Optimising Bauxite Residue Deliquoring and Consolidation

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Abstract

The effective management of bauxite residue represents one of the most significant long-term issues facing the alumina industry. Although significant progress has been made in recent years in pre-disposal thickening technology, understanding of the principles underlying post-disposal management of residue to enhance deliquoring (Mud Farming) using twin Archimedes Screw Tractors (ASTs commonly known as Amphirols) is not as advanced. Reviews of several operations have indicated examples of site-specific methodologies with limited relevance to the underlying dynamics and reference to, or reliance on common rules of thumb that lead to inconsistent performance across residue storage areas or between operations (using the same equipment and similar residue characteristics) through ineffective application of ASTs for homogenous, full-depth residue consolidation. Data is presented of an optimised consolidation management approach developed at BWAPL to ensure residue consolidation to desired strength targets with existing equipment whilst minimising disposal area footprint. The regime requires strict control around residue deposition practice with key parameters being residue depth, consolidation time and number of active cells determining open area and number of ASTs. Other important aspects to be considered include seasonal conditions such as rain extent and dust formation risk and control. A simple model can be applied to define active working area requirements based on residue characteristics, production rates and required AST coverage capacity. This approach allows BWAPL to operate at higher residue deposition intensities and to consolidate residue faster and to higher strengths independent of residue solids content. Although proven for the BWAPL case, the logic is transferrable to any alumina residue or similar slurry deposition operation.

Keywords:

Bauxite residue, residue depth, Amphirol, AST, cell/surface area, consolidation, residue solids content, deliquoring, upstream embankment, mud farming.

Introduction

Management of bauxite residue is one of the most significant issues facing the alumina industry. Over the last 25 years considerable progress has been made in developing new technologies to reduce the impacts from the storage of bauxite residue. However, the catastrophic failure of an embankment at the Magyar Alumina Plant (in Ajka, western Hungary) in October 2010 and the subsequent inundation and fatalities in nearby villages only highlight that as an industry far more work is needed.

The most obvious advance in bauxite residue management has been the development of high-density disposal, or dry stacking, technologies. This approach has provided significant benefit by reducing the size of storage facilities by increasing the density and strength of bauxite residue. Importantly, this increase in strength has allowed the development of upstream embankment construction methods, where new embankments are constructed on deposited bauxite residue “upstream” of the existing embankment (Figure 1). Generally, this enables additional capacity to be created at a lower overall cost than increasing the capacity through alternate means.

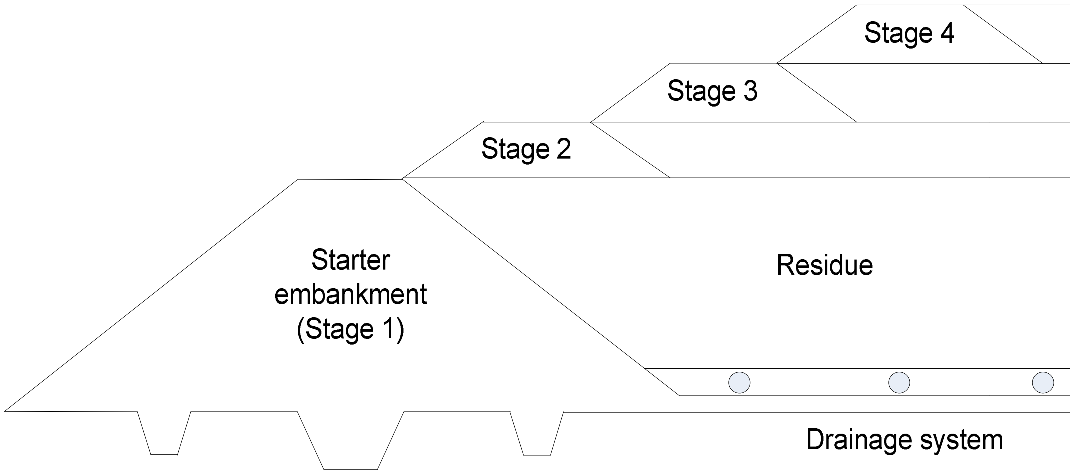

Figure 1 Schematic of upstream embankment construction method

The conventional approach of importing materials to ensure stable foundation for the upstream embankment entails significant cost. Therefore the variation commonly implemented is to use bauxite residue as the foundation layer (or at least as an integral component of it) for the upstream embankment construction process. This approach requires each layer of deposited residue to achieve enough strength through deliquoring (via surface runoff, underdrainage and evaporation) and subsequent consolidation to resist shear induced from further layers deposited above, to ultimately become an integral component of the strength of the overall impoundment structure. This of course can theoretically be achieved through extended fallow periods between deposition events to allow for self-weight consolidation. However, in practice whilst reducing the immediate capital cost this not only leads to a significant expansion in required residue storage footprint but is inhibited by crusting behaviour, subsequently entrapping liquor and leaving low strength layers. It is therefore of paramount importance within this method that steps are undertaken to ensure homogenous residue strength development of all stages of deposition.

The extremely slow strength development usually associated with fine-grained tailings subjected to the passive self-weight consolidation approach commonly leads to the pursuit of higher residue densities from thickeners seen as being integral to the solution. The theory being the higher the residue solids of the slurry, the quicker target strength can be achieved. In practice, and as previously indicated, bauxite residue is associated with a complex liquor that crusts and entraps moisture, which results in the strength stratification effect commonly observed in many storage facilities.

Mud farming of bauxite residue using ASTs (Figure 2) is a recognised means of accelerating this process. The effective application of ASTs maintains deliquoring by preventing crust formation and subsequent liquor entrapment, whilst maximising the available benefits of natural evaporation and drainage properties.

A survey of several operations throughout the industry utilising the same equipment on residue with similar characteristics revealed a broad range of management strategies, consolidation rates, initial deposition densities, equipment capability perceptions with varied final strength results, even though the final shear strength targets were similar. Although it is appreciated that much of this can be attributed to a diversity of residue properties, whereby small differences can lead to large effects, limited data exists for justification of the logic applied to both AST use and residue impoundment management to maximise consolidation whilst minimising operational footprint.

It is suspected that a contributing factor to the disparity between operations lies within the reductionist, small-scale versus holistic, large-scale approach to residue consolidation. More specifically:

- Laboratory-determined residue consolidation parameters were found to be relied upon without revalidation of field observations and;
- Small scale, shallow deliquoring behaviour is not necessarily representative of large scale, deep deposition practice.

Figure 2 An AST being commissioned in fresh bauxite residue.

This is not to say that laboratory and small scale trials are redundant, but moreover that they need to be replicated in, and adjusted to suit large-scale application. Similarly, data trends derived from laboratory work can provide useful guidelines for expected performance but field practices need to be suitably modified to realise these outcomes. Furthermore, the optimal regime for ASTs cannot be pre-determined or trialled on small-scale tests (or in the laboratory), but is readily defined through vigilant field data acquisition at full-scale production rates. This work aims to provide a detailed framework of key parameters that need to be understood in order to optimise the use of ASTs leading to optimal consolidation rates and minimised storage facility footprint.

Key Points for Bauxite Residue Consolidation and AST Optimisation

Preliminary Deliquoring/Consolidation Rate Data

Many residue impoundment design reports rely upon modelled residue consolidation rates defined from accelerated consolidation trials undertaken at a range of residue solids contents, but lack any information on how to optimise or maintain the process. This leads to the common industry perception of high discharge solids being seen as integral to rapid consolidation. This holds true for self-weight consolidation, but only if the final field practice is representative of the scale of the original experiment. More importantly, the most valuable piece of data that can be derived from these trials is commonly overlooked in many operations examined, and that is definition of the maximum deliquoring rate.

The maximum deliquoring rate is dependent on the nature of the residue and also the system within which it is placed. As indicated by Somoygi (1979) and Glenister and Cooling (1985), improved residue consolidation will take place in the presence of effective drainage. This is facilitated by both upward and downward flow driven by the maximum pore pressure within the saturated slurry. The outcome of this process is the presence of “bleed-water” and underdrainage flows as is commonly observed in the field.

Once the maximum deliquoring rate is defined, data conversion to equivalent weight or volume percent solids increases can be defined with strategies developed to try and sustain this rate and thus minimise consolidation time. Figure 3 provides an example of field definition of preliminary deliquoring rate. This method also provides a way of measuring the extent of residue discharge that needs to be included in short-term volumetric storage budgets.

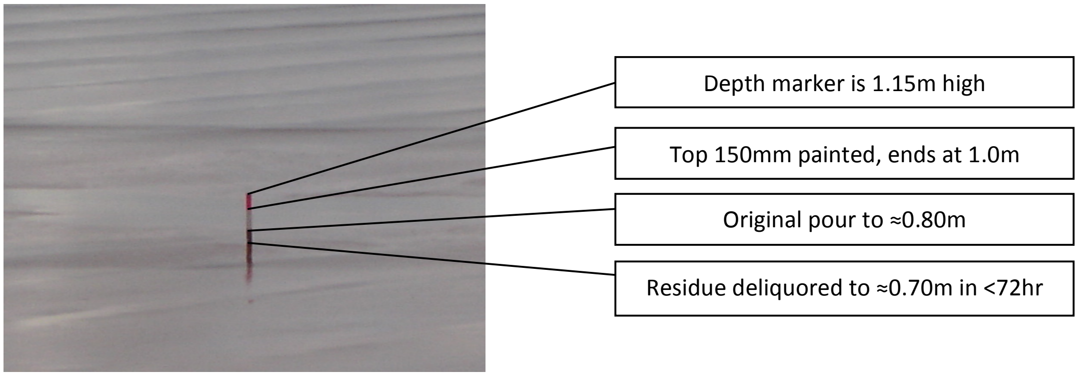

Figure 3 Example of residue deliquoring in an area 48-72 hours after pouring at 56 wt% solids. Deliquoring rate calculated to be 14-21 m^3/Ha/hr, or an increasing solids content of 1.7-2.5 wt%/dy.

AST - Background

ASTs have been historically used to access very low strength ground conditions such as snow, swampy terrain or reclaimed land. The mode of application has been widely adopted by, but not necessarily well-adapted to the alumina industry as no standard data or regime is available to optimise consolidation in practice. This is due to a combination of propriety held information of individual refineries and the unique and highly variable nature of bauxite residues. In addition, there is an oversimplification of what the AST can achieve resulting in poor application of the technology. Therefore, optimised residue consolidation practices need to be defined by each refinery incorporating the specific characteristics of the bauxite residue, the design of the AST and other site-specific factors. In BWAPLs' (BHP Billiton Worsley Alumina) case, mud farming at the bauxite residue disposal area (BRDA) is managed using several ASTs. The following are the key parameters required to optimise AST performance and residue consolidation.

1 Residue depth – initial and final

As a starting point, data provided by equipment suppliers (e.g. maximum machine working depth), first principles (machine weight, displacement and residue density) and field observation (equipment performance measurement) indicate that the most important factor in bauxite residue management is initial deposition depth. For most ASTs used in Australia, the above information and shear vane data support a maximum initial residue depth to be no greater than 1.2 m. Residue depths beyond this cannot be directly or effectively consolidated by ASTs because as residue depth increases, AST access is inhibited or speed significantly reduced, thus coverage capacity is compromised.

Furthermore, as the AST only consolidates up to approximately 0.8 m of residue, initial depth is also dependant on residue solids content. For example, higher solids contents may dictate shallower pours to prevent the final residue profile exceeding 0.8 m. If initial or final depth is exceeded, the lower residue region beyond the effective working depth has its liquor trapped between two low-permeability layers for extended periods. This trend is clearly evident in all historic shear vanes collected from residue storage areas subjected to deep deposition practices. BWAPL has demonstrated the optimal initial deposition depth for its residue is 1.1 m.

2 AST coverage capacity

The ability of an AST to effectively cover residue impoundments is closely linked to residue characteristics and deposition depth. For example, ASTs perform quite differently on clay versus silt and may by unable to access deep residue areas at all. ASTs used in the alumina industry are specifically designed to deliquor residue placed as a layer over a firm foundation. The loading effect of the machine accelerates the overall rate of liquor removal. Using the machine in deeper layers eliminates this benefit and usually results in a lower overall rate of liquor removal. Also, without the benefit of the foundation layer the overall rate of progress of the machine will be slowed. Therefore, once the maximum working depth has been defined for a particular operation, a GPS tracking study is required for determination of machine coverage capability.

3 AST scroll frequency

Interestingly, there is potential to over-use ASTs, both at initial and final stages of deposition. For example, within the first few weeks after deposition the residue strength properties are extremely low and difficult to accurately quantify, leading to visual indicators being more useful in the field to determine scrolling frequency. At early stages of consolidation, ASTs merely maintain deliquoring, but the rate is ultimately a function of residue particle size distribution, density and liquor composition. In essence the residue must have settled sufficiently to have enough strength to permit the passage of the AST without the action of the scrolls re-pulping the residue. Careful definition of inter-scrolling period is required as more frequent AST passes within the first two weeks after deposition can do more to resuspend residue than to consolidate it.

Conversely, continued use of ASTs in residue that exceeds a shear stress of > 25 kPa does little to further consolidation (although may be required for dust suppression), especially when other equipment can access the residue at this point. It is therefore necessary to define clear guidelines as to when AST activity is commence, the timing between passes and its endpoint.

4 AST scroll pattern

The final important aspect of enhanced AST consolidation is that the machines need to pass each layer several times and in different orientations depending on residue characteristics, deposition depth, previous layer morphology and local climatology. Some operations are capable of achieving desired strength within three passes, whereas others require as many as ten. Also, the choice of scrolling methods employed by operators can include:

- Single scrolling
    - Where the machine makes a single pass over a layer of residue and returns to the impoundment perimeter on a new track. Involves cutting a new track at the “wet end” of the deposition.
- Double scrolling
    - Where a machine makes two passes over the same scroll track. This is used primarily in the early phase of the drying cycle to maximise local impact of the scroll and where turning into a new track in the “wet end” is not possible. This process creates wider and deeper scroll tracks than a single pass and ensures the deliquoring process is maintained. The issue with this approach is that reduces the effective machine coverage.
- Split scrolling
    - Generally each machine pass will split the scroll tracks from a previous pass. This ensures that the entire residue layer is impacted by the mud farming process and that no local areas of low density or strength impact future disposal operations.
- Transverse/cross scrolling
    - At early stages of consolidation, this approach is used to prevent machines being channelled into the previous layers’ scroll lines, in cases where the previous scroll lines are not suitable for optimising deliquoring of the new layer.
    - Conversely, towards the end of the drying cycle the rate of drainage flow will reduce thereby increasing the relative importance of evaporative drying. By crosshatching the existing scroll lines the evaporative surface can be further opened up and maintain a higher overall deliquoring rate. In addition, this approach serves as a means of increasing the surface roughness of the residue layer.

The critical aspect of all scrolling is to eliminate the presence of pooled liquor or rainfall. This is achieved with straight, uniform scroll patterns from the elevated areas to the lower or better drained areas. Any deviation from this approach creates opportunities for slowing of overall deliquoring performance.

Summary

Irrespective of the ultimate number of passes or pattern within a scrolling campaign, bauxite residue should be managed in order to conclude AST consolidation within 5-6 weeks subsequent to deposition, potentially followed by a period of ripping or other additional works if required by strength targets or seasonal conditions (i.e. dust control).

Therefore, a campaign of a range of residue deposition depths followed by detailed data acquisition prior to each subsequent pass is required to define the optimal residue deposition depth, number of passes, type of scrolling regime and optimal inter-scrolling period for a specific operation. This in turn will lead to definition of required machine coverage to ensure homogenous consolidation.

Residue Properties and Management

High weight percent residue solids are advantageous at the point of discharge for reducing self-weight consolidation time and limiting residue discharge volumes, but it must be remembered that residue storage and management can be tailored to suit residue parameters. This is in contrast to the common refinery design practice that usually dictates a residue solids content as high as practical with no consideration given to how this subsequently dictates residue management. It is therefore important to design refineries in parallel with residue management practice options derived from the various potential refinery outputs. A key point being that specifying an exact target (usually as high as physically possible) may not be necessary as opposed to an acceptable range with a clearly defined strategy to optimise residue consolidation and strength development suited to this range. Critically, pursuit of ever higher discharge densities can lead to an increase in overall BRDA opex as earthmoving solutions may be required to compensate for the deterioration in residue flow properties.

Perhaps the single most important factor to be determined from any consolidation regime is the solids content/relative density achieved once the residue reaches target strength (consolidation shrinkage extent). Although this value may differ from the optimal moisture content defined in geotechnical analyses, it is invaluable for defining the required actual medium-term residue storage capacity. It is therefore, important to define the final/expected volume as opposed to spending excessive capital on minimising the initial discharge volume.

A basic deposition strategy

The key tenet of this paper is recognising that by adopting mud farming to optimise the residue disposal operation requires the development of operational tools to monitor and forecast performance. Such an approach has been developed by BWAPL and Table1 provides an example of this simplified deposition model and key input parameters. The model was developed from the starting point of defining and then optimising consolidation rates an AST is capable of achieving in a specific operation, followed by how the storage facility needs to be designed in order to maintain this rate and finally, relating these parameters to the refinery outputs. Note that this approach is the reverse to nominal refinery and residue storage design practice.

Table: 1 Example of a basic residue deposition model

Residue Properties and refinery discharge parameters	Solids density	g/cm^3	Liquor density	g/cm^3
	Residue solids flow rate			TPH
	Residue solids content			wt%
	Volumetric flow rate			m^3/dy
	Slurry to consolidated correction			%
	Volumetric filling budget (90% of total discharge)			m^3/dy
	Medium-term volumetric storage budget			m^3/dy
Residue storage facility design and operational parameters	Planned residue deposition depth			m
	Forecast daily coverage to intended depth			Ha
	Time to consolidate			dy
	Number of cells available			
	Required open area			Ha
	Cell size required			Ha
	time to fill a cell			dy
Residue consolidation and management requirements	Number of ASTs available			
	Average daily distance capability			km
	Average daily coverage capacity			Ha
	Combined fleet coverage capacity			Ha
	Number of passes required to consolidate			
	Required AST coverage capacity			Ha

Table 1 demonstrates that the deposition strategy is divided into three sections that flow from the top down to ultimately dictate AST-optimised consolidation management requirements. However, within this approach, the most important factor is defined as the required open surface area, not only as this has the largest impact on the refinery water balance, but also as minimising area simplifies residue and consolidation management.

The advantage of using such an approach is that when refinery outputs change, the residue management practices can be updated to suit the new parameters. Thus, aiming for a specific initial solids content is no longer a key driving force in residue consolidation, but rather one of several interrelated factors to be considered within an optimised residue consolidation strategy. Although the discharge solids significantly impact pumping capacity and short-term open area requirement, only the final residue density and volume are considered for the long-term storage budget, as (ideally) the same final density will always be achieved (Figure 4). This single aspect is by far the dominating issue in determining operational forward plans, capital expenditure and closure considerations.

Also, the time to consolidate, whilst variable with residue solids output, is not of prime consideration as lower solids slurries tend to deliquor quicker (Figure 3) and ASTs are able to provide minor corrections in deliquoring rates by adjusting mud farming intensity.

Normal residue storage practice assumes that if a reduction in deposition depth is undertaken that the consequence will be an expansion in footprint. It has been demonstrated at BWAPL that this is not the case and contrary to common perception for two reasons:

1) The management regime is cyclic and is scheduled around consolidation time, whereby each cell is revisited as soon as strength targets are realised.
2) The algorithm used for determining open area is non-linear and leads to definition of the minimum open area required. Additional area beyond this value is required for construction, but this is defined by site-specific civil works capabilities.

For BWAPL, application of an algorithm and the above strategic approach allows for the current open area of 124 Ha being adequate (on average) for an 8 MTPY residue management operation (64 kT/Ha/Yr).

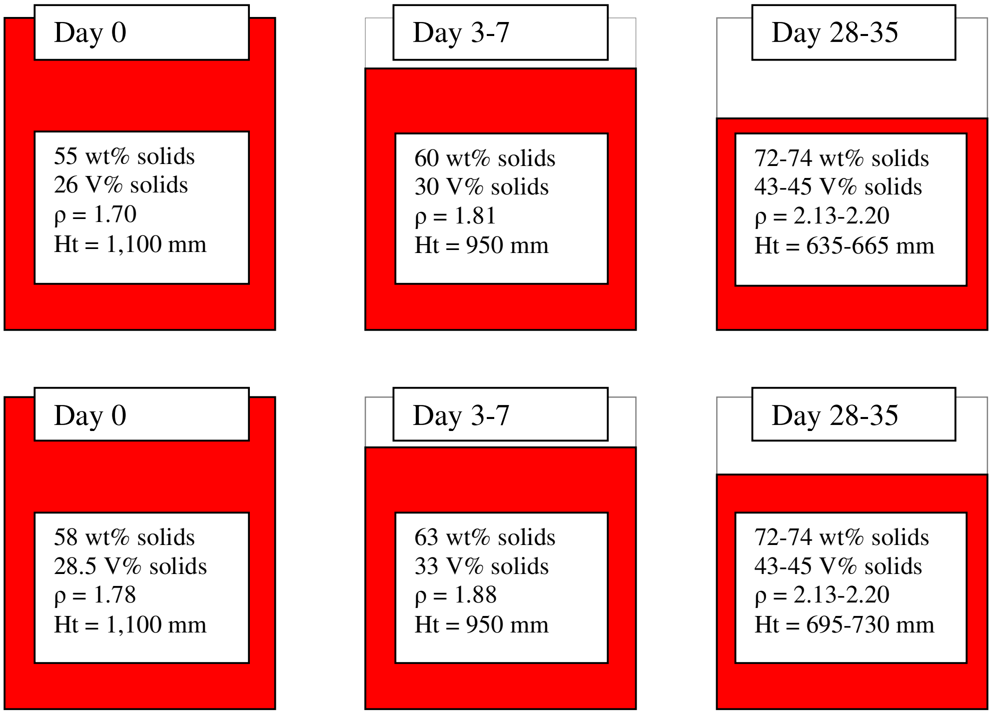

Figure 4 Progression of consolidation with discharge at 55 or 58 wt% solids.

It is also important to note that soon after residue deposition, in some locations, dust formation can become a dominant factor in residue management. However, within this approach to residue management required surface area is coupled with consolidation time and cell rotation, and therefore no area lies fallow for significant periods, thus minimising the need for additional dust suppression systems.

Strategy in Practice

Figure 5 provides a comparison with laboratory-scale self-weight consolidation rates started at two different wt% solids against an optimised AST consolidation regime. For the particular operation examined, 54.5 wt% solids (initial residue solids) was considered to be catastrophic with respect to long term storage and consolidation requirements i.e. the time required to achieve the required final residue solids was too long to enable sustainable operation. However, the implementation of an optimised AST regime (field data from the same location) with the same starting wt% solids indicates a reduction in consolidation time by up to 60 weeks (>12 months).

From Figure 4 (and assuming a 72.5-74.0 wt% final solids target), application of this strategy, (when compared to operation without ASTs) provided:

- A 65% reduction in the potential consolidation time at the higher initial residue solids target (63.0 wt% solids – beyond plant equipment capabilities, and prohibitive due to discharge limitations) and;
- A 90% reduction in the potential consolidation time at the lower (perceived as catastrophic) solids target (54.5 wt% solids).

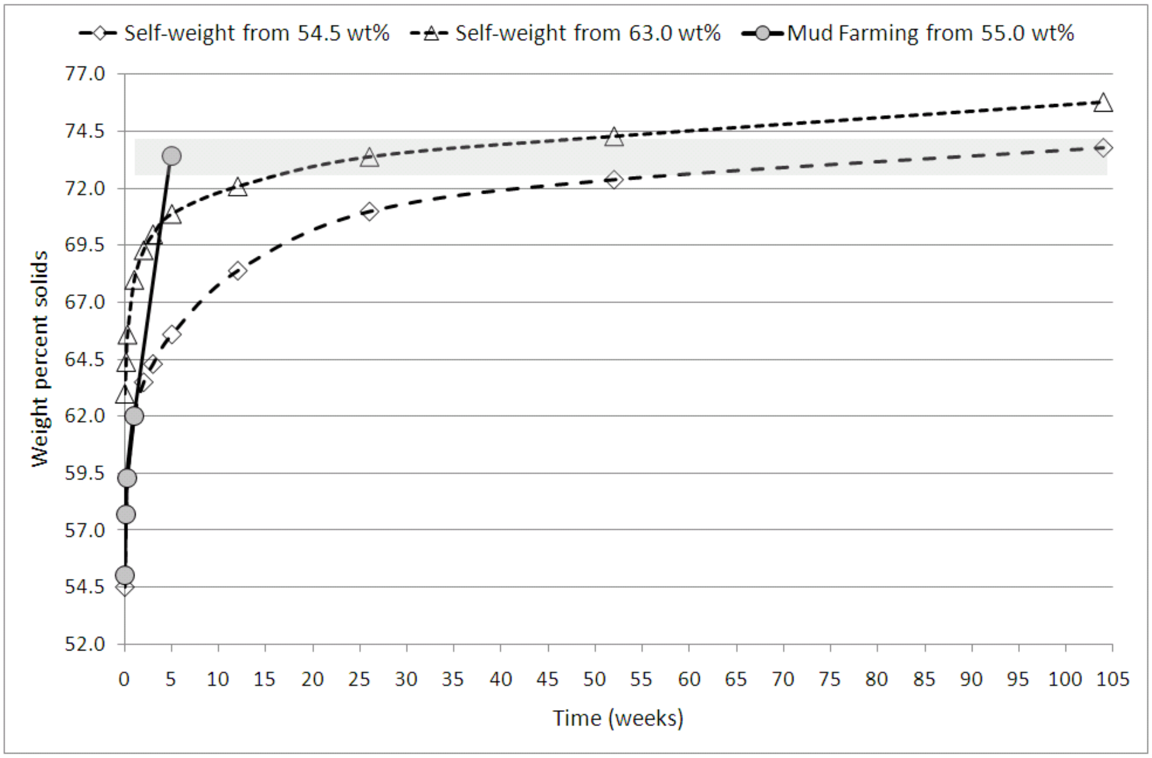

Figure 5 Effect of an enhanced AST consolidation regime on residue consolidation rate versus natural consolidation rates. Shaded area between 72.5 and 74.0 wt% solids indicates target solids content for continued construction.

Figure 5 provides support for the hypothesis that a full-scale optimised residue consolidation regime closely follows the slope of the maximum (initial) residue deliquoring rate, as defined from laboratory trials. Therefore, although the original intent of the laboratory data is no longer applicable to full-scale practice, the data can provide a new tool for reasonably predicting the potential of an AST-enhanced mud farming regime. This relationship may not always be this clear as in the example provided for all operations and therefore further assessment of this approach is recommended in other mud farming operations.

Conclusion

Data collated thus far with respect to the BWAPL AST-enhanced consolidation strategy indicate a significant and sustainable reduction in consolidation time for operations, less dependent on discharge rates or residue solids content than previously perceived. Of utmost critical importance for optimised consolidation is the strict control around residue deposition depth, as exceeding the effective working depth of ASTs inhibits equipment performance, increases consolidation time and thus required open deposition area. The parameters provided in this report are only indicative and need to be redefined and/or adapted to suit individual operations, seasonal conditions, specific residue characteristics and discharge rates.

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