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White paper: Portland-limestone cements in paste backfill – performance limits and hidden environmental costs

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Abstract

Portland-limestone cements (PLC) are increasingly promoted as a sustainable option in cement production, where partial clinker replacement reduces CO_2 emissions. While effective in concrete, this assumption has been transferred uncritically to cemented paste backfill (CPB). In CPB systems, which are dominated by ultra-fine tailings and a relatively small binder fraction, the mechanisms that make limestone beneficial in concrete are largely absent. Instead, limestone additions can negatively impact water demand and strength development.

This paper re-assesses the role of PLC in CPB by reviewing underlying mechanisms, published performance data, and environmental implications. Evidence indicates that limestone substitution often leads to reduced mechanical strength, higher binder requirements, and increased susceptibility to chemical deterioration, ultimately undermining sustainability claims.

The paper argues that use of PLC in CPB represents misplaced sustainability and highlights alternative binders, particularly through the use of locally available supplementary cementitious materials, that offer more credible economic and environmental benefits for mine backfilling.

Keywords: *Portland-limestone cement, limestone, cemented paste backfill, backfill, ultra-fine tailings, sustainability, supplementary cementitious materials*

1 Introduction

Studies in South Africa have noted that slag production has decreased with the closure of major steel plants, while the availability of quality fly ash is expected to fall as energy generation shifts away from coal. As limestone is abundant and locally quarried, Portland-limestone cement (PLC) has become the most common clinker replacement across the African continent (Leo 2022; Lowitt 2020). The scarcity of traditional supplementary cementitious materials (SCMs) is not unique to Africa however, as Romaniuk (2024) describes the global decline in fly ash and slag production as an emerging limitation for paste backfill operations. Tennis et al. (2024) note that while PLC has been permitted in standards for more than a decade, its widespread adoption accelerated markedly after 2021, driven by declining availability of fly ash, slag and supply constraints on ordinary Portland cement (OPC); resulting in PLC becoming the default general-purpose cement in several markets.

In concrete applications, the benefits of limestone replacement of cement (typically <15%) are mainly physical in nature and are realised through improved particle packing (i.e. the 'fine filler effect') and provision of nucleation points for hydration products (Tennis et al. 2024).

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However, in cemented paste backfill (CPB), the particle system is already dominated by ultra-fine tailings particles, while the binder† fraction constitutes only a small percentage of the total mix. Thus, the conventional mechanisms by which PLC can enhance concrete are not applicable in CPB. With the drive for sustainability in the cement industry, PLC has been promoted uncritically onto the backfill industry without due diligence in determining whether the performance enhancements are transferrable, and importantly, if there are in fact environmental benefits.

This paper re-assesses the role of PLC in CPB by reviewing underlying mechanisms, published performance data and test work to evaluate the environmental implications.

2 Literature review

2.1 Limestone in concrete

Tennis et al. (2024), in the Portland Cement Association State-of-the-art Report on PLC, describe the beneficial mechanisms of limestone addition in conventional concrete as primarily physical, with limited chemical contributions. Finely ground limestone particles improve packing density by filling voids between cement grains (the 'filler effect'), thereby reducing porosity and enhancing early-age strength. These particles also act as nucleation sites for the precipitation of hydration products, accelerating early hydration of alite and aluminate phases.

Chemically, limestone can partially react with tricalcium aluminate (C_3A) to form carboaluminate phases, which contribute modestly to microstructural refinement. Together, these effects enhance early strength and workability when the limestone replacement remains below 15% of the cement mass.

2.2 Limestone in cemented paste backfill

CPB contains a high proportion of ultra-fine particles. Most CPB have at least 20% of particles passing 20 µm, with up to 80% passing 20 µm seen in the industry (Salvoldi & Gerhardi 2025), implying that in certain instances the tailings fraction is finer than the cement addition to the backfill (i.e. the cement represents the coarse fraction in the mix in some CPB applications).

At these particle size distributions, the addition of limestone as a fine filler provides no physical benefit and the abundance of fine tailings already provides sufficient surfaces for hydration product nucleation. Instead, the addition increases the fine fraction and substitution of OPC raises the water:binder (W:B) ratio.

Few studies have directly examined OPC replacement with limestone in CPB. Nevertheless, the cement industry has increasingly promoted PLC for environmental reasons, largely extrapolating from their known benefits in concrete. However, as far as the authors are aware, no first-principles reassessment has been undertaken to verify whether these mechanisms are relevant in CPB systems. While strength reductions can be mitigated by increasing binder content, this approach contradicts the intended sustainability objectives, as higher cement consumption offsets any theoretical carbon savings.

Existing studies consistently indicate reduced mechanical performance and potential durability concerns when limestone is incorporated into CPB. The key findings are:

- Strength reduction and higher binder demand: literature shows that PLC produces lower unconfined compressive strength (UCS) values in CPB compared to OPC at the same binder dosage. To achieve equivalent strength, more binder is required, offsetting any theoretical carbon savings.

† Note that cement and binder are used interchangeably. In backfill, the term binder is more commonly used. Cement usually refers to ordinary Portland cement, while binder refers to all cementitious materials in a mix including supplementary cementitious materials.

- Durability risks: in certain mines, limestone cements exhibit reduced resistance to sulphate attack and acid generation.

Hu et al. (2019) showed that in CPB with lead–zinc tailings containing up to 20% limestone (LS) replacement, early-age UCS was markedly reduced. At later ages, strength partially recovered but remained below the control OPC mix.

Chang et al. (2022) tested ground granulated blast furnace slag (GGBS) and 'lime' in their experiment, with some mixes using flue gas de-sulphurised gypsum and limestone on lead–zinc tailings. The limestone addition was kept modest at maximum 5% but did not outperform the equivalent pure OPC. It should be noted that it is unclear in the paper whether the 'lime' is quicklime, or calcium hydroxide.

Sagade (2023) showed that in CPB composed of silica tailings (99.8% quartz), utilising ternary binders (OPC, GGBS, LS), only limestone additions less than 10% didn't show significant strength loss. Higher limestone contents depress UCS at all ages and could not be counteracted by SCM.

Ouffa et al. (2025) studied ternary and quaternary binders (general purpose cement, LS, metakaolin and GGBS) blends on gold tailings and observed that limestone consistently reduced the UCS. Furthermore, even in quaternary blends he recommended to limit limestone to 5% confirming any increase in this impacted strength in CPB.

Benzaazoua et al. (1999) documented sulphate attack in CPB of polymetallic (Cu–Zn–Au–Ag) tailings containing calcium hydrates and carbonates. The addition of limestone (calcium carbonate) is expected to exacerbate any sulphate driven degradation, and the use of PLC may lead to significant long-term strength loss. This impact should be thoroughly investigated before switching cement types.

Zheng et al. (2016) also reported lower strengths with limestone-modified binders on copper tailings, though the comparison was affected by uncontrolled variations in the W:B ratio as the slump was the primary comparison target for addition of admixtures.

The literature review consistently indicates reduced mechanical performance and potential long-term durability risks compared with OPC across a range of tailings types. This trend supports the proposition that the underlying mechanism is primarily physical rather than chemical, as previously described for concrete systems. However, few controlled studies have systematically compared limestone and OPC-based CPB under identical conditions. To address this gap, laboratory test work was conducted as part of this study to evaluate the mechanical and microstructural implications of limestone addition in CPB.

3 Test work

Test work was conducted at the Paterson & Cooke laboratories located in Cape Town, South Africa, as part of paste backfill design and execution projects for a copper, as well as platinum tailings CPB. The following test data will be presented:

- solids density
- maximum solids packing concentration
- particle size distribution (PSD)
- mineralogy
- cement quality (ISObar)
- rheology test work
- UCS test work.

3.1 Solids density and bed packing concentration

The solids density of the tailings was determined using a helium gas pycnometer (ASTM D5550-14; ASTM International 2014), which measures the skeletal solids density. The measured solids densities are shown in Table 1.

The bed packing concentrations by volume are also presented in Table 1. The settled bed packing is measured using the Paterson & Cooke standard test method, a pragmatic method developed and applied extensively for slurry and backfill materials characterisation. A schematic of the test is shown in Figure 1. The freely settled bed packing concentration is measured by allowing a slurry sample to settle for 24 hours in a measuring flask and measuring the settled bed volume. The maximum settled bed is then measured by applying a hydraulic pressure of 400 kPa across the settled bed with the water allowed to drain through the solids bed.

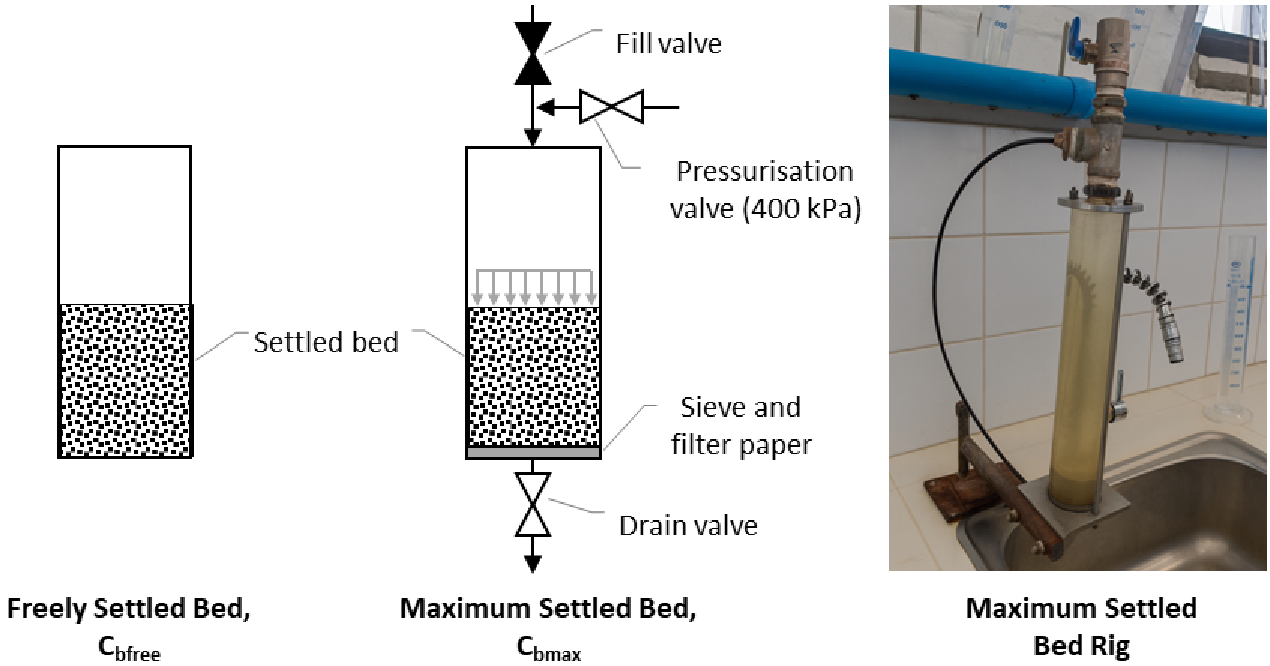

Figure 1 Paterson & Cooke bed packing test schematic

These values provide information on how well the material packs and are a good metric to estimate the nominal and maximum mass concentration that can be achieved by thickening, as well as the backfill mass concentration ranges that will be targeted.

Table 1 Tailings solids densities and particle packing

Sample measured	Solids density	Freely settled bed packing concentration	Maximum bed packing concentration
Copper tailings	2,660 kg/m³	37%v	58%v
Platinum tailings	3,730 kg/m³	42%v	53%v

3.2 Particle size distribution

The material’s PSD was determined through a combination of wet sieving to 25 µm and laser diffraction particle size measurement. A comparison of the PSDs for the tailings is shown in Figure 2.

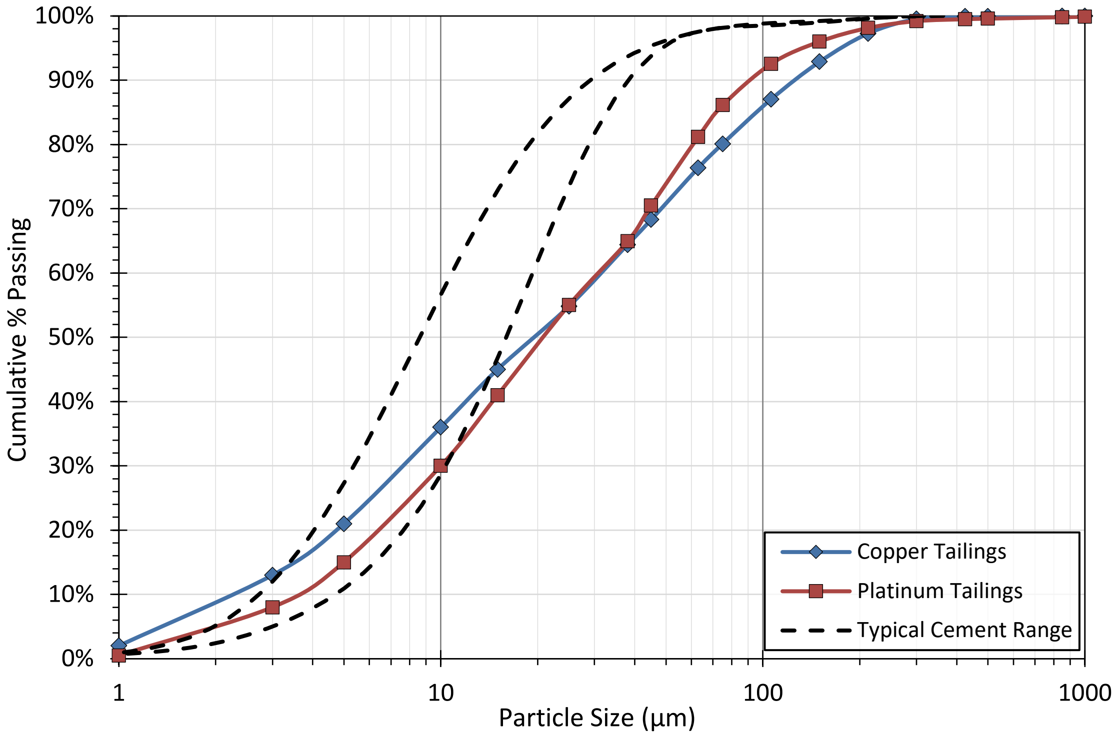

Figure 2 Particle size distribution comparison

3.3 Cement quality

The cement mortar (ISO bar) tests confirm the strength of the cement after a fixed curing time. The cement quality tests are based on EN 196-1:2016 edition 2 (European Committee for Standardization 2016), in which samples are prepared with a mix using 3 parts neutral silica sand, one part cement and mixed with a half part water to obtain a water:cement ratio of 0.5.

Table 2 presents the compressive strength results for the tested cement types. Some cement types did not achieve a strength designation, with the lowest one being 32.5 MPa at 28 days. These cements are specifically made for backfill purposes and are not intended for general use. Note that the acronyms used for the cement type are taken from Fulton's Concrete Technology (Owens 2009).

Table 2 Cement quality test results

Cement Type	Tailings	Description	Strength designation	2 days (MPa)	7 days (MPa)	28 days (MPa)
CEM I	Cu	ordinary Portland cement (OPC)	42.5 N	13.5	30.9	40.9
CEM I	Pt	ordinary Portland cement (OPC)	52.5 N	22.1	45.1	52.6
CEM II A-V	Cu	Portland-fly ash cement (PFC) (15%)	42.5 N	14.4	32.1	42.4
CEM II B-V	Pt	PFC (30%)	42.5 N	12.8	27.7	41.9
CEM II A-L	Cu, Pt	Portland-limestone cement (PLC)	42.5R	27.8	45.6	48.8
CEM II B-Q	Cu, Pt	Portland-pozzolana cement (PPC)	32.5 N	8.6	19.5	36.5
CEM III A	Cu	Blast furnace cement (BFC)	NA	4.4	11.2	26.2
CEM V B-SV	Cu	Composite cement (CMC)	NA	3.1	9.8	26.5

3.4 Mineralogy

Mineralogy of the tailings samples was determined using X-ray diffraction. The mineralogy of the tailings samples is presented in Table 3. For clarity and comparison purposes, similar minerals have been grouped and smaller percentages are not shown.

Table 3 Mineralogy comparison

Sample	Copper tailings (%)	Platinum tailings (%)
Quartz	40	–
Calcite	26	–
Feldspars	7	12
Chlorite	15	–
Phyllosilicates	12	10
Chromite	–	33
Pyroxenes	–	30
Clay Minerals	–	10
Amphibole	–	4
Other	–	1

3.5 Cemented rheology

The rheology of both tailings samples was measured using a rotational viscometer using the bob and infinite cup method. The measured data was corrected for end effect, as well as secondary and undeveloped flow for shear rates between 5 and 300 1/s. The data was analysed by applying the Bingham plastic model for both the viscosity and yield stress measurements.

The tests were completed at a nominal cement concentration of 5% binder to provide insight into the design ranges that were used for the UCS test work. A comparative rheology measurement was also completed on the CPB during the UCS test campaign for reference.

The yield stress and viscosity curves for the tailings are shown in Figure 3. For comparison purposes, only the curves that correspond to the 5% binder addition are provided and the extensive rheology dataset is outside the scope of this paper.

The addition of binder to a tailings sample can provide a substantial increase in rheological parameters (i.e. uncemented versus cemented). This is primarily dominated by the change in pH of the matrix. Once the water becomes supersaturated with calcium and other alkali ions, the pH of the system stabilises. Subsequent changes in rheology, aside from time dependent effects are generally dominated by modifications in PSD as the binder content increases.

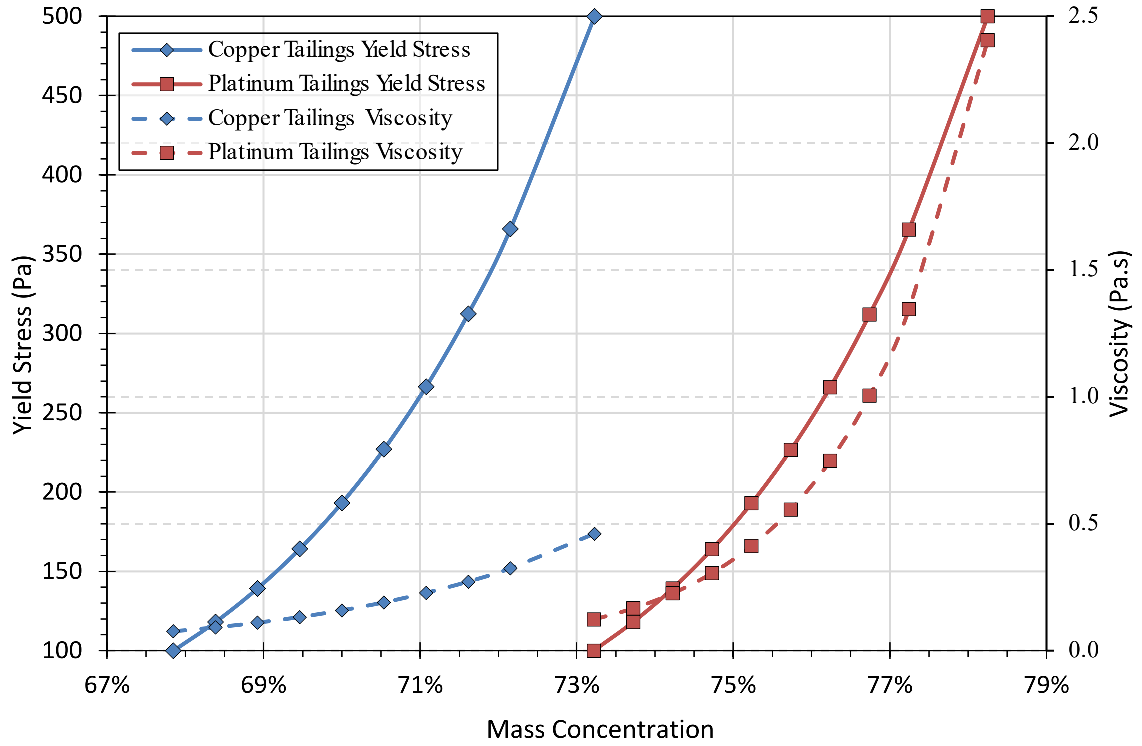

Figure 3 Yield stress versus mass concentration comparison

Note that the markers on the graph are shown for clarity only and don't represent data points. The curves plotted are the correlation curves obtained from the measured data.

3.6 Strength tests

The UCS tests were conducted in accordance with ASTM D4832-02 (ASTM International 2010), the standard test method for preparing and testing of controlled low strength material test cylinders. Following the standard, compressive strengths were completed at 7, 14 and 28 days.

Figures 4 to 11 show the 7, 14, 28 and 56-day strength results for the copper and platinum tailings respectively. These curing periods are particularly relevant for plug pours and assessing the strength of the cured paste within typical mine sequencing timeframe used in vertical stope mining methods.

For the platinum tailings, OPC tests were performed only for preliminary screening, as OPC is no longer readily available and Portland-fly ash cement (PFC) is used operationally due to its local availability near the mine site. No 14-day tests were conducted on OPC, therefore the hatched values in Figure 8 are only shown for reference and are interpolated values.

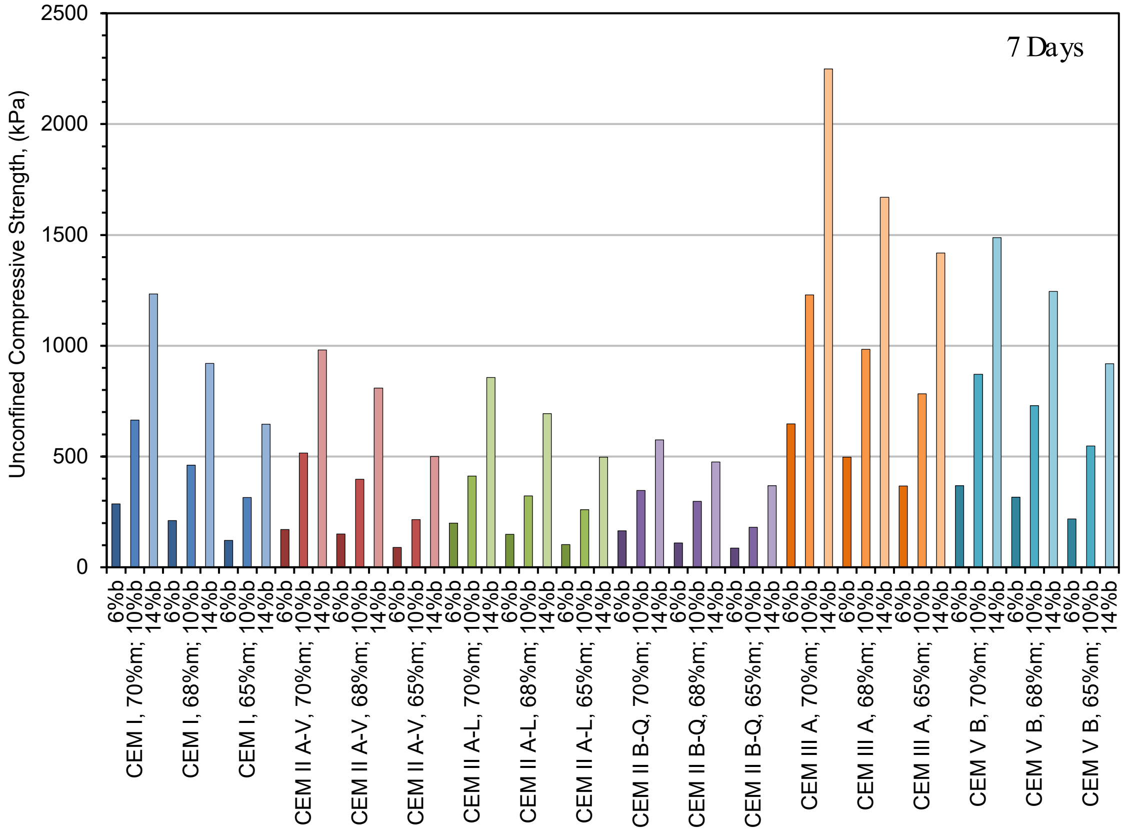

Figure 4 7-day unconfined compressive strength results for copper tailings

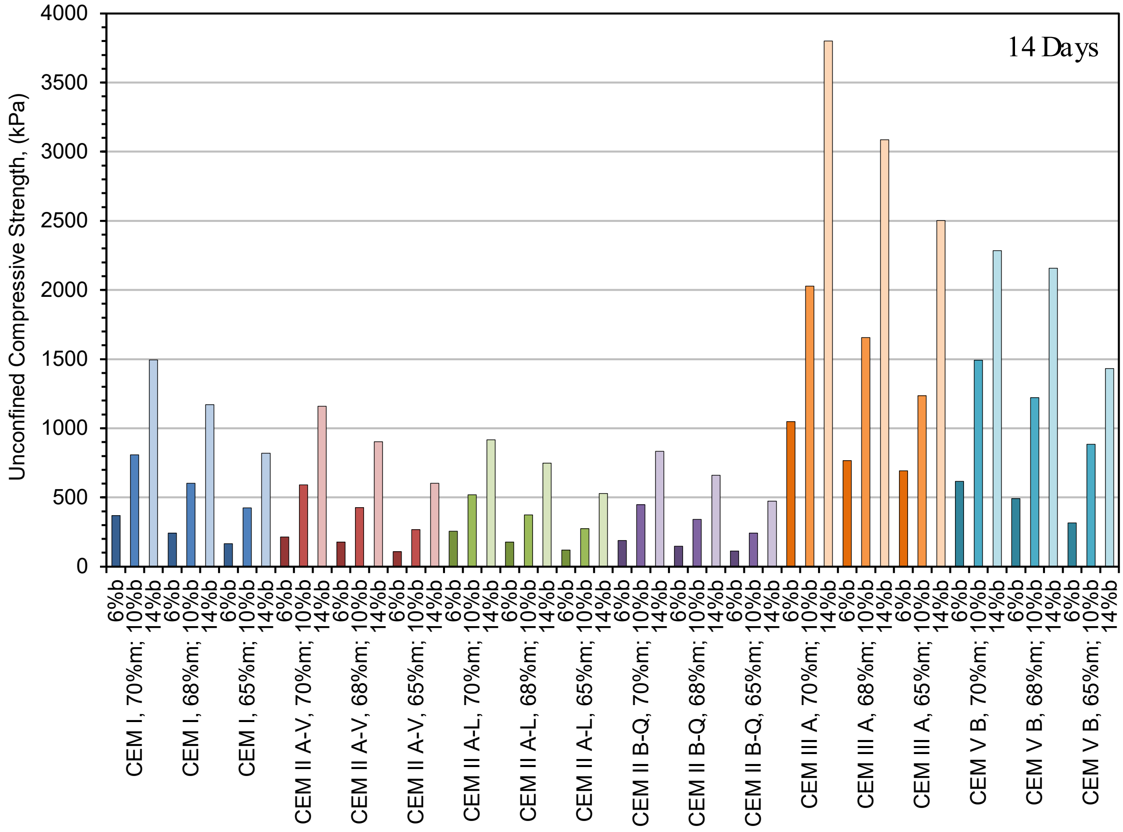

Figure 5 14-day unconfined compressive strength results for copper tailings

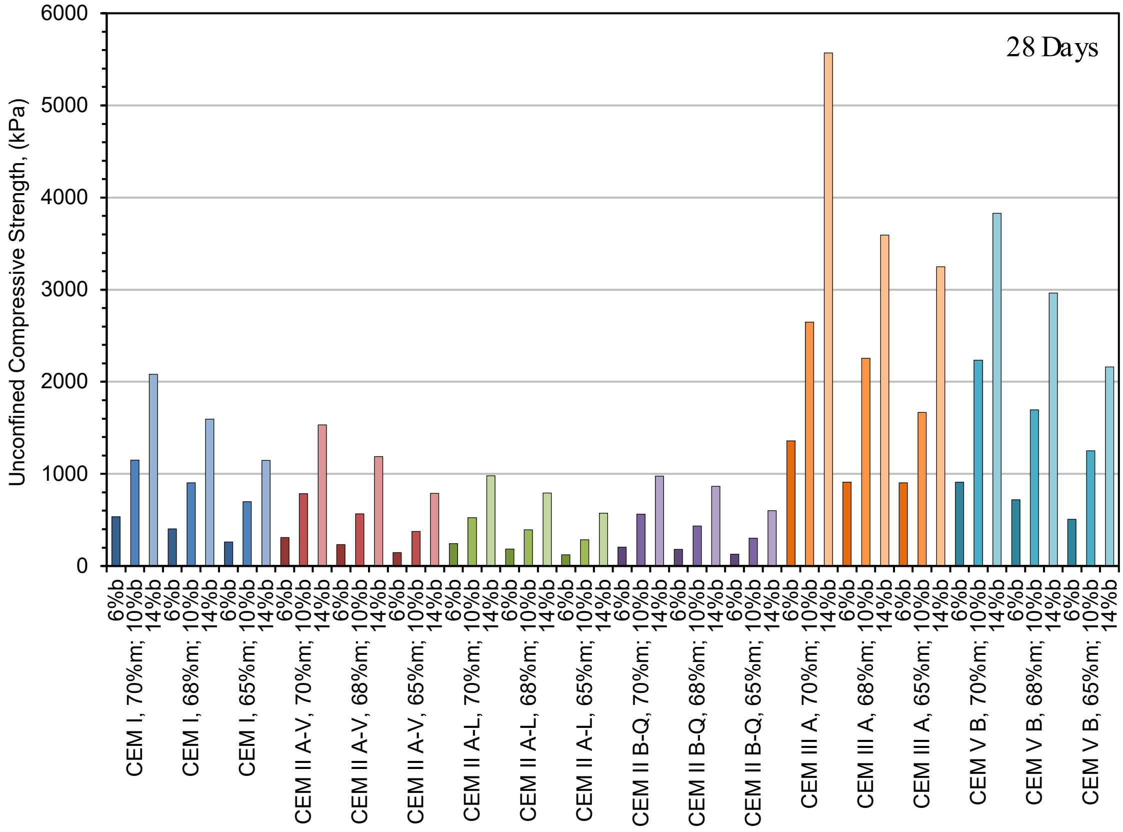

Figure 6 28-day unconfined compressive strength results for copper tailings

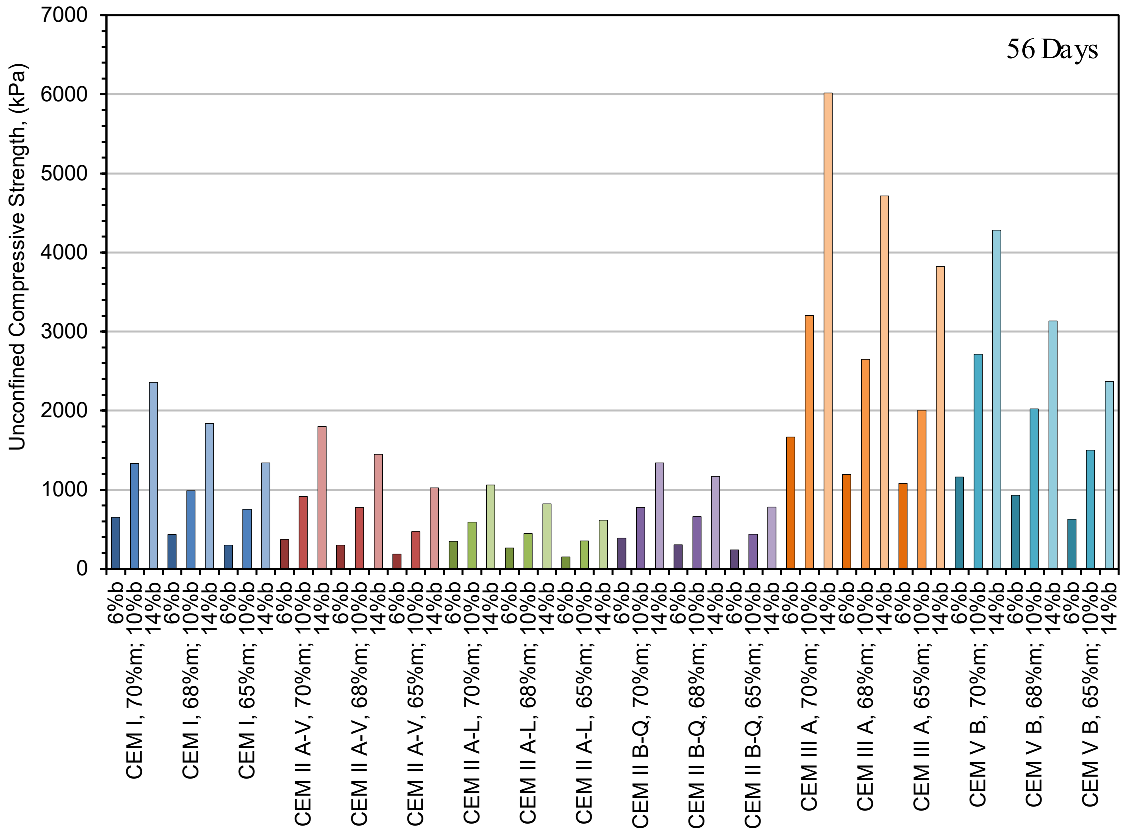

Figure 7 56-day unconfined compressive strength results for copper tailings

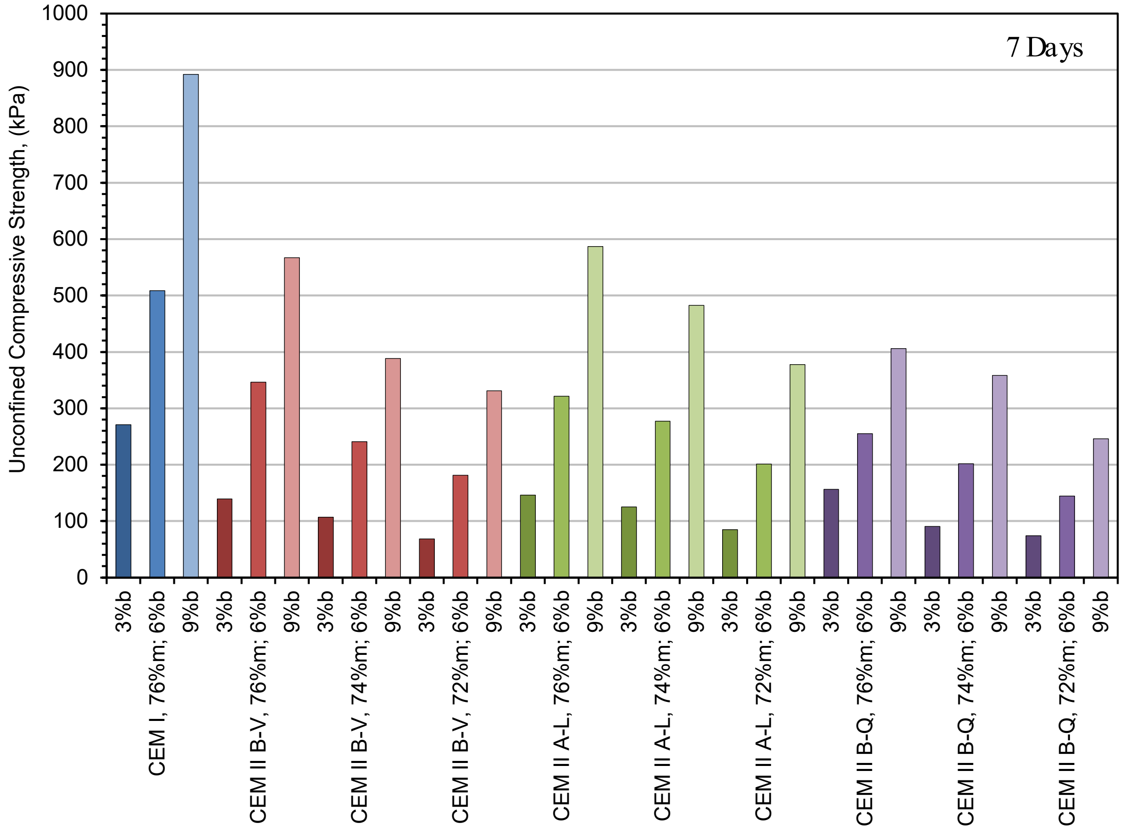

Figure 8 **7-day unconfined compressive strength results for platinum tailings**

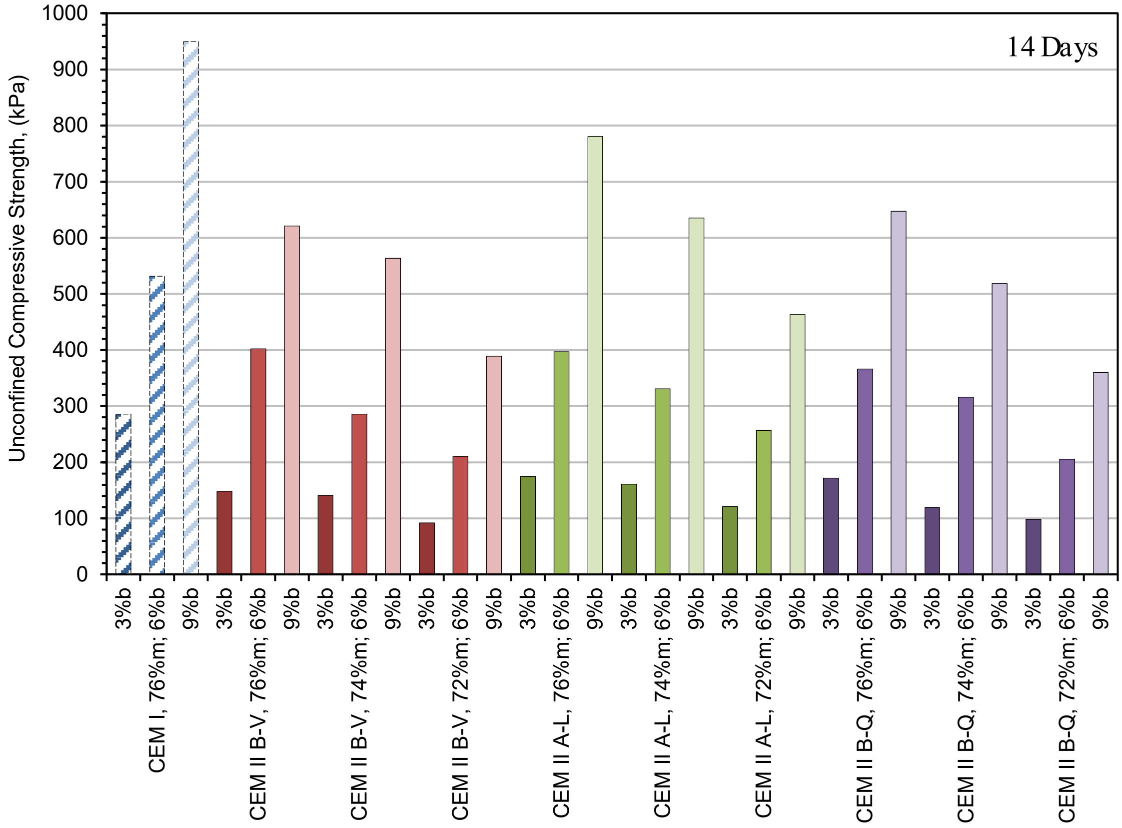

Figure 9 **14-day unconfined compressive strength results for platinum tailings**

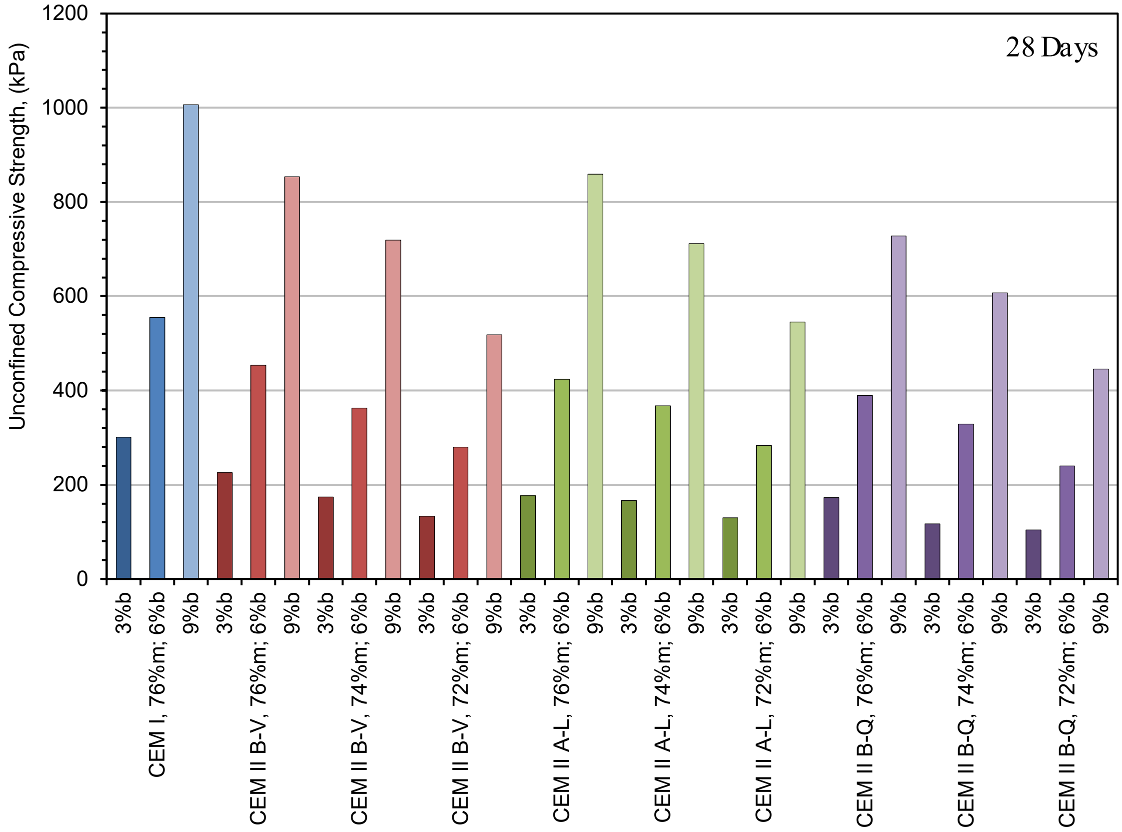

Figure 10 28-day unconfined compressive strength results for platinum tailings

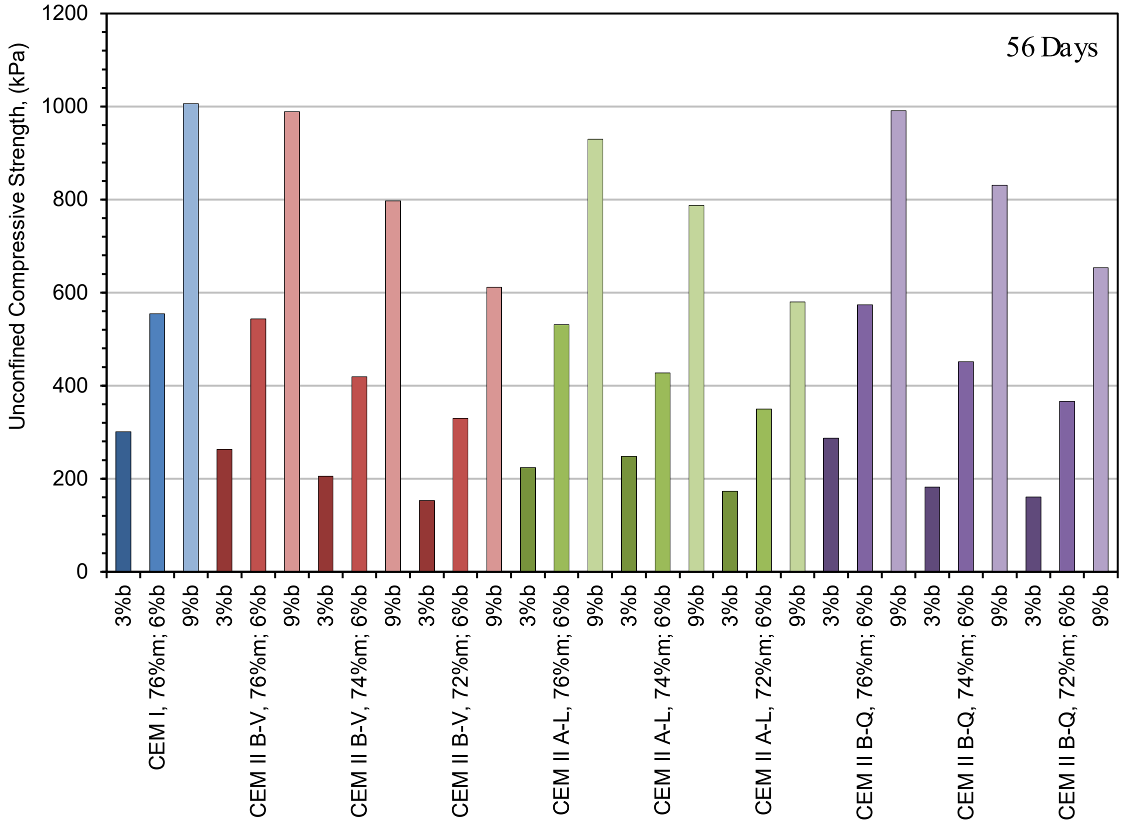

Figure 11 56-day unconfined compressive strength results for platinum tailings

4 Discussion

4.1 Strength reduction for limestone cement

Table 4 shows the OPC and PLC results along with the corresponding percentage reduction in strength for the copper tailings. The data indicate a clear strength reduction for the limestone cement across all ages compared to the OPC.

At 28 days the average strength penalty is about 50% for a 15% clinker replacement, which is larger than expected. This points to an additional physical mechanism, likely a packing and stiffness effect caused by substituting angular, denser tailings with lower density, softer calcium carbonate.

Table 4 Copper tailings unconfined compressive strength comparison

Mix	7-day strength (kPa)			14-day strength (kPa)			28-day strength (kPa)		
	OPC	PLC	%	OPC	PLC	%	OPC	PLC	%
70 %m; 6 %b	286	200	−30	368	255	−31	535	245	−54
70 %m; 10 %b	664	411	−38	808	520	−36	1,151	526	−54
70 %m; 14 %b	1,234	857	−31	1,495	917	−39	2,080	980	−53
68 %m; 6 %b	211	149	−29	241	178	−26	403	185	−54
68 %m; 10 %b	462	322	−30	602	374	−38	902	392	−57
68 %m; 14 %b	920	694	−25	1,171	749	−36	1,595	794	−50
65 %m; 6 %b	122	103	−16	165	119	−28	260	123	−53
65 %m; 10 %b	314	260	−17	426	275	−35	698	285	−59
65 %m; 14 %b	645	497	−23	820	528	−36	1,148	574	−50

Table 5 shows the PFC and PLC results along with the corresponding percentage reduction (negative) or percentage increase (positive) in strength for the platinum tailings. The results show that a PFC with a 30% cement replacement performs worse than PLC with a 15% cement replacement at early ages, but perform similarly at 28 days. 56-day results show that post 28-days PFC keeps improving due to the pozzolanic activity.

Table 5 Platinum tailings unconfined compressive strength comparison

Mix	7-day strength (kPa)			14-day strength (kPa)			28-day strength (kPa)		
	PFC	PLC	%	PFC	PLC	%	PFC	PLC	%
76 %m; 3 %b	139	146	5	149	175	17	226	177	−22
76 %m; 6 %b	346	321	−7	402	397	−1	454	424	−7
76 %m; 9 %b	567	587	3	621	781	26	854	859	1
74 %m; 3 %b	107	125	17	141	161	14	174	167	−4
74 %m; 6 %b	241	277	15	286	331	16	363	368	1
74 %m; 9 %b	389	482	24	564	635	13	719	712	−1
72 %m; 3 %b	69	85	24	92	121	32	133	130	−2
72 %m; 6 %b	181	201	11	211	257	22	280	283	1
72 %m; 9 %b	331	378	14	389	463	19	518	545	5

4.2 Additional binder requirement

Cement is a hydraulic binder that reacts with water and it is well understood in the concrete industry that the W:B ratio is the main metric that determines strength (Grieve 2009). This has been validated to be applicable to paste backfill as well (Treinen et al. 2010; Wilson & Leacy 2023).

The W:B ratio is a superior metric for control and design as it is unaffected by the mass concentration of the paste. While binder content (the ratio of dry binder mass to total dry material) is commonly used, the W:B ratio provides a more consistent basis for evaluation across different materials.

Figures 12 and 13 show the UCS strength curves for the 28-day results that were used to calculate the equivalent mix design and binder content required for the UCS versus binder curves.

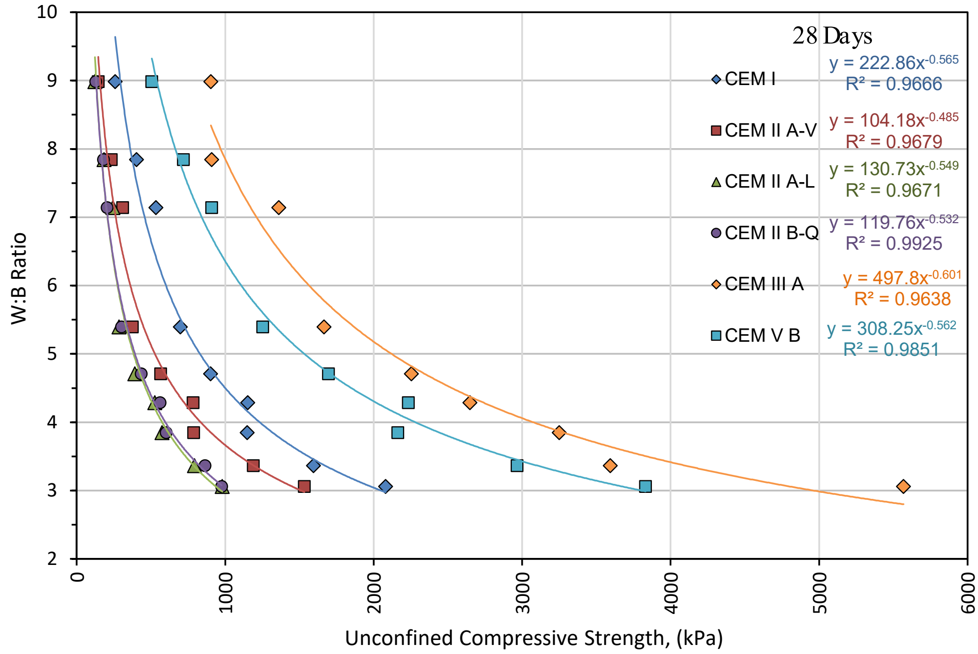

Figure 12 Copper tailings – unconfined compressive strength versus water to binder ratio curves

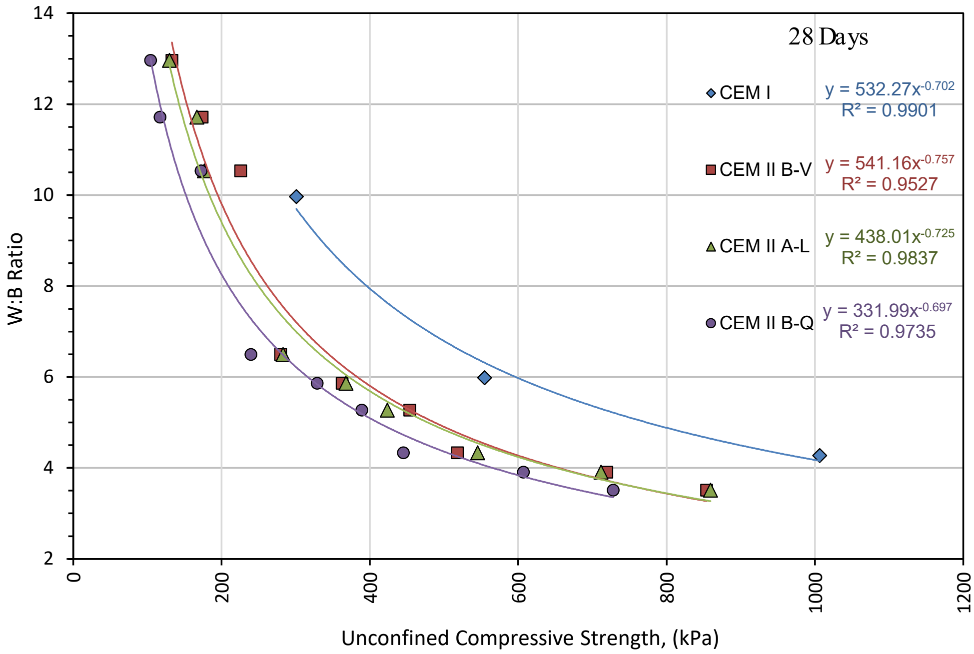

Figure 13 Platinum tailings – unconfined compressive strength versus water to binder ratio curves

Figures 14 and 15 show the mass of binder required per m³ of backfill to achieve the required strength for the yield stress range indicated for the respective tailings tested.

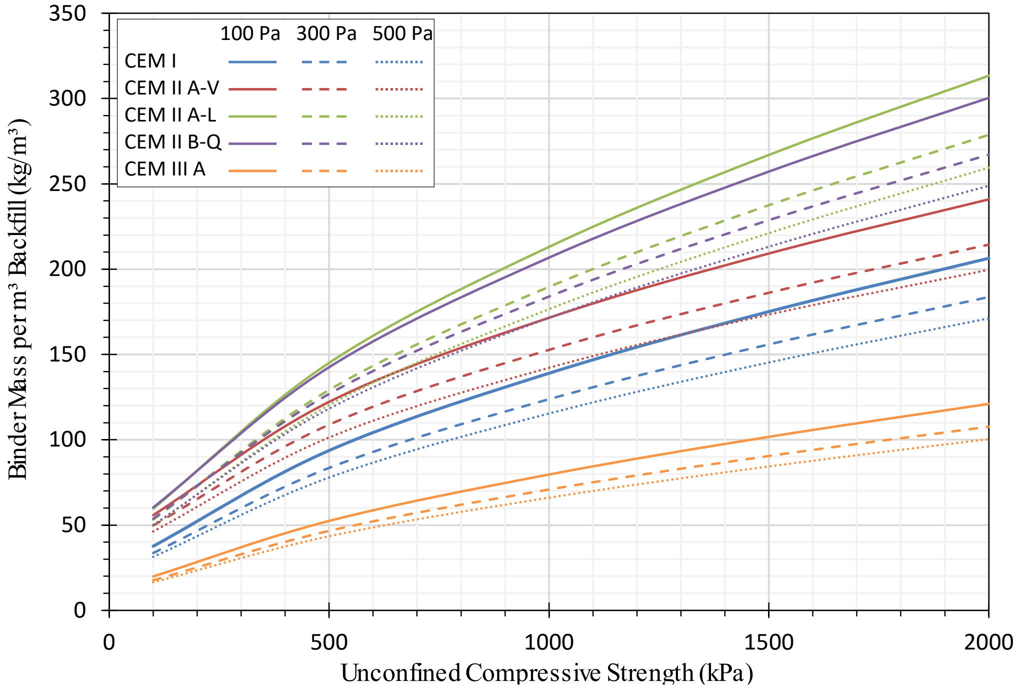

Figure 14 Copper tailings – binder mass required per m³ of cemented paste backfill for the yield stress indicated

Figure 14 shows that the lowest binder content required is for a blast furnace cement (BFC, CEM III A), followed by an OPC (CEM I), then PFC (CEM II B-V), with the Portland-pozzolana cement (PPC, CEM II B-Q) and PLC (CEM II A-L) overlapping.

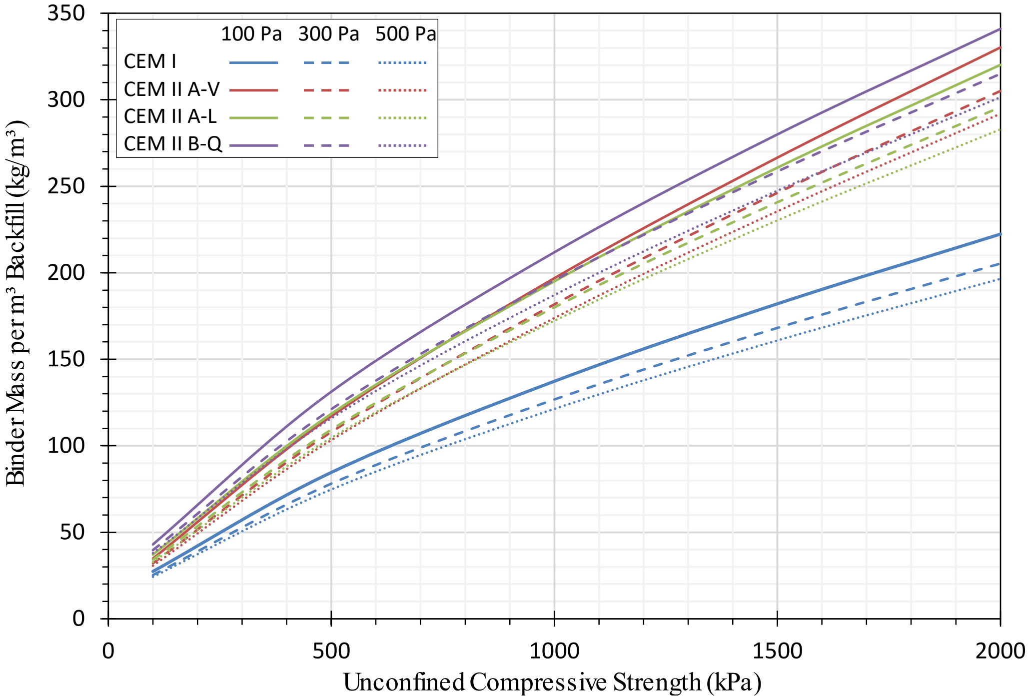

Figure 15 Platinum tailings – binder mass required per m³ of cemented paste backfill for the yield stress indicated

Figure 15 shows that the lowest binder content required is for an OPC (CEM I), with the PFC (CEM II B-V) and PLC (CEM II A-L) overlapping, showing that a 30% replacement of clinker with fly ash achieves similar results compared to a 15% clinker replacement with limestone. The PPC (CEM II B-Q) performed the worst, but also substantially overlaps the PLC at a 30% clinker replacement. At a clinker replacement similar to PLC, the PPC is expected to outperform the PLC substantially.

Tables 6 and 7 show the OPC and PLC mass per m³ of backfill (BF) required to achieve the indicated strengths for the copper tailings along with the additional mass of PLC required, calculated from the strength curves.

Table 6 Mix design comparison for copper tailings

Yield stress	**100 Pa**			**300 Pa**			**500 Pa**		
Mass concentration	**62 %m**			**68 %m**			**71 %m**		
Target strength (kPa)	500	1,000	2,000	500	1,000	2000	500	1,000	2,000
Water:OPC ratio	6.7	4.5	3.0	6.7	4.5	3.0	6.7	4.5	3.0
OPC/ m³ BF (kg)	94	139	206	83	124	184	78	115	171
Water:PLC ratio	4.3	2.9	2.0	4.3	2.9	2.0	4.3	2.9	2.0
Effective Water:OPC for PLC	5.1	3.5	2.4	5.1	3.5	2.4	5.1	3.5	2.4
PLC / m³ BF (kg)	145	213	313	129	190	279	120	177	260
Extra PLC mass (kg)	51	74	107	46	66	95	43	61	88
Extra PLC mass (% of OPC mix)	55%	53%	52%	55%	53%	52%	55%	53%	52%

Table 7 Mix design comparison for platinum tailings

Yield stress	**100 Pa**			**300 Pa**			**500 Pa**		
Mass concentration	**73 %m**			**77 %m**			**78 %m**		
Target strength (kPa)	500	1,000	2,000	500	1,000	2000	500	1,000	2,000
Water:OPC ratio	6.8	4.2	2.6	6.8	4.2	2.6	6.8	4.2	2.6
OPC/ m³ BF (kg)	85	137	222	78	127	205	75	121	196
Water:PLC ratio	4.8	2.9	1.8	4.8	2.9	1.8	4.8	2.9	1.8
Effective Water:OPC for PLC	5.7	3.4	2.1	5.7	3.4	2.1	5.7	3.4	2.1
PLC / m³ BF (kg)	118	195	320	109	180	296	105	172	283
Extra PLC mass (kg)	34	58	98	31	53	90	30	51	87
Extra PLC mass (% of OPC mix)	40%	42%	44%	40%	42%	44%	40%	42%	44%

4.3 Environmental and economic implications

The results are used to calculate the additional carbon cost when switching to limestone cement for a mine that requires 1,000,000 m³/annum backfill (3 Mtpa mining throughput). Using the cradle-to-grave carbon costs published by the Portland Cement Association for PLC at 846 kg CO_2/t (Portland Cement Association 2023b) and OPC at 920 kg CO_2/t (Portland Cement Association 2023a), the associated carbon costs were calculated and shown in Table 8. The additional carbon cost of switching from a PLC to an OPC is shown as a percentage of the OPC carbon costs in the last row.

Table 8 Carbon cost comparison for copper and platinum tailings

Tailings	Copper tailings			Platinum tailings		
Yield stress	300 Pa			300 Pa		
Target strength (kPa)	500	1,000	2,000	500	1,000	2,000
OPC/ m^3 BF (kg)	83	124	184	78	127	205
PLC / m^3 BF (kg)	129	190	279	109	180	296
OPC mass / year (kt)	83	124	184	78	127	205
PLC mass / year (kt)	129	190	279	109	180	296
OPC carbon cost (kt CO_2)	77	114	169	72	117	189
PLC carbon cost (kt CO_2)	109	160	236	93	152	250
Additional carbon (kt CO_2)	42%	41%	40%	29%	31%	32%

The literature and test results show that to achieve equivalent strength more PLC is required, offsetting theoretical carbon savings. The limestone needs to be quarried, transported to the cement producer, crushed and milled, transported to the mine site and then added to the backfill.

All these unit processes add costs without any benefit, and in some instances can even be detrimental. With all the additional steps incurring a carbon cost, and the ultimate addition not adding any benefit to the CPB, this represents a significant additional carbon cost for backfill applications.

4.4 Real environmental savings opportunities

Elimination of PLC from applications in CPB ensures efficient material usage, more predictable performance and minimised total binder requirement. In terms of life cycle emissions per unit strength, OPC remains the more sustainable option in backfill applications.

To realise actual environmental and economic benefits, locally sourced SCM should be investigated. SCM's used in backfill do not need to be 'concrete grade' to be beneficial in backfill. Locally sourced SCM's in close proximity to mine sites are significantly more cost and environmentally effective even if they have limited activity. Any cement producer that has the flexibility of incorporating locally sourced materials into the cement delivered will be able to demonstrate significantly better economic and sustainability credits.

The results also show that the PPC (calcined clay replacement) and PFC with 30% replacement of OPC exhibited lower early-age strengths but performed similar to PLC at 28 days. These binders therefore present a greater potential for carbon reduction, achieving roughly double the clinker substitution of PLC while maintaining comparable long-term strength. Further testing and baseline carbon cost analyses are recommended to confirm whether their overall carbon footprint is indeed lower than that of OPC and will have to be evaluated on a case-by-case basis.

GGBS, where available, typically enables substantial reductions in binder content and can achieve 50% or greater cement replacement. It is therefore likely to represent the most sustainable option, although its performance must also be evaluated on a case-by-case basis considering the specific tailings characteristics and transport costs and distances for GGBS.

5 Conclusion

In CPB the mechanisms by which PLC enhances concrete are not applicable as the material system is dominated by ultra-fine tailings particles. The results from both the literature review and laboratory testing support this reasoning and observation, showing that limestone addition provides no measurable benefit and may in fact negatively influence strength regardless of tailings type, supporting the view that the underlying mechanism is primarily physical rather than chemical.

Conversely, SCMs such as calcined clay, fly ash, and GGBS show greater potential for binder optimisation, offering genuine CO_2 savings. The findings underline the need for mine-specific binder optimisation tests and locally sourced SCM to ensure that carbon reduction can be achieved.

Using PLC in CPB therefore represents a case of misplaced sustainability. The industry must reassess its material choices based on application-specific performance and environmental outcomes.

It is advised to eliminate the use of PLC in CPB and only utilise PLC if a technical and economic benefit can be clearly demonstrated (i.e. test work based). Furthermore, it is advised to shift from a per-tonne CO_2 delivered to a per m^3 of backfill placed metric to evaluate environmental impacts.

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References

ASTM International 2010, *Standard Test Method for Preparation and Testing of Controlled Low Strength Material (CLSM) Test Cylinders (ASTM D4832-10),* West Conshohocken.

ASTM International 2014, *Specific Gravity of Soil Solids by Gas Pycnometer (ASTM D5550-14)*, ASTM International, West Conshohocken.

Benzaazoua, M, Ouellet, J, Servant, S, Newman, P & Verburg, R 1999, 'Cementitious backfill with high sulfur content: physical, chemical, and mineralogical characterization', *Cement and Concrete Research*, vol. 29, no. 5, pp. 719–725.

Chang, Y, Xue, L, Zhao, Z & Wang, X 2022, 'Immobilization of Cr (VI)-containing tailings by using slag-cementing materials for cemented paste backfill: influence of sulfate and limestone addition', preprint, Luliang University, Lvliang.

European Committee for Standardization 2016, *Methods of testing cement - Part 1 Determination of strength (EN 196-1:2016)*, Brussels.

Grieve, G 2009, 'Chapter 1: cementitious material', in G Owens (ed.), *Fulton's Concrete Technology*, 9th edn, Cement & Concrete Institute, Midrand.

Hu, J, Ding, X, Ren, Q, Luo, Z & Jiang, Q 2019, 'Effect of incorporating waste limestone powder into solid waste cemented paste backfill material', *Applied Sciences*, vol. 9, no. 10.

Leo, ES 2022, *Development of Low-Clinker Concrete: Partial Replacement of Cement with Calcined Clay and Limestone, Based on Selected African raw Materials*, PhD thesis, University of Cape Town, Cape Town.

Lowitt, S 2020, *Towards the decarbonisation of the South African cement industry: opportunities and challenges*, Trade and Industrial Policy Strategies, Pretoria.

Ouffa, N, Belem, T, Trauchessec, R & Fortecoëffe, Y 2025, 'Effect of replacing Portland cement with limestone, metakaolin and blast furnace slag on the unconfined compressive strength of cemented paste backfill', in AB Fourie, A Copeland, V Daigle & C MacRobert (eds), *Paste 2025: Proceedings of the 27th International Conference on Paste, Thickened and Filtered Tailings*, Australian Centre for Geomechanics, Perth, pp. 591–606, https://doi.org/10.36487/ACG_repo/2555_42

Owens, G (ed.) 2009, *Fulton's Concrete Technology*, 9th edn, Cement and Concrete Institute, Midrand.

Portland Cement Association (2023a) *Environmental Product Declaration: Portland Cement (Type I/II, ASTM C150)*, Portland Cement Association, Skokie, pp. 1–20.

Portland Cement Association (2023b) *Environmental Product Declaration: Portland Limestone Cement (Type IL, ASTM C595)*, Portland Cement Association, Skokie, pp. 1–21.

Romaniuk, NA, McFarlane, L & Hariharan, N 2024, 'Development of slag alternatives for paste backfill operations', in AB Fourie & D Reid (eds), *Paste 2024: Proceedings of the 26th International Conference on Paste, Thickened and Filtered Tailings*, Australian Centre for Geomechanics, Perth, pp. 535–544, https://doi.org/10.36487/ACG_repo/2455_42

Sagade, A 2023, *Fresh and Hardened Properties of Cemented Paste Backfill with Ternary Binder*, MASc thesis, University of Ottawa, Ottawa.

Salvoldi, B & Gerhardi, J 2025, 'Micro paste: producing paste backfill utilising ultra-fine copper tailings', in AB Fourie, A Copeland, V Daigle & C MacRobert (eds), *Paste 2025: Proceedings of the 27th International Conference on Paste, Thickened and Filtered Tailings*, Australian Centre for Geomechanics, Perth, pp. 221–232, https://doi.org/10.36487/ACG_repo/2555_15

Tennis, PD, Thomas, MDA, Weiss, WJ, Farny, JA & Giannini, ER 2024, *State-of-the-art Report on use of Limestone in Cements at Levels of up to 15%*, Portland Cement Association, Washington.

Treinen, JM, Cooke, R & Sutherland, D 2010, 'Paste backfill design case study — Efemçukuru project', in R Jewell & AB Fourie (eds), *Paste 2010: Proceedings of the 13th International Seminar on Paste and Thickened Tailings*, Australian Centre for Geomechanics, Perth, pp. 209–216, https://doi.org/10.36487/ACG_rep/1063_18_Treinen

Wilson, SC & Leacy, PWJ 2023, 'Optimal paste backfill specification development', in GW Wilson, NA Beier, DC Sego, AB Fourie & D Reid (eds), *Paste 2023: Proceedings of the 25th International Conference on Paste, Thickened and Filtered Tailings*, University of Alberta, Edmonton, and Australian Centre for Geomechanics, Perth, pp. 294–306, https://doi.org/10.36487/ACG_repo/2355_22

Zheng, J, Zhu, Y & Zhao, Z 2016, 'Utilization of limestone powder and water-reducing admixture in cemented paste backfill of coarse copper mine tailings', *Construction and Building Materials*, vol. 124, pp. 31–36.