

## **Discrete-Zone Mixing of Net-Acid-Neutralizing and Net-Acid-Generating Rock: Avoiding the Argument over Appropriate Ratios**

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### **ABSTRACT**

There is currently some pessimism over mixing of net-acid-neutralizing (NAN) and net-acid-generating (NAG) rock to obtain indefinite near-neutral seepage from mined-rock piles. This is due in large part to the lack of well-documented, successful cases of blending and layering, and to the knowledge of unsuccessful attempts.

Past work often defined a potentially successful mix in terms of the ratio of net-acid-neutralizing rock to net-acid-generating rock. For example, one case study indicated the bulk pile-wide ratio was approximately 3:1. Since this exceeded a common ratio used in acid-base accounting, no acidic drainage was predicted. However, acidic drainage appeared within two years.

A large part of the ambiguity in mixing arises from attempts to predict success based on a ratio. This paper looks in detail at simple discrete-zone mixing, where at least one truckload of NAG rock is placed in a particular location with no further rehandling or dozing. The lack of acidic drainage in this scenario is dependent on the intervening distance between the discrete NAG zones, along flowpaths occupied by NAN rock. Calculations show that the bulk mixing ratio of a mined-rock pile is not an accurate indication of whether near-neutral drainage can be maintained. For example, a pile with a bulk ratio around 300:1 could still release some acidic drainage. Calculations also show that the minimum separation distance of the NAG zones (L) can be so great, even with typical NAG and NAN rock, that the mixed pile could safely contain only a few percent of NAG rock, which would not be sufficient for many minesites with NAG rock.

The comparison to a more elaborate, computer-based statistical model shows that the simple discrete-zone approach will provide a reliable yes-no indication of whether any acidic drainage will leave a pile. However, predictions of whether combined downstream drainages will be acidic depend on numerous site-specific physical and geochemical factors within and below a pile that cannot be modelled in a general way, like the number of flowpaths and the nature of their intersections.

### **INTRODUCTION AND TERMINOLOGY**

One technique for the control of drainage pH from net-acid-generating (NAG) mined materials, like waste rock and tailings, is the addition of net-acid-neutralizing (NAN) material, like limestone or NAN waste rock. If successful, this mixture indefinitely prevents drainage pH from becoming acidic, although metal leaching is still frequently problematic (Morin and Hutt, 1997a; Mehling et al., 1997). In theory, this is a simple concept, but in the real world the concept does not often work well. In fact, some people cannot even agree on definitions of important relevant terminology, like blending, layering, and net acid generating. So definitions are the first steps in resolving some problems.

Net acid generating (NAG) refers here to any mass of rock with a net deficit of effective, active neutralization potential (NP). NAG rock may actually have significant amounts of NP, and thus will not release acidic drainage for many years, but the excess of sulphide and acid potential ensures some day the acidic drainage will appear. Net acid neutralizing (NAN) refers here to any mass of rock with a net excess of effective, active NP, that is, NP that effectively neutralizes acidic drainage under on-site conditions to pH 5 or greater.

In this paper, "mixing" refers to any combination, blending, or layering of NAG and NAN rock. It is a generic term, because more specific terms can be ambiguous. For example, layering is envisioned as discrete layers of material, whereas blending is a non-layered combination (Mehling et al., 1997; Mehling Environmental Management, 1998). However, because mined rock exists as discrete particles, blended rock on a macroscale could actually be layered rock on a microscale. Therefore, it could be difficult to prove under field conditions

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that any “blended” rock was not actually “layered” in some way. In any case, NAG rock layers as thin as 0.1 m can behave geochemically as if adjacent NAN layers were not present (Case Study 6.4-5 in Morin and Hutt, 1997a; Morin and Hutt, 1997b), so blending would have to be remarkably thorough on small scales to avoid arguments that it is layered in some way. The use here of “mixing” is intended to avoid these arguments.

“Mixing” in this paper is also generic for another reason - the real world under active mining conditions. While it is scientifically pleasing to imagine truckloads of rock being mixed in a cement mixer to thoroughly combine NAG and NAN rock, this has not and will not happen at most minesites. Additionally, mistakes can occur. For example, the authors have seen a site where workers were paid an environmental bonus to deliver NAG and NAN rock to separate stockpiles. However, because the workers were paid a much higher performance bonus, they sometimes opted for the expediency of dumping in the closest stockpile. This created two randomly mixed piles and both were releasing acidic drainage.

Therefore, “mixing” refers to any combination of NAG and NAN material. In one type of mixing envisioned here, each truckload of rock is defined as NAG or NAN, and each NAG truckload is dumped in a discrete location within one pile, with minimal rehandling or grading by a dozer. This is referred to as “discrete-zone mixing” (Figure 1).

## BASIC THEORY

The theory behind discrete-zone mixing is relatively simple. Each discrete zone of NAG rock will eventually release a maximum amount of net acidity over the life of a free-draining mined-rock pile. To avoid entirely the chance that any one drainage pathway will be acidic, each NAG zone must be separated from other NAG zones and the discharge points by sufficient NP (the effect of human error and other issues on this safe, conservative scenario are discussed later). If available NAN rock has minimal excess NP, then relatively large distances (“L”) of intervening NAN rock are needed to provide the cumulative excess NAN (Figure 1). If available NAN rock has high excess NP, then separating distances between NAG zones can be low.

Although drainage of water through most free-draining mined-rock piles is generally downward, various physical and chemical factors can cause near-lateral flow for at least some distance. For example, truck-traffic surfaces and large zones of finer-grained rock could cause near-lateral flow in some regions of a pile. Therefore, to be safe, the distances between a NAG zone and all underlying and laterally adjacent NAG zones should be equal to, or greater than, L (Figure 1). If drainage patterns are conclusively shown to be vertically downwards, then separating distances apply only to the next deeper zone directly below. Since this leads to  $L=0$  in a lateral direction, it is synonymous with horizontal layering which is discussed later in this paper.

Based on this discrete-zone mixing (Figure 1), the minimum distance between NAG zones can be calculated relatively easily. The required input parameters and examples follow.

## DESIGN OF A DISCRETE-ZONE PILE

As an example, a minesite has both NAG and NAN rock and wishes to mix them together in one free-draining pile to avoid acidic drainage. The minimum net potential ratio ( $NPR = \text{effective NP/acid potential}$ , from acid-base accounting) to ensure no net acidity from small-scale rock samples is set at 2.0 in this example, so “ReqNPR” = 2.0 (Table 1).

The NAG rock has a deficit of NP, defined as “DefNP”, at 141 t  $\text{CaCO}_3$ /1000 t, which is based on sulphide content of 3%S, an effective NP of 47 t/1000 t, a resulting NPR of 0.5, and the above requirement of  $NPR > 2.0$  to neutralize all acidity. For safety in predictions, DefNP should be a relatively high, rather than average, value as shown later in this paper. The bulk density of the NAG rock is set at 1.7 t/m<sup>3</sup> (“BDNAG” = 1.7 t/m<sup>3</sup>).

The NAN rock has an excess of effective NP, defined as “ExNP”, of 31 t/1000 t, which is based on sulphide content of 1%S, an effective NP of 94 t/1000 t, a resulting NPR of 3.0, and the above requirement that the NPR cannot fall below 2.0 during neutralization of external acidity. ExNP should be a relatively low, rather than average, value for safety in predictions (discussed in more detail later). The bulk density of the NAN rock is set at 1.7 t/m<sup>3</sup> (“BDNAN” = 1.7 t/m<sup>3</sup>).

Each truck at the minesite can carry and dump 100 t as a discrete load, so “WtNAG” = 100 t (Table 1). Each load is dumped as an approximate cube with dimensions of 3.9 m on a side ( $[100 \text{ t}/1.7 \text{ t/m}^3]^{1/3}$ ). So the cross-sectional area perpendicular to flow ( $X^2$ ) is 15.1 m<sup>2</sup>.

The final important parameter is channelling, which limits the contact of acidic water from NAG rock with significant amounts of NP in the NAN rock. Case studies have reported that infiltration through waste rock contacts as little as 5-20% of the rock surfaces (Morin and Hutt, 1997a). So, for this example, the channelling factor (CH) is set at 0.10, meaning only 10% of the NAN rock and its NP is exposed to acidic drainage. This will increase the required distance between NAG zones proportionally, by factor of 10, which is discussed in more detail in a later section.

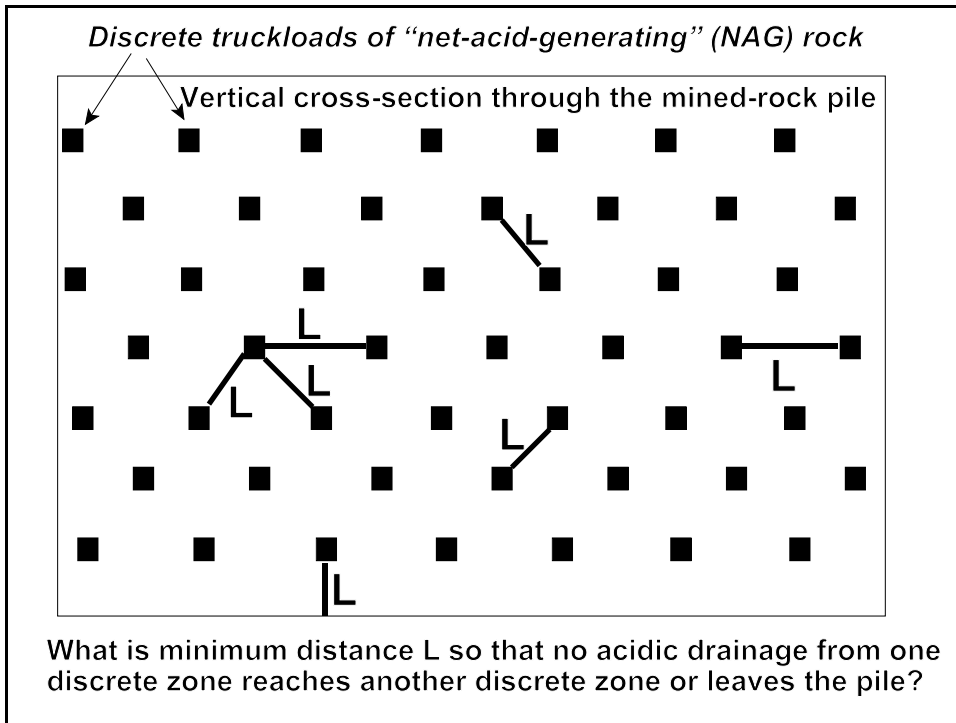


Figure 1 Schematic vertical cross-section through a discrete-zone mined-rock pile.

**Table 1 Example of input parameters for the design of a discrete-zone waste-rock dump**

Variable	Explanation	Selected Value
ReqNPR	Required site-specific NPR to ensure near-neutral pH indefinitely	2.0
DefNP	Net deficit of NP in NAG rock below ReqNPR	141 t/1000 t
BDNAG	Bulk density of NAG rock	1.7 t/m <sup>3</sup>
ExNP	Net excess of NP in NAN rock above ReqNPR	31 t/1000 t
BDNAN	Bulk density of NAN rock	1.7 t/m <sup>3</sup>
WtNAG	Weight of each discrete zone of NAG rock	100 t
X <sup>2</sup>	Cross-section area of NAG rock perpendicular to water movement	15.1 m <sup>2</sup> (each NAG zone assumed to be a cube)
CH	Channelling factor, indicating the proportion of the NAN rock and its NP in contact with acidic drainage	0.1

The applicable equation for calculating the separating distance (L, Figure 1) between the discrete NAG zones is:

$$L = [\text{DefNP} * \text{WtNAG} * \text{ReqNPR}] / [\text{ExNP} * X^2 * \text{BDNAN} * \text{CH}] \quad (1)$$

For this example (Table 1), L is calculated as:

$$L = [141 \text{ t}/1000 \text{ t} * 100 \text{ t} * 2.0] / [31 \text{ t}/1000 \text{ t} * 15.1 \text{ m}^2 * 1.7 \text{ t}/\text{m}^3 * 0.1] \quad (2a)$$

$$L = 354 \text{ m} \quad (2b)$$

Because L is so large, the height of the pile would have to be at least 358 m (354 + 3.9 m) just so that one horizontal plane of NAG zones could be placed at the top to safely ensure that no acidic drainage would reach the bottom. This would still apply even if drainage were consistently downward, L in the lateral direction were zero, and the NAG rock was thus placed as a continuous horizontal layer. Obviously, the construction of such a high rock pile would be impossible for most minesites.

Nevertheless, this example makes an important point, because the selected parameters are not unusual. The deficit of NP in NAG rock would have to be cut from 141 to less than a negligible 6 t/1000 t (NPR of 1.94 which is already very close to ReqNPR = 2.0) before more than one horizontal plane could be placed in a 30-meter-high dump. All this indicates that discrete-zone mixing, as well as layering and blending, of a significant volume of NAG rock cannot normally be carried out with high confidence of success or a low risk of some acidic drainage. Perhaps this is the explanation for Mehling Environmental Management (1998) and Mehling et al. (1997) not locating or identifying “safe blends” and field-scale case studies. Put simply, the characteristics and volumes of NAG and NAN rock at many sulphide-bearing minesites are apparently not suitable for safe discrete-zone mixing. This is discussed further using nearly pure limestone in the next section.

#### PILE-WIDE RATIOS OF NAG AND NAN ROCK

Because acid-base-accounting analyses (ABA) are interpreted through NPR using mathematical division, this simplistic small-scale approach has occasionally been extrapolated to entire mined-rock piles. For example, one waste-rock dump was designed with layers of NAG and NAN rock, involving expensive double handling of NAN rock, so that the overall pile-wide NPR would be roughly 3.0 (Denholm and Hallam, 1991). However, physical factors like the short circuiting of drainage through NAG layers led to the appearance of some acidic drainage within two years (Morin and Hutt, 1997b). Thus, NPR values have little significance on a large scale.

This irrelevance of pile-wide NPR can be shown in another way for discrete-zone mixing, by adjusting the preceding example (Table 1). The geochemical characteristics of the NAN rock are converted to nearly pure limestone. Thus, %S = 0.1, NP = 1000 t/1000 t (assuming basically all the limestone is reactive and available), the resulting NPR is 320, and the ExNP is 997 t/1000t. Based on Equation 1, L now equals 11 m.

With L=11 m and a discrete-NAG-zone dimension of  $A_{x,y,orz} = 3.9 \text{ m}$  in all three directions (a cube), the number of discrete zones that would fit in a pile can be calculated by using:

$$\begin{aligned} \text{Maximum number of discrete zones in one x, y, or z (height) direction } (M_{x,y,orz}) &= \\ &= [\text{dump length in x, y, or z direction } (D_{x,y,orz} \text{ in m}) - L \text{ (in m)}] / \\ &= [L \text{ (in m)} + A_{x,y,orz} \text{ (in m)}] \quad (3) \\ &\text{with } M_{x,y,orz} \text{ rounded down to the nearest integer} \end{aligned}$$

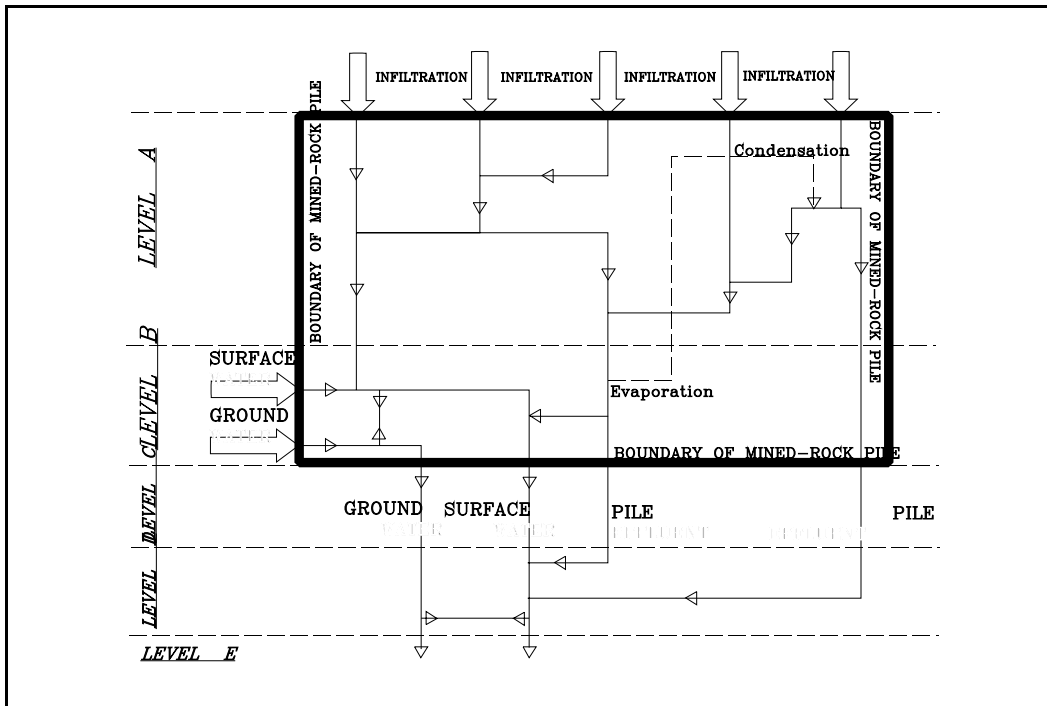
Then,

$$\text{Total maximum number of discrete zones in entire dump } (N) = M_x * M_y * M_z \quad (4)$$

Based on a 10,000,000 t pile with a bulk density of 1.7 t/m<sup>3</sup> and dimensions of 410 m by 410 m by 35 m high, then 676 discrete 100-t NAG zones (26 x 26 x 1) could be safely incorporated. In other words, to safely mix the NAG rock, only 67,600 t (0.68% of the entire pile) could be added to 9,932,400 t of limestone with an NPR of 320.

Adjusting the above into pile-wide NPR values can be accomplished in two ways. First, the total amount of sulphide and NP in the pile can be calculated, leading to a pile-wide NPR of 266. This is dramatically higher than the small-scale criterion of 2.0, but is necessary for ensuring no acidic drainage. Second, the weighted value (67,600 t) at NPR = 0.5 and the weighted value at NPR = 320, indicates the pile-wide NPR is 318, or higher than 266 calculated the first way. Thus, the concept of dump-wide NPR is inaccurate and ultimately irrelevant for controlling acidic drainage.

This point can be made even further by simply adjusting the 10,000,000 t pile to new dimensions of 31 m by 31 m by 28 m high. In this case, 961 discrete 100-t NAG zones can be incorporated into the pile, rather than



**Figure 2 Schematic diagram of flowpaths through a mined-rock pile; Level A represents most of the rock; Level B is the base of the pile; Levels C to E represent the surrounding environment at increasingly greater distances (adapted from Morin and Hutt, 1997a).**

only 676 in the previous configuration (a 42% increase). The two corresponding pile-wide NPR values now become 311 (compared to 266) and 317 (compared to 318). This again shows that non-geochemical factors like pile configuration and distances between NAG zones can greatly affect the design of safe discrete-zone mixing, the amount of NAG rock that can be incorporated into a pile, and the pile-wide NPR value.

#### POTENTIAL COMPLICATIONS IN DISCRETE-ZONE MIXING

The previous sections indicated that the minimum distance of separation of discrete NAG zones ( $L$ , Figure 1) is critical in ensuring no acidic water reaches an adjacent zone, which would then dissolve additional NP within and downgradient of this next zone, and lead to a self-propagating acidic zone. At the base and edges of a pile,  $L$  is also important to ensure no acidic drainage leaves the rock.

Since mistakes and miscalculations can happen, it is informative to evaluate the consequences of discrete zones whose separation is less than  $L$ . Theoretically, this would create a chain reaction, where additional NP that was in place further downgradient would be consumed earlier and by upgradient zones. However, there are safety factors incorporated into the preceding examples and concepts, based on the channelling factor ( $CH$ ). This factor reflects the channelling of acidic water (Figure 2) in that it does not contact all NP in NAN rock nor any available NP in NAG rock. In reality, diffuse flow patterns, heavy precipitation events, and ongoing weathering can be expected to occasionally move acidic water into contact with additional NAN rock. Nevertheless, the results of the preceding example ( $L = 354$  m from Equation 2 and  $L = 11$  m for pure limestone) could only decrease by a maximum factor of 10 if absolutely all NP in all NAN rock remained reactive and eventually participated fully in acid neutralization.

For many cases, this adjustment to channelling would make little difference. For example, most minesites with sulphide rock usually find that more than a few percent of their waste rock is NAG, and, based on the pure limestone example above, the amount of NAG rock that can be incorporated would increase from 0.68% by weight to perhaps 7% at most. So even the total dismissal of channelling ( $CH = 1.0$ ), as shown in the next section, could still preclude mixing as an ARD control at many minesites.

Any water moving through NAN rock will dissolve some NP and contain alkalinity, and then occasionally combine with acidic water (e.g., Figure 2). However, alkalinity in pH-neutral mine-rock waters will rarely exceed 500 mg/L, whereas acidity in acidic water is typically above 2000 mg/L to as high as 100,000 mg/L. Therefore, on an equal flow-rate basis, one acidic flowpath would have to combine with four to 200 near-neutral

flowpaths to produce a combined near-neutral flow. This is particularly relevant for flowpaths leaving the pile along the base or sides. If all exit flowpaths combine within the pile and report to one location, then the prediction of whether the water will be acidic or neutral, upon failure to maintain L separation, depends on the number of acidic and neutral flows. Again, if neutral flows outnumber acidic flows by 4:1 to 200:1, then the combined drainage will likely be near neutral. Alternatively, if neutral flows report to one discharge location and acidic flows report to another, there will be both acidic and neutral drainage from the pile. Such a case has been documented (Morin and Hutt, 1997b) and is conceptually understood (Figure 2).

Therefore, the prediction of overall acidic or neutral drainage upon a failure to maintain L separation in a discrete-zone pile cannot be made in a general sense. The prediction depends on numerous site-specific physical and geochemical factors as discussed above, like the number of flowpaths and the nature of their intersections.

## COMPARISON TO PREVIOUS WORK

Kempton et al. (1997) created a more elaborate approach to discrete-zone mixing, and analyzed random versus organized placement of NAG rock in a rock pile. Their analysis focussed on arid and semiarid climates, but the approach is similar to the one here. The best way to illustrate the differences is to adapt the input parameters of Table 1 to their study.

Although Kempton et al. (1997) used computer-based statistical modelling, their data can be adapted to Equation 1 and Figure 1. First, based on their humidity cells,  $NNP = 0 \text{ t}/1000 \text{ t}$  separated NAG and NAN material, although some excess NP is usually required elsewhere. As a result, average  $DefNP = 15.4 \text{ t}/1000 \text{ t}$  and average  $ExNP = 144 \text{ t}/1000 \text{ t}$ .  $ReqNPR$  was set at 1.2 according to government requirements, although values greater than 1.2 often apply (Morin and Hutt, 2000, these proceedings). No channelling was assumed, so  $CH = 1.0$ . Finally, only vertical flow was considered, so there was no lateral separation required between the NAG material (horizontal  $L = 0$ ) and, in fact, the rock was modelled as 6-m-thick horizontal layers. This allows a much greater amount of NAG rock to be placed within the pile compared to discrete zones. Based on an assumed bulk density of  $1.7 \text{ t}/\text{m}^3$  and considering a vertical column of  $1 \text{ m}^2$  cross-sectional area so that a 6-m layer would contain 10.2 t of rock, the resulting L is:

$$L = [15.4 \text{ t}/1000 \text{ t} * 10.2 \text{ t} * 1.2] / [144 \text{ t}/1000 \text{ t} * 1 \text{ m}^2 * 1.7 \text{ t}/\text{m}^3 * 1.0] \quad (5a)$$

$$L = 0.77 \text{ m} \quad (5b)$$

In the  $1 \text{ m}^2$  vertical column of 100 m height, there can be a maximum of fourteen 6-m-thick layers  $[(100 - 0.77) / (0.77 + 6)]$ . These 14 layers would represent 84% of the pile. Since estimates for their site indicated 50% of the rock was NAG, this pile can accept all 50% and more based on the discrete-zone approach with horizontal  $L=0$ .

Interestingly, the results of Kempton et al. (1997) were more pessimistic. With a statistic model that randomly selected  $DefNP$  and  $ExNP$  from a range of values, and with a vertical column that included 15 m of NAN rock at the base, Kempton et al. found that 15% of the base would release net acidity.

The discrepancy between their study and the discrete-zone approach lies in the  $DefNP$  and  $ExNP$  values. Equation 5 uses average values, instead of poorer-case values which leads to greater safety in predictions. If  $DefNP$  is set to  $200 \text{ t}/1000 \text{ t}$  and  $ExNP$  is set to  $20 \text{ t}/1000 \text{ t}$  based on probability plots in their Figure 2 (these values are roughly in the outer 5% of their ranges), then the recalculated L is 72 m. This means that the pile cannot even safely accept one 6-m layer. As a result, layering with 50% of NAG rock would lead to acidic drainage.

Kempton et al. (1997) also noted that increasing the thickness of the layers increased the amount of net acidity at the base nearly proportionally. This can also be seen in Equations 1, 3, and 4, where an increasing thickness would lead to an increasing  $WtNAG$ , which in turn leads to a proportional increase in L and a near proportional decrease in the number of layers permitted in the vertical column to completely avoid any acidic drainage.

Based on this, the simple discrete-zone approach will provide an indication if some acidic drainage will leave a pile. However, detailed predictions of the extent and severity of the acidic drainage require more detailed modelling, like that of Kempton et al. (1997) for relatively simple scenarios like vertical flow, or more intensive modelling of scenarios like Figure 2 which is not yet available.

## CONCLUSION

This paper has examined simple discrete-zone mixing, where at least one truckload of NAG rock is placed in a particular location with no further handling or dozing. According to Equation 1, the absence of acidic drainage is dependent on the intervening distance between the discrete NAG zones, along flowpaths occupied by NAN rock. Calculations have shown that minimum separation distance (L) can be so great, even with typical NAG and NAN rock, that the mixed pile could safely contain only a few percent of NAG rock, which would not be

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sufficient for many minesites with NAG rock. Other calculations have shown that the physical configuration of a pile, while maintaining a constant volume, can change the amount of allowable NAG rock by several tens of percent.

The bulk mixing ratio of a mined-rock pile was found not to be an accurate indication of whether near-neutral drainage can be maintained. For example, a pile with a bulk ratio around 300:1, containing approximately 99% limestone and 1% NAG rock, could still release some acidic drainage if L separation was not maintained.

The comparison to a more elaborate, computer-based statistical model by Kempton et al. (1997) showed that the simple discrete-zone approach will provide a reliable yes-no indication of whether any acidic drainage will leave a pile. However, predictions of whether combined downstream drainages will be acidic depend on numerous site-specific physical and geochemical factors, like the number of flowpaths and the nature of their intersections, that cannot be modelled in a general way.

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