REPORT ON THE PRELIMINARY TESTS ON THE TRANSALLOYS Mn SLAG TO CONSIDER ITS SUITABILITY AS AN AGGREGATE IN CONCRETE

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CLIENT

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Note: This report has been written in a style that is instructive, with the view of promoting understanding for the reader who may not be a qualified concrete technologist or acquainted with the various tests and methods used in testing concrete and its constituent materials.

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1 Background and scope

Dr Van Niekerk was appointed by Infotox (Pty) Ltd (on behalf of Transalloys (Pty) Ltd, to assess the suitability of using the Mn slag produced through their facilities and processes as aggregate in concrete. To conduct the assessment, a site visit had to be conducted at the Transalloys plant complex and associated Mn slag dump. The plant is situated on the Remaining Extent of Portion 34 of the farm Elandsfontein 309 JS near eMalahleni. The samples were taken to do the "fit for purpose" test to consider whether the current Mn slag will be suitable for use as an aggregate in concrete. The Mn slag samples were further subjected to the following tests:-

- Grading: to determine whether the crushed Mn slag has a grading that is suitable for concrete material/use.
- Lumps of iron: to assess whether the Mn slag is suitably free of iron particles so that concrete structures, when exposed to rain or dampness, does not show later exhibition of brown stains.
- CaO lumps: to assess if the Mn slag is free of calcium oxide lumps to ensure that no surface craters appears later after use.

2 Sampling procedure

The initial plan was to take five samples from the Mn slag dump for analysis. However, during the further assessment of the Mn slag dump, it became apparent that the anticipated number of samples will not be a representative sample; instead five additional random samples were taken, to bring the total of the samples taken to ten. The Mn slag samples were taken from the new arisings material disposal on top of the slag dump at a space of 30 meters apart, with each sample consisting of at least two shovels. The view of the Mn slag dump and the specific areas where samples were taken is shown in figure 2, below.

Figure 1: View of the top of the Mn slag dump

It was further observed that the Mn slag dump consisted of a mixture of coarse and fine aggregate material as depicted in figure 2 below and that the proportion of fine to coarse aggregate varied considerably across the Mn slag dump, but generally the coarse aggregate is dominant as is evident in figure 3.

Figure 2: **Closer view of the Mn slag at the top of the dump – In this picture both coarse and fine aggregate are noticeably present.**

Figure 3: **The visual assessment showed that there was a greater proportion of course aggregate, and in places virtually no evidence of fine aggregate as in this picture.**

An additional sample (Sample 11) of the washed aggregate with particles size minus 7mm and plus 0.63mm, was collected presumably from a stockpile near the washing/screening plant, and finally a sample of the washed minus 0.63mm material (Sample 12) was collected from the Mn slimes dam.

3 Laboratory tests

3.1 Grading

During the laboratory analysis, the twelve samples were homogenised and spread out in an even layer on plastic bags and exposed to the direct sunlight as shown in figure 4, to allow the material to dry out. Following the exposure of the material to the sun and the drying process, the samples were further quartered (figure 5) to obtain a more manageable quantity for the sieve tests.

Figure 4: **The twelve samples were spread out on plastic bags and left to dry in the sun**

The samples were first put through a nest of six sieves with aperture sizes 37.0mm, 26.5mm, 19mm, 13.5mm, 9.5mm and 6.7mm for determining the 'coarse aggregate' grading, and this was followed by putting the minus 6.7mm fraction of each sample through a second nest of sieves with sizes 4.75mm, 2.36mm, 1.18mm, 0.6mm, 0.3mm, 0.15mm and 0.075mm to obtain the 'fine aggregate' grading. The two nests of sieves are respectively shown on the LHS and RHS of figure 5.

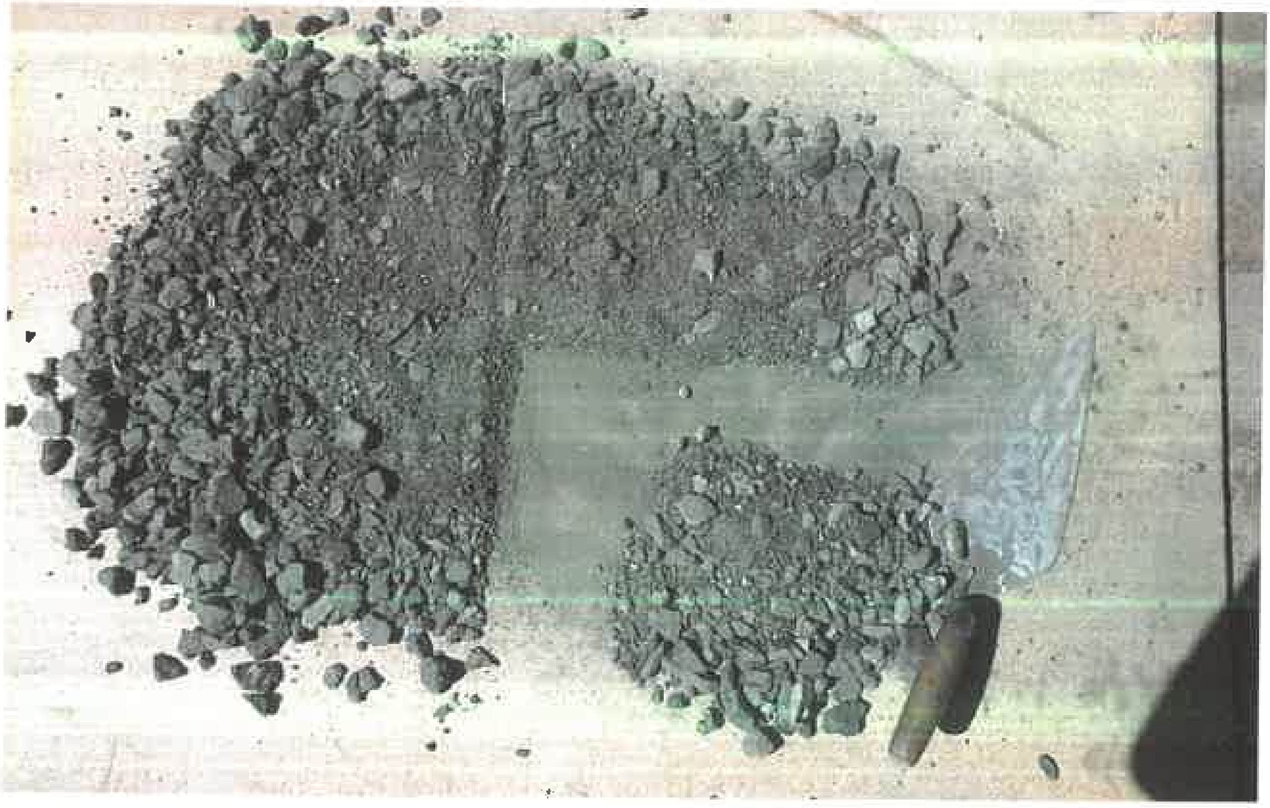


Figure 5: The samples were quartered down to approximately 2kg in preparation for the sieve test

Figure 6: Two nests of sieves were used for separating the samples into coarse aggregate (see LHS nest) and fine aggregate (see RHS nest).

3.2 Iron particles

After determining a particular fraction on a particular sieve as part of the grading procedure, the fraction was poured into a plastic container, spread out, and then a relatively strong magnet was held just above the face of the material and moved over the full area as indicated in figure 7 below.

The material that was lifted by the magnet, as demonstrated in figure 8, was then wiped off into a bowl. This procedure was continued until virtually all the magnetic material had been removed from the container to the bowl.

Following the above step, the mass of the magnetic material was recorded. This procedure was repeated for all the sieves of a particular grading, until the magnetic particles for the whole sample had been cumulatively transferred into the bowl and then photographed. The final contents of the bowl therefore contained a variety of sizes as may be seen in figure 9 below.

Note that figure 7 and figure 8 relates to the very fine fractions of Sample 12, representing the Mn slimes dam material sample – hence the absence of any coarse particles in the bowl for this specific sample.

Figure 7: **A magnet was held just over the top of the various fractions of each sample to lift the magnetic material (in this case for sample 12).**

Figure 8: The magnetic material may be seen to cling to the base of the magnet before being wiped off into the bowl

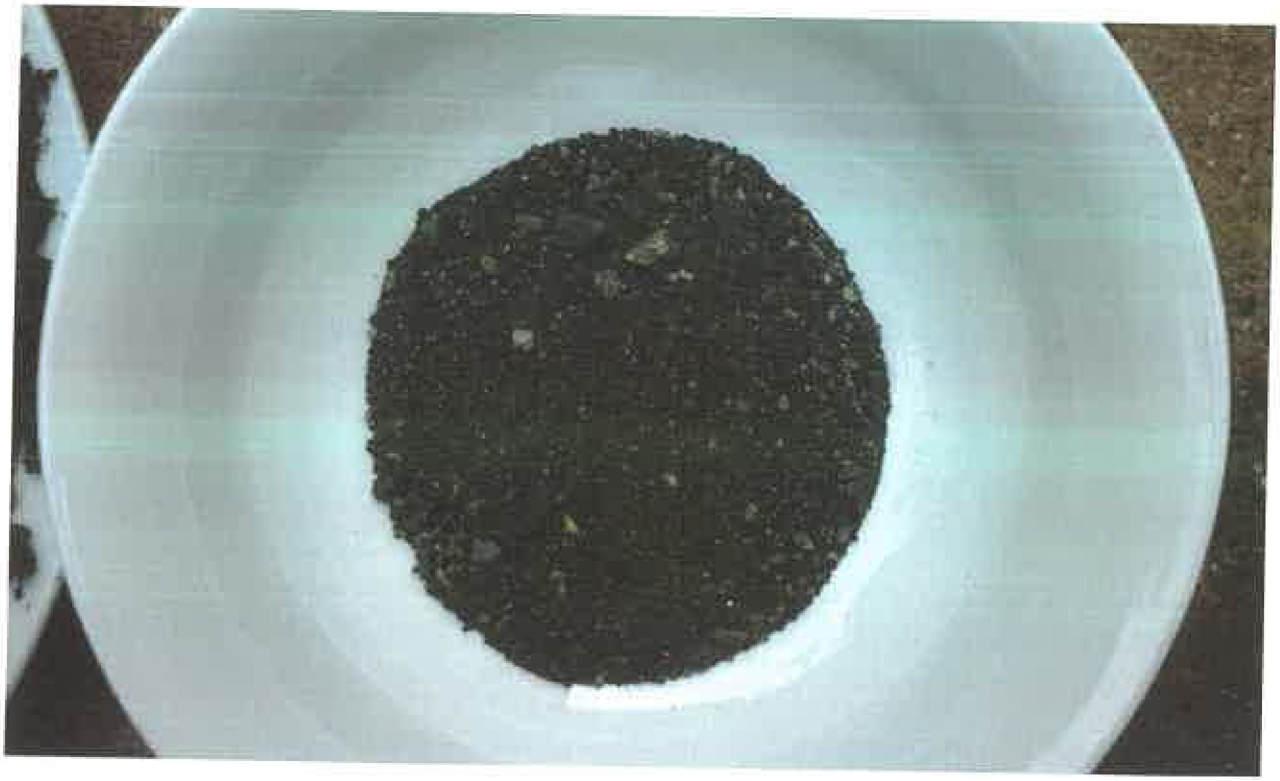


Figure 9: Combined magnetic material from all the sieves - corresponding to Sample 1 in this case. It is clear that there are a variety of sizes, from the lifted material from each sieve, but no particles above 9,6mm were lifted – except for one exception.

3.3 Calcium oxide lumps

In order to check for lumps of calcium oxide, disc-shaped mortar specimens were made using 40mm segments of a PVC pipe as the 'moulds', then a mortar mix was prepared using the fine aggregate material from each sample, except that in the case of samples 6 and 7, which had so little or less fine aggregate and there was no enough or adequate material for making the required discs, and hence only 10 discs were made in total – refer to figure 10 below. Thereafter the discs were placed in a pressure vessel (figure 11) and steamed at low pressure for at least 10 hours (figure 12). After cooling, the discs were inspected for 'pop outs'.

(It should be noted that the lime lumps are generally small, usually less than 5mm, and hence mortar discs suffice for this test. It would have been impractical to test for concrete as the samples would have to be substantially larger to accommodate the coarse aggregate – for example, 100mm cubes, which take up more space in the pressure vessel).

Figure 10; **Disc shaped specimens made from the fine aggregate of the various slag samples.**

Figure 11: Discs inside pressure vessel.

Figure 12: Low pressure steam vessel

4 Results

The results will be considered under the three 'show stopper' criteria for a concrete aggregate as follows:

4.1 Grading

4.1.1 Grading results for the fine aggregate on the Mn slag dump

The results of the fine aggregate grading's done on the Mn slag dump samples are shown in figure 13, where 10 graphs are shown with respective titles 'Sample 1FA' to 'Sample 10FA'. The X axis represents the size of the particles, and the Y axis represents the percentage passing through the various sieves.

The grading results are indicated by the blue curve in each case. The ideal envelope for concrete fine aggregate as recommended by the Cement and Concrete Institute (C&CI) are represented by the green and red curves, where the green curve is the recommended fine limit, and the red curve is the recommended coarse limit. Thus if the blue curve is above the green curve the corresponding sample is finer than recommended. Conversely if the blue curve is below the red curve the corresponding sample is coarser than recommended.

Findings and interpretation:

It is evident that most of the samples were too course as evidenced by Samples 2, 3, 4, 5, 8, 10. The blue curve in Sample 1 followed the coarse limit quiet closely, except that it was lacking in the finer fractions below 0.6mm. Samples 6 and 7 were too coarse in the coarser fractions and too fine in the finer fractions. Sample 9 was too fine throughout.

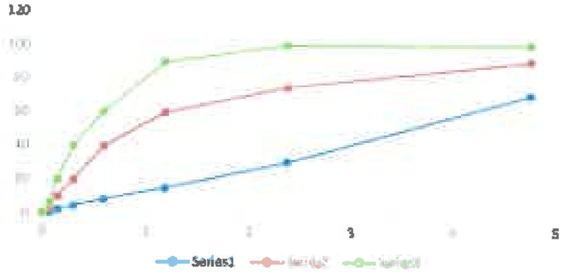
In fine aggregate the most important fractions are the finer fractions, especially the 0.15mm, 0.3mm fractions, as they influence the concrete's workability (easy to mix, place, and vibrate). Also, too little of the finer fractions will result in 'bleeding' (water coming to the surface after placement). Hence while samples 3, 4, 5, 6, 7 can be described as coarser than ideal with regard to the coarser fractions (1.18mm to 4.75mm), this aggregate will nevertheless have good workability as the finer fractions are within the required envelope recommended by the Cement and Concrete Institute.

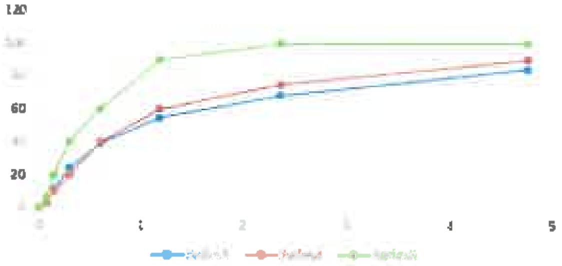
Conversely Sample 1 is within the envelope for the coarser fractions, but is too coarse with regard to the finer fractions which will negatively affects the concrete's workability and bleeding performance. Samples 2 and 10 are too coarse for all fractions and will have poor workability and severe bleeding.

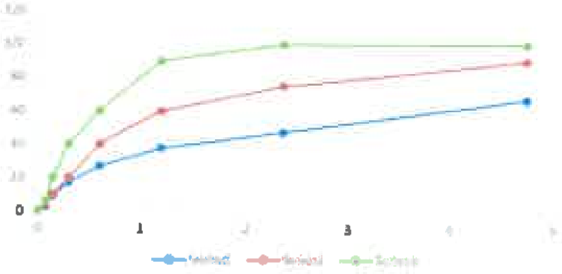
On the other hand, sample 9 is too fine, and this will make it substantially 'cohesive' and 'sticky', negatively affecting its workability. Concrete made with too much fine material is also likely to require more water (increased water demand) which will negatively affect its strength and result in increased plastic shrinkage and later on drying shrinkage – these are more serious defects as they affect important performance characteristics of concrete.

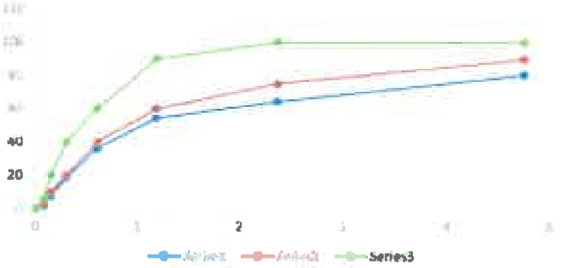
In figure 13 the varying position of the blue line indicates that the fineness of the fine aggregate fluctuates considerably depending on where the samples were taken on the Mn slag dump. But it does appear that there is something of a balance between the fine and coarse gradings, which suggests that if the fine aggregate is homogenised, as suggested in figure 18 (section 4.1.6), the resultant grading may fall within the envelope.

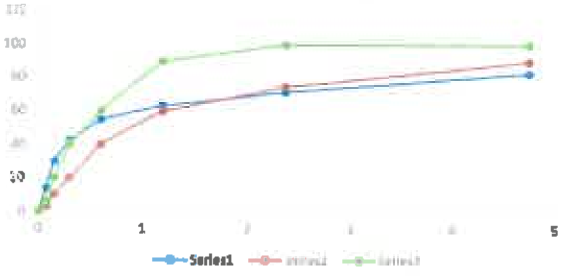
It should also be noted that the C&CI ideal envelope is only a guideline, and it is possible to produce perfectly good concrete with a fine aggregate that falls outside this envelope. One of the ways of assessing a fine aggregate in this regard is to make a mortar specimen and check its workability. This was in fact done, quite fortuitously, although only in a very qualitative way, in the process making the discs of section 3.3, and it was found that in general the mortar mixes had good mixing and flow properties.

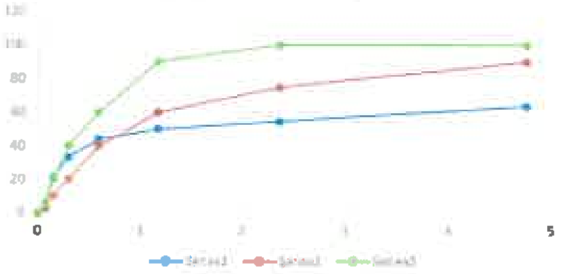

Sample 2FA - 30m on top of dump


Sample 3FA - 60m on top of dump


Sample 4FA - 90m on top of dump


Sample 5FA - 120m on top of dump


Sample 6FA - 150m on top of dump


Sample 7FA - 180m on top of dump

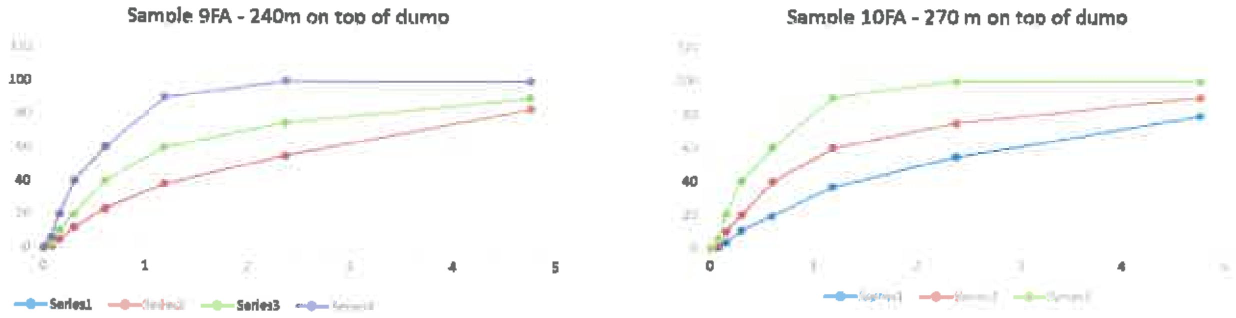


Figure 13: Grading Analysis of Fine Aggregate samples from the dump

4.1.2 Grading results for the minus 7mm aggregate (Sample 11)

Figure 14 shows the result of the grading analysis of the minus 7mm aggregate taken presumably from a stockpile near the screening/washing plant. (It was explained to the writer that after the minus 7mm fraction is screened/washed, it is taken to a metal recovery plant, after which it is presumably stockpiled separately).

Sample 11 is clearly far coarser than any of the fine aggregate samples from the dump, and is also characterised by the virtual absence of the 0.6mm, 0.3mm, 0.15mm, and 0.075mm fractions - testimony to the effectiveness of the washing operation and subsequent screening out of these fractions through a 0.63mm screen.

Findings and interpretation:

The material is too fine to be used as coarse aggregate, but also too coarse to be used as a fine aggregate in conventional concrete as typically used in concrete structures. However, it may very likely be useable as the 'coarse aggregate' in the *manufacture of bricks* and *concrete pavers* where 'semi-dry' concrete is used, and where the coarse aggregate must be substantially finer – to ensure that the resultant appearance of the brick/paver is not rough and to prevent damage to the specialised moulds used in the highly automated machines which are used to make/produce these products.

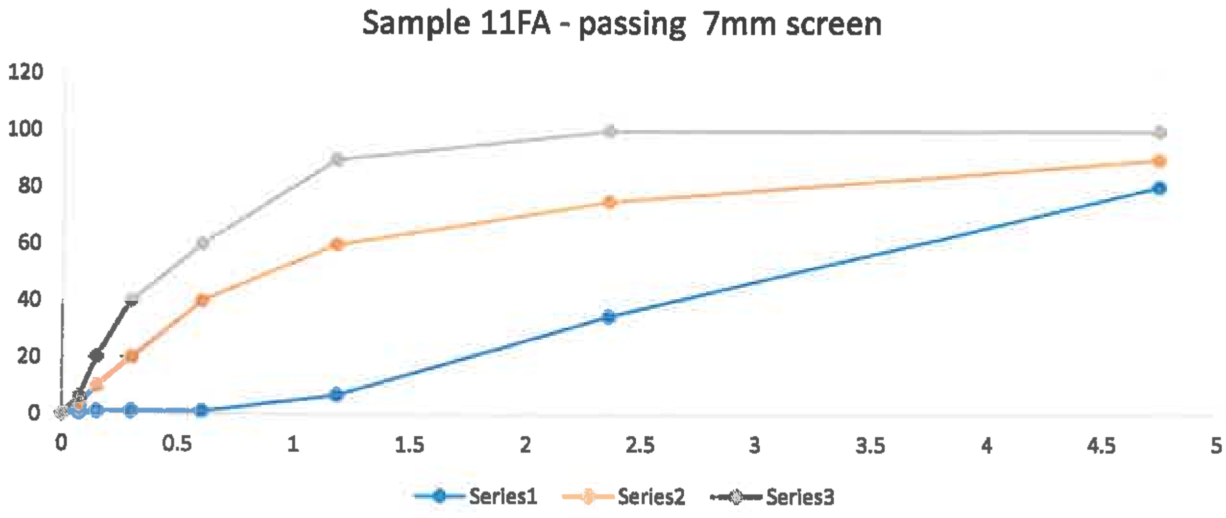


Figure 14: Grading Analysis of minus 7mm Fine Aggregate – Sample 11

4.1.3 Grading results for the minus 0.63mm slimes material

Figure 15 shows the grading analysis of the sample from the Mn slimes dam. It lies completely out of the ideal grading envelope on the fine side, and is characterised by a complete of absence of particles larger than 0.6mm, which is not surprising as the material on the Mn slimes dam is washed through a 0.63mm screen. Furthermore it may be seen that 60% of the particles are smaller than the 0.075mm screen (less than 75 microns).

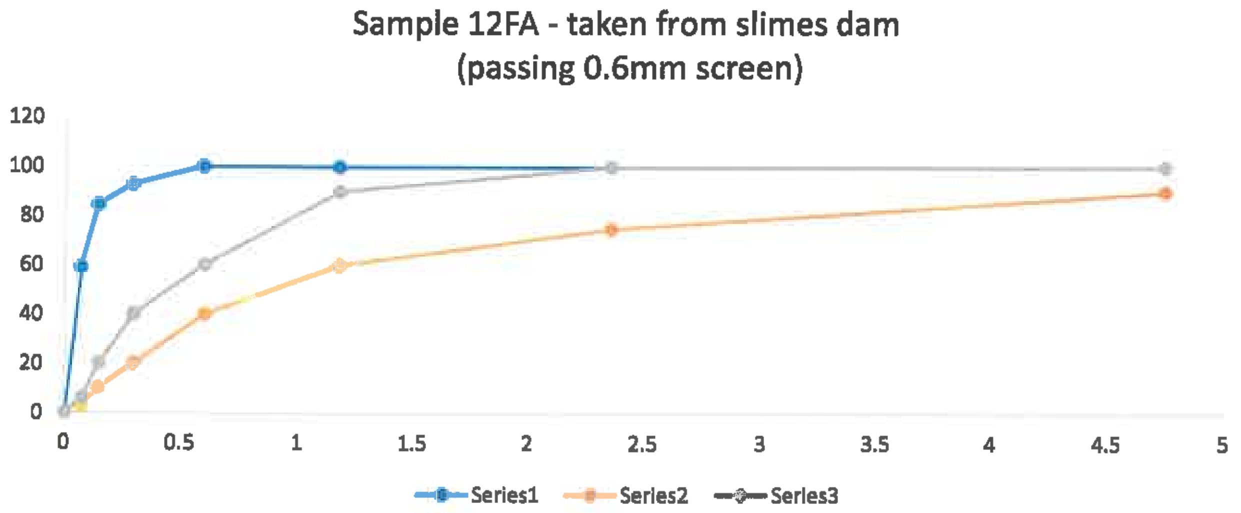


Figure 15: **Grading analysis of fine material from tailings dam**

Findings and interpretation:

While a small percentage of very fine material such as minus 0.075mm in the fine aggregate is not detrimental to concrete, up to 5%, and even 10% in some instances, if the ultra-fines goes up to 60%. There will be a significant reduction in the compressive strength and a substantial increase in plastic shrinkage and later on drying shrinkage. These are most undesirable properties in concrete. The material from the Mn slimes dam should therefore not be considered for use in concrete.

4.1.4 Grading results of the coarse aggregate on the Mn slag dump

Figure 16 below shows the results of the 10 coarse aggregate grading analyses corresponding to the 10 samples. (See 3.1 for methodology). The coarse and fine limits are given in SABS-1083 and for a 19mm aggregate may be stated as:

- 100% should pass through the 26.5mm sieve.
- 85% to 100% should pass through the 19mm sieve
- 0% to a maximum of 50% should pass through the 13.2mm sieve.
- 0% to a maximum of 25% should pass through 9.6mm sieve.
- 0% to a maximum of 5% should pass through the 6.7mm sieve.

In figure 16 (as with figure 13) the fine limit is shown by the green curves and the coarse limit is shown by the red curves. The curve representing the grading of the samples is shown by the blue curve.

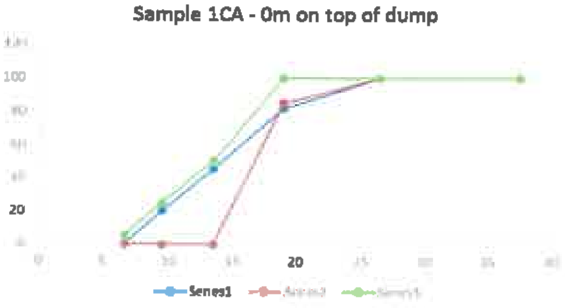
The following observations may be made with regard to the coarse grading curves of the various samples:

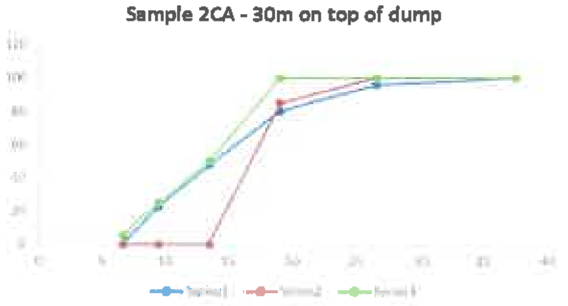
(a) Sample 1: The grading curve was within the envelope except that 82% of the aggregate was finer than 19mm, whereas only 85% finer is recommended.
(b) Sample 2: The grading curve was within the envelope except that 80% of the aggregate was finer than 19mm, whereas only 85% finer is recommended, and 96% was finer than 26,5mm whereas 100% should be finer.
(c) Sample 3: Same comment as sample 1 (in this case 83% was finer than 19mm – it should be 85% to 100%)
(d) Sample 4: Same comment as sample 2 (in this case 72% was finer than 19mm and 96% finer than 26.5mm)
(e) Sample 5: The grading curve was within the envelope except that 52% of the aggregate was finer than 13.5mm, whereas only 50% finer is recommended.
(f) Sample 6: The grading curve was substantially too coarse, with just 80% of the aggregate finer than 26.5mm, whereas 100% finer is recommended, and 25% was finer than 19mm whereas a minimum of 85% finer is recommended.
(g) Sample 7: Same comment as sample 2 (in this case 61% was finer than 19mm and 98% finer than 26.5mm)
(h) Sample 8: Same comment as sample 5 (in this case 59% was finer than 13.5mm whereas only 50% finer is recommended).
(i) Sample 9: Same comment as sample 2 (in this case 69% was finer than 19mm and 95% finer than 26.5mm)
(j) Sample 10: The grading curve was within the envelope except that 60% of the aggregate was finer than 13.5mm, whereas only 50% finer is recommended, and 31% was finer than 9.5mm, whereas only 25% finer is recommended.

Findings and Interpretation:

The general trend in the results is that there is too much aggregate coarser than 19mm and in three of the samples there was too much aggregate finer than 13.5mm. However, this is does not necessarily mean that the coarse aggregate in the Mn slag dump is unusable. On the contrary, with some screening and homogenization (see section 4.1.6) the coarse aggregate could quite easily fall within the 19mm envelope.

It has been observed that the coarse aggregate from the Mn slag dump is somewhat angular in shape and has sharp edges relative to an ideal aggregate (which would be rounder or more cubical in shape and have blunt edges). This does not make it unsuitable for making excellent concrete, but the mix should be skilfully designed by a concrete technologist to take this into account and to ensure that it has good workability.


Sample 1CA - 0m on top of dump


Sample 2CA - 30m on top of dump

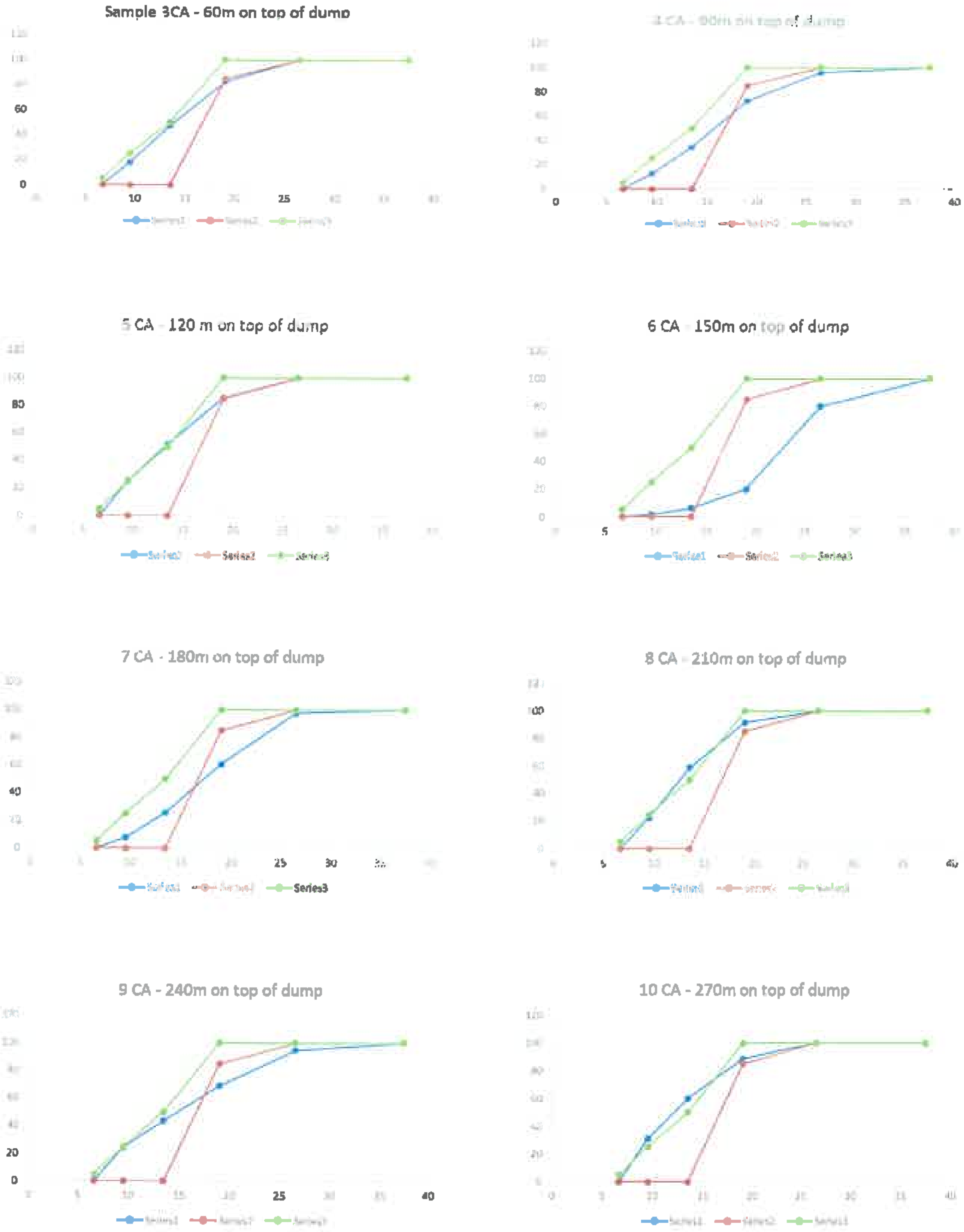


Figure 16: Coarse-aggregate grading-analysis for the 10 samples from the top of the Mn slag dump

4.1.5 Relative proportions of fine and coarse aggregate on the slag dump

It was mentioned earlier that the proportion of course to fine aggregate is not consistent on the dump, and this is qualitatively evident by comparing figure 2 and 3. It is also quantitatively demonstrated by figure 17 below – the data for this was obtained from the various grading analyses.

Findings and Interpretation:

Figure 17 shows that in six of the samples the proportion of coarse aggregate (blue) substantially exceeds the proportion of fine aggregate (orange), and only in four of the ten samples did the fine aggregate approximate to 50%.

Regardless of the percentages that are indicated in figure 17, before the aggregate on the Mn slag can be used for manufacturing concrete, the coarse and fine aggregate will need to be separated as referred to in section 4.1.6 above.

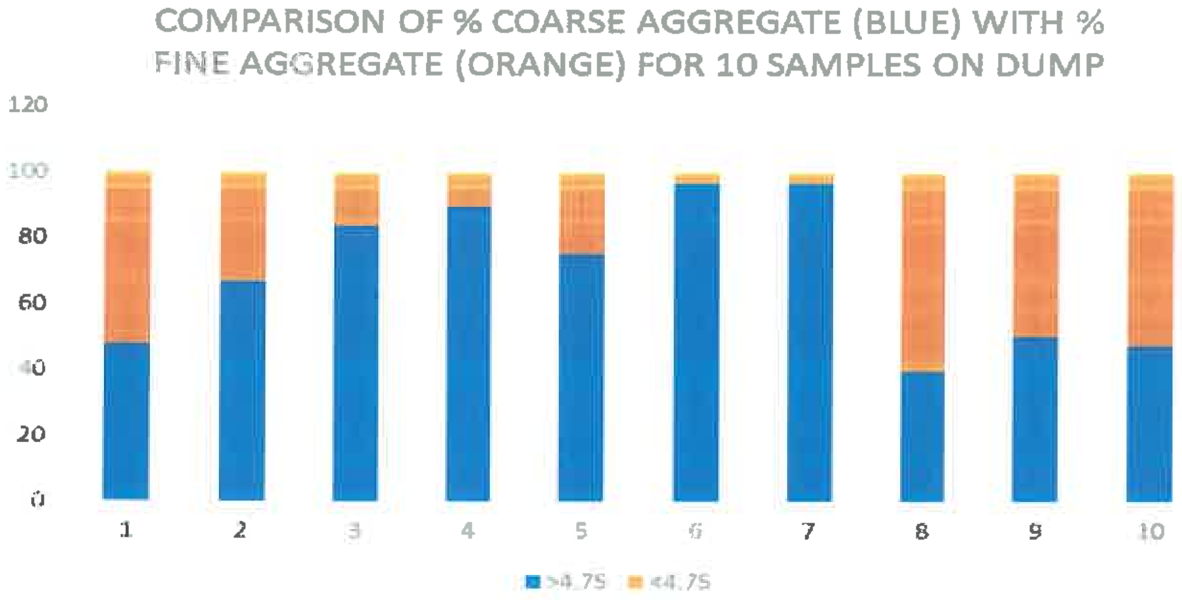


Figure 17: **Relative proportions of coarse and fine aggregate**

4.1.6 Suggested screening operation

Figure 18 shows a suggested screening arrangement to rework the Mn slag dump into three stockpiles of 38mm coarse aggregate, 19mm coarse aggregate, and fine aggregate. It may be seen from figure 16 that the +26mm,-38mm fraction (38mm coarse aggregate) for the 10 samples is respectively 0%,4%,0%,4%,0%,20%,2%,0%,5%,0%, or an average of 3.5%. Thus while 38mm aggregate is not in great demand, there are a number of applications for which it would be quite suitable, and in fact superior to 19mm. If this material is sold at a discount price there is every likelihood that it will not mount up into a large unwanted stockpile, and especially as it only represents 3.5% of the coarse aggregate, and even less of the total material in the Mn slag dump, perhaps 2%. (Noting that these numbers are based on only ten samples, which probably do not accurately represent the true proportions of the materials in the Mn slag dump).

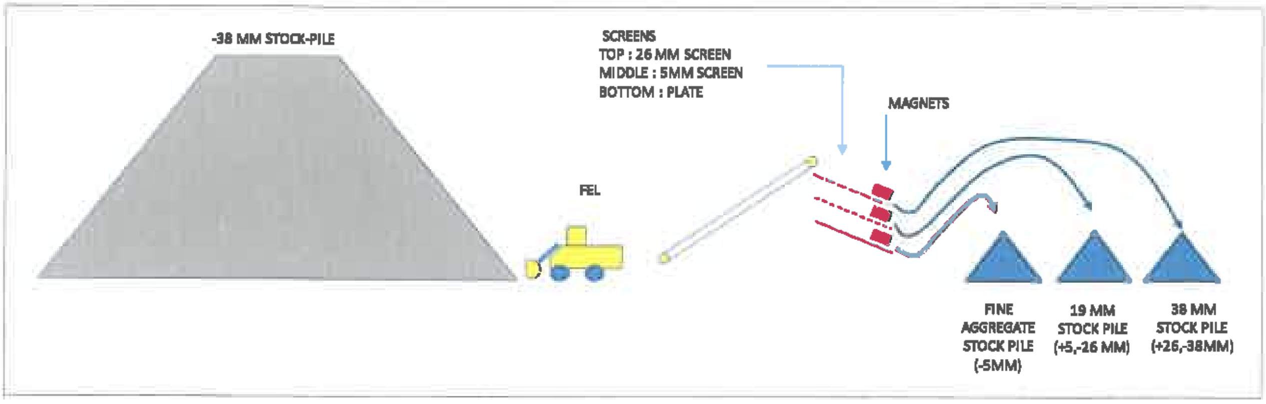


Figure 18: **Suggested screening arrangement to rework the dump into 26mm coarse aggregate, 19mm coarse aggregate, and fine aggregate.**

It should be noted that by stockpiling the three aggregate streams into cones, a significant amount of homogenization occurs, i.e. averaging out the differences in the curves associated with figure 12 for fine aggregate and figure 16 for coarse aggregate. Moreover, with some tweaking and perhaps an additional screen, it may be possible to keep the grading within the C&CI envelope for course and fine aggregate.

4.1.7 Mn slag new arisings

For the Mn slag new arisings, some tweaking of the cone crusher is advised to ensure that at least 85% of the Mn slag is finer that the 19mm size and this will also have the effect of reducing the plus 26.5 mm fraction to a negligible amount.

Findings and interpretation:

Although the majority of the aggregate in the Mn slag dump is course aggregate, there is still a significant percentage of fine aggregate, as is evident from figure 17. This raises the question: "How does it get there, given that all particles less than 7mm are removed at the screening plant and then presumably separately stockpiled?". At the same time, the minus 0.63mm material is removed and taken to the Mn slimes dam. So there should be no fine aggregate going to the Mn slag dump – and yet the grading's show this not to be the case.

4.2 Magnetic Particles

As already mentioned, concrete made with an aggregate that has a percentage of iron particles is likely to develop some brown stains at the surface if it is exposed to rain or damp conditions. While this does not pose a threat to its structural integrity, it can be aesthetically unacceptable in a building or paved surface for example.

The iron particles that are embedded 15 mm or more are unlikely to corrode as the highly alkaline environment at this depth with a pH around 12.5 is likely to be maintained for the life of the structure – the high pH come coming from the cement. On the other hand, iron particle close to the surface, are more likely to corrode as the products of cement hydration near the surface react with the carbon dioxide in the atmosphere and 'carbonation' occurs, resulting in a drop in the concrete's pH in this region, and once the pH drops below 9, the iron lumps will begin to corrode. Noting that the ingress of CO2 is much slower in dense well compacted concrete, with relatively high cement content – it is unlikely to go deeper than 5 to 10mm, but for poorly compacted concrete with low cement content, it could easily reach 30mm in the course of ten years.

The percentage of iron in samples 1 to 11, obtained according to the procedure described in 3.2 is illustrated in figure 19. The average iron content of the ten samples taken from the Mn slag dump was 1.45%, and this is significantly less than that of sample 11, with a magnetic content of 2.5%.

An interesting phenomenon occurred with sample 12 (representing the Mn slimes dam material) in that a far greater percentage of this material was lifted by the magnet, a total of 55%. In fact, about three times more material was magnetically lifted in sample 12, than with the other 11 samples combined – as illustrated in figure 20.

Findings and Interpretation:

It is unlikely that just because 55% of sample 12 can be lifted with a magnet that 55% of the Mn slimes dam is iron. It may have something to do with the fineness of the material in the sample – so the finer and lighter the particles the less iron is required in the particles for them to be lifted. On the other hand it, it may be that there is a relatively high content of iron in the minus 0.63mm slime material and this should be further investigated.

The grading results also showed that particles above 9.6mm in size were not lifted by the magnet, except in one instance. While it is likely that there were iron particles present in the larger aggregate, embedded on the outside or inside, the increasing gravitational pull with increasing size of aggregate exceeded the magnetic force acting on the relatively small embedded iron lumps. Fortunately such lumps are unlikely to be a nuisance with regard to staining as generally the larger aggregate particle will keep it away from near the concrete's surface where carbonation occurs.

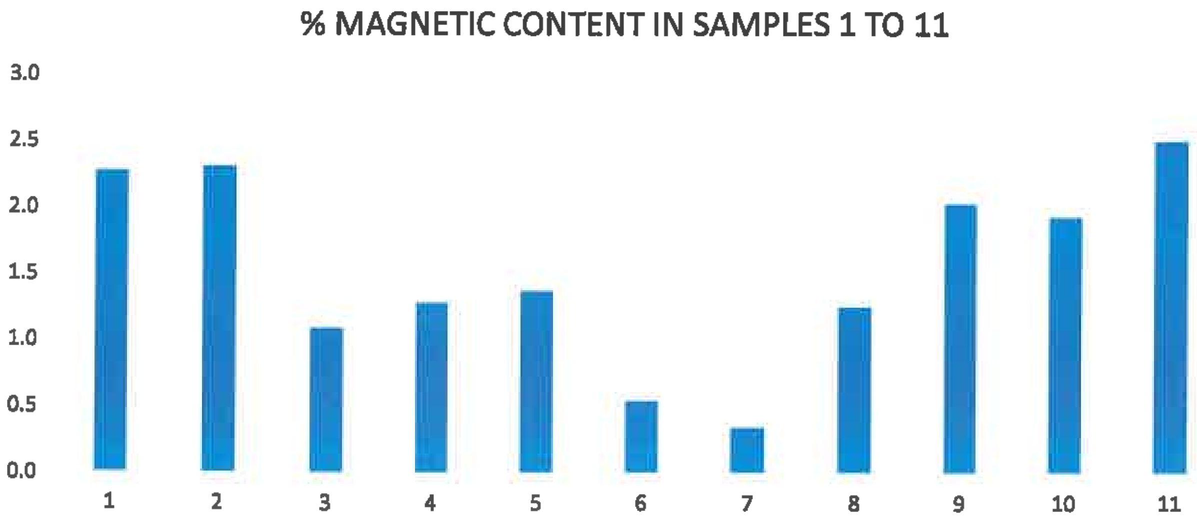


Figure 19: **Percentage of magnetic material in samples 1 through 11**

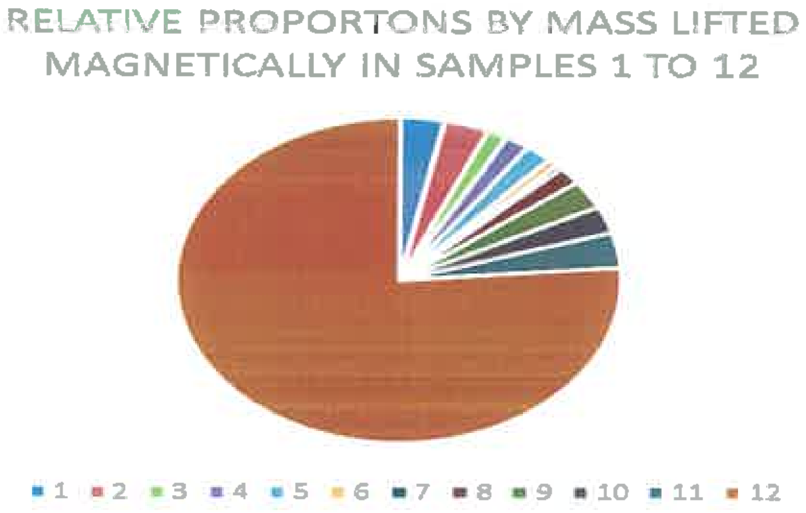


Figure 20: **Relative percentage of lifted material for samples 1 through 12.**

4.3 Calcium oxide lumps

There was no evidence of 'pop out' craters in the concrete discs that had been subjected to low pressure steam for over 10 hours. This indicates that the fine aggregate is substantially free from CaO and CaO.MgO lumps – a very positive result.

5 Conclusions and Recommendations

Assuming that the ten samples taken on the Mn slag dump are roughly a representative of the Mn slag dump, the following conclusions and recommendations may be made:

(a) The coarse aggregate in the current Mn slag dump is suitable for concrete production, but if it is to be sold as a 19mm aggregate, which is the most popular size, then the plus 26,5mm fraction will have to be screened off – fortunately this is only about 3.5% of the total coarse aggregate. This aggregate should be separately stockpiled and can be sold as 38mm aggregate.

(b) The fine aggregate in the Mn slag dump should be screened off from the coarse aggregate.

(c) The 38 mm aggregate, 19mm aggregate, and fine aggregate should be stockpiled in a cone fashion to homogenise them – as indicated in figure 18.

(d) Even before homogenization the fine aggregate appeared to make a workable mortar during the making of the mortar discs (see 3.3). This workability should be confirmed by doing laboratory concrete mix designs on a homogenised fine aggregate.

(e) There does not appear to be any CaO or CaO. MgO in the Mn slag dump which is a very positive result.

(f) There is a small percentage of approximately 1.5% of iron in the fine aggregate from the Mn slag dump, and this will need to be removed before the aggregate can be used in concrete. To this end, it is recommended that powerful electromagnets be installed at the lower end of each of the screens and the vibrating plate – as indicated in figure 18. No expense should be spared in this regard to ensure that staining does not occur in years to come. (The advantage of installing the magnets at the lower end of the screens and plate is that the material will be bouncing and will also be thinly spread over the full width of the screen – clearly this will make the magnets more effective).

(g) There appears to be more than 50% of magnetic material in the Mn slime material and this phenomenon should be investigated further – it may even be that the slimes material can be used as a raw feed if it is shown to be high in iron content.

(h) Tests should be done with the -7mm aggregate that is screened off at the current washing/screening plant to check its suitability as a coarse aggregate in 'semi-dry' concrete such as is used in the production of concrete bricks, pavers, and some concrete pipe processes, etc.

(i) In conclusion, it appears from these preliminary tests, that the SiMn slag is fit for the purpose of making concrete, provided every effort is made to remove the iron lumps from the coarse and fine aggregate, and that this aggregate is suitably screened and homogenized.

(j) These preliminary tests should be followed by some of the more commonly used standard aggregate and concrete tests that will be of interest to material engineers, specifiers, and end users.