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A comprehensive study of the paste recipe for the Victoria project: part 1

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Abstract

KGHM's Victoria mine (Sudbury, Ontario, Canada) requires an atypical paste backfill plant design as there will not be a mill constructed on the mine site. The lack of tailings necessitates that the mine uses its development rock waste stockpile to produce backfill material to service production. Supporting backfill design, the lab programs focused on evaluating various blends of alluvial sand with ground waste rock to produce a technically and financially viable paste product capable of satisfying the mine's requirements.

A comprehensive paste fill lab testing program has been undertaken by both Paterson and Cooke and WSP Canada Inc. Conducted sequentially and independently by these 2 consulting firms, the investigation focused on the impact of various materials and mix parameters on the short-term strength performance of paste backfill. Parameters considered in the formulation of the paste recipe included rock mineralogy, application of grinding technology, particle size distribution of the grind, alluvial sand properties, fines content, and binder type. This paper focuses on the variation of the strength of the paste fill samples with respect to 3 parameters: sand type, binder ratio, and fines content.

In addition to the binder ratio, the interaction between sand particle size distribution and binder was found to be critical in optimising paste recipe performance. Fines content was also found to have a significant impact on strength and binder requirement. The study provides essential insight into the design and implementation of cost-effective and performance-optimised paste backfill systems for deep mining environments. Recommendations are provided to guide material selection and mix design strategies that balance strength requirements with material availability and economic considerations.

Keywords: *paste fill recipe, high-pressure grinding rollers, ground waste rock, strength*

1 Introduction

KGHM's Victoria project is situated 35 km west of the city of Sudbury, (Ontario, Canada) and is fully owned by KGHM International. The Victoria project is in the prolific Sudbury mining camp, an environment historically mined, for over 110 years, for its sulphide nickel, copper, cobalt, and precious metal orebodies. The historic Victoria mine operated in 2 phases: from 1900–1923 and again from 1973–1978. In 2002, the mineral deposit rights to the Victoria area were acquired by FNX Mining Company. As a result of the purchase of the merger-created Canadian mining company Quadra FNX by KGHM Polska Miedź S.A., in 2012, the Victoria project became a part of the KGHM Group. Diamond drilling has identified mineralisation zones containing nickel, copper, and precious metals at depths ranging from 1,000–2,250 m. According to the current development plan, a ventilation shaft with a diameter of 6.7 m is being sunk from the surface to a depth of 1,860 m. Additionally, the production shaft, with a diameter of 7.6 m, will be sunk from the surface to a depth of 2,000 m.

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The polymetallic orebodies at the Victoria project are hosted in rocks of the Southern Province, located near the southwestern margin of the elliptical Sudbury Igneous Complex (SIC), where the SIC intersects with the radial Worthington Offset dyke. The site is underlain by steeply southwest-dipping metasedimentary, bimodal volcanic, and mafic intrusive rocks, predominantly attributed to the Stobie Formation within the Elliot Lake Group of the Huronian Supergroup. Quartz diorite sheets were emplaced into this stratigraphy around the time of the SIC's formation, following a meteorite impact at 1,850 Ma (Krogh et al. 1984, Mungall & Hanley 2004). These sheets, along with marginal metabreccias, serve as hosts for the Ni-Cu-PGE deposits at Victoria.

Paste fill and hydraulic cemented sandfill have been popular in many Canadian mines. Paste fill has been of special interest due to its curing characteristics, lower binder dosing rates, minimal bleed water, and delivery method (pipe system). Paste fill generally requires mine tailing products to produce a cohesive paste when mixed with cement and water. Waste material from ore processing forms the tailings material (Potvin et al. 2005). Paste is being considered for Victoria mine for its non-shrinking properties (not bleeding water), lower water content, non-segregating characteristics, and laminar flow in the pipe system. Given a lack of available tailings, the bulk of the fill for the Victoria mine is designed to use high-pressure ground mine waste rock and alluvial sand.

Due to the flexibility of operation, reduced need for grinding space as well as significantly lower energy consumption, high-pressure grinding rollers (HPGR) technology was considered for producing material to replace tailings in the paste recipe for Victoria mine. KGHM International retained Paterson and Cooke (P&C) in 2014 and WSP Canada Inc in 2024 to carry out laboratory testing on recipes comprised of Victoria ground waste rock (GWR), aggregate and external sand samples to assess an optimised paste backfill recipe. The sand samples were collected from different pits and quarries in Greater Sudbury. The GWR samples were produced by Corem Research Institute using HPGR and dry milling technology from the mine's waste rock samples. The unconfined compressive strength (UCS) testing was performed on backfill recipes at different short-term (7 and 28 days) ages.

This paper provides a comparison of laboratory results obtained from 2 independent testing programs carried out by P&C and WSP. Conducted separately and in sequence, these investigations examined how different materials and mix parameters influence both the short-term and mid-term strength performance of paste backfill.

2 Test procedure

Across the lab testing programs, 3 different sets of waste rock were processed for testing. The first phase of the study was executed with P&C (2014), who used core samples obtained during the drilling program. Phases 2 and 3 were executed with WSP-sampled waste rock from the primary stockpile at the site. All samples were shipped to the Corem Research Institute in Montreal for crushing and grinding to produce GWR for paste. Waste rock samples drawn represented the upper strata of the Victoria mine shaft development, as shaft sinking was still in early phases at the time. Different GWR materials were produced with different grain size distributions and fine contents (size specifications) along with a sample of crushed (but not ground) aggregate (−9.5 mm). Recipes for rheology and strength testing included 100% GWR, blends of GWR and sands drawn from various pits around the Sudbury basin and/or aggregate. Final fines content of the blended paste recipes targeted approximately 20–25% passing 20 µm. Two cementitious binders were evaluated across the programs: 90/10 binder (90% a specialty slag blend and 10% ordinary Portland cement) and 100% general use limestone (GUL) cement. Only the results of mixes using the 90/10 binder will be presented here.

3 Test results

The current stope design of the Victoria mine requires a 7 and 14-day strength of 480 and 670 kPa, respectively. The test program focuses on recipes to reach these targets, while keeping the economy of the operation in consideration. This section reviews the test results in terms of strength at 7, 14 and 28-day age. The results will be discussed in terms of the strength and particle size distribution (PSD) of the aggregates.

3.1 Sand type

Sand type is expected to influence the strength gain of paste backfill due to its specific PSD grading uniformity (C_u)[†], fines content including silt and sand, and mineralisation. P&C used sand from 3 different pits in Greater Sudbury: the Carman-HF, Carman Trill, and Massey pits. They blended the silt and sand from the Massey pit on a 50–50% ratio to produce the sand material. The PSDs of the 3 products are illustrated in Figure 1. The Massey sand blend and the Carman-HF sand are coarser than the Carman Trill (larger D_{50}). However, the Massey sand mix and the Carman Trill have a better (larger) uniformity factor. These 3 sands were mixed with GWR (with 30% finer than 20 µm) in a 50–50% ratio. Five per cent binder was used in all these mixes.

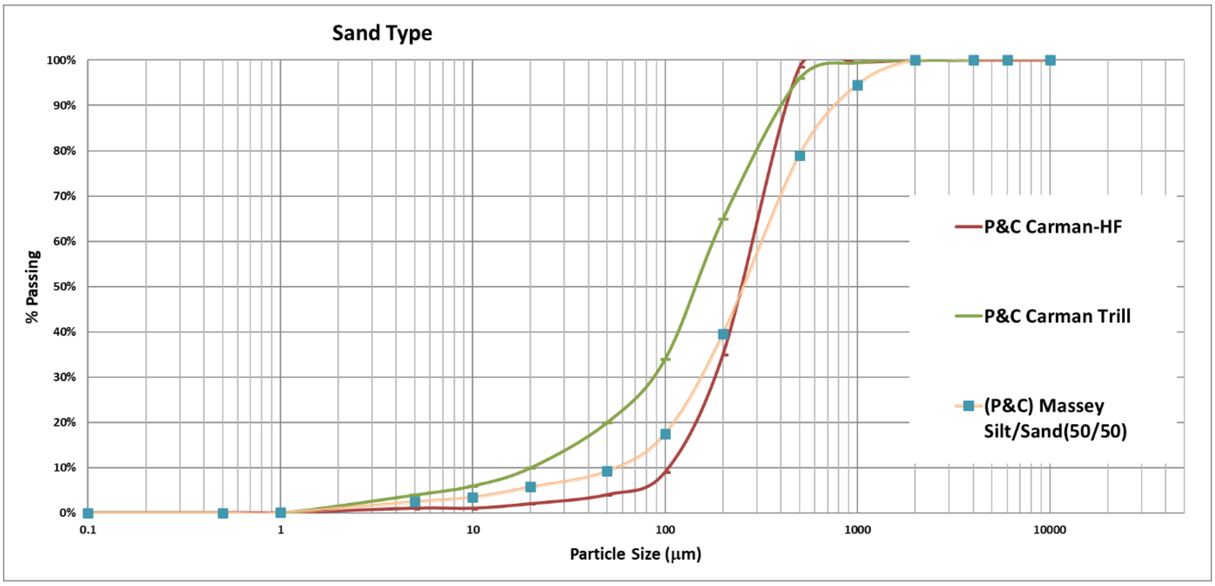


Figure 1 Particle size distribution of Carman-HF, Carman Trill and Massey sand mix (2014 testing by Paterson & Cooke)

The 7-day and 28-day strengths of these 3 mixes are listed in Table 1. Carman Trill sand showed superior strength after 7 days. Massey sand mix gained larger strength at 28 days. The Carman-HF sand mix was the weakest at both 7 days and 28 days. Despite Carman-HF sand having a larger D_{50} compared to Carman Trill, it shows a smaller uniformity factor.

Table 1 Unconfined compressive strength comparison of different sand types

Sand	Binder type	Binder	C_u	D_{50} µm	Unconfined compressive strength		
					7 days	14 days	28 days
Massey sand/silt	90/10	5%	6.4	240	771	–	3,160
Carman Trill	90/10	5%	9	130	1,005	–	2,723
Carman HF	90/10	5%	2.3	235	50	–	710

WSP used 2 different sand sources (Carlyle sand samples S1 and S2) sampled from the same pit (Carlyle pit). These sand samples were mixed with the same type of GWR (GWR Run 2) to produce 2 different sand blends (named WSP 4AAA and WSP 4B). These 2 mixes were both made with 40% sand and 60% GWR. The PSD

[†] The uniformity factor (C_u) is defined as the ratio of particle diameter at 60% passing point (D_{60}) to particle diameter at 10% passing point (D_{10}) (Wang et al. 2023).

graphs of the GWR cyclone ultra fine (UF) were very close to the GWR PSD that P&C used in their mix 12 (but with 50% GWR, 50% sand). The PSD graphs of each mix are illustrated in Figure 2.

As can be seen in Figure 2, P&C mix 12 has a larger D_{50} compared to the other 2 mixes. The uniformity factor corresponding to mixes WSP 4AAA, 4B, and PC 12 are respectively 10.7, 19.4, and 12.4. Mix 4B has a slightly larger D_{50} compared to 4AAA. PC 12 has a significantly larger D_{50} with respect to the other 2 mixes. Table 2 summarises the strength test results of these mixes. The results are also plotted in Figure 3. As can be seen, PC 12 shows higher strength at 7 and 28 days. The reason could be related to Sand Number 2 being coarser than Sand Number 1 (Carlyle sand), however, other factors considered were sand and GWR minerology and grinding methods. No relation can be established here between strength and the coefficient of uniformity.

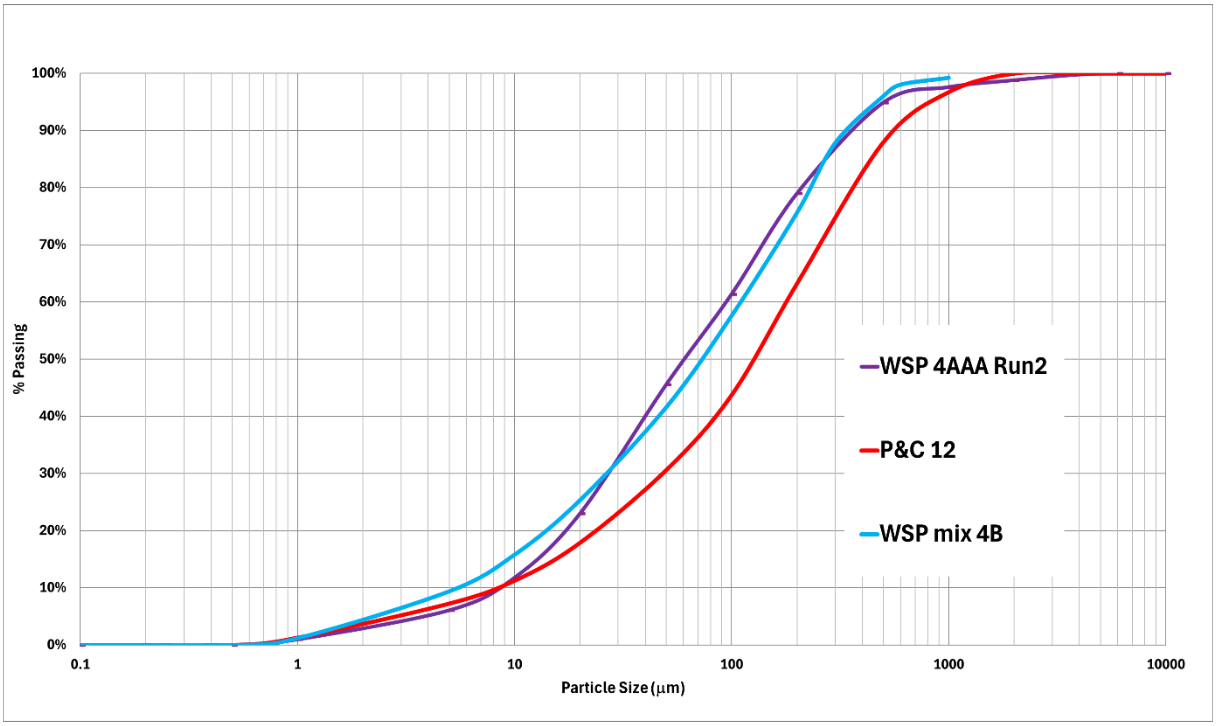


Figure 2 Particle size distribution graphs of mix WSP 4AAA Run2, PC 12 and WSP 4B (P&C refers to the 2014 tests)

Table2 Strength of mixes with different sand particle size distributions

Mix	Binder type	Binder	C_u	D_{50}	Unconfined compressive strength		
					7 days	14 days	28 days
P&C 12 (2014)	90/10	5%	12.4	102	771	–	3,160
WSP 4AAA run2	90/10	5%	10.7	60	127	–	1,651
WSP 4B	90/10	5%	19.4	72	590	1,550	2,082

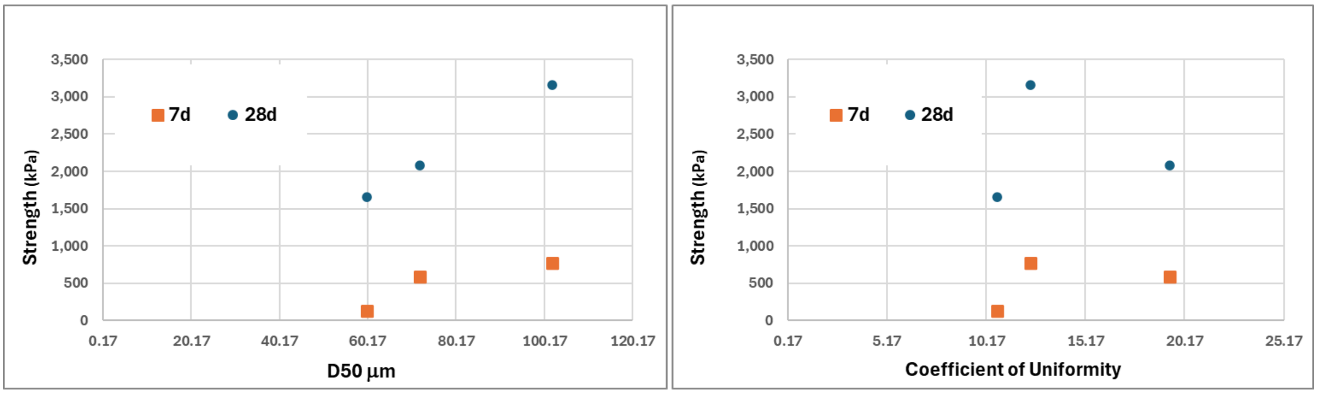


Figure 3 Strength versus D_{50} and uniformity factor

To further understand the reason for the strength difference, the particle size distribution graphs of these 2 sands and the mixed GWR are shown in Figure 4. Sand Number 2 used in mix WSP 4B (with HPGR GWR) has a larger D_{50}, while its uniformity factor ($C_u = 5.4$) is smaller than that of Sand Number 1 (Carlyle Sand $C_u = 12.5$), meaning it is less uniform. Since the PSD graphs of the GWR used in these 2 mixes are close, one can conclude that D_{50} has a more significant influence on the results than uniformity (within the ranges of these tests). Mix P&C 12 has a larger D_{50} and uniformity parameter, and shows significantly higher strength. Another observation here is that the 7-day strength of WSP 4AAA is significantly lower. It could be related to a smaller D_{50} and higher fine content of Sand Number 1 (Carlyle Sand S1).

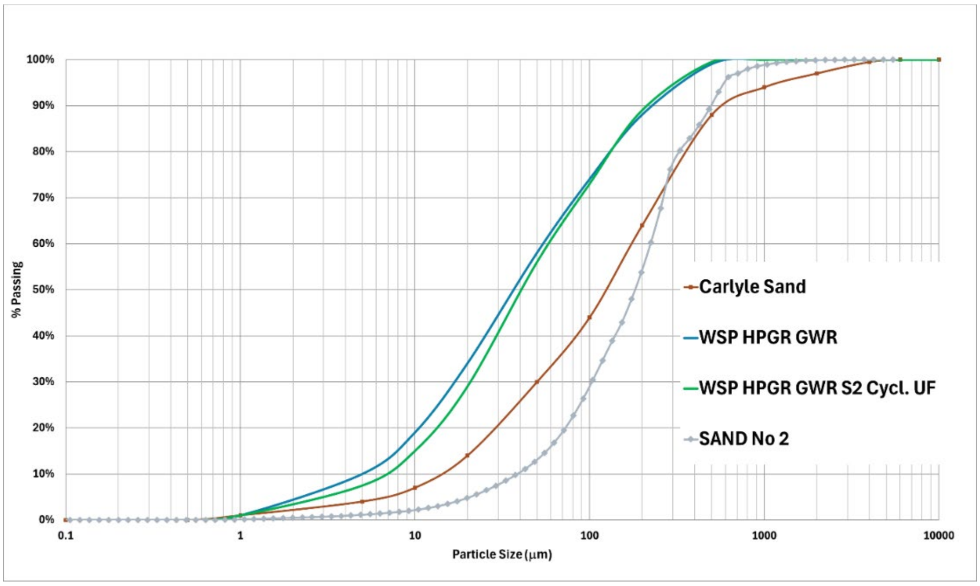


Figure 4 Particle size distribution graphs of Carlyle Sand S1 and S2 and the 2 ground waste rock (GWR) used in the mixes

3.2 Binder ratio

WSP and P&C both conducted a series of tests to find out the optimal binder ratio to reach the target strength. All P&C recipes used pure GWR (HPGR) with no sand or aggregate. Recipes P&C 3, 4, and 5 had 23% passing 20 mm in their GWR material, while P&C 6, 7, and 8 were prepared using GWR with 31% passing 20 mm. WSP 5A and 6A were mixed with 50% sand and 50% GWR material, with GWR containing 30% passing 20 mm, yielding a blend with 27% passing 20 mm. The PSDs of these tests are plotted in Figure 5.

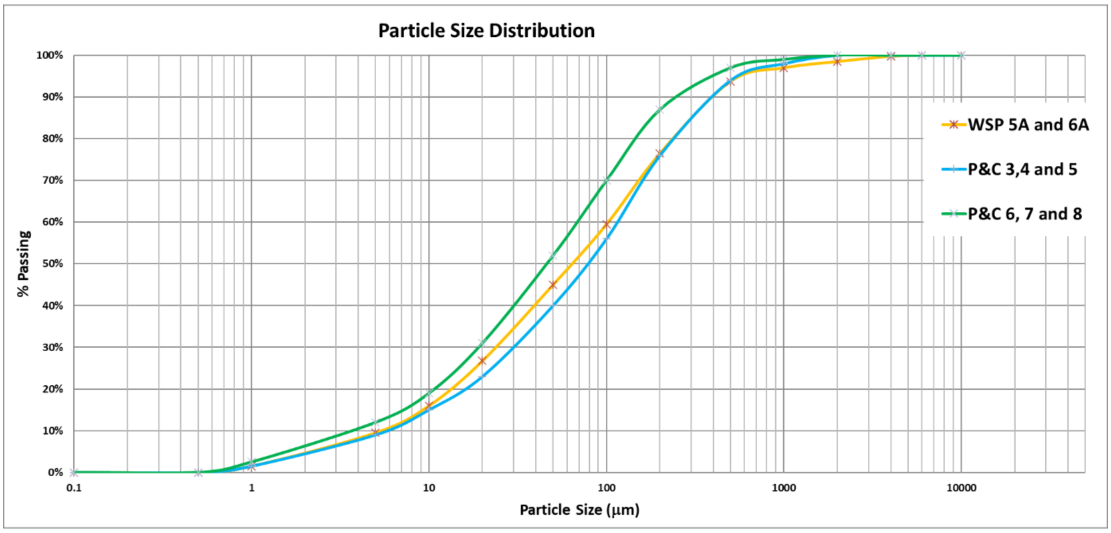


Figure 5 Particle size distribution of WSP and P&C mixes examining the binder ratio (P&C refers to the 2014 testing)

The P&C mixes with 20% passing 20 μm (PC 3, 4, and 5) showed that the binder ratio would have a major impact on the paste strength. The UCS values versus binder ratio are listed in Table 3 and illustrated in Figure 6. Increasing the binder ratio from 3 to 5% increased 7 d and 28 d strength by more than 2 times. Increasing binder from 3 to 7% also improved the strength by 3 times on 28-day strength and more on 7-day.

Table 3 The impact of the binder ratio on the strength of ground waste rock with 20% passing 20 μm

Mix	Binder type	Binder	Unconfined compressive strength		
			7 day	14 day	28 day
P&C 3 (2014)	90/10	3%	693	–	1,214
P&C 4 (2014)	90/10	5%	1,400	–	2,755
P&C 5 (2014)	90/10	7%	2,445	–	3,742

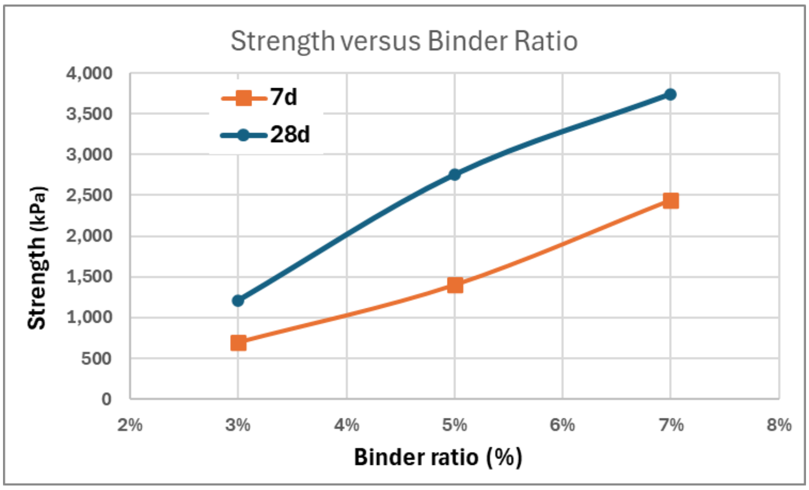


Figure 6 Strength versus binder ratio for P&C mix tests with 20% passing 20 μm (P&C refers to the 2014 testing)

The strength of the mixes with 30% passing 20 μm (PC 6, 7, and 8) also significantly improved as the binder ratio increased, as shown in Table 4. The results are plotted in Figure 7. The improvement in these mix series is more pronounced compared to mixes with less fines. The reason is that the 3% binder ratio has a lower strength compared to P&C mix 3 due to higher fine content. Overall, these mixes have lower strength compared to the recipes with 20% passing 20 μm.

Table 4 The impact of the binder ratio on the strength of ground waste rock with 30% passing 20 μm

Mix	Binder type	Binder	Unconfined compressive strength		
			7 day	14 day	28 day
P&C 6 (2014)	90/10	3%	434	–	876
P&C 7 (2014)	90/10	5%	1,267	–	2,277
P&C 8 (2014)	90/10	7%	1,968	–	2,973

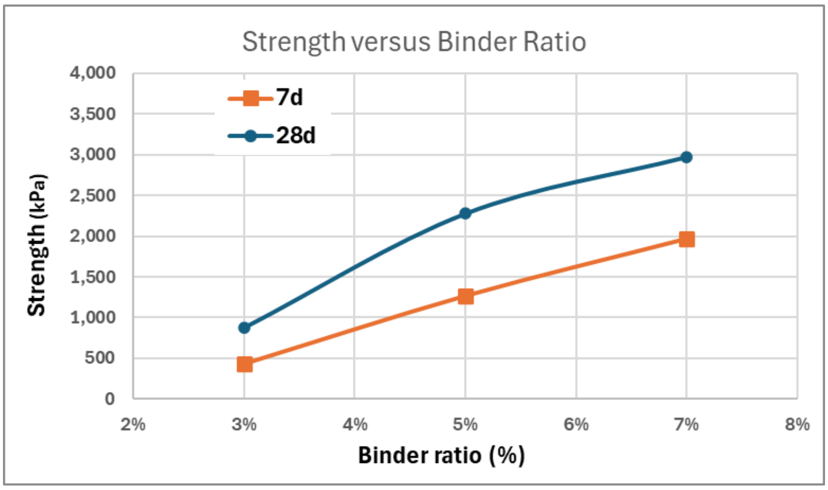


Figure 7 Strength versus binder ratio for P&C mix tests with 30% passing 20 μm (P&C refers to the 2014 testing)

WSP examined the impact of binder ratio on the strength of 2 mixes with 50% sand and 50% GWR. The GWR in these mixes had approximately 30% passing 20 μm. The results of these tests are listed in Table 5 and illustrated in Figure 8. The mix with 3% binder unexpectedly showed very low strength. The mix with 5% binder yields very low 7-day strength. However, it reached 1,210 kPa at 28-day age. A portion of this behaviour could be related to high levels of platy material in the GWR. It could also be related to high levels of fines, which were found to delay strength gain.

Table 5 The impact of the binder ratio on the strength of the recipe with 50% sand and 50% ground waste rock with 30% passing 20 μm

Mix	Binder type	Binder	Unconfined compressive strength		
			7 day	14 day	28 day
WSP 5A	90/10	3%	6	15	137
WSP 6A	90/10	5%	69	–	1,219

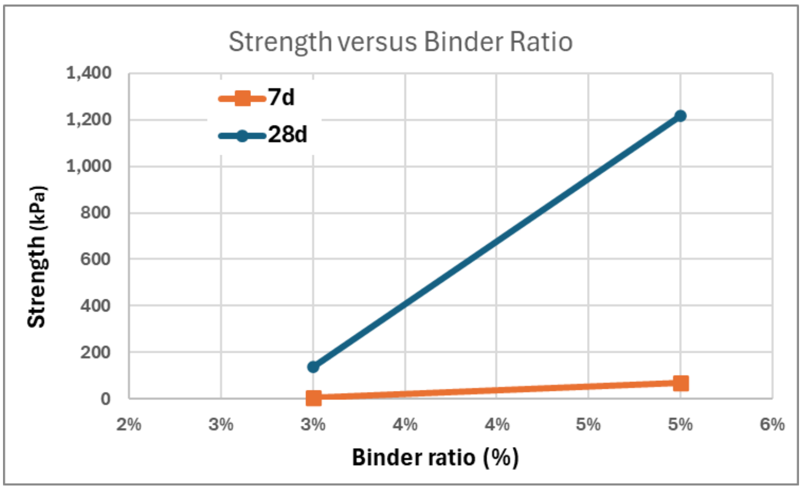


Figure 8 Strength versus binder ratio for WSP mix tests approximately 30% passing 20 mµ

3.3 Fines content

The fines content is believed to have a significant impact on the strength of backfill mixes. Fine-grain materials generally require more cement due to larger surface areas. The larger surface area demands more cement for covering the sand particles and filling voids. To thoroughly examine the impact of the fine content, 2 different GWR materials with different fine contents were tested at different binder ratios in mixes PC 3 to 8. PC 3, 4, and 5 have a D_{50} of 75 µm with 23% passing 20 µm, while PC 6, 7, and 8 have a D_{50} of 44 µm and 31% passing 20 µm.

Test results of PC 3 and 6 indicate that at a 3% binder ratio, reducing fines from 31 to 23% results in approximately 50% strength improvement, as shown in Table 6 and Figure 9. At 5% binder ratio, PC 4 shows higher strength at 7 days and 28 days. However, the strength ratio of the 2 mixes is not as large as that of 3% binder ratio (Table 7). A similar trend was observed for mix PC 5 and PC 8 at a binder ratio of 7% (Table 8 and Figure 9). As illustrated in Figure 9, all mixes generally showed a similar trend in gaining strength over time. The 28-day strength improvement from 3 to 5% binder is much more pronounced compared to the same improvement from 5 to 7% binder overall ranges of fines.

Table 6 The impact of fines at 3% binder ratio with pure ground waste rock

Mix	Binder type	Binder	D_{50}	<20 mm	Unconfined compressive strength		
					7 day	14 day	28 day
P&C 3 (2014)	90/10	3%	75 µm	23%	693	–	1,214
P&C 6 (2014)	90/10	3%	44 µm	31%	434	–	876

Table 7 The impact of fines at 5% binder ratio with pure ground waste rock

Mix	Binder type	Binder	D_{50}	<20 mm	Unconfined compressive strength		
					7 day	14 day	28 day
P&C 4 (2014)	90/10	5%	75 µm	23%	1,400	–	2,755
P&C 7 (2014)	90/10	5%	44 µm	31%	1,267	–	2,277

Table 8 The impact of fines at 5% binder ratio with pure ground waste rock

Mix	Binder type	Binder	D_{50}	<20 mm	Unconfined compressive strength		
					7 day	14 day	28 day
P&C 5 (2014)	90/10	7%	75 µm	23%	2,445	–	3,742
P&C 8 (2014)	90/10	7%	44 µm	31%	1,968	–	2,973

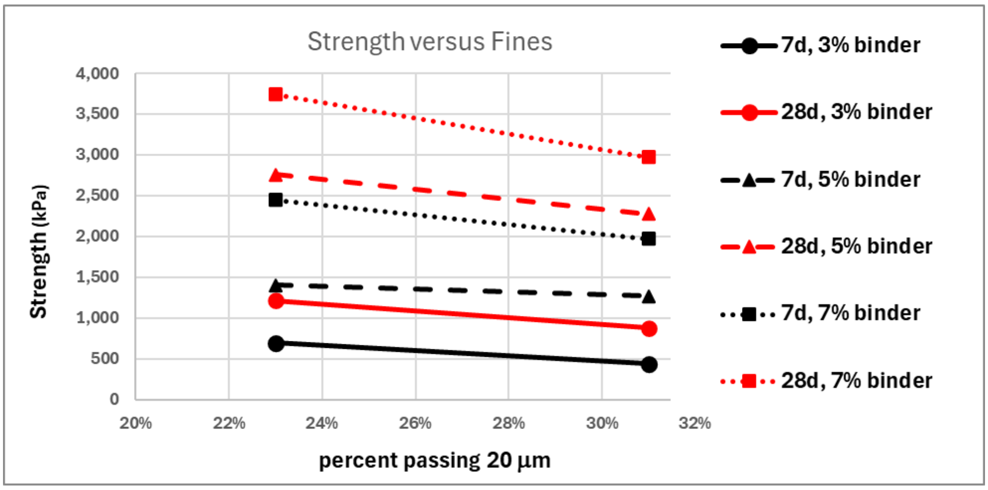
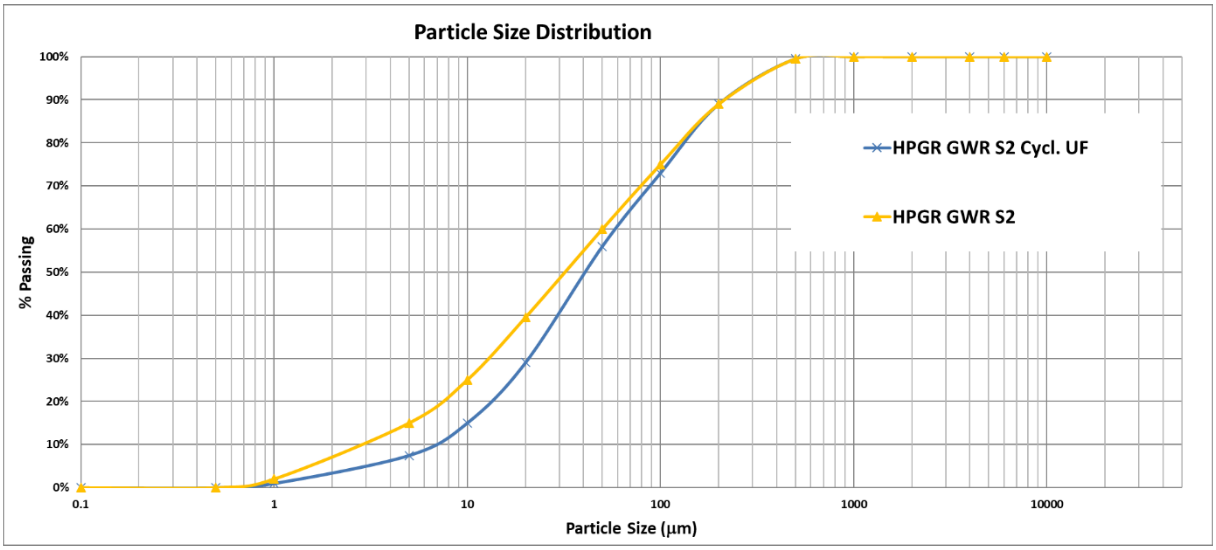


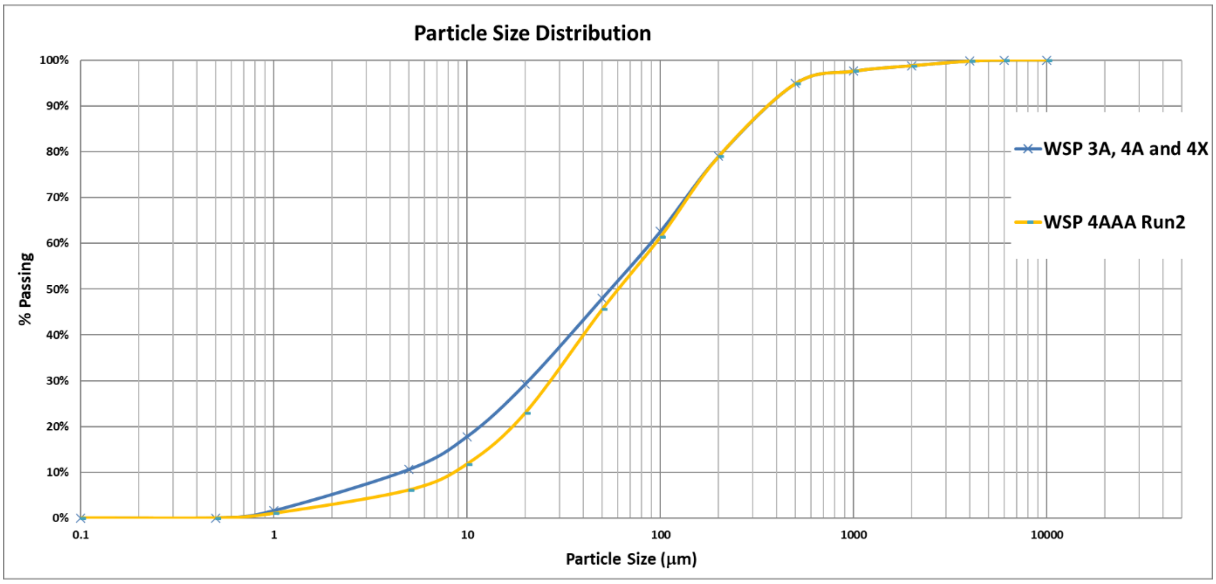
Figure 9 Strength versus fines (per cent passing 20 µm) in P&C mix testing (2014)

In 2 separate mixes, WSP reduced the amount of fines in the GWR by using the hydrocycloning method[‡]. This resulted in an increase in D_{50} from 32 to 42 mm, in addition to reducing the fines content. The process of cycloning removed the fines in the HPGR and brought the fines below 20 µm from 39 to 29%, as shown in Figure 10a. This GWR HPGR material was then blended with the same sand (60% GWR, 40% sand) to produce 2 different blends (WSP 4A and 4AAA Run2). The PSD graphs of the 2 GWR materials and the resulting sand blend are shown in Figure 10. These 2 blends have very close D_{50} values; however, the percent passing 20 µm in WSP 4A is 30%, while that of mix WSP 4AAA falls to 23%. This reduction in fines increased the strength by approximately 50%, as shown in Table 9 and Figure 11. Figure 11 shows that the mixes achieved significant strength over 28 days. The strength gain for WSP 4AAA mix was better due to fines being removed.

[‡] Hydrocyclone separation is a method of separating particles according to their density and particle size in a centrifugal force field (Wang et al. 2024).



(a)



(b)

Figure 10 Particle size distribution of (a) the 2 different ground waste rock materials and (b) the resulting sand blends for mixes WSP 4A and 4AAA

Table 9 The impact of fines at 5% binder ratio with pure ground waste rock

Mix	Binder type	Binder	D_{50}	<20 mm	Unconfined compressive strength		
					7 day	14 day	28 day
WSP 4A	90/10	5%	53 μm	30%	84	–	1,218
WSP 4AAA	90/10	5%	60 μm	23%	127	–	1,651

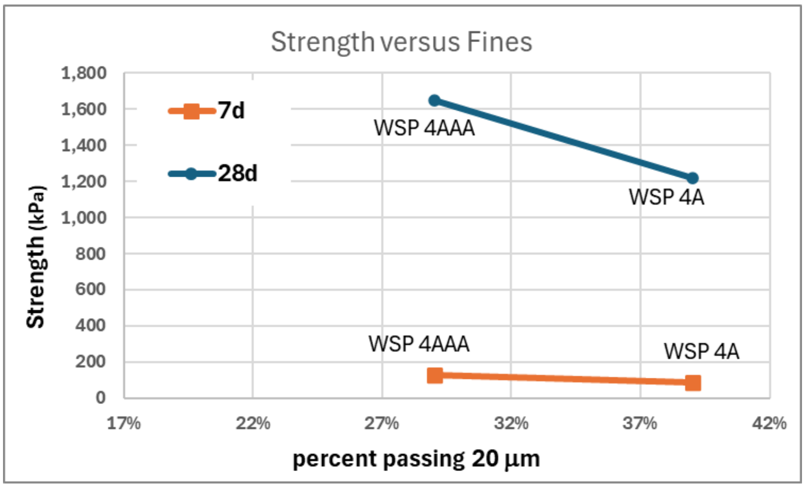


Figure 11 Strength versus fines in WSP mix tests

In a separate mix, the same GWR material that was used in 4AAA was mixed with a new, coarser sand of the same pit (S2) to produce a coarser sand blend (WSP 4B). The PSD graphs of these 2 mixes, along with P&C 12, are plotted in Figure 2. The D_{50} of WSP 4AAA and 4B are respectively 60 and 73 µm as opposed to 120 µm for PC 12. Fines below 20 µm for these 3 recipe mixes are 24, 26 and 18%, as listed in Table 2. Mix WSB 4B has a smaller D_{50} but a lower fines content compared to WSP 4AAA.

Mix WSP 4AAA showed far smaller 7-day strength compared to WSP 4B. The strength difference of these 2 mixes becomes smaller at 28 days. Clearly, the strength of the paste fill increases with the D_{50} parameter. This increase is more pronounced at 7 days. A larger D50 parameter, together with less fines, can significantly improve the paste strength at 7 and 28 days.

4 Conclusion

With a similar D_{50}, the uniformity coefficient was found to significantly influence the strength of paste fill. Well-graded aggregates were shown to have significantly higher strength compared to poorly graded material. In the case of having similarly graded aggregates, D_{50} was found to be a significant parameter affecting paste fill strength, provided that other parameters remain the same.

As expected, a higher binder ratio increases the strength of the paste fill. It was found that at a 3% binder ratio and high fines content will define the strength of the mix. This is due to the larger surface area of the particles. With poorly graded materials with high fines content, the mix can barely gain strength over a 4-week period.

A higher binder ratio can compensate for higher fines content. However, higher fines content can delay the strength gain. Some mixes with higher fines barely gained strength at 7 days. However, they showed significant strength at 28 days. A higher binder ratio can be considered in cases if low-fines aggregates are available.

Within the range of the material used in this study, the work presented in this paper indicates that an optimal range of PSD for an ideal blend can be established to reach maximum paste fill strength. One can conclude that a target sand for Victoria's paste fill program should have a D_{50} value in the range of 175–240 µm and a uniformity factor of 6.4 and less than 285% fines (below 20 µm) to maximise the strength. The acceptable HPGR GWR range of PSD should have a D_{50} of 50–100 µm, with fines of between 20 and 30% and a uniformity factor of 9–10. A mix of this target sand with the acceptable HPGR GWR blend would provide an optimal mix for Victoria mine's paste fill. This will help create a paste fill management plan for efficient and economical operation of the paste fill plant.

The test work accomplished in this program established a functional range of PSD for the Victoria backfill program. Future work will focus on variable GWR from various pits around the Carlyle pit modulating the various binder contents to establish operating parameters.

5 Future work

At the time of writing, a new sand with a larger D_{50} is being used to study the potential improvement in UCS. The HPGR GWR of round 1 and round 2 of the tests indicated various mineralogies. The impact of the minerals (especially platy minerals) on the strength of the mixes is also being studied. The influence of both 90/10 and GUL binders is also being examined. The D_{50} of HPGR GWR was also increased for future testing. Additionally, a set of GWR was produced using a traditional ball mill. GUL and 90/10 binders are both used to compare their impact on strength gain. The results will be published in a separate paper.

Acknowledgement

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