Mine Closure 2025 – S Knutsson, AB Fourie & M Tibbett (eds)

doi:10.36487/ACG_repo/2515_78

Complete closure landforms: geomorphic design with commingled tailings and waste rock

David Barsi [a], **Neeltje Slingerland** [b,*]

[a] *University of Alberta, Canada*

[b] *WSP, Canada*

Abstract

Traditional mine waste structures (waste rock dumps and tailings facilities requiring dams) have the potential to create long-term physical and chemical stability challenges and often require perpetual monitoring and maintenance. In response to this risk, commingled facilities have been proposed whereby waste rock and dewatered tailings are mixed and co-disposed of in one facility, supporting both physical and chemical stability. Additionally, an often-unrealised benefit of commingled materials is the ability to compact and shape them similarly to natural soils.

This work investigated the closure implications of the present (traditional) mine waste management approaches used at mine sites around the world. Failures of closure landforms were investigated and categorised, contributing factors for the failure mode were identified, and potential mitigation or prevention measures identified. The assessment indicated that commingled mine waste materials in combination with a geomorphic landform approach results in substantial opportunities, including reduced long-term monitoring, reduced long-term water treatment, and reduced lifecycle costs.

Keywords: *commingled mine waste, geomorphic landform design, opportunity assessment*

1 Introduction

Traditional practices in mine waste management and closure often see the development of two typical landforms: waste rock piles and slurried tailings facilities with large retention dams. It is known that these two types of landforms have the potential to create long-term challenges and have imbedded failure modes, both in physical and chemical stability. While waste rock piles tend to be physically stable, geochemical stability including acid rock drainage (ARD) and metal leaching are well documented and expensive long-term management realities for many sites. The development of the GARD Guide, published in 2009 (www.gardguide.com), was a result of the historical and ongoing need to address environmental damage that can be caused by these waste rock structures. Conversely, typical slurried or fine tailings storage landforms have water capped, or highly saturated, tailings stored behind retaining dams. Such tailings facilities have improved chemical stability due to oxygen being restricted from entering the system, but they have significant physical stability risks. Numerous high-profile tailings facility failures have occurred in recent years, such as at the Mount Polley Mine (Morgenstern et al. 2015), the Fundão tailings dam at Samarco Mine (Morgenstern et al. 2016), Dam I at Córrego do Feijão Mine (Robertson et al. 2019) and the lesser-known tailings stack at Pau Branco Mine (Manuelzao 2022).

Traditional mine waste structures typically require monitoring in perpetuity due to inherent long-term risks resulting from their design. By investigating failures in closed tailings landforms, preventative measures can be developed that address long-term chemical and physical stability issues.

* Corresponding author. Email address: n.slingerland@wsp.com

2 Historical database

The Center for Science in Public Participation (CSP^2) has developed a database of tailings dam (physical) failures from 1915 to present (CSP^2 2025) and presents an extensive list of 368 failures related to tailings dams, general tailings, waste rock dumps and heap leach piles. Using definitions from ICOLD (ICOLD-UNEP 2001), each of these failures was classified. Sixty-four of these physical failures occurred in 'inactive' structures or landforms; as there were no indications that these structures were intended to be altered at a future point in time, all inactive structures were considered as closure landforms for this study. Nine distinct failure classifications were identified for the 64 failures of inactive facilities, as shown in Table 1. From this list, overtopping and Earthquake were the most frequent classifications, while structural (including structural inadequacies, inadequate or failed decants) was the third most frequent. Other, less-frequent categories include slope instability, seepage, foundation, mine subsidence and erosion (surficial).

Table 1 Physical failure classifications for closed landforms

Number	Classification	Description
3	SI	Slope instability – static failure
1	SE	Seepage – seepage and internal erosion
2	FN	Foundation – structural and foundation conditions
21	OT	Overtopping
8	ST	Structural – structural inadequacies, inadequate or failed decants
21	EQ	Earthquake – seismic instability
1	MS	Mine subsidence
1	ER	Erosion – external erosion
6	U	Unknown

3 Physical failures in closed landforms

Three of the most common physical failure modes in closure landforms appear to be overtopping, seismic instability and inadequate or failed decants leading to structural issues. These three failure modes were focused on as they have the most recorded cases in the CSP^2 database. In the worst of these incidents there were releases of large volumes of mine waste, long runouts of material and, in some cases, fatalities.

3.1 Overtopping

As described in the CSP^2 database (CSP^2 2025) and based on definitions from ICOLD (ICOLD-UNEP 2001), the overtopping classification refers to water flowing over the top of a dam. As tailings dams are made from erodible material, these events can lead to erosion of the dam and lead to failure. Twenty-one of these events were recorded in 'inactive' or closure landforms. The majority of these events can be attributed to extreme weather, mostly through heavy rainfall, rapid melting of a deep snowpack, 1:100-year flood events and, in one case, a hurricane. There are also cases where failures in adjacent mine waste structures and natural slopes caused a cascading failure as they interacted with the tailings storage area to cause overtopping. In one case a natural stream migrated over time into the mine storage facility, causing it to fill and overtop.

3.2 Seismic instability

Seismic instability appears to be another major cause of failures in closure landforms, with 21 recorded cases from the database. Fortunately, almost half of these incidents did not lead to total failures of the storage landforms. Seismic events caused large crest deformations, large crack formations and often small (not catastrophic) landslides. For these lower consequence incidents, the clean-up and repair of the containment facilities would be costly. These high costs could fall to mining companies or the public if the closure landforms are relinquished. Unfortunately, the other half of the events did lead to tailings dam failures, either through liquefaction or other seismically induced deformations. The costs involved with these failures is much higher.

3.3 Structural inadequacies

These incidents are attributed to the failure of drainage systems in the mine waste storage facilities. The poor design or construction of drainage features at these facilities led to failures such as blowouts of the drainage tunnels, or improper drainage paths carrying contaminants to inappropriate destinations. This commonly led to material release and contamination of rivers, roads, neighbourhoods and agricultural areas. In some cases the poor drainage systems led to contamination of groundwater. In one case the poor drainage system led to the oversaturation of dry-stacked tailings, causing a landslide.

4 Other types of failure in closed landforms

As previously noted, other forms of failure exist when considering tailings facility closure: the hierarchy (as outlined in the Asia-Pacific Economic Co-operation (APEC) Checklist for Governments (APEC Mining Task Force 2018) and later adopted by the GARD Guide (Chapter 11, International Network for Acid Prevention 2024, Figure 1)) places physical stability at the base of the pyramid such that it is required for all other forms of stability to be possible. However, this does not mean that a waste storage facility cannot fail in any other way. From a regulatory perspective, many jurisdictions require bonding or financial assurance for closure, whereby the bond is returned to the owner when closure success criteria are successfully achieved, or the site is demonstrated to be on a trajectory towards achievement where long time frames are concerned. Closure success criteria may be related to geochemistry targets, ecological targets and achievement of specified land use; accordingly, a mine waste structure at closure may fail by not meeting any of these previously identified targets. During operations we typically think of failure in the physical sense, but in failing to maintain physical stability, the facility also fails to achieve its intended (land) use and may fail chemically due to the release of sediment or contaminants.

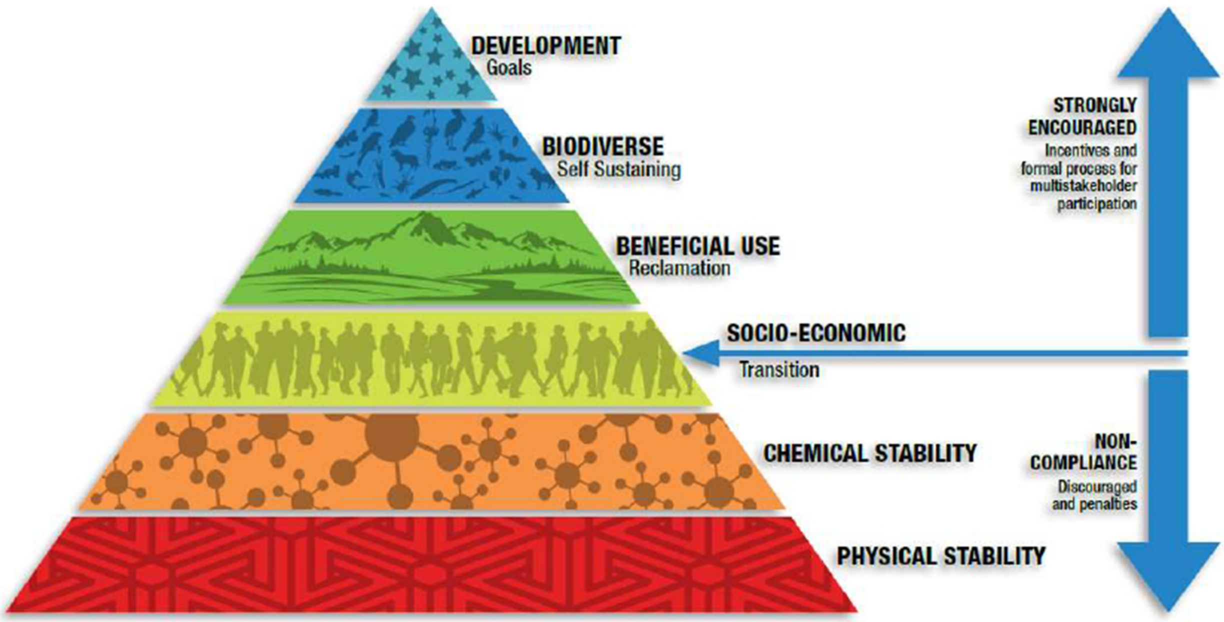

Figure 1 Hierarchy of closure needs (from APEC Mining Task Force 2018)

4.1 Chemical failures in closed landforms

Chemical stability may be a misnomer (chemistry is in a state of perpetual flux for most water bodies, groundwater sources and landforms as a whole), but this is a common term used to describe a state where water in, on or draining from the landform does not pose a risk to people, wildlife or the environment. Examples of chemical instability include ARD and surface water or seepage with very high or very low pH, high levels of dissolved metals or other constituents of concern, radioactivity, high salt content, etc. Ideally, undesirable geochemistry is identified early and planned for such that environmental degradation resulting from undesirable geochemistry is prevented altogether.

While tailings can be acid generating, metal leaching, radioactive, or have very high or very low pH, etc., more typically when we think of the chemical instability of mine waste structures we think of waste rock dumps. This is due to the reactor created through common waste rock dump construction practices whereby water infiltrates down fine layers and oxygen is sucked in from large openings at the base created by the large particle size (Figure 2). The combination of water, oxygen and freshly exposed rock surfaces, paired with a construction method that creates the opportunity for reactions to take place within them, has created countless instances of geochemical failure at closure, some of which have applied perpetual management methods to limit downstream impacts.

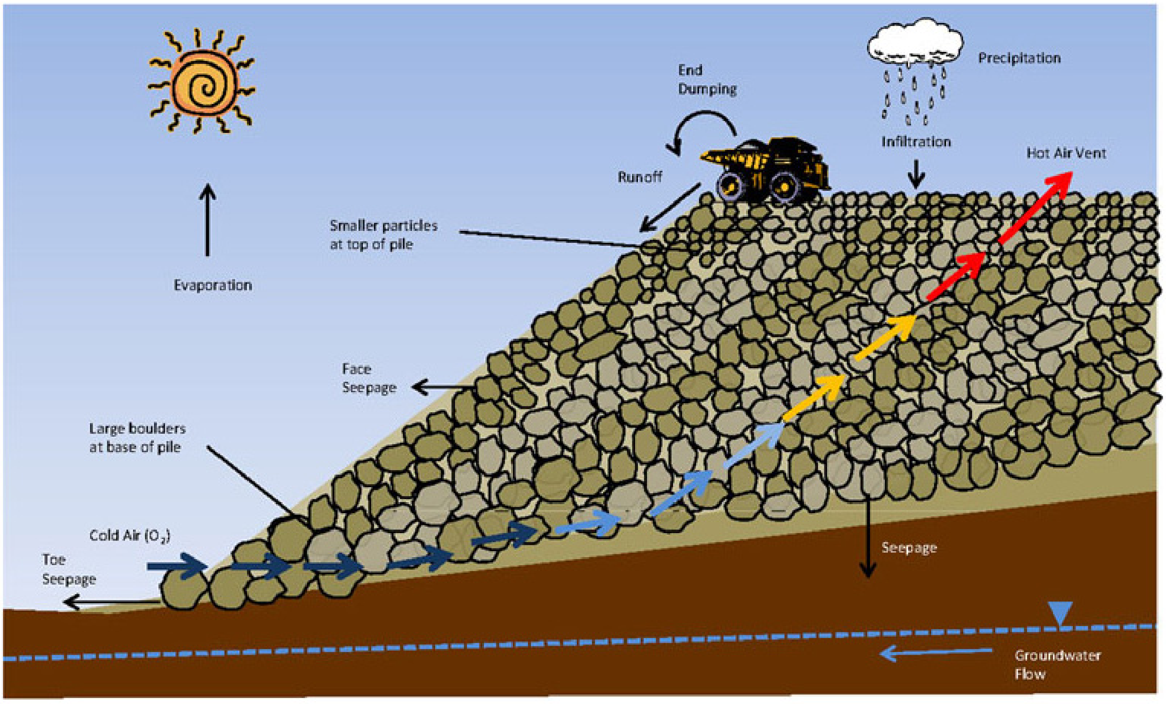

Figure 2 Sources and pathways of chemical instability in a waste rock dump (www.gardguide.com)

4.2 Land use failures in closed landforms

A critical component of mine closure is establishing a new post-mining land use (or uses) for the landform. This may be the provision of an ecological habitat or something more anthropogenic in nature, such as a botanical garden, agricultural fields for cultivation or grazing, or a sculptural landform like those created by Charles Jencks or Maya Lin. Common failure modes for the desired land use include surface erosion and inadequate revegetation.

5 Potential solutions

Identifying common failure modes in closure landforms allows for the subsequent identification of solutions that prevent these failure modes. Solutions were considered for each of the failure modes with the goal of removing the mode entirely. In some cases the presented solutions require ongoing monitoring or maintenance. While recognising this is undesirable, it may yet be unavoidable. A summary of potential solutions is provided in Table 2.

Table 2 Summary of failure modes at closure and potential solutions

Failure mode	Potential solutions
Physical – overtopping	Remove the pond and the potential for a pond to form in the future; manage ARD potential using an alternate method Non-erodible dam slopes should overtopping occur Upland landform design with efficient water-shedding capability
Physical – seismic instability	Ensure materials are dilative when exposed to seismic stresses (i.e. remove water from tailings and compact tailings) Materials withstand anticipated loading conditions in the future (including post-seismic)
Physical – structural inadequacies (with water conveyance structures)	Spillways are sufficiently large and frequently maintained to convey design storms* Multiple spillways for redundancy Geomorphic landform design for efficient water shedding
Chemical – ARD or metal leaching	Identification, segregation and encapsulation of potentially acid generating or contaminating material Oxygen barrier: water cover* Oxygen barrier: create low-permeability material Restrict water infiltration via a cover system*
Land use – inadequate vegetation cover or biodiversity	Soil testing and appropriate amendments Increased soil/rooting depth Geomorphic landform design to reduce soil loss and increase biodiversity
Land use – surface erosion (fluvial, F, or eolian, E)	Armour surface with coarse non-erodible rock if aligned with post-mining land use (F, E) Increase surface roughness with vegetation (F, E) Geomorphic landform design (F, E)

* Perpetual monitoring and maintenance required: not a walk-away solution.

5.1 Physical failure modes

5.1.1 Overtopping

Traditional tailings storage facility (TSF) designs rely on water caps and high saturation to limit the amount of oxygen that can enter the tailings. By limiting oxygen in the system, ARD reactions can be significantly slowed or halted altogether. However, these water levels can be disturbed in closure by extreme weather events or slope instability, even outside of the TSF. Whether in operation or in closure, the water levels need to be managed to prevent overtopping events that can lead to excessive erosion and material release. The solution to the physical hazard that saturated tailings and a pond creates is to remove the ponds. This necessitates a new control measure for ARD. To guard against a pond re-forming in the future (in consideration of settlement due to tailings consolidation, for example) waste materials should be deposited as freestanding water-shedding landforms.

In some instances, removal of the pond is not possible and sufficient freeboard is provided. In this case overtopping may still be possible in the future due to storms, winds or other climate influences.

Accordingly, the slopes of these mine waste structures should be non-erodible such that even if there is an overtopping, the retaining structure is not at risk of a catastrophic failure.

Dewatered tailings are one emerging solution that can be used to change a TSF from a water-retaining structure into freestanding 'stacks'. However, as exemplified by the tailings stack failure at Pau Branco Mine in 2022, which failed into a water reservoir that subsequently overtopped, tailings stacks are not immune from overtopping failures where large surface water volumes are present.

Even dewatered tailings deposited in stacks will require some level of water management as run-off needs to be collected and treated, and measures also need to be taken to avoid infiltration into the groundwater where water quality is a concern. Since retention of filtered tailings behind a dam would allow for a pond to be re-established in the future, commingling tailings with waste rock could provide additional robustness while avoiding reliance on a dam altogether.

5.1.2 Seismic instability

Both waste rock piles and TSFs are susceptible to damage from seismic events, which are capable of triggering liquefaction in natural materials. As the materials shake and the particles rearrange, excess porewater pressures can be generated. If the excess pore pressure cannot dissipate quickly then the material can liquify, causing catastrophic failure. By creating mine waste materials that behave in a more dilative manner, the risk of liquefaction can be reduced. This is often achieved through material densification.

Again, dewatered tailings have been used as a replacement for traditional loose, wet, fine tailings. By dewatering the tailings, deposits can be created that are easily compactible, either by self-weight consolidation or with industrial equipment. Such a deposit is less susceptible to liquefaction as seismic activity will tend to loosen the material and, with less water in the system, it is more difficult to generate excess pore pressures. As demonstrated by O'Brien (1986) and referenced by the Canadian Dam Association (CDA) (Martin et al. 2019), the severity of liquefaction events can be estimated from material properties. Figure 3 demonstrates the theory explored by O'Brien, with dewatered (filtered) tailings falling in the green zone. This zone is characterised by landslide behaviour as the expected consequence of material failure.

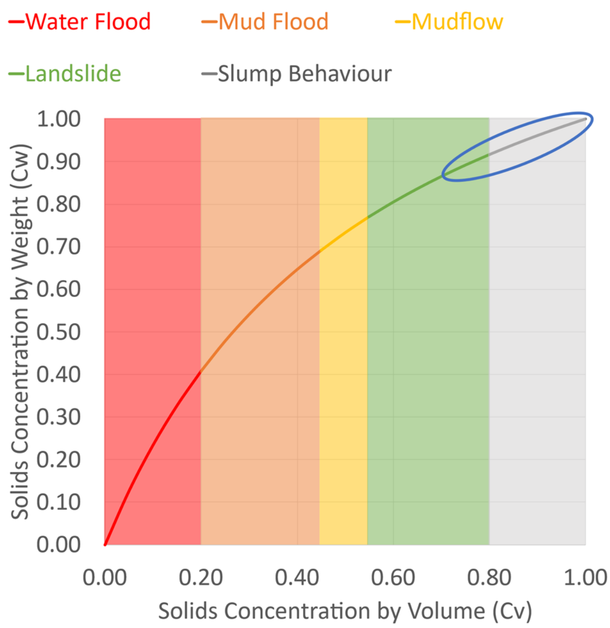

Figure 3 Estimating flow characteristics (after O'Brien 1986)

A more robust method to increase the material's physical stability is to use commingled mine waste materials. As seen in Figure 3, commingled mine waste materials can fall in the upper green zone and into the grey zone. These estimations were made using data from a study of commingled materials and include various mixtures from five different metal mines across North and South America (Barsi & Wilson 2023).

By further increasing the solids content of the waste materials the expected failure behaviour becomes slumping. As seismic activity cannot be removed as a variable, improving the failure behaviour is important. Material slumping is a far more manageable outcome than mudflows and mudslides that can develop when using traditional mine waste strategies. Such improvements could see failures being restricted to within the mine boundaries instead of many kilometres downstream.

Regardless of the method applied, the solution must provide for materials that can withstand the anticipated future loading conditions, including post-seismic strength, as closure is for perpetuity and multiple seismic events are possible during such a time frame.

5.1.3 Structural inadequacies

This incident type referred to failures in the drainage systems that led to material release from closed tailings facilities. Releases could take the form of intrusion into the groundwater, overtopping containment structures due to a lack of sufficient drainage, or blowouts of the drainage structures. While overtopping was discussed in Sections 3.1 and 5.1.1, failures attributed to structural inadequacies at closure were predominantly the result of an inability to remove water efficiently. To eliminate the need to remove such great volumes of water from a TSF, two approaches are presented: (1) decrease the permeability of the mine waste to increase overland flow and reduce the risk of raising the phreatic surface within the structure and/or (2) increase the water-shedding efficiency of the landform.

For option one, dewatered or commingled materials take on the low permeability of the dewatered tailings, increasing surface water run-off. This, in combination with a surface water design that efficiently sheds water, could achieve intended outcomes. Efficient water shedding could be attained either through adequately sized and maintained spillways, multiple spillways which provide efficiency and redundancy, or through a geomorphic landform design.

Commingled materials provide a low permeability for increased surface water flow while also having the potential for reshaping into irregular forms such as is required for geomorphic landform designs. When studying commingled mine waste materials at the laboratory scale, Barsi & Wilson (2023) found that these materials could be generated with high densities and low hydraulic conductivities while also having a high saturation and low overall moisture content. This combination of material properties suggest that deposits made from these materials would hold water well, shedding excess water easily. Such structures would not need a containment dam. The risk of overtopping from poor drainage would disappear as large water-retaining dams would no longer be required, the risk of a drainage blowout would be removed as drainage systems would be collecting from very low conductivity material, and groundwater contamination could easily be monitored and mitigated due to very low hydraulic conductivities.

5.2 Other types of failure modes

5.2.1 Geochemical failure

Geochemical failures are most evident in the water draining from the landform, also called seepage. Some types of geochemical instability, such as radioactivity, are also inherent to the landform but may be transmitted via seepage. The ideal course of action for geochemical issues is prevention where possible: do not mine rock that has adverse geochemistry outcomes. Where this is not possible, prevent the generation of adverse geochemistry through material management i.e. diligent characterisation of waste materials, segregation and encapsulation of potentially contaminating materials. Other options if this is not possible include construction of an oxygen barrier cover, such as a water cover, or a low-permeability clay cap. Note that covers have a design life and are therefore not a walk-away solution. If excluding oxygen is not possible, or not desirable given the contaminant of concern, excluding water may be a viable option: this may also present in the form of a low-permeability cover.

A more permanent option may be to design the waste material such that it is all low permeability, thereby reducing the need for cover replacement. Dewatered fine tailings is one such material that has low permeability, thereby reducing water and oxygen ingress. Similarly to encapsulation, this option would ideally be initiated prior to mine initiation and be a key consideration in the processing methods, mine waste design and overall mine plan.

5.2.2 Failure to achieve post-mining land use

Two common challenges have been highlighted in the failure to achieve post-mining land use(s): (1) poor vegetation coverage or inadequate vegetation coverage (for example, monocultures and lack of biodiversity resulting from homogenous topography); and (2) excess surface erosion that inhibits the targeted post-mining land use.

Vegetation growth may be inhibited by a variety of issues including lack of organics, excessively fine textured soil leading to insufficient oxygen supply to the roots, or lack of soil to grow vegetation. Soil or surficial material testing is a helpful first step in identifying the specific challenge and making decisions for amendments. Amendments could include the addition of growth medium or organics such as wood chips, fertilisers, etc. Biodiversity can be increased through the addition of microtopography like mounding or by constructing a geomorphic landform design where the final landform is more reminiscent of the natural terrain in terms of surface moisture variability.

Surface erosion caused physical failure of a closed tailings facility in only one case documented in the CSP^2 database (CSP^2 2025) but it is a common cause of: (1) ongoing and perpetual maintenance on mine sites; (2) the inability to decommission sedimentation ponds or re-establish natural drainage/directly discharge into the downstream environment; and (3) failure to achieve post-mining land use. Erosion can be managed according to the cause: wind (eolian) erosion requires that the surface roughness be increased such that wind speeds decrease and their erosion potential is reduced: this can be done through revegetation, armouring with large rocks on the surface, or geomorphic landform design. Erosion caused by surface water (fluvial erosion) can be managed through surface armouring with rock (erosion reduction varies with rock diameter), revegetation (erosion reduction varies with the vegetation species) or with geomorphic landform design. Geomorphic landform design leads to efficient surface water shedding, variable topography and surficial soil moisture content such that both the surface water and biodiversity are improved. Note that surface treatments must also be aligned with the post-mining land use, so rock armour to eliminate surface erosion would not be a solution for a site with a target land use of agricultural crops, for example.

5.3 Summary of potential solutions

Potential solutions have been outlined generally in the preceding sections, and some methods of achieving these solutions are presented in Table 3.

Dewatered tailings technologies have been increasingly utilised in recent years as the technology improves, and as better water and waste management practices are needed to meet modern challenges. Dewatered tailings cover a wide range of moisture contents utilising various technologies to remove and recycle water from tailings. Some notable methods include thickeners, vacuum filters and filter presses. Different technologies allow for different levels of moisture to be removed and require different levels of energy to operate. On the wet end of the spectrum, treated tailings can still be pumped for disposal. With further dewatering, material can be trucked or conveyed and stacked for deposition.

Commingled mine waste aims to blend the tailings and waste rock into a homogenous material that can be deposited and shaped much like natural earth materials. Burden (2021) determined that such mixtures could have strength properties that were equal to or greater than waste rock alone and that such mixtures could reduce the build-up of pore pressures during deposition. Studies by Wickland (2006) and Burden (2021) have developed much of the theory that is required to design optimum blend ratios for commingled materials. Further research of commingled mixtures suggests that these materials can have favourable properties even when mixtures are not optimum (Barsi & Wilson 2023), which may allow overall material volumes to be optimally managed.

Table 3 Summary of solutions and approaches

Scoring: +1: Support/Enhance 0: Aligned −1: Detract	Final landform approach External: benched/contour banks with spillway	External: linear slopes, elevated pond with multiple spillways	External: geomorphic landform, no pond	Internal: contractive or reactive materials, dams or end-tipped slopes, compacted cap.	Internal: dilative or layered/encapsulated material, dams or end-tipped, compacted cap.	Internal: commingled material, cover
Mitigation or prevention measure						
Physical						
No pond or potential for a future pond (no saturated tails)	−1	−1	+1	−1	−1	0
Upland landform with efficient water shedding capability	−1	0	+1	0	0	+1
Dilative materials	0	0	0	−1	0	0
Increased geotechnical stability (static and seismic)	0	−1	0	−1	+1	0
Redundancy in surface drainage	−1	+1	+1	−1	−1	+1
Acceptable erosion rates on slopes	−1	−1	+1	−1	−1	+1
Chemical						
Identify, segregate, and encapsulate or layer contaminated or reactive material	−1	−1	+1	−1	+1	−1
Reduce permeability of material – compaction	−1	−1	0	+1	+1	0
Reduce permeability of material – co-disposal	−1	−1	0	−1	+1	+1
Freezing	0	0	0	+1	+1	+1
Land use						
Appropriate growth medium stockpile management, and quantities available	0	0	0	0	0	0
Soils testing and amendments as needed	0	0	0	0	0	0
Appropriate vegetation species and diversity for microclimates on site	0	0	0	0	0	0
Increased surface roughness through armouring or soil grading	0	0	0	0	0	0
Inclusive of landscape ecology principles	−1	0	+1	−1	−1	+1
Geomorphic design (landform design + revegetation design + soil placement plan)	−1	−1	+1	−1	−1	+1
TOTALS:	**−9**	**-6**	**+7**	**−7**	**0**	**+6**

Geomorphic landform design has benefits for a range of closure aspects, including physical stability, chemical stability and post-mining land use achievement. Geomorphic landform design can be completed with the same or similar footprints to traditional approaches, with the added benefits of reducing surface erosion, efficiently shedding surface water (reducing infiltration) and increasing biodiversity due to variable surface water moisture levels. If geomorphic design is aligned with the post-closure land use, this is a multi-benefit option to explore.

Of the solutions and approaches proposed, Table 3 presents the geomorphic design, and the commingled waste rock and tailings approaches, that most enhance the desired outcomes identified. These two methods may be used in conjunction for a wholistic closure solution with great potential to achieve the desired closure outcomes.

6 Discussion

The use of commingled mine waste materials in conjunction with geomorphic landform design could provide solutions for some of the most common failure modes associated with closure landforms. Additional benefits include the potential for:

- reduction to the surface area required for mine waste materials
- reduction in the amount of material rehandling by developing the final landforms early on
- reduction in the amount of material dewatering that is required
- increased biodiversity
- reduction in maintenance for erosion
- expedited surface water discharge to the environment
- improved geochemical performance due to restricted oxygen and water ingress.

6.1 Surface area savings

Traditional mine waste management schemes generate two main waste streams for coarser and finer materials. By commingling the two waste streams, a material is generated that can minimise the overall volumes of waste material. The fine material can occupy and fill the voids of the waste rock. Considering that waste rock can have bulking factors in the range of 1.5–1.8, significant volume reductions can be achieved. The commingled material also has improved material properties, allowing for it to be stacked with steeper slopes, and higher shear strengths than the individual materials alone (Burden 2021). These characteristics of commingled materials can greatly reduce the surface area that is required for large tailings and waste rock storage areas.

6.2 Material handling

As commingled materials can be deposited and shaped using existing methods it is feasible that the deposition of the final closure landforms could begin early in the mining process. As the materials are produced, they can be commingled and moved to their final placement area. This could reduce the amount of rehandling that can occur with traditional management techniques. Often the separate materials are moved to their own storage facilities where they remain for much of the mining process. Near the end of mine life these materials may need to be relocated, regraded, resurfaced or covered for closure purposes. All of this extra material handling can add substantial time and cost to closure plans. Additionally, with the expected favourable shaping characteristics of the material, more diverse landforms can be developed which better meet closure goals for all the stakeholders.

6.3 Dewatering requirements

While dewatered tailings are showing numerous advantages for mine waste management it is still difficult to achieve high levels of dewatering and costs remain high. It can also be a challenge to dewater large volumes of material quickly. A benefit of commingled materials is that the amount of tailings dewatering can actually be reduced. By adding waste rock that is essentially dry (or close to dry), the mixture can be diluted with additional dry mass, allowing for wetter tailings to be added. Data from Barsi & Wilson (2023), recreated with permission in Figure 2, demonstrate that commingled mixtures can be compacted to densities similar to waste rock, and with lower moisture contents than tailings alone. By reducing the overall dewatering requirements the technology requirements are also reduced, which could save a substantial amount of capex.

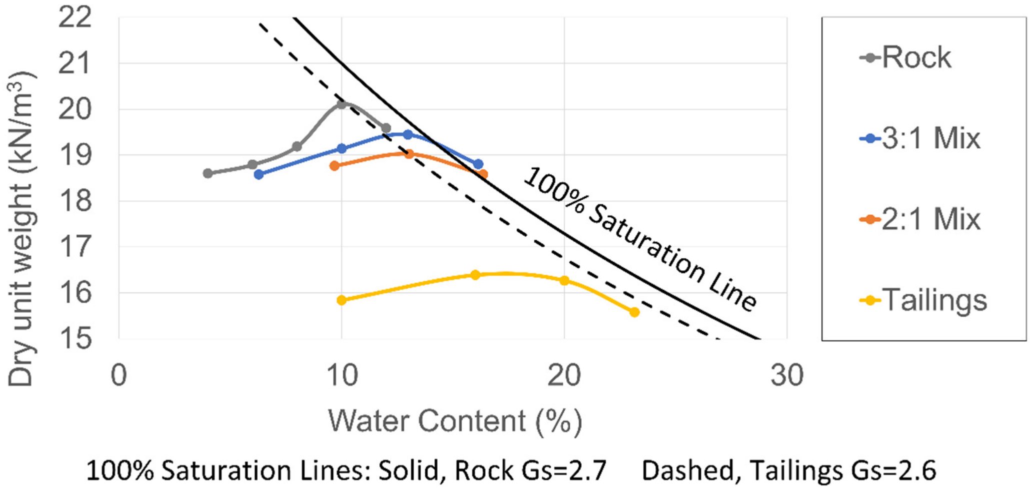

Figure 4 Example of moisture contents in compacted mine waste materials (Barsi & Wilson 2023)

7 Conclusion

A database of mine waste structure failures developed by CSP[2] was explored, and data for closure landforms were found. These data were classified based on failure type, with three common causes being determined. The causes were discussed with respect to how they impact traditional mine waste structures in closure. Potential solutions to these failure modes were then discussed, with emerging technologies such as dewatered tailings and commingled mine waste being explored. Finally, seeing that the potential of commingled materials could be greater than dewatered tailings alone, additional benefits of the method were explored. Findings are based on a desktop study and introductory laboratory-scale testing. More advanced laboratory testing and field-scale testing will be required to further study these materials and their potential benefits for mine waste management strategies.

Acknowledgement

The authors gratefully acknowledge Dr Ralph Burden for the many insightful discussions that contributed to this work.

References

APEC Mining Task Force 2018, *Mine Closure Checklist for Governments*, https://www.apec.org/docs/default-source/Publications/2018/3/Mine-Closure-Checklist-for-Governments/218_MTF_Mine-Closure_Checklist-for-Governments.pdf

Barsi, D & Wilson, GW 2023, 'General properties of commingled materials for mix designs', *Minerals*, vol. 14, no. 1, https://doi.org/10.3390/min14010030

Burden, R 2021, *Using Co-Disposal Techniques to Achieve Stable "Dry-Stacked" Tailings: Geotechnical Properties of Blended Waste Rock and Tailings in Oil Sands and Metal Mining*, PhD thesis, University of Alberta, Edmonton.

CSP[2] 2025, *TSF Failures 1915-15Apr25*, spreadsheet, https://www.csp2.org/tsf-failures-from-1915

ICOLD-UNEP 2001, *Tailings Dams Risk of Dangerous Occurrences—Lessons Learnt From Practical Experiences*, Bulletin 121.

International Network for Acid Prevention 2024, *Global Acid Rock Drainage Guide, Chapter 11: Sustainable Mine Closure*, https://www.inap.com.au/wp-content/uploads/GARD-Guide_Chapter-11.pdf

Manuelzao 2022, *Estrutura de Mina da Vallourec se Rompe em Nova Lima* (Vallourec Mine Structure Collapses in Nova Lima), https://manuelzao.ufmg.br/estrutura-da-mina-pau-branco-da-vallourec-se-rompe-em-nova-lima

Martin, V, Al-Mamun, M & Small, A 2019, 'CDA technical bulletin on tailings dam breach analyses', in J Tournier, T Bennett & J Bibeau (eds), *Sustainable and Safe Dams Around the World*, CRC Press, Boca Raton, pp. 3484–3498, https://doi.org/10.1201/9780429319778-313

Morgenstern, NR, Vick, SG & Van Zyl, D 2015, *Report on Mount Polley Tailings Storage Facility Breach. Independent Expert Engineering Investigation and Review Panel*, Province of British Columbia, Ministry of Energy and Mines, https://www.mountpolleyreviewpanel.ca/sites/default/files/report/ReportonMountPolleyTailingsStorageFacilityBreach.pdf

Morgenstern, NR, Vick, SG, Viotti, CB & Watts, BD 2016, *Report on the Immediate Causes of the Failure of the Fundão Dam. Fundão Tailings Dam Review Panel*, Cleary Gottlieb Steen & Hamilton LLP, https://www.fundaoinvestigation.com/the-panel-report

O'Brien, JS 1986, *Physical Processes, Rheology And Modeling Of Mud Flows*, PhD thesis, Colorado State University, Fort Collins.

Robertson, PK, de Melo, L, Williams, DJ & Wilson, GW 2019, *Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I*, https://bdrb1investigationstacc.z15.web.core.windows.net/assets/Feijao-Dam-I-Expert-Panel-Report-ENG.pdf

Wickland, BE 2006, *Volume Change and Permeability of Mixtures of Waste Rock and Fine Tailings*, PhD thesis, University of Saskatchewan, Saskatoon.