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Optimal Design and Operation of Raw Material Stockpile Homogenisers

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Optimale Auslegung von Mischbett-Halden für Rohstoffe
Conception optimale et fonctionnement d'homogénéisateurs de stockage de matériaux bruts
Diseño y explotación óptimos de los homogeneizadores de pilas de materias primas
原料備蓄ホモジナイザーの最適設計と操作
原料堆积均质器的最佳设计和运转
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Summary

Layered stockpiles have the primary property of removing low frequency variability in quality although they reduce high frequency as well. Provided they are well designed the change in mean quality from pile to pile can be reduced to that acceptable for powder reactor control.

A method for optimal stockpile design is given, involving microscopic computer simulation of the layering geometry and the allocation of successive significant quality values along each layer with the determination of arithmetic weighted averages of quality for reclamation of successive well mixed quantities. Performance criteria and design guidelines are presented. This paper is the second of two concerned with stockpile design and operation criteria.[*]

Nomenclature

a	Heuristic choice of range of correlation or influence of quality variable
j	Counter
k	Data lag
v_s	Traverse speed (m/min)
A	Stockpile cross-section
AR(i)	Autoregressive process of order i
ΔC	Difference in mean batch to quality level
ΔK	Quantity of material per reclaimed slice
L	Stockpile length
LSF	Lime saturation factor
M	Stockpile capacity
N	Number of layers
N_c	Maximum number of layers for the chevron stockpile for a particular outer layer maximum thickness
N_c^*	Limiting value of effective number of layers
Q	Material layering rate (t/h)
Q_c	Critical or significant quantity of well mixed powder
ΔR	Quantity of material per layer
$R_{x_1 x_k}$	Autocorrelation function
S_w	Reclamation slice width
T_{res}	Pseudo stockpile mean residence time
V_p	Volume of Q_c quantity
V_s	Volume of sub-Q_c quantity
W	Stockpile width
X	Distance from boom to pile centre
α	Angle of repose
μ_t	Process noise
θ	Angle of inclination of the side acting reclamation boom
ϱ	Bulk density (t/m³)
σ^2	Variance (apparent)
σ_0/σ_1	Variability reduction ratio
ϕ	Time series model fitted parameter (AR)

1. General Introduction

Mineral chemical quality heterogeneity can be considered on several levels varying in scale and size. The types encountered in mineral solids during their preparation and processing being related essentially to the way in which such minerals evolved during their formation, the nature of the quarrying methods utilised and the types of handling and preparation procedures employed.

Each quarrying, crushing, grinding, storage and handling procedure in some small way contributes directly to the overall variability of the material.

Each fragmentation from blasting to crushing, each recycling of ore in continuous transport, each hopper and each stockpile introduces a certain amount of restructuring of the spatial distribution of natural mineralisation.

Mineral raw materials have a somewhat chaotic random spatial chemical variability. This observation is true both if one considers the variation in chemical quality with spatial position within the un-quarried ore-body as a whole, or if one monitors by sampling, the variability with respect to time of the ex-quarry mineral as it flows past a given point on a conveyor as it goes to be processed.

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[*] Schofield, C. G., "Review of Raw Material Stacking and Reclamation Methods", bulk solids handling Vol. 1 (1981) pp. 429—436.

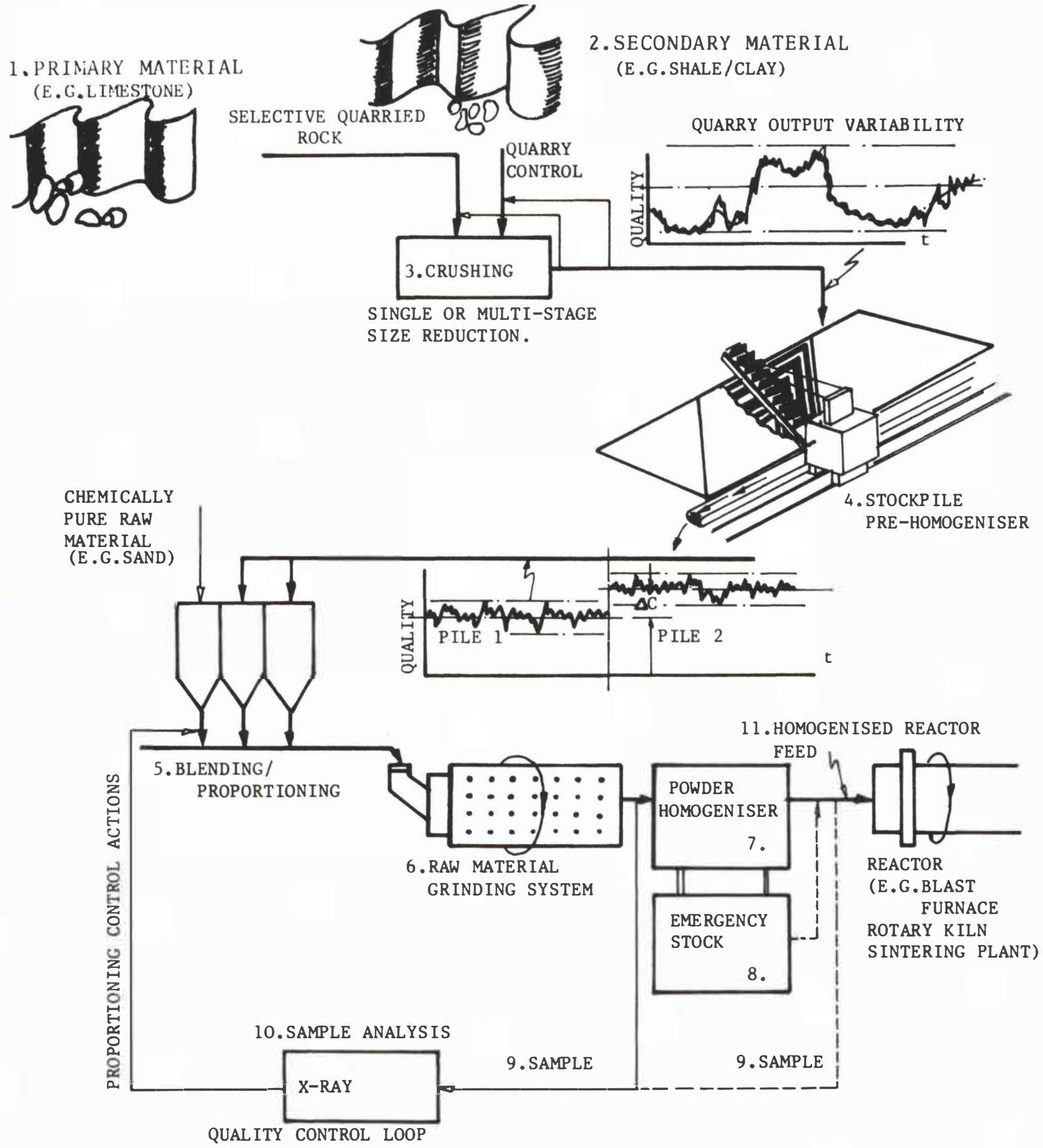


Fig. 1: General minerals processing raw materials preparation and homogenisation system

In many minerals processing systems there is a subsystem with the role of pretreating quarried or mined rock and producing, via a sequence of interacting processing elements, a fine powder, homogeneous in the time coordinate direction.

As a focus for discussion, let us consider a typical pre-reactor raw material homogenisation system as shown in Fig. 1 which depicts all the elemental units potentially utilised in the homogenisation of any mineral raw material.

There are therefore essentially four main processing areas available for raw material homogenisation:

- The quarry
- The crushed stone stockpile system
- The material grinding system
- The powder homogenisation system.

1. Selective raw material quarrying methods based on available knowledge of the site/deposit can provide a valuable crude initial homogenisation capable of greatly reducing the range of quality variation within the as-quarried raw material.

Its importance cannot be over emphasised because by careful implementation of selective quarrying procedures based on predictive control, that is, ahead of the quarry face sampling forming the basis of quarry management decisions, the dependence upon automated sample analysis equipment and downstream units could be much reduced.

Mainly through his experience (backed by geological data and ahead-of-the-face sampling) the quarry manager knows fairly accurately to within metres in some cases the spatial position on a face where material with a specific chemical quality is located. The validity of this remark will obviously vary from site to site and implies a combined function of the skills and acumen of the individual quarry manager coupled with the rate of chemical variation within the relevant deposit.

However, in general terms, shift and period average quality targets are usually met, although short term variability is likely to be rapid and of considerable deviation.

With regard to mineral homogenisation and stable reactor control the quarry manager is undoubtedly a key figure in the entire operation as downstream variability is directly related and influenced by his actions.

It is therefore essential that the process designer furnish the quarry manager both with the facility and techniques to allow accurate monitoring of quality levels and quality trends in the advancing quarry face, thereby ensuring that decisions made regarding homogenisation at the quarry face are the correct ones.

2. The stockpile pre-homogeniser (Stage 4) with typically a capacity in the region of one weeks production, has a dual purpose within the overall pre-reactor system in that not only is it capable of acting as a buffer for varying production rates between the quarry and the reactor, but by careful material stacking (usually in a longitudinal direction) and material reclaiming (usually orthogonal to the direction of stacking) the stockpile may be used for low frequency material quality variability filtering.

   The detailed mechanisms of mixing operative within the pre-homogeniser are in reality complex and as a result little understood by process designers, with the result that units and ancillary equipment tend to be overdesigned and costly. In many sites where the quality of the raw materials utilised are consistently high the need for a high capital cost plant such as the pre-homogeniser stockpile cannot be justifed, nor in some cases is it necessary. However, with steadily increasing demands for a higher quality product coupled with the attendant and inevitable worldwide use of lower and more variable raw materials the stockpile pre-homogeniser is fast becoming a standard item in the typical material preparation system.

3. The third main area available for mineral homogenisation is the raw material grinding system (Stage 6) and in particular the modern large ball mill systems which are essentially particle size reduction devices with the additional ability to act as low pass material quality variation filters.

   Again it must be said that process design has in the past tended to overlook the importance of ball mill systems for raw material homogenisation, which because of their internal method of operation and large retention time have a certain potential for mixing.

4. The fourth area available for homogenisation within the overall system is the powder blending system (Stage 7).

   After grinding the product is then in the form of a very fine powder, which when fluidised by air at a high velocity has similar mixing properties to a liquid. This fluidising effect and the resultant ease of mixing is utilised advantageously within the powder homogenisation system.

   Such systems which typically have a material retention time greater than five hours are capable of effective high frequency quality filtering with the ability to smooth out step changes in quality which will inevitably occur due to batch processing in the linear stockpile pre-homogeniser.

2. The Stockpile Pre-Homogeniser

The linear stockpile pre-homogeniser (Stage 4, Fig. 1) because of its ability for low frequency quality variation filtering through successive piles has found wide acceptance within the industry and its use may be divided into two groups:

— Combined homogenisation of several raw materials

— Single material homogenisation.

Combined homogenisation of several raw materials requires that the various material input flow streams be of a balanced known chemical composition with the proportioning of the components performed before stacking.

Irregular particle size difference between the component materials however, often causes partial material segregation resulting in a substantial deviation around output quality set points.

Separate homogenisation of the individual raw material components is the easiest of the two methods to apply as it does not rely too heavily on detailed sample and analysis equipment or raw material proportioning procedures — as only the monitoring of mean quality levels is necessary.

Crushed material typically with a particle size distribution of less than five centimetres is homogenised at the pre-homogeniser stage.

Many different equipment types and stacking configurations are employed within the industry for material layering and reclamation. The main criterion affecting the choice of such equipment and layering configurations, is a function of the desired stockpile input-output material quality variability reduction, the inherent material physical properties and the space and capital expenditure available [1, 2, 3, 4].

The more efficient the mixing process operative within the stockpile homogeniser the smaller is the size of plant required to achieve a specified reduction in variability, thus lowering the capital costs involved.

Attempts have been made within the U.K. cement industry to achieve effective homogenisation via underground discharge/reclamation systems which run longitudinally beneath conical/rectangular stockpiles. However, such systems rely too heavily on chance for effective operation, with consistency of output quality and level of variability reduction substantially below that of a properly designed layered stockpile, which will always be smaller and more efficient than the unlayered stockpile if a careful integrated design is carried out.

The traditional *black box* lumped parameter approach to stockpile design adopted by the majority of homogenisation equipment manufacturers is, unless based upon measured performance characteristics of fixed geometry design, to be regarded as being inaccurate and only approximate, essentially because of the inherent complexities of the mechanisms of mixing that are operative within the stockpile.

Optimal design can only be undertaken in a realistic manner by direct digital computer simulation of the microscopically detailed method of operation.

3. Process Parameter Design Constraints

If the entire usable contents of a particular deposit were to be quarried and perfectly homogenised in one large stockpile the resultant output mean quality would be that of the deposit. Problems of selective quarrying, pile to pile mean quality variation ΔC would be dispensed with and the processing units and reactor would be guaranteed a constant mean quality continuous material supply.

Although such a specification represents one optimal solution (if $N \rightarrow \infty$), from a homogenisation point of view it is neither practical nor cost effective. Of course, in a realistic design situation a compromise must be made between the capital outlay in the purchase of land, equipment etc. and the desirable and practical efficiency of the pre-homogeniser.

In the main the present day approach to the specification of the requisite size and capacity of the stockpile homogeniser is essentially a function of fulfilling the minimum buffer storage requirements with any capacity over and above this being subject to the quantity and cost of available land. Typically no consideration is given to the requisite capacity/residence time requirements in order that a certain required input/output raw material variability reduction can be achieved.

In reality the designer is restricted in his approach to an optimal solution by certain operational and stockpile geometric parameter constraints and considerations which are essentially related to the intrinsic properties of the raw materials and the characteristics of the various stockpiling/stacking configurations employed.

For example consider the following:

3.1 Linear Stockpile Volumetric Efficiency

During the initial stages of reclaiming a new linear stockpile material output quality is not representative of the stockpile mean quality due to the fact that the number of layers cut by the reclaimer $\ll N$ and not until the reclaimer reaches the body of the stockpile where material is then being extracted from all parts of the cross-sectional area is the output representative. This initial stage is due to the structure of the material within the end cones of the pile and is consequently repeated during the latter stages of reclaiming the pile. Standard practice which compensates for the above variation in quality is to either:

1. Layer the end cone material onto another stockpile.
2. Use the initial end cone as above and leave the rear end of the pile in situ effectively as a retaining wall for new material during subsequent layering.

Because the end cones can represent a large percentage of the total capacity, it is clearly desirable to minimise the quantity of material contained within them so that the volumetric pile efficiency is maximised. This efficiency is a function of the ratio of the length of the stockpile to its width (that is L/W ratio).

Volumetric pile efficiency

$$= \frac{\text{volume of pile used}}{\text{total volume laid down}} \times 100 \qquad (1)$$

where the volume used is that of the central horizontal triangular section. Fig. 2 shows this relationship for both the above cases.

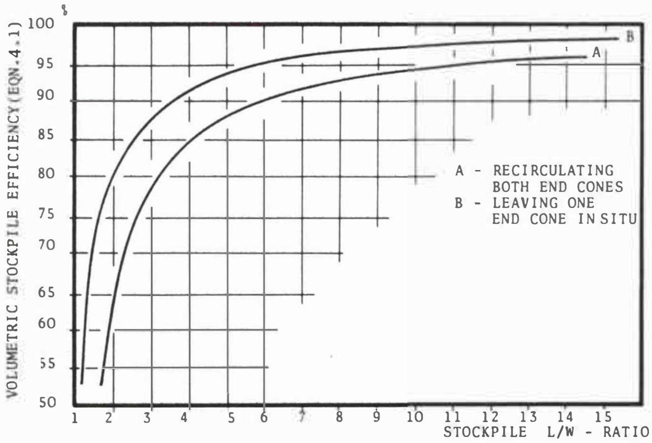


Fig. 2: Volumetric efficiency for the longitudinal stockpile pre-homogeniser

It may be seen that for adequate volumetric efficiency (i.e., 95%) L/W must be > 5 when recirculating one end cone and > 10 when recirculating both. Even so, considering a typical cement plant stockpile (~ 25,000 tonnes) some 1,250 tonnes would be double handled.

Realistically, from an operational cost point of view, the L/W ratio should be at least 5 and ideally > 10.

The L/W upper limit would be fixed either by its relationship with M (stockpile capacity) assuming W is set (by cost considerations) or by land availability. In the majority of installations facility is usually provided for a nominal 50% increase in storage capacity at low capital cost by simply extending the rails on which the reclaimer runs and hence the length of the stockpile.

Taking account of the above points, therefore, a long thin stockpile is more economically viable than a short wide one.

3.2 Constraints Imposed by Particle Size Distribution

More often than not it is the subsequent downstream processes which dictate the size distribution of the material supplied and homogenised within the stockpile.

In the iron and steel industry, to promote uniform smelting in the blast furnace, ore is homogenised with a size distribution of —0.7 cm. In the cement industry which typically utilises closed circuit ball mills for powder grinding, optimum unit power consumption dictates that the crushed stone fed to the mill via the stockpile should be within the size distribution —4 cm and should an Aerofall mill be utilised for grinding, the distribution is likely to be —13 cm.

In the specification of the stockpile feed rate, it is usual practice to have both a constant stacker traverse speed and a constant stacking capacity, hence the quantity of material and the cross-sectional area of each layer is in such cases constant. Therefore for a *Chevron* layered stockpile the layer thickness diminishes towards the outer-most layer [1]. Because of this fact selection of the stacker traverse speed is based on the following considerations:

Stockpile capacity $\approx N \times$ quantity of material per layer

$$N \times \phi_m / L \approx A \cdot p_s \cdot \text{Stockpile length}$$

Hence

$$N \approx \frac{A \cdot p_s \cdot L \cdot 60}{(\phi_m / v_s) \cdot L} \approx \frac{v_s \cdot A \cdot p_s \cdot 60}{\phi_m} \qquad (2)$$

where

N = Number of layers
v_s = Stacker traverse speed in m/min
A = Stockpile cross-section
ϕ_m = Stacking capacity t/h
p_s = Bulk density in t/m³

Quite clearly for a given stockpile volume and stacking capacity for a certain N, there exists a series of possibilities for the L/W and v_s; available area and the most economical layout usually dictates the solution selected. N the postulated number of layers as determined by the majority of equipment manufacturers and suppliers, is based on simple Gaussian statistical relationships [4, 5].

However, what is not generally realised in using these relationships is that the concept of N layers is justified only if the thickness of the Nth layer is greater than the raw material maximum particle size otherwise material in the outer layers will not be evenly distributed. Fig. 3 shows the functional relationship between maximum particle size (minimum thickness of outer layer) and the maximum number of layers for different stockpile base widths using the assumption of a 35° angle of repose.

The maximum number of layers so determined would be classified as N_c which for a certain particle size distribution and stockpile width should not be exceeded.

For example, consider a stockpile width of 30 m with an angle of repose of 35° layering material of —4 cm in a *Chevron* manner then with reference to Fig. 3 it may be seen that if more than 110 layers (N_c) were placed on the stockpile, those layers greater than N_c would not contribute to blending in the same manner as the layers less than N_c.

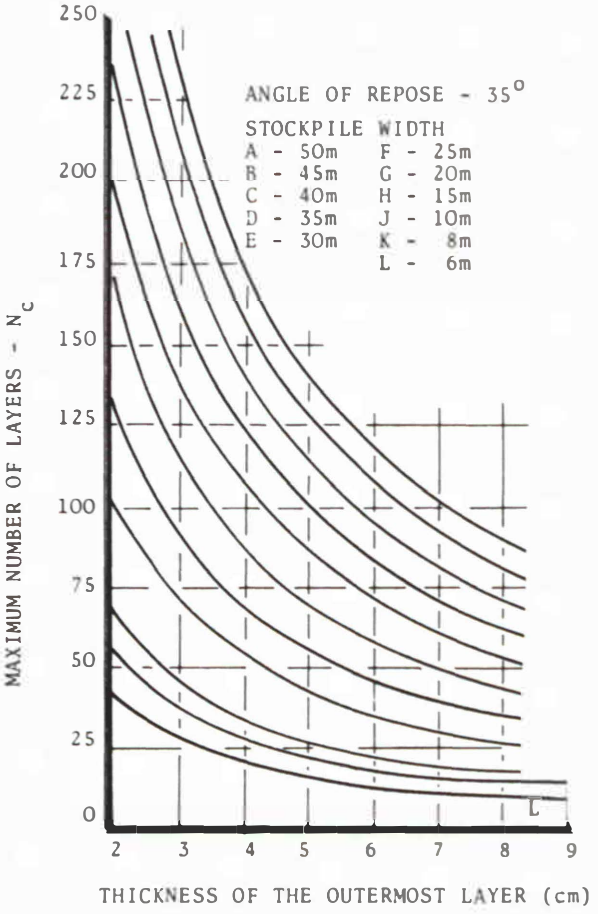


Fig. 3: Physical and geometric relationship between W and N_c

If $N > N_c$ then substantial segregation would be evident in the additional layers and it is unlikely that material would be distributed over the whole of the stockpile surface. However, if the barrel or Disc Reclaimer is used [1, 2, 3] when $N > N_c$ or if a Q_c mixing device is downstream, virtually no effect on the output quality variability will be observed, as for example the barrel reclaimer takes material from all parts of the stockpile cross-sectional area thereby ensuring that the effects of segregation are minimised.

3.3 Concept of the Critical Sample Quantity Q_c

Accurate determination of the critical sampling quantity Q_c is an important factor in the detailed design of the overall raw material homogenisation system.

Its value is assessed as the maximum quantity of off specification material of a specified analytical quality, for example, the maximum stockpile output quality which if allowed to enter the kiln, would just perturb the product quality outside the desired set limits (Stage 12, Fig. 1).

Its value may be determined through the use of the residence time distribution function of the powder reactor whose input is supplied by the stockpile for a tolerable range of variability specified. It is far better to underestimate the value of Q_c than to overestimate it because overestimation using a value $Q_{c_A} > Q_{c_c}$ would give an optimistic view of the variability filtering capability of the overall system in view of the averaging process implied by considering larger sample sizes. The use of Q_c is a concept which is fundamental to accurate and realistic homogenisation system process design. Fig. 3a shows a typical non-ideal composite

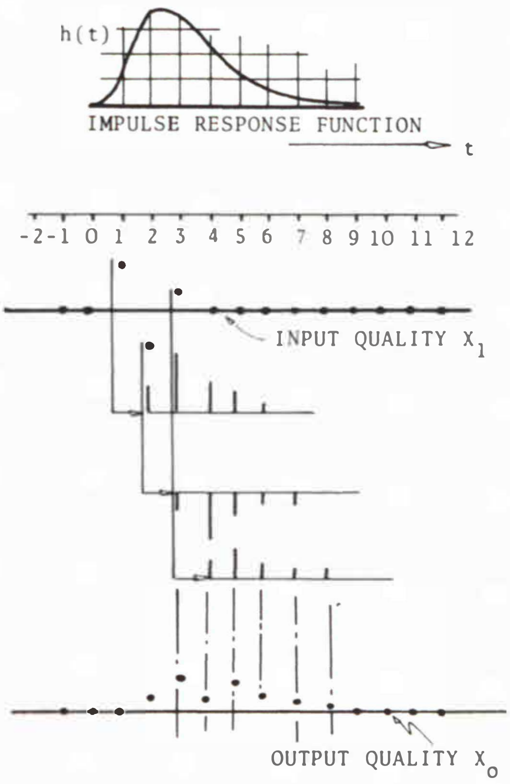


Fig. 3a: Composite response to random changes in quality

response to random quality changes, from which it may be seen that the system impulse response to successive unit pulses are mixed together due to the overlapping of the separate pulse responses. Because of this, every process which has residence time flow characteristics other than plug flow [6] has a basic capacity for mixing.

The response of a particular system or sub-system processing unit (e.g., kiln, ball mill, fluidized homogeniser) can be used to give a physical insight into the value of Q_c for the system. Because of the basic differences with regard to the form of the impulse response shape each unit will have a unique value for Q_c.

In the design and simulation of the overall homogenisation system, the particular value of Q_c to be used is that which appertains to the sensitivity of the process reactor.

For example, with reference to cement manufacture, process control conditions and quality considerations for large kilns dictate that the kiln feed should ideally be within ± 1.5% LSF of target, *and for large scale rotary kilns (e.g., 2,000 t/d)* Q_c is typically equal to 30 tonnes for this size of kiln.

This quantity if expressed in physical terms can be visualised as the quantity of material or payload of a typical quarry dumper truck. Hence for this size of plant the critical sampling quantity is 30 tonnes and system design must ensure that the kiln must only experience off specification material in the form of sudden impulses in quantities less than Q_c.

4. Development of a Microscopic Simulation Model

To reduce the number of variables under consideration, permitting a more concise presentation of simulation experimental results, enabling a reduction in the number of experiments, dimensional analysis/groups are valuable. The homogenisation efficiency of the stockpile is a function of:

1. The geometric parameters of the stockpile.
2. The methods and type of plant employed for material layering and reclaiming.
3. The raw material characteristics quantified in terms of the critical sample quantity Q_c, particle size und quality.

For simplicity, particle size segregation phenomena are omitted from the simulation model assuming these can be spread over the section by careful design and are thoroughly mixed by down-stream processes. Material reclamation is taken as orthogonal to the direction of layering und the stacking out feed rate is taken as a constant.

For developing the general method of stockpile design we restrict the study to consider *Chevron* layering only, either single or in multi-triangular form, because of its practical importance and relative simplicity, but still include as options all the different types of material reclamation.

The stockpile variability reduction ratio σ_0/σ, and the batch to batch quality variation $\overline{\Delta C}$ are a function of three principle dimensionless groups;

$$\sigma_0/\sigma_1 = f(L/W, S_w/W, N) \tag{3}$$

Therefore:

$$f(L/W, S_w/W, N, \sigma_0/\sigma_1) = 0 \tag{4}$$

considering the input variability time series $X_i(t)$ where each point describes the quality of a sample size Q_c. Of primary importance from a mixing point of view is the microscopic way in which this variability is distributed within the stockpile. Therefore, of equal importance to the number of layers N is the quantity of material deposited per layer ΔR and in particular the relationship between ΔR and Q_c.

Therefore, the variables of particular relevance with regard to system performance are, L/W expressed in terms of M, S_w/W expressed in terms of ΔK, ΔR and N.

Hence for a given type of variability, material and Q_c:

$$\sigma_0/\sigma_1 = f(\Delta R, \Delta K, M, N) \tag{5}$$

ΔK may in some instances be disregarded but such an assumption is only valid for the barrel and Disc Reclaimers or where downstream mixing is adequate and where S_w is sufficiently small so that the assumption of $\Delta K \ll Q_c$ is valid.

For reclaimers such as the side-acting reclaimer, where $\Delta K > Q_c$ and slice to slice mixing cannot be regarded as perfect, the effect of ΔK is important.

Because of the relationship between ΔK and S_w/W, specification of ΔK for a given L/W or M implies specification of S_w and boom width for the side-acting reclaimer.

4.1 Side-Acting Reclaimer

This method of operation of the side-acting reclaimer (Fig. 4) is chosen as a basis for detailed simulation. Material layering is assumed to be in a *Chevron* manner with single position discharge in a longitudinal manner. By considering the side-acting reclaimer, the flexibility of the simulation model is not restricted because by modelling this type of reclaimer we can:

1. Make quantitative conclusions as to the efficiency and optimal parameter specification with particular reference to the side-acting reclaimer.
2. By considering a range of slice reclamation widths, i.e., $S_w \rightarrow 0$, conclusions may be drawn regarding desirable slice width or machine advancement/step length for the end type reclaimer, be it the barrel, disc or bucket wheel.

4.2 General Aspects of the Model

The basic objectives are to be able to determine the variability of the output material in Q_c quantities as a function of time during the whole pile reclamation, and to establish in a quantitative manner the pile to pile average variations subject to certain imposed input variability characteristics.

In order to achieve this, there is a need to enumerate for each position of the hinged reclaiming booms arc of sweep across the pile, the exact proportions of each input layer in the section of slice being reclaimed at that point in time. Fig. 5 shows the parameters and concept of solution used.

The first step is to obtain an expression for the volume of the stockpile lying above the reclaiming boom for each slice and for any angle of inclination of the boom θ.

In the following the assumption is made that a vertical transverse slice is taken, whereas in practice, an oblique slice at 35° (α°) is reclaimed with a combined vertical and longitudinal transverse movement (Fig. 6). The two systems are, however, identical in respect to the relative proportions of the component layers.

Referring to Fig. 5, a horizontal line is drawn through the intersection of the boom and the centre line of the pile (*ac*),

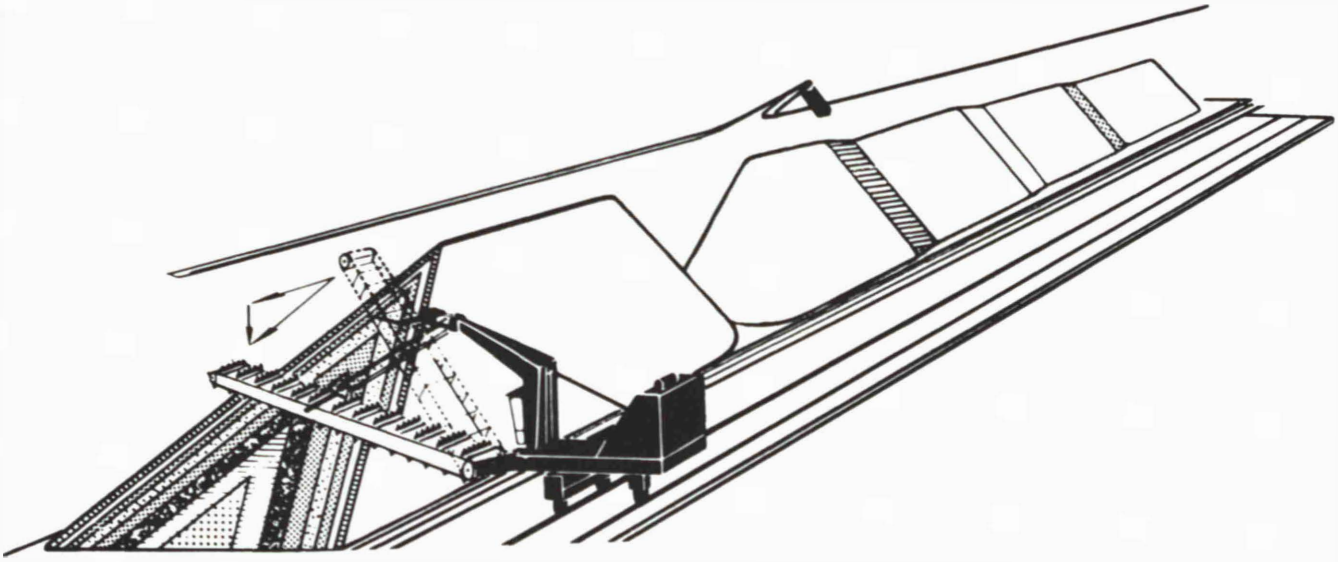


Fig. 4: Side-acting scraper reclaimer

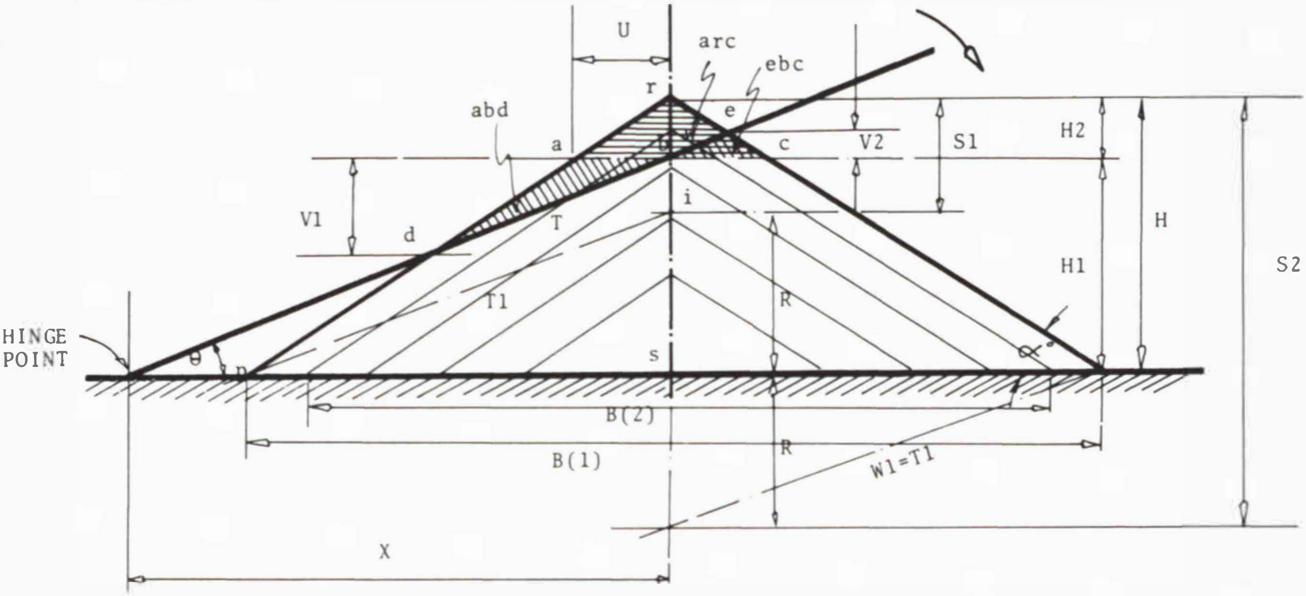


Fig. 5: Slice reclamation via the side-acting reclaimer — *Chevron* layering

thus three areas are formed relating to the total area above the boom at any angle θ, these are A1 (*arc*), A2 (*abd*), and A3 (*ebc*).

Hence the total area above the boom is given by:

$$ATOT = A1 + A2 - A3$$

It is now necessary to find the area between two successive increments of θ. This can be done by subtracting ATOT ($J - 1$) from ATOT (J) where J has values from θ_{max} to 0; this is represented by ASEG (J). The increment between successive values of J can be made as small or as large as required (Fig. 6).

The next stage is to find the area of any part layer lying in the Jth segment; a calculation of ASEG (J) being necessary for the Ith layer in the stockpile, (where $I = 1, N$).

Subtracting ASEG ($I + 1, J$) from ASEG (I, J) will thus yield the area of the Ith layer in the Jth segment; this is represented by AREA (I, J).

The whole procedure is demonstrated in Fig. 6. It will be appreciated that ASEG (I, J) contains anything from 1 to N layers (depending on J), thus AREA (I, J) for $I = 1$ may remain zero until 50 % or so of the slice has been reclaimed.

The method of layering and the assignment of quality values to specific quantities of material is undertaken within the model in the following manner:

Quality values along a time axis are assigned in a manner similar to the layering sequence, i.e., in a zig-zag manner. In this way a two-dimensional matrix of quality values is built up, with each block or element of the matrix representing the quality of a quantity Q_c. As such the physical representation of each block within the stockpile model is therefore a roof shaped element of material ΔX long, with a cross-sectional area and shape equal to that of the Ith layer cross-section (Fig. 7).

The stockpile simulation output is, in terms of average segment Q_c quality, calculated on a percentage area basis, i.e., if layer 1 represents 50 % of the material reclaimed for a given quantity Q_c, then a 50 % weighting is attached to the quality value for that layer. Output is in the form of a time series where each value represents a quantity Q_c at time intervals Δt.

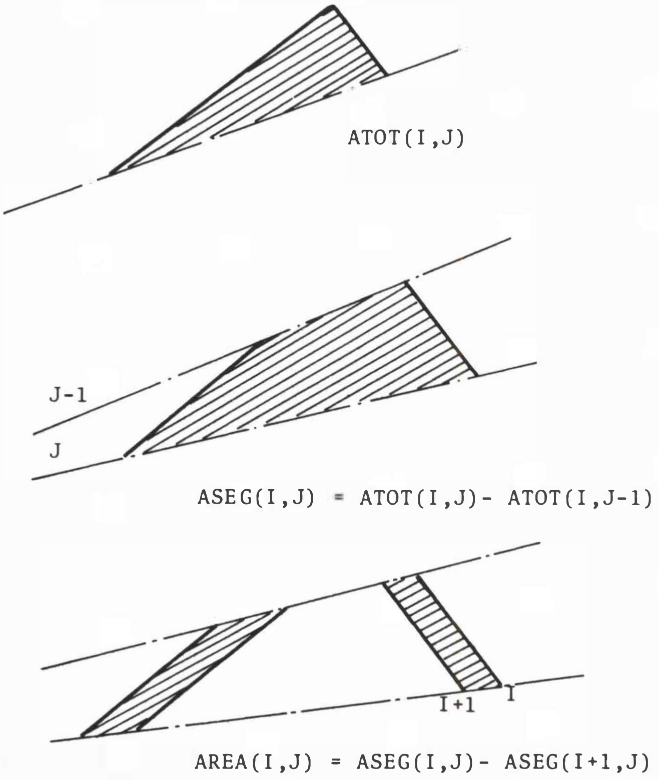


Fig. 6: Model parameter definitions for slicewise reclamation using the side-acting swing boom reclaimer

Naturally, because the method of operation of the digital computer is in a discrete step-wise form, simulation must also be in a similar manner, and although the operation of the side-acting reclaimer is via a continuous sweeping action the simulation actually digitises this method of reclamation. In so doing, the boom operation was allowed to be continuous until the quantity Q_c had been reclaimed, the relevant output quality was then calculated and continuous reclamation subsequently resumed until a further Q_c segment had been reclaimed.

Effective Double Averaging: The problem of *double averaging* arises because due to the geometric configurations of the stockpile and the reclaiming procedure, fractions of each volume of Q_c (as deposited) have to be manipulated within the model and it would be incorrect to use this assigned quality value for smaller volumes because of the sample volume — sample variance relationship.

The concept of *double averaging* is shown in Fig. 7. It is well known that as the volume of a sample decreases, its variance and therefore its variability increase. If the sub-quantities can be considered statistically independent then this relationship is given by:

$$\sigma_p^2 \cdot V_p = \sigma_s^2 \cdot V_s \qquad (6)$$

where σ_p^2 and σ_s^2 are the variance of the population and sample respectively, and V_p and V_s are the volumes of the respective sample sizes. It follows that Eqn. 6 can be reduced to the more familiar form

$$\sigma_p = \sigma_s / N \qquad (7)$$

where $N = V_p / V_s$.

In the case under question V_p represents the volume of Q_c and V_s the sub-Q_c volume present in a fraction of each layer in a Q_c segment.

The quality value assigned to each quantity Q_c of the input time series is an average value representing the average quality for each 30 tonnes of material and for this sample size we have a complete picture in statistical terms, that is the relevant mean and standard deviation. For smaller quantities such information is destroyed during the averaging process of sample collection and analysis.

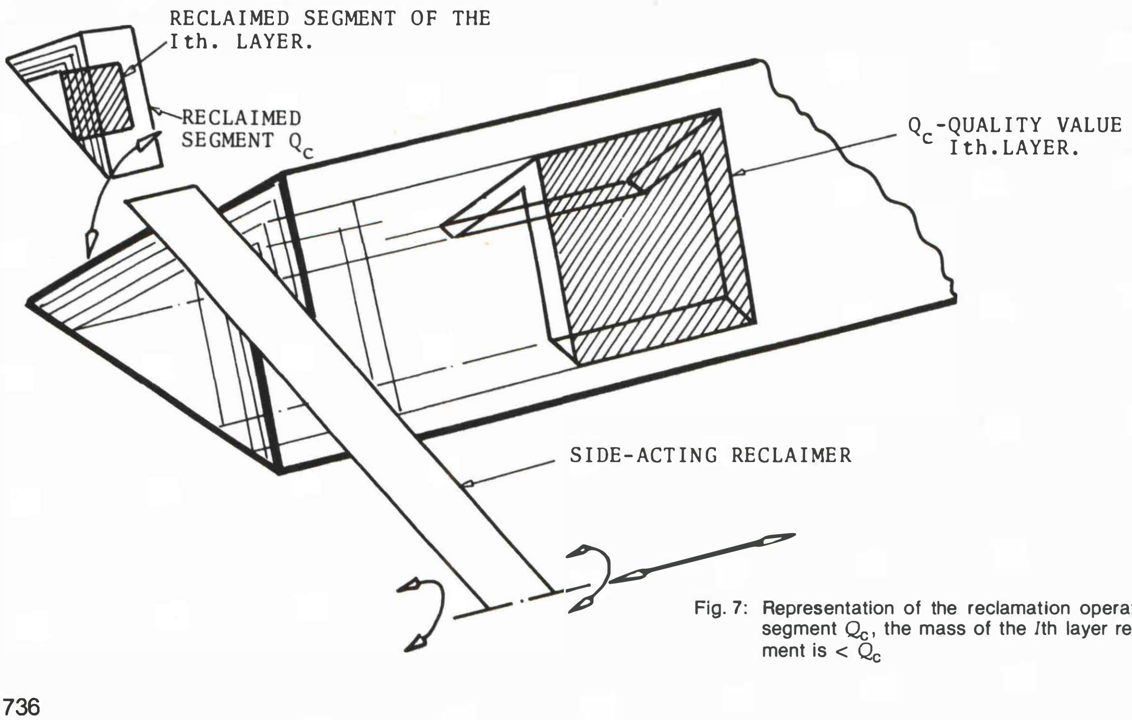


Fig. 7: Representation of the reclamation operation showing that for a segment Q_c, the mass of the *I*th layer reclaimed within the segment is $< Q_c$

However, there are numerous cases where typical variable grade deposits may be approximated by the so called log-normal frequency distribution [7, 8, 9]. Such a hypothesis appears to be justified regardless of sample size [10], neglecting of course any sample to sample correlation.

As we already have the sample mean (i.e., Q_c quality) and the sub-Q_c quantity variance (Eqn. 7), it is therefore a matter of course to generate random variates which would be constrained to follow the log-normal frequency distribution. Such new values are then assigned to sub-Q_c quantities.

Extension to Encompass the Multi-Triangular Type *Chevron* Stockpile: The need may arise perhaps due to the inherent problems of segregation to consider a multi-triangular form of the Chevron layering procedure. The structure of the simulation model described briefly above, can be readily adapted to such a form. With reference to Fig. 8, as the boom descends from the apex (position 1), reclamation is exactly as modelled in the single triangular *Chevron* model except that $X = (X_1 + X_2)/2$ and all the height parameters have to be adjusted by a factor equal to H_A. This continues until position 2 is reached, at which point reclamation is from two distinct areas, A and $(C + D)$. Reclaimed material quality assessment for area A is straightforward utilising the above algorithm with $X = X_1$, to which has to be added a slightly modified program which will take account of geometric layering configurations and parameter values of the centre section, $(C + D)$.

Section B can be incorporated simply by setting $X = X_2$. In essence, therefore, three algorithms are needed, two of which are a duplication of the single triangular routine described above, with the third being of a form similar to the other two only altered slightly to account for the different geometries.

Even though the application of the layering technique shown in Fig. 8 would realistically involve only a marginal additional increase in capital cost and complexity, the majority of minerals processing engineers do not find the basic need for such a layering sequence, and typically utilise the simple *Chevron* stacking arrangement.

5. Optimal Stockpile

In a realistic operational situation, with manual material feed control using selective quarrying procedures, the stockpile homogeniser input quality is more likely to maintain a roughly consistent average over the medium time period Δt (where $\Delta t > 3$ hrs) being essentially of a pseudo random nature [10, 11], than to exhibit singular long-term deterministic trends. Short-term trends may be present in isolated cases due, for example, to continuous working along a particular quarry face.

The approach adopted here for stockpile input quality data characterisation, is to work with pre-filtered differenced data, in order that the standard deviation parameter (σ) may be utilised as a realistic quantitative measure of quality and thereby the ratio of output to input standard deviation (σ_0/σ_1) taken as a measure of range reduction and homogenisation efficiency for suitably random data.

Deterministic trends, for example, periodic variability, are averaged separately for each reclaimed slice by taking account of the layering procedures and suitably adding the resultant quality in Q_c quantities to the random component average.

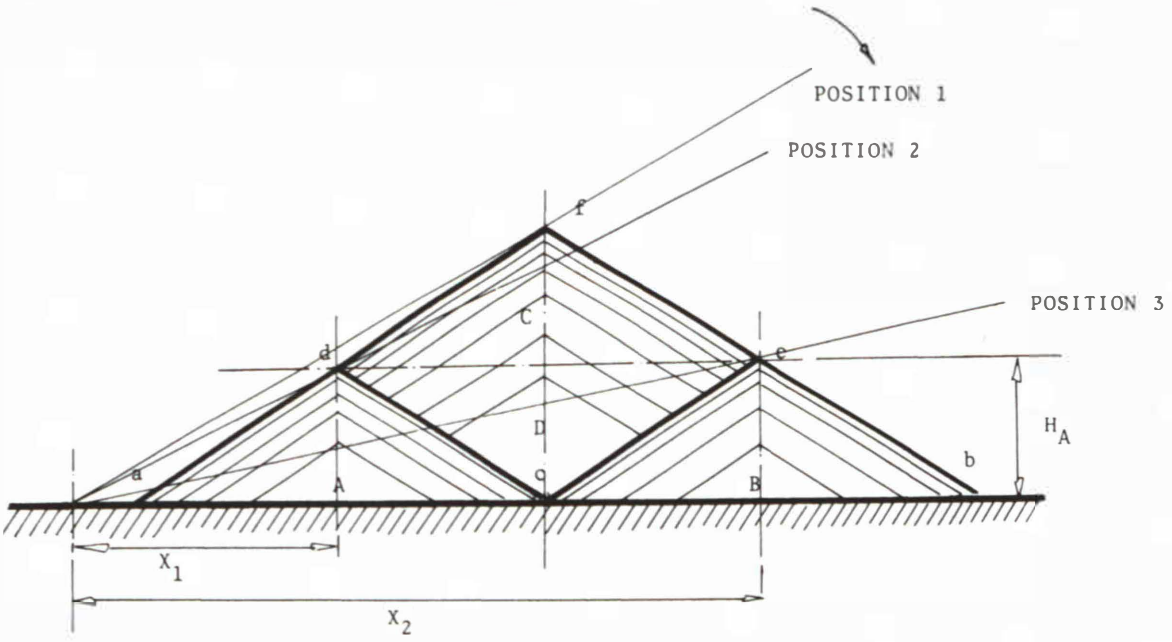
Therefore deterministic and random parts of the overall variability input are considered separately.

Our particular aim is to evaluate (in the form of design graphs and reference charts), the capability of the stockpile homogeniser for filtering a selection of input quality variability forms where fluctuations are both random and deterministic, characterised by random changes of frequency, amplitude and phase.

The results of extensive digital computer simulation experimentation utilising the stockpile model outlined above are discussed and presented below.

In order that the derived simulation results detailed below could find universal application within the minerals processing industry, the developed pre-homogeniser simulation model was subjected to a wide spectrum of input variability characteristic forms.

Fig. 8: Multi-triangular *Chevron* layering with reclamation via a side-acting scraper



The majority of minerals have heterogeneity characteristics ($R_{x_1x_1}(k)$) which can be described by a decaying exponential form, indicating that they may be approximated by an autoregressive process (e.g., AR(1) or AR(2)) model [1, 2, 13, 14].

1st Order: $[x_t]_f = \phi_1 x_{t-1} + \xi_t$ (8)

2nd Order: $[x_t]_f = \phi_1 x_{t-1} + \phi_2 x_{t-2} + \xi_t$ (9)

where ξ_t is a totally-random, stationary, zero mean, residual.

Fig. 9 shows a series of correlation relationships for data characterised by an AR(1) process where the parameter ϕ_1 is positive and < 1.0. We can see that as $\phi_1 \to 1.0$, the effective autocorrelation time or range of influence tends to infinity, and as $\phi_1 \to 0$, the range of influence tends to 0 (i.e., completely random variablity).

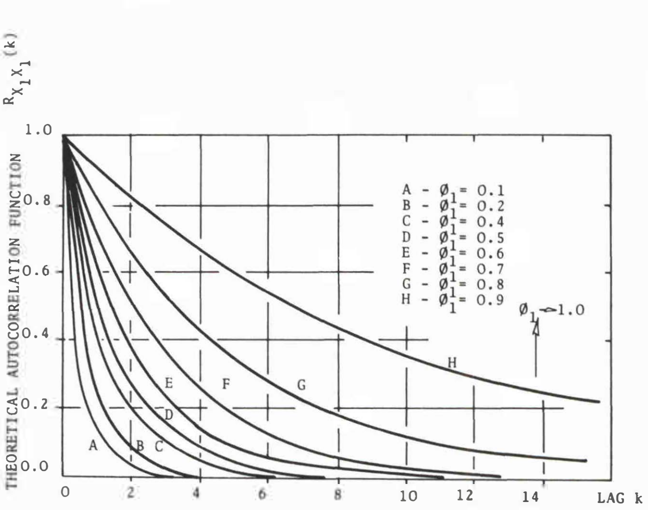


Fig. 9: AR(1) process — relationship between ϕ_1 and the effective autocorrelation time 'a' expressed as a function of k and the sampling-t

The first order autoregressive process model given by the difference equation Eqn. 8 was used to generate suitable stockpile quality data input to the simulation model.

5.1 Range of Influence

The concept of a range of influence is introduced as a time parameter (hrs), where on considering any series of quality values obtained via discrete sampling of a continuous signal, adjacent values will be related for a specific number of sample lags and expressed as the product of k and the sampling interval ΔT (hrs). This quantity is denoted by a.

The quantity that a represents, may be obtained from the product of a and Q.

For an AR(1) process, the relationship between ϕ_1 and the effective autocorrelation time a is shown in Fig. 9.

For any quality variability time series a is uniquely defined and obtained via the following.

1. Difference the raw material quality time series sufficiently to remove any trends.
2. Calculate the residual data autocorrelation function.
3. Define a as a significant time width on the residual autocorrelation function.
4. The characteristic autocorrelation time is taken as up to the point when $R_{x_1x_1}(k) \leq 0.01$.

Because of this finite sample to sample interrelationship, and the basic batchwise operation of the stockpile prehomogeniser, the overall effectiveness of a particular stockpile with regard to short term efficiency (within each pile), and long term (between successive piles) variances, will be influenced by the value of the parameter ϕ_1 and hence a.

As $N \to \infty$ the short term variability reduction ratio would be expected to tend to zero. This is not the case, however, with regard to the long term variability reduction ratio, because for example, when a stockpile is built with a large number of layers, each section of the pile contains the average of the total pile quality; but when $a \gg 0$ this variation deviates significantly from the long term average taken over several piles.

That is when $a \gg 0$ the significance of ΔC and hence its variance increases in comparison to the within pile short term variance.

Hence, we define:

σ_1(ST), σ_0(ST) — The amount by which the stockpile output and input quality deviates from its mean over the short term.

σ_1(LT), σ_0(LT) — The amount by which the stockpile output and input quality deviates from the overall output and input quality over successive stockpiles.

σ_1(LT) is the standard deviation of the variation of individual Q_C segment qualities away from the long term mean input quality.

σ_0(LT) is the standard deviation of the variation of individual stockpile mean qualities away from the long term mean output quality calculated over ten or more stockpiles.

σ_0(LT) may be interpreted as a pile to pile ΔC variation.

Fig. 10 shows how the above are calculated.

Quite clearly:

σ_0(ST)/σ_1(ST)	provides a realistic measure of efficiency in the short term filtering out of high frequency fluctuations (and depends on N, ΔR, M, ΔK), but over estimates the actual long term performance of the stockpile.
σ_0(LT)/σ_1(LT)	The long term variability reduction ratio is taken as an accurate and realistic measure of actual performance.

Extensive simulation results show that:

1. Both the long and the short term variability reduction ratios expressed as a function of N, for all parameter combinations coincide as $a \to 0$, and the reaultant curve approaches the relationship of $\sigma_0/\sigma_1 = 1/\sqrt{N}$.
2. As $a \to \infty$ (i.e., $>$ 1,000 hrs), the short term variability reduction ratio approaches the following relationships:

   $\sigma_0(\mathrm{ST})/\sigma_1(\mathrm{ST}) \approx 1/N^{0.98} \approx 1/N \quad N < 100$ (10)

   $\sigma_0(\mathrm{ST})/\sigma_1(\mathrm{ST}) \approx 0.005 \quad N > 100$ (11)
3. For a certain range of influence a and a specific set of parameter values, σ_0/σ_1(LT) reduces as N increases, until a certain point is reached (i.e., at N_c^* — critical number of

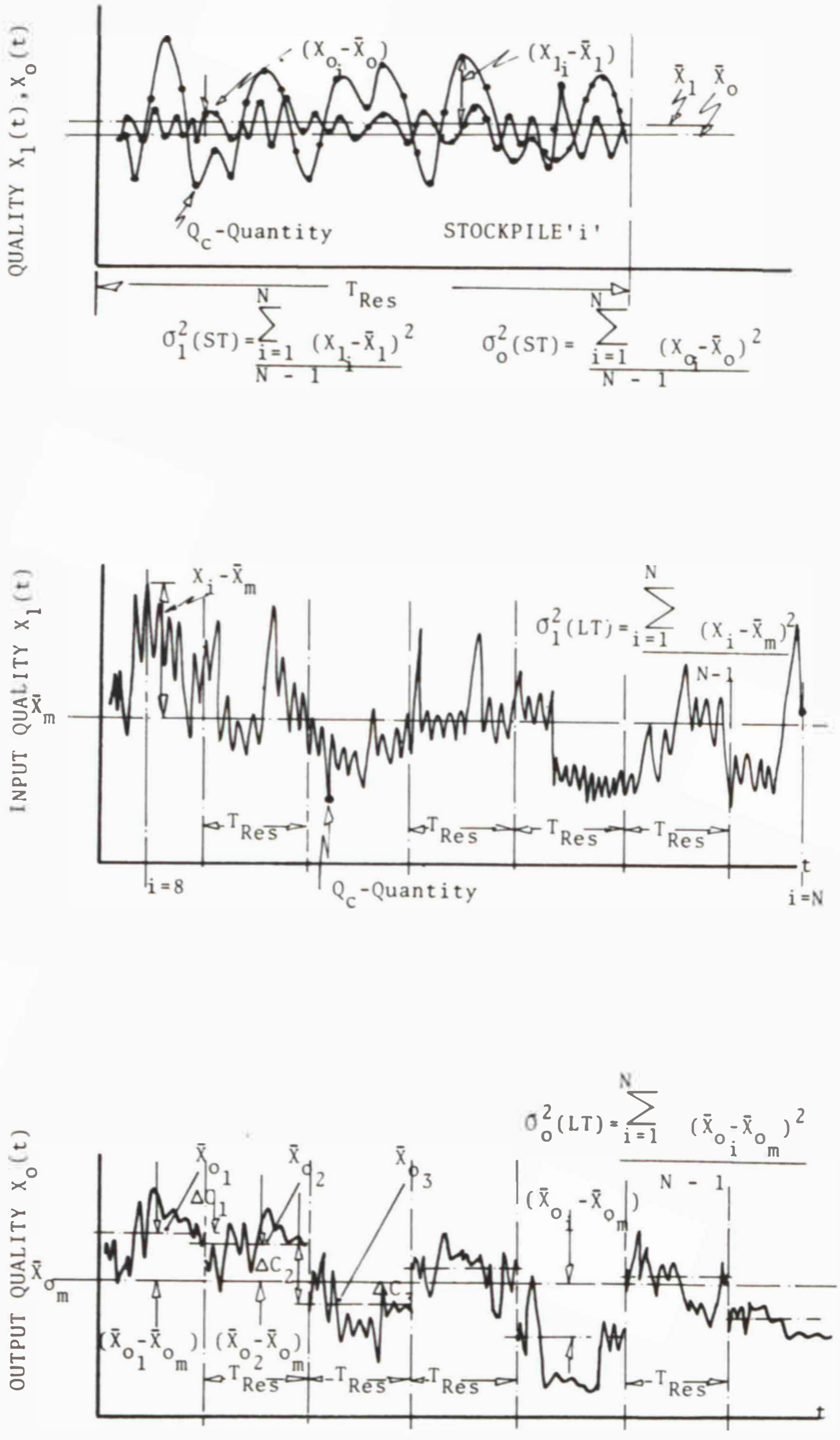


Fig. 10: Stockpile input and output variability relationships

layers) beyond this (i.e., where $N > N_c'$) the additional layers do not effect any reduction in variability.

4. The difference between $\sigma_0(ST)/\sigma_1(ST)$ and $\sigma_0(LT)/\sigma_1(LT)$ is considerable, particularly as $a \gg 0$ (i.e., > 10 hrs) indicating that the between pile variance becomes the dominant part of the total overall long term quality variation. This is clearly important in terms of practical production process control.

5. For a given set of input data, (i.e., a = constant) the major limiting factors with regard to long term efficiency are the size of the pile, M, and the feed rate, Q.

   As the ratio M/Q (T_{Res}) → ∞ the effectiveness increases for any given N.

Figs. 11 and 12 present in brief the model simulation results and provide a simple yet direct optimal approach to pre-homogeniser design.

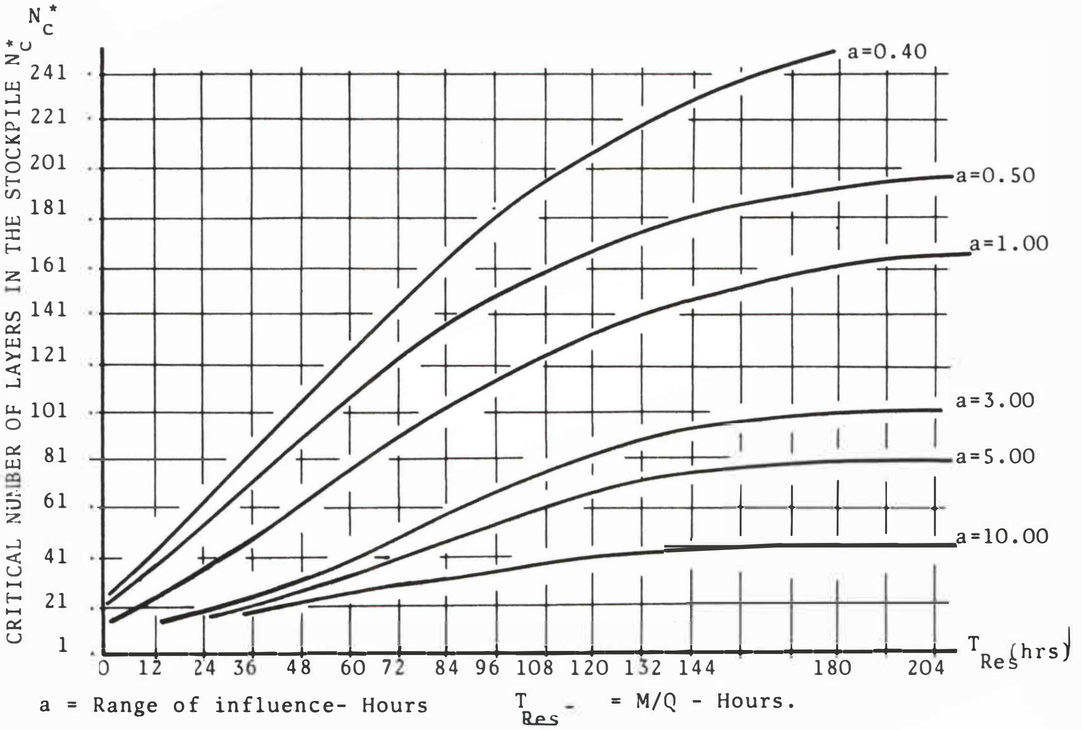


Fig. 11: Critical number of layers in the stockpile N_c^* as a function of T_{res}, and the input variabilitity range of influence

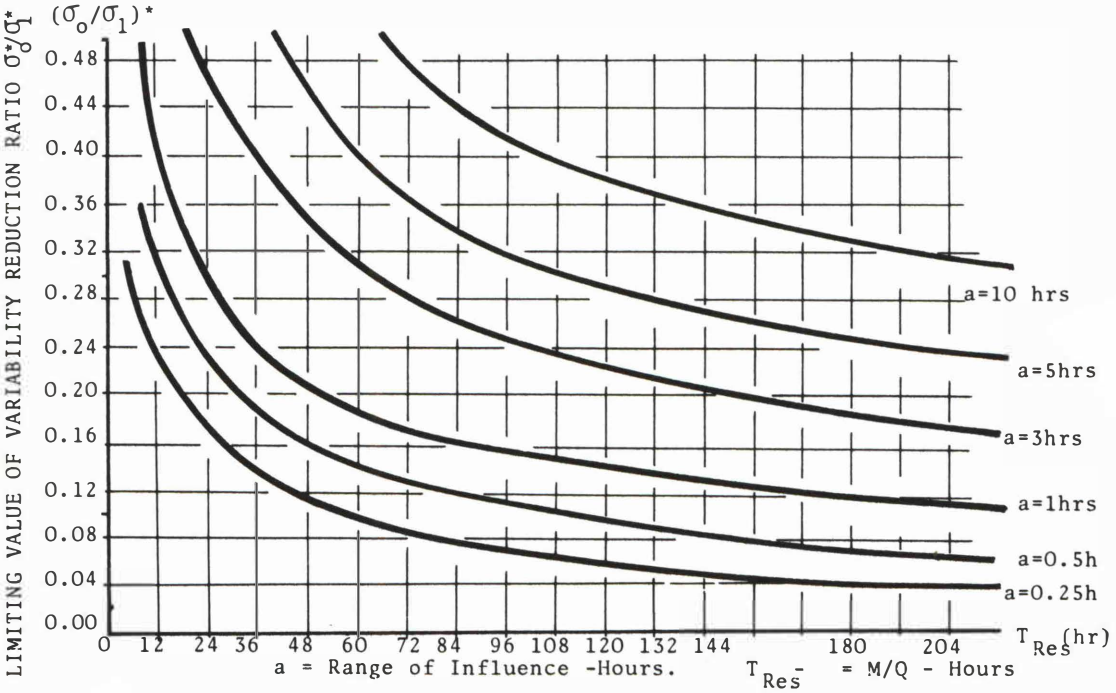


Fig. 12: Limiting value of long term variabilitity reduction ratio as a function of 'a' and T_{res}

6. Stockpile Design Case Study

6.1 Cement Works Uprating

An existing cement works is to be uprated to include a 2,200 t/d rotary kiln. Because of its sensitivity to variations in input raw meal feed quality, the kiln feed is required to deviate from target LSF by no more than ± 1.5 % LSF.

Raw material is supplied to the works from three sources, two of which are to be regarded as homogeneous with respect to quality. However, the third, which is the major source, is a highly variable limestone material. Proportioning of the raw materials is undertaken before the milling stage.

The target of 95 % LSF and associated tolerance band can be achieved effectively by utilising the existing powder blending fluidised silo system, if the limestone raw material quality pre-proportioning stage is restricted to 100 % LSF ± 10 % LSF (Fig. 1).

In order to meet the new quality requirements, it is proposed to include within the new process design a limestone stockpile pre-homogeniser.

The quarry output feed rate is 300 t/h.

Extensive sampling tests show that the characteristics of the material can be described well by a AR(1) process model, with an effective correlation time of 1.0 hrs σ_x = 13 % LSF (ex-quarry). What are the required design parameters for the pre-homogeniser?

Theoretically a variability reduction ratio of σ_0/σ_1(LT) = 0.25 is required. However, the maximum ΔC that would be permissible (pre-proportioning stage) is 10 % LSF.

If it is assumed that over the long term, the mean values of the individual stockpile outputs $\bar{X}_{0_i}$ (i = 1, 2, 3, . . . , M) are randomly distributed then:

68 % of the $\bar{X}_{0_i}$'s will lie within ± 1 σ_0(LT) of $\bar{X}_{0_m}$ and the max ΔC would be 2 σ_0(LT) i.e., σ_0(LT) = 5/3 = 1.66 % LSF. Hence the required variability reduction ratio is:

$$\sigma_0/\sigma_1(\mathrm{LT}) = 1.66/13 = 0.128$$

Design solutions show that a capacity in the region of 50,000 tonnes would be required, assuming a L/W > 5/1 and a slice width < 15 cm, with the required number of layers ≈ 150 (Figs. 11 and 12).

6.2 Green-Field Site Design

The above rather over-simplified example, shows how relatively straightforward design might be if one was simply considering an extension to an existing works, where, as would be expected, in-depth very detailed knowledge of *as quarried* raw material quality characteristics and variability would be readily available.

The best the designer can do in a green-field site situation where the only available information is likely to be sparsely distributed bore-hole data, is to:

1. Extract the variance of the quality variable of interest from all available sources, and construct frequency distribution and cumulative frequency plots. Hence, an estimate of $\sigma_{x_1}^2$ has been obtained.
2. Assume a likely *range of influence* — a — it is far better to over-estimate this value than to underestimate it. With regard to limestones/anhydrites etc., the above discussion indicates that an assumption of $a \geq 2$ hrs would be adequate — this however depends on the type, and effectiveness of quarry control and proportioning procedures.
3. Calculate the required variability reduction ratio and then simply utilise the design solutions presented in Figs. 11 and 12.

7. Summary of Stockpile Design Relationships

The variability filtering capability of the stockpile prehomogeniser can be assessed on two basic levels:

1. The variability filtering capability of the single stockpile (short term efficiency).
2. The long-term variability filtering capability which includes both within and between pile quality variances.

The latter is the most accurate because it is the long-term performance that is of primary importance to the process designer, as the short-term variability reduction ratio gives an over optimistic assessment of actual plant performance for $a \gg 0$. As $a \rightarrow 0$ the long and short term variability reduction performances expressed as a function of N coincide.

The long-term ratio σ_0/σ_1(LT) for a certain T_{Res} and range of influence a reduces with increasing N until a point is reached N_c^*, beyond which additional layers have negligible effect.

This overall relationship of N_c^* expressed as a function of T_{Res} and a is shown graphically in Fig. 11.

The limiting value for N_c^* (for all a) as $T_{Res} \rightarrow 0$ is $N_{c(\min)}^* < 25$ layers.

The smaller the range of influence, the larger is the corresponding N_c^* for a certain T_{Res}.

The curves of Fig. 11 are approximated by the following relationship:

$$N_c^* = \frac{T_{Res}^{1.082}}{a^{0.756}} \tag{12}$$

which indicates that the crucial non-dimensional design parameter affecting stockpile performance is a function of T_{Res}/a.

The corresponding limiting values of the long-term variability reduction ratio for each "T_{Res}, a" combination are shown in Fig. 12.

It can be seen that the effectiveness of the stockpile for any particular input variability (a constant) increases as $T_{Res} \rightarrow \infty$, the smaller the range of influence the more effective a certain M/Q — T_{Res} combination.

A suitable design procedure is illustrated below:

1. Identify the range of influence of the quality variable of interest a in the ex-quarry/ex-mine raw material, and establish the desired pre-homogeniser variability reduction ratio, taking into account the maximum permissible average pile to pile mean quality difference $\overline{\Delta C}$.
2. The requisite T_{Res} for the relevant range of influence is obtained directly from Fig. 12.
3. The critical number of layers N_c^* may be deduced directly from Fig. 11 using the value of T_{Res} obtained via Fig. 12.

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