Chapter 4

Fabric Analysis

4.1 BACKGROUND

The hypothesis for this thesis states that **accurate simulation of the behaviour of gold tailings under laboratory conditions requires appropriate replication of the material fabric.** The general understanding is that samples prepared using different laboratory preparation methods behave differently due to a difference in fabric which ensues upon reconstitution. This chapter presents the fabric of undisturbed, moist tamped and slurry deposited gold tailings samples at the same void ratio as observed under the SEM. Visual fabric analysis is the basis on which the sample fabric is compared. The implications of the observed fabric on the behaviour of gold tailings and possible modes of particle interaction are discussed.

4.2 VISUAL FABRIC ANALYSIS

As mentioned in Chapter 3, SEM was chosen over physical methods of fabric analysis because SEM images allowed interactions at a particulate level to be observed physically. Quantitative analysis of the observed fabric was complicated and was therefore not used.

SEM images were taken of all samples before testing at magnifications of 50, 200, 500, 1000 and 2000. SEM images of all samples at 50, 200 and 1000 times magnification are attached in *Appendix D*. SEM images of samples after testing were not used as no fabric differences could be observed between the undisturbed and the reconstituted samples. As suggested by Zlatovic and Ishihara (1997), all fabric is destroyed when the samples reach the critical state.

Fabric comparison was made between each material type (ie pond, middle beach and upper beach) as particle properties and size distribution were different for each material type.

4.2.1 General fabric of gold tailings

The composition of gold tailings has been shown by authors such as Hamel and Gunderson (1973), Mittle and Morgenstern (1975) and Vermeulen (2001) to consist of coarse, rotund particles with finer, plate-like flat particles. This was further demonstrated by the SEM images obtained for this project. As exemplified by *Figure 4-1*, the MB sample at 1000 times magnification showed gold tailings consisting of rotund and platy particles.

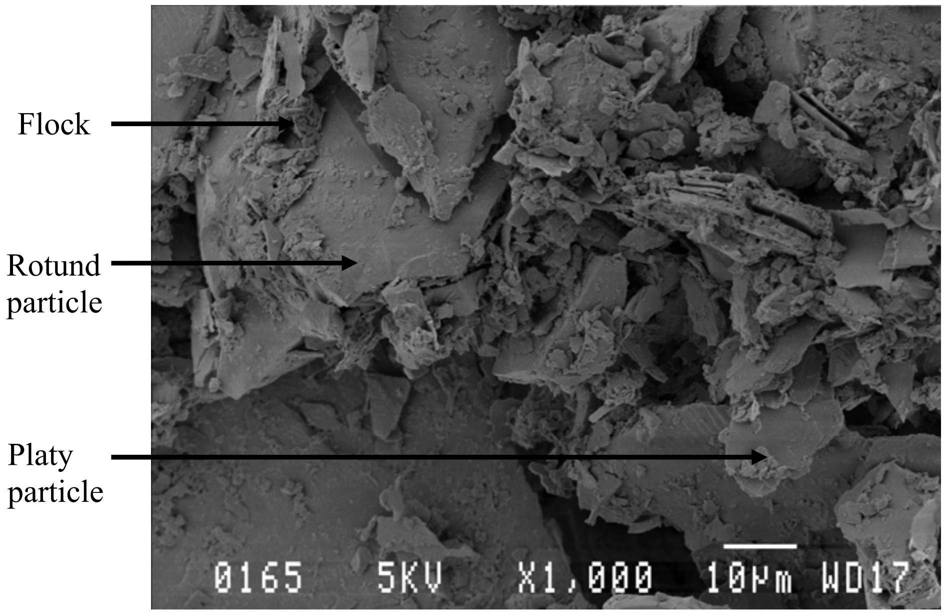


Figure 4-1. Physical constitution of gold tailings at 1000 times magnification

It was interesting to note that, besides the rotund and platy particles, flocks of particles also existed, as demonstrated in *Figure 4-1*. These flocks existed in various quantities (most abundant in pond samples) and sizes in the range of 5µm. The flocks consisted of fine platy and/or rotund particles, and were probably a result of the addition of flocculent to facilitate settlement during deposition.

4.2.2 Pond samples

The SEM images showed that pond material consisted mainly of platy particles in the silt and clay-size range and only a few silt-sized rotund particles. The general trend of the fabric of pond samples at various magnifications was that the rotund particles were scarce and not in direct contact with each other, but were dispersed in a matrix of platy particles and flocks (*Figure 4-2a)*, similar to the partially or fully dispersed states proposed by Thevanayagam et al (2002) for sand-silt mixtures (*Figure 4-2b).*

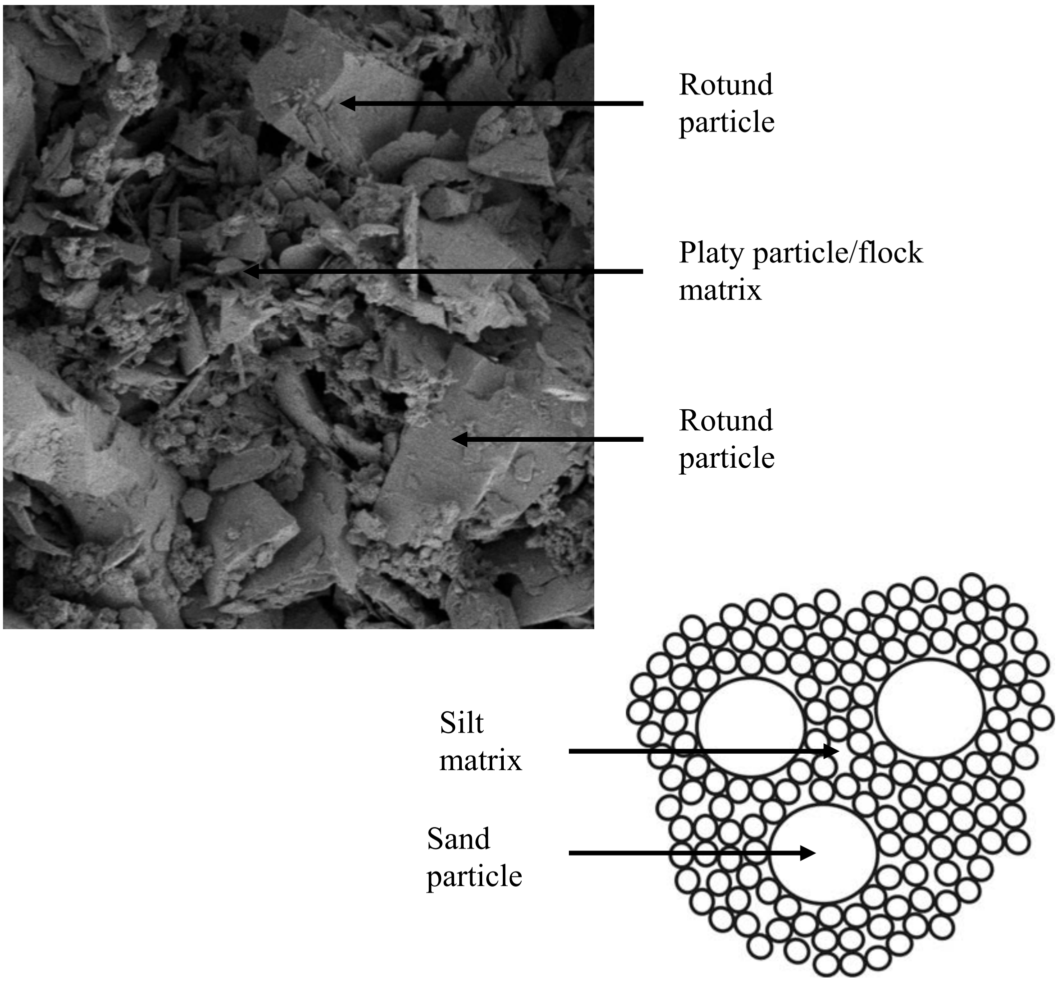
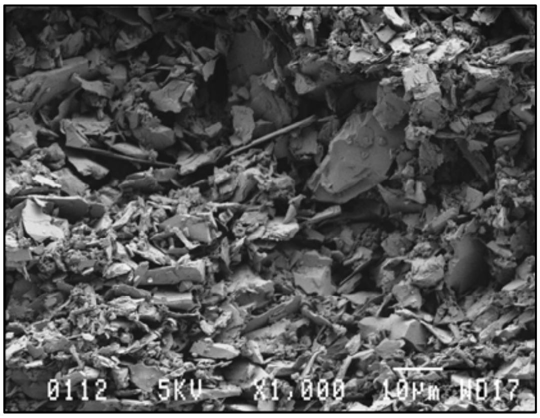
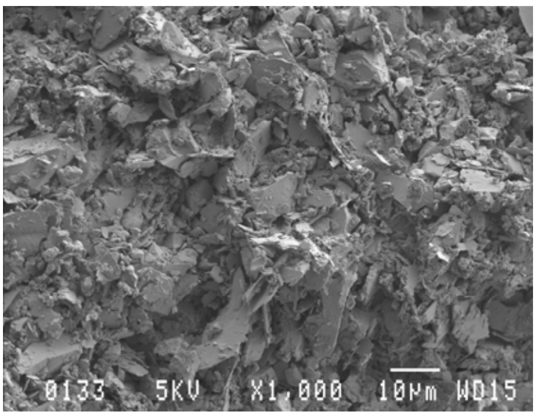


Figure 4-2. Dispersed state of rotund particles in gold tailings compared with sand-silt mixtures.

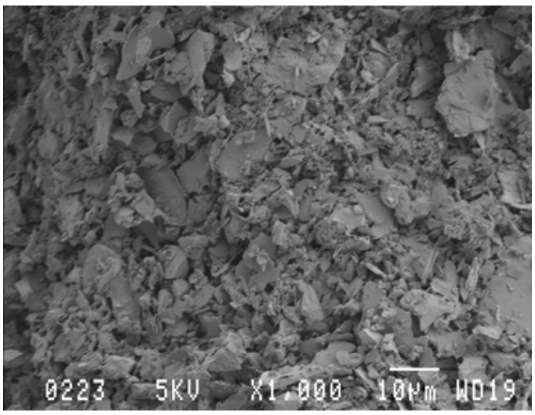
The SEM images also showed that there is no visible difference between the randomly orientated fabric of moist tamped and slurry samples (*Figure 4-3b* and *c*). It appears that the high compaction stresses required to prepare the moist tamped pond samples have erased any initial fabric which ensued upon sample preparation. The undisturbed consolidation samples (*Figure 4-3a*) however contained particles with some horizontal orientation. This could be expected in a depositional environment where platy particles settle in still water, analogous to that of a leaf falling through air. No specific particle orientation could be observed in any of the moist tamped or slurry shear samples. The horizontal particle orientation previously observed in undisturbed consolidation samples was also visible in the undisturbed shear samples. This indicated that the shear samples retained the horizontal particle orientation throughout the consolidation process.



a) Undisturbed



b) Moist tamped



c) Slurry

Figure 4-3. Particle orientation of pond consolidation samples.

4.2.3 Middle beach samples

The SEM images showed that the middle beach material was significantly coarser than the pond material, comprising both rotund and platy particles. This can be demonstrated by comparing undisturbed pond (*Figure b* page 191) and MB (*Figure b* page 196) images at 200 times magnification. The rotund particles in middle beach material were also significantly larger than those observed in pond material.

On examining the fabric of middle beach consolidation samples, one significant difference could be observed. At low magnifications, moist tamping created an aggregated fabric which was also visible, but to a lesser degree, in both the undisturbed or slurry samples. This is demonstrated in *Figure 4-4a*. At higher magnifications (*Figure 4-4b*), it was visible that these aggregates were composed of finer, rotund or platy particles, clinging closely to the coarse rotund particle. These platy particles generally appeared to be orientated parallel to the surface of the rotund particle, as demonstrated in *Figure 4-5*. Similar conclusions have been drawn by Theron (2004) on mica-sand mixtures. The aggregates originated during the process of moist tamping where capillary suctions are known to hold soil particles together. The aggregates were not visible to the naked eye during sample preparation, but are clearly visible from the SEM images.

It is interesting to note that although these aggregates originated from the capillary suction between the gold tailings particles, subsequent saturation did not disintegrate these them. The same distinct aggregation could be observed after consolidation and creep in the moist tamped shear 200 and 400 samples, but to a lesser degree. It appeared that although some aggregates may have been destroyed during consolidation, the general aggregated fabric was still visible. No specific particle orientation was identified in any of the consolidation or shear middle beach samples.

The aggregation observed in the moist tamped consolidation and shear samples may have some influence on the behaviour of the gold tailings.

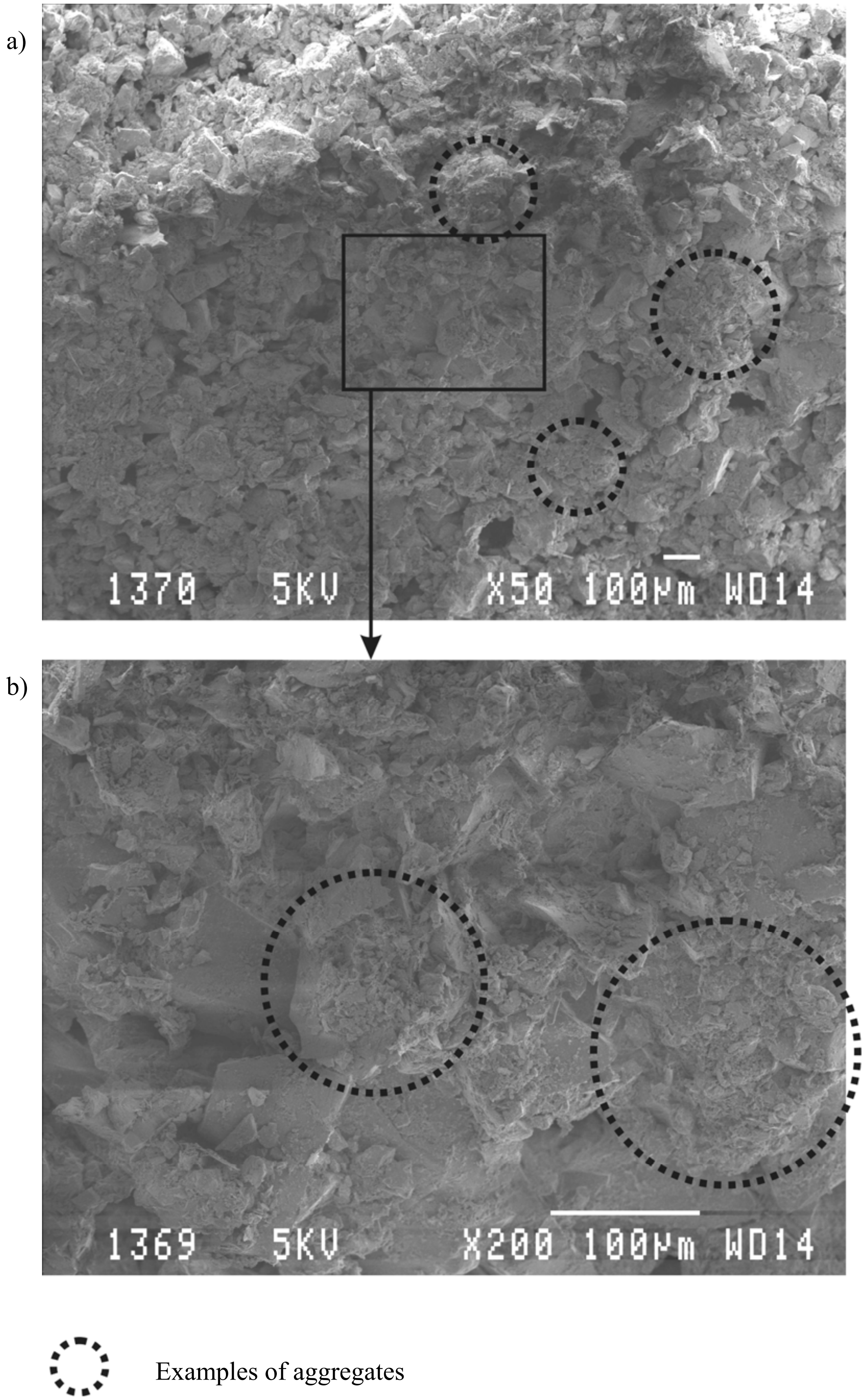


Figure 4-4. Aggregated fabric of moist tamped MB consolidation samples

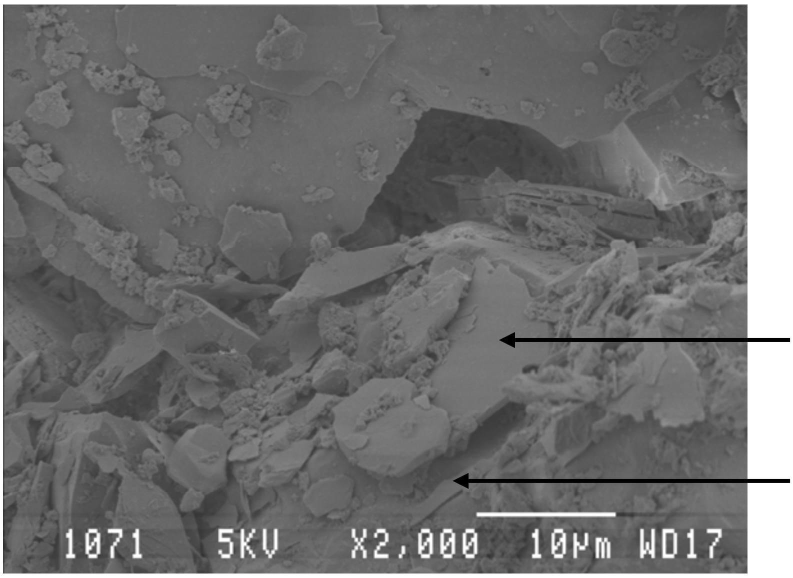


Figure 4-5. Platy particles aligned parallel to the rotund surface

4.2.4 Upper beach samples

Upper beach material consisted of rotund and platy particle similar in size to those of the middle beach material. Upper beach samples, however, existed in a denser state than middle beach samples. Fabric of upper beach samples was similar to that observed in middle beach samples. Moist tamped samples also showed a pronounced aggregated fabric (demonstrated by *Figure (a)* page 202 and *Figure (d)* page 203) which was less obvious in the undisturbed or slurry samples. Similar to the middle beach samples, these aggregates appeared to remain intact after consolidation. Particle orientation was not visible in any of the upper beach test samples.

4.2.5 Fabric classification

The fabric of gold tailings has been described in the previous section. It was, however, important that the fabric be classified systematically in order for comparisons to be made. The existence of aggregates could be considered an important fabric feature observed in gold tailings, and classification of fabric is thus based on the visibility of the aggregation. According to the Oxford English Dictionary, the word 'aggregation' indicates 'the action or process of collecting particles into a mass, or particulars into a whole'. The American Heritage Dictionary describes aggregation as 'composed of a mixture of minerals separable by mechanical means'. For the purpose of this thesis, aggregation is defined as 'the collection of particles of various sizes and shapes into a mass which, under certain conditions, behaves as a single body.

Aggregates existed in various quantities in all samples. Two types or sizes of aggregates could be seen in the SEM images: small aggregates or flocks (as shown in *Figure 4-1*) in the order of 5 to 20µm and large aggregates in the order of 50 to 200µm. This is demonstrated in *Figure 4-6*. All samples contained small aggregates. These small aggregates were composed mainly of platy particles and had probably been formed as a result of the addition of flocculent to facilitate settlement of tailings in the dam. The large aggregates were composed of a collection of rotund particles, platy particles and flocks, and could be abundantly seen in the MB and UB samples. Undisturbed and slurry samples contained small quantities of these large aggregates, but moist tamped samples seemed to be dominated by these large aggregates.

Fabric classification was based on visual differences as described in the previous sections. Features which were common to all samples are not included in the classification. Two parameters were used to describe the fabric of gold tailings:

- *Aggregation*: refers to the collection of rotund particles, platy particles and flocks forming the large aggregates as demonstrated in *Figure 4-6*. Flocks as shown in *Figure 4*-1 were common to all samples and were not included in the classification. Samples were classified either as aggregated or non-aggregated based on visual assessment:

    - *Aggregated*: Platy particles and/or flocks adhere closely to rotund particles forming aggregates (*Figure 4-7).*
    - *Non-aggregated*: Platy particles and flocks are loosely dispersed around and between rotund particles (*Figure 4-8*).

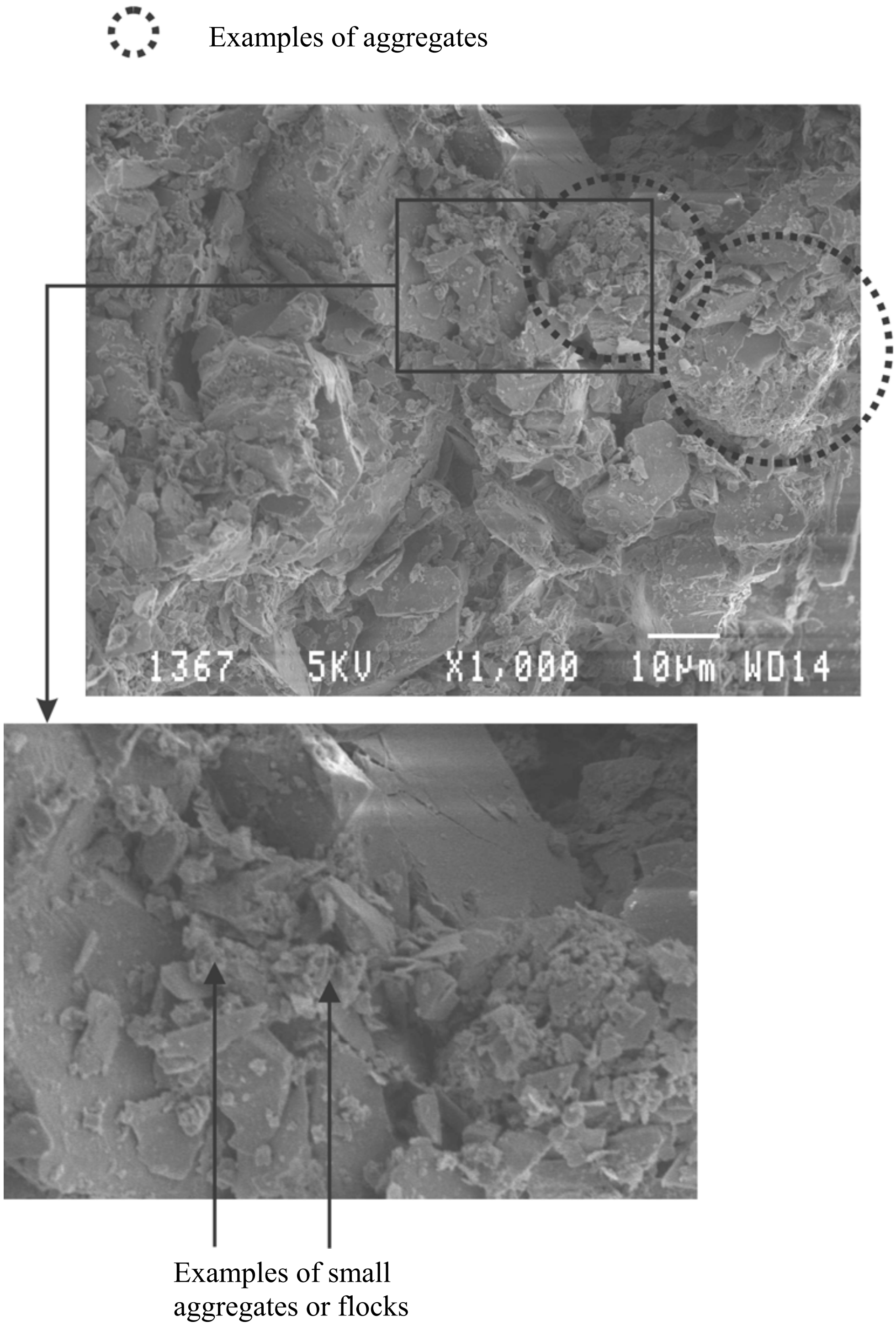


Figure 4-6. Illustration of small and large aggregates in gold tailings

Classification as aggregated required that two criteria be met simultaneously:

1. At low magnifications (50X), sample must appear to constitute 'individual particles'.

2. At high magnifications (1000X), these 'individual particles' must be observed to constitute a collection of rotund and platy particles.

It should be noted that, with the two criteria, samples may have contained some aggregates, but may not have been classified as aggregated. Furthermore, zooming was always at the centre of the images and therefore at higher magnifications the image may not represent the majority of the sample.

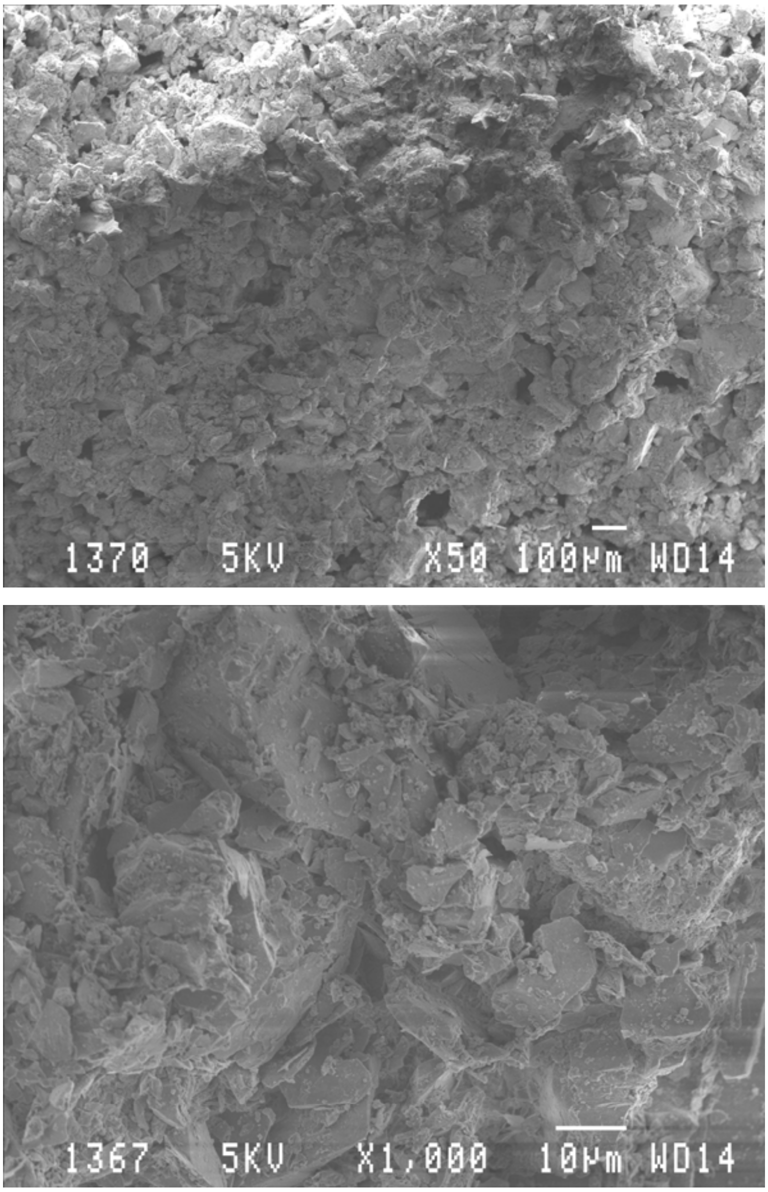


Figure 4-7. Aggregated fabric of gold tailings

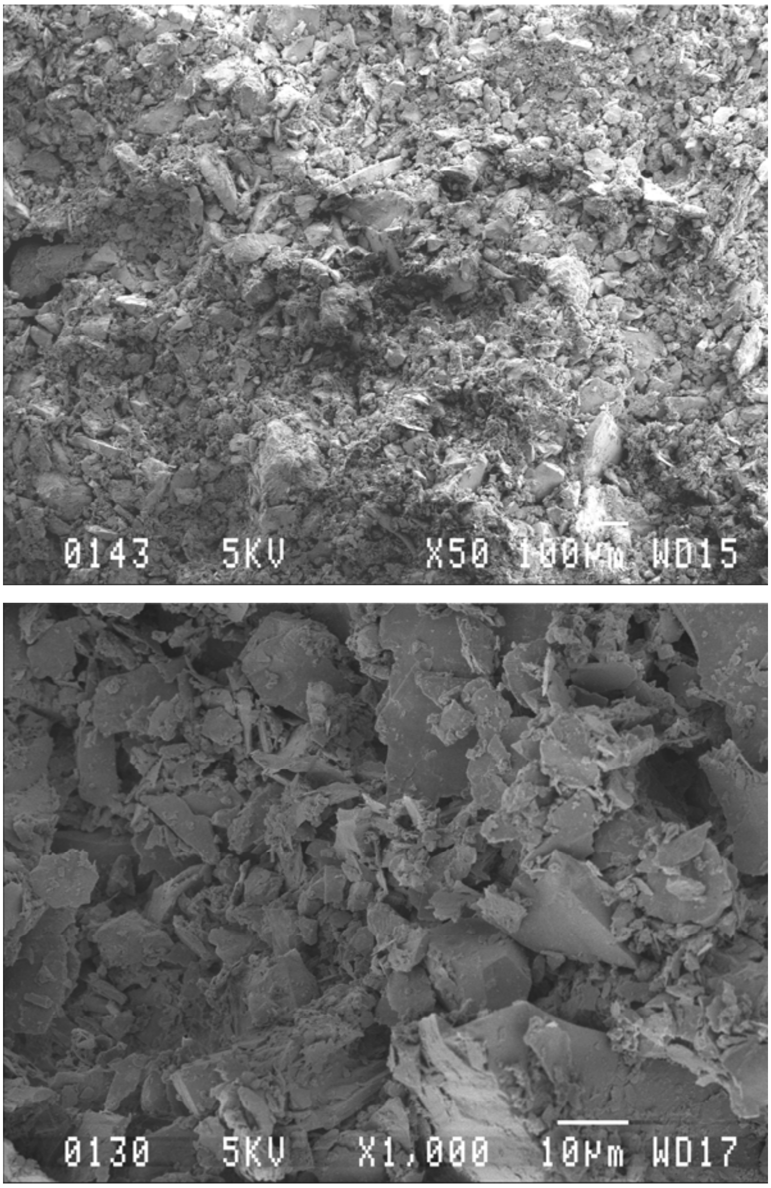


Figure 4-8. Non-aggregated fabric of gold tailings

- *Orientation*: describes the general spatial orientation of the particles and/or aggregates as observed in the SEM images:
    - *Orientated*: Majority of particles and aggregates are orientated in the same axis (*Figure 4-9 (a)*).
    - *Non-orientated*: Particles and aggregates are randomly orientated (*Figure 4-9 (b)*).

a)

b)

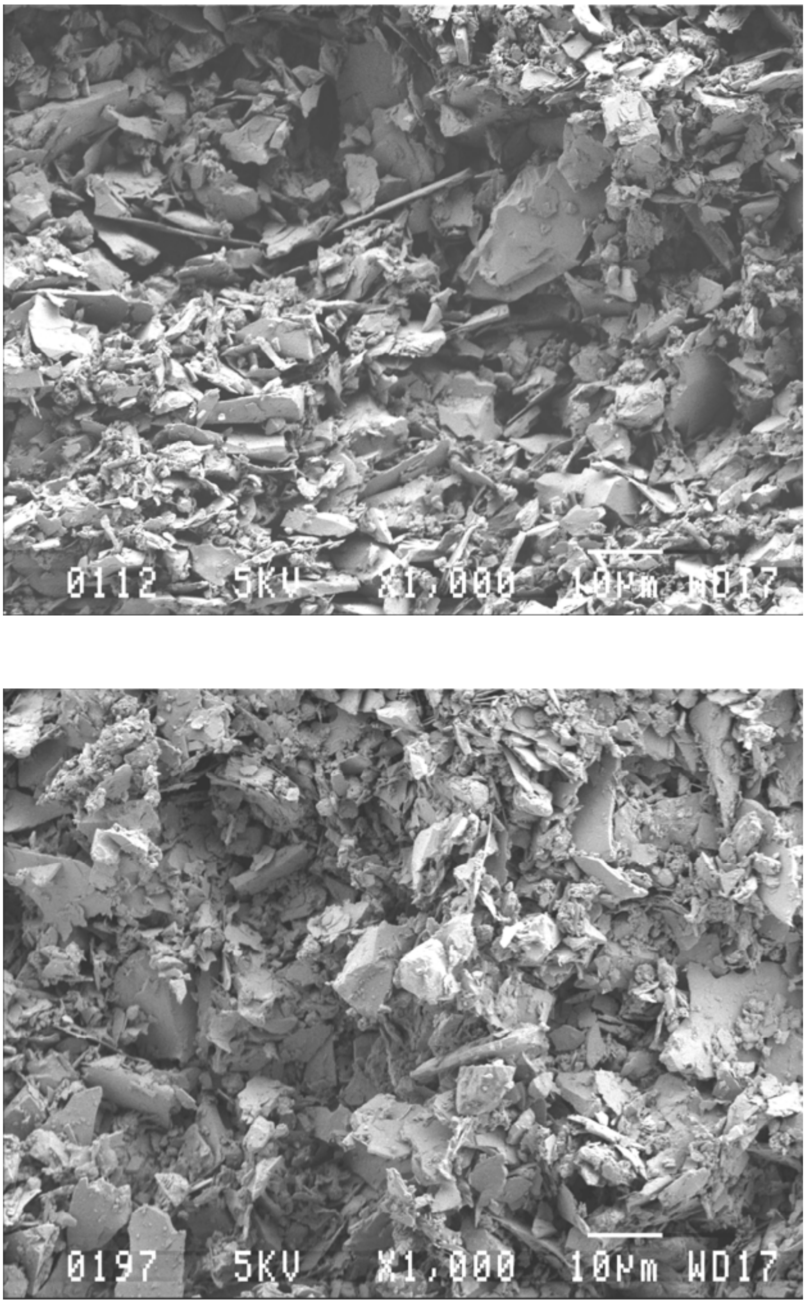


Figure 4-9. Orientated and non-orientated fabric for gold tailings.

To simplify the classification, the fabric was classified into four structural levels:

Level 1: non-aggregated and non-orientated.

Level 2: aggregated but non-orientated.

Level 3: non-aggregated and orientated.

Level 4: aggregated and orientated.

It should be emphasized that the classification is qualitatively assessed based on the overall appearance of the images as perceived by the author, and results may vary according to the observer. According to the classification described above, the fabric of gold tailings can be classified as shown in *Table 4-1*. A 'consolidation' sample demonstrates the fabric before consolidation and 'shear 200' or 'shear 400' samples show the fabric after consolidation (to 200kPa or 400kPa) and creep, and observed before shear.

Material	History	Undisturbed	Moist tamped	Slurry
Pond	Consolidation	3	1	1
	Shear 200	3	1	1
	Shear 400	3	1	1
Middle beach	Consolidation	1	2	1
	Shear 200	1	2	1
	Shear 400	1	2	1
Upper beach	Consolidation	1	2	1
	Shear 200	1	2	1
	Shear 400	1	2	1

Table 4-1. Levels of fabric observed in gold tailings.

Pond samples

Table 4-1 shows that the undisturbed pond samples have a non-aggregated and orientated fabric (level 3) while both the moist tamped and slurry samples have level 1 fabric which is non-aggregated and non-orientated. Comparison of results shown in *Table 4-1* indicates that all pond samples have similar non-aggregated fabric, irrespective of the sample preparation method or stress history. Upon close inspection, it was clear that flocks could be observed in all pond samples. According to the definition, pond samples are generally classified as 'non-aggregated', despite of the presence of these flocks.

The only difference observed in pond samples was that some horizontal orientation could be observed in undisturbed samples, but not in the moist tamped and slurry samples. This may be a result of the depositional environment of the undisturbed pond material as described in section 4.2.2. This initial orientation was also observed in the shear fabric samples. This implies that consolidation does not destroy the initial orientation and the initial fabric was preserved after consolidation and creep.

In general it appears that neither laboratory reconstitution methods (moist tamping or slurry) could reproduce the orientated fabric observed. This may be a problem in terms of laboratory testing of pond tailings if the behaviour is sensitive to the sample fabric.

Middle and upper beach samples

Middle and upper beach samples show similar trends in terms of fabric and are thus discussed in the same section. The fabric of undisturbed and slurry middle beach and upper beach samples appear similar with a level 1, non-aggregated and non-orientated classification. This is similar to the conclusions reached by authors such as Vaid et al. (1990) and Vaid and Sivathalayalan (2000), that water pluviation produces a similar sand fabric to that of natural sands. Moist tamped middle beach and upper beach samples however, exhibit a level 2, aggregated and non-orientated fabric. The fabric of the middle and upper beach samples appear similar before and after consolidation, indicating that the initial fabric which ensued upon sample preparation remained intact after consolidation. This difference in fabric observed in gold tailings samples before shear commenced may affect the behaviour of gold tailings during shear.

Typical SEM images of all samples are collated in *Table 4-2*. It should be noted that the images of pond samples are at a magnification of 500 times whereas the middle and upper beach samples are at 50 times magnification.

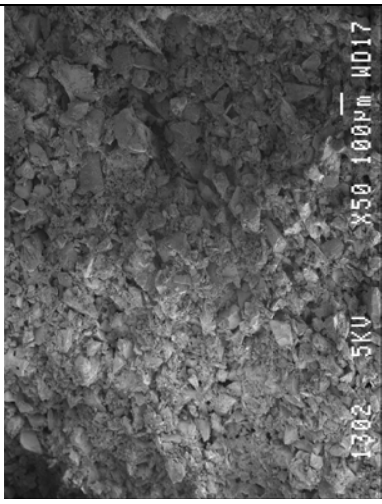
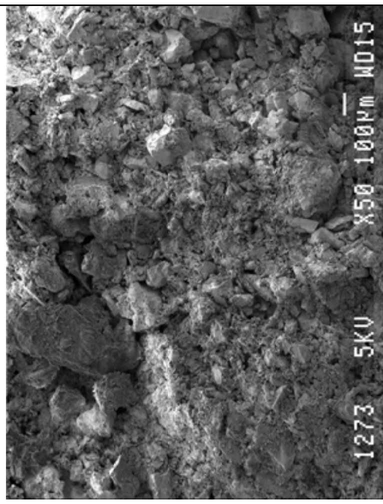
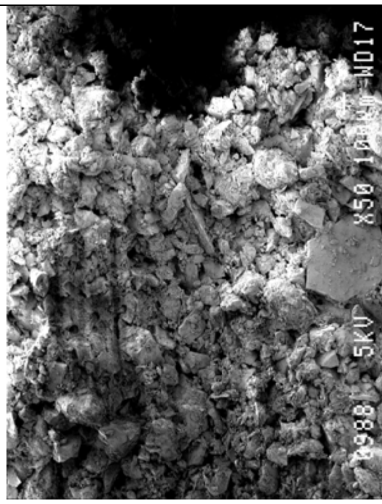
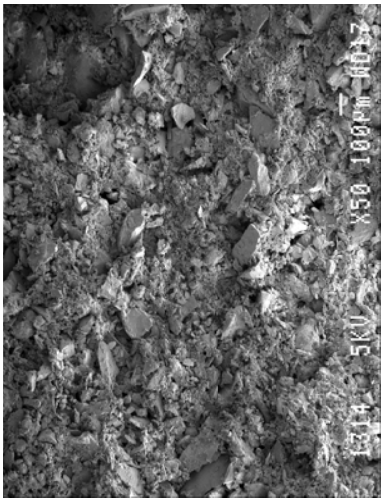
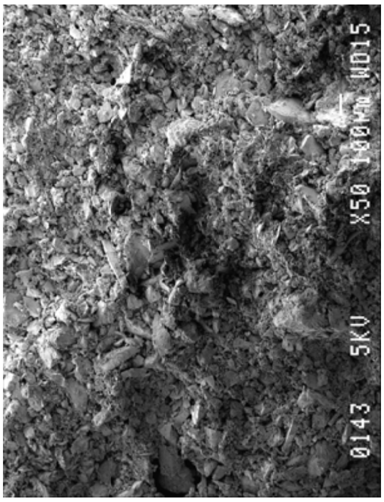
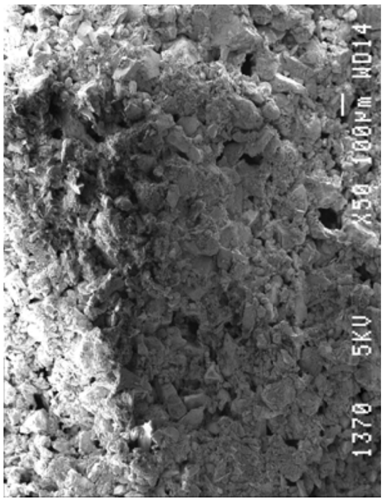
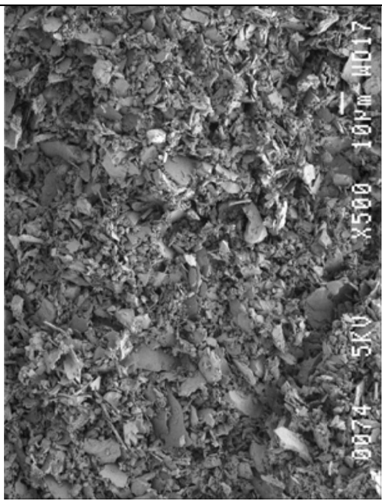
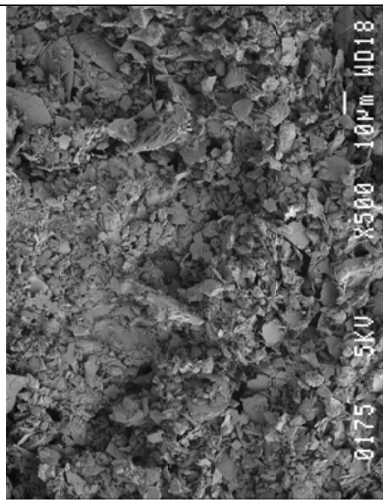
Upper beach			
Middle beach			
Pond			
	Undisturbed	**Slurry**	**Moist tamped**

Table 4-2. Typical SEM images of undisturbed and reconstituted gold tailings.

4.3 SIGNIFICANCE OF AGGREGATION IN GOLD TAILINGS

In this section, the significance of aggregation in gold tailings is discussed. Natural soils with an aggregated fabric show some difference in behaviour to homogeneous soils and thus the effects of aggregation may be responsible for any difference in behaviour observed in samples prepared using different laboratory preparation methods.

4.3.1 Origin of aggregation

Aggregation in natural soils occurs as a result of swelling and shrinkage as well as biological and chemical processes (Babel et al., 1995). Aggregate formation in natural soils is however, most frequently brought about by stress release and shear failure processes (Hartge and Rathe, 1983).

In a moist tamped specimen, soil particles are held together by suction in the pore fluid which exists between soil particles. The effect may be amplified in material such as gold tailings where a significant amount of fine platy particles are present. Aggregation in gold tailings therefore appears to be an artefact of moist tamping as it is not present in undisturbed or slurry samples.

4.3.2 Particle interaction of aggregated gold tailings

The difference in fabric between aggregated and non-aggregated middle and upper beach samples may be visualized at macro level as simply a difference in homogeneity and at micro scale as a difference in the mode of particle contact. Gold tailings are generally composed of rotund and platy, non-colloidal particles, and the behaviour of the material is dominated by mechanical particle contact. Following the definition of aggregation and non-aggregation, a model can be postulated with regard to particle interaction in aggregated and non-aggregated gold tailings samples. Aggregated samples are composed of platy particles and flocks clinging tightly around the rotund particles forming a stiff outer shell similar to that described in *Figure 4-10 (a)*. The orientation of these platy particles is generally parallel to the surface of the rotund particle, similar to those observed by Theron (2004). On a macro scale, the aggregates system comprising rotund particles and a stiff platy shell is analogous to a particle with rough but brittle surface, as demonstrated in *Figure 4-10 (b).* At a particulate scale, isotropic compression will induce forces normal to the orientation of the platy shell, resulting in higher bulk stiffness values for aggregated samples in comparison with undisturbed or slurry samples. Shear force transfer between aggregates will also occur through the platy contacts, but at an angle tangential to the orientation of the platy particles. This results in a reduced shear strength and stiffness in comparison with the undisturbed and slurry counterparts.

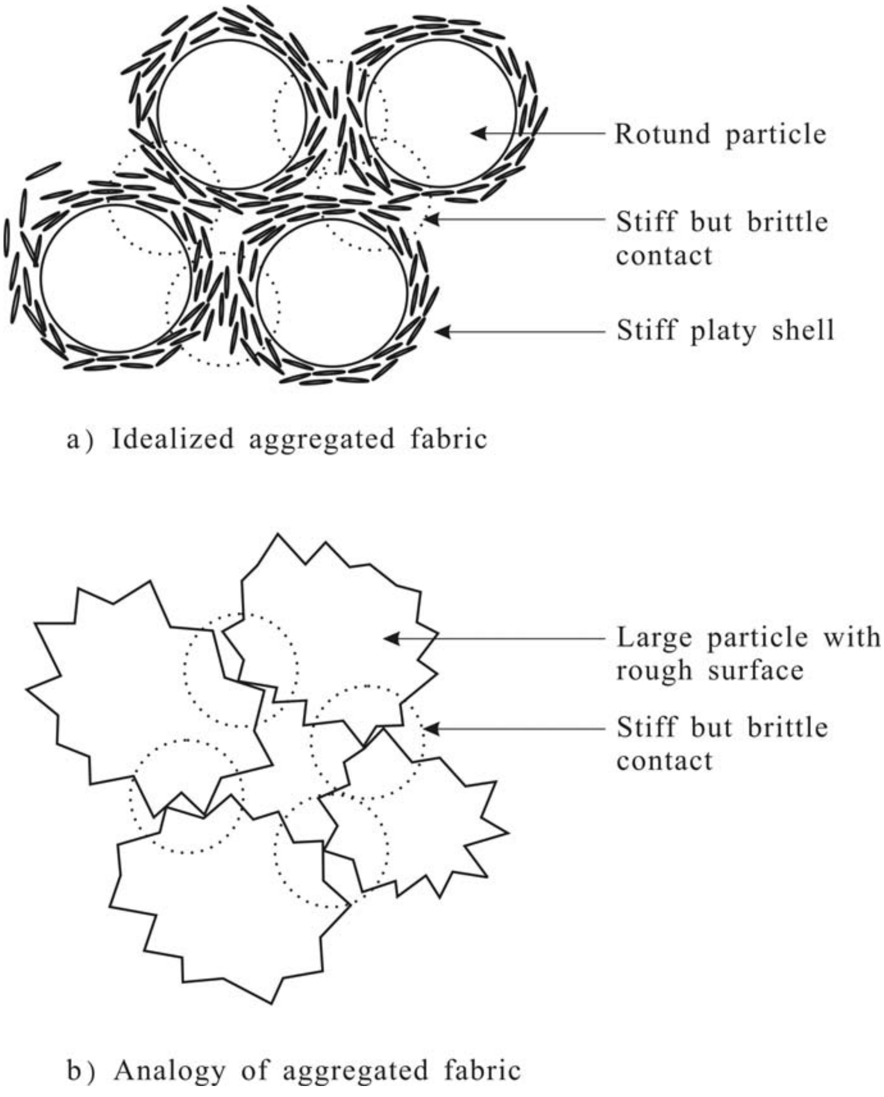


Figure 4-10. Idealized particle interaction in aggregated gold tailings.

The undisturbed and slurry deposited samples exhibit non-aggregated fabric and the mode of particle contact is dependent on the proportion of the platy particles/flocks in the sample. At low platy particle/flock content, rotund particles will be in direct contact with each other and the platy particles and flocks will only occupy the voids between the rotund particles, as shown in *Figure 4-11 (a).* The behaviour of the sample will be dominated by the rotund particles, with the platy particles and flocks playing a secondary role. At higher platy particle/flock content, as shown in *Figure 4-11(b)*, the rotund particles will be dispersed in a matrix of platy particles and flocks similar to that observed in the pond samples. The behaviour of the sample will be dominated by the platy particle/flock matrix with the rotund particles playing a supporting role.

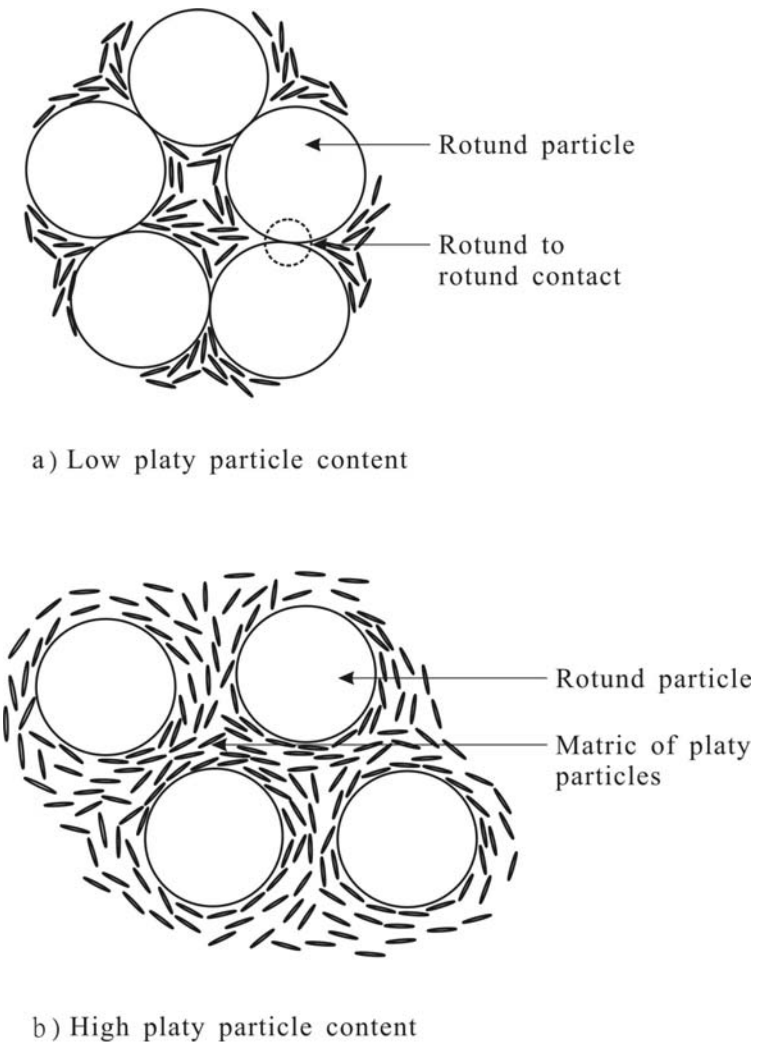


Figure 4-11. Idealized particle interaction in non-aggregated gold tailings.

The postulated models indicate significantly different modes of particle contact in aggregated and non-aggregated gold tailings. The behaviour of cohesionless soils such as gold tailings is dominated by mechanical particulate interaction, and thus it can be expected that some difference in behaviour will be observed in the test samples. Aggregation has been shown to affect the behaviour of natural and artificial soils and this is discussed in the following section.

4.3.3 The effect of aggregation on the behaviour of soils

An aggregated fabric can affect the mechanical behaviour of a soil. Engineering behaviour of cohesionless soils is dominated by mechanical interaction between the particles. In the case of gold tailings, this includes the rolling or sliding of rotund particles and the bending or sliding of platy particles. The possible effects of aggregation on the engineering behaviour of gold tailings will be discussed on a particulate level in this section.

Hydraulic conductivity

Aggregated soils consist of inter-aggregate pores (pores between aggregates) and intra-aggregate pores (pores between particles within aggregates). The inter-aggregate pores are larger and more continuous, while the intra-aggregate pore system is smaller and less continuous (Horn et al., 1995). The large inter-aggregate pores facilitate the movement of water through the soil, resulting in a higher permeability in aggregated soils in comparison with homogeneous soils.

Compressibility

Olsen and Mesri (1970) investigated the compressibility behaviour of ground muscovite and concluded that at high consolidation pressures, compressibility and swelling are governed by the flexure of the nearly parallel platy particles. In gold tailings, however, platy particles are actively or passively located between the rotund particles in a random orientation. Compressibility should thus be controlled by the mechanical sliding of the platy particles relative to each other and also relative to the rotund particles.

Matyas et al. (1984) investigated the compressibility of uranium tailings samples and concluded that the fine tailings appear to be more compressible than the coarse tailings. This was noted by other researchers such as Robertson (1987) and Vermeulen (2001). The compressibility of the undisturbed fine silt sample was also higher than its reconstituted version. It is, however, unclear whether moist tamping was used to prepare the reconstituted samples.

According to Terzaghi (1925), the compressibility of cohesionless materials is determined by the grain size, uniformity, volume of voids and mica content. Aggregation in gold tailings can be viewed as a form of heterogeneity which may affect the compressibility of gold tailings. Particle interaction in moist tamped samples may be similar to that of sand-mica mixtures. Moore (1971) showed that the compressibility of sand could be increased with the addition of mica. It seems that the introduction of mica between the sand particles increases the compressibility of the mixture. The mica-sand mixture is analogous to gold tailings, which is essentially a mixture of platy and rotund particles. Mica is generally significantly larger than typical tailings platy particles, and is less affected by surface forces. The analogy of mica-sand mixtures to gold tailings would then be invalid, as surface forces between platy particles may yield a stiffer sample with lower compressibility.

Stiffness

The small strain shear stiffness G_{max} of undisturbed and moist tamped silty sand tailings and natural silt samples at similar void ratios was investigated by Høeg et al. (2000). They concluded that G_{max} obtained for moist tamped samples is generally 20 to 30% lower than that obtained for the undisturbed samples. As no evidence of cementation was found, the effect was ascribed to differences in the fabric.

The stiffness of a soil is a measure of the deformation response to a given stress increment. A sample with high compressibility also has a lower stiffness. It is expected that undisturbed and slurry samples which have more uniform fabric will have higher small strain stiffness than moist tamped samples which are dominated by platy contacts. At medium and large strains the stiffness should converge to a unique value which is material dependent, as all fabric is progressively destroyed upon continued shear.

Shear behaviour

It has been shown by researchers such as Zlatovic and Ishihara (1997) that the effective angle of friction is independent of the fabric, as all fabric is destroyed when the sample reaches the ultimate condition.

According to Horn et al. (1995), undisturbed, aggregated soils have higher strength than homogenized soils, but both are significantly lower than that observed for a single aggregate. The stress-strain curve for the aggregate also shows a clear peak corresponding to the strength of the aggregate where after the strength decreases drastically upon continued straining.

According to the postulated particle contact model, moist tamped samples will demonstrate strain-softening behaviour when the platy contacts between the aggregates disintegrate.

4.4 SUMMARY

The chapter presented the fabric of gold tailings observed from SEM images of samples tested as part of the experimental programme. The SEM images showed that some visible differences could be observed in the fabric of gold tailings. According to the fabric observed, modes of particle interaction were postulated. In the next chapter, the observed behaviour will be explained in accordance with the postulated particle contact model.