast cycle in hard rock tunnelling and cavern excavation. To facilitate composite lining construction without discarding the structural capacity of the

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first-pass lining, a VRSC formula is being developed to improve the structural performance in vibration resistance and at the same time, enhance the flexural strength, toughness and residual strength. The VRSC development has shown promising interim results and brings insights on the enhancement of constructability, cost effectiveness and sustainability in the long-term strategic rock cavern development.

On the other hand, stabilization of loose fill slopes is always challenging in terms of constructability, cost and construction time of the works. Recompacting the top 3 m of loose fill is an acceptable solution, while pit-by-pit construction method is commonly adopted on sites with constraints, such as presence of mature trees and limited working area. However, manual operations inside pits with limited working space at steep terrain make pit-by-pit method very difficult and time consuming, not to mention the safety concerns of working in pits, difficulties in achieving an adequate degree of compaction and conducting the quality assurance test. To cope with such challenges, DM-4, a self-compacting backfilling material originally designed for trench backfilling for the Highways Department (HyD), was developed and found feasible in addressing the difficulties encountered in the pit-by-pit fill replacement works. This new material has a high flowability and short hardening time while exhibiting comparable properties to soil, such as strength and permeability. These characteristics make DM-4 an ideal alternative to compacting fill material in pits for enhanced constructability, cost effectiveness and safety in slope upgrading works.

2 The Development of Vibration Resistant Sprayed Concrete (VRSC)

2.1 Methodology

2.1.1 Theoretical Analysis and Simulation

To understand the blasting-based tunnel excavation process, numerical models for simulating the dynamic response in the tunnel environment were established to assess the blasting-induced vibration propagation in the sprayed concrete lining, maximum vibration velocity, the relation between explosive force impulse and surface vibration amplitude nearby, and the influence of explosive force impulse on the performance of the sprayed concrete lining.

2.1.2 Vibration Resistant Sprayed Concrete Formulation

Fibre was introduced to the VRSC formula for enhancing the tensile and flexural performance, residual strength, toughness and energy absorption capacity. Different fibre types may show different effects on VRSC's workability (including spraying capability) and mechanical performance. Various types of fibres with different geometry were evaluated, including synthetic macro fibre and steel fibre. Furthermore, polymer-modified cementitious material powder was introduced into the VRSC formula to enhance the bonding between the sprayed concrete lining and rock substrate and hence reduce the rebound during spraying and improving the water-tightness and durability.

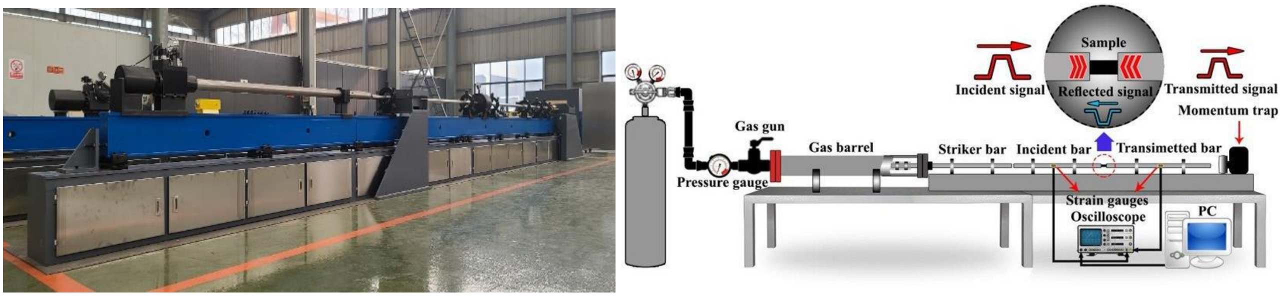

Figure 1: The image and schematic drawing of SHPB

To assess the effects of blasting vibration on the performance of VRSC and determine the corresponding design acceptance criteria, a set of systematic evaluation procedures was designed. A dynamic material test will be conducted in the future with a Split Hopkinson Pressure Bar (SHPB) system as shown in Figure 1. In principle, a sprayed concrete lining is vulnerable to tensile stress that causes delamination or structural damage. A SHPB-based experiment simulates such scenarios by attaching a VRSC sample onto the end of the incident bar to simulate the effect of wave propagation on the sample. This experiment is also named the reflected-wave experiment. Finite element simulation of the SHPB test was conducted to correlate the dynamic stress and velocity fields in a sample for streamlining the complex testing and evaluation procedures. Further elaboration on the SHPB simulation is presented in Section 2.2.2.

2.2 Modelling and Simulation

2.2.1 Simulation Models

Two-dimensional and three-dimensional finite-element models of the tunnel were established based on Ansell’s tunnel configurations and calculations (Ansell, 2004, 2007; Ahmed & Ansell, 2012, 2014) to determine the correlation between the mass of explosive charges, maximum impact on lining in term of stress and vibration speed in term of PPV. Soil and rock were simplified as an equivalent continuum material with the failure criterion following a pressure-sensitive model (e.g., the Drucker–Prager model). Material models for concrete and the sprayed concrete lining will be established based on the actual measured data from sites (or referred to the related literature) later. In the simulation, the detonation of the explosives in the cylindrical drill holes is simplified to being initial pressure impulses (e.g., a triangular impulse). The simulation was conducted by employing an explicit finite element solver, and the results were then interpreted as some snapshots of velocity and stress fields and the detailed velocity/stress variations with time at several concerned points after an explosion. The results helped us establish the relation between the pressure impulse—which may be related to the mass of explosives—and the maximum impact/vibration speed at the areas of sprayed concrete lining and determine the requirements of adhesiveness and strength of sprayed concrete lining under explosive force.

Based on the specific construction requirements for drill and blast tunnelling projects in Hong Kong, the analysis can be repeated to obtain the relation between tensile stress and distance from the explosion centre. A required safety distance of the sprayed concrete lining was established based on the data from the simulation. Figure 2 shows the constructed 3D model of a tunnel under the blast loading. Figure 3 shows the relationship between the distance from the explosive centre and PPV with different TNT equivalents after the simulation.

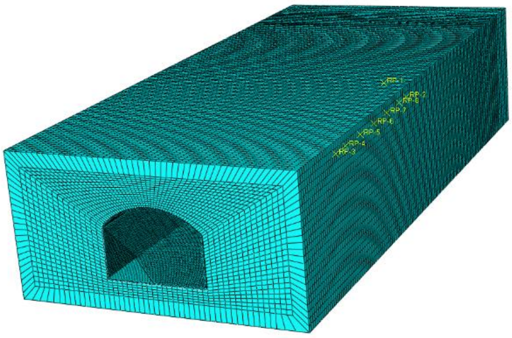

Figure 2: The 3D finite-element model of a tunnel under the blast load

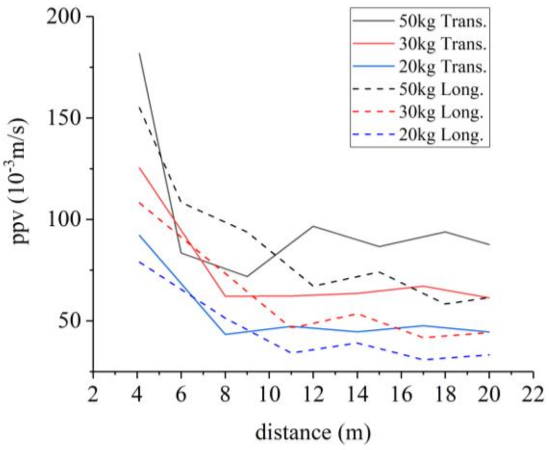

Figure 3: The simulation results of blasting radius versus measured PPV, with different TNT equivalent (kg)

2.2.2 Split Hopkinson Pressure Bar (SHPB) Simulation

Before the SHPB simulation, it is critical to understand the nature of explosive waves generated by tunnel blasting. The explosive waves are initially isotropic pressure waves that propagate in all directions. However, the geometry of the tunnel complicates the wave propagation. For example, when a pressure wave reaches the tunnel wall, it results in compressive waves along and perpendicular to the wall. The compressive wave perpendicular to the wall bounces back when it hits the interface or surface, and this reflected wave from the surface becomes tensile. This is because the free surface is stress-free; an incident compressive wave must be balanced by a tensile wave to satisfy the stress-free state on the surface. Such a tensile wave induces the tensile stresses leading to delamination or spalling, which is a major concern in sprayed concrete lining, i.e., the sprayed concrete lining must resist a certain magnitude of tensile stresses normal to the interface. As such, a uni-directional SHPB test is adopted. In addition, it is noted that a wave has a wavelength or a duration of substantial stresses. Hence, static tests are not recommended because the action time of the tensile stresses is very short (e.g., within 1 millisecond). SHPB is therefore the tool to generate a stress wave with a finite duration, which suits the purpose.

The exact requirements of the dynamic strengths of concrete and concrete-rock bonding can only be determined based on the simulation results of tunnel blasting after the numerical model is validated by the on-site measurement of surface vibrations. To determine the dynamic properties of sprayed concrete and rock-concrete interface, SHPB experiments are necessary. Associated with the SHPB experiment to be done in the next phase of the project, SHPB simulations were conducted to assist our experimental design. Figure 4 shows the simulation results, indicating that the incident wave generated by the projectile was a uniaxial compression wave. The reflection from the interfaces and sample surface led to tensile waves; this phenomenon was in line with the stress wave propagation theory. Figure 5 (a) shows the simulation results on the interface between the sprayed concrete and rock. Figure 5 (b) shows the simulation results of tensile stresses measured on the same interface with different striker velocities of the aluminium (Al) striker.

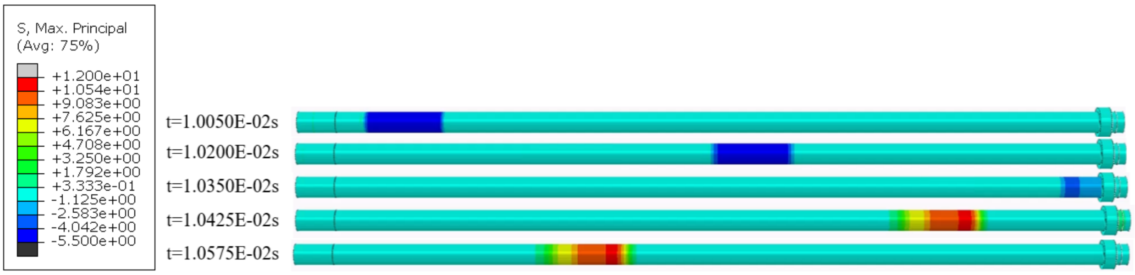

Figure 4: The propagation of stress wave in the SHPB (Positive as tensile)

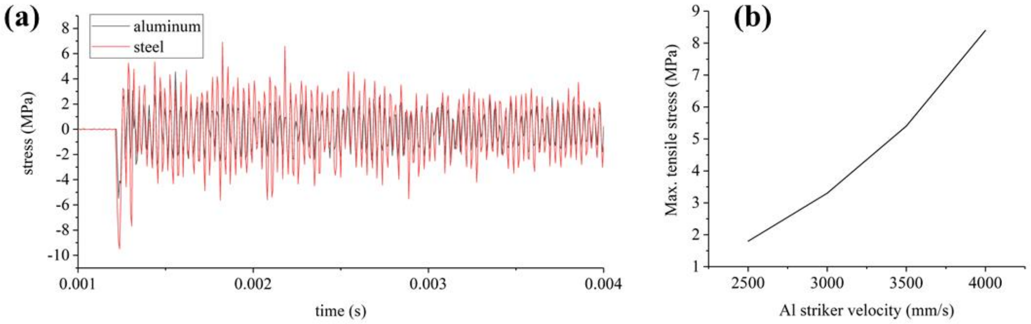

Figure 5: (a) The stress curves (Al and steel strikers, where positive and negative stresses are tensile and compressive respectively), & (b) the relations between Al striker velocity and maximum tensile stress measured on the sprayed concrete-rock interface

The SHPB simulations have shown that the actual measured PPV values during tunnel blasting together with the known quantities of explosives can be used to evaluate the relationship between PPV and tensile stresses that the VRSC lining has experienced. These numerical simulations provide useful and important information for the design of the SHPB test and give insights on completing and improving the SHPB setup. Moreover, they serve as a guideline for the VRSC mix design optimization such as the requirement on bond strength to the rock substrate at a specific distance away from the blast centre.

2.3 Site Trial for Scale-up Production of VRSC

A site trial for scale-up production of VRSC was conducted for determining the mechanical properties and quantifying the performance of VRSC in a realistic construction process and environment. Laboratory testing such as flexural tests and direct pull-out tests were conducted. Flexural testing on beam specimens is important as it provides the fundamental significance of crack opening response when the concrete is under tensile loading; while plate or slab bending testing is more related to the energy absorption capacity, especially in the practical applications where the load-carrying capacity of concrete at large deformation is critical, and the design is primarily empirical. Direct pull-out testing examines the bond strength between the VRSC and the rock substrate, which is related to a typical failure mode of sprayed concrete lining.

2.3.1 Scale-up Production

To verify the mechanical performance subject to transportation, the produced VRSC was transported from the concrete mixing plant at Yuen Long to the construction site located at Sha Tin, as shown in Figure 6. On site, flow table tests were conducted, and the temperature of the fresh VRSC were recorded. VRSC cubes, prisms and panels were also prepared for compressive strength tests, flexural strength tests, toughness and energy absorption capacity measurement respectively at specified ages, as shown in Figure 7.

2.3.2 VRSC Performance

Table 1 shows the fresh VRSC performance which satisfies the requirements on workability, consistency and temperature both in the plant and on site. The produced VRSC showed a flow table value above 600 mm even at 2 hours after water addition, fulfilling the general concrete requirements. No bleeding was found in the fresh VRSC. The initial and final setting times of the produced VRSC were measured as 540 minutes and 625 minutes respectively. The temperature of fresh VRSC was around 26°C at the plant but raised to 29.9°C on site.

Figure 6: (a) The concrete truck arrived on-site, and (b) fresh VRSC was poured for testing

Figure 7: The fresh VRSC (a) prisms, and (b) cubes and panels

Table 1: Performance of the fresh VRSC

Fresh concrete properties	**Condition**	**Results**
Flow table value (FTV)	Initial	615 mm
	15 mins after addition of water	635 mm
	120 mins (on-site)	620 mm
Bleeding	At plant	No observed
	On-site	No observed
Setting time	Initial	540 mins
	Final	625 mins
Temperature	Initial	26.0 °C
	15 mins	25.9 °C
	120 mins (on-site)	29.9 °C

Table 2: Performance of the hardened VRSC

Testing Item	**Age**	**Requirement**	**Results**
Compressive Strength	24 hrs	≥ 14 MPa	18.5 MPa
	7 days	≥ 25 MPa	50.5 MPa
	28 days	≥ 35 MPa	63.1 MPa
Flexural Strength	28 days	≥ 5.0 MPa	7.0 MPa
Toughness Index I_5	7 days	≥ 3.5	3.8
	28 days	≥ 4.0	4.4

Toughness index I_{10}	7 days	≥ 5.0	7.0
	28 days	≥ 6.0	8.3
Residual Strength $R_{5.10}$	7 days	N/A	67.0
	28 days	≥ 60	78.7
Energy Absorption Capacity	28 days	≥ 700 J	1430 J

The values of measured compressive strength, flexural strength and toughness and the energy absorption capacity of the hardened VRSC are shown in Table 2, in which the requirements are also included. Although no accelerator was used, the 1-day compressive strength of the produced VRSC reached 18.5 MPa, fulfilling the requirements of 14 MPa. The 7-day and 28-day compressive strength reached 50 MPa and 63 MPa, respectively, both above the required values. The measured flexural strength, toughness index, residual strength and energy absorption capacity are all well-above the required values.

2.4 Current Status of Development and Way Forward

The formulation of VRSC has been characterized in the laboratory and plant trial. The results from the plant trial were found consistent with the result of the laboratory trial, which showed excellent mechanical performance. To test the sprayability, rebound and mechanical performance of VRSC on site, further site trials will be conducted in the next phase of the project where VRSC is applied to a rock substrate in the tunnel by mechanical spraying, as well as sprayed concrete panels for testing. To simulate the effect of blasting, the VRSC lining will be subject to blasting impacts where vibration monitoring will be done to measure the PPV experienced. The measured PPV data will be studied and used to calibrate the numerical simulation model.

3 Self-Compacting Backfilling Material

3.1 Development of the DM-4 Backfilling Material

Facing the increasing need for frequent and rapid trench filling in roadworks, an universally applicable self-compacting backfilling material – DM-4 (hereinafter the DM-4 backfilling material) was developed by NAMI as initiated by the Highways Department (HyD). The development of the DM-4 backfilling material focused on the following aspects: high applicability, self-compacting ability and high flowability, making it a suitable backfilling material for trenches with congested pipe/cable networks. It also has a high thermal conductivity which fits the specific requirement for power cables. In terms of strength development, the DM-4 backfilling material was designed to gain strength rapidly after application, which increases the construction productivity and reduces the time of road reinstatement works. With these special characteristics, GEO launched a separate project on applying the DM-4 backfilling material on slopes as an alternative material for 'pit-by-pit' fill replacement for slope upgrading works under the Landslip Prevention and Mitigation (LPMit) Programme. More details of the site trials are presented in Section 3.3.

The DM-4 backfilling material has a high flowability (> 200mm slump) and a 28-day compressive strength lower than 1 MPa, designed for trench backfilling to allow easy manual excavation in the future. The formula verification and optimization for slope backfilling application was conducted in the NAMI laboratory. Plant trials were carried out in a local concrete plant to verify the scale-up producibility and consistency in mechanical properties of the DM-4 backfilling material. The volume of the proposed backfilling works, material discharge method and required laboratory and field testing details were also discussed and agreed with the relevant stakeholders before the site trials. The detailed arrangement and results of the site trials are presented in Section 3.3.

3.2 Formulation of the DM-4 Backfilling Material

The core part of the DM-4 formulation was the compatibility among cementitious materials, aggregates and admixtures. The DM-4 matrix was developed based on raw materials selected on their availability in the local market, such as Ordinary Portland Cement (OPC) and Pulverised Fuel Ash (PFA) as binders. In addition, different types of non-pozzolanic fine fillers, such as crushed rock fines (CRF), were also studied and applied in the formulation.

Among the major characteristics mentioned in Section 3.1, workability is the most important parameter to facilitate the backfilling application on-site. A high workability makes the DM-4 backfilling material highly pumpable and flowable. The mix formula was then optimized to achieve a balance between workability and compressive strength without causing segregation and bleeding but maintain a minimum slump loss. To lower the density, a nano-foam, which is an ultrastable and nano size foam developed by NAMI (Sun et al, 2019), was introduced into the mix. It also improved the workability and further reduced the risk of bleeding.

To verify the mechanical properties and performance of the DM-4 backfilling material, a series of laboratory and field tests on density, flowability, hardening time, initial strength and compressive strength were done, which are briefly presented in the sub-sections below.

3.2.1 Density

The wet density was measured on the site from two samples collected from the concrete truck by filling a 1 L volume cubic mould with the slurry of the DM-4 backfilling material. Figure 8 shows the wet density test carried out on site.

3.2.2 Flowability

The consistency of the slurry of the DM-4 backfilling material without segregation was checked upon delivery to the site by flowability testing in accordance with ASTM D6103. One sample of not less than 20 L was collected from the initial discharge of the batch, and the second sample of not less than 20 L was collected after half volume of the batch had been discharged for the flowability test. Figure 9 shows the flowability test carried out on site before placement.

Figure 8: Measurement of wet density on site

Figure 9: Measurement of flowability on site

3.2.3 Hardening Time

Two samples of the DM-4 backfilling material of 2.65 L were collected from the first discharge of the concrete truck and tested in accordance with BS EN 13294 standard in the NAMI laboratory. Figure 10 shows the hardening time test carried out in NAMI laboratory for a sample casted on site.

Figure 10: Hardening time testing apparatus in NAMI laboratory

3.2.4 Initial Strength

Before further works can be commenced on the surface of the backfilled area, the suitability for load application was tested according to ASTM D6024. A half-spherical weight was dropped five times from a height of 108-114 mm onto the surface of the backfilling material. The diameter of the resulting indentation was measured and compared to the established criteria. Figure 11 shows the initial strength test conducted on site by a "Kelly-ball" apparatus.

Figure 11: "Kelly-ball" test conducted on site

3.2.5 Compressive Strength

To evaluate the compressive strength of backfilling material, 100 mm cube samples were collected on site. The samples were covered to eliminate water evaporation and kept at room temperature before drying to an oven-dry density and the compressive strength test at 3, 7 and 28 days with reference to Construction Standard CS1:2010. Figure 12 shows the compressive strength test in NAMI laboratory.

Figure 12: Sample for compressive strength testing

3.3 Site trials for Slope Upgrading Works

After a series of site trials for trench backfilling of public utility works in 2020, NAMI successfully verified the production process and performance of the self-compacting backfilling material under practical situations. Since 2021, NAMI collaborated with the GEO and applied the DM-4 backfilling material in slope upgrading works under the LPMit Programme. The material has been used in both large and small scale backfilling operations since then. In smaller sites or areas inaccessible with a concrete truck, the DM-4 backfilling material was mixed on-site with a continuous mortar mixer and pumped into the pits. In larger operations starting from approximately 6 cubic meters, the material was pre-mixed in a concrete batching plant and delivered to the site by a concrete truck. During the site trials, the backfilling operation was tested by pumping the DM-4 backfilling material into a pit by a concrete pump. Specific arrangements should be taken into consideration before the pumping, such as checking the connection between pumping tubes and sealing of gaps between any formwork and soil to avoid leakage of the DM-4 backfilling material. Due to its high flowability, a single truckload of approximately 6 cubic meters of backfilling material can be pumped into the slope pits in less than 15 minutes. After the placement, the backfilled area was left to set before testing the initial load-bearing capacity of the hardened surface.

As a result of collaboration between NAMI and the GEO, over 500 m^3 of the DM-4 backfilling material has been successfully placed in various slope upgrading works sites since 2021. The use of the DM-4 backfilling material reduced significantly the manual handling and labour required for the fill replacement works for enhanced site safety. The availability of a dry-mix option and the feasibility to convey the material using concrete pump made the material particularly useful in overcoming site access constraints. The ease in placement and simple quality control of the material also led to a remarkable shortening of the construction duration. Having the successful results from the various site trials and conditions, additional slope sites involving the use of the DM-4 backfilling material are being arranged with a view to consolidating experience.

Figure 13: Overview of slope site at Lei Uk Tsuen, Shatin

Figure 14: Pumping backfilling material from concrete truck to the pit (Lei Uk Tsuen)

Figure 15: Slope works after placement of backfilling material (Lei Uk Tsuen)

3.4 Backfilling Material in Action

A pilot application of the DM-4 backfilling material was conducted at a site at Lei Uk Tsuen, Shatin as shown in Figure 13 to 15. Table 3 below shows the testing results which satisfy the acceptance criteria in terms of wet density, flowability, hardening time, initial strength and compressive strength. No segregation was found during the flowability test on site.

Table 3: Test results of backfilling material site trial at Lei Uk Tsuen, Shatin

Test items	Acceptance Criteria	Results
Flowability	> 200 mm (without segregation)	220mm without any segregation
Wet density	1900 kg/m^3-2100kg/m^3	2066kg/m^3
Hardening time	Reach 3.5 N/mm^2 within 24 hours	5.0 N/mm^2 at 23 hours
Initial strength	< 75 mm (indentation diameter)	64.0 mm at 21 hours
Compressive strength	0.3 - 1.0 MPa (28-day)	(0.54±0.03) MPa – 3-day (0.77±0.02) MPa – 7-day (0.95±0.05) MPa – 28-day

Other supplementary verifications carried out also confirmed that the shear strength and the permeability of the DM-4 backfilling material fulfilled the design requirements of typical compacted fill in slope upgrading works.

3.5 Current Status of Development and Way Forward

After a number of site trials, the feasibility about the use of the DM-4 backfilling material in slope upgrading works was successfully proven. In terms of supply of the material for use in the local construction industry, the DM-4 backfilling material has been licensed to four local companies for producing and selling the relevant products since 2021. Moving forward, the findings of the site trials on slopes are being consolidated for review and improvement. A standard material specification is intended to be prepared for promoting a wider use of such self-compacting backfilling material in slope engineering works in the near future.

4 Conclusion

4.1 The Development of VRSC

The models for simulating tunnelling blasting and Split Hopkinson Pressure Bar (SHPB) experiments have been well established in the project. The simulation results provided very good insights on the corelation between PPV, tensile stresses and safe distances, which are very important for optimizing the design and construction requirements of sprayed concrete lining and concrete mix design. These models can also be extended for simulating a complete drill and blast cycle in a rock cavern and providing essential information that facilitates the sprayed concrete lining design.

Scale-up production of VRSC was successfully carried out in a ready mix concrete plant, with the performance of the produced VRSC fulfilling the currently in-use general requirements of sprayed concrete as permanent lining material in a rock cavern development project.

To conclude, the main objective of VRSC development is to streamline the construction cycle of drill and blast tunnelling, enhance overall cost-effectiveness and improve construction safety. Upon the completion of the project and its successful application in the field, a single pass tunnel lining can be assessed and verified to attain adequate resistance to blasting vibration without concerns about the damage on its structural integrity. First, this could assure a safe working environment by eliminating the risk of concrete fall (due to slow hardening and insufficient/loss of adhesion) during the construction stage within a shorter period after spraying. Second, the single pass lining could now be considered as a permanent lining or part of a permanent composite lining, which could result in a huge potential saving from the reduction in volume of rock excavation and the overall lining thickness.

4.2 The Development of Self-compacting Backfilling Material

The use of the novel material in the site trials completed so far has demonstrated that the construction time and the manual handling involved in the fill replacement works on slopes could be significantly reduced. In the future, more applications of the DM-4 backfilling material, in addition to trench backfilling for roadworks and fill replacement in slope upgrading works, will be explored. With the above background together with potential further development of a mix with higher permeability, lower density and shorter setting time, it is anticipated that the use of the DM-4 backfilling material will be further expanded in terms of quantity and scope of applications in view of the benefits to the Government departments, consultants and contractors in their projects.

5 Declarations

5.1 Acknowledgements

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5.2 Publisher’s Note

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